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 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

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:

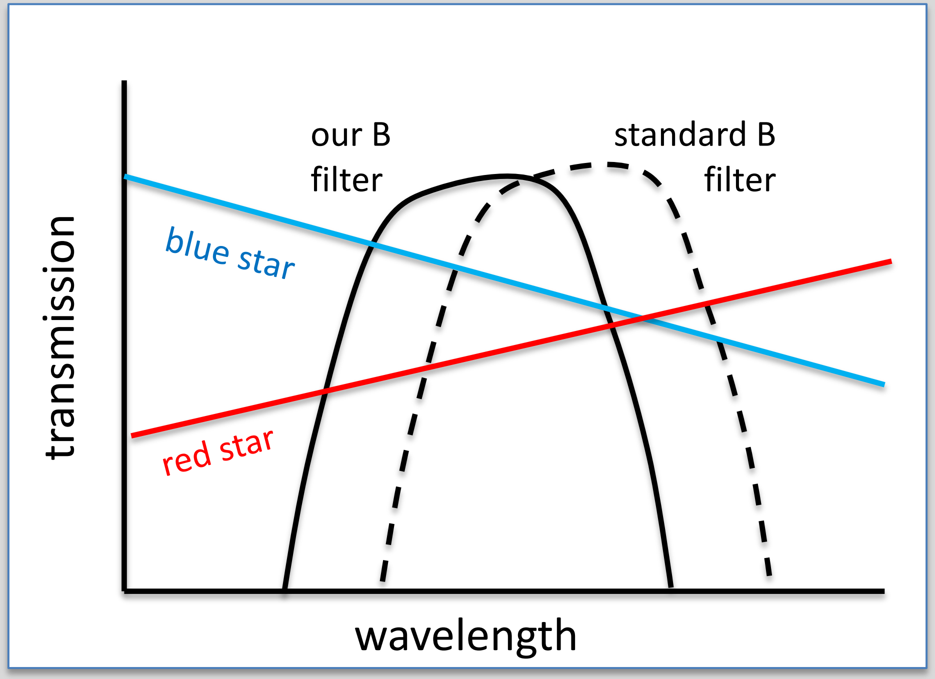
remember: ***instrumental magnitude*** is just a logarithmic measure of uncalibrated flux on the detector:

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

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

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

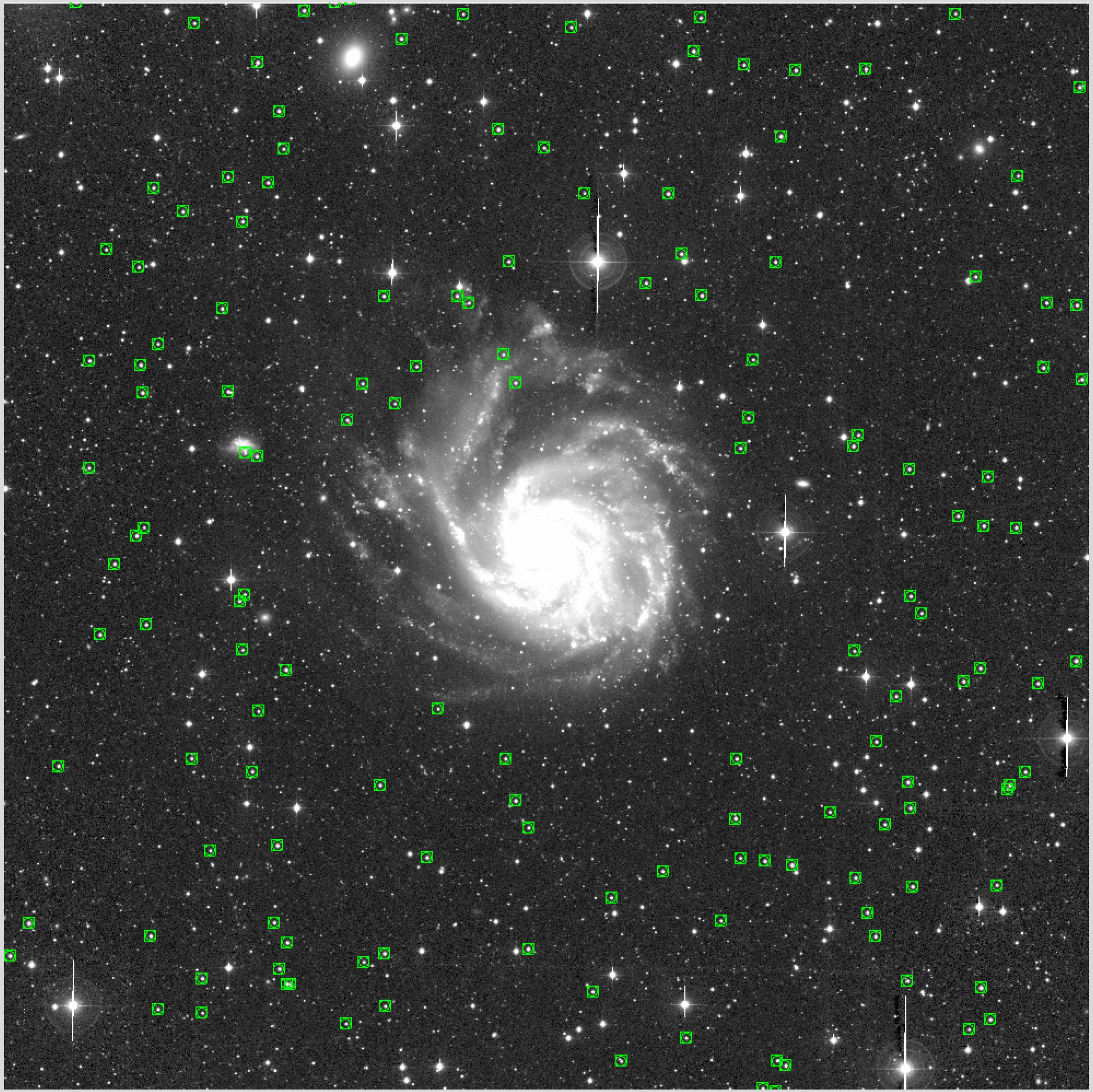
Each star on a given image gives a value for $m_{inst} - m_B$ and $(B - V)$, so plot $m_{inst} - m_B$ against $(B - V)$ for many stars on the image, and then fit a line:

- 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:

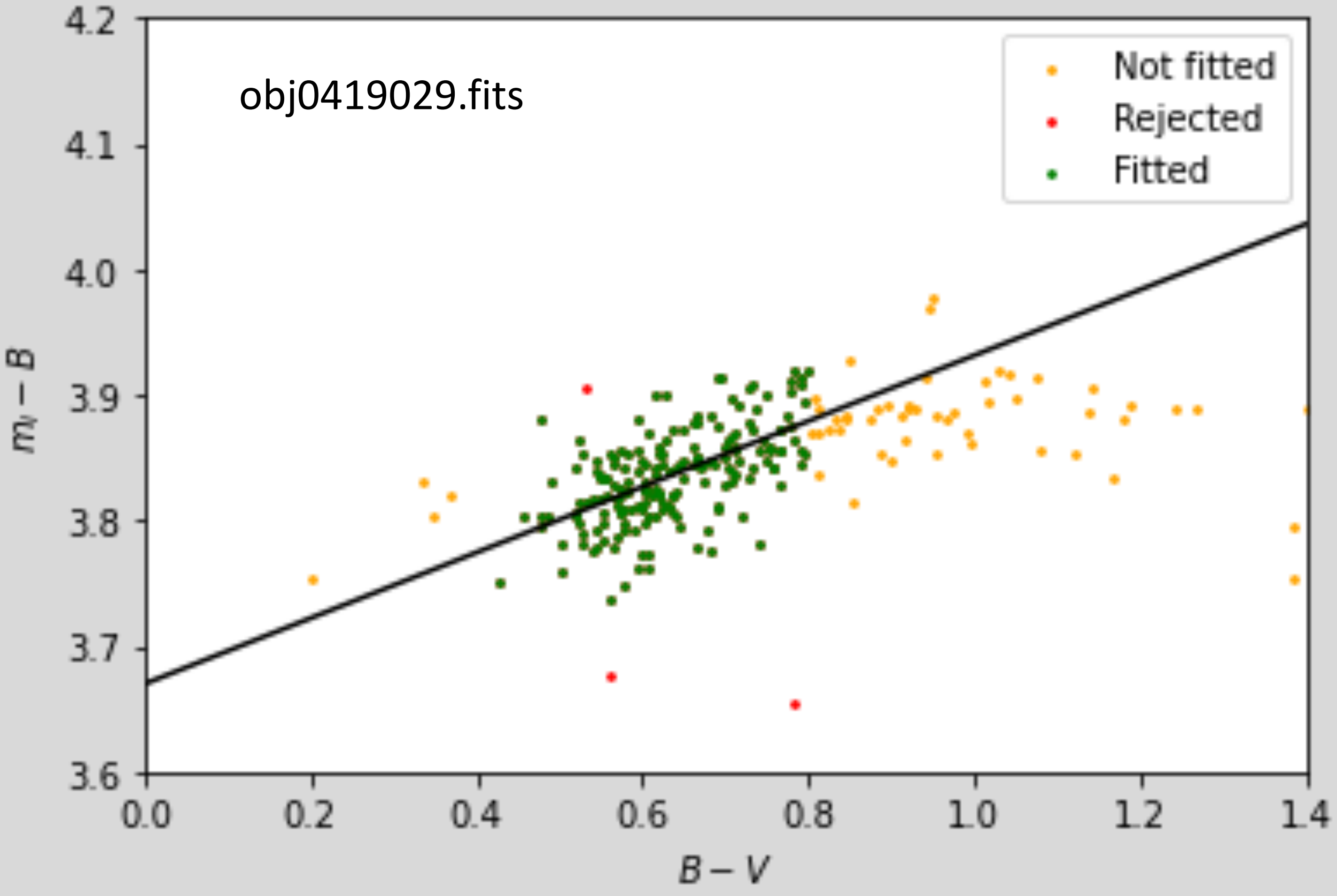
$$m_{inst} = -2.5\log\left(I_{ADU}/t_{exp}\right) + 25$$

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

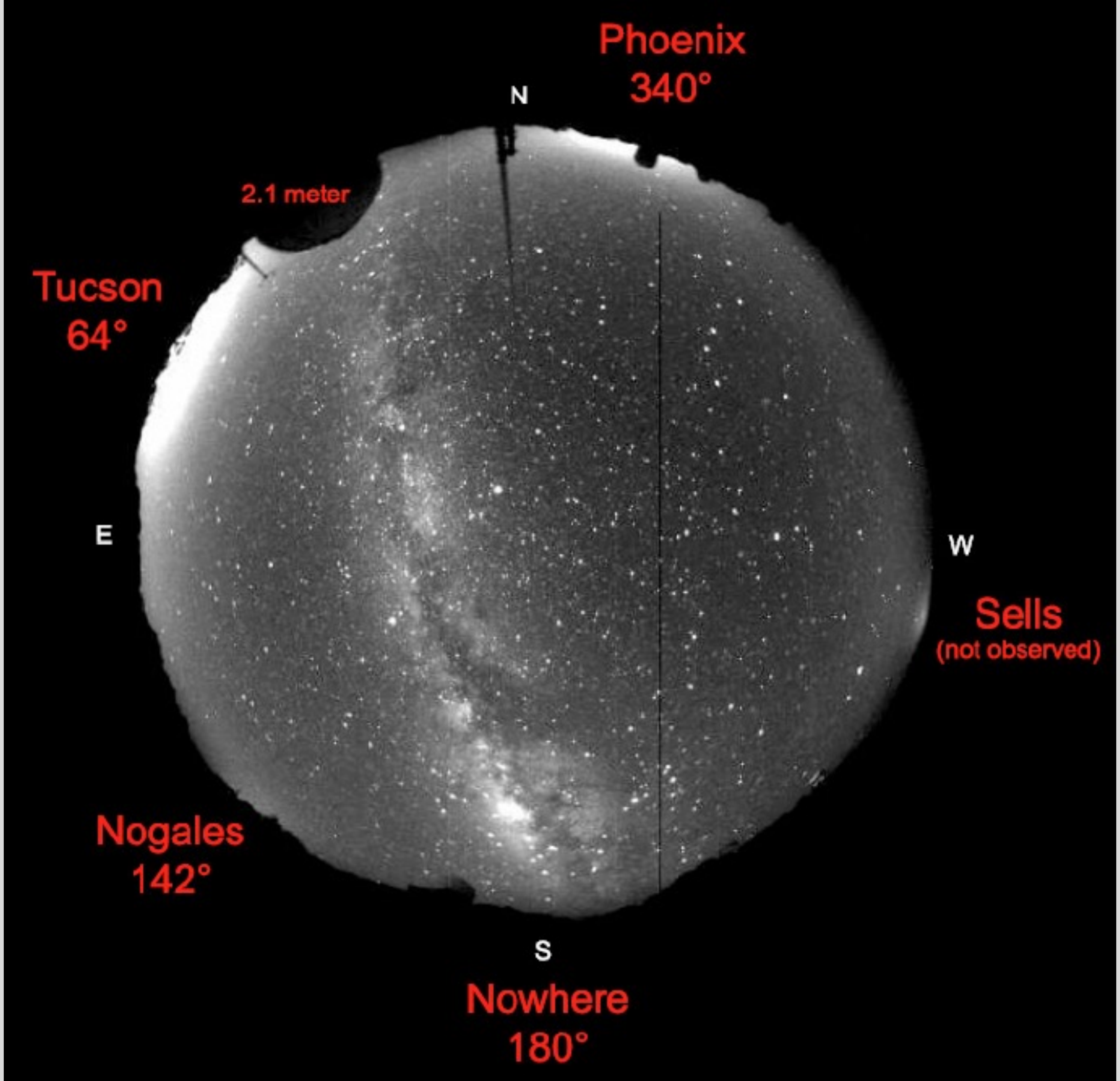
Sky brightness can change from night to night, and over the course of a single night, and also depends on airmass and direction you are observing. So the images all have different sky levels and we have to subtract off this sky level *before* combining.

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

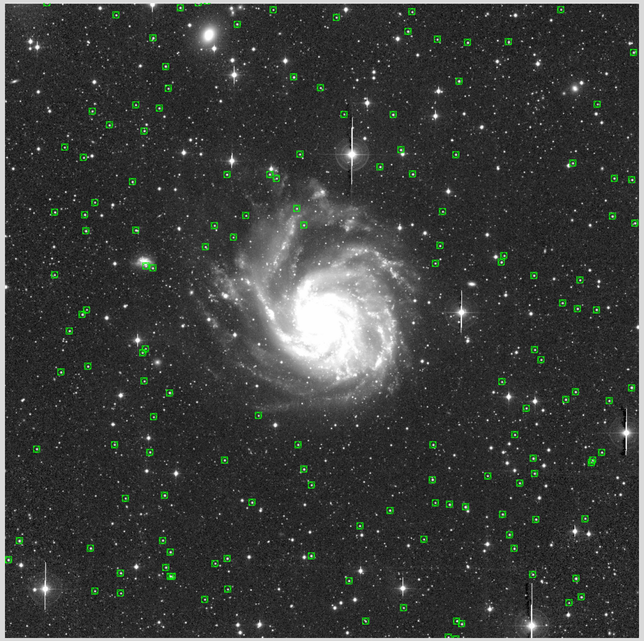
Sky brightness can change from night to night, and over the course of a single night, and also depends on airmass and direction you are observing. So the images all have different sky levels and we have to subtract off this sky level *before* combining.

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

Images are in FITS format, consisting of two parts:

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

Image: array of pixel intensity values

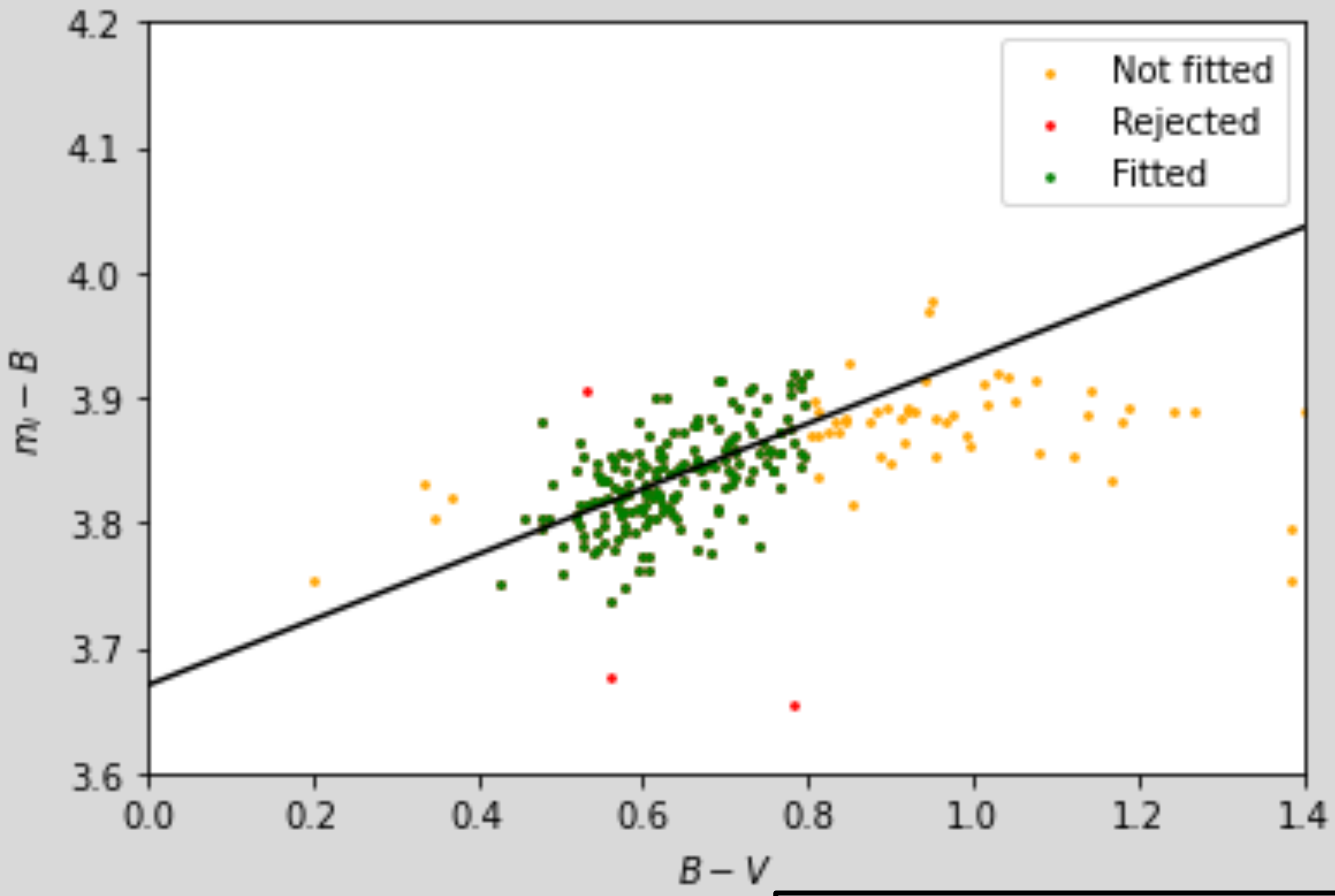
Header: information about the image

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

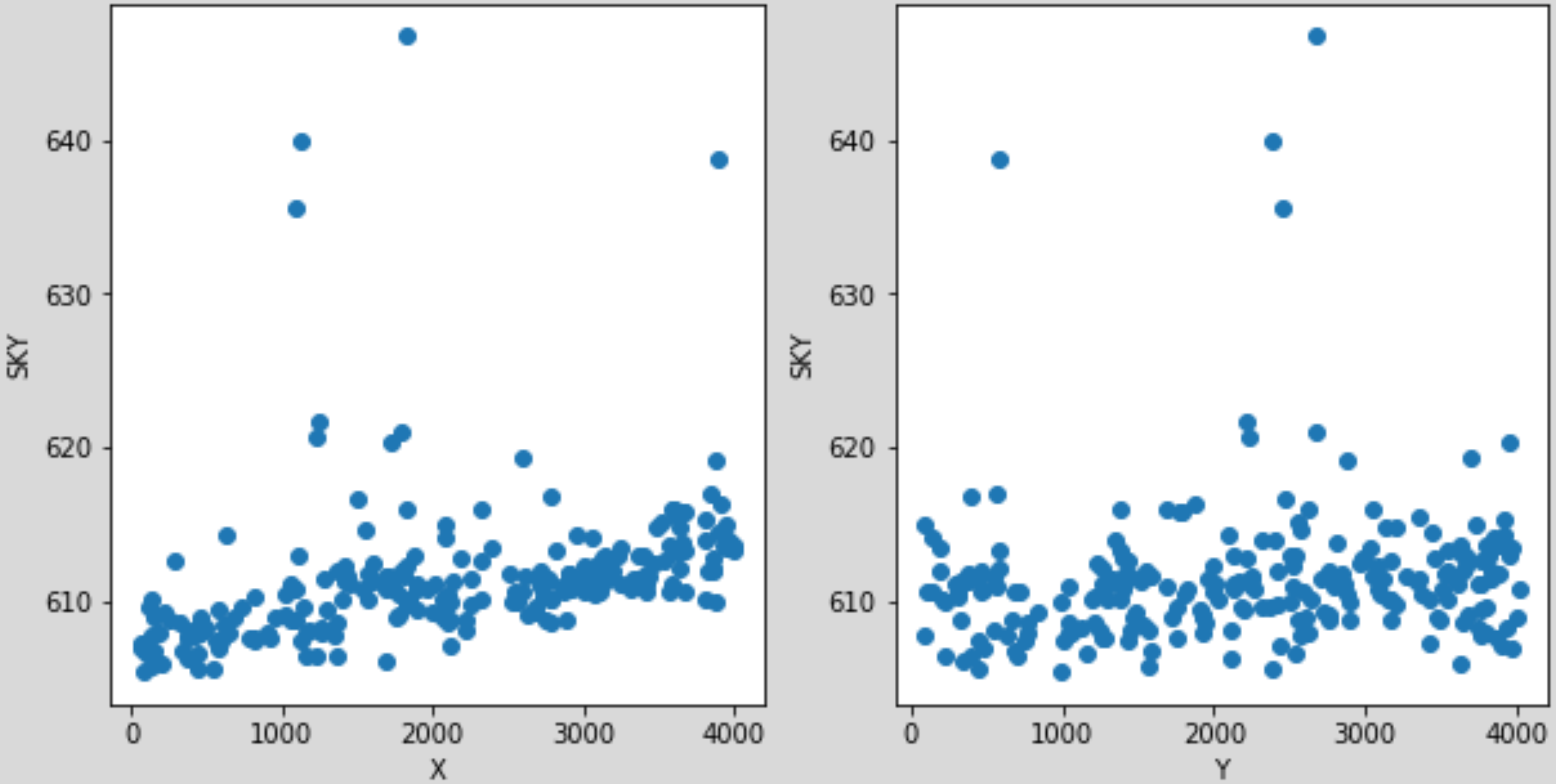


Fit a line to the data to estimate color term and zeropoint.

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

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

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.

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

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