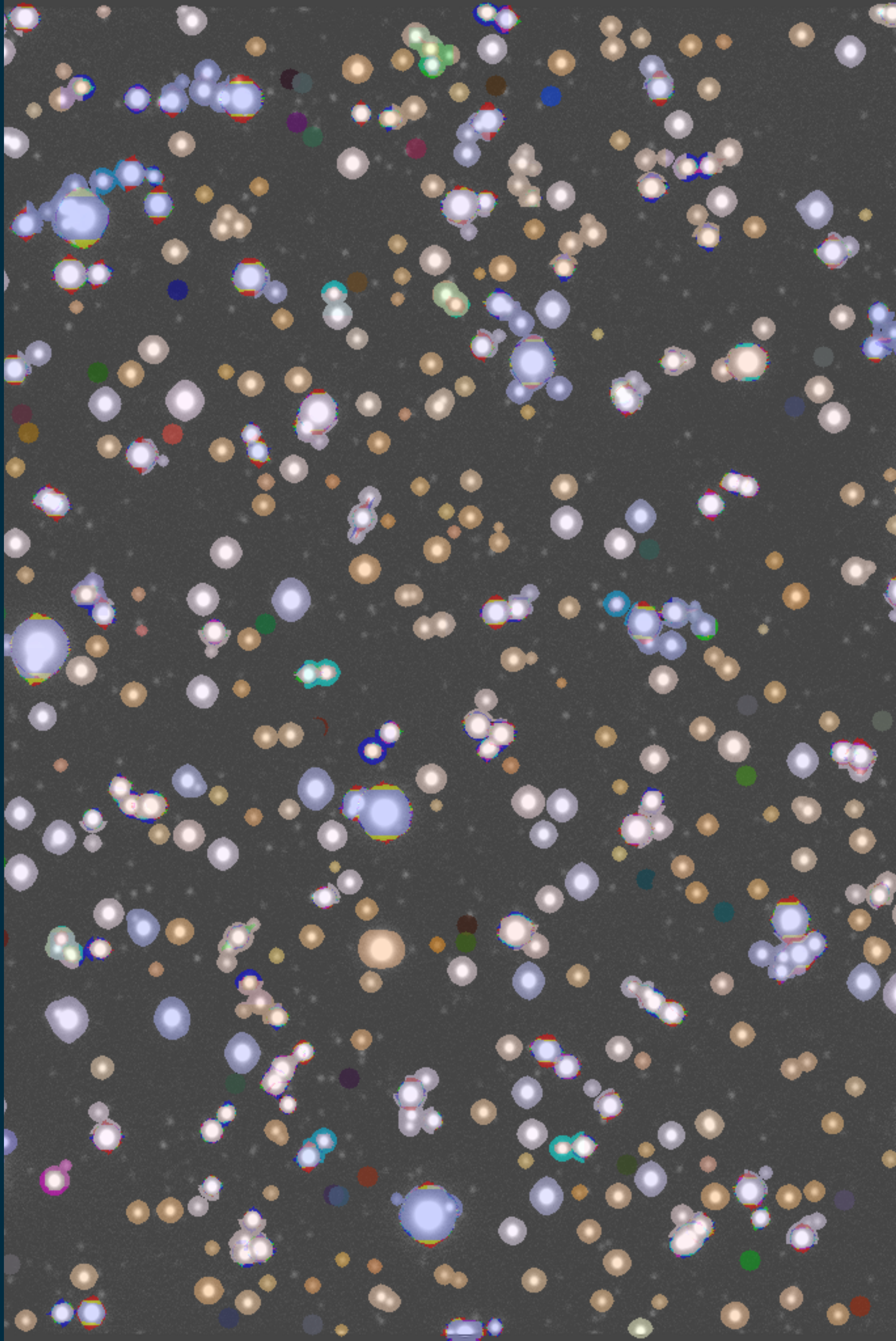
Creating Dcr-Matched Templates For Image Differencing

Ian Sullivan

Large Synoptic Survey Telescope



Overview

DCR overview

Iterative forward modeling

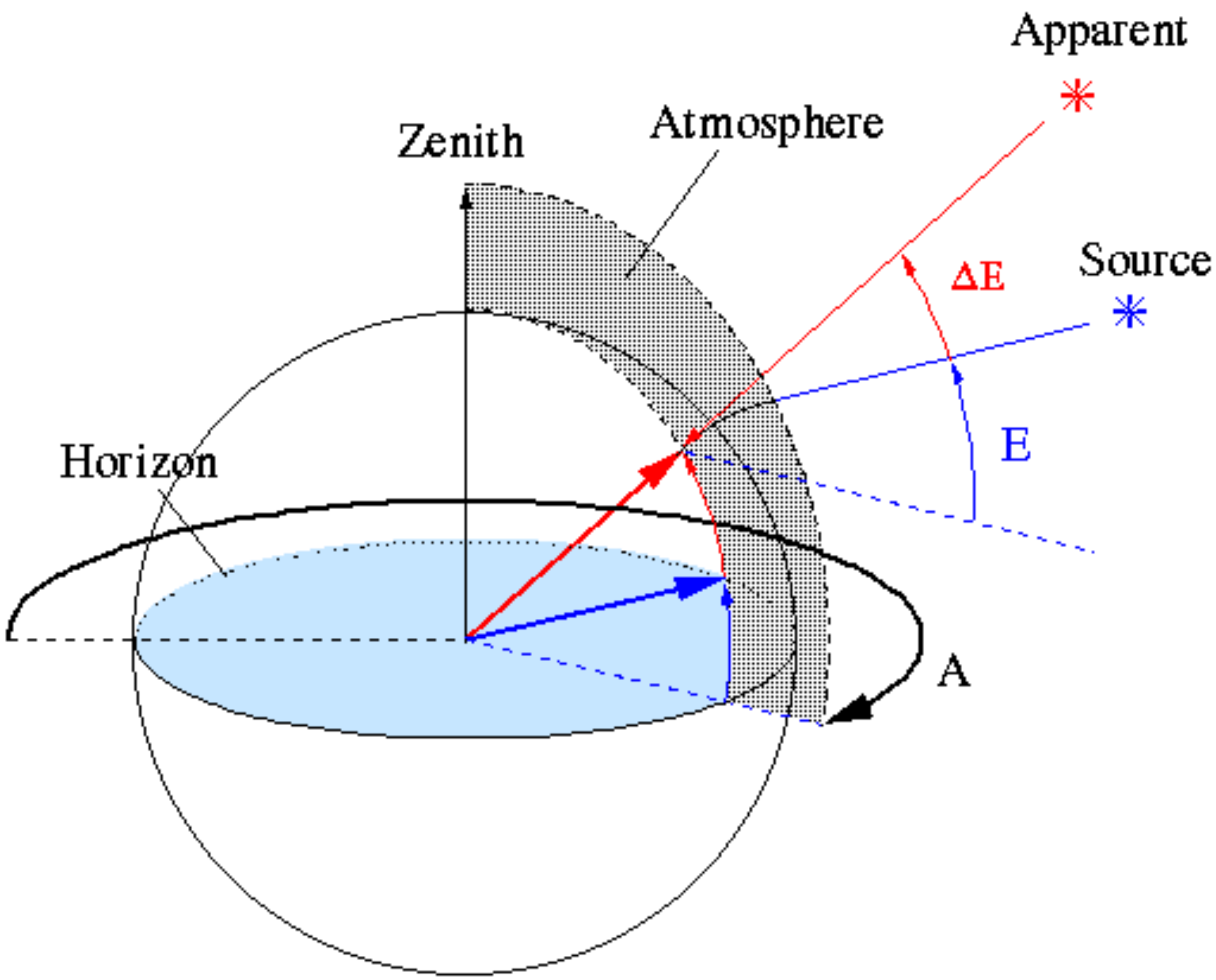
Improved image differencing

Single-filter color estimates

DCR Overview

Refraction deflects the apparent position of sources towards zenith.

The amplitude of refraction depends on environmental factors and the wavelength of incident light.



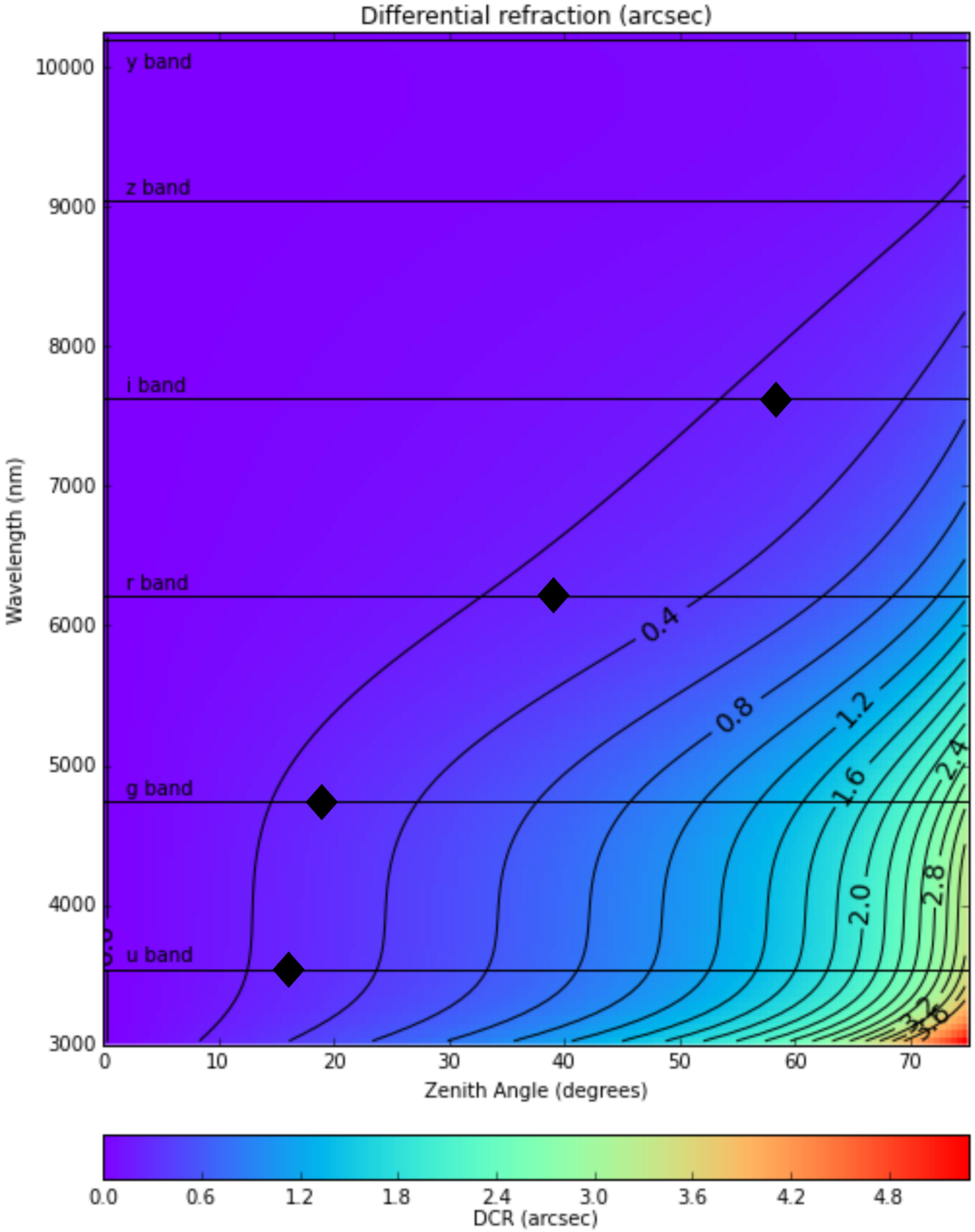
Differential Chromatic Refraction (DCR) occurs when the index of refraction of the atmosphere changes significantly across the bandwidth of a filter

DCR Overview

When do we care about DCR?

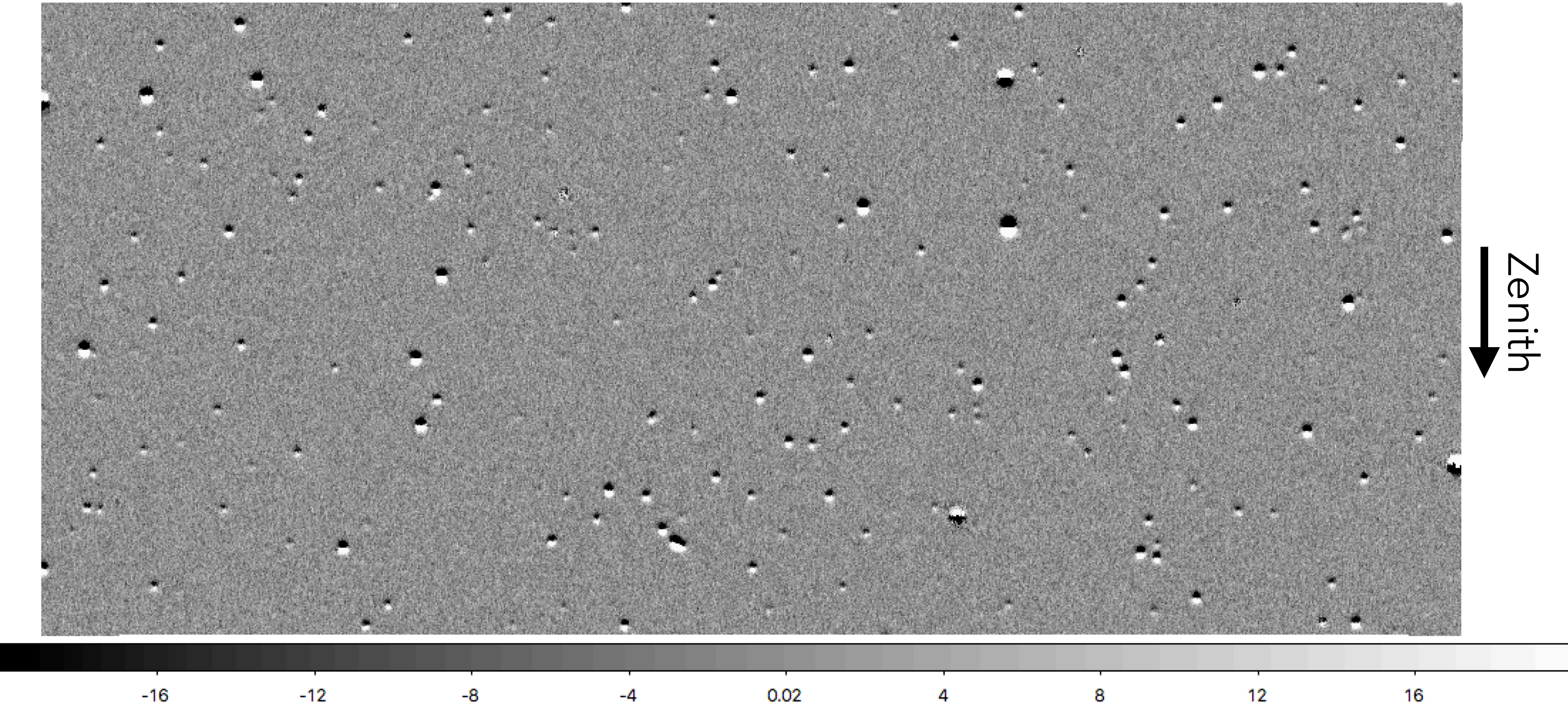
Worst case DCR estimate:
Take the relative deflection between two parallel beams of monochromatic light at the red and blue edges of a filter bandpass

The diamonds mark the angles where the maximum DCR equals one LSST pixel in each filter



DCR Overview

Uncorrected DCR leads to dipoles in difference imaging

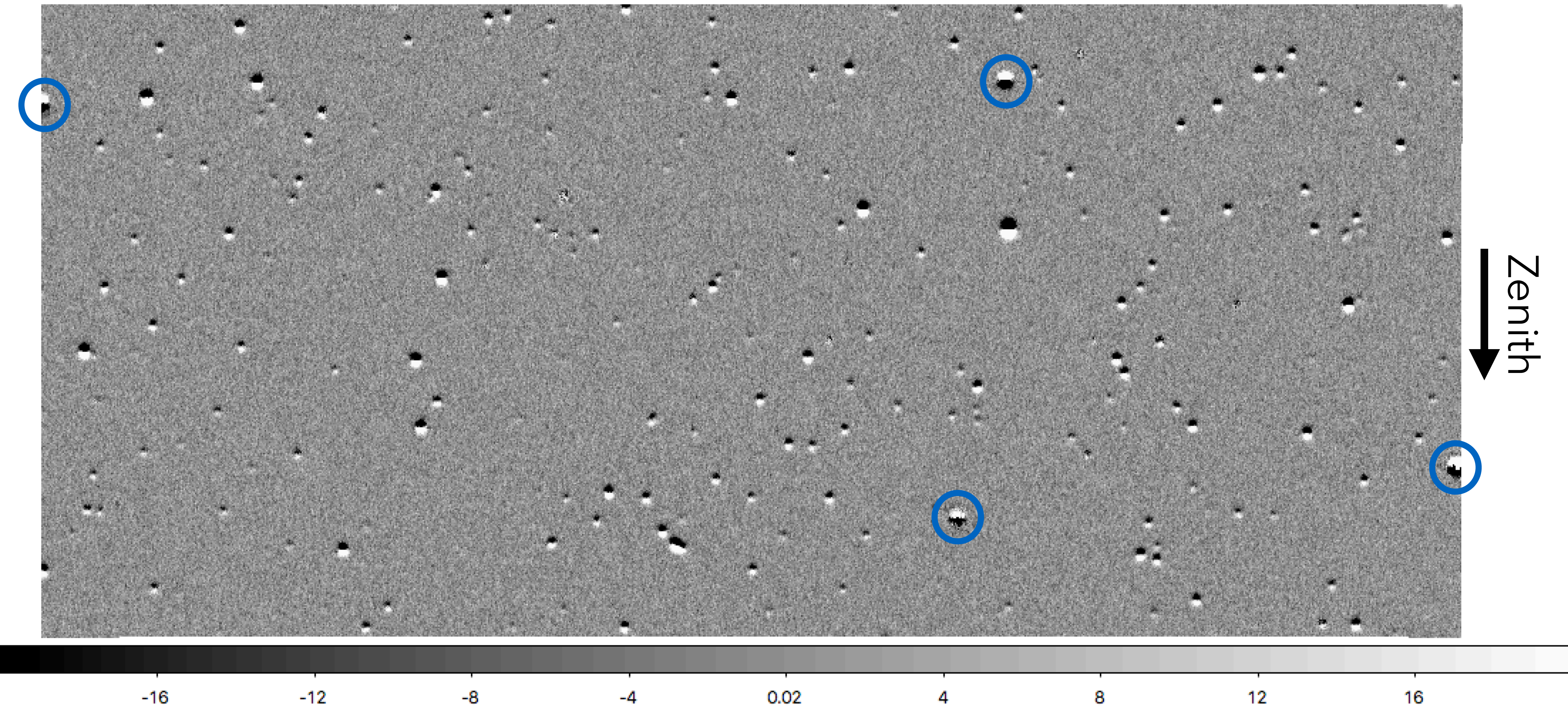


Simulated airmass 1.3 observation - zenith template in g-band, with no astrometric calibration.

Calibration and PSF-matching may fix many dipoles, but will make some worse

DCR Overview

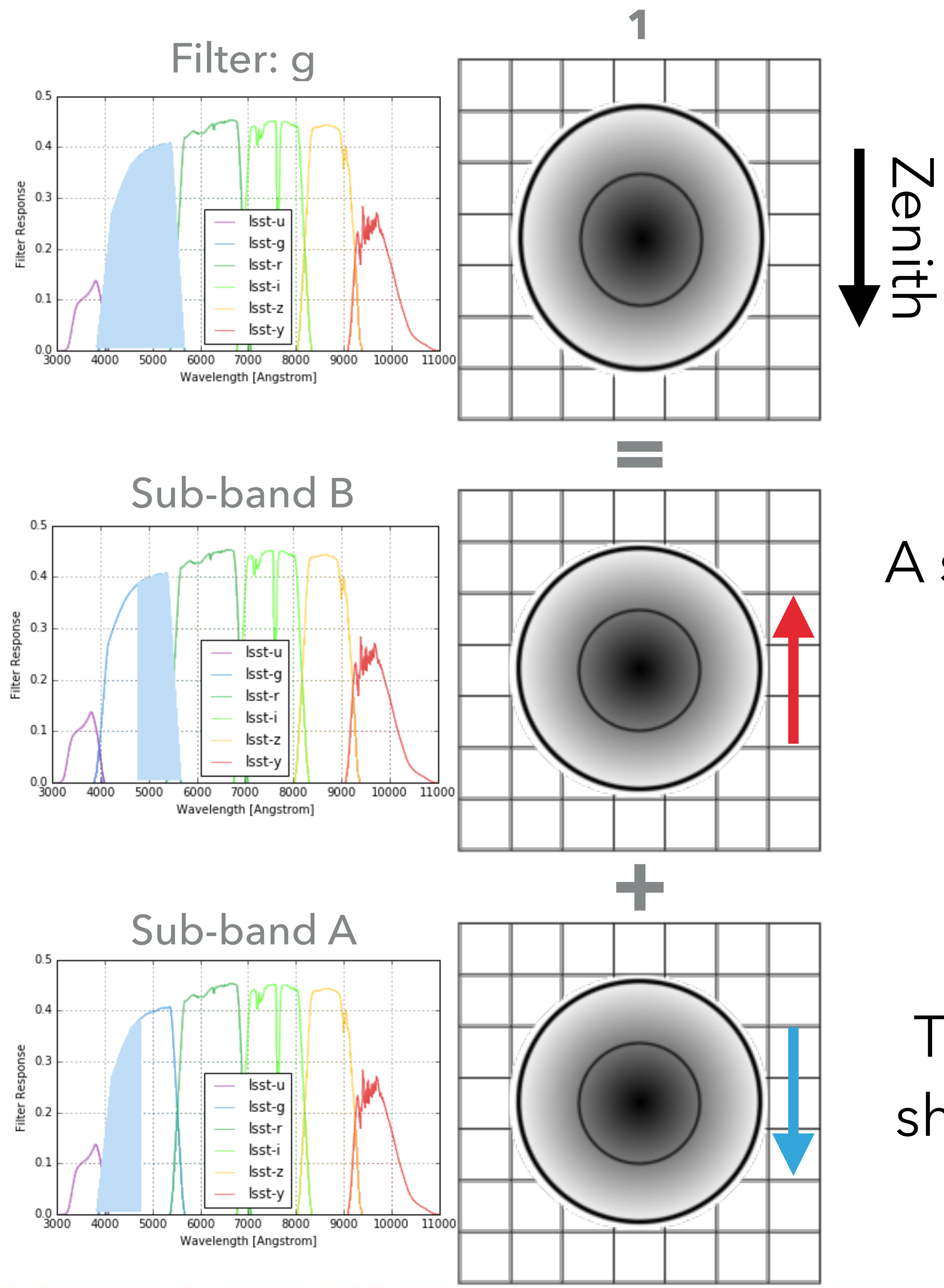
Uncorrected DCR leads to dipoles in difference imaging



Simulated airmass 1.3 observation - zenith template in g-band, with no astrometric calibration.

Calibration and PSF-matching may fix many dipoles, but will make some worse

Forward Modeling



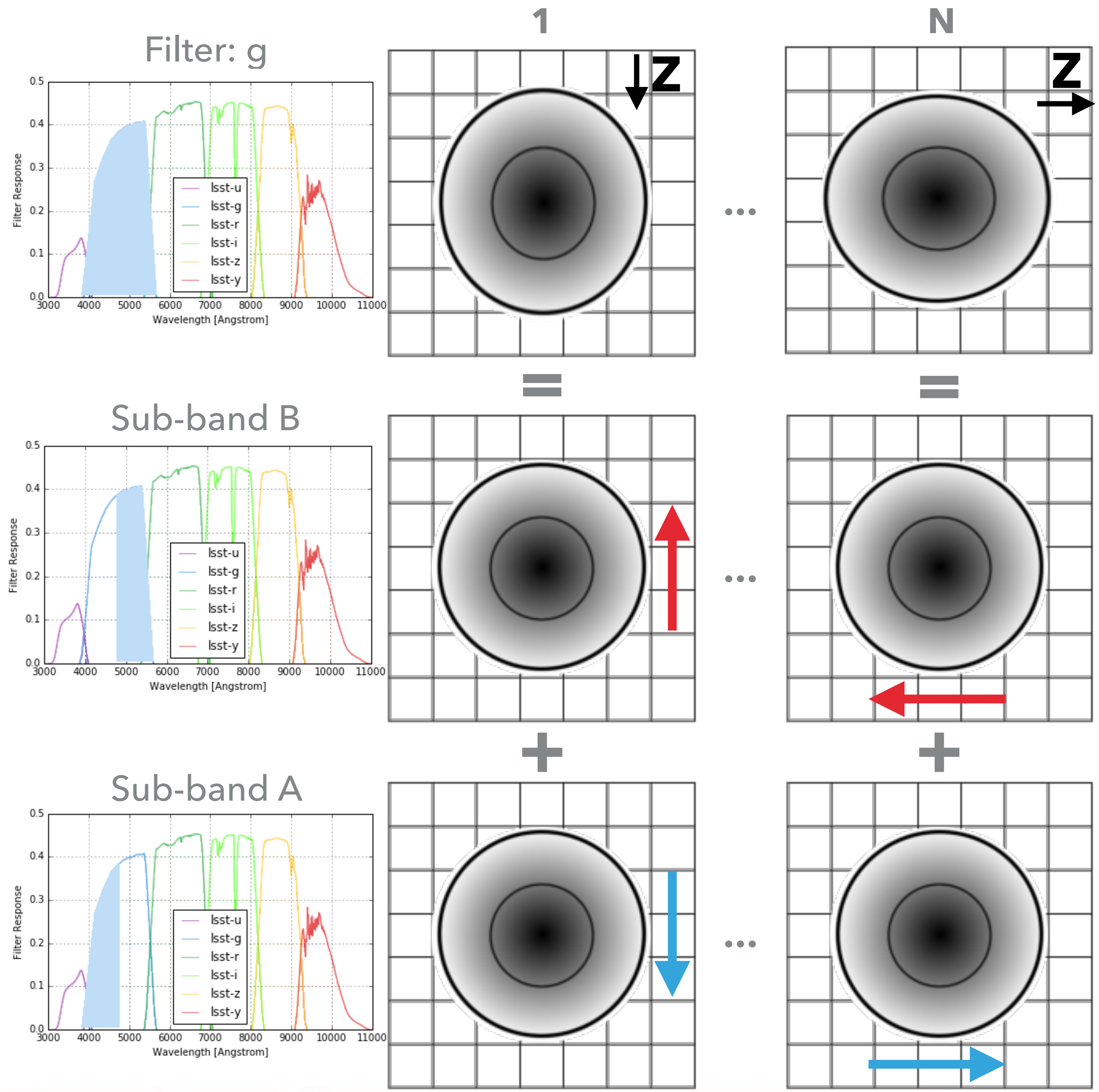
Each pixel in an image contains flux smeared out along the zenith direction

A small sub-band of the full filter bandwidth has negligible DCR

The sub-band model is shifted towards zenith relative to the center of the band

The original image can be reproduced by shifting and stacking models from all of the sub-bands.

Forward Modeling



Repeated observations of the same field see the flux smeared in different directions

Only the direction and magnitude of the shift of the sub-band models depends on the observing conditions.

The pixel values of the models do not change

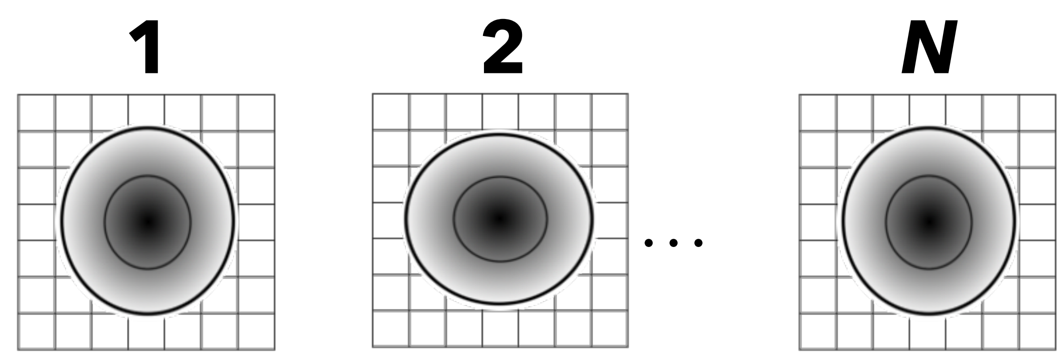
Iterative Forward Modeling

Each image is the sum of a series of convolutions with the sub-band models:

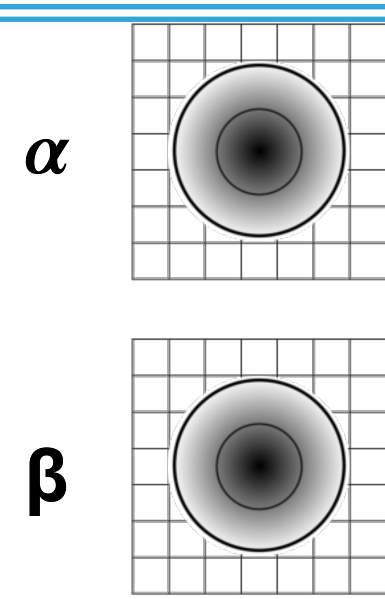
$$\sum_{\alpha} B_{i\alpha} \vec{y_\alpha} = \vec{s_i}$$

If the convolution kernel ***B*** is a shift, then $B^{\star}_{\alpha i} B_{i\alpha} = \mathbb{1}$

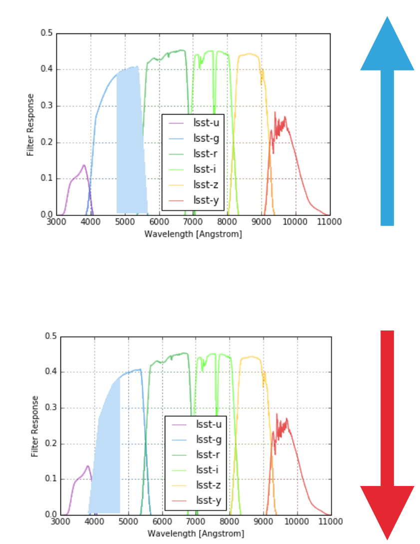
Pixel values of each image *i* : $\vec{s_i}$



Pixel values of each sub-band $\boldsymbol{\alpha}$: $\vec{y_\alpha}$



The DCR shift of sub-band $\boldsymbol{\alpha}$ for the observing conditions of image *i* : $B_{i\alpha}$



Iterative Forward Modeling

Each image is the sum of a series of convolutions with the sub-band models:

$$\sum_{\alpha} B_{i\alpha} \overrightarrow{y_\alpha} = \overrightarrow{s_i}$$

If the convolution kernel ***B*** is a shift, then $B^\star_{\alpha i} B_{i\alpha} = \mathbb{1}$

And we can re-write the above equation to solve for a single sub-band model

$$\overrightarrow{y_\gamma} = B^\star_{\gamma i} \overrightarrow{s_i} - B^\star_{\gamma i} \sum_{\alpha \neq \gamma} B_{i\alpha} \overrightarrow{y_\alpha}$$

=> To solve for $\overrightarrow{y_\gamma}$, use an iterative solution and plug in the results from the previous iteration for $\overrightarrow{y_\alpha}$

Note: to prevent oscillating solutions, after each iteration use the average of the new and old solutions for the next iteration

Iterative Forward Modeling

Extension to variable PSFs

A work in progress!

$$\sum_\alpha B_{i\alpha} Q^{(i)} \overrightarrow{y_\alpha} = P \overrightarrow{s_i}$$

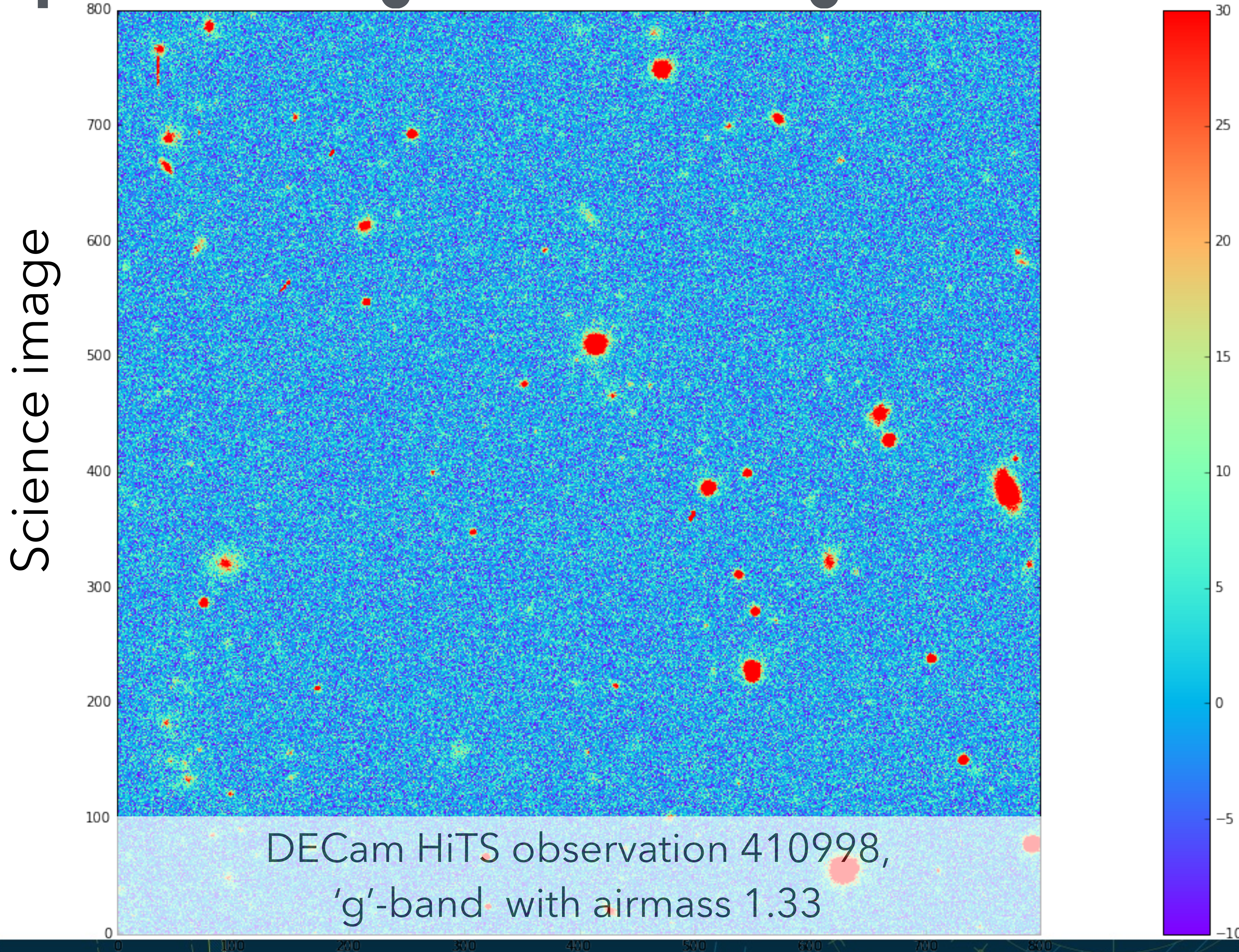
P: PSF of the sub-band models
$\boldsymbol{Q_i}$: Measured PSF of each image *i*

which gives an iterative solution of

$$Q^{(i)} \overrightarrow{y_\gamma} = B^\star_{\gamma i} P \overrightarrow{s_i} - B^\star_{\gamma i} \sum_{\alpha \neq \gamma} B_{i\alpha} Q^{(i)} \overrightarrow{y_\alpha}$$

Then, after each iteration we need to solve for $\overrightarrow{y_\alpha}$ given solutions of $Q^{(i)} \overrightarrow{y_\alpha}$ for each image *i*

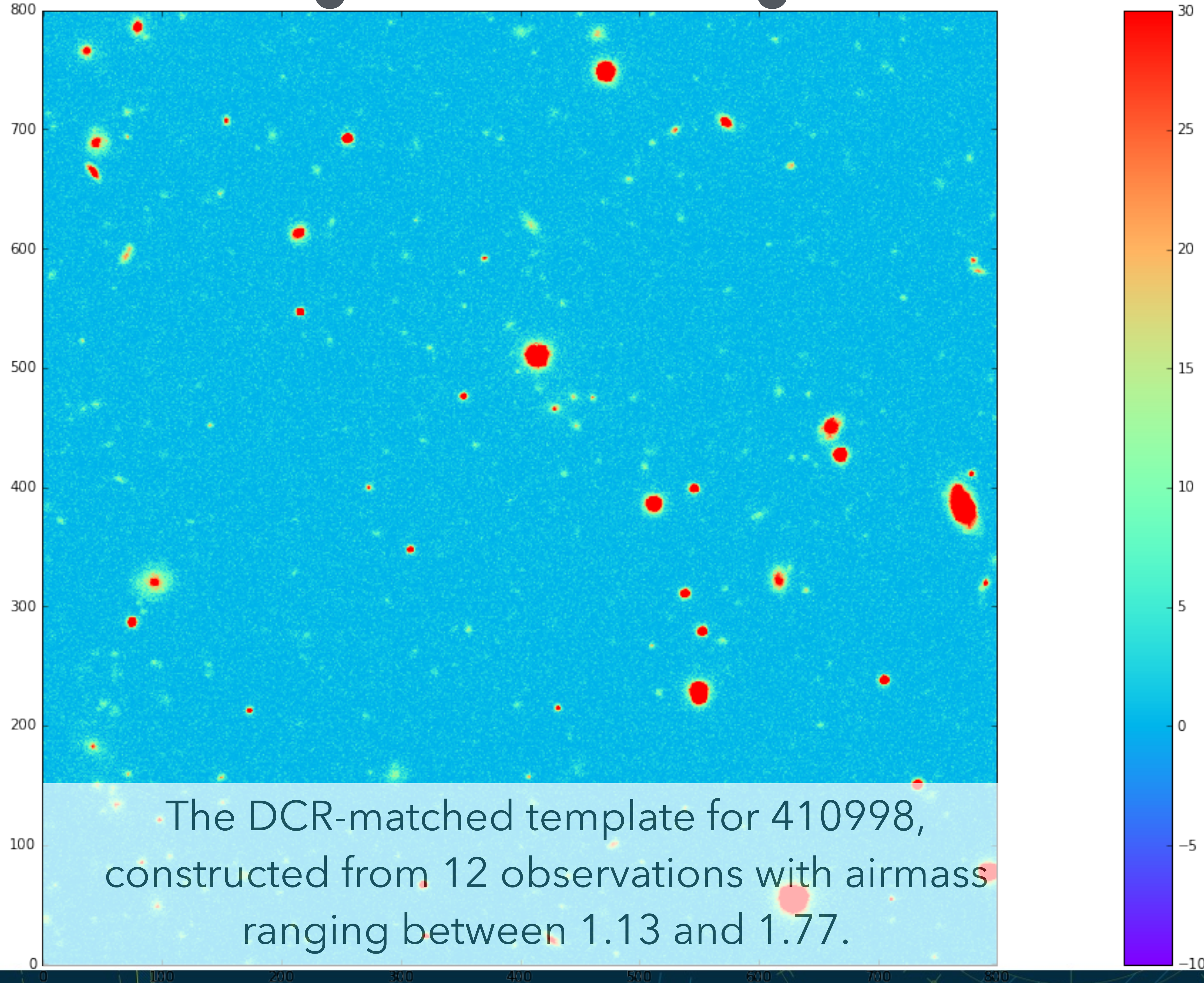
Improved Image Differencing



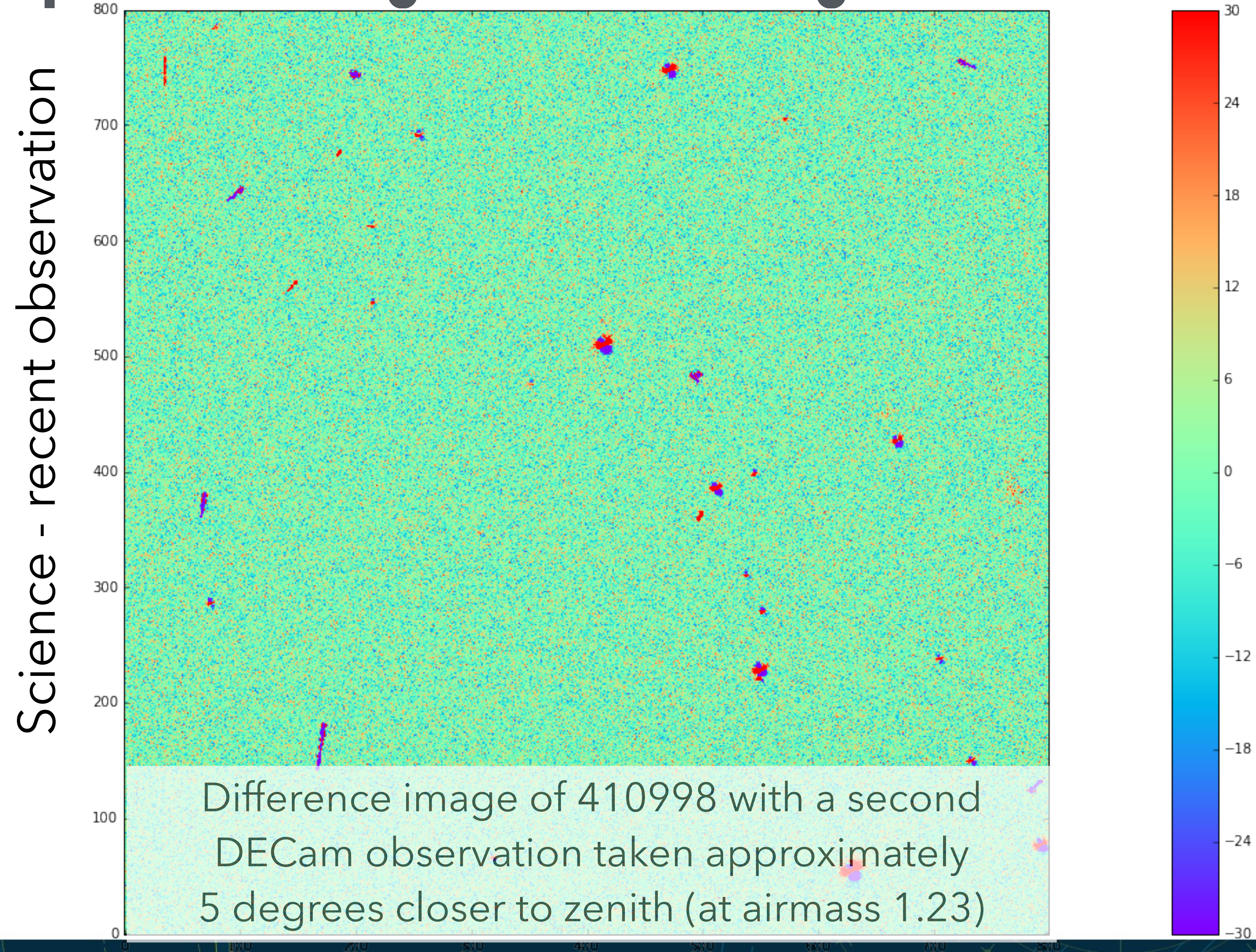
DECam HiTS observation 410998,
'g'-band with airmass 1.33

Improved Image Differencing

Matched template

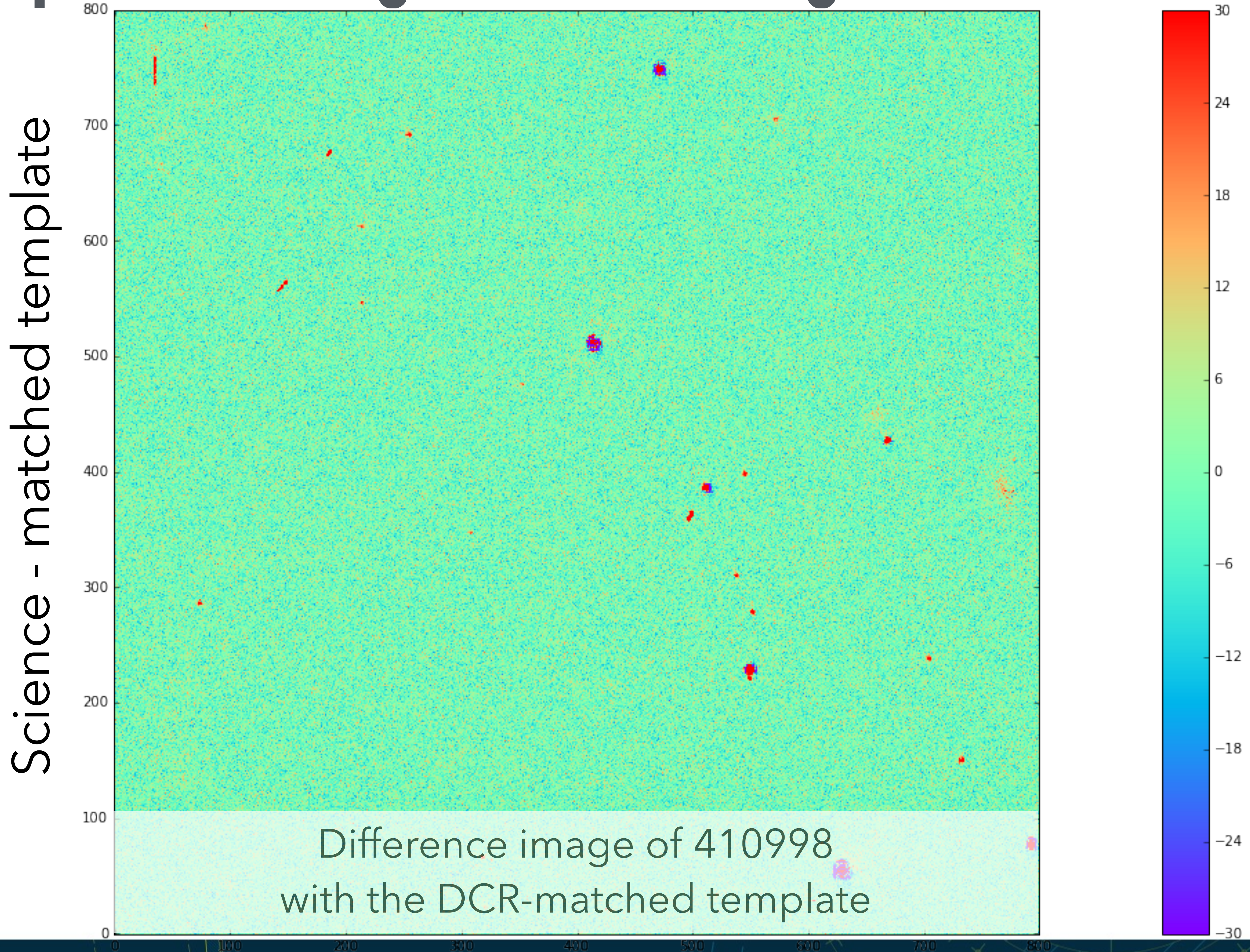


Improved Image Differencing



Difference image of 410998 with a second DECam observation taken approximately 5 degrees closer to zenith (at airmass 1.23)

Improved Image Differencing

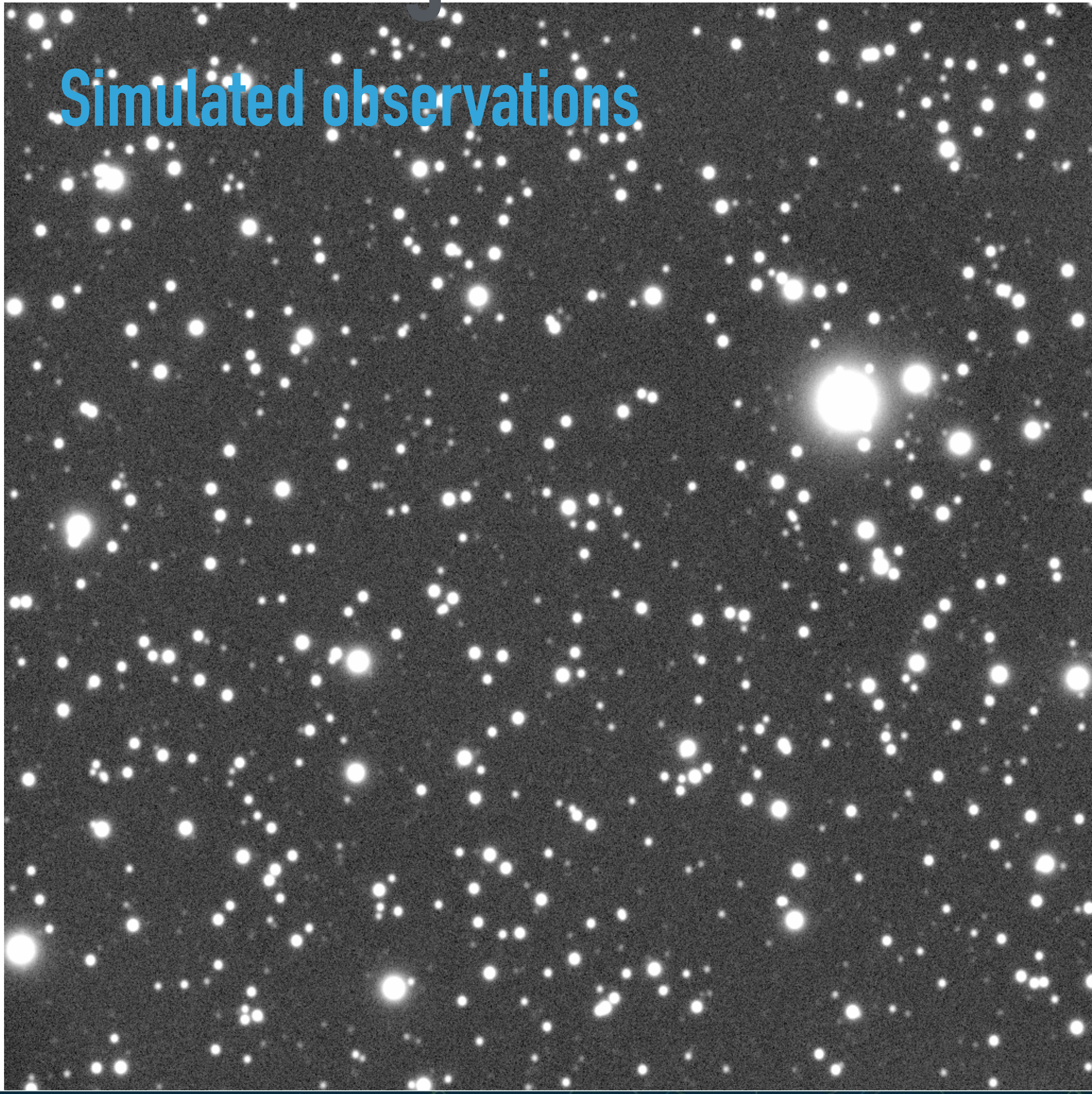


Improved Image Differencing

A simulated g-band airmass 1.3 image.

Stars simulated using Kurucz SEDs and Kolmogorov PSFs

No galaxies, transients, or variable sources

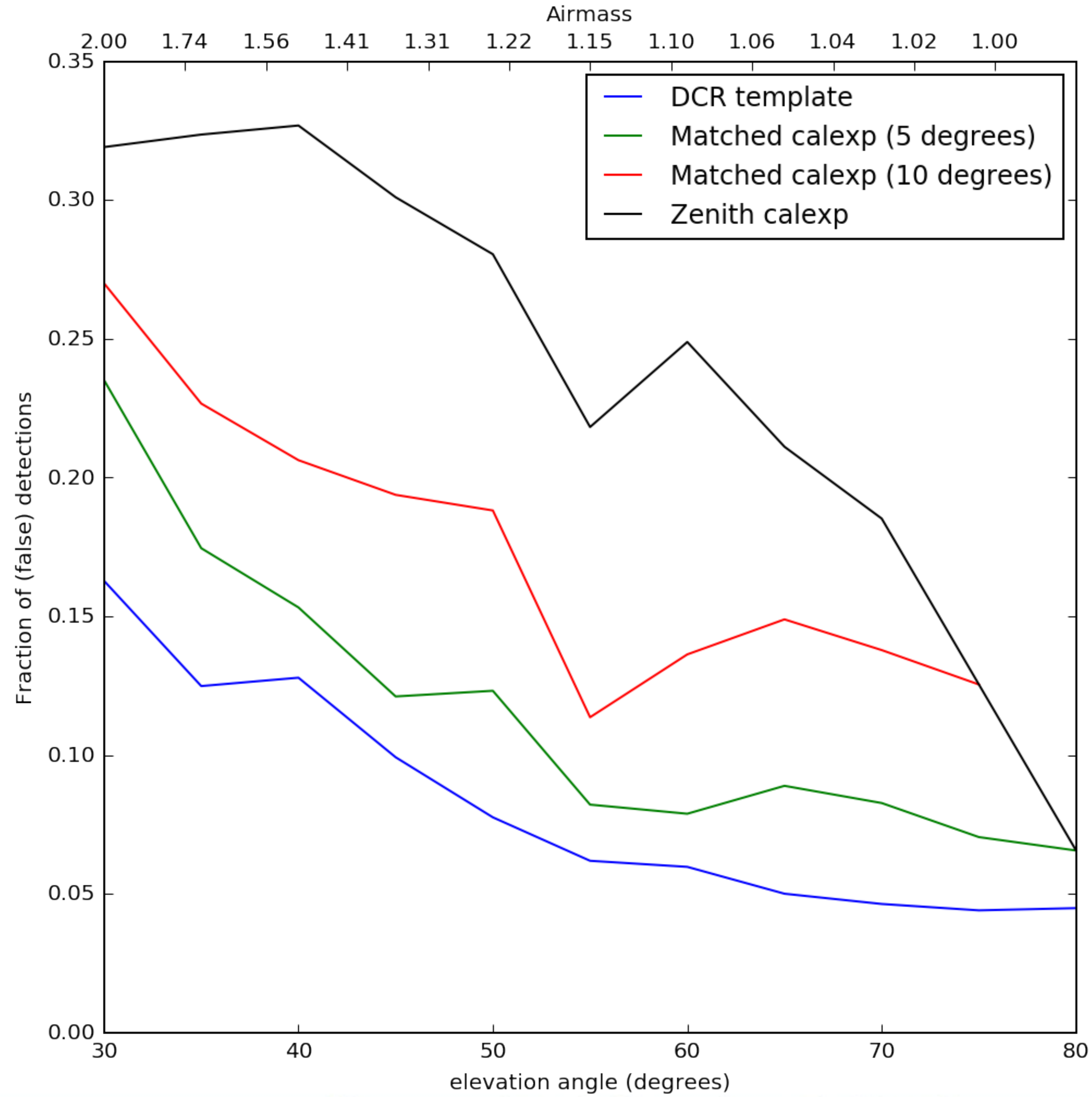


Improved Image Differencing

Simulated observations

DCR-matched templates subtract well far from zenith

Fewer 5-σ detections in the difference image than simply using a nearby observation as the template

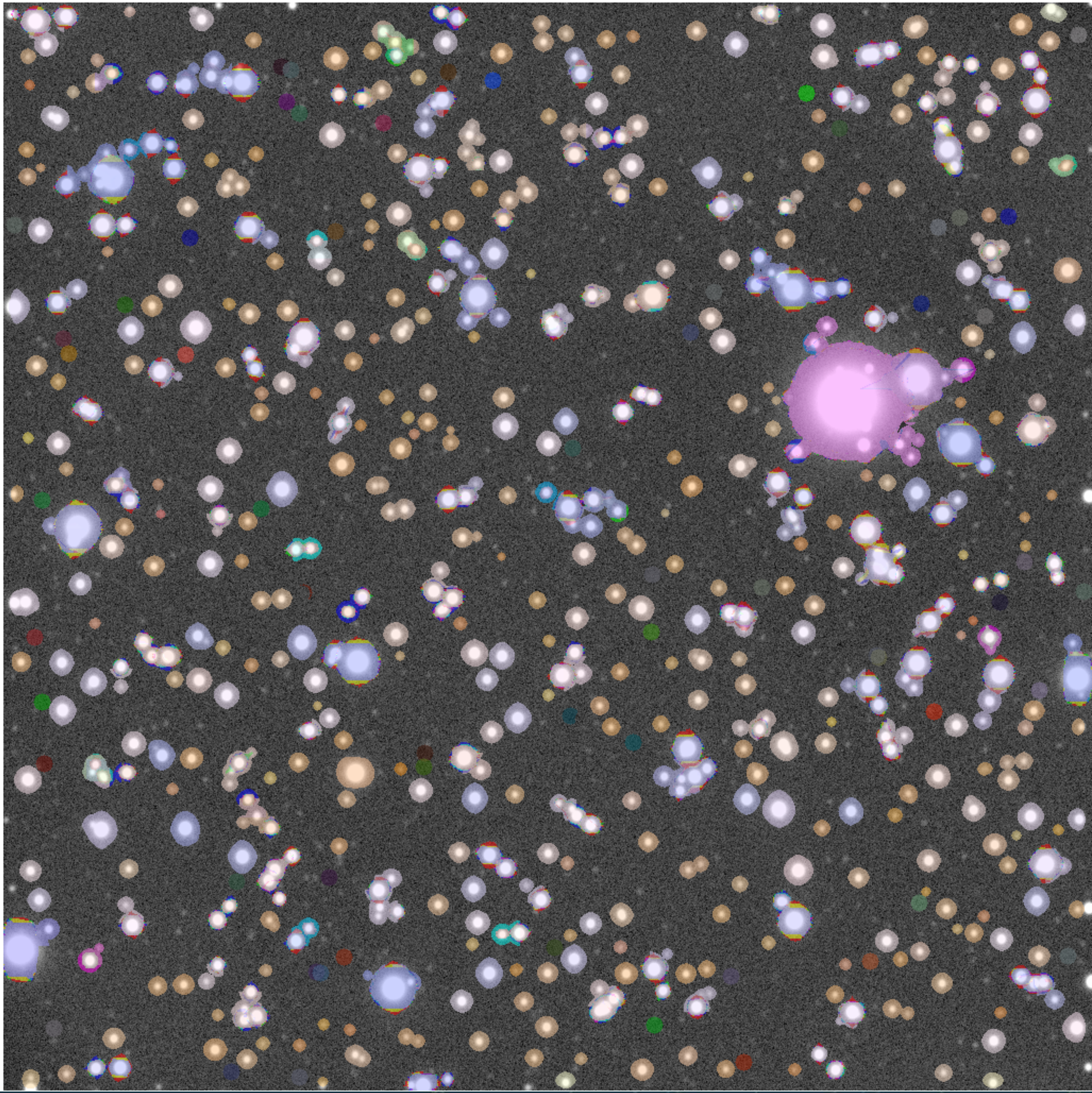


Single-filter colors

The DCR sub-band model is built from 8 simulated observations between airmass 2.0 and 1.0

After detecting sources, forced photometry was run on each of three sub-bands.

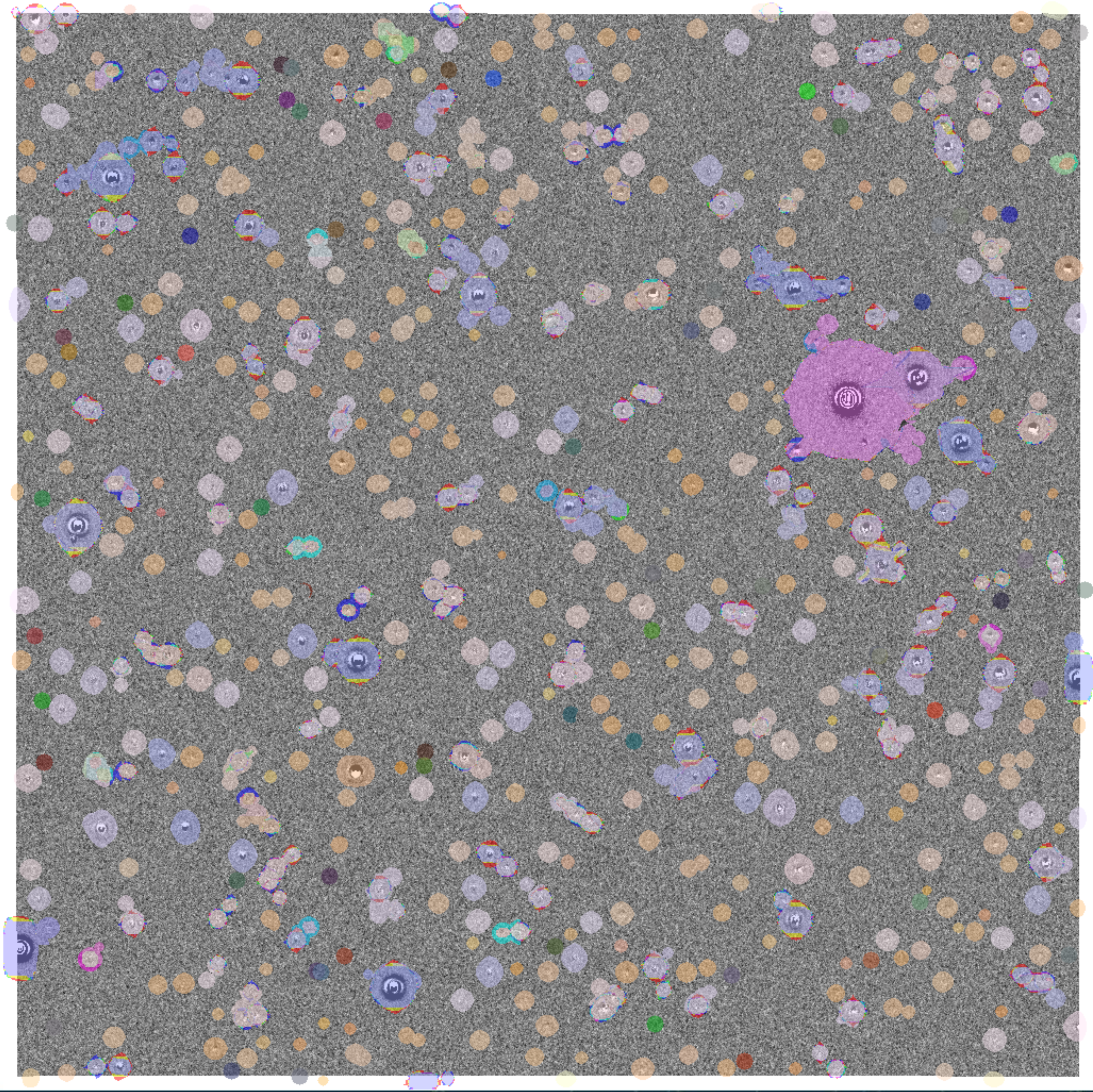
The footprint of every detected source is filled with the measured fluxes from the sub-bands, converted to RGB



Single-filter colors

The simulated airmass 1.3 image minus an airmass 1.22 simulated image (5 degrees closer to zenith)

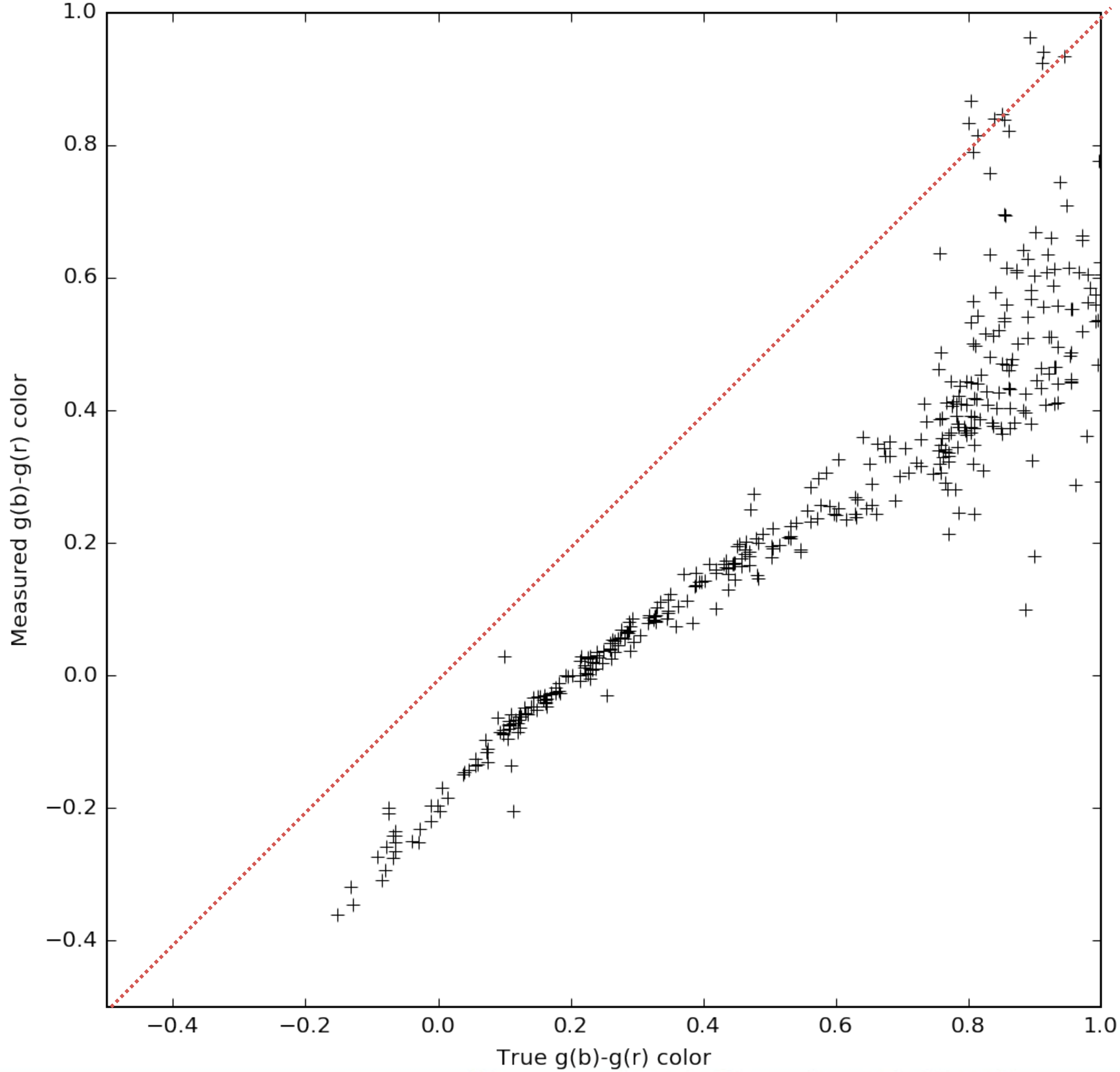
The DCR-derived colors can help classify image subtraction errors



Single-filter colors

We know the true spectrum of each source within g-band

So we can compare the measured color between sub-bands to the true color



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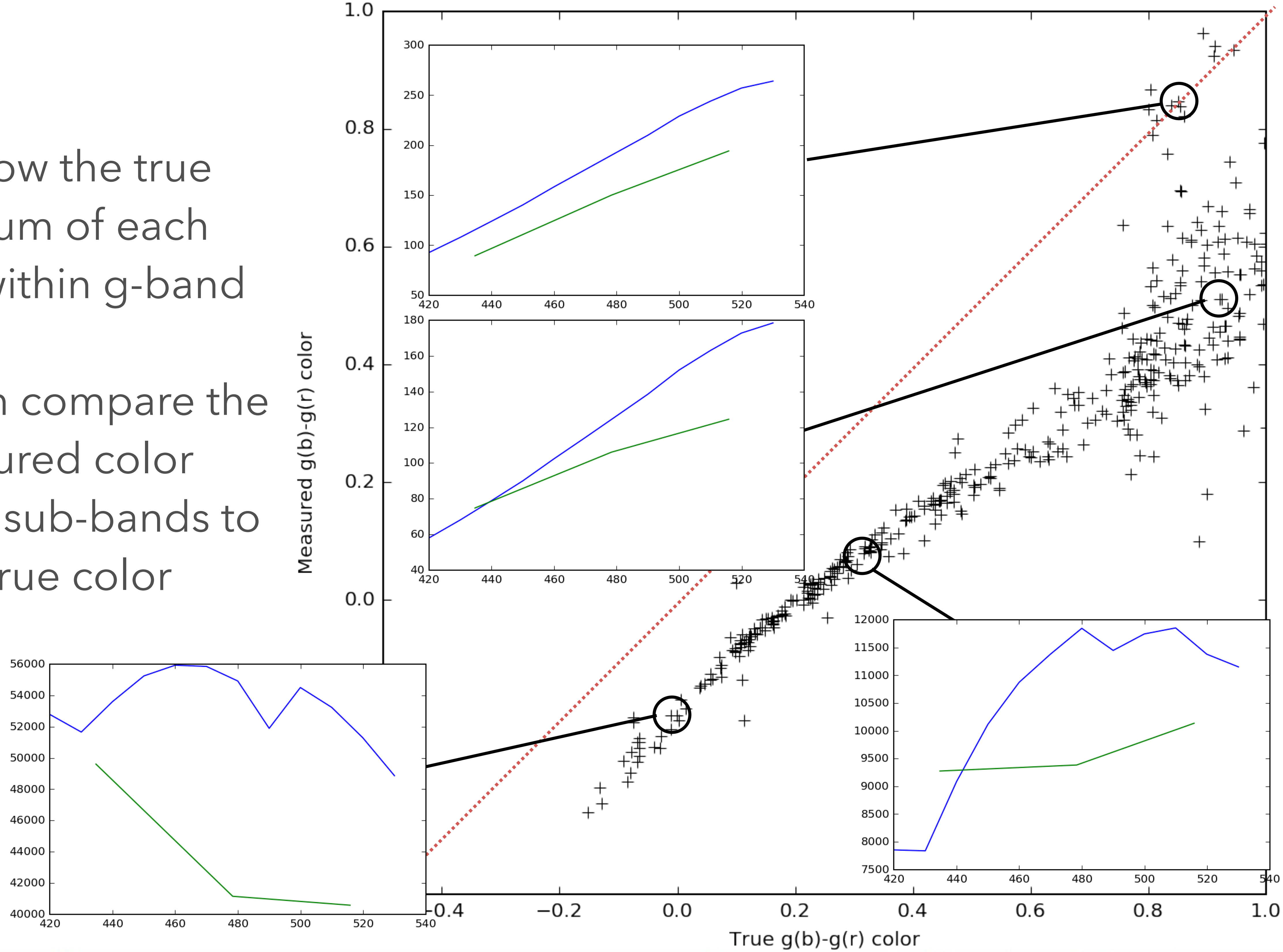
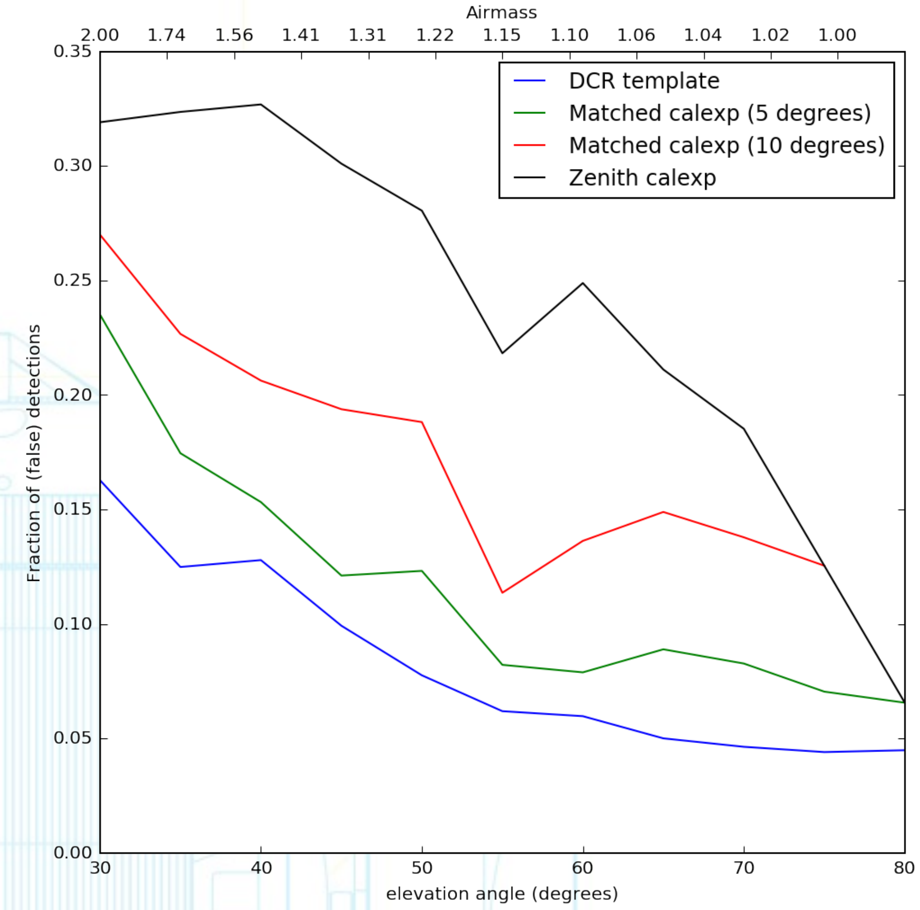
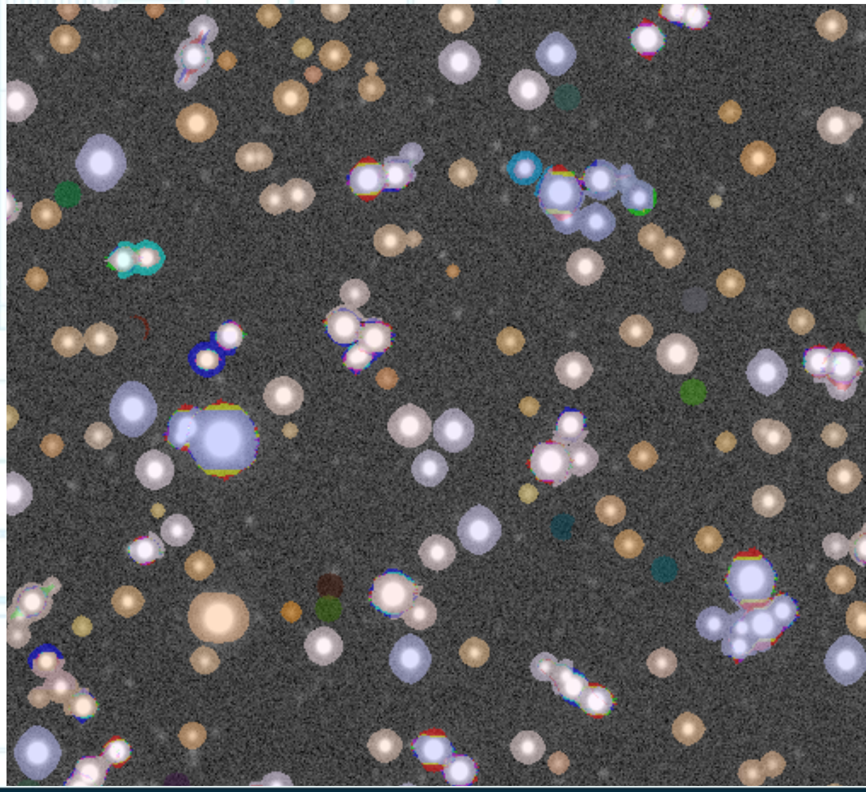


Summary

DCR-matched templates show promise

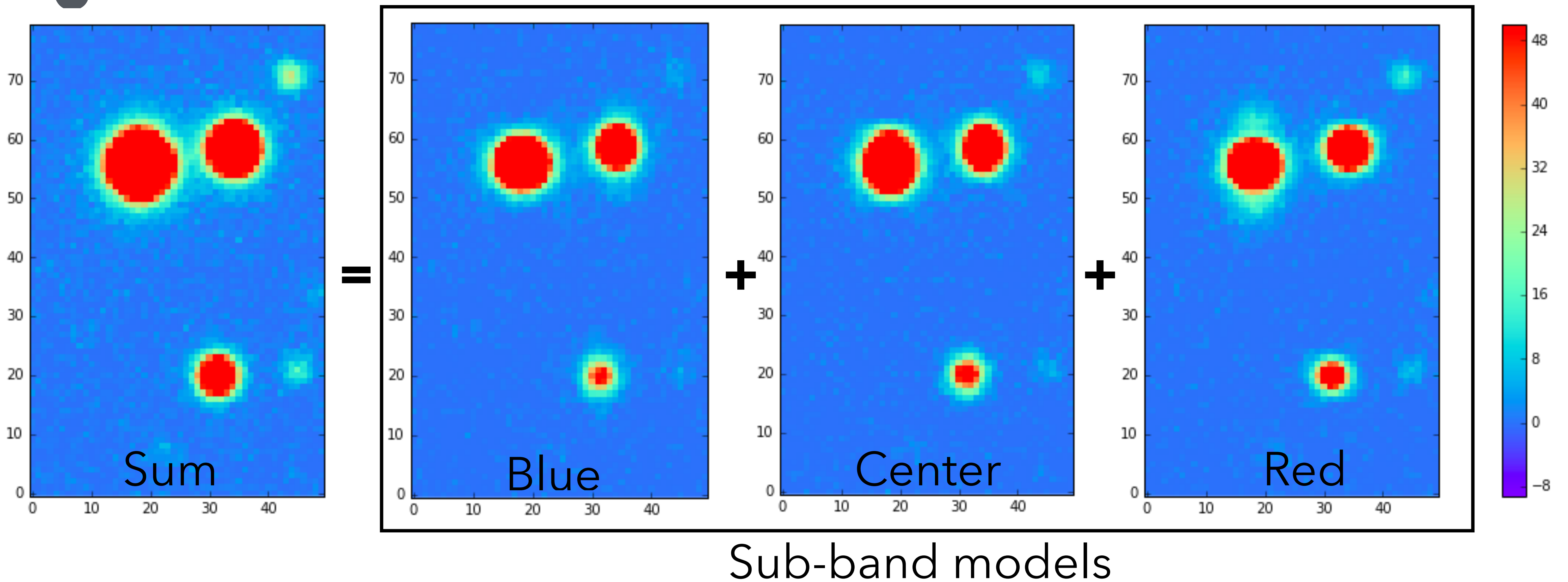
- By forward-modeling DCR we can use all observations to build our template, regardless of airmass or parallactic angle
  - Can include more effects in the model if known, such as different detector responses
- DCR-matched templates perform well in image differencing
  - We can still use our favorite image differencing algorithm
- We can extract color information from observations taken with a single filter
- Code is in development, but available: https://github.com/lsst-dm/experimental_DCR





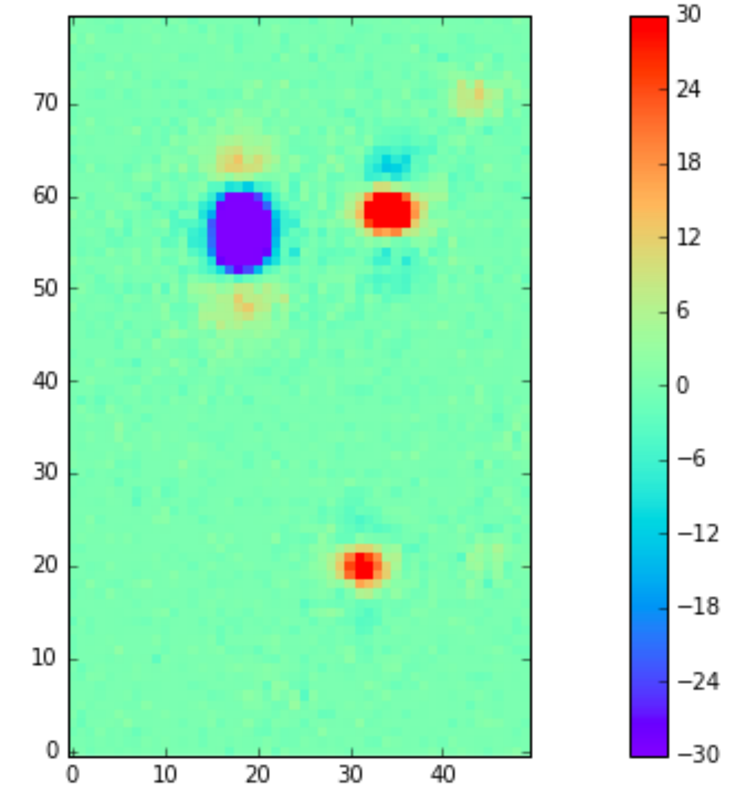
Extras

Single-filter colors



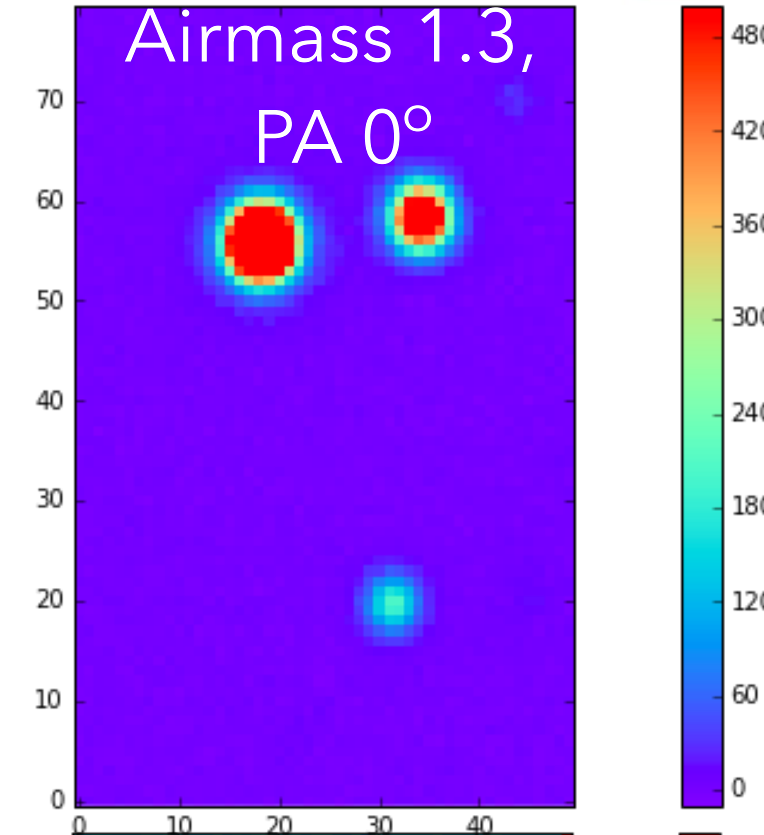
The sub-band models pick up real frequency structure … but also some artifacts

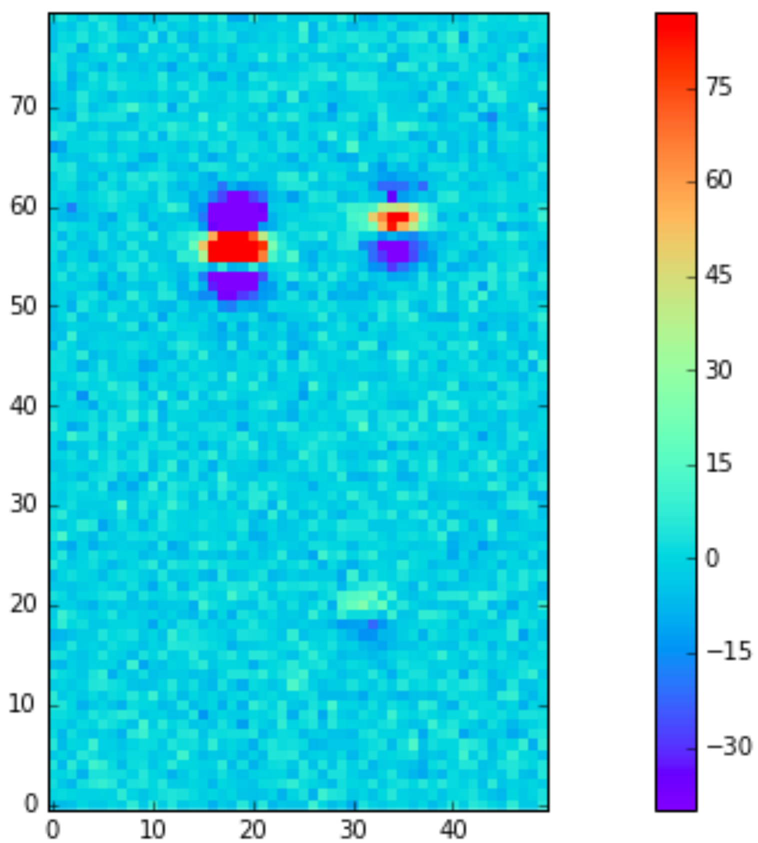
Sub-band Red - Blue:



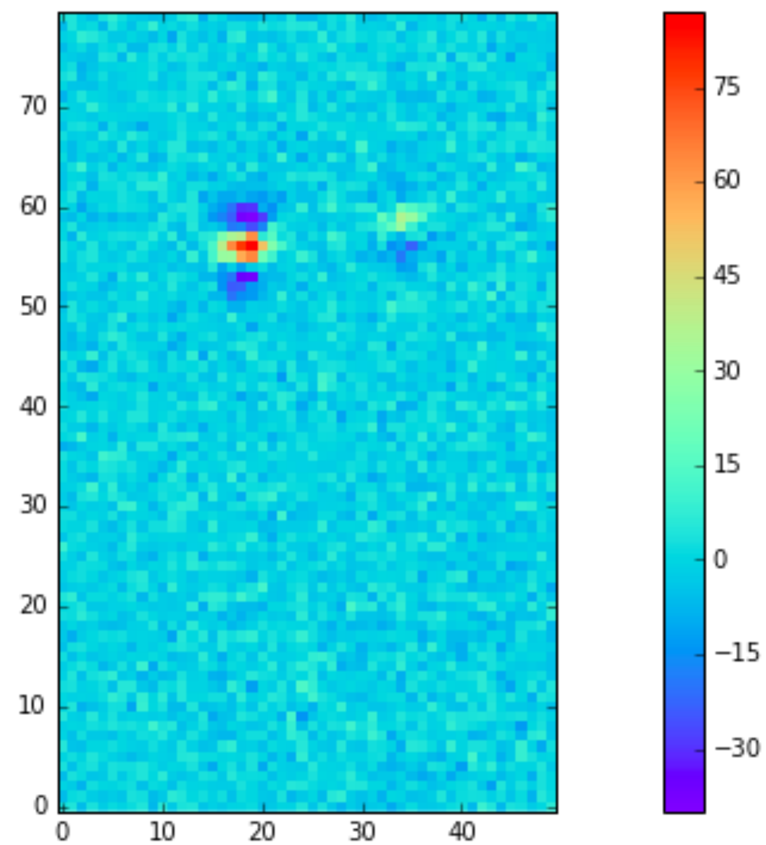
DCR - matched template

The difference images below use different template images to subtract from the science image at right

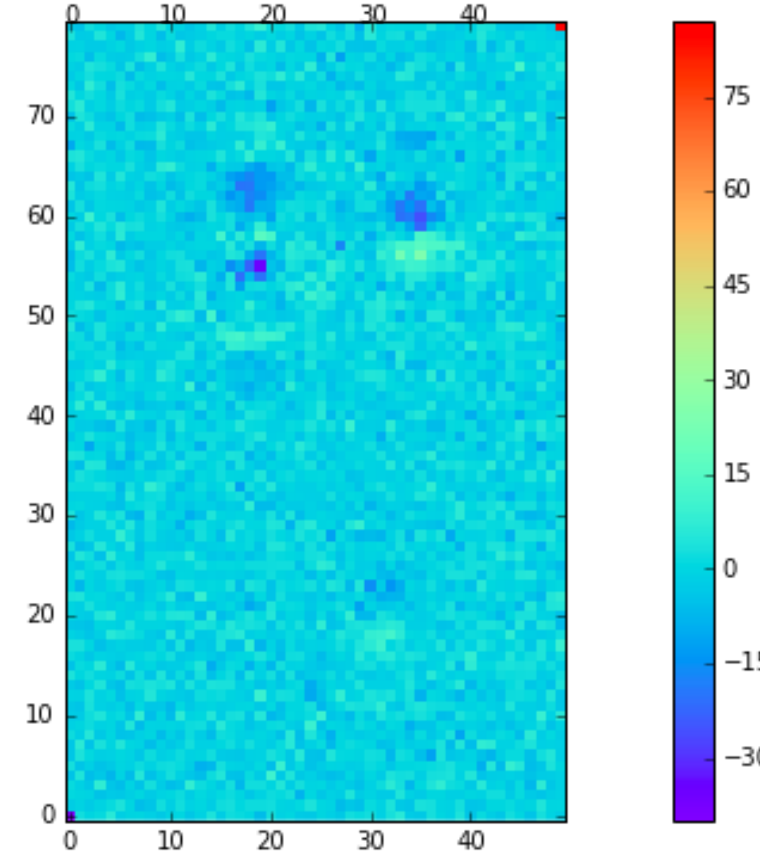




Template: zenith



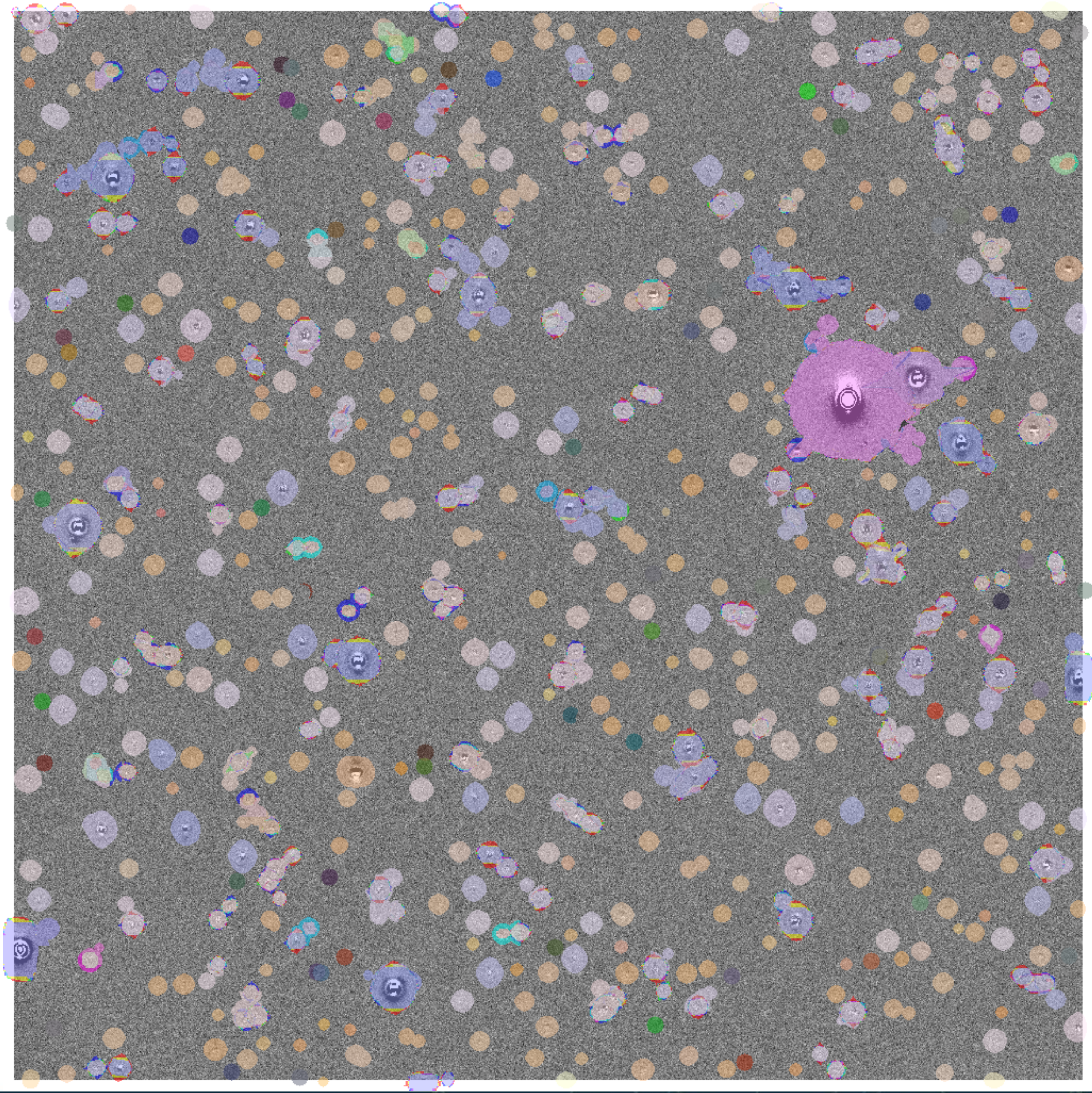
Template: obs. 10 away



Template: DCR model

Single-filter colors

A simulated airmass 1.3 image minus it's DCR-matched template

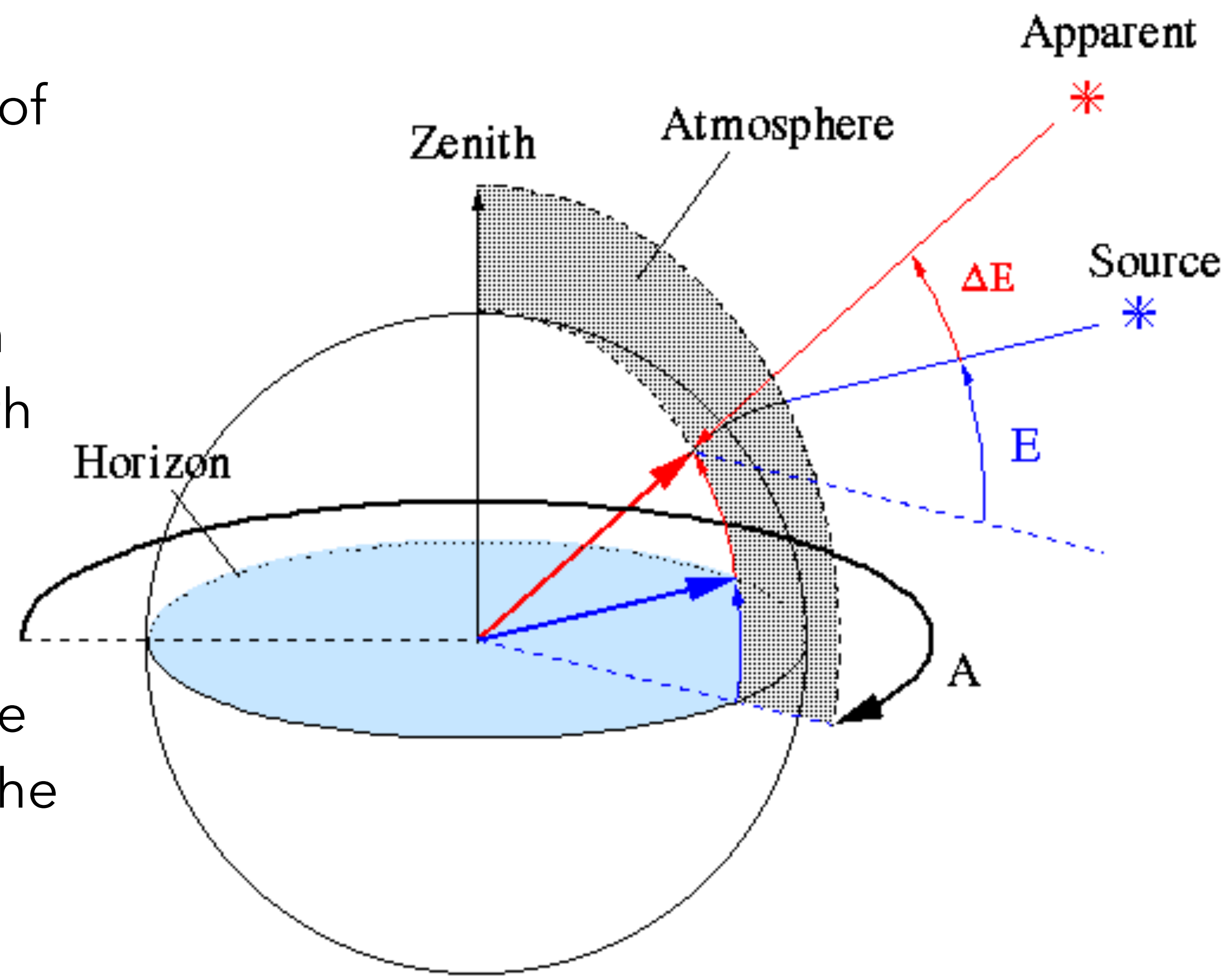


DCR Overview

Refraction deflects the apparent position of sources towards zenith.

The amplitude of refraction depends on environmental factors and the wavelength of incident light.

Differential Chromatic Refraction (DCR) occurs when the index of refraction of the atmosphere changes significantly across the bandwidth of a filter



$$n_0(\lambda) = 1 + \left(\left[2371.34 + \frac{683939.7}{130-\sigma(\lambda)} + \frac{4547.3}{38.9-\sigma(\lambda)^2} \right] D_s + \left(6487.31 + 58.058\sigma(\lambda)^2 - 0.71150\sigma(\lambda)^4 + 0.08851\sigma(\lambda)^6 \right) D_w \right) \times 10^{-8}$$

Environmental factors

$$\begin{cases} \sigma(\lambda) = 10^4/\lambda \quad (\mu m^{-1}) \\ D_s = \left[1 + (P_s - P_w)\left(57.90 \times 10^{-8} - \frac{9.3250\times10^{-4}}{T} + \frac{0.25844}{T^2} \right) \right] \frac{(P_s - P_w)}{T} \\ D_w = \left[1 + P_w\left(1 + 3.7 \times 10^{-4} P_w\right)\left(-2.37321 \times 10^{-3} + \frac{2.23366}{T} - \frac{710.792}{T^2} + \frac{7.75141\times10^4}{T^3} \right) \right] \frac{P_w}{T} \\ P_w = RH \times 10^{-4} \times e^{(77.3450+0.0057T-7235.0/T)}/T^{8.2} \end{cases}$$