# Creating Dcr-Matched Templates For Image Differencing

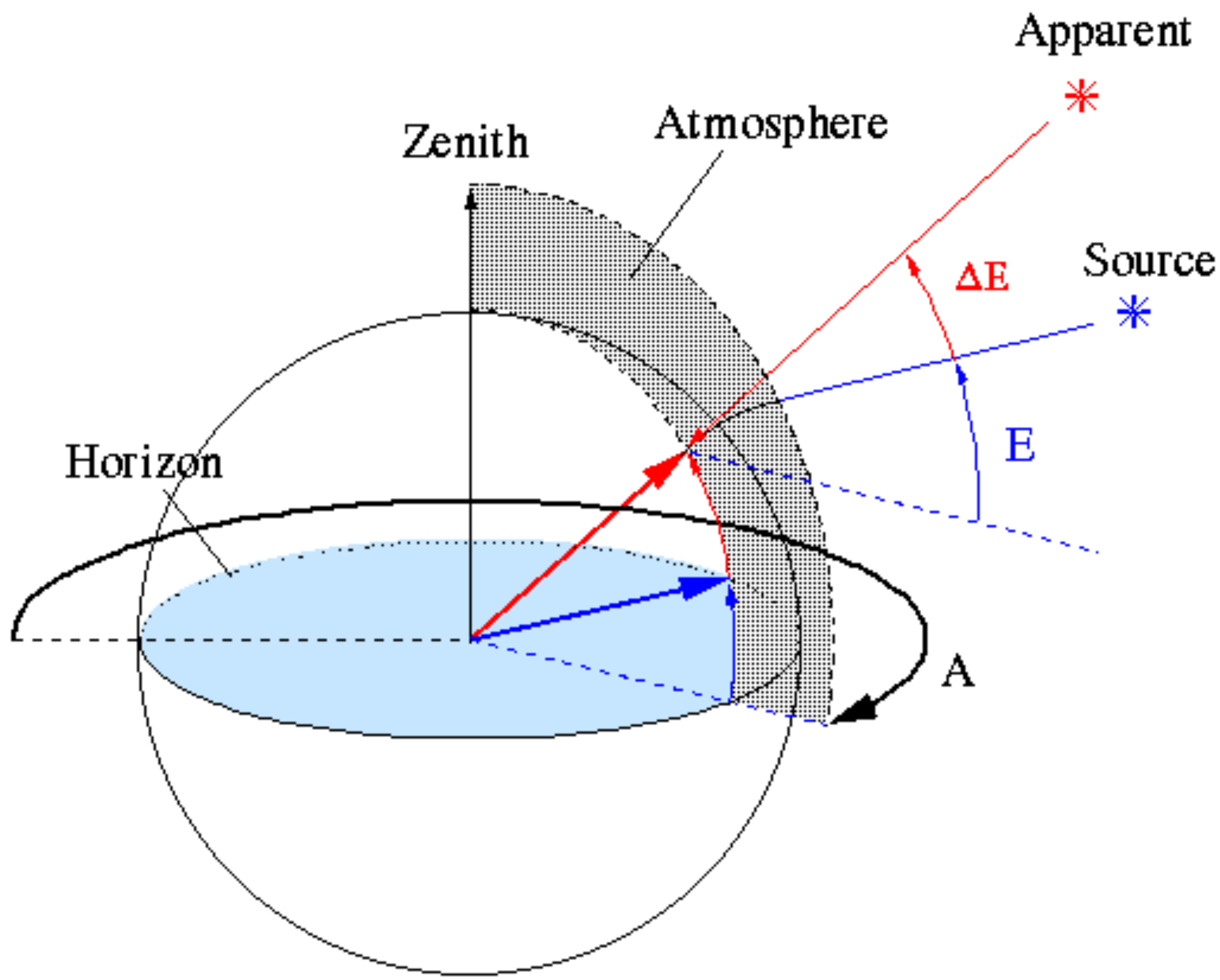
Ian Sullivan

Large Synoptic Survey Telescope

# DCR Overview

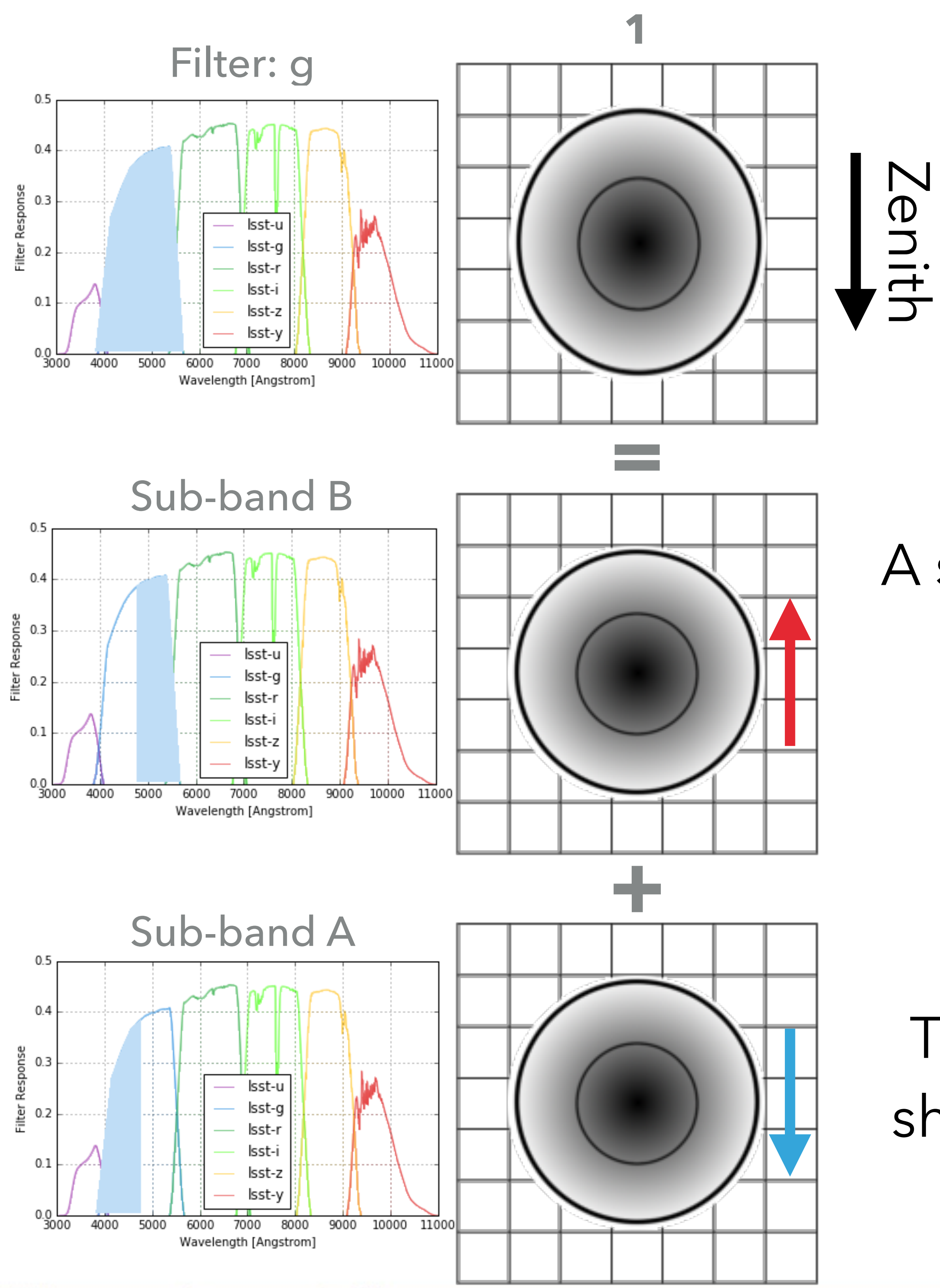
Refraction deflects the apparent position of sources towards zenith.

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

# Forward Modeling



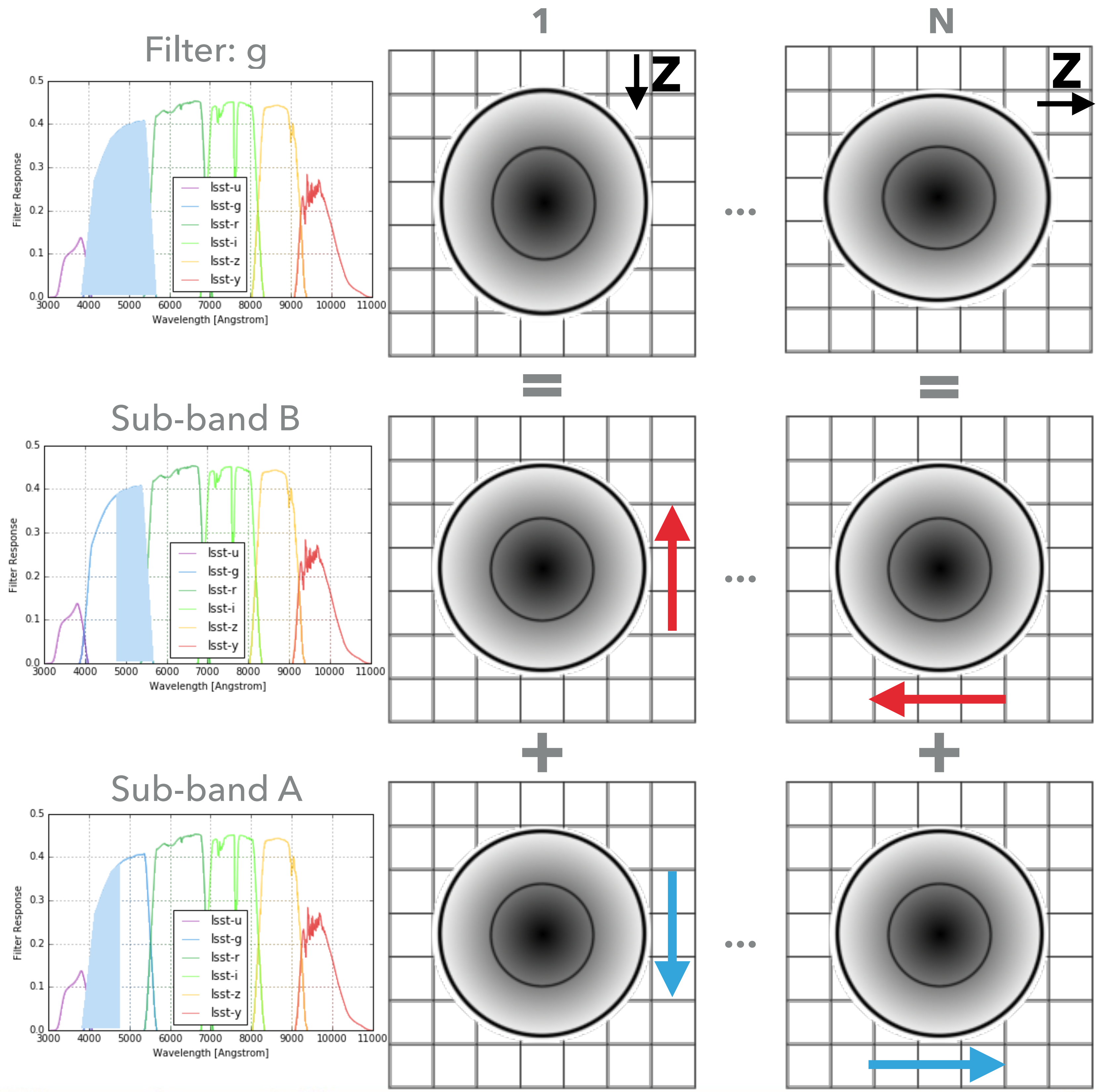

Each pixel in an image contains flux smeared out along the zenith direction

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

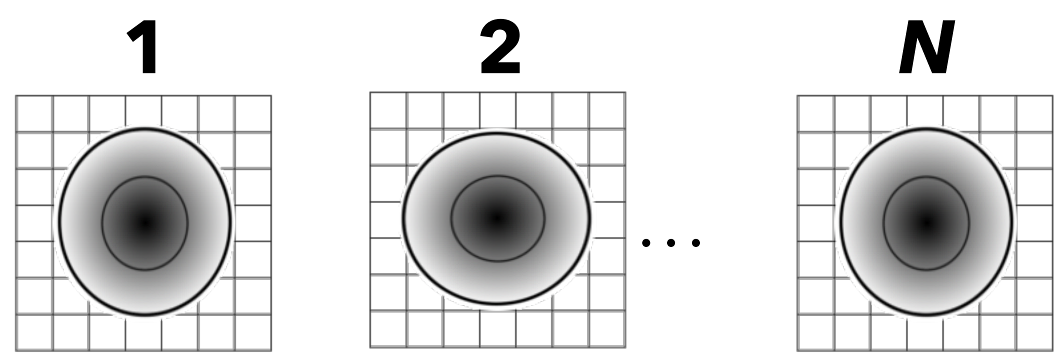
# Iterative Forward Modeling

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 $B^{\star}_{\alpha i} B_{i\alpha} = \mathbb{1}$

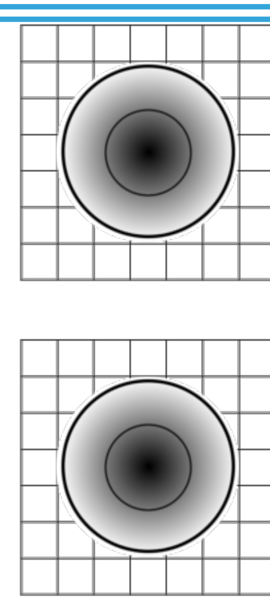
Pixel values of each image *i* : $\vec{s_i}$



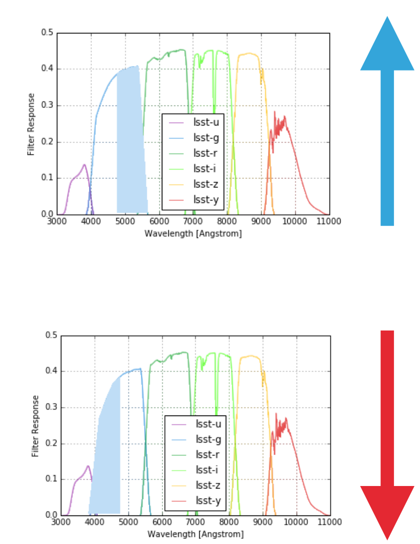

Pixel values of each sub-band ***α*** : $\vec{y_\alpha}$

***α***

**β**



The DCR shift of sub-band ***α*** 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:

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

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

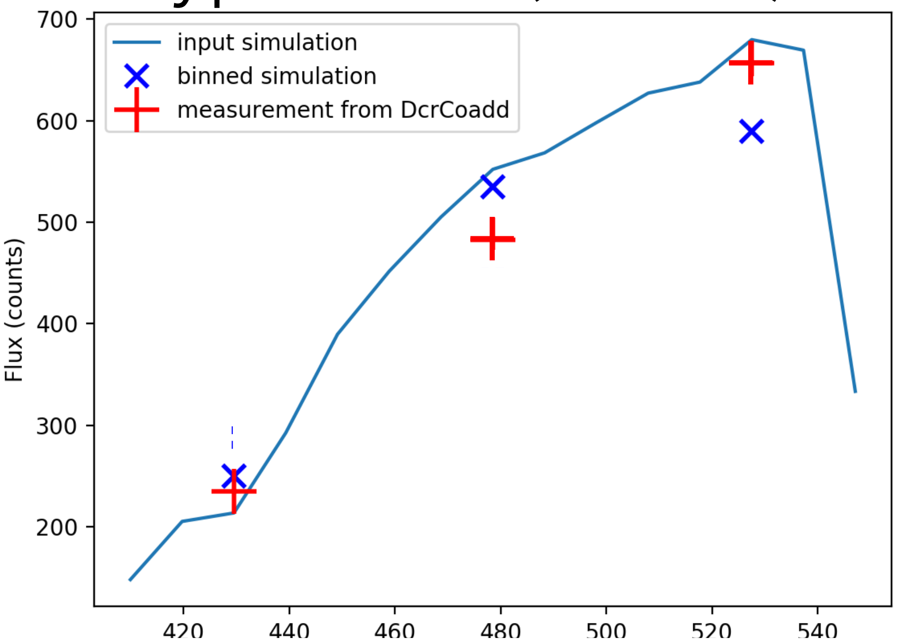
$$\vec{y_\gamma} = B^{\star}_{\gamma i} \vec{s_i} - B^{\star}_{\gamma i} \sum_{\alpha \neq \gamma} B_{i\alpha} \vec{y_\alpha}$$

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

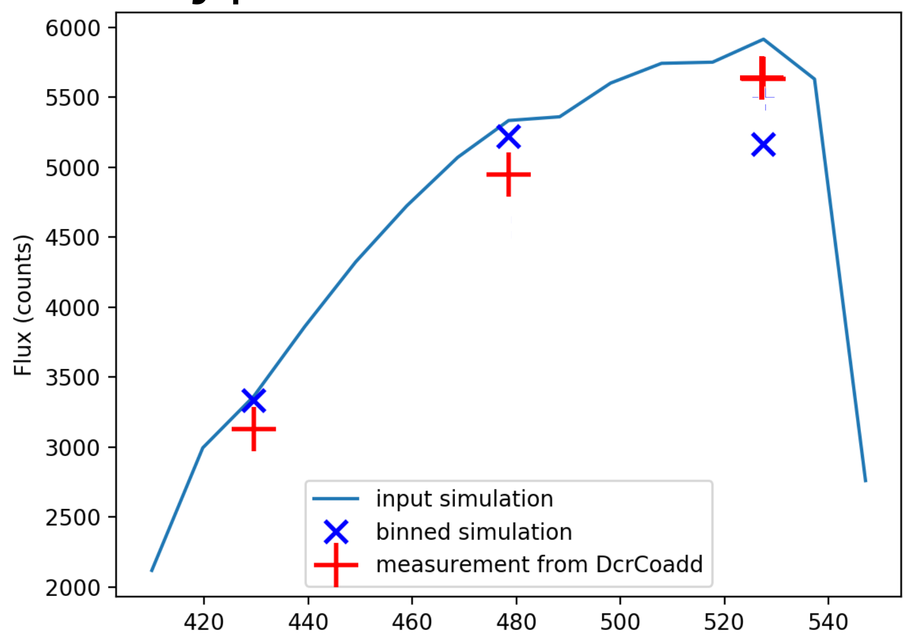
Note: to prevent oscillating solutions, after each iteration use the average of the new and old solutions for the next iteration

# Simulations – recovered star spectra

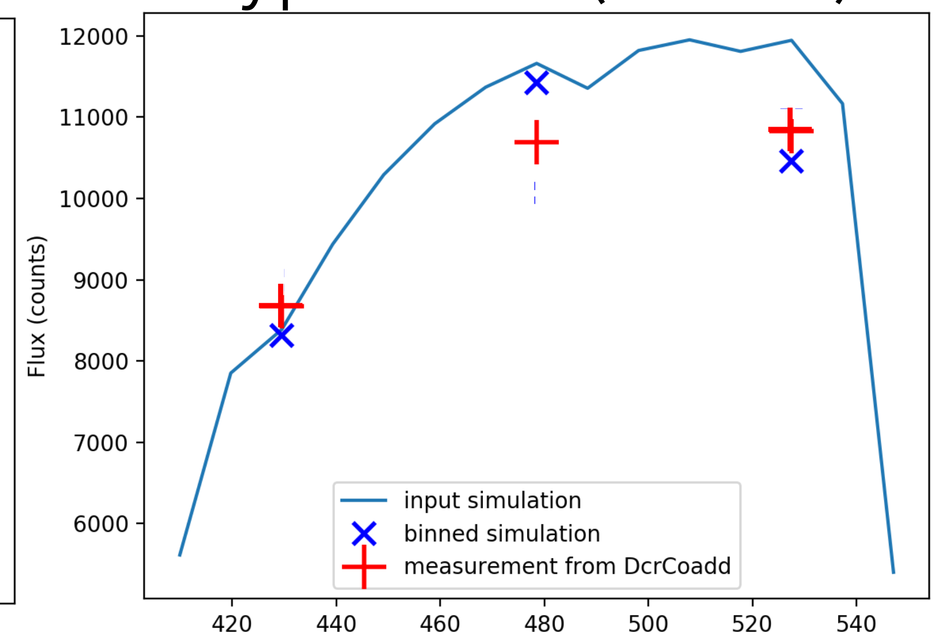
Type K star (4090K)

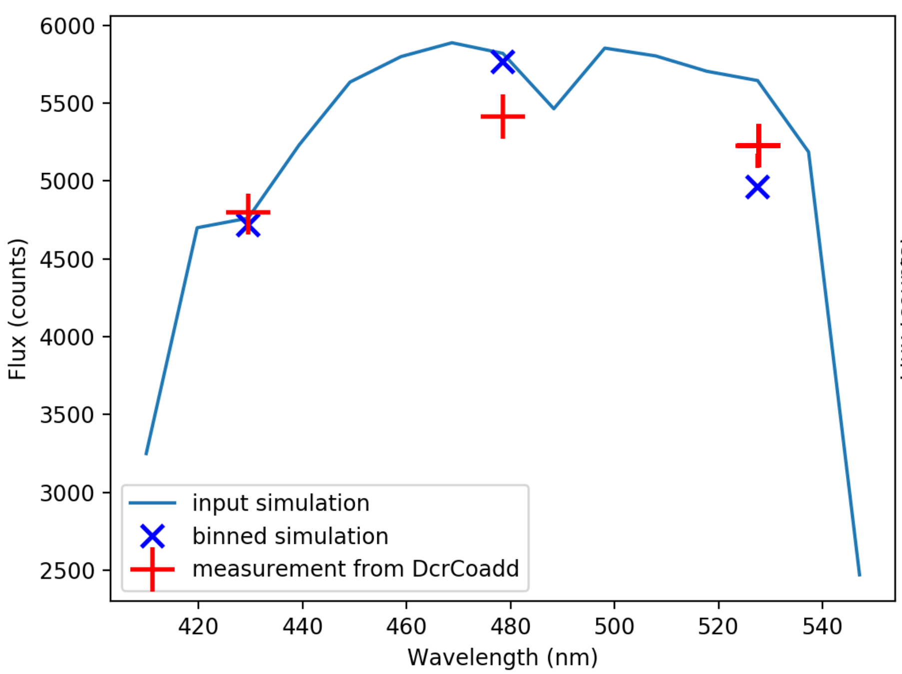



Type G star (5400K)

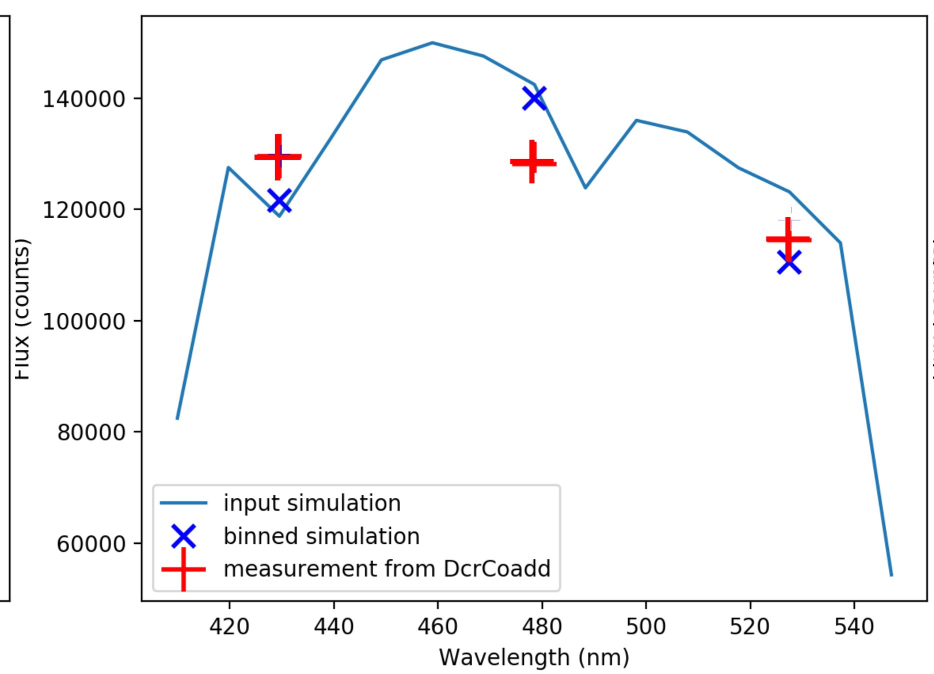



Type F star (6400K)

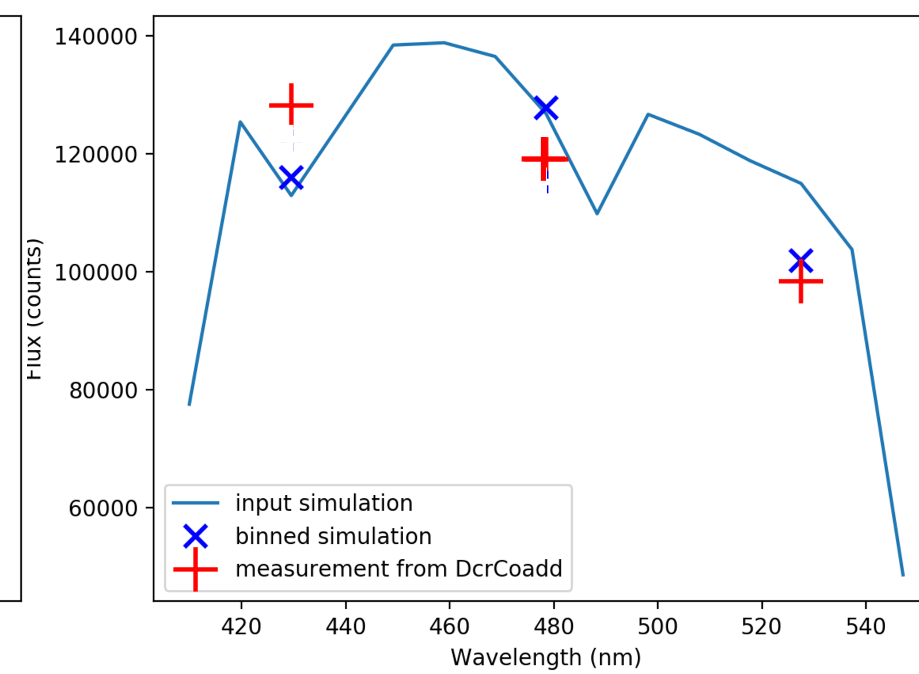



Type F star (6900K)



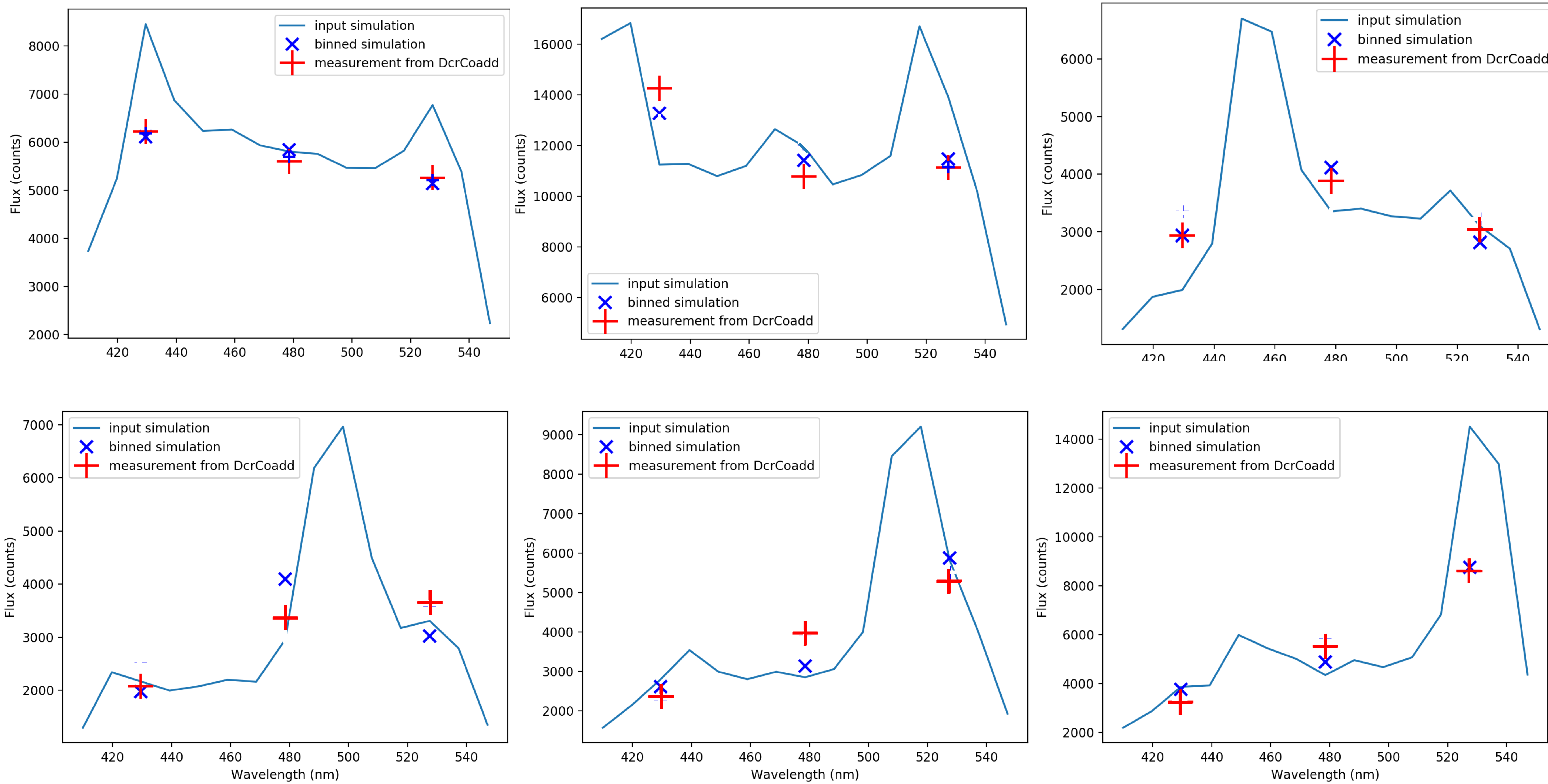

Type A star (10000K)




Type B star (17000K)

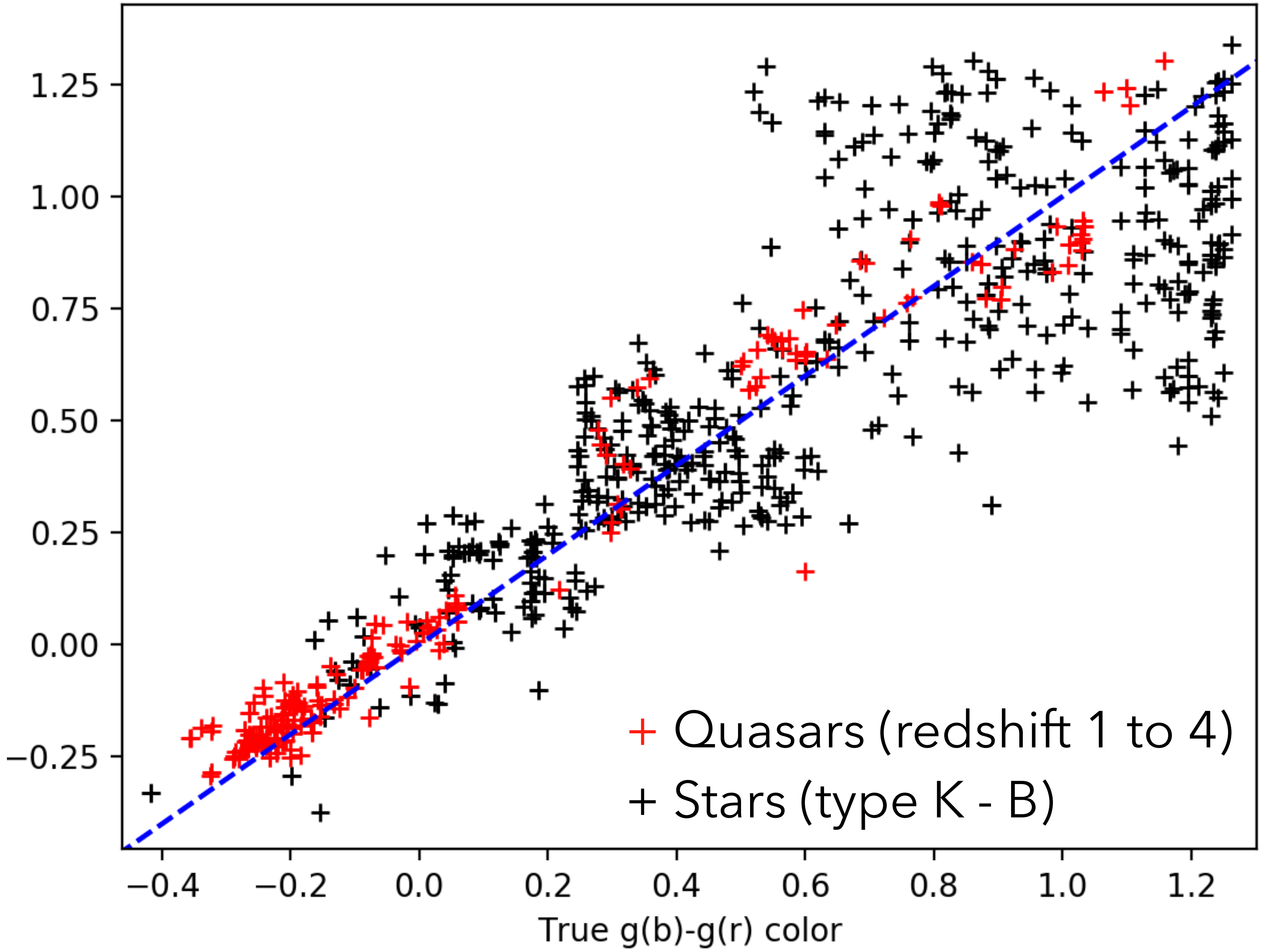
# Simulations – recovered quasar spectra

z = 1.80 | z = 2.38 | z = 2.73




z = 3.07 | z = 3.23 | z = 3.38

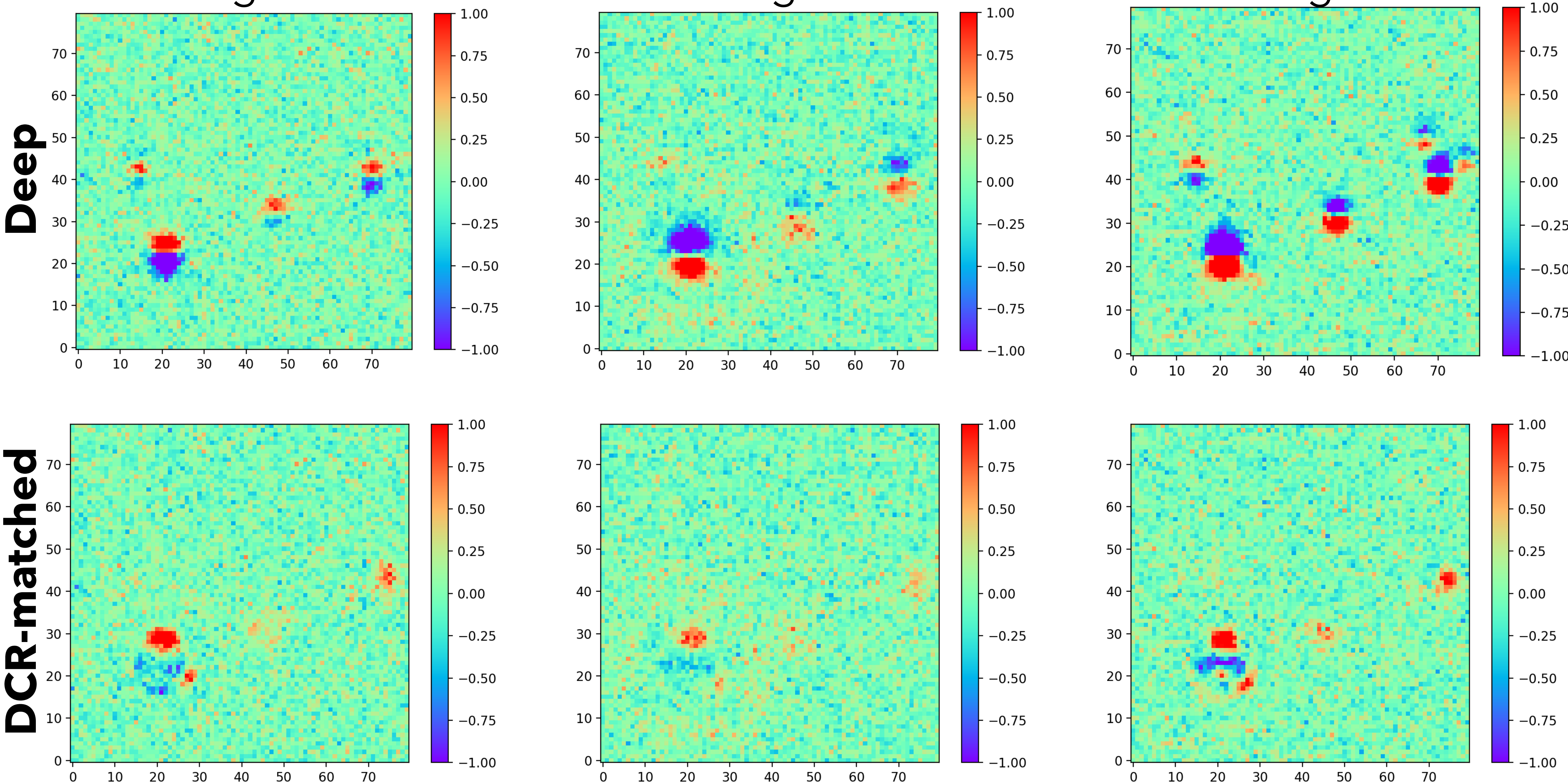
# Simulations – recovered colors




The sub-band color of simulated sources is accurately recovered

# DCR image differences – residuals

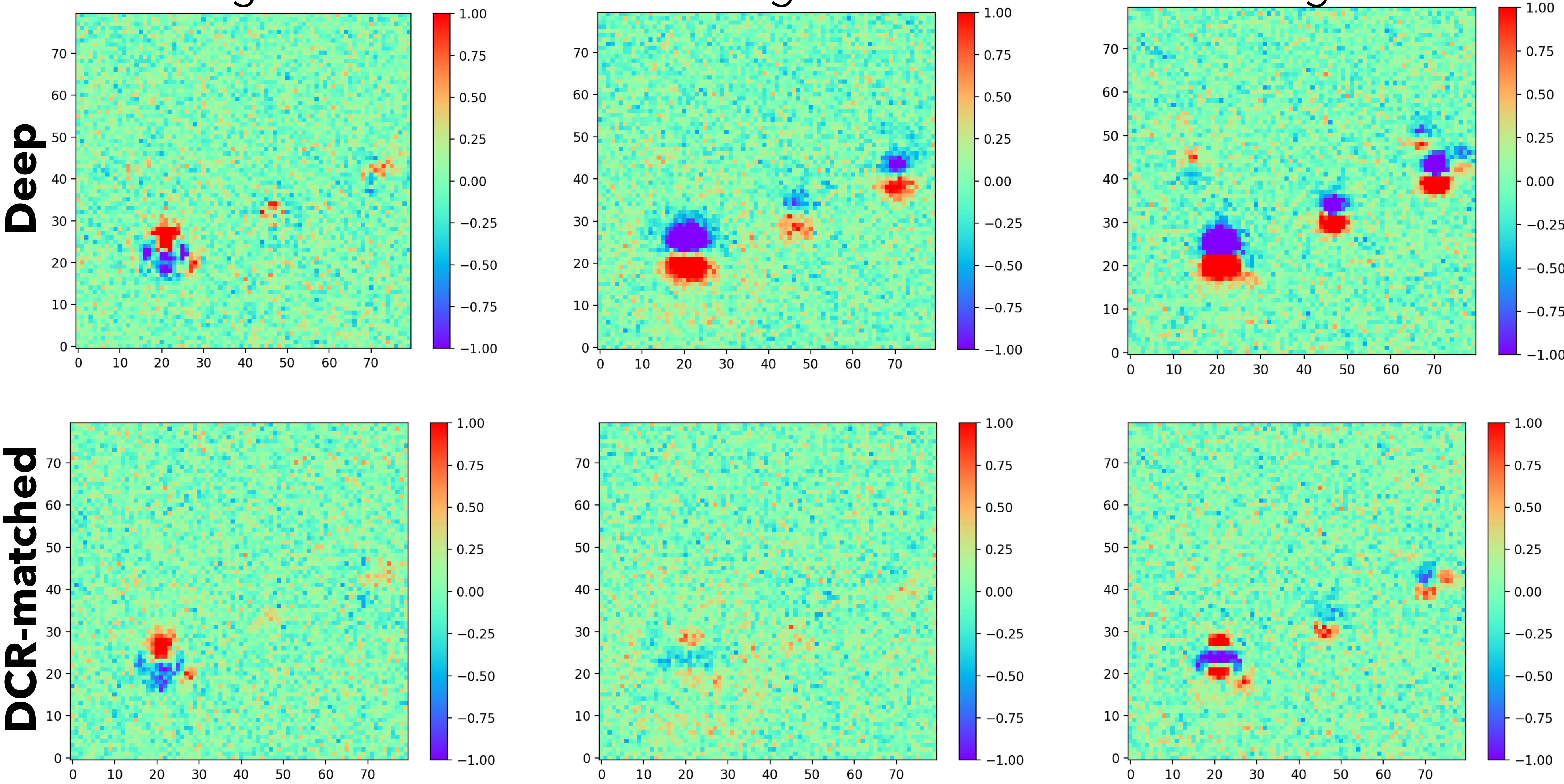
airmass 1.04 seeing 0.95″ | airmass 1.11 seeing 1.38″ | airmass 1.26 seeing 0.88″




Templates built from constant seeing observations

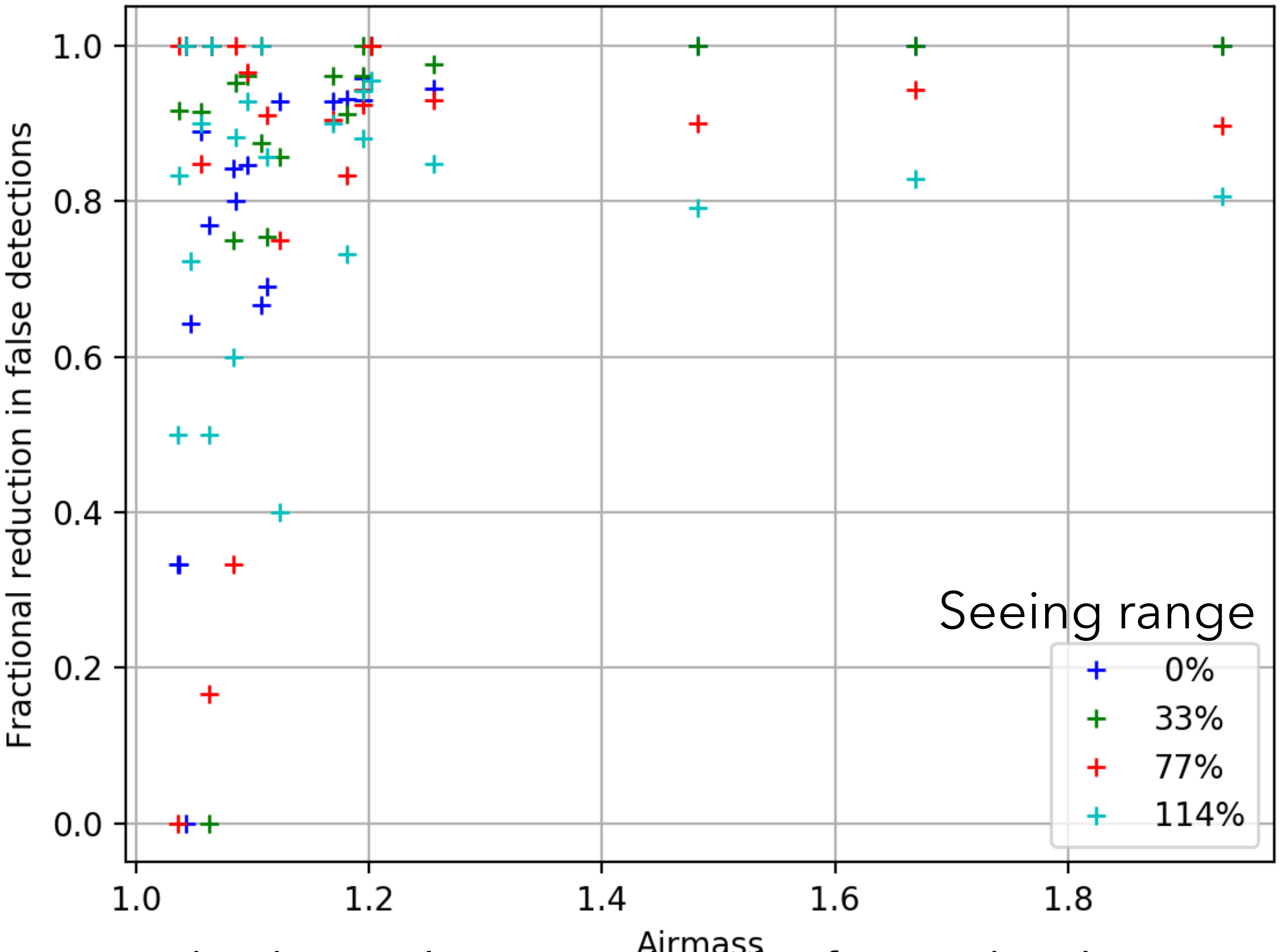
# DCR image differences – residuals

airmass 1.04 seeing 0.95″ | airmass 1.11 seeing 1.38″ | airmass 1.26 seeing 0.88″



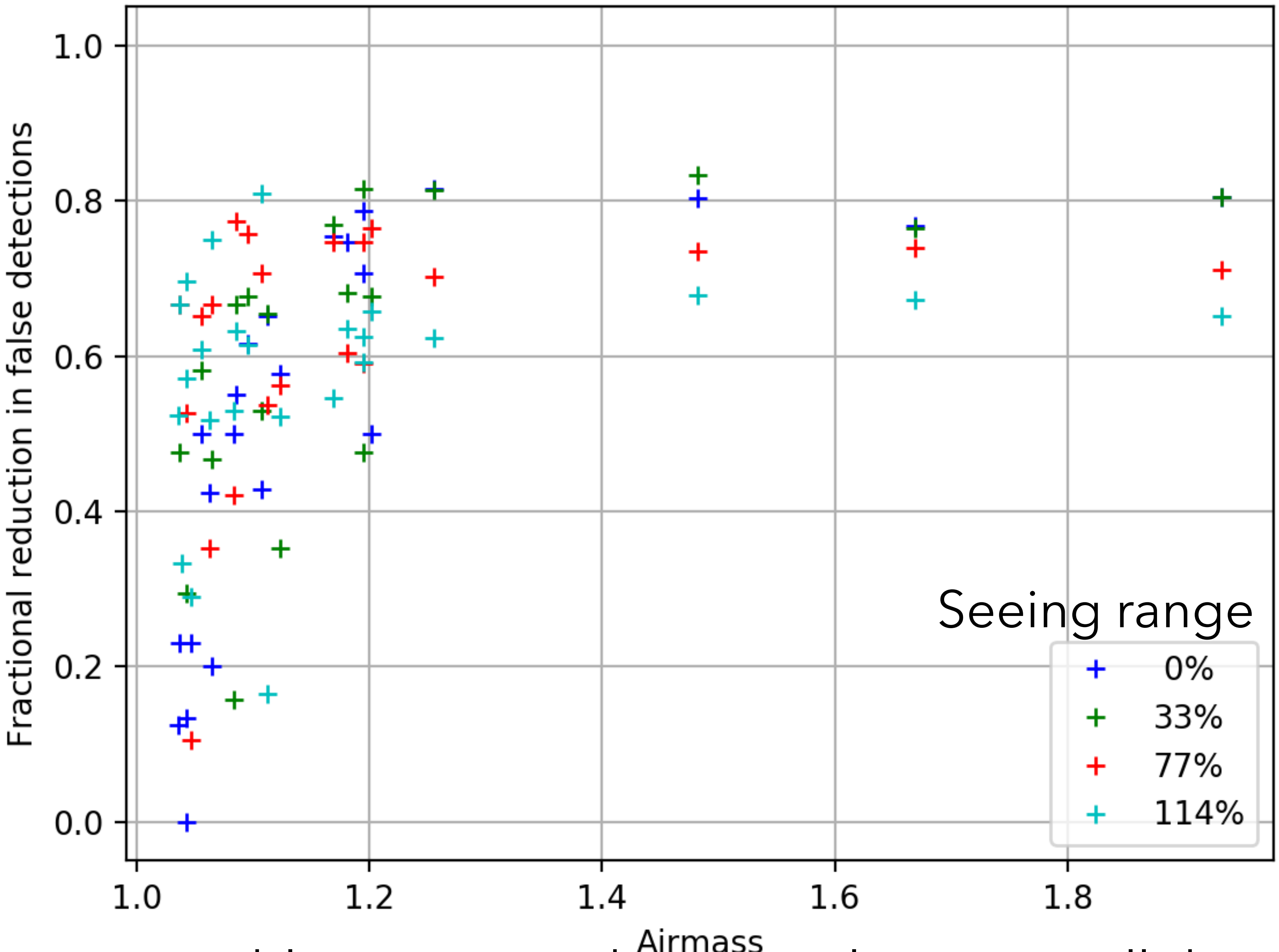

Templates built from 0.60″-0.97″ variable seeing observations

# DCR image differences – fewer dipoles




The DCR-matched templates result in far fewer dipoles compared to deep coadd templates in almost all cases, with the greatest reductions for science images above airmass 1.1

# DCR image differences – fewer false detections




There are no variable sources in these simulations, so all detections are false detections. The reduction in the number of false detections (not just counting dipoles) is less dramatic, but still significant.

# Conclusion

- The DCR modeling and image differencing code is included in the LSST stack
- 4x fewer false positives above airmass 1.1
- Tolerates a 60% range of seeing
- New science opportunities using single band spectra
- Ongoing investigations:
  - Crowded fields
  - Processing precursor data (Decam HiTS) at NCSA
  - Interaction between DCR and astrometric errors/proper motion
  - Extension to properly handle variable PSFs

More on variable seeing:
https://dmtn-121.lsst.io

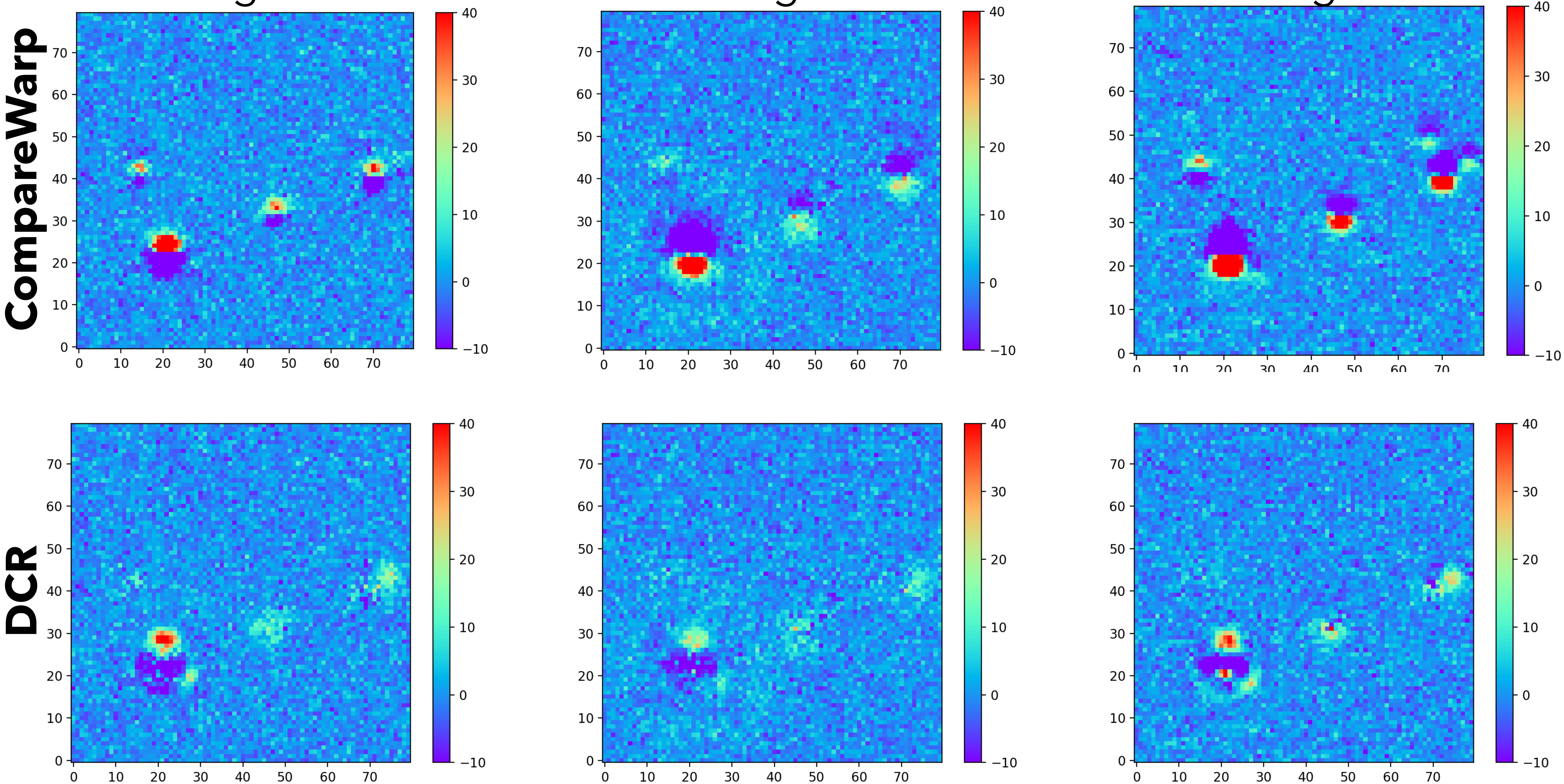
More background:
https://arxiv.org/pdf/1807.07211.pdf

Background and derivation:
https://dmtn-037.lsst.io

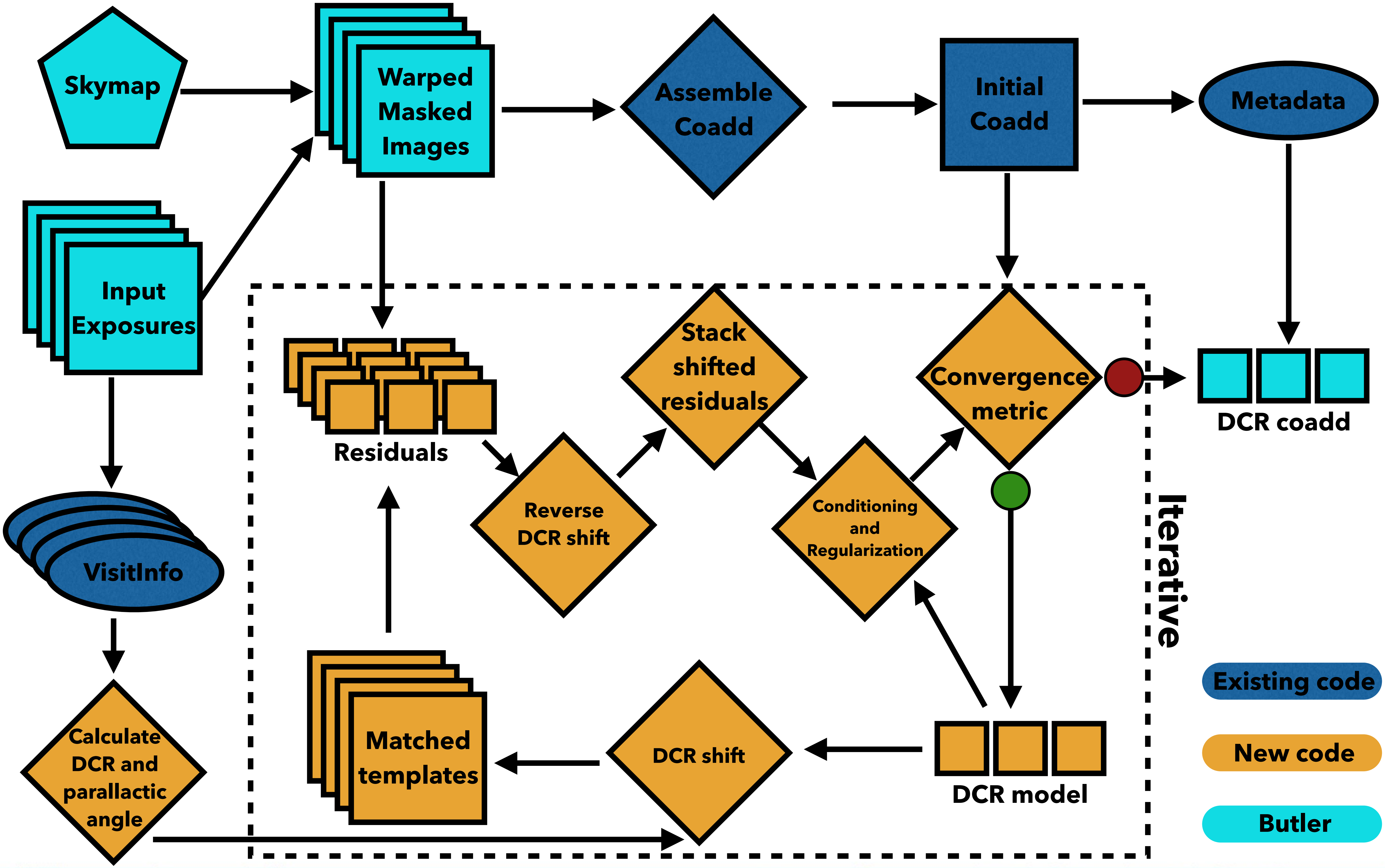
# Extras

# DCR image differences – residuals

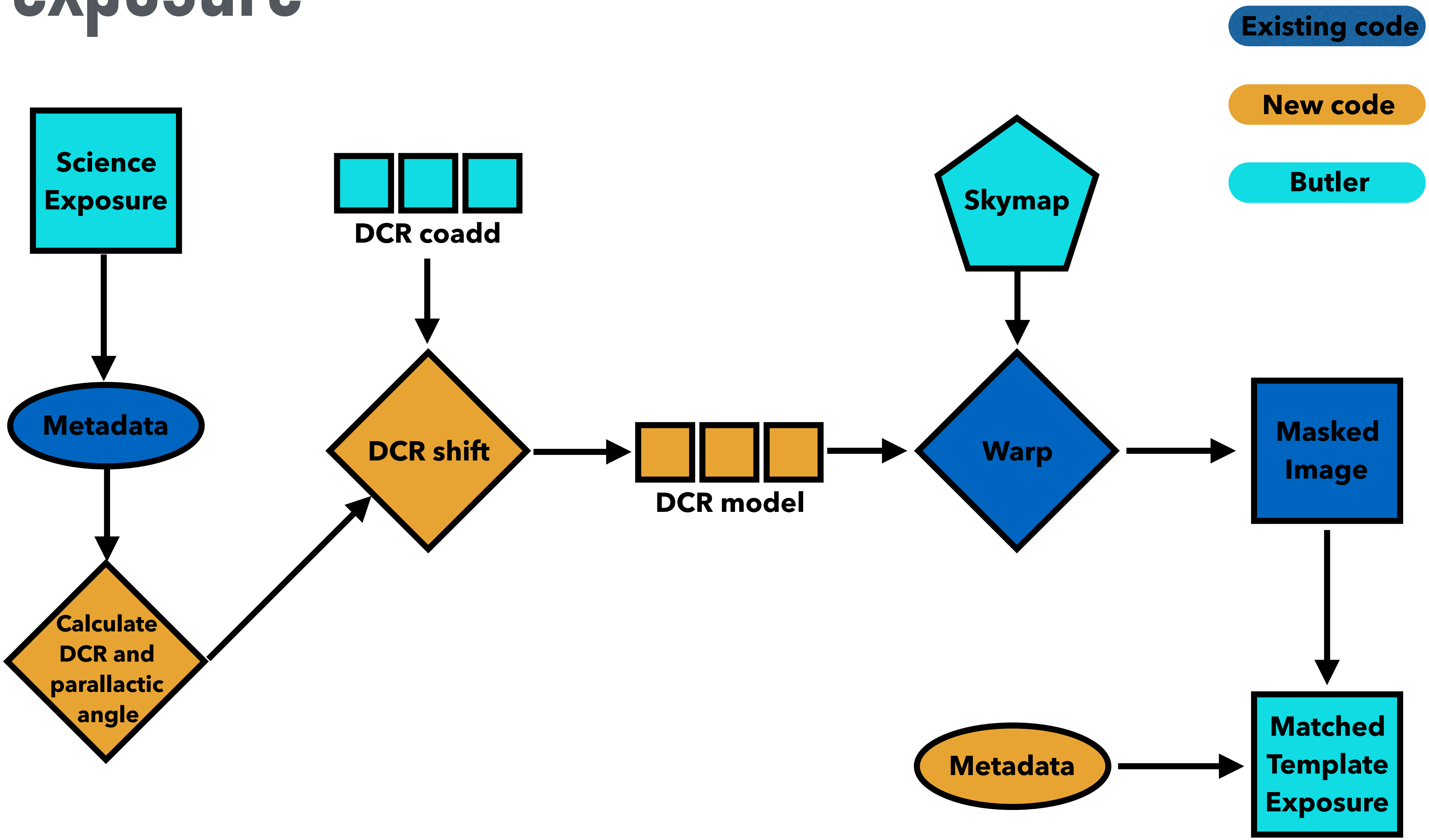
airmass 1.04 seeing 0.95″ | airmass 1.11 seeing 1.38″ | airmass 1.26 seeing 0.88″



# Steps to building a DCR coadd



# Steps to building a DCR matched exposure



# Testing the impacts of variable seeing

Use OpSim feature-based scheduler to simulate observing conditions for two years

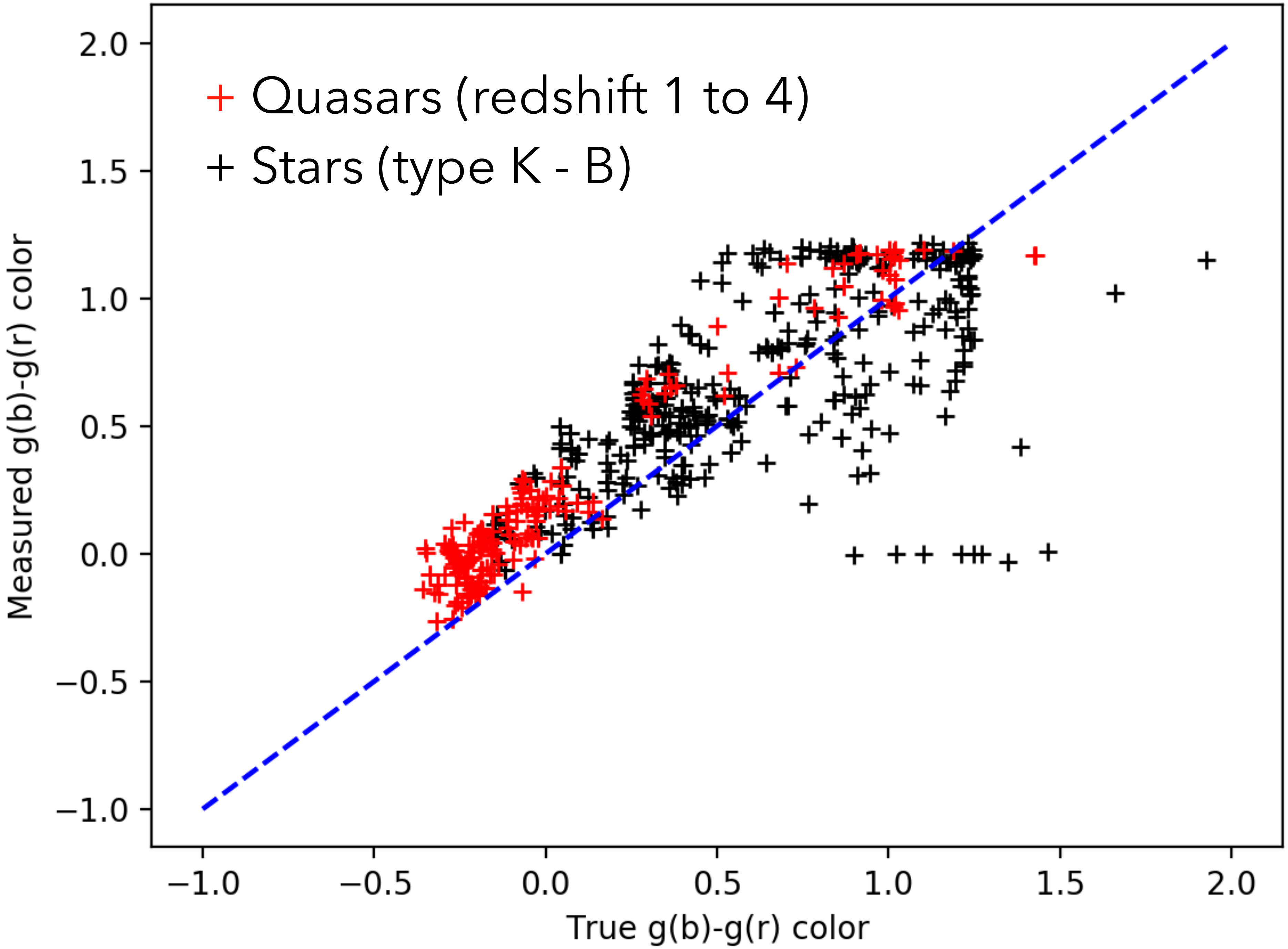
The templates

- 8 observations in the first year to build the template
- 10 sets of simulated images
  - modify only the allowed seeing range in each, from constant 0.6″ seeing to variable 0.6″-1.28″ seeing

The science images

- 24 observations in the second year
- Use the simulated observing conditions without modification
- Use the same science images with each template

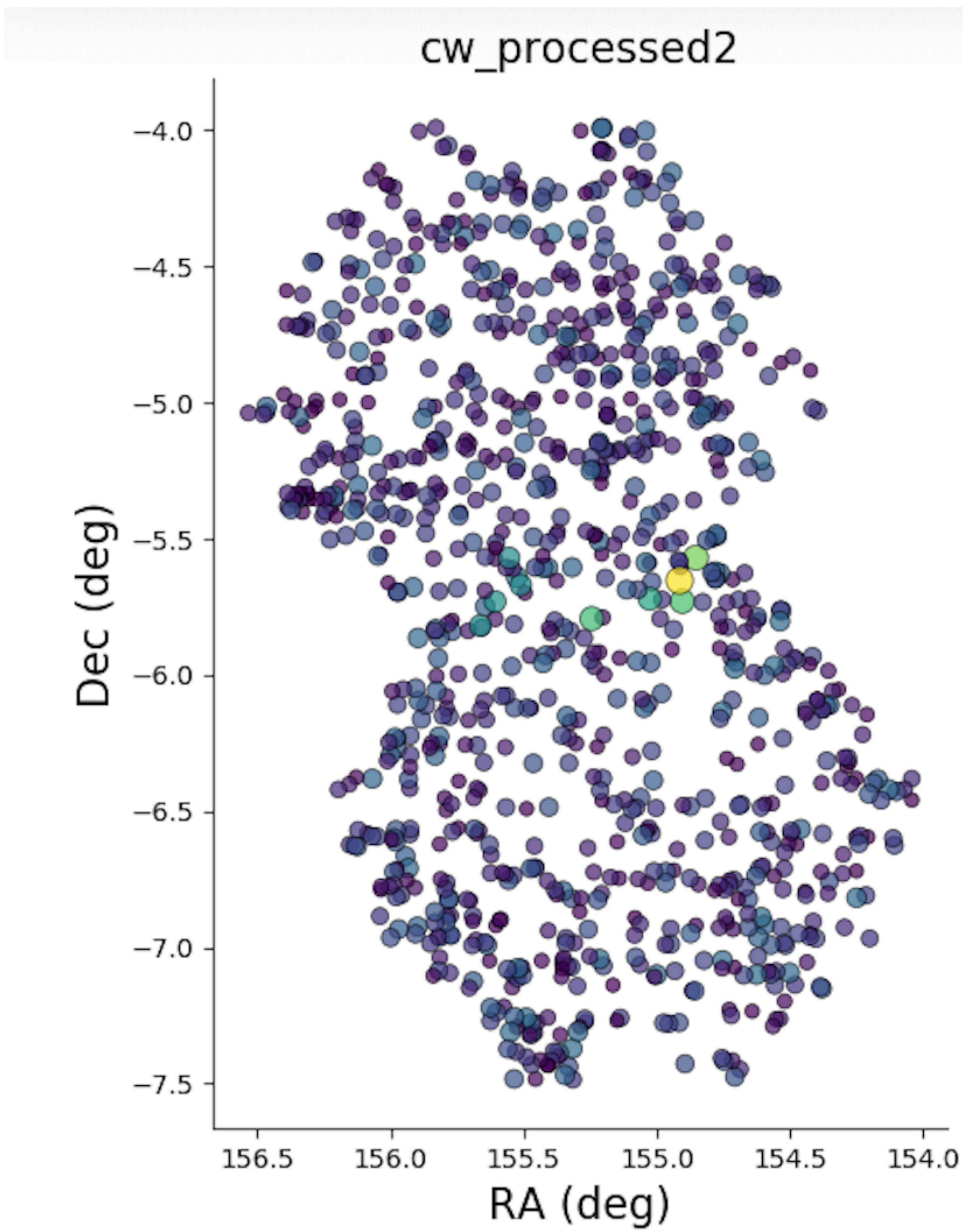
# Simulations – astrometric errors

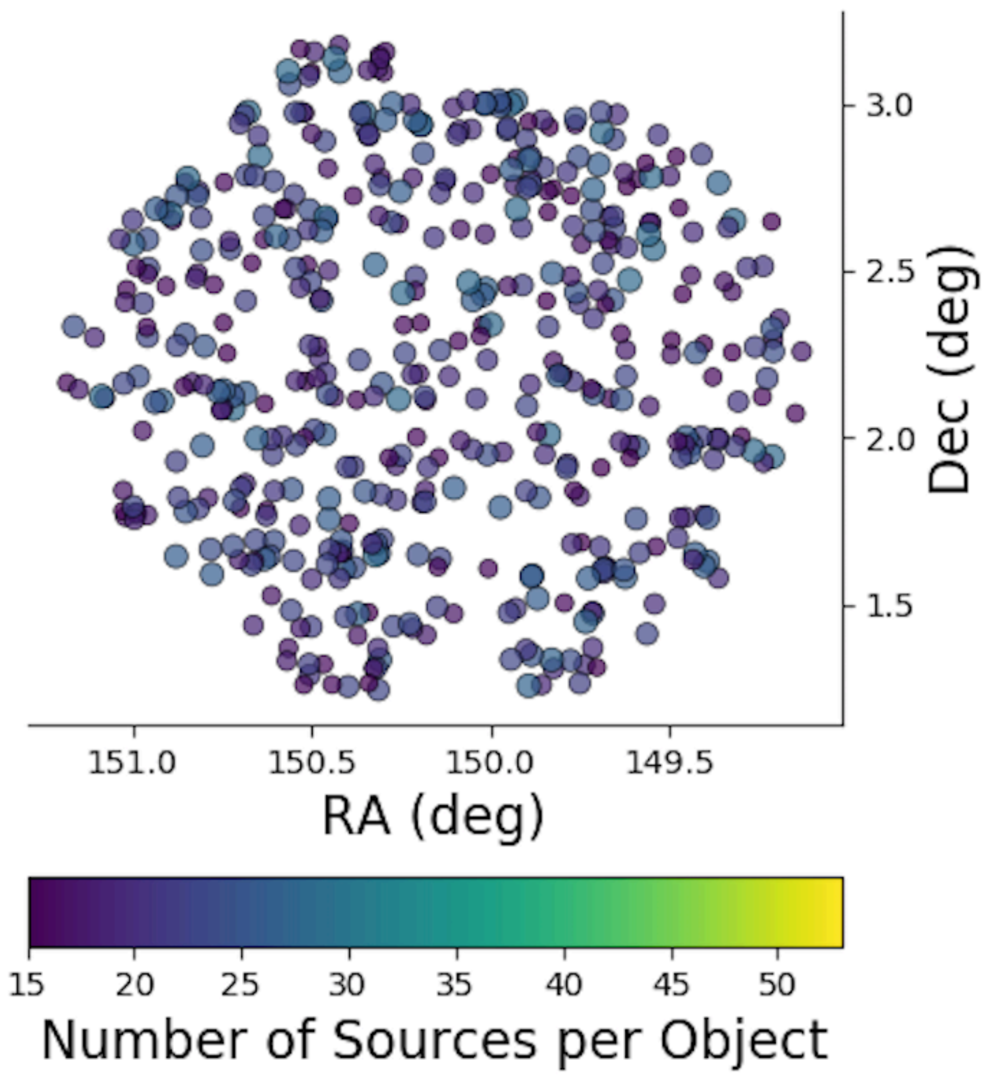



The simulations have "perfect" astrometry
Astrometric calibration introduces position errors

# DECam HiTS reprocessing

2015 - 2014 image differencing
**Standard coadd** templates



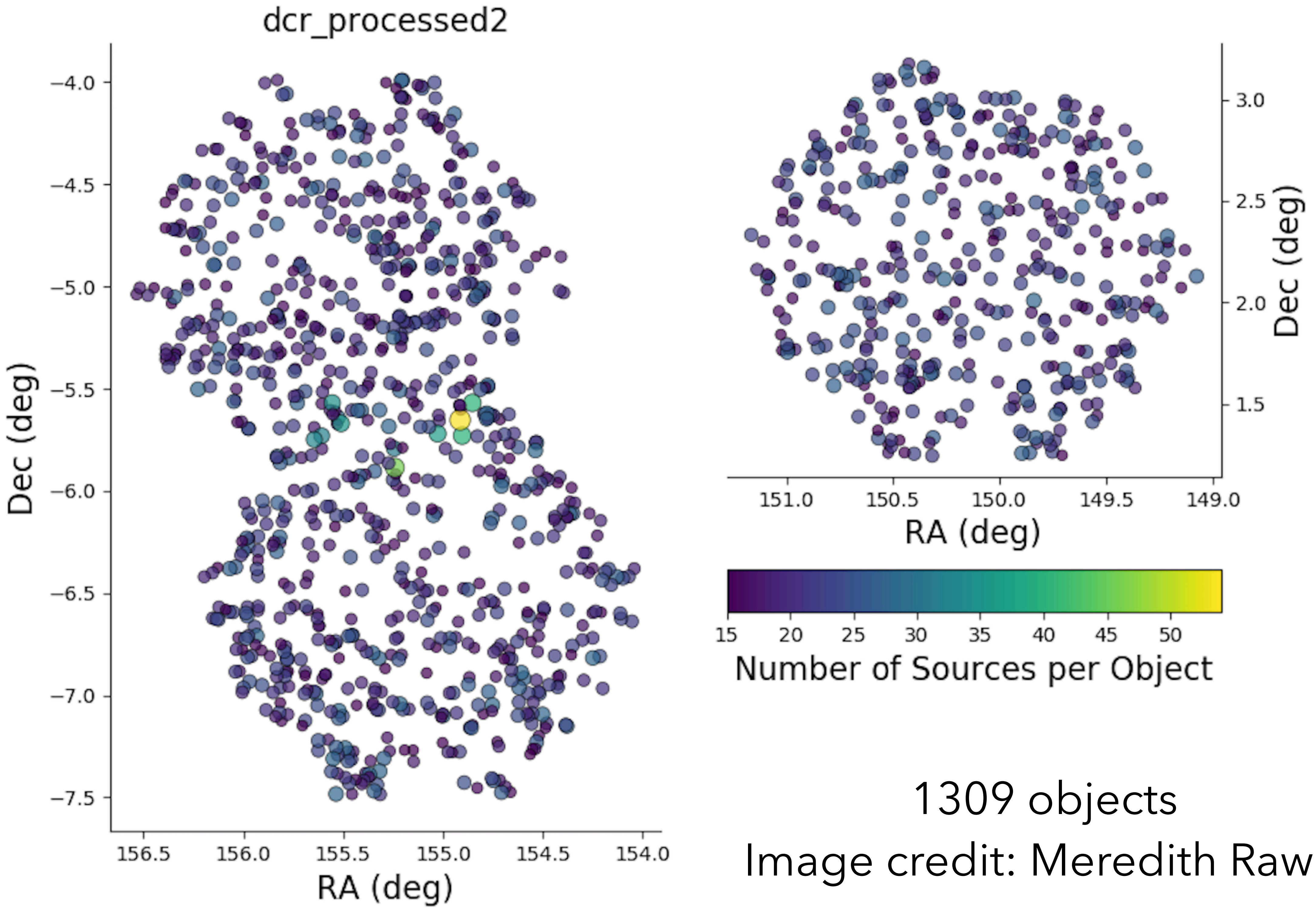




1485 objects

Image credit: Meredith Rawls

# DECam HiTS reprocessing

2015 - 2014 image differencing
**DCR-matched** templates




1309 objects

Image credit: Meredith Rawls

# Iterative Forward Modeling

## Extension to variable PSFs

A work in progress!

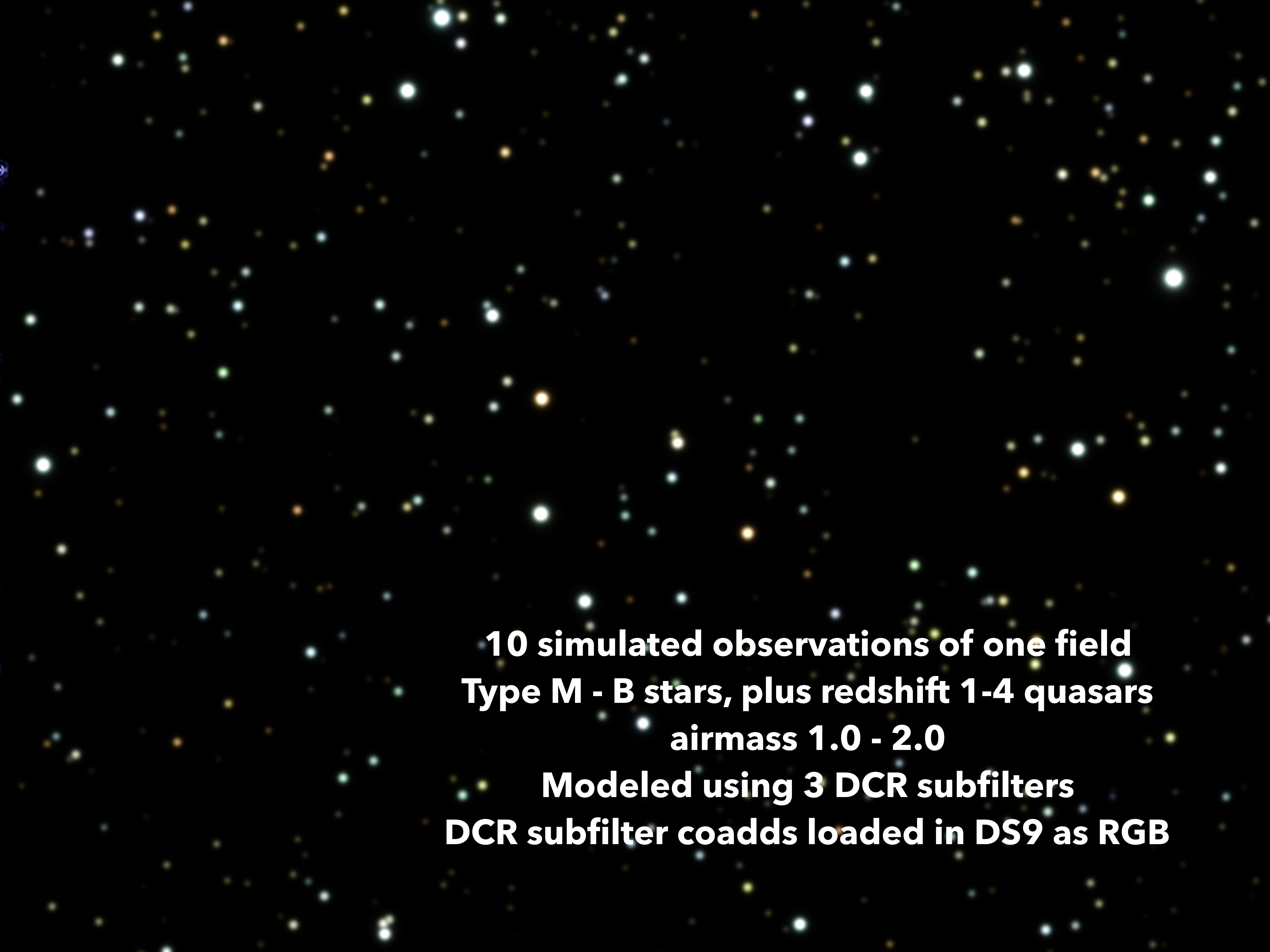
$$\sum_{\alpha} B_{i\alpha} Q^{(i)} \overrightarrow{y_\alpha} = P \overrightarrow{s_i}$$

***P***: PSF of the sub-band models
***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*


10 simulated observations of one field
Type M - B stars, plus redshift 1-4 quasars
airmass 1.0 - 2.0
Modeled using 3 DCR subfilters
DCR subfilter coadds loaded in DS9 as RGB