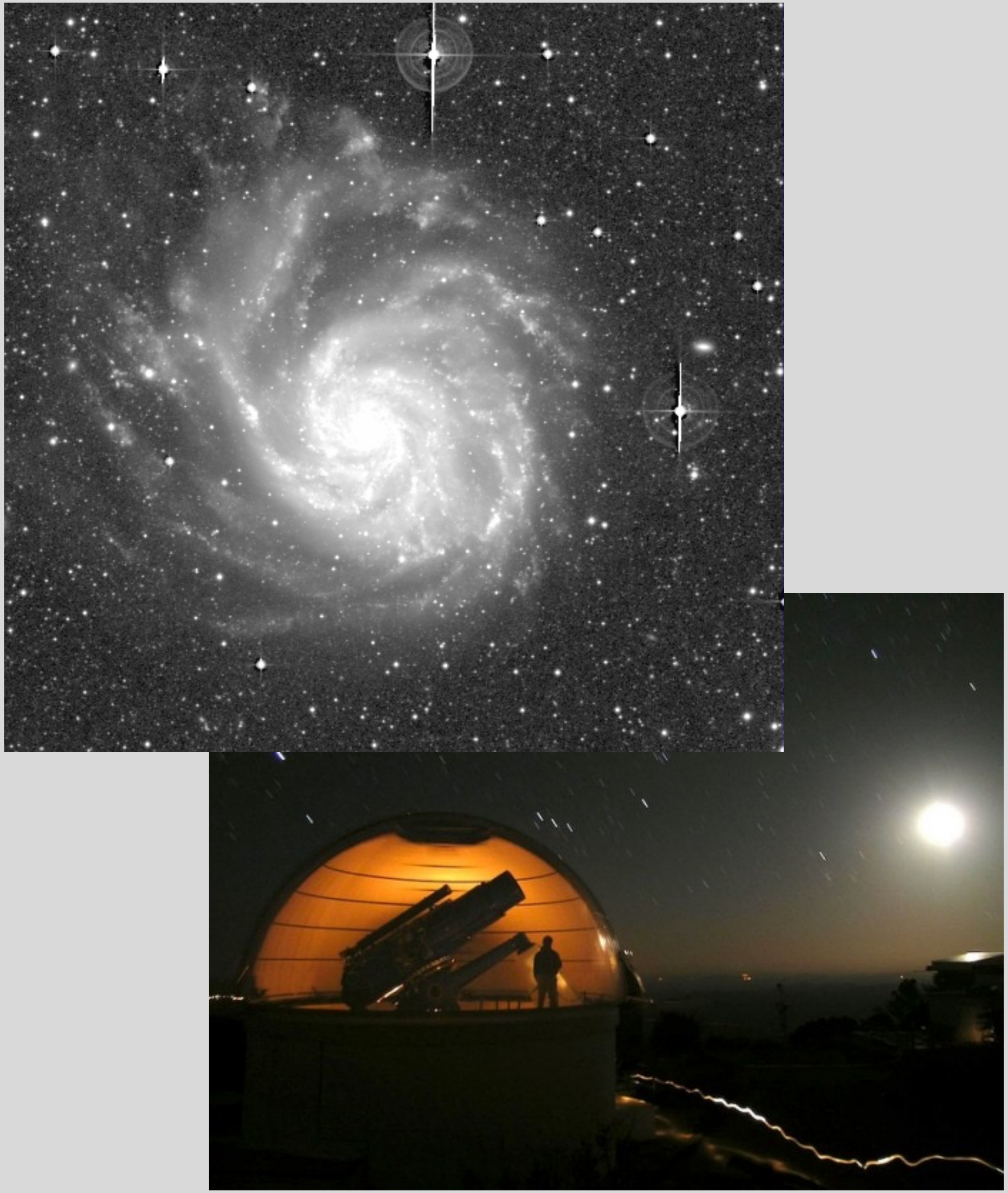
M101 Data Reduction and Analysis Project

We have a set of imaging data for the spiral galaxy M101, taken in two filters (B and V) using CWRU's Burrell Schmidt Telescope.

Project Goals:

- Work through data reduction process from raw data to scientific-ready imaging.
- Work out photometric calibration and how to extract accurate photometric data
- Measure surface brightness profile, fit exponential model.
- Measure color profile, interpret in context of galaxy evolution models.
- Write up project in "research journal style".



Why so many images?

Filter	Season	Number of Images	Exposure time
B	Spring 2009	8	1200s
V	Spring 2010	8	900s

We can digitally combine individual images together into one master image of much better depth and quality.

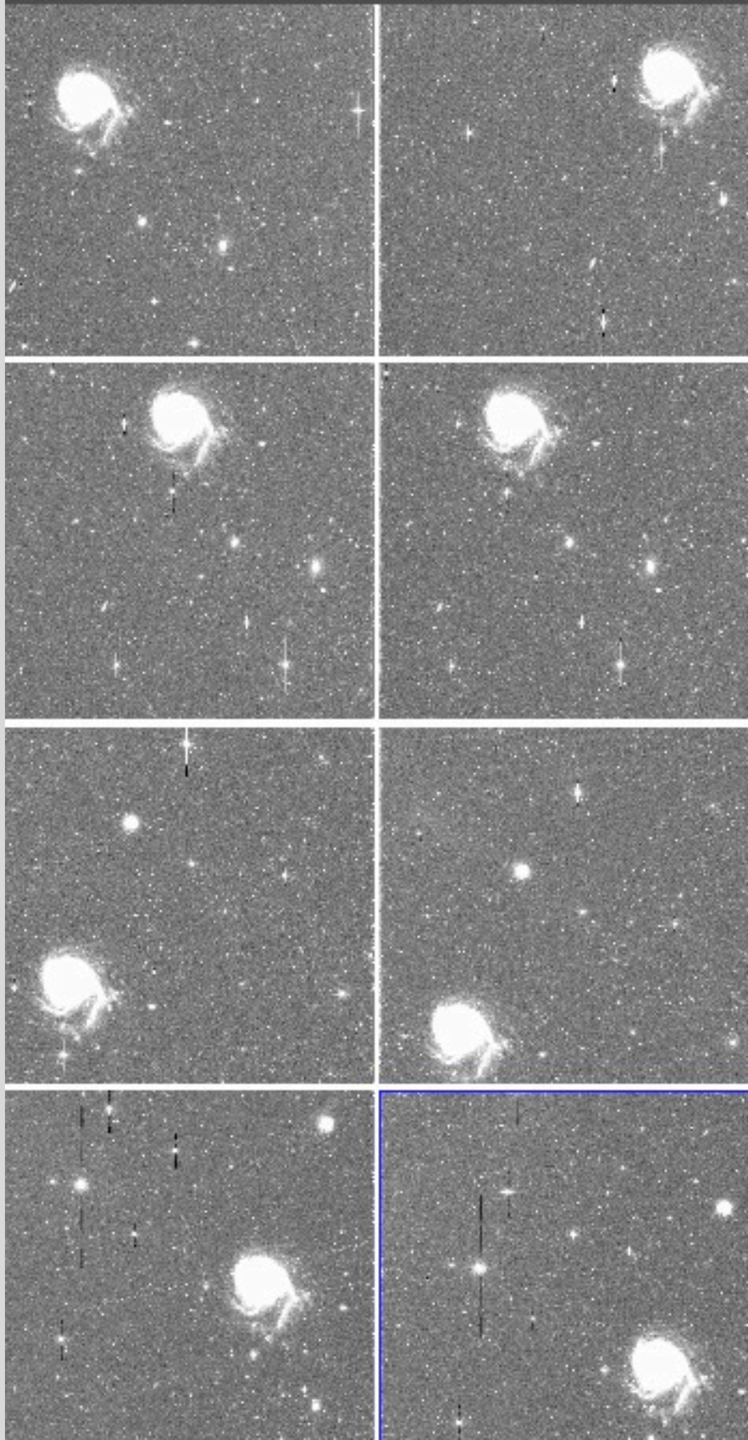
Advantage #1: Increase exposure time and signal-to-noise.

Advantage #2: Correct for image contaminants (cosmic rays, satellite trails, scattered light)

Advantage #3: Correct for detector problems (bad columns, flat fielding variations, etc)

Advantage #4: Reduce observing risk. (If something goes wrong, you only lose one exposure!)

Dithering: the telescope is pointed differently each time so that the galaxy shows up in a different spot on the detector ⇒



Remember the concept of image math and image combining

Images can be thought of as 2D arrays or matrices of intensity values

Images can be added, subtracted, multiplied, and divided by one another, or by a single value. This is done on a pixel by pixel basis.

An "image stack" can be thought of as a 3D array, with the third dimension being the different images in the stack.

When we do an "average" or "median" combine, we are averaging or medianing the values of each pixel down the third dimension (ie, the stack).

Basic Reduction to Individual images

Remember CCD data reduction steps

- Zero correction
  - take many zero-second images without exposing the CCD to light.
  - Average them together to create a “master zero” showing fixed pattern noise.
  - Subtract that master zero from all the “object frames”
- Flat fielding
  - Divide the object images by a “flat field” image: an image showing sensitivity/gain variations across the image.
  - Since the sensitivity is wavelength dependent, each filter must have its own flat field.

Recapping what we did last time

- We examined the zero images, looked at the random read noise level (~ 1.5 ADU/pix), verified it was consistant.
- We averaged 16 zero images together to make a ”master zero”. In that master zero we saw the noise level went down and we could see the residual “fixed pattern noise”
- We examined the flat field, saw the variations due to in sensitivity and gain issues.
- We took the object images, subtracted off the master zero, then divided by the flat field to produce reduced images.

Next steps: Photometric calibration and Sky subtraction

Photometric Calibration

Images were taken at different airmasses (and sometimes on different nights) so they have different photometric properties. The same star will produce fewer counts when observed at greater airmass. We can't just average all the images together, we have to scale them in intensity to a "common zeropoint" to correct for the photometric differences.

Method #1: Observe standard stars, work out overall photometric solution, then apply to object images:

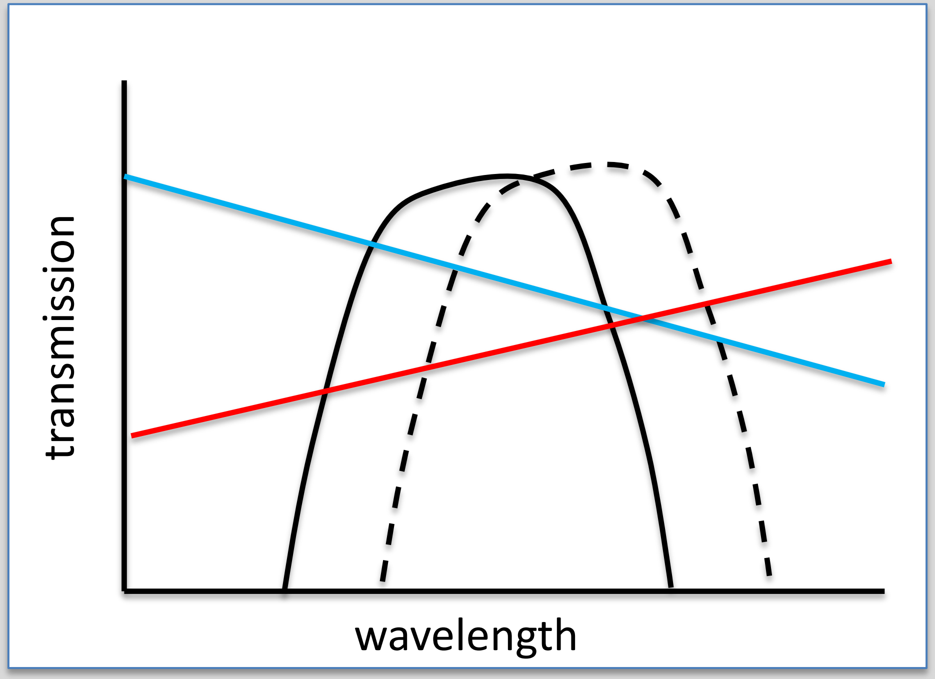
remember: ***instrumental magnitude*** is just a logarithmic measure of uncalibrated flux on the detector:

$$m_{inst} = -2.5\log(ADU/time) + const$$

$$m_{inst} - m_B = C_B(B-V) + K_B\sec(z) + ZP_B$$

Why the color term? Our filters are slightly different from standard Johnson B and V filters.

The brightness of the star will be a bit different through our filters than through standard B, V filters, and the difference will depend on the color of the star.



Photometric Calibration

Images were taken at different airmasses (and sometimes on different nights) so they have different photometric properties. The same star will produce fewer counts when observed at greater airmass. We can’t just average all the images together, we have to scale them in intensity to a “common zeropoint” to correct for the photometric differences.

Method #2 (What we will do): If you have many stars of known brightness (m_B) and $(B-V)$ color on your object images, you can calibrate the solution directly *for each image*:

$$m_{inst} - m_B = C_B(B-V) + ZP_{B,IMAGE}$$

where $ZP_{B,IMAGE} = K_B \sec(z) + ZP_B$.

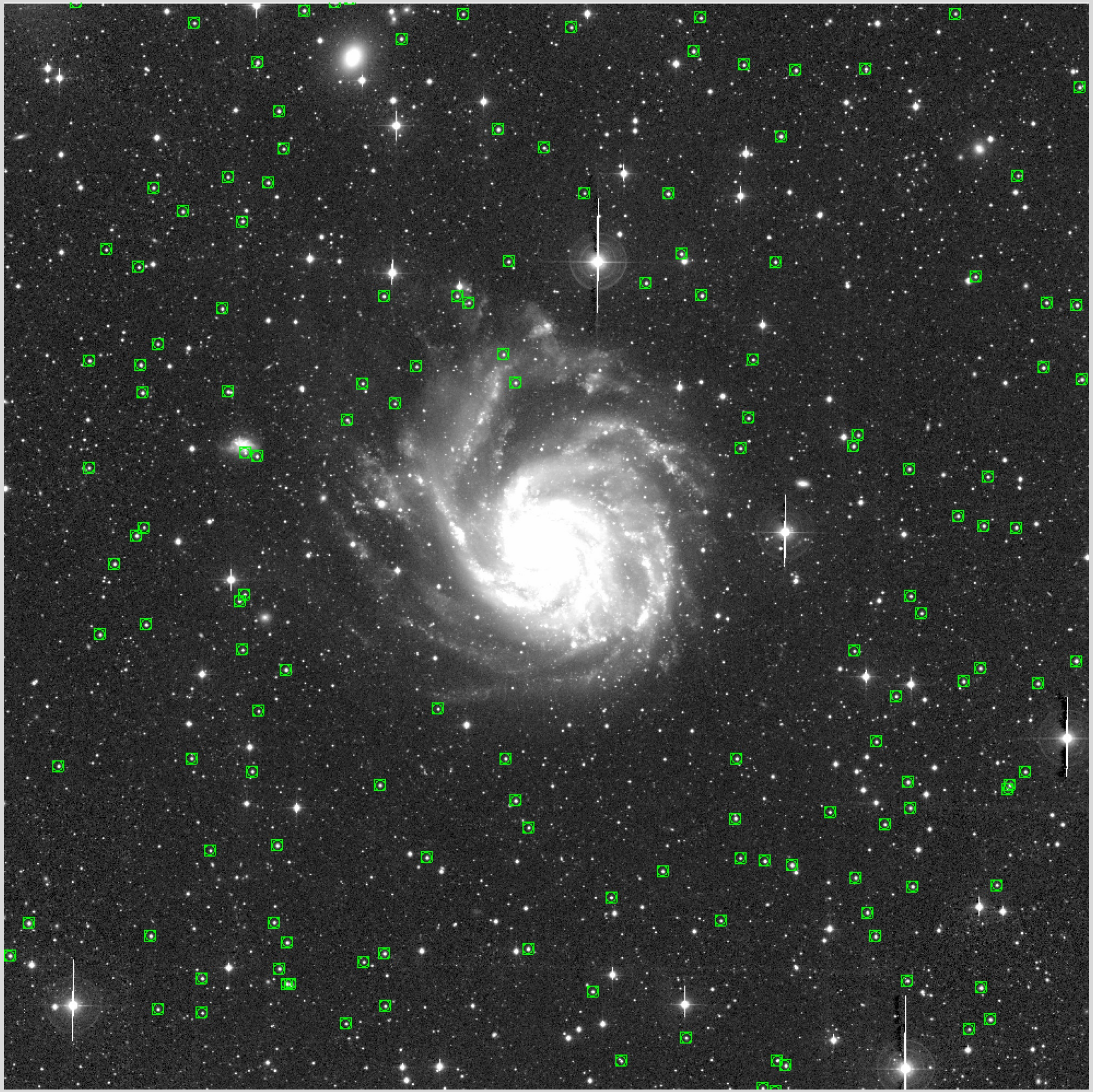
Each star on a given image gives a value for $m_{inst} - m_B$ and $(B-V)$, so plot $m_{inst} - m_B$ against $(B-V)$ for many stars on the image, and then fit a line:

- C_B = slope
- $ZP_{B,IMAGE}$ = intercept

Our Approach

On each images, there are a hundred or so stars that have well-calibrated true magnitudes from the Sloan Digital Sky Survey (green boxes).

Aperture photometry of the “Sloan Stars” will give us instrumental magnitudes, from which we can calibrate the photometric zeropoints and color terms.



For each image, we calculate an instrumental magnitude for SDSS stars on the field:

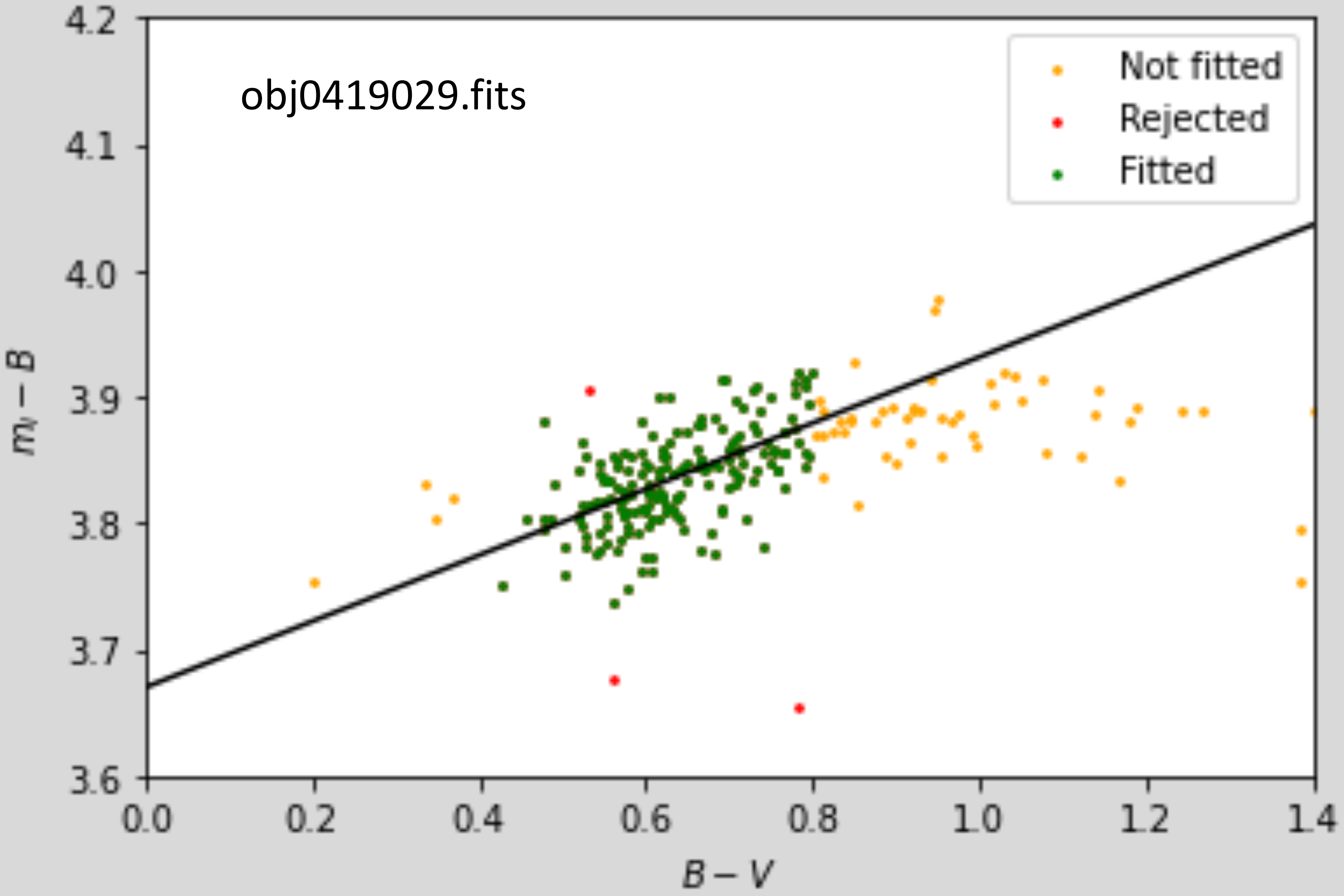
$$m_{inst} = -2.5\log\left(I_{ADU}/t_{exp}\right) + 25$$

then calibrate a photometric solution

$$m_{inst} - m_B = C_B(B - V) + ZP_{B,IMAGE}$$

Note how errors build up at every step

- The S/N calculation tell you the errors in measuring the flux.
- The errors in the photometric solution add to that uncertainty when calculating a calibrated magnitude.



$$C_B \text{ (slope) } = 0.262 \pm 0.027$$
$$ZP_{B,IMAGE} \text{ (intercept)} = 3.670 \pm 0.017$$

Sky Subtraction

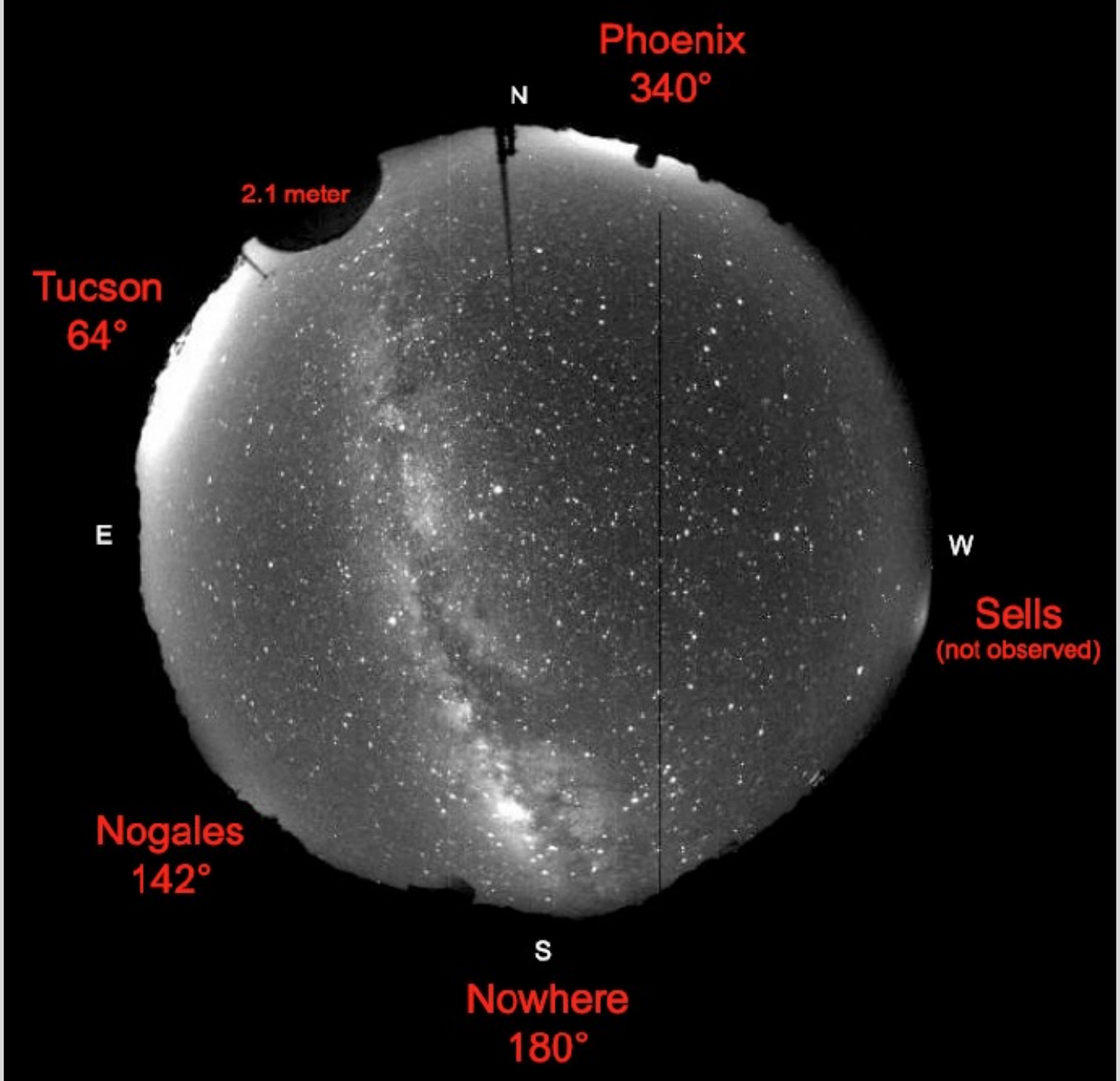
Sky brightness can change from night to night, and over the course of a single night, and also depends on airmass and direction you are observing. So the images all have different sky levels and we have to subtract off this sky level *before* combining.

Method #1: Measure sky at many spots across the image, work out an average value, subtract that value off the image.

SKY = average sky

But the sky level may not be uniform across the image!

So a constant sky value may not be a great model.



Sky Subtraction

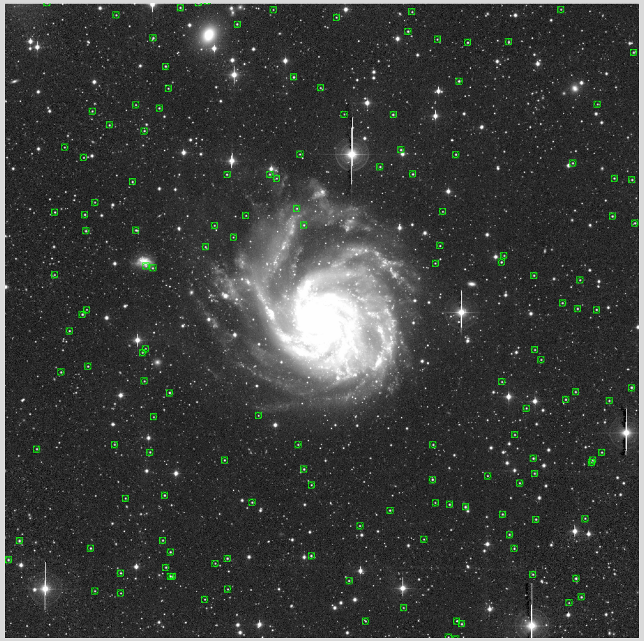
Sky brightness can change from night to night, and over the course of a single night, and also depends on airmass and direction you are observing. So the images all have different sky levels and we have to subtract off this sky level *before* combining.

Method #2 (what we will do): Measure sky at many spots across the image, fit a plane to the sky level as a function of X,Y position on the image.

$$SKY = X \times \nabla_{SKY,X} + Y \times \nabla_{SKY,Y} + SKY_0$$

where $\nabla_{SKY,X}$ and $\nabla_{SKY,Y}$ are the sky gradients in the X and Y direction on the image, respectively, SKY_0 is an average sky level.

How do we do this? Use the sky estimate around each Sloan star (from the photometric calibration step) as a function of X and Y to fit and subtract a sky plane from each image.



Astronomical Image File Formats: FITS images

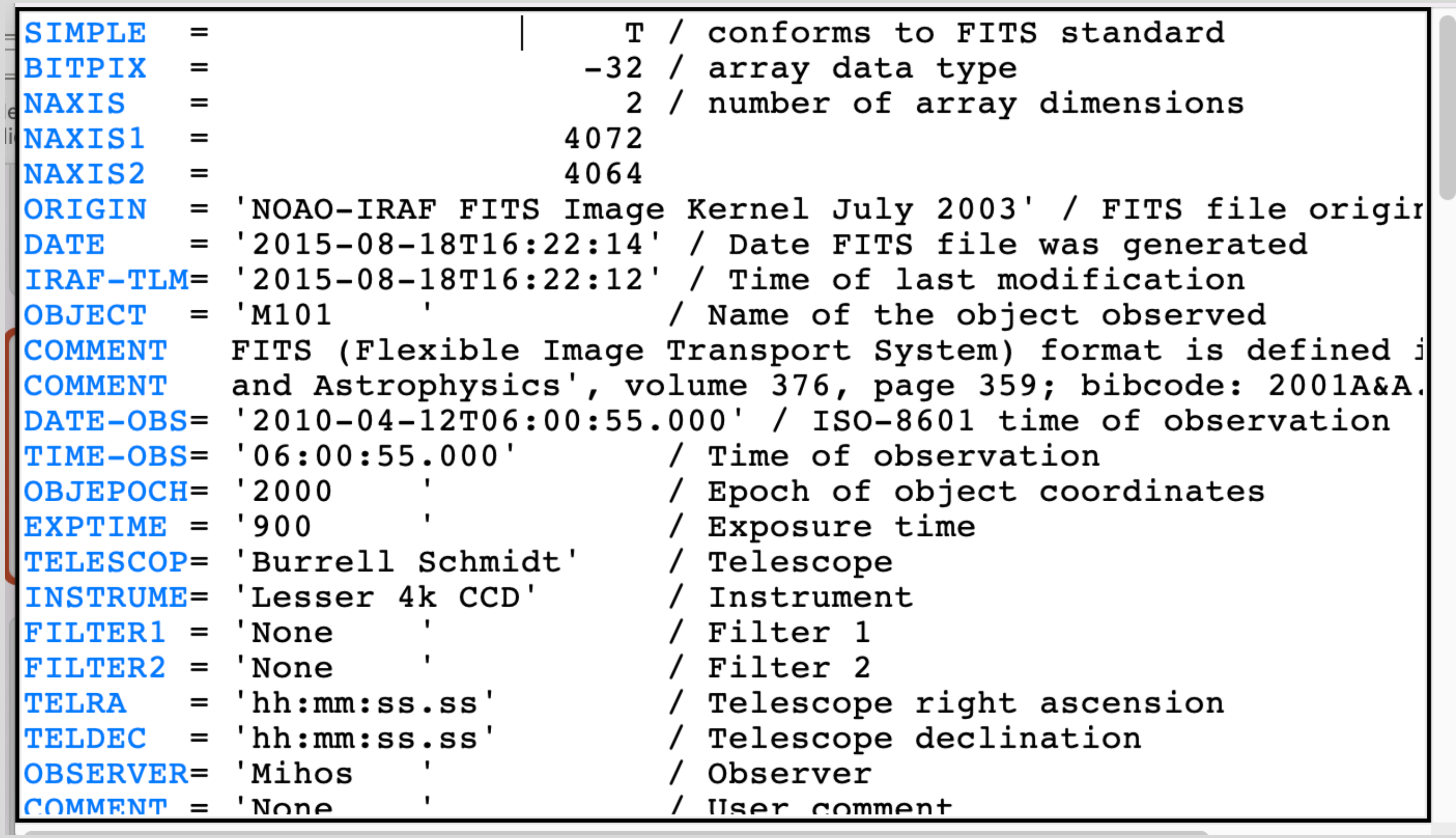
Tip: In ds9, view the header via *File --> Header*

Images are in FITS format, consisting of two parts:

Image: array of pixel intensity values

Header: information about the image

KEYWORD = ‘VALUE’ / comment

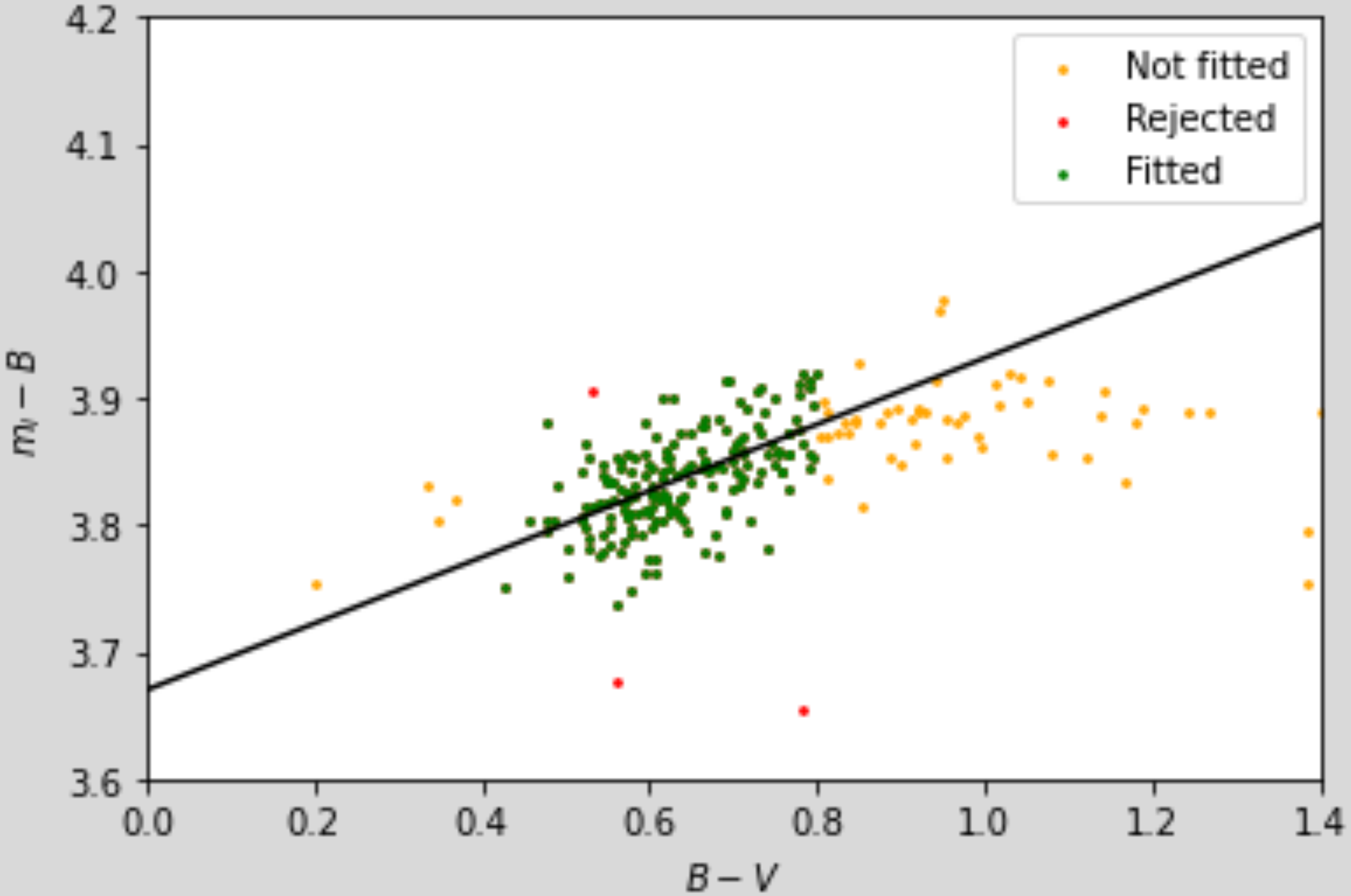


```
SIMPLE  =                    T / conforms to FITS standard
BITPIX  =                  -32 / array data type
NAXIS   =                    2 / number of array dimensions
NAXIS1  =                 4072
NAXIS2  =                 4064
ORIGIN  = 'NOAO-IRAF FITS Image Kernel July 2003' / FITS file origi
DATE    = '2015-08-18T16:22:14' / Date FITS file was generated
IRAF-TLM= '2015-08-18T16:22:12' / Time of last modification
OBJECT  = 'M101    '           / Name of the object observed
COMMENT   FITS (Flexible Image Transport System) format is defined i
COMMENT   and Astrophysics', volume 376, page 359; bibcode: 2001A&A.
DATE-OBS= '2010-04-12T06:00:55.000' / ISO-8601 time of observation
TIME-OBS= '06:00:55.000'       / Time of observation
OBJEPOCH= '2000    '           / Epoch of object coordinates
EXPTIME = '900     '           / Exposure time
TELESCOP= 'Burrell Schmidt'    / Telescope
INSTRUME= 'Lesser 4k CCD'      / Instrument
FILTER1 = 'None    '           / Filter 1
FILTER2 = 'None    '           / Filter 2
TELRA   = 'hh:mm:ss.ss'        / Telescope right ascension
TELDEC  = 'hh:mm:ss.ss'        / Telescope declination
OBSERVER= 'Mihos   '           / Observer
COMMENT = 'None    '           / User comment
```

Photometric Solution fit for the B-band image obj0419029.fits:

Remember instrumental magnitude:

$$m_{inst} = -2.5\log\left(I_{ADU}/t_{exp}\right) + 25$$



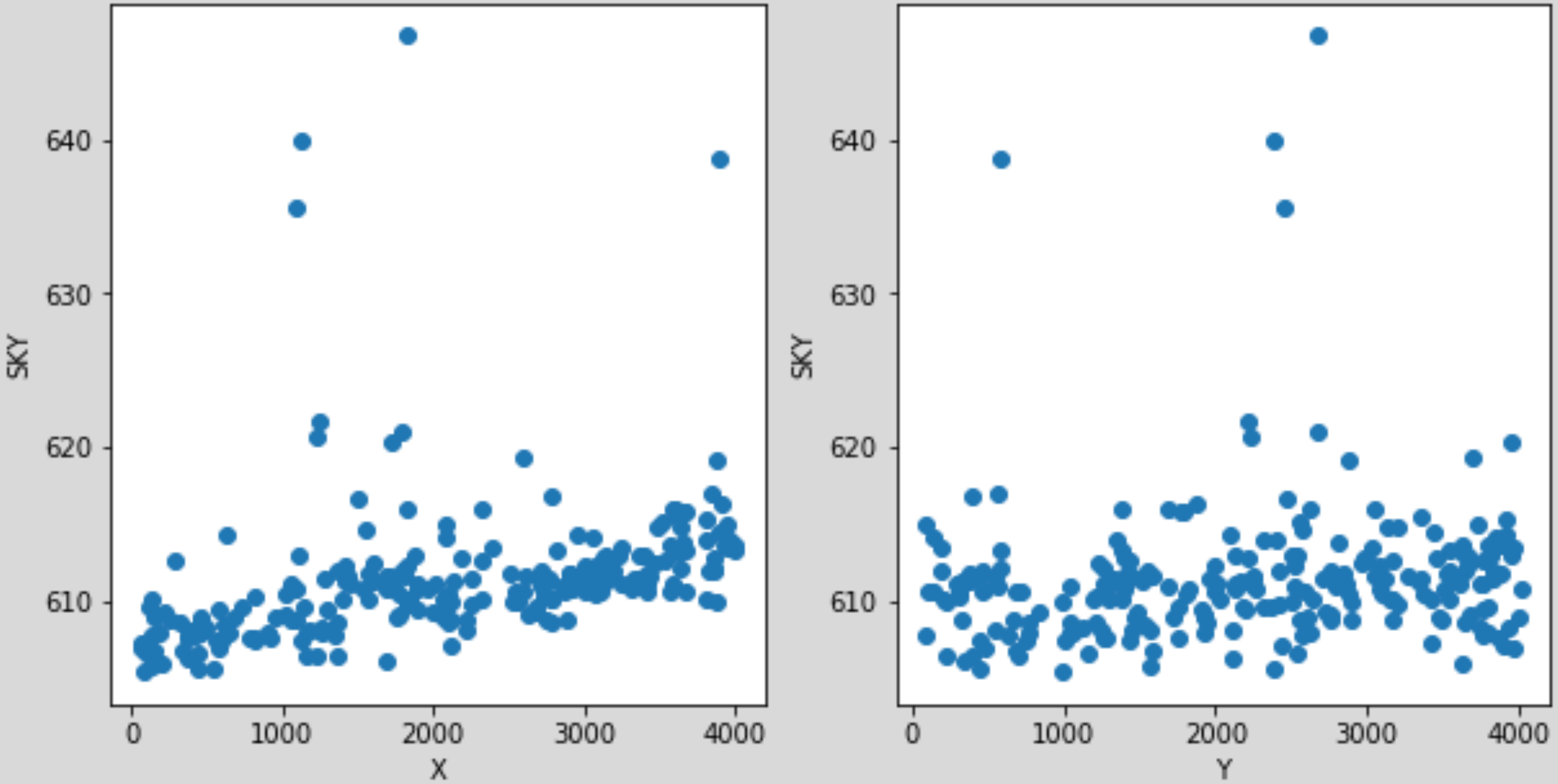
Fit a line to the data to estimate color term and zeropoint.

$$m_{inst} - m_B = C_B(B - V) + ZP_{B,IMAGE}$$

$$C_B \text{ (slope)} = 0.262 \pm 0.027$$

$$ZP_{B,IMAGE} \text{ (intercept)} = 3.670 \pm 0.017$$

Sky values as a function of X and Y for the B-band image obj0419029.fits:



Fit and subtract a 2D plane to remove the sky background.

$$SKY = X \times \nabla_{SKY,X} + Y \times \nabla_{SKY,Y} + SKY_0$$

$$\nabla_{SKY,X} = 1.468\ (\pm 0.082) \times 10^{-3}\ \mathrm{ADU/pix}$$
$$\nabla_{SKY,Y} = 0.440\ (\pm 0.084) \times 10^{-3}\ \mathrm{ADU/pix}$$
$$SKY_0 = 606.50 \pm 0.27\ \mathrm{ADU}$$

This process (calibration and sky subtraction) prepares each image for combining. We do this for all images in the B and V image sets,

CalibrateImages.ipyb calculates photometric solutions for all images and write out new versions of each image with the sky levels subtracted off.

Look at photometric solutions and sky levels for the B-band images.

Differences in color term

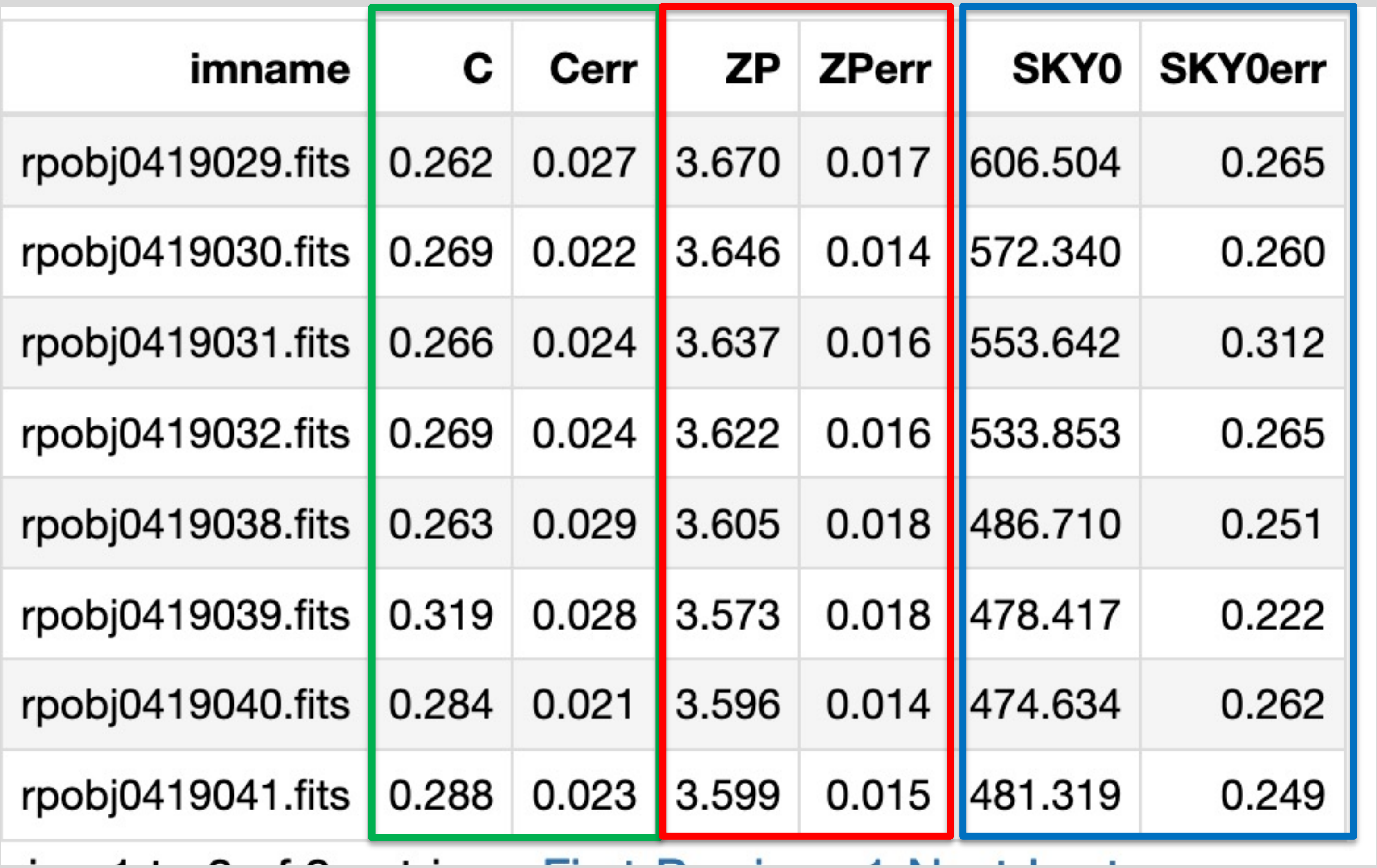
Mostly random scatter

Differences in zeropoint

Real, systematic changes. Images were taken at different airmasses

Differences is sky level

Real, systematic changes. Images were taken at different airmasses and times.



imname	C	Cerr	ZP	ZPerr	SKY0	SKY0err
rpobj0419029.fits	0.262	0.027	3.670	0.017	606.504	0.265
rpobj0419030.fits	0.269	0.022	3.646	0.014	572.340	0.260
rpobj0419031.fits	0.266	0.024	3.637	0.016	553.642	0.312
rpobj0419032.fits	0.269	0.024	3.622	0.016	533.853	0.265
rpobj0419038.fits	0.263	0.029	3.605	0.018	486.710	0.251
rpobj0419039.fits	0.319	0.028	3.573	0.018	478.417	0.222
rpobj0419040.fits	0.284	0.021	3.596	0.014	474.634	0.262
rpobj0419041.fits	0.288	0.023	3.599	0.015	481.319	0.249

What’s next?

Each image also has contamination/noise in it due to:

- CCD Read noise (remember: subtracting off the master eliminates the fixed pattern noise, but not the random read noise. That cannot be removed from an individual image.

- Variations in sky intensity

- Scattered light and reflections inside the telescope

- Satellites passing through the field of view

- Bad pixels and columns in the CCD

- Cosmic rays

To reduce noise and remove contamination, we want to

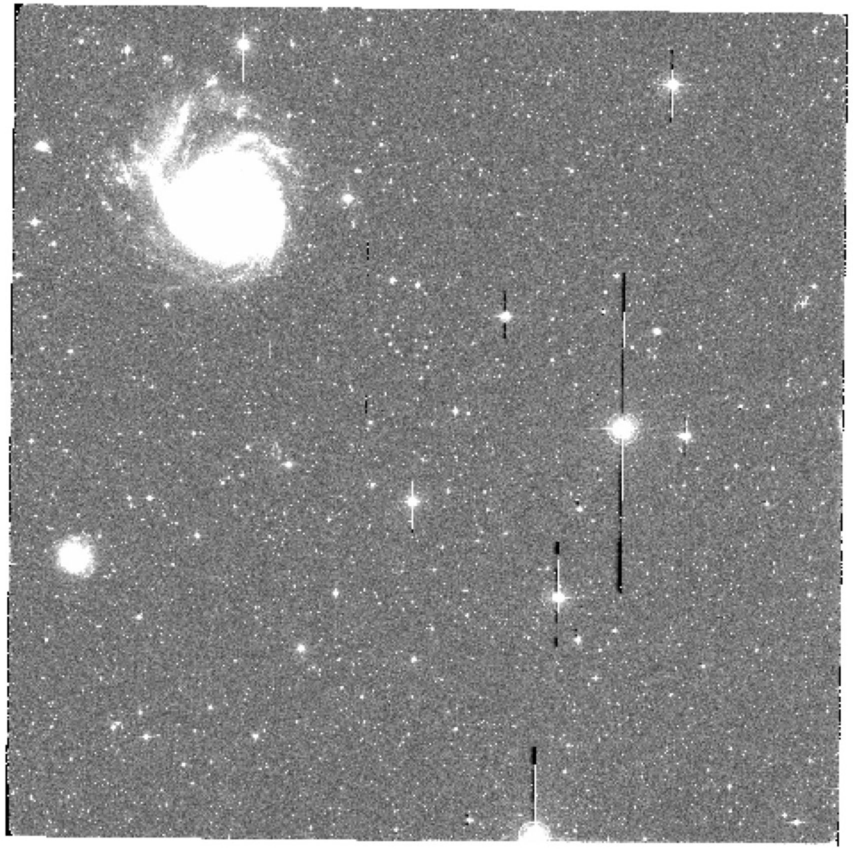
- ***shift*** *each image so that M101 is at the same spot*
- ***scale*** *each image to a common intensity*
- *do a* ***median stack*** *of all the images.*

Shifting the images to a common center: “Image re-registration”

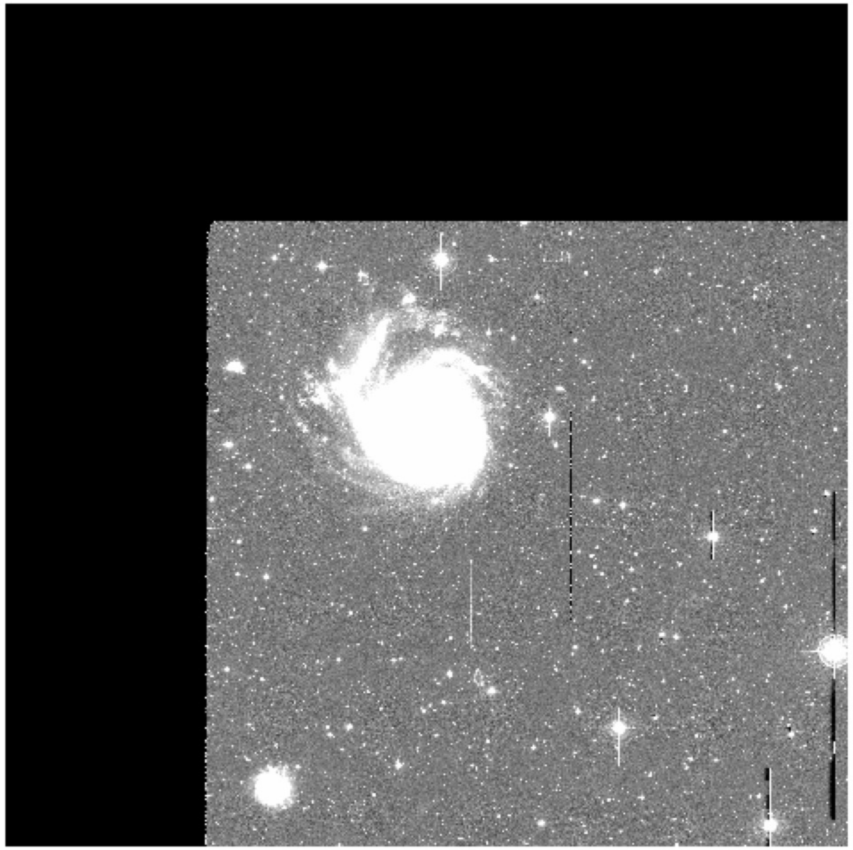
Simplest version: XY integer pixel shift (“shift flux in each pixel over 100 pixels and down 200 pixels”)

In reality: non-integer XY shifts, plus rotation. Geometric transformation is mathematically intensive, and introduces additional uncertainty into the data.

Original Image



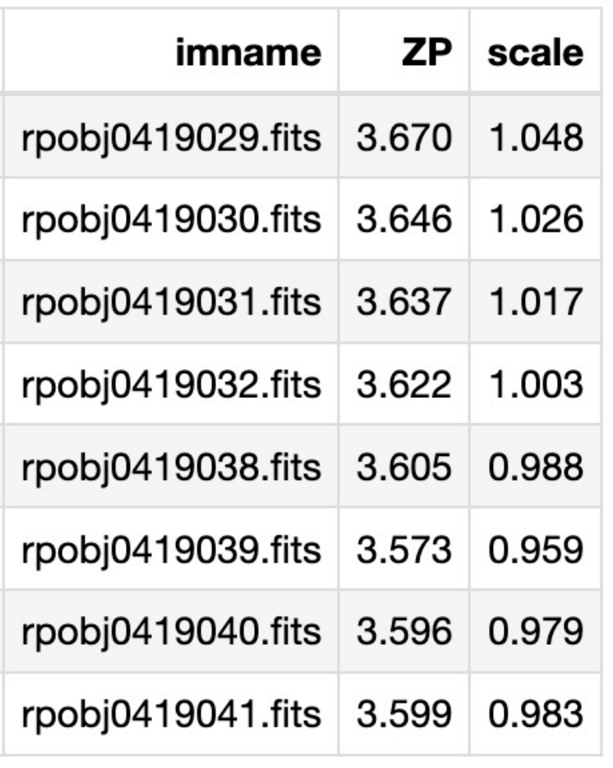
Re-registered Image



Applying Zeropoints: Photometric Scaling

The same star will have different numbers of counts in each image due to the different zeropoints. We can define a “final zeropoint” and scale each image up or down in intensity to match this average zeropoint.

```
ZP_FINAL = np.average(ZP_image)
```



imname	ZP	scale
rpobj0419029.fits	3.670	1.048
rpobj0419030.fits	3.646	1.026
rpobj0419031.fits	3.637	1.017
rpobj0419032.fits	3.622	1.003
rpobj0419038.fits	3.605	0.988
rpobj0419039.fits	3.573	0.959
rpobj0419040.fits	3.596	0.979
rpobj0419041.fits	3.599	0.983

Since zeropoints are in magnitudes, we can say

$$ZP_{final} - ZP_{image} = -2.5\log\left(I_{final}/I_{image}\right)$$

Then we scale each image in intensity by a factor of

$$I_{final} = I_{image} \times 10^{-0.4\left(ZP_{final} - ZP_{image}\right)}$$

That 10^ term is the photometric scaling we multiply each image by to get them on the same final zeropoint. After scaling all the images this way, a given star should have the same number of counts (+/- noise) in each image.

Final Image Combine

1. Scale each image in intensity to match the average zeropoint:

$$I_{scaled} = I_{image} \times 10^{-0.4\left(ZP_{avg} - ZP_{image}\right)}$$

2. Re-register each image so that M101 is at the center of the image.

3. Create a final image by calculating a the median pixel intensity along a stack of the shifted, scaled images.

This takes 3-5 minutes…..

Applying your photometric solution to the final combined images

Part 1: Instrumental magnitudes

In the notebooks, we defined Instrumental magnitudes in terms of counts/second:

$$m_{inst} = -2.5\log\left(I/t_{exp}\right) + 25$$

So in analyzing the reduced images, we need to define our instrumental magnitudes the same way.

And since we medianed the images (rather than summing them), t_{exp} is the exposure time of an individual image:

- V images: 900 seconds (15 mins)
- B images: 1200 seconds (20 mins)

So turn counts into instrumental magnitudes using those values.

Applying your photometric solution to the final combined images

Part 2: Turn instrumental magnitudes into real magnitudes

Our photometric solution:

$$m_{inst,B} - m_B = C_B(B - V) + ZP_B$$

$$m_{inst,V} - m_V = C_V(B - V) + ZP_V$$

FINAL	**B**	**V**
C	0.277	0.233
ZP	3.619	3.541
EXPTIME	1200	900

Applying your photometric solution to the final combined images

Part 2: Turn instrumental magnitudes into real magnitudes

Our photometric solution:

$$m_B = m_{inst,B} - C_B(B - V) - ZP_B$$

$$m_V = m_{inst,V} - C_V(B - V) - ZP_V$$

FINAL	**B**	**V**
C	0.277	0.233
ZP	3.619	3.541
EXPTIME	1200	900

Applying your photometric solution to the final combined images

Part 2: Turn instrumental magnitudes into real magnitudes

Our photometric solution:

$$m_B = m_{inst,B} - C_B(B-V) - ZP_B$$

$$m_V = m_{inst,V} - C_V(B-V) - ZP_V$$

FINAL	**B**	**V**
C	0.277	0.233
ZP	3.619	3.541
EXPTIME	1200	900

But wait…

Subtract one from the other:

$$m_B - m_V = \left[m_{inst,B} - m_{inst,V}\right] - [C_B - C_V](B-V) - [ZP_B - ZP_V]$$

$$B - V = \left[m_{inst,B} - m_{inst,V}\right] - [C_B - C_V](B-V) - [ZP_B - ZP_V]$$

$$(B-V)(1 + [C_B - C_V]) = \left[m_{inst,B} - m_{inst,V}\right] - [ZP_B - ZP_V]$$

$$(B-V) = \left(\left[m_{inst,B} - m_{inst,V}\right] - [ZP_B - ZP_V]\right)/\left((1 + [C_B - C_V])\right)$$

Applying your photometric solution to the final combined images

Summary

First measure counts and calculate instrumental magnitudes in each filter:

$$m_{inst,B} = -2.5\log\left(I_B/t_{exp,B}\right) + 25$$
$$m_{inst,V} = -2.5\log\left(I_V/t_{exp,V}\right) + 25$$

Then calculate the color:

$$(B-V) = \left(\left[m_{inst,B} - m_{inst,V}\right] - [ZP_B - ZP_V]\right)/\left((1 + [C_B - C_V])\right)$$

Then insert that color into the photometric solution to calculate magnitudes:

$$m_B = m_{inst,B} \; - C_B(B-V) - ZP_B$$

$$m_V = m_{inst,V} \; - C_V(B-V) - ZP_V$$

FINAL	**B**	**V**
C	0.277	0.233
ZP	3.619	3.541
EXPTIME	1200	900

One last step – correcting for galactic extinction

After all photometry is done and you have your “final” magnitudes and colors, you want to correct for galactic extinction. Dust in the Milky Way (which we are looking through) both dims and reddens the light from M101.

Look up the galactic extinction on NED, using the estimate from Schlafly and Finkbeiner (2011). Then correct for extinction in each band by doing:

$$m_{B,0} = m_{B,obs} - A_B$$
$$m_{V,0} = m_{V,obs} - A_V$$

And then correct the color by doing either

$$(B-V)_0 = (B-V)_{obs} - (A_B - A_V)$$

or

$$(B-V)_0 = m_{B,0} - m_{V,0}$$

But not both! That is, don’t calculate your color from the corrected magnitude and then *also* apply the reddening correction.

Applying your photometric solution to the final combined images

Summary

First measure counts and calculate instrumental magnitudes in each filter:

$$m_{inst,B} = -2.5\log\left(I_B/t_{exp,B}\right) + 25$$
$$m_{inst,V} = -2.5\log\left(I_V/t_{exp,V}\right) + 25$$

Then calculate the color:

$$(B-V) = \left(\left[m_{inst,B} - m_{inst,V}\right] - [ZP_B - ZP_V]\right)/\left((1 + [C_B - C_V])\right)$$

Then insert that color into the photometric solution to calculate magnitudes:

$$m_B = m_{inst,B} \ - C_B(B-V) - ZP_B$$

$$m_V = m_{inst,V} \ - C_V(B-V) - ZP_V$$

Fill in this table using the info from the image headers ⇒

FINAL	**B**	**V**
C		
ZP		
EXPTIME	1200	900

Working with your final combined images

In a terminal window:

- `cd ~/M101`
- `mv Bdata/stack_med.fits M101B.fits`
- `mv Vdata/stack_med.fits M101V.fits`
- `ds9 M101B.fits M101V.fits &`

In ds9:

- Frame → Single Frame
- Frame → Lock → Frame → WCS
- Scale → Scale Parameters → -10 to 3,000
- Scale → Log
- Frame → Lock → Scale
- Frame → Lock → Colorbar

This sets up ds9 so you can zoom, pan, and change the display stretch on one image, then hit "tab" and see the other image similarly displayed.

ds9 regions (Regions → Shape):

- Ruler: will measure distances on image in different units
- Circles: for photometry
  - Make region around object, measure total flux in object
  - Move region to nearby blank sky, measure total flux in blank sky
  - Subtract blank sky flux from object flux to get total flux
  - You can also enter a (α, δ) or (X, Y) coordinate for the region center and it will move to that position.