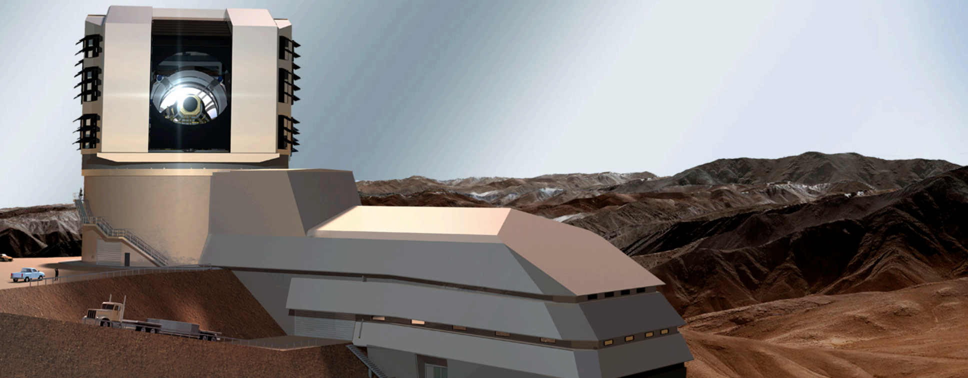
Robert Lupton
LSST Pipeline Scientist

How Bright Is That Object?

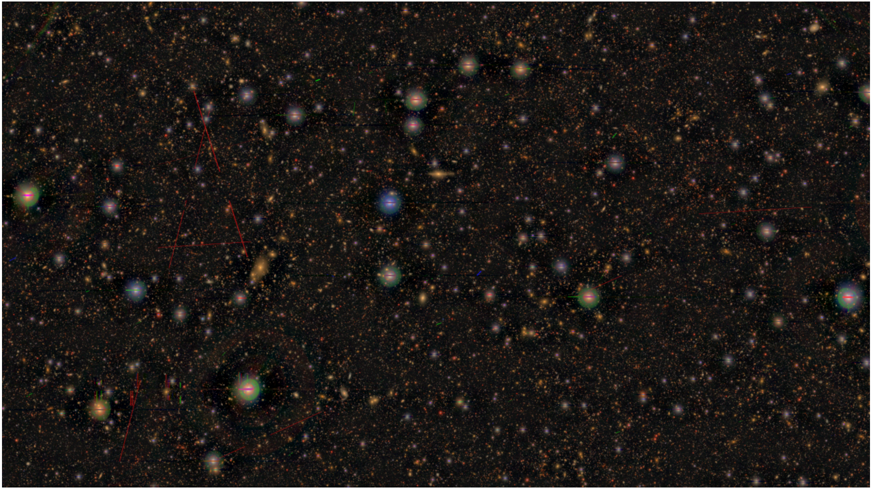
2017-06-12



What Will LSST Data Look Like?

The HSC project have have 1.5 hours per band in *gr*; *c.* 3 hours per band in *izy* in Cosmos (280/550 visits), and Michitaro Koike at NAOJ has written a nice tool ‘hscMap’ to visualise the true-colour images. I have an unofficial copy on my laptop, but here’s a link to NAOJ’s page.

What Will LSST Data Look Like?



g-r-i true-colour composite of COSMOS

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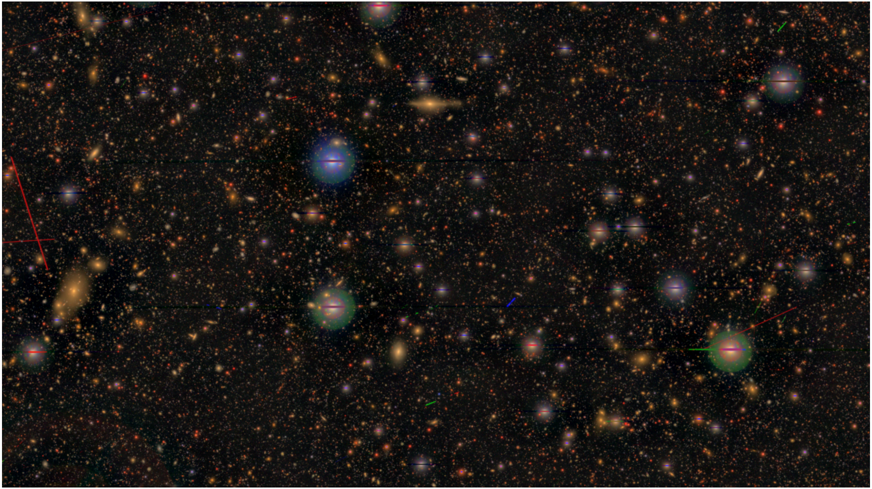

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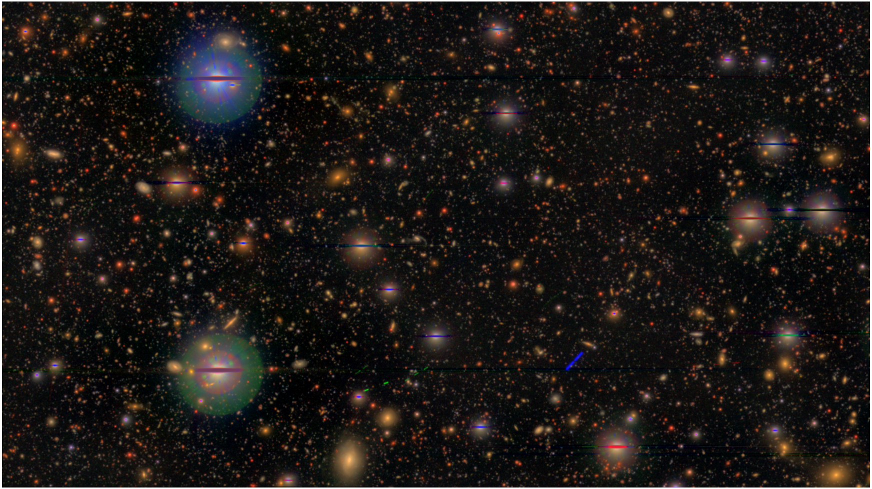

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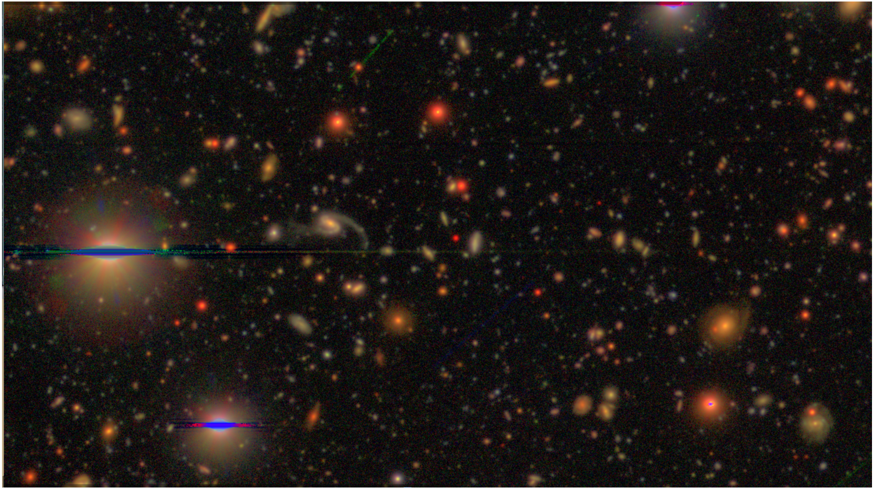

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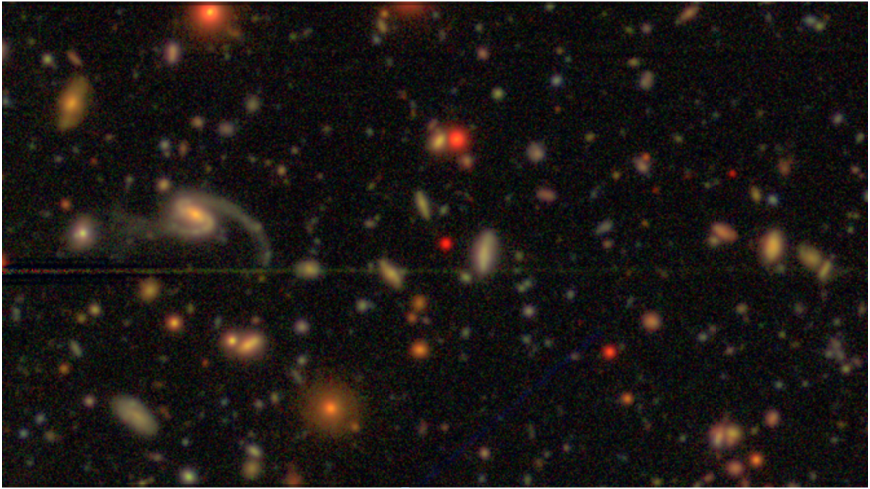

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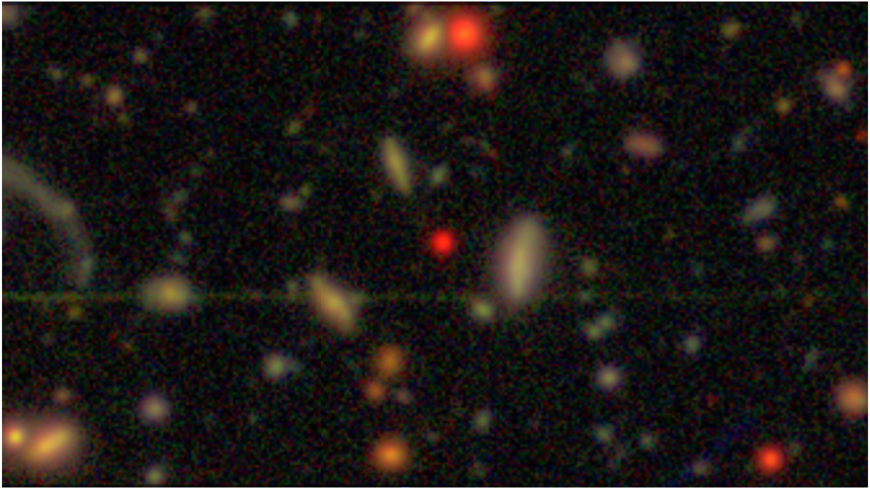

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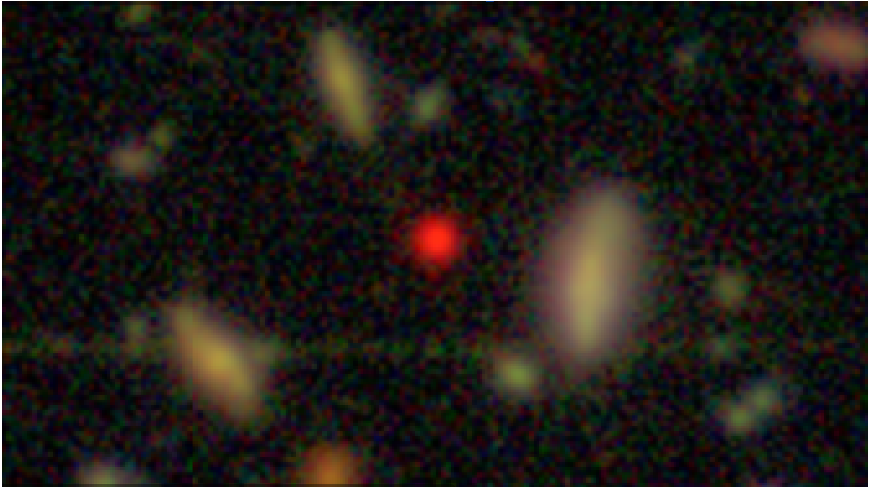

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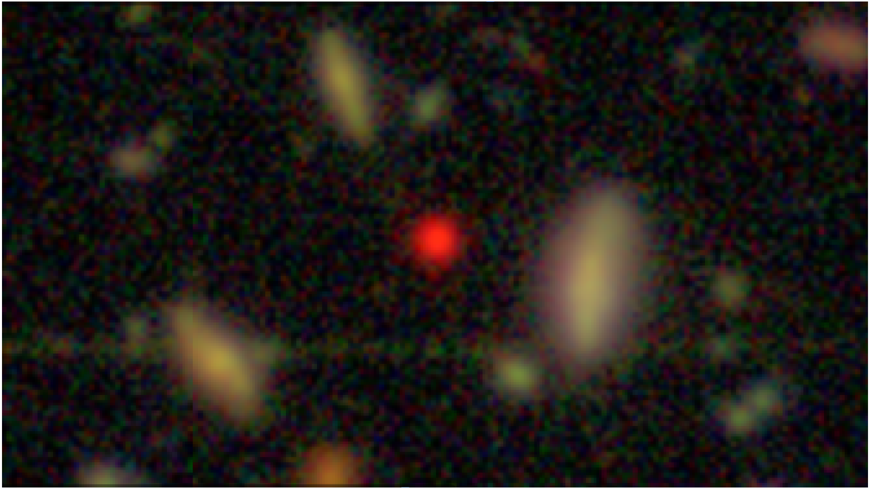
The Background Level



The background of the picture is black, but only because I've subtracted a pedestal from each image

Question 1: Whence comes the pedestal (‘sky’) level?

List as many contributions as you can to the ‘sky’ level.

Answer 1

Things I thought of were:

- Night sky emission (O_2, OH)
- Zodiacal light/Gegenschein
- Starlight scattered from the atmosphere
- Moonlight scattered from the atmosphere
- Galactic cirrus
- Extra-Galactic background

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- Night sky emission (Na, Hg, $\ldots$)
- Scattered and Ghost light from the telescope
- Dark current in the CCDs
- Glow from the ion pumps

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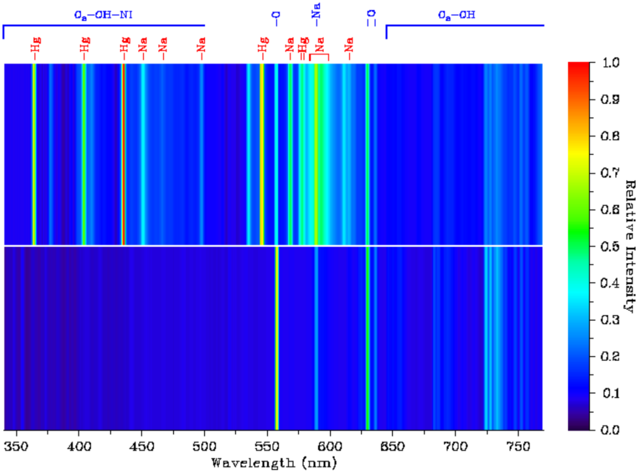
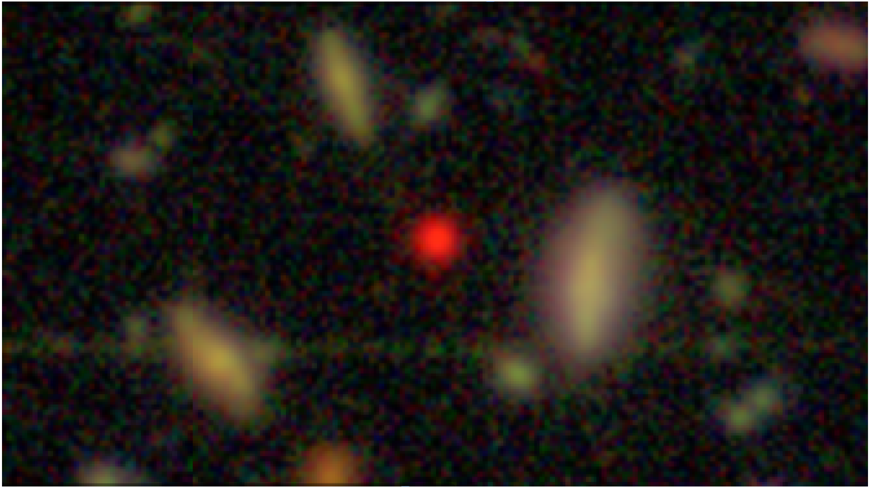


O₂–OH–NI
–O
–Na
=O
O₂–OH
–Hg
–Hg
–Hg
–Na
–Na
–Na
–Hg
–Na
=Hg
Na
–Na
350
400
450
500
550
600
650
700
750
Wavelength (nm)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Relative Intensity

The Background Level

Let’s ignore spatial structure in the sky; this isn’t really a good approximation but it would take us too far afield to address the problem. I’ve masked the obvious objects.



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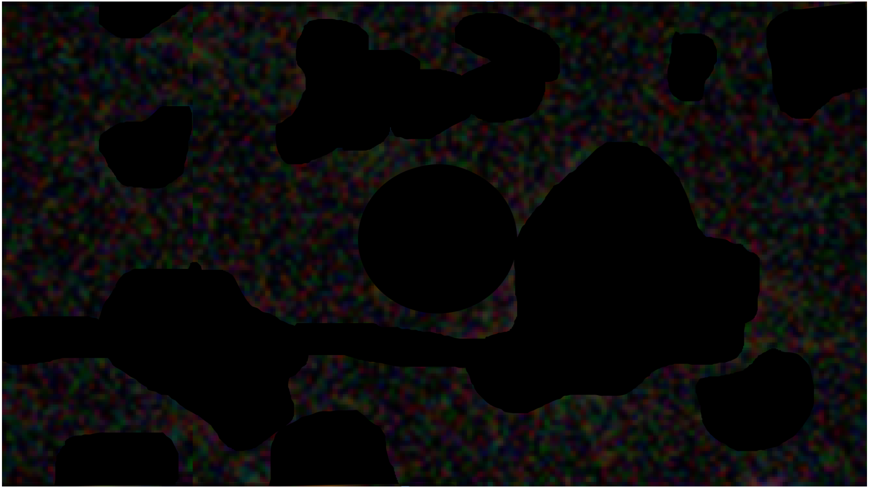

Question 2: What measurement on the unmasked pixels should I use to define the sky level?

Answer 2

Popular answers are:

- The Mean
- The Mode
- The Median
- A Clipped Mean

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We can subtract the background level, but we cannot (of course) subtract its noise.

Calibration

We really want to know how bright stars are in physical units such as Janskys ($10^{-26} W\, m^{-2}\, Hz^{-1}$) or AB magnitudes (zero-point 3631 Jy);

$$S_\nu[mJy] \equiv 10^{-0.4(m_{AB}-23.90)}$$

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These days we have standard stars over most of the sky (from SDSS and PanSTARRS, and soon DES). Even better, it seems likely that we'll be able to use GAIA to provide above-the-atmosphere standards over the entire sky.

Definitions

Let us assume that the star's profile, the PSF, is given by $\phi(\boldsymbol{x})$, normalised such that

$$\sum_i \phi(\boldsymbol{x}_i) = 1$$

and that its amplitude (and flux) is A, measured in electrons. Let's take the noise in the background ϵ to be homoschedastic and Gaussian: $N(0, \sigma^2)$ (*i.e.* the per pixel variance is σ^2)

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Let's agree to ignore uncertainties in the (subtracted) background level.

N.b. because we took A to be measured in electrons, each of which corresponds to a photon, A's standard deviation is $\sqrt{A}$.

Question 3: Does the pixelisation matter?

Our image is continuous, but we only measure its integral over a pixel.

How does this affect the PSF?

Answer 3:

We measure

$$\begin{aligned} I_p &= \int_{x_p-0.5}^{x_p+0.5} I(x)\,dx \\ &= \int_{-\infty}^{\infty} P(x-x_p) I(x)\,dx \\ &= (P \otimes I)\,(x_p) \end{aligned}$$

where

$$P(x) = \begin{cases} 1 & |x| \leq 0.5 \\ 0 & |x| > 0.5 \end{cases}$$

i.e. We replace the PSF ϕ by $\phi \otimes P$

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i.e. We replace the PSF ϕ by $\phi \otimes P$; but the latter is the function that we measure.
So the sampling causes no fundamental problems for the PSF, although it can make it (much) harder to measure if the data is not at least Nyquist sampled.

Question 4: Does the pixelisation matter?

Does the pixellisation have any affect on photometry for an image sampled no worse than the Nyquist rate?

Answer 4:

If we are well sampled,

$$I(x) = \sum_i \frac{\sin(\pi(x-i))}{\pi(x-i)} I_i$$

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A flux measurement is just an integral over the continuous image:

$$\begin{aligned}
F &= \int_a^b I(x) w(x)\, dx \\
&= \int_a^b \sum_i \frac{\sin(\pi(x-i))}{\pi(x-i)} I_i w(x)\, dx \\
&= \sum_i I_i \int_a^b \frac{\sin(\pi(x-i))}{\pi(x-i)} w(x)\, dx \\
&\equiv \sum_i w_i I_i
\end{aligned}$$

So we can perform photometry without loss of precision due to the sampling.

Bright Stars

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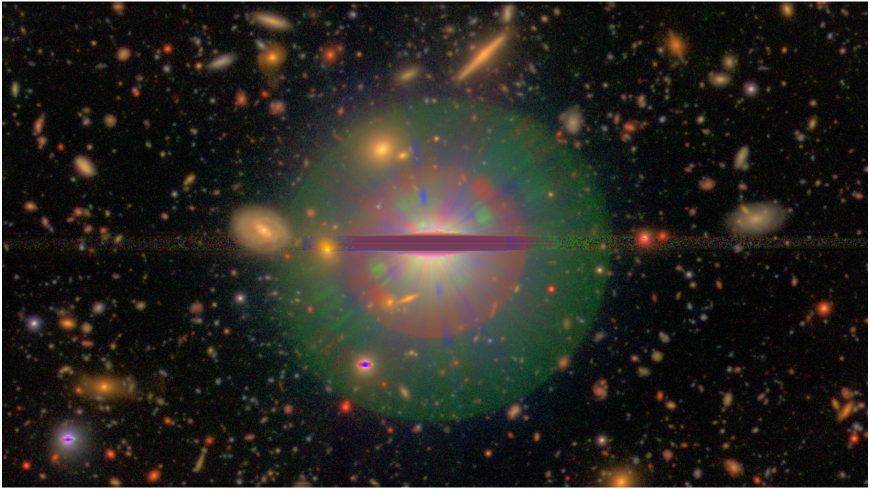

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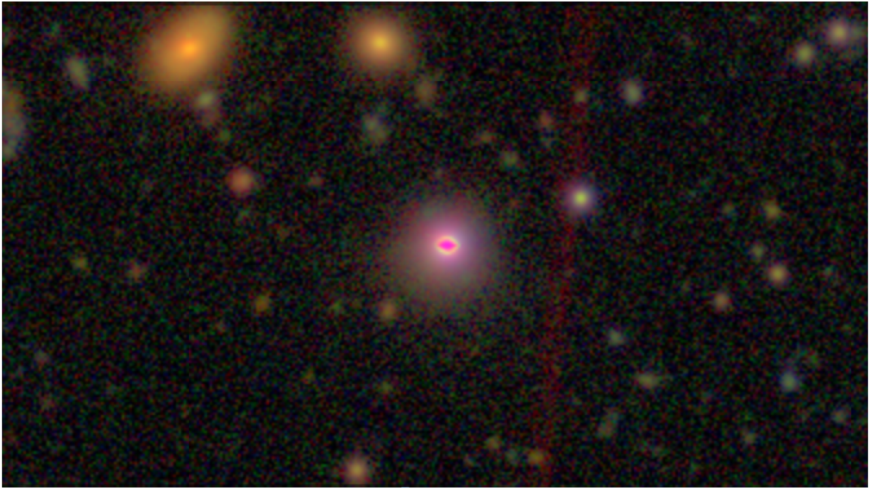

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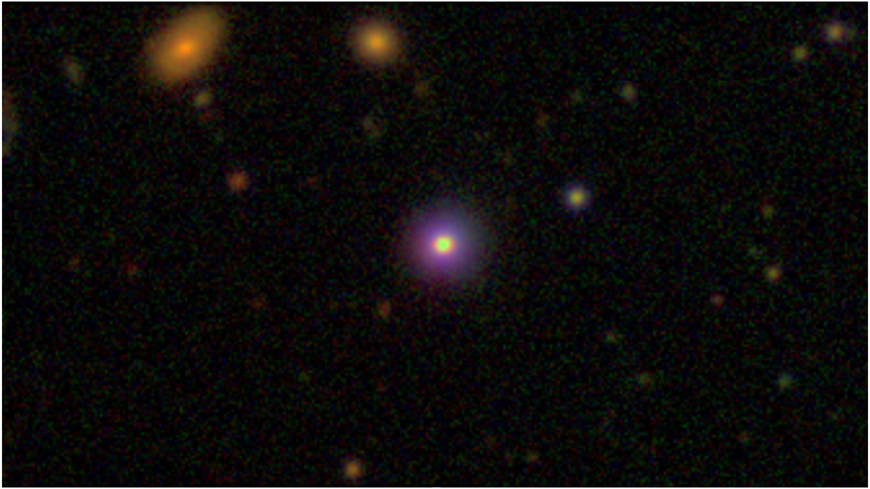

Question 5: What pixel measurements should I make to find the number of counts in a bright star?

By ‘bright’ I mean that the background noise is negligible relative to the photon noise in the star.

Answer 5

Choose a largish circular aperture of radius R centered on the star, and add up all the pixel values.

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Choose a largish circular aperture of radius R centered on the star, and add up all the pixel values.
If you are worried about spatial structure in the background, choose a larger annulus with the same centre and estimate the sky level there.

Question 6: Does it matter if the inner radius of the background annulus is too small?

Note that we're asking about the choice of pixels, not the annulus's area (which affects the variance of the sky estimate).

Answer 6:

No, not if you are using an sky estimator (such as the mean) that is linear in the counts.
You'll remove some fraction of the light from the star, but because you did exactly the same thing to your standard star the ratio is still correct. This is really not very different from choosing a small value of R.

Question 7: What is the variance of your estimate of the star's flux?

You'll remember that the star's profile is $A\phi(\boldsymbol{x})$ and the background variance is σ^2.

Answer 7:

Our model is that

$$I_i = A\phi(\boldsymbol{x}_i) + \epsilon_i$$

and we estimate the flux as

$$\hat{A} = \frac{1}{\sum_{|\boldsymbol{x}_i| \le R} \phi(\boldsymbol{x}_i)} \sum_{|\boldsymbol{x}_i| \le R} I_i \equiv f \sum_{|\boldsymbol{x}_i| \le R} I_i$$

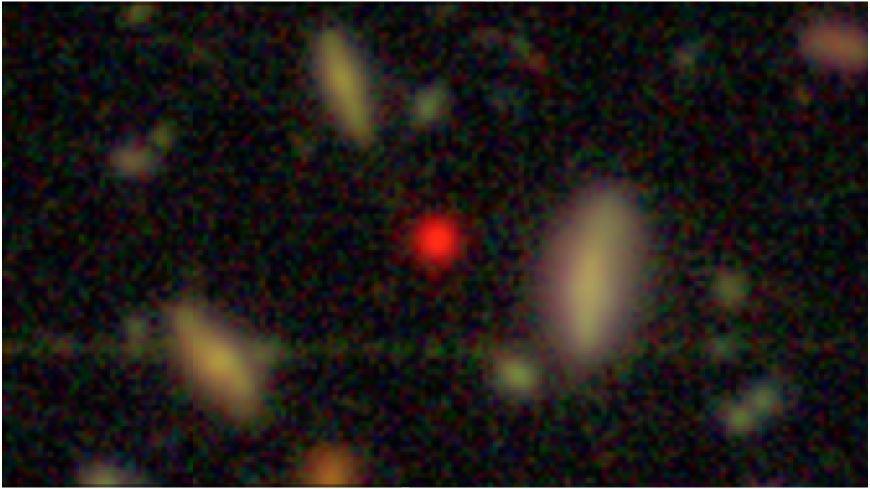
(*N.b.* $f > 1$).

$\hat{A}$'s variance is

$$\mathrm{Var}\left(\hat{A}\right) = f^2 \sum_{|\boldsymbol{x}_i| \le R} \left(A\phi(\boldsymbol{x}_i) + \sigma^2\right) = f^2 \left(A + \pi R^2 \sigma^2\right)$$

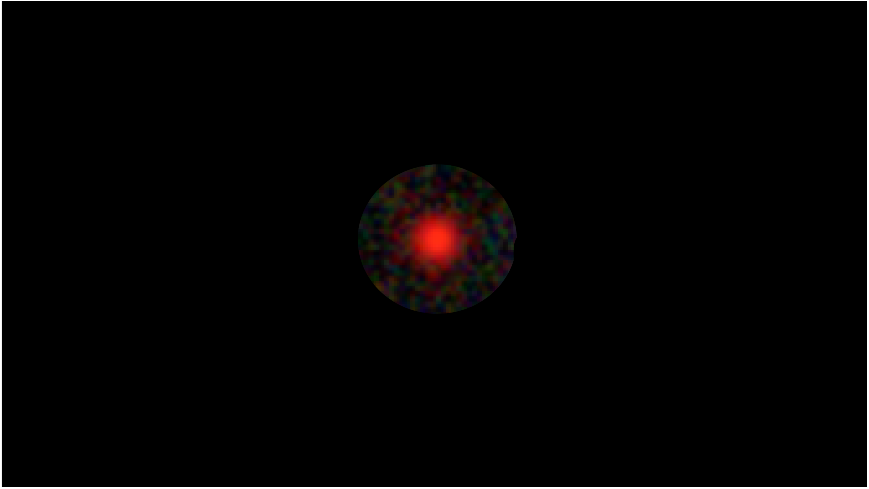
We said that the the star was 'bright', so neglecting the background noise we recover the irreducible Poisson noise as $R \to \infty$ and $f \to 1$.

Faint Stars



That red spot is a faint star. How bright is it?

Faint Stars



That red spot is a faint star. How bright is it? Let's assume that it's isolated.

Question 8: What pixel measurements should I make to find the number of counts in a faint star?

By ‘faint’ I mean that the the photon noise in the star is negligible relative to the background noise.
Assume that you know the star’s PSF and centroid (maybe we are interested in measuring its variability, or the optical flux of a well-localised LIGO source).

Answer 8

We'll use a maximum likelihood estimator. Our model is that

$$I_i = A\phi(\boldsymbol{x}_i) + \epsilon_i$$

so

$$\ln \mathcal{L} = \sum_i \frac{\left(I_i - A\phi(\boldsymbol{x}_i)\right)^2}{\sigma_i^2}$$

and differentiating with respect to A we find that

$$\hat{A} = \frac{\sum_i I_i \phi(\boldsymbol{x}_i)/\sigma_i^2}{\sum_i \phi^2(\boldsymbol{x}_i)/\sigma_i^2}$$

Because we assumed that the star's photon noise was negligible, $\sigma_i = \sigma$ and this reduces to

$$\hat{A} = \frac{\sum_i I_i \phi(\boldsymbol{x}_i)}{\sum_i \phi^2(\boldsymbol{x}_i)}$$

with variance

$$\mathrm{Var}(A) = \frac{\sigma^2}{\sum_i \phi^2(\boldsymbol{x}_i)} \equiv n_{\mathrm{eff}}\, \sigma^2$$

Question 9: What is $\hat{A}$'s variance if the PSF is a Gaussian?

I.e. what's the value of

$$n_{\text{eff}} \equiv \frac{1}{\sum_i \phi^2(\boldsymbol{x}_i)}$$

if $\phi \sim N(0, \alpha^2)$? What's n_{eff} if ϕ is constant over a disk of radius R?

Bonus question: If you're quick with integrals and good at numerical optimisation, what's the optimal value of R for a circular aperture for faint stars with this seeing profile, and what's the lowest variance that you can obtain?

Answer 9

For the Gaussian case,

$$\mathrm{Var}(A) = 4\pi\alpha^2\,\sigma^2$$

For the uniform disk, remembering that ϕ sums to unity and thus

$$\phi(r) = \begin{cases} 1/(\pi R^2) & \text{r < R} \\ 0 & \text{r > R,} \end{cases}$$

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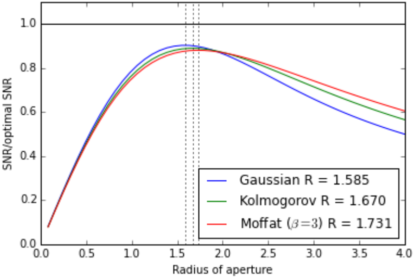

Question 10: Should I have kept the per-pixel variance?

I replaced σ_i by σ (arguing that it was essentially the same for faint objects). Was this a good idea?

Answer 10

Yes.

Answer 10

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Using constant weighting for every pixel is slightly suboptimal (it overweights the slightly-noiser core of the brighter stars), but more importantly if the PSF model isn't quite right the discrepancies between the data and the model are weighted *differently* for bright and faint stars.

The violates our promise that we will faithfully measure the ratio of fluxes for bright stars (*e.g.* our standards) and faint ones (whose properties we care about). We've traded noise for bias, and this is almost always a bad idea.

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For a Gaussian PSF, using a constant weight increases the photon noise from the object by 33%.

Galaxies are harder

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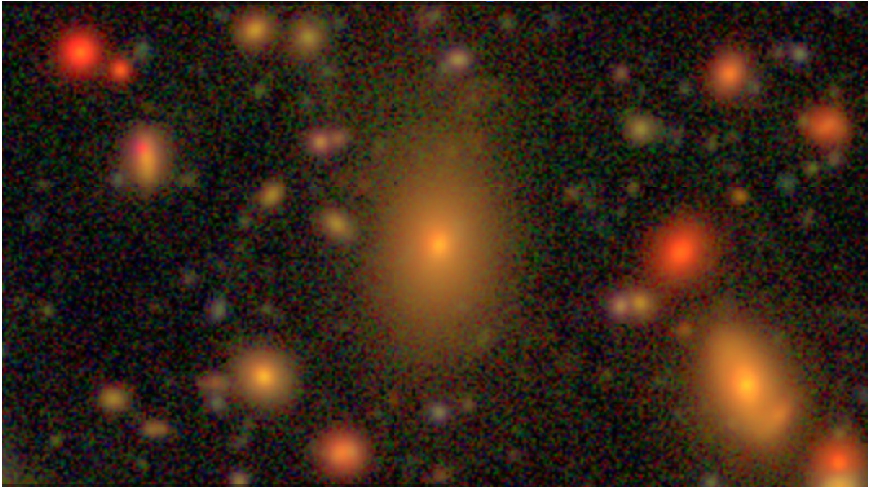

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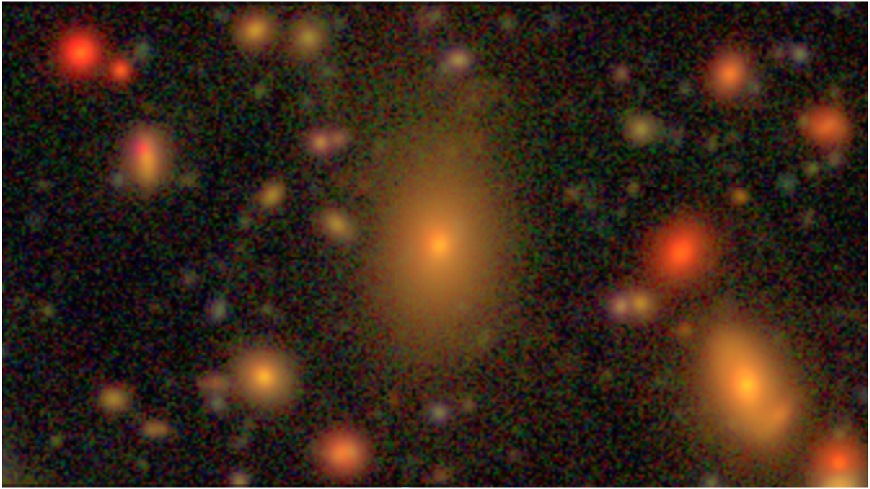
Note that astronomers use the word 'colour' to mean the ratio of the flux measured through different filters. Because we traditionally use logarithmic units (magnitudes), the colour is expressed as the difference of two magnitudes, *e.g.* $g - r$.

Simple Galaxies



Let’s start with the simple case;

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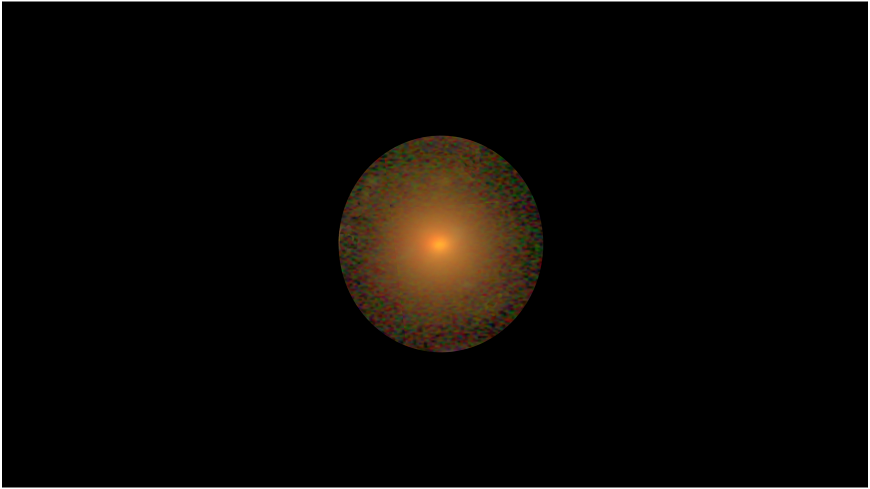

isolated circular galaxies where we’re only interested in one band

Question 11: What radius should I use to measure a circular galaxy's aperture flux?

What pixel measurements should I make to find the number of counts in some band (*e.g.* g) in a bright circular galaxy with known centroid? We can use a circular aperture, but how should we choose the radius?

By 'bright' I again mean that the background noise is negligible relative to the photon noise in the galaxy.

Answer 11

- An isophotal radius (*e.g.* 25 mag arcsec^{-2})
- A multiple (*e.g.* 2.5) of the Kron radius
- A multiple (*e.g.* 2) of the Petrosian radius

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The Kron radius R_K is defined as

$$R_K \equiv \frac{\int_A r\, I(r)\, 2\pi r\, dr}{\int_A I(r)\, 2\pi r\, dr}$$

for some area A around the galaxy.
The Petrosian radius R_P is defined in terms of the Petrosian ratio $\mathcal{R}_{\mathcal{P}}$;

$$\mathcal{R}_P(r) \equiv \frac{I(r)}{\frac{1}{\pi r^2} \int_0^r I(s)\, 2\pi s\, ds};$$

$$\mathcal{R}_P(R_P) = f_P$$

SDSS used $f_P = 0.2$

Elliptical Galaxies

Galaxies with elliptical isophotes are not really much more complicated once we've chosen an axis ratio and position angle a/b and ψ (or equivalently e_1 and e_2). The radius r formularum on the previous slide are interpreted as the size of the ellipse (conventionally $\sqrt{ab}$).

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The problem comes in defining the shape of the ellipse. Ideally it would:

- be robustly measurable
- reduce to circular for marginally resolved objects

Elliptical Galaxies

Galaxies with elliptical isophotes are not really much more complicated once we've chosen an axis ratio and position angle a/b and ψ (or equivalently e_1 and e_2). The radius r formularum on the previous slide are interpreted as the size of the ellipse (conventionally $\sqrt{ab}$).

The problem comes in defining the shape of the ellipse. Ideally it would:

- be robustly measurable
- reduce to circular for marginally resolved objects

HSC uses 'adaptive Gaussian moments', but I'm not all that happy with the results. We need to find a way to impose some sort of prior before LSST goes on the sky.

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If there are isophotal twists (*e.g.* in S0s, or triaxial elliptical galaxies) the problem is, of course, ill-posed.

Question 12: What is ‘Formularum’?

In the sentence

- The radius r formularum on the previous slide are interpreted as the size of the ellipse (conventionally $\sqrt{ab}$).

what is ‘formularum’?

Answer 12

The genitive plural of "formula"

Question 13: What pixel measurements should I make to find the number of counts in a faint galaxy?

What pixel measurements should I make to find the number of counts in some band (*e.g.* g) in a faint circular galaxy?

By ‘faint’ I mean that the the photon noise in the galaxy is negligible relative to the background noise.

Answer 13

We'll use a maximum likelihood estimator; the problem is that the appropriate model is not obvious. A popular choice is a Sérsic profile

$$\mathcal{S}(r; r_e, n) = Ae^{-(r/r_e)^{1/n}}$$

with flux $A\, r_e^2\, f(n)$, so our model becomes

$$I_i = A\, \mathcal{S}(\boldsymbol{x}_i; r_e, n) \otimes \phi(\boldsymbol{x}_i) + \epsilon_i$$

so

$$\ln \mathcal{L} = \sum_i \frac{\left(I_i - A\, \mathcal{S}(\boldsymbol{x}_i; r_e, n) \otimes \phi(\boldsymbol{x}_i)\right)^2}{\sigma_i^2}$$

and we can estimate $\hat{A}$ (and $\hat{n}$ and $\hat{r_e}$) numerically; note that each step involves a convolution with the PSF (and this can be tricky if r_e is comparable to the size of the pixels).

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As with stars, dividing each pixel by its variance can lead to biases as a function of magnitude; this is particularly a problem with $\hat{A}$ but biases in the other parameters are also worrying.

Elliptical Galaxies

In reality we fit two more parameters (*e.g.* a/b and ψ or e_1 and e_2) to allow for the galaxy's ellipticity.

Question 14: Why are you not following the Bayesian Way?

I used a maximum-likelihood estimator, with implicit uninformative priors.
What priors would have been better?

Answer 14

- Using a positivity prior on r_e seems pretty safe.
- Priors on n are reasonably non-controversial.
- priors on e_1 and e_2 are easier than using a/b (an uninformative prior for ψ is fine).

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- In general, informative priors lead to violating the condition that making an object a factor of two fainter changes our estimate of its flux by some other factor. Whether this is a problem is a scientific question that I'm not going to answer here; render unto cosmologists that which is cosmologists'.

Galaxy Colours

What should we do if we want to measure the colour of our galaxy (assumed to be free of colour gradients for now)?

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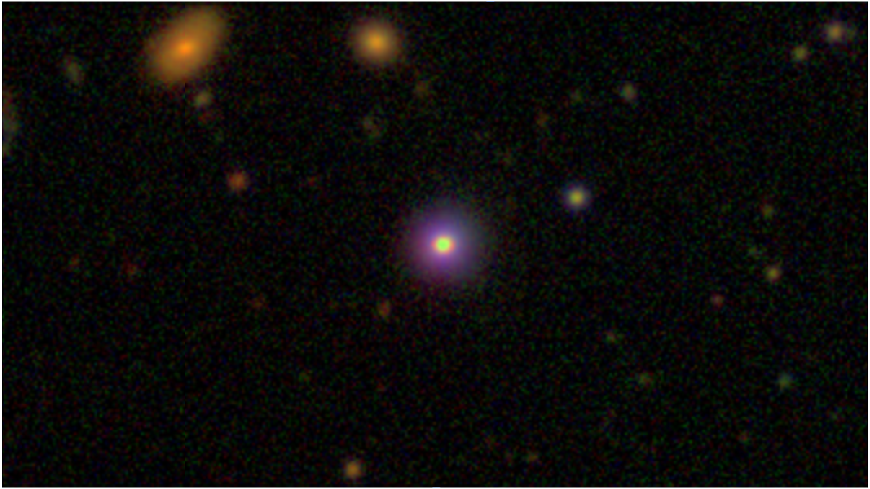
The problem is that the seeing can be different in each band.



Question 15: How should I handle Variable Seeing?

This is only a problem if the galaxy's size is comparable to the seeing; so please ponder that case.

Answer 15

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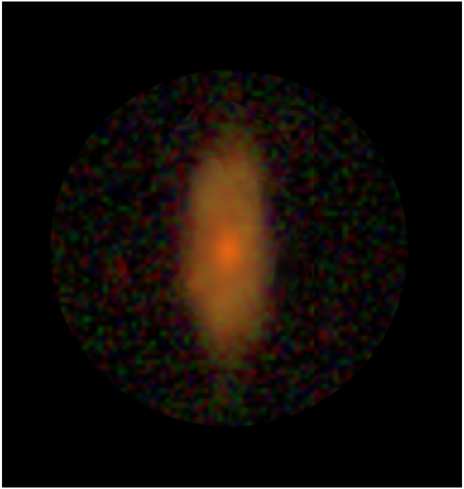
Well, as an alternative you *could* use an enormous aperture, but that carries an unacceptable noise penalty for most applications.

Colour Gradients

Real galaxies have colour gradients



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In many cases colour gradients are better thought of as multiple components with distinct colours (*e.g.* a bulge and a disk). This isn't always true (*e.g.* metallicity gradients in giant ellipticals).

The Curious Case of the Constant PSF

If the PSF in each band is the same (or has been made the same) and we don't require a total flux or a total colour (*e.g.* to guess a star formation history) we can use *any* 'aperture' to measure a colour.

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Question 16: How should I measure colours if the PSFs are different in each band?

Please consider both cases:

- We care about the colour of the entire galaxy
- We care about the colour of some well-defined stellar population

Answer 16

Tricky.

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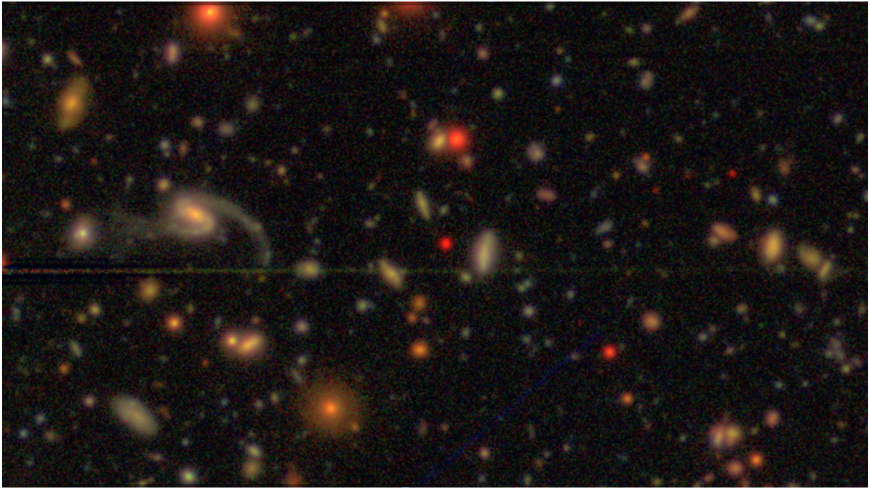
Or we can degrade the seeing to a constant and refer to the previous discussion.

Question 17: What should you do if the galaxies are not isolated?

Answer 17

Panic.



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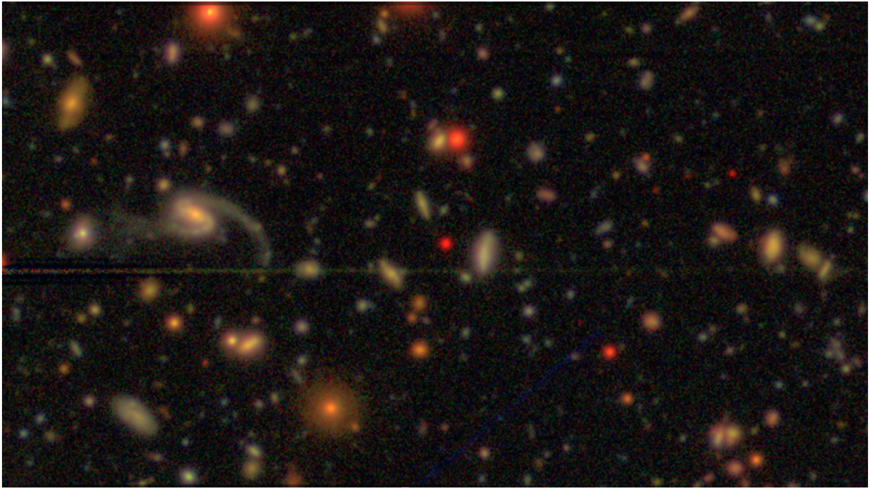

And/or invite me back to France to talk about deblenders.