

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, work out structural properties of the galaxy.
- Measure color profile, interpret colors and gradient in context of galaxy evolution models.
- Write up project in “research journal style”.



Why so many images?

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

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

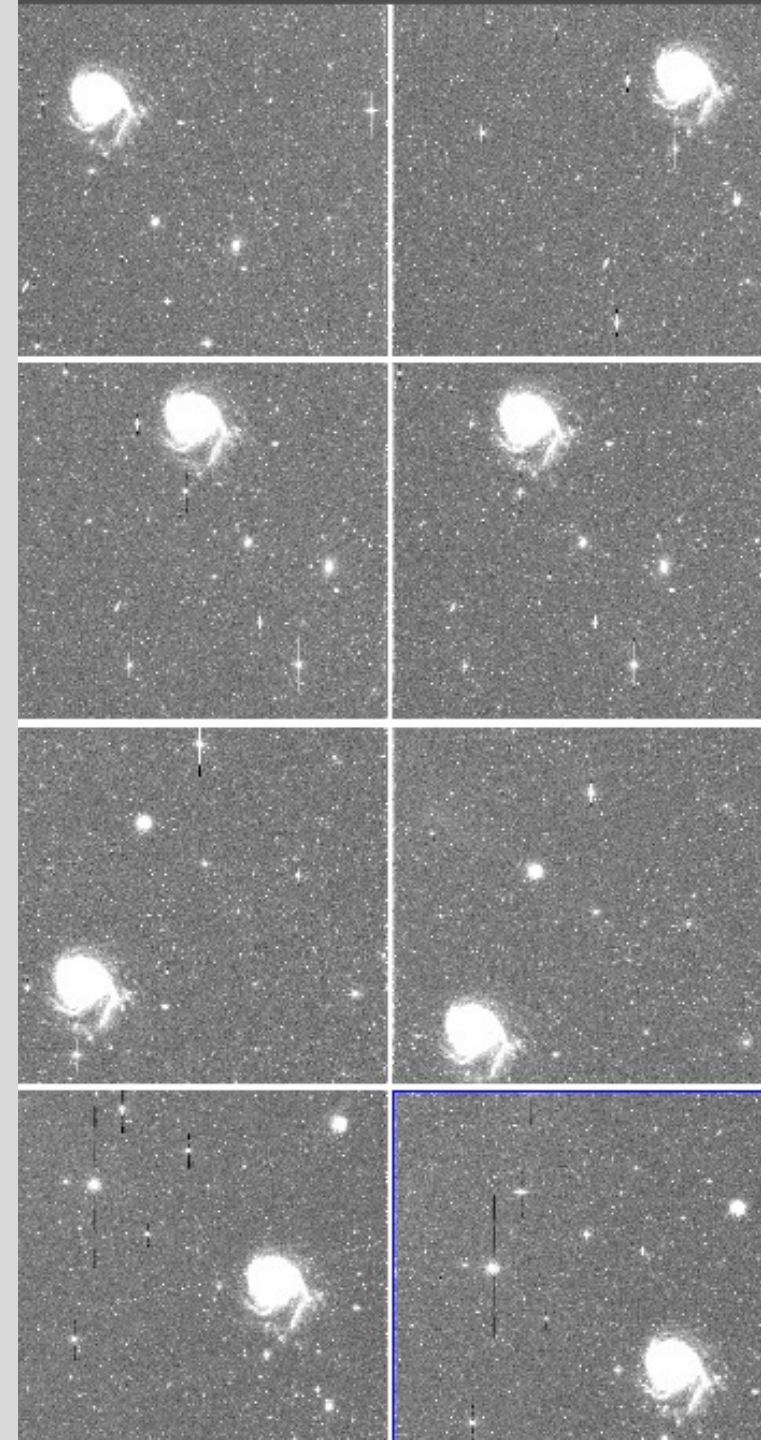
Advantage #1: Increase exposure time and signal-to-noise.

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 ⇒



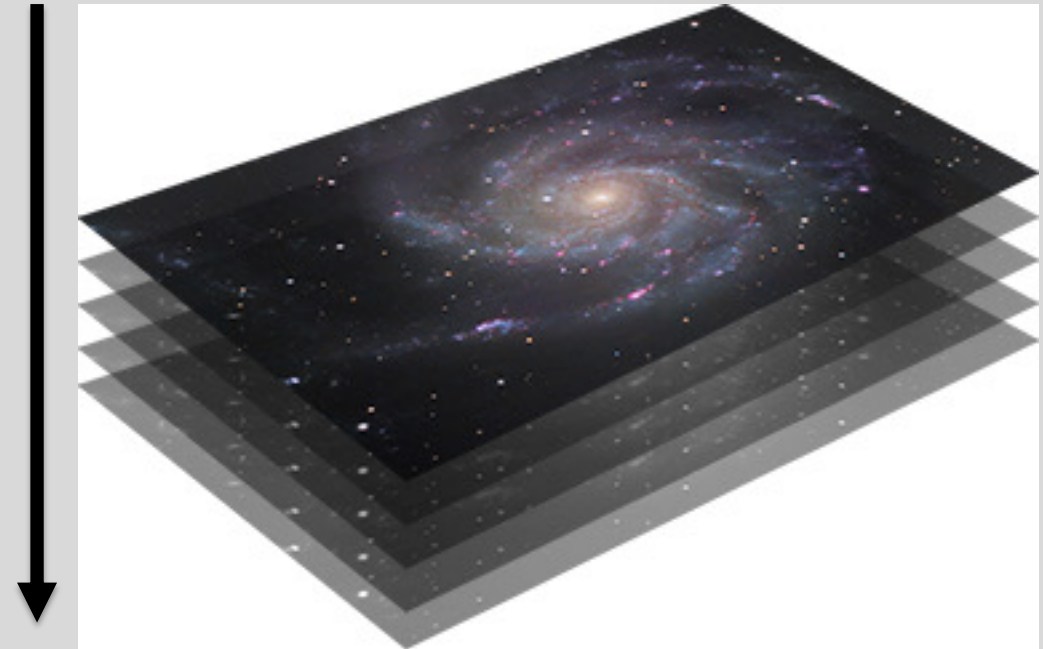
Remember the concept of image math and image combining

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 consistent.
- We averaged 25 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

Getting started today

Move into your V band data directory: **cd ~/Desktop/M101/Vdata**

Open up your assigned image: **ds9 <imname>**

And work through the worksheet.

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:

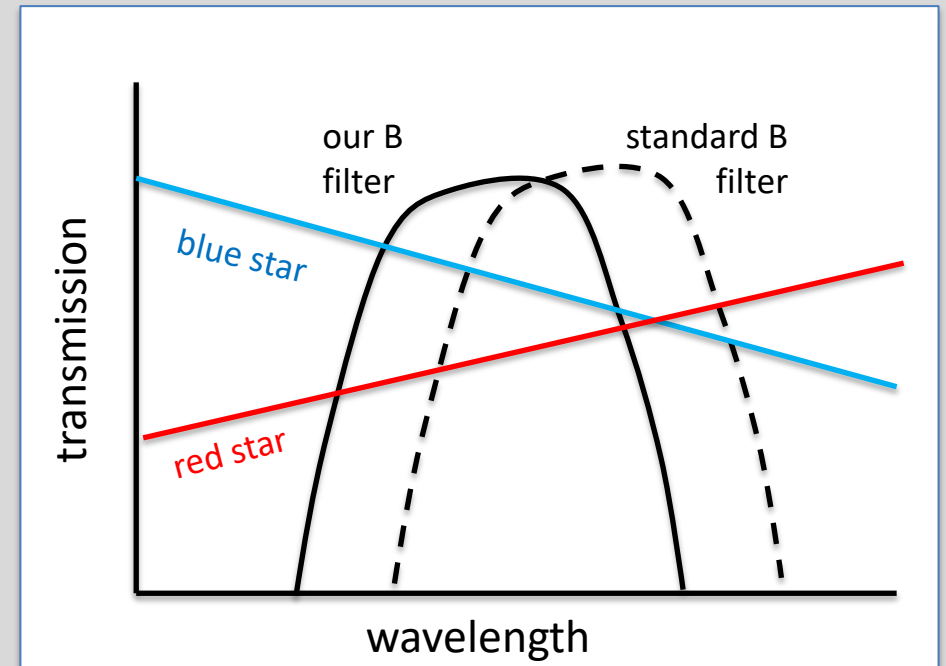
remember: **instrumental magnitude** is just a logarithmic measure of uncalibrated flux on the detector:

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

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

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

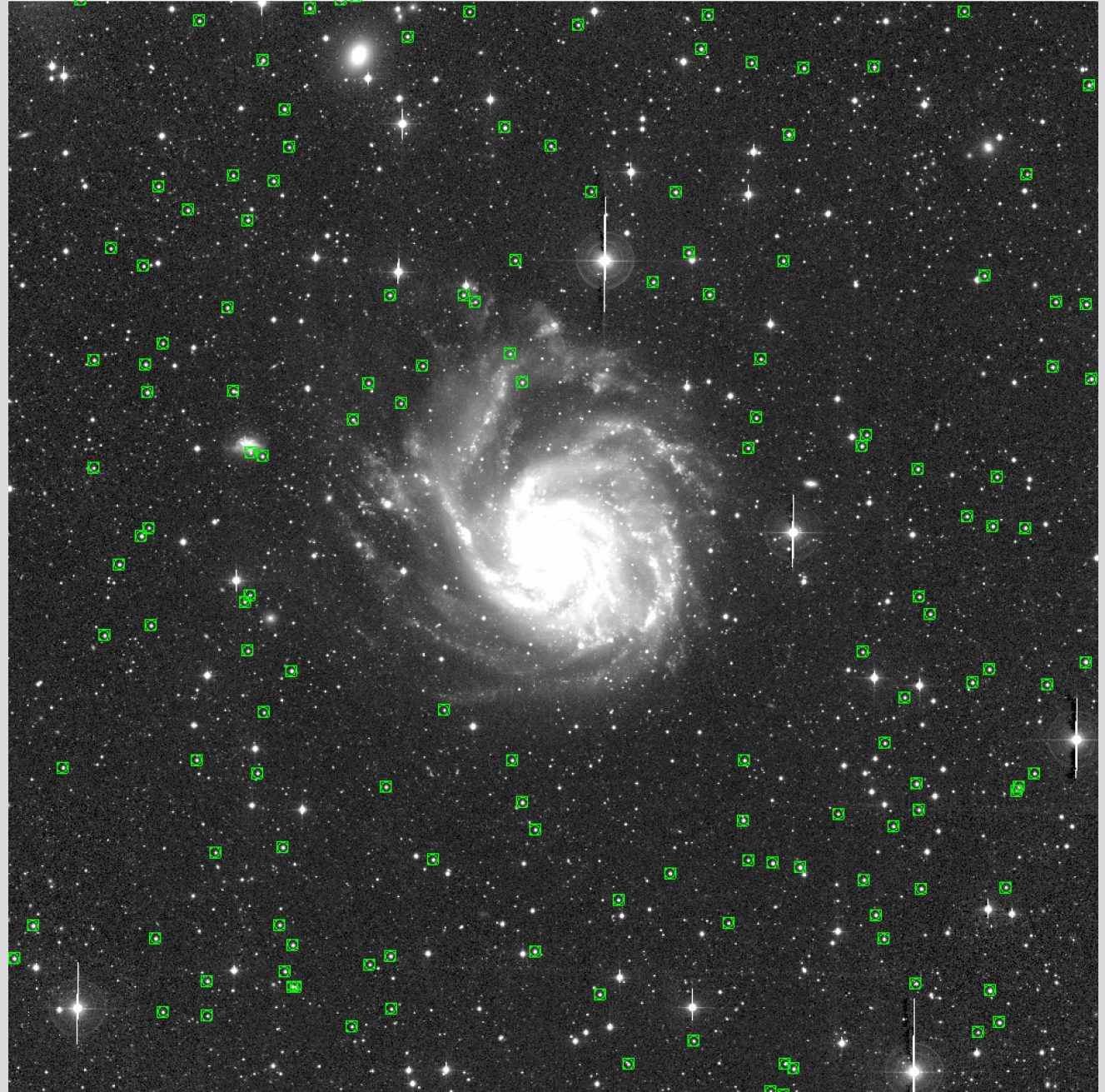
Each star on a given image gives a value for $m_{inst} - m_B$ and $(B - V)$, so plot $m_{inst} - m_B$ against $(B - V)$ for many stars on the image, and then fit a line:

- 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:

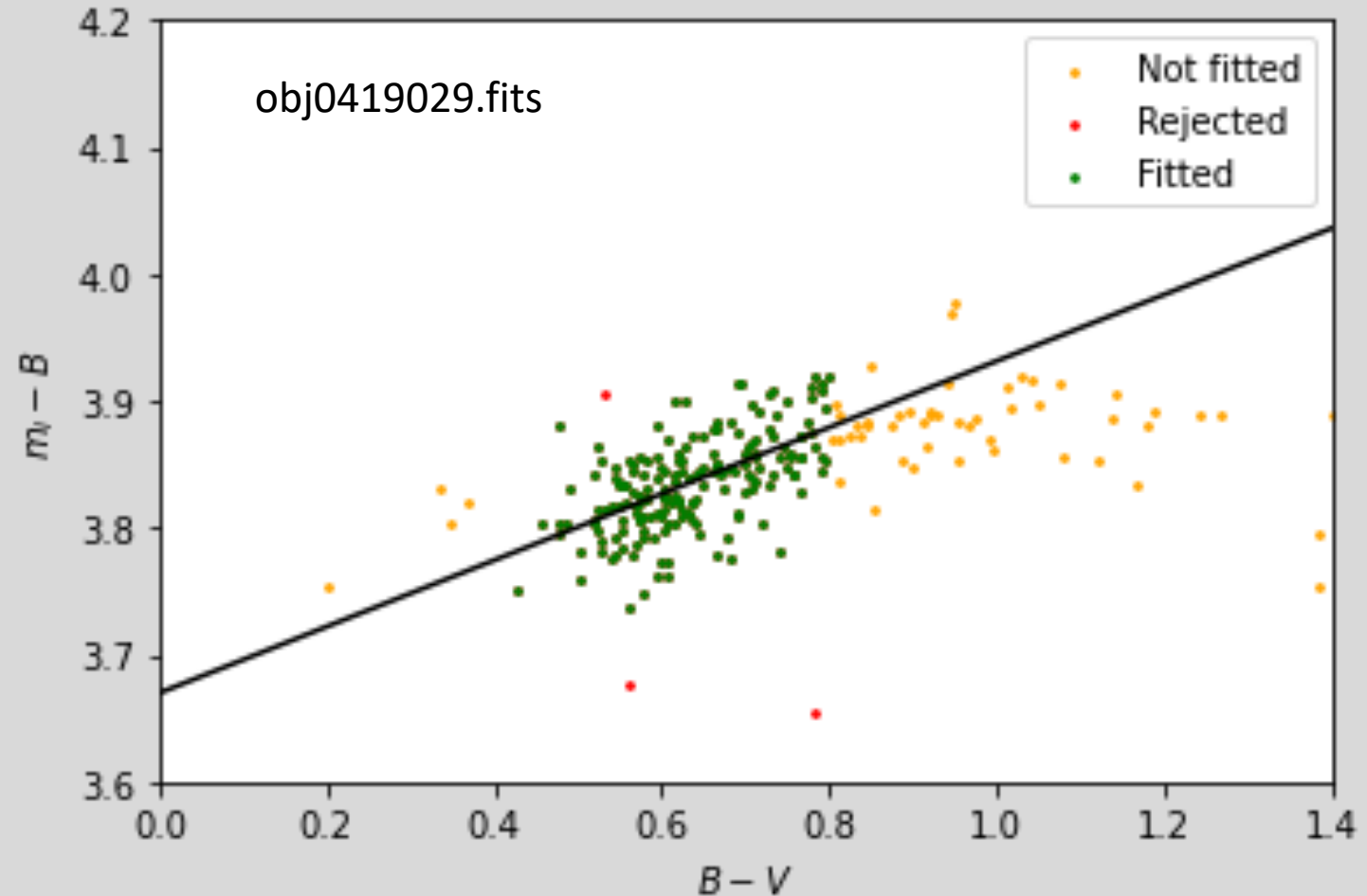
$$m_{inst} = -2.5 \log(I_{ADU}/t_{exp}) + 25$$

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

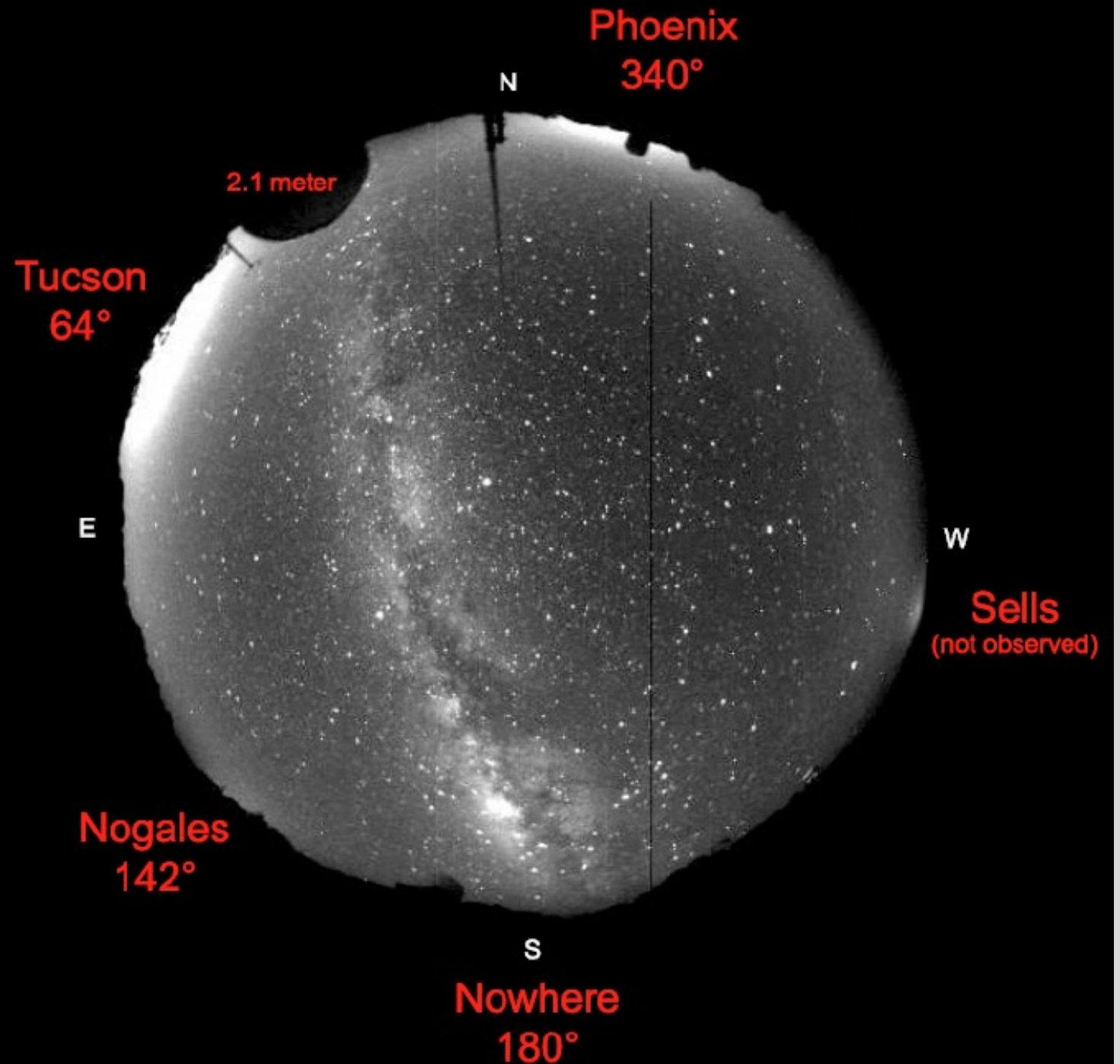
Sky brightness can change from night to night, and over the course of a single night, and also depends on airmass and direction you are observing. So the images all have different sky levels and we have to subtract off this sky level *before* combining.

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

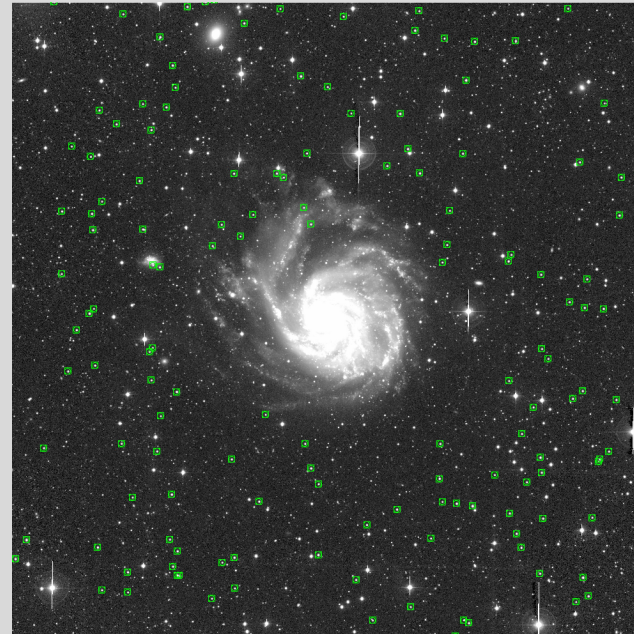
Sky brightness can change from night to night, and over the course of a single night, and also depends on airmass and direction you are observing. So the images all have different sky levels and we have to subtract off this sky level *before* combining.

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

Images are in FITS format, consisting of two parts:

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

Image: array of pixel intensity values

Header: information about the image

KEYWORD = 'VALUE' / comment

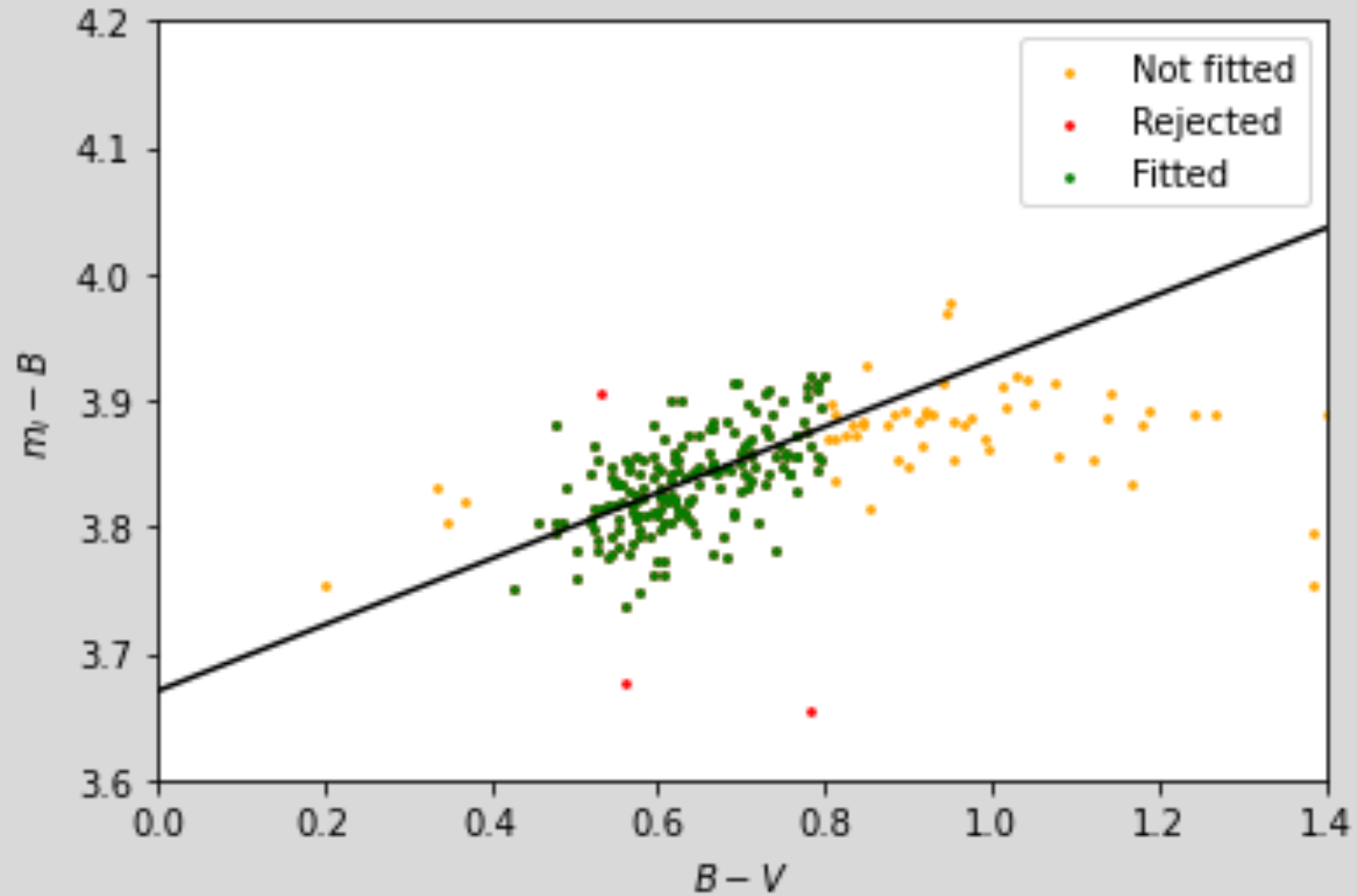


```
SIMPLE = | T / conforms to FITS standard
BITPIX = -32 / array data type
NAXIS = 2 / number of array dimensions
NAXIS1 = 4072
NAXIS2 = 4064
ORIGIN = 'NOAO-IRAF FITS Image Kernel July 2003' / FITS file origin
DATE = '2015-08-18T16:22:14' / Date FITS file was generated
IRAF-TLM= '2015-08-18T16:22:12' / Time of last modification
OBJECT = 'M101' / Name of the object observed
COMMENT FITS (Flexible Image Transport System) format is defined in
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:

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



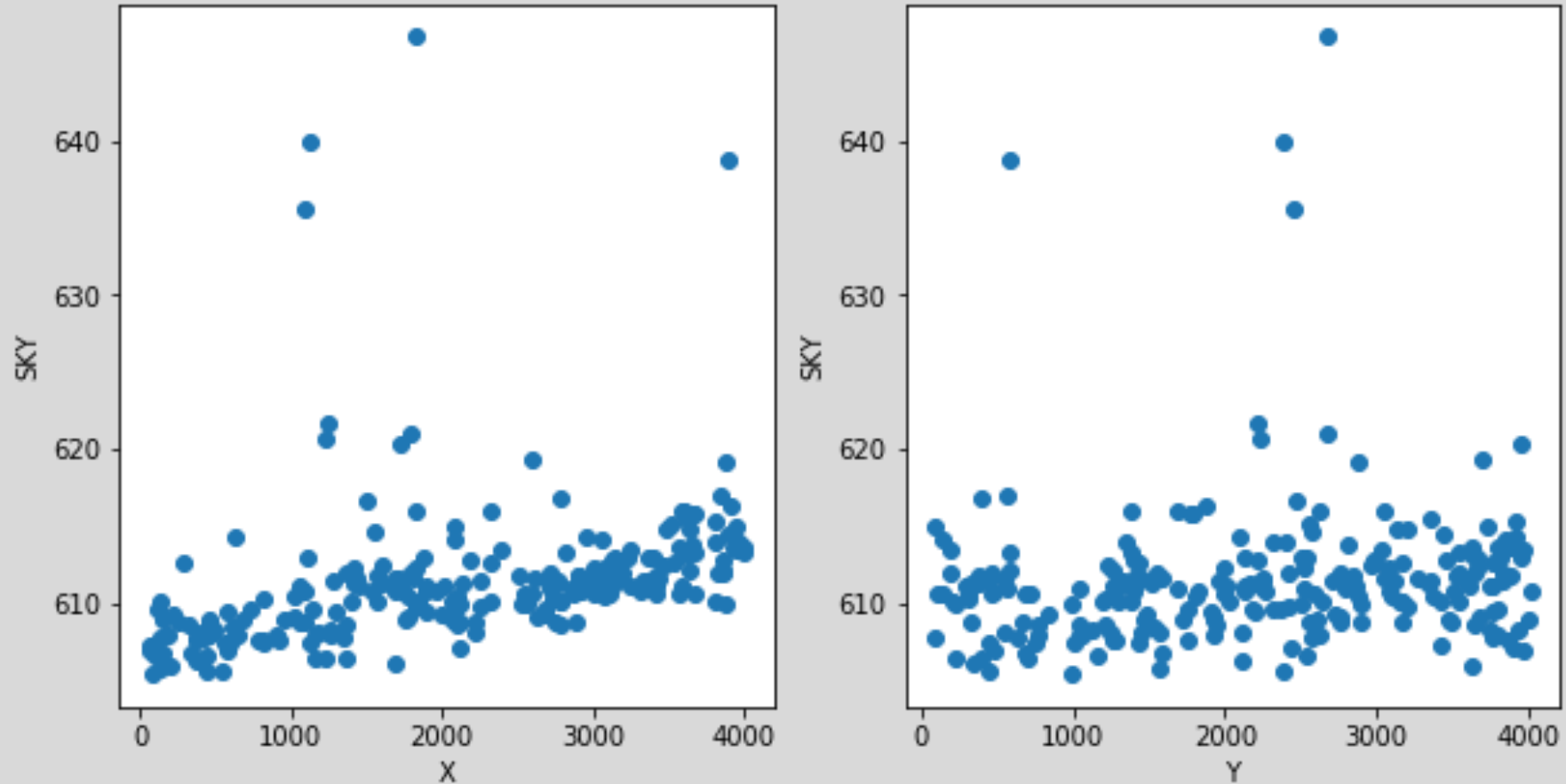
Fit a line to the data to estimate color term and zeropoint.

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

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

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

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.

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

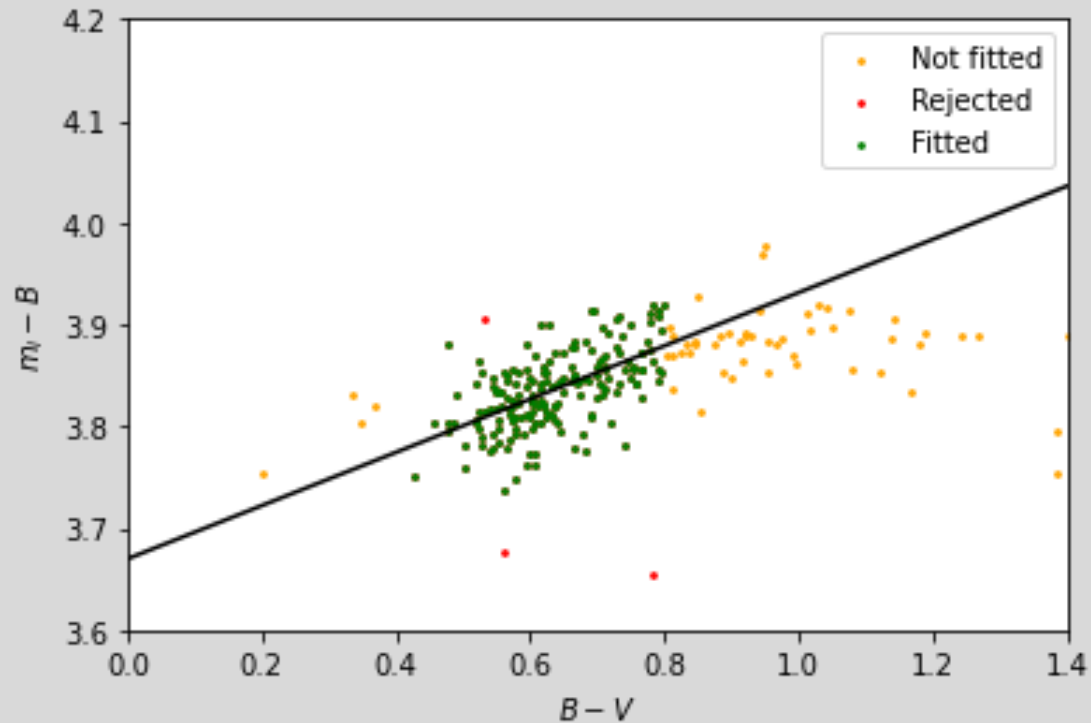
$$\nabla_{SKY,X} = 1.468 (\pm 0.082) \times 10^{-3} \text{ ADU/pix}$$

$$\nabla_{SKY,Y} = 0.440 (\pm 0.084) \times 10^{-3} \text{ ADU/pix}$$

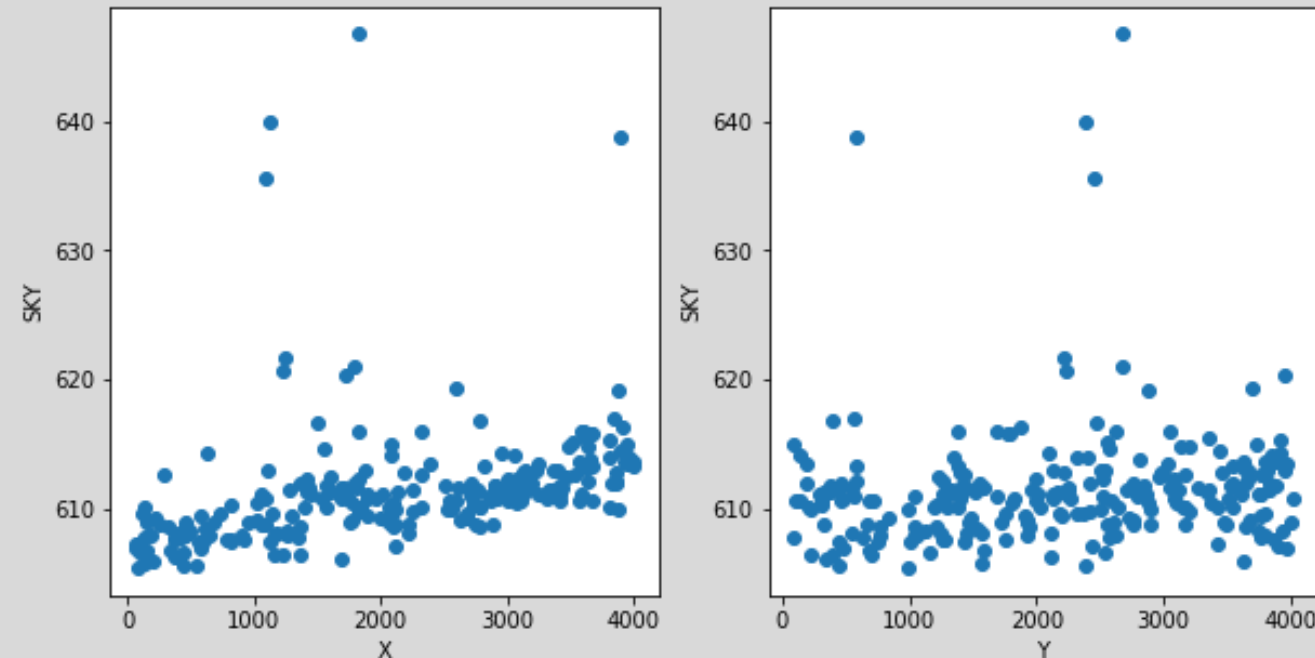
$$SKY_0 = 606.50 \pm 0.27 \text{ ADU}$$

Recapping what we did last time, for each image

Photometric Calibration



Sky Fit and Subtraction



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

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

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

all this info
written into
image headers

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

$$\nabla_{SKY,X} = 1.468 (\pm 0.082) \times 10^{-3} \text{ ADU/pix}$$

$$\nabla_{SKY,Y} = 0.440 (\pm 0.084) \times 10^{-3} \text{ ADU/pix}$$

$$SKY_0 = 606.50 \pm 0.27 \text{ ADU}$$

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, fits the sky plane, then writes 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 (C)

Mostly random scatter

Differences in zeropoint (ZP)

Real, systematic changes. Images were taken at different airmasses

Differences in sky level (SKY0)

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

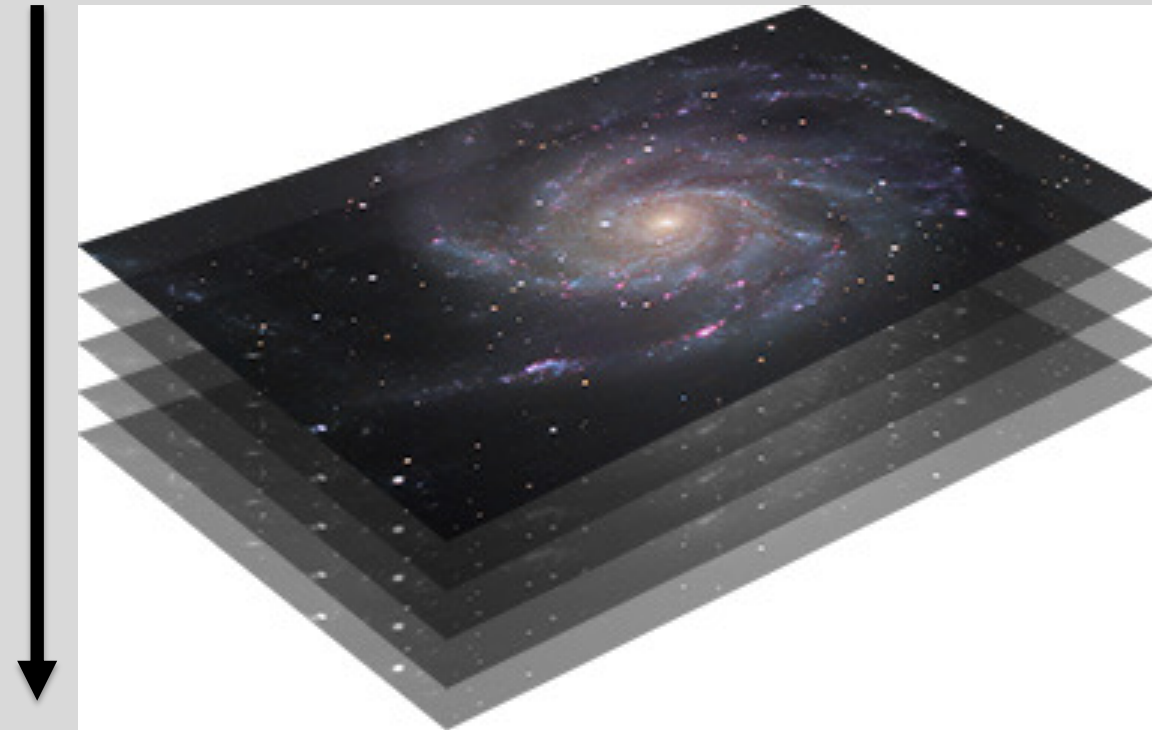
What's next?

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.

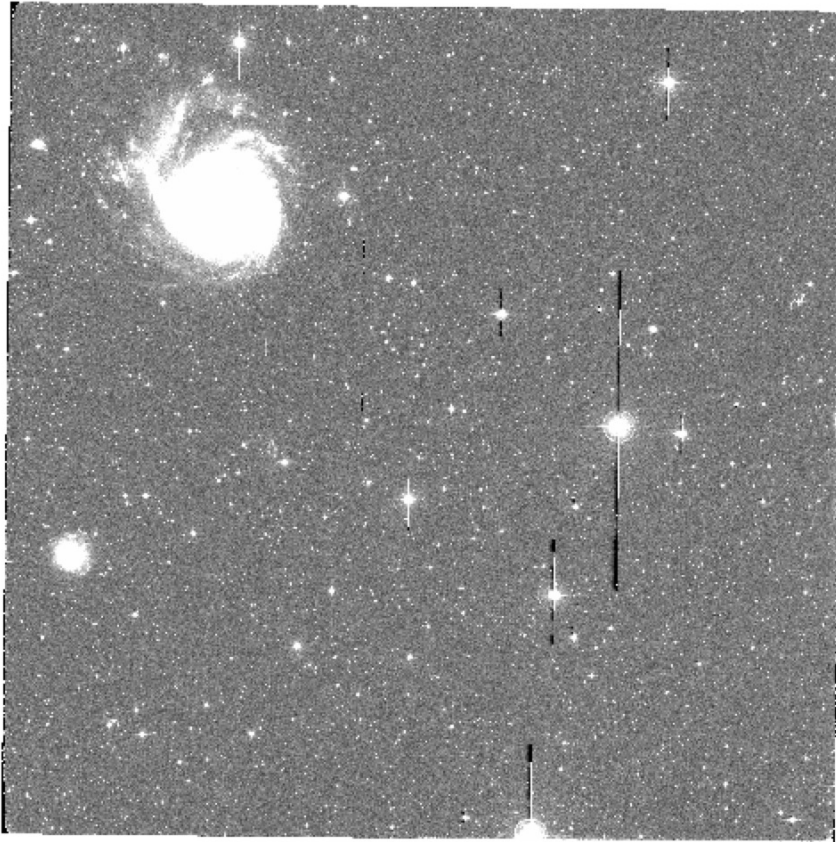


Shifting the images to a common center: “Image re-registration”

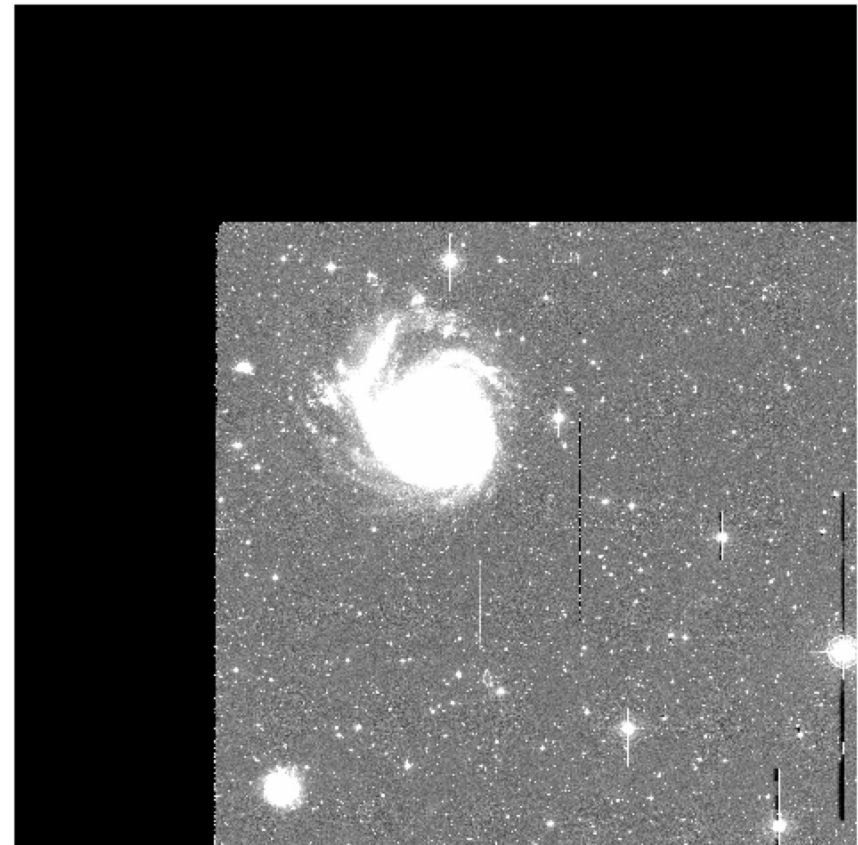
Simplest version: XY integer pixel shift (“shift flux in each pixel over 100 pixels and down 200 pixels”)

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.

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

Since zeropoints are in magnitudes, we can say

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

Then we scale each image in intensity by a factor of

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

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

That 10^{\wedge} 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.

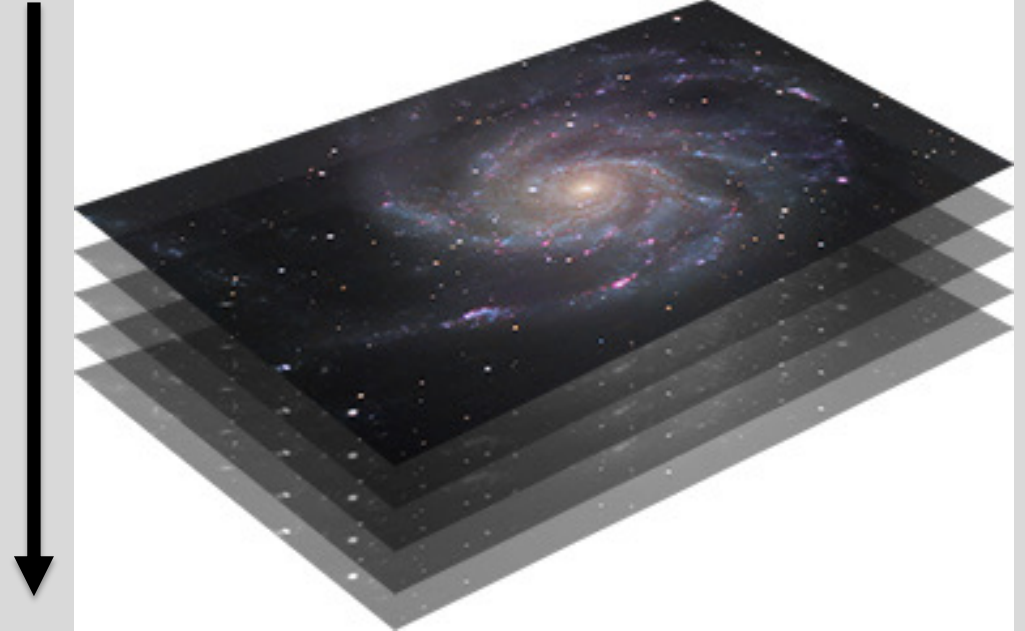
Final Image Combine

1. Re-register each image so that M101 is at the center of the image.
2. Scale each image in intensity to match the average zeropoint:

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

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

This takes 3-5 minutes for each of the B and V stacks.....



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:

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

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 the first step in doing photometry is to measure counts in each of the B and V images, and turn those into instrumental magnitudes ($m_{inst,B}$ and $m_{inst,V}$) using those exposure times.

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	average color term for all images
ZP	3.619	3.541	average ZP that all images were scaled to.
EXPTIME	1200	900	exposure time per image

Applying your photometric solution to the final combined images

Part 2: Turn instrumental magnitudes into real magnitudes

Our photometric solution:

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

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

But wait....

FINAL	B	V	
C	0.277	0.233	average color term for all images
ZP	3.619	3.541	average ZP that all images were scaled to.
EXPTIME	1200	900	exposure time per image

Solve two equations with two unknowns:

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

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

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

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

Applying your photometric solution to the final combined images

Summary

First measure counts and calculate instrumental magnitudes in each filter:

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

Then calculate the color:

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

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	average color term for all images
ZP	3.619	3.541	average ZP that all images were scaled to.
EXPTIME	1200	900	exposure time per image

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:

$$\begin{aligned}m_{B,0} &= m_{B,obs} - A_B \\ m_{V,0} &= m_{V,obs} - A_V\end{aligned}$$

And then calculate the color one of two ways:

correct the observed color:

or

calculate the color from the corrected magnitudes:

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

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

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

And don't try to correct for galactic extinction before calculating your final observed magnitudes and colors!

Photometry.ipynb: turns counts on the images (I_B, I_V) into calibrated apparent magnitudes (m_B, m_V).

```
In [ ]: import numpy as np
```

```
In [ ]: def photsol(IB,IV):  
  
    # UPDATE THESE VALUES!  
    exptime_B, ZP_B, cterm_B = 0., 0., 0.  
    exptime_V, ZP_V, cterm_V = 0., 0., 0.  
  
    m_inst_B=-2.5*np.log10(IB/exptime_B)+25.0  
    m_inst_V=-2.5*np.log10(IV/exptime_V)+25.0  
  
    BmV=((m_inst_B-m_inst_V)-(ZP_B-ZP_V))/(1.0+(cterm_B-cterm_V))  
  
    mB=m_inst_B-cterm_B*BmV-ZP_B  
    mV=m_inst_V-cterm_V*BmV-ZP_V  
  
    return mB,mV
```

```
In [ ]: IB, IV = 1.0,1.0  
        mB, mV = photsol(IB,IV)  
        print('mB = {:.2f}, mV = {:.2f}'.format(mB,mV))
```

(then for the final answer, you also want to correct those magnitudes for Milky Way galactic extinction)

Deriving M101 Properties: Surface Brightness and Color Profile

~~Remember what you did in HW #2 for M84:~~

- ~~• Image in one filter (V)~~
- ~~• Binned pixels by radius, got median pixel intensity (I_{med}) as a function of radius~~
- ~~• Turned pixel intensity into magnitude using 1-band photometric solution:~~

$$~~m = -2.5 \log(I_{med}) + 28.60~~$$

- ~~• Turned magnitude into surface brightness given the area of an individual pixel:~~

$$~~\mu = m + 2.5 \log(1.45^2)~~$$



But for the M101 data it's *different*:

- Images in two filters (B and V)
- Bin pixels by radius, get average/median pixel intensity for each image ($I_{med,B}$ and $I_{med,V}$) as a function of binned radius
- Turn pixel intensities into magnitude and color using the 2-band photometric solution function we worked out in class (See the Photometry.ipynb worksheet on the M101 Lab page)

- Turn magnitude into surface brightness given the area of an individual pixel:

$$\mu = m + 2.5 \log(1.45^2)$$

The answer is shown in Mihos et al (2013), so you know what you are aiming for.



Deriving M101 Properties: Scale length and central surface brightness

Remember that M101 is a spiral galaxy, and we characterize its light profile as an exponential: $I(r) = I_0 e^{-r/h}$

Rewritten using surface brightness this becomes $\mu(r) = \mu_0 + \frac{2.5}{h \ln 10} r$

Fit a straight line to your surface brightness profile (decide what range of radii is best to fit and explain/justify your choice!) and use the fit to derive the central surface brightness (μ_0) and scale length (h).

Deriving M101 Properties: Total Apparent Magnitude

With your fitted values of central surface brightness (μ_0) and scale length (h), derive the total apparent magnitude of M101: $m_{tot} = \mu_0 - 2.5 \log(2\pi h^2)$. (*We worked this out in one of the ASTR 323 Homeworks!*)

Deriving M101 Properties: Physical Parameters

Use the distance to M101 (cite your source!) to convert observed properties (apparent magnitude, scale length in arcminutes, etc) into physical properties (absolute magnitude, luminosity, scale length in kiloparsecs).



Handling Uncertainties

Quantitative: Propagating Random Errors

Use the uncertainties in your fits (slope, intercept) to derive uncertainties in your scale length (h) and central surface brightness (μ_0).

Use the uncertainties in h and μ_0 to derive uncertainty in total apparent magnitude (m_{tot}).

Qualitative: Discussing Systematic Errors

Systematic errors are much more difficult to quantify. Instead, I want you to think and discuss sources of systematic errors and how they might (qualitatively) change your results.



Thinking, Discussion, and Interpretation

Compare your fitted parameters and colors/profiles to those published in the scientific literature, both for M101 specifically and for spiral galaxies more generally. *I want to see more than just a comparison to Mihos et al 2013!*

Think about what it means that you see a particular color profile. What's happening in the galaxy to give these colors? Why might it change with radius?

Think about / discuss the morphology of M101 as seen in your images: its shape, spiral structure, asymmetry, structure in the inner parts vs the outskirts, presence/absence of a central bulge, etc.

Discuss these issues in the context of galaxy evolution (inside-out galaxy formation, disk galaxy evolution, galaxy interactions, etc).



Research Starting Points (*but not ending points!*):

- My galaxies classes ([ASTR 222](#) and [ASTR 323](#))
- Bill Janesh's galaxies class ([ASTR 222](#))
- van der Kruit and Freeman review paper "[Galaxy Disks](#)", in the Annual Review of Astronomy and Astrophysics (ARAA)
- Blanton and Moustakas review paper "[Physical Properties and Environments of Nearby Galaxies](#)" in ARAA
- Mihos et al (2013): "[The Extended Optical Disk of M101](#)"