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# Creating DCR-Matched Templates for Image Differencing

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# Conclusion

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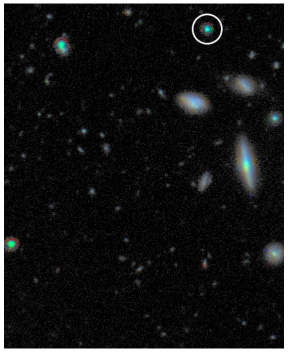
- The DCR modeling and image differencing code is included in the LSST stack
- 4x reduction in false positives above airmass 1.1 (simulated data)
- Currently tolerates a 50% range of seeing
- New science opportunities using single band spectra
- Ongoing investigations:
  - Extension to properly handle variable PSFs
  - Processing precursor data (Decam HiTS) at NCSA
  - Interaction between DCR and astrometric errors/proper motion
  - Crowded fields



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

# DCR Overview

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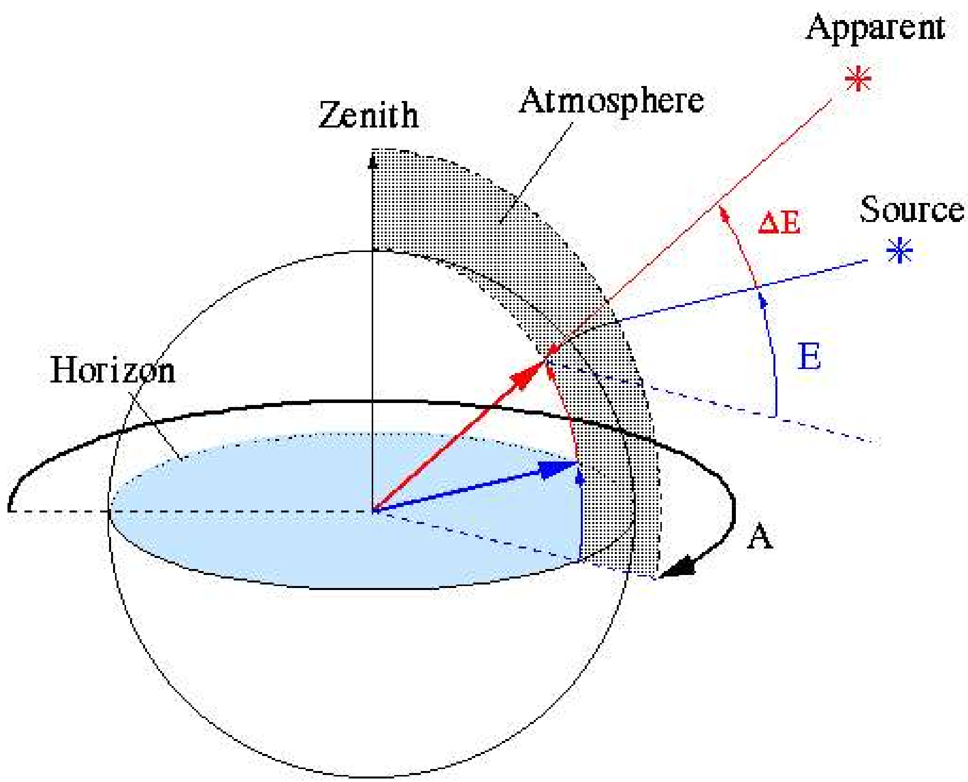
Refraction deflects the apparent position of sources towards zenith.

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

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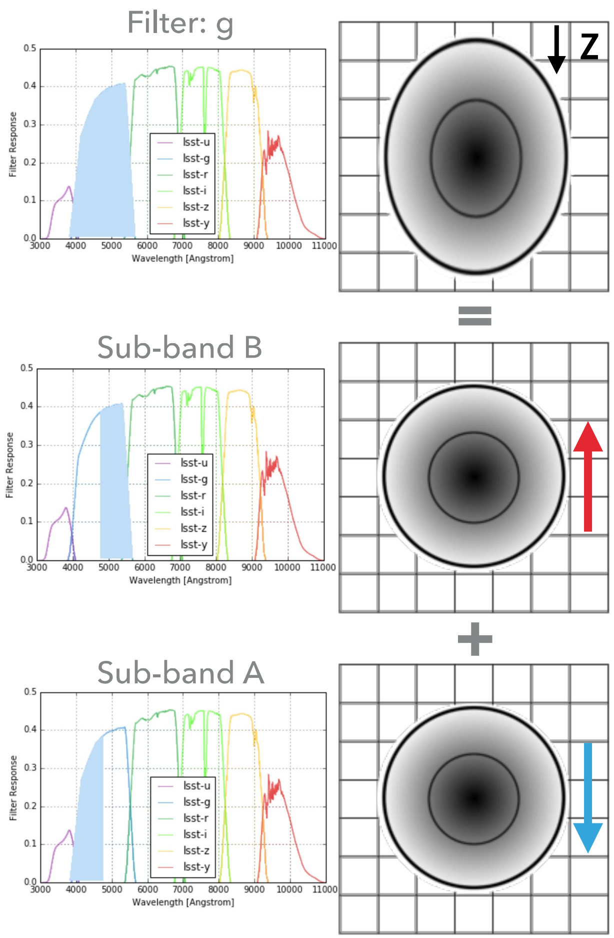



Each pixel in an image contains flux smeared out along the zenith direction

Assume that a small sub-band of the full filter bandwidth has negligible DCR

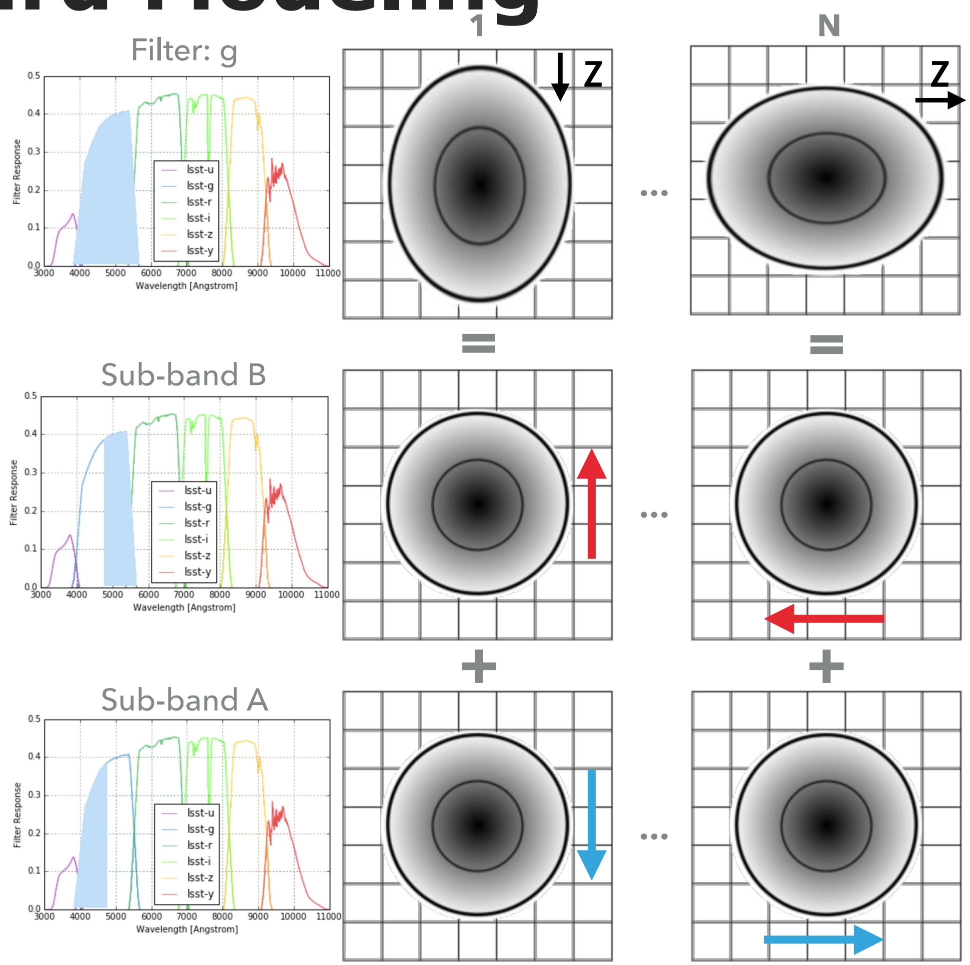
The sub-band model is shifted towards zenith relative to the center of the band

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

The approximation becomes more accurate with more, narrower, 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

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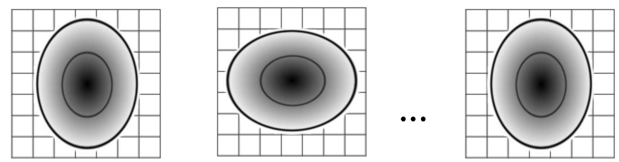
Each image is the sum of a series of convolutions with the sub-band models: $\sum_{\alpha} B_{i\alpha} \vec{y_\alpha} = \vec{s_i}$

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

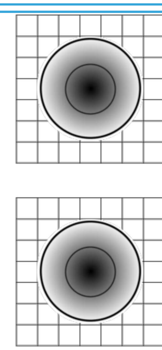
Pixel values of each image *i* : $\vec{s_i}$

1 2 … ***N***

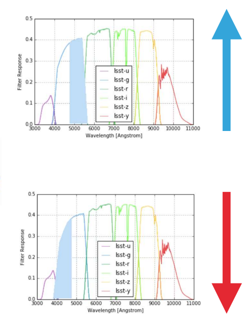


Pixel values of each sub-band $\boldsymbol{\alpha}$ : $\vec{y_\alpha}$

$\alpha$ β



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



# Iterative Forward Modeling

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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

More details: https://dmtn-037.lsst.io

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**This is also how we construct a DCR-matched template for future science observations**

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# DCR image differences - residuals

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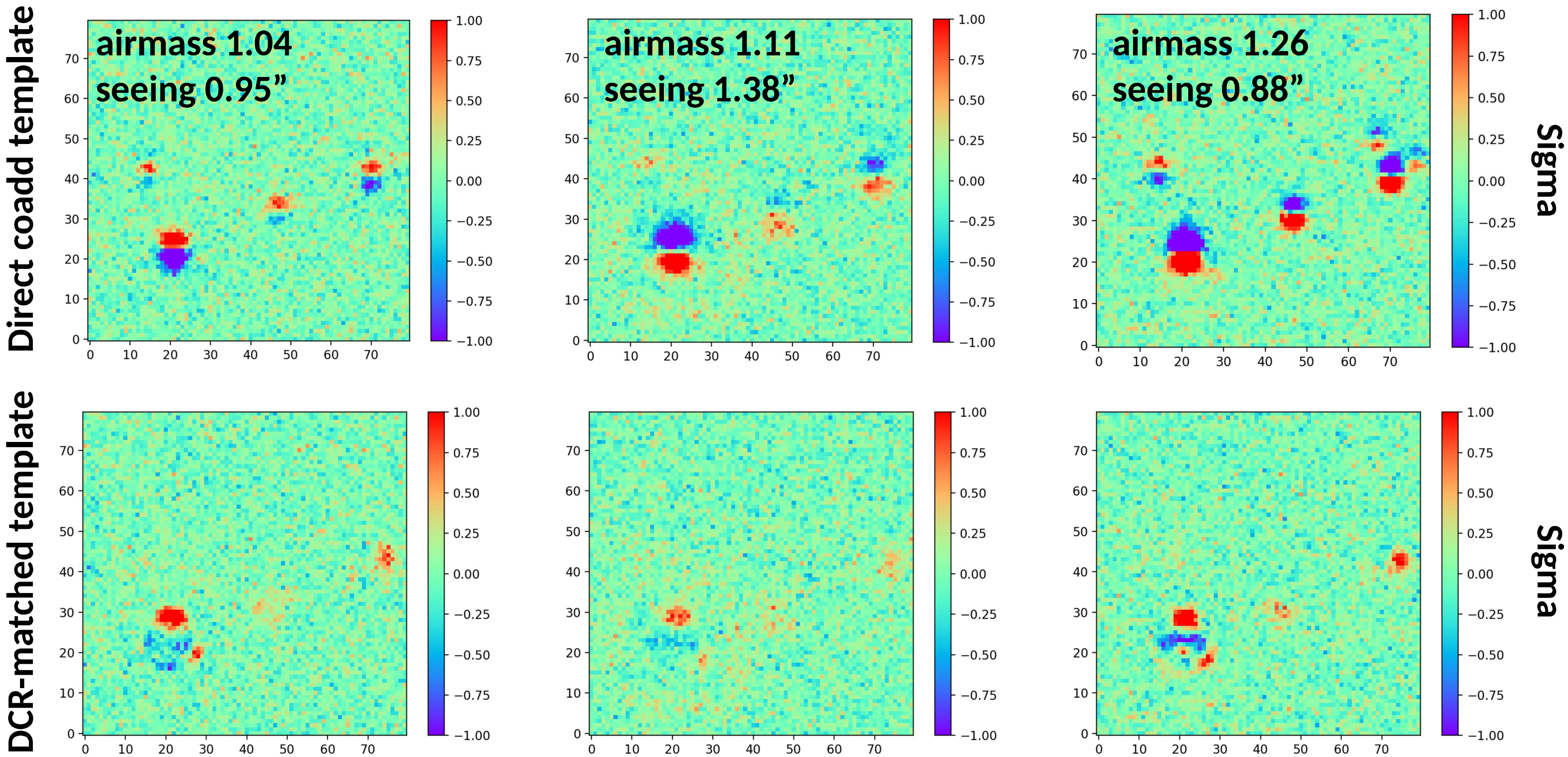


**Templates built with:**

- 8 observations
- Airmass 1.05 - 1.95
- 0.60” Seeing for all observations
- 3 sub-band model
- **Simulated data**

# Variable PSFs

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Two approaches:

1. Use direct warps and restrict the range of seeing
   - Inexact forward modeling
   - High airmass observations more likely to be cut
2. Use PSF-matched warps
   - Loss of information
   - Correlated noise, etc.. (recall Jim Bosch's talk on Tuesday)
   - Ideally would first correct the PSF for DCR

# DCR image differences - fewer false detections

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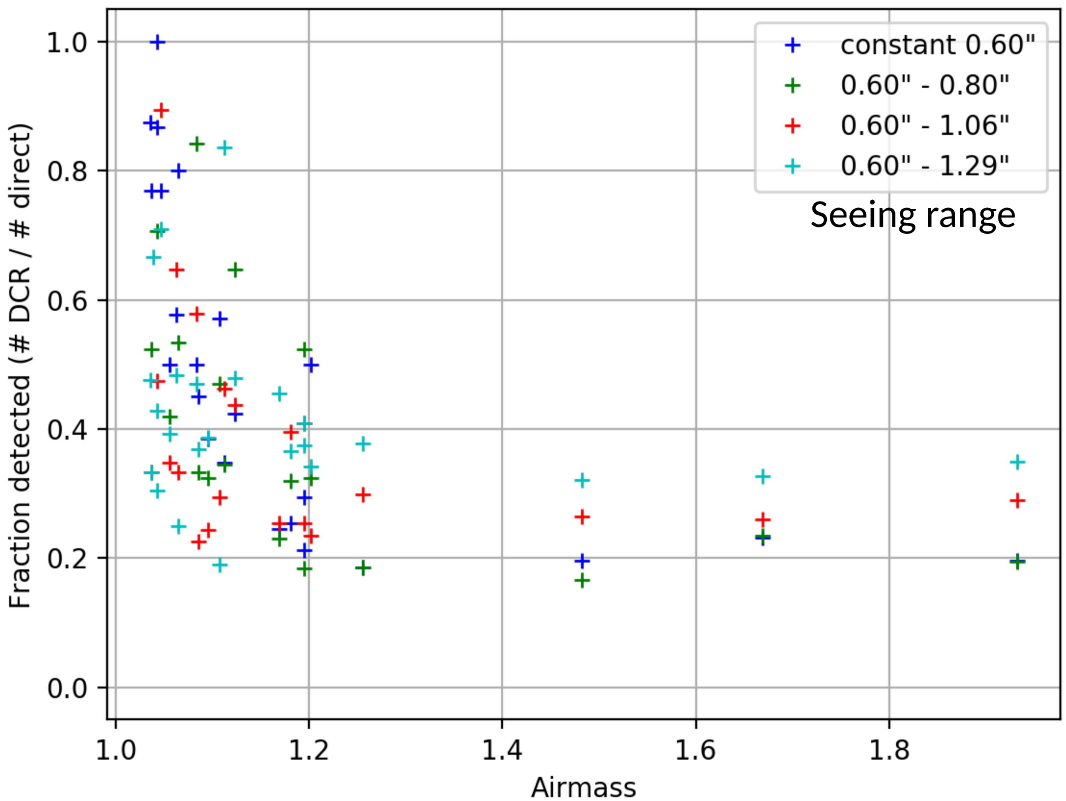



**The DCR model template**

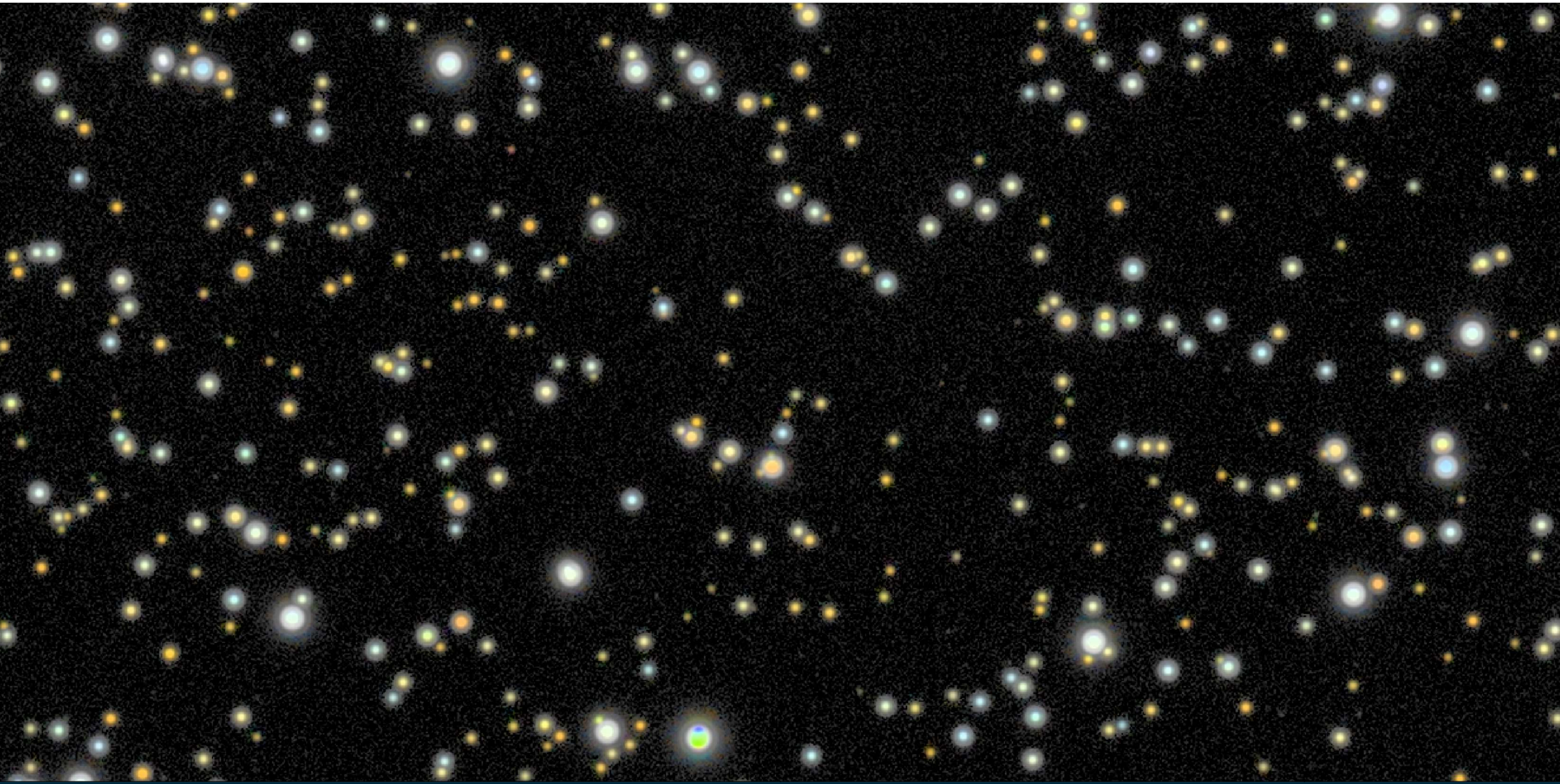
- 8 observations in the first year to build the template
- 4 sets of **simulated** images
- Modify only the allowed seeing range in each, from constant 0.6" seeing to variable 0.6"-1.28" seeing

**The science images**

- 24 observations in the second year
- Use the same "science" images with each template

**Difference image comparison**

- Also make direct coadds from each set of simulated first year images.
- Compare the number of sources detected in each science image using the DCR model vs the direct coadd
- There are no variable sources in these simulations, so **all detections are false detections**.



# Simulations - recovered star spectra

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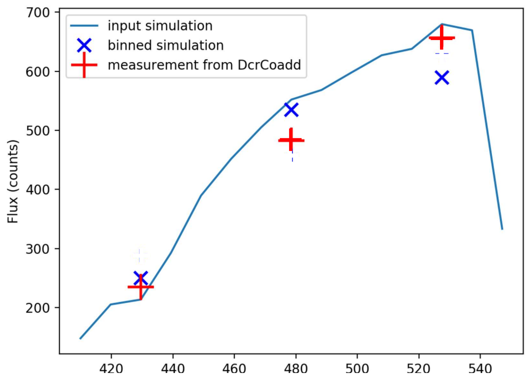
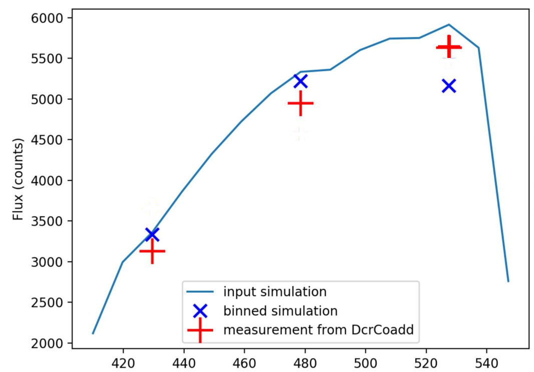
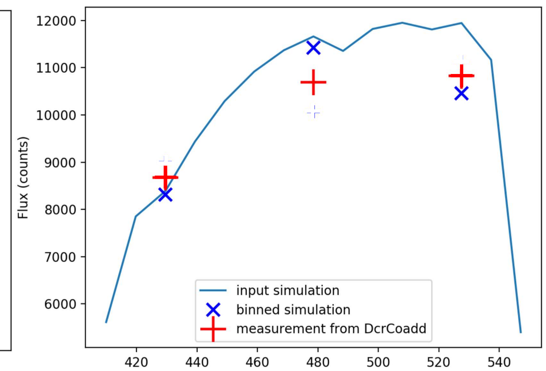
Type K star (4090K)

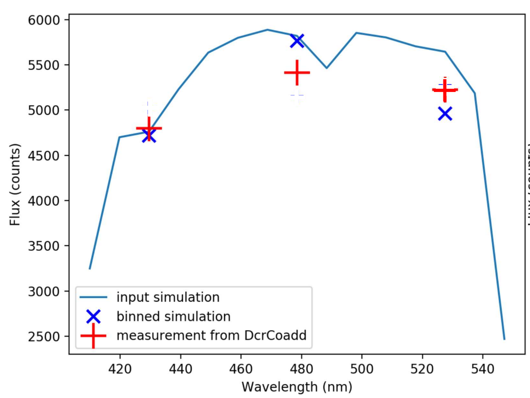



Type G star (5400K)

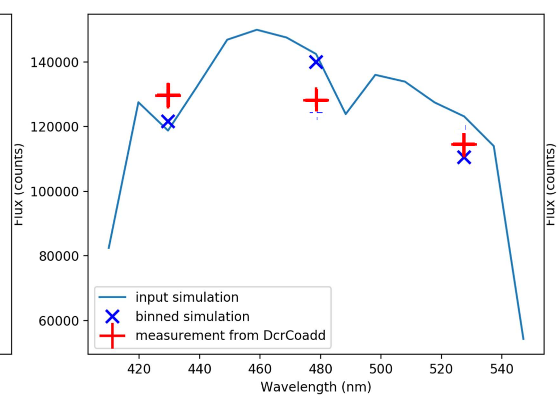



Type F star (6400K)

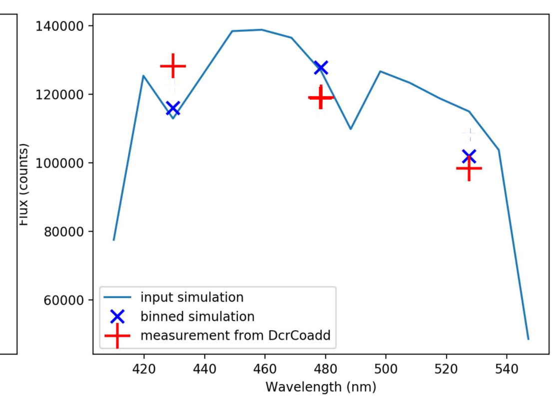



Type F star (6900K)




Type A star (10000K)




Type B star (17000K)



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# Simulations - recovered quasar spectra

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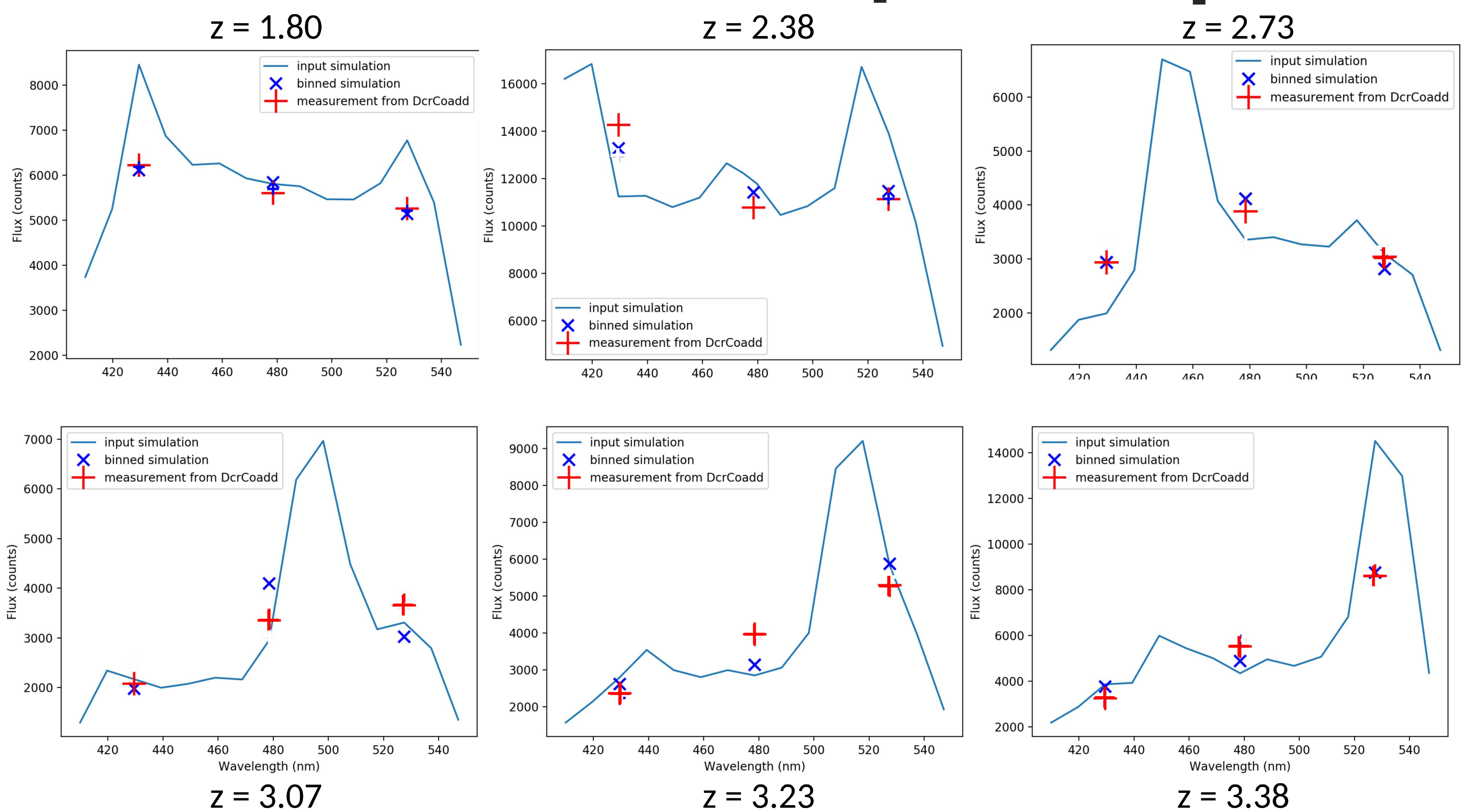
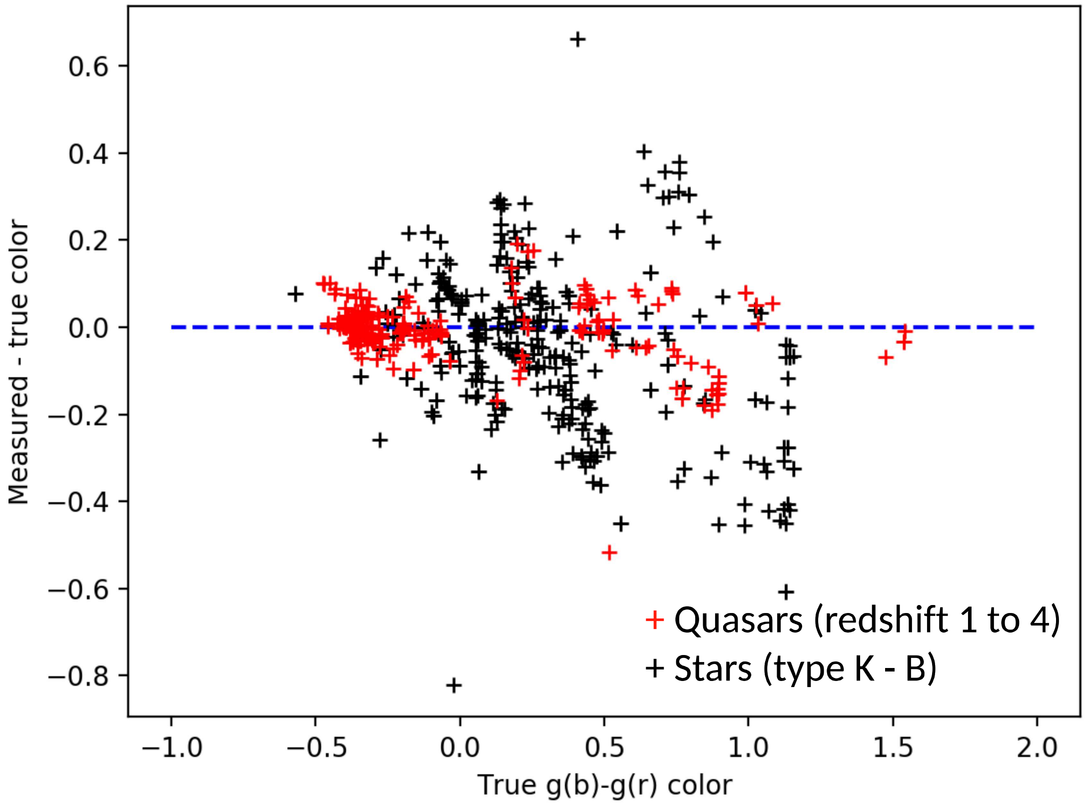



Input quasar spectra from Vanden Berk+2001

# Simulations - recovered colors

Rubin Observatory




Compare the simulated binned color vs the measured color of matched sources

- The colors are consistent
- Many more bright quasars in these simulations than reality
- Scatter increases for faint sources
- Astrometric calibration is turned off…

# Simulations - astrometric errors

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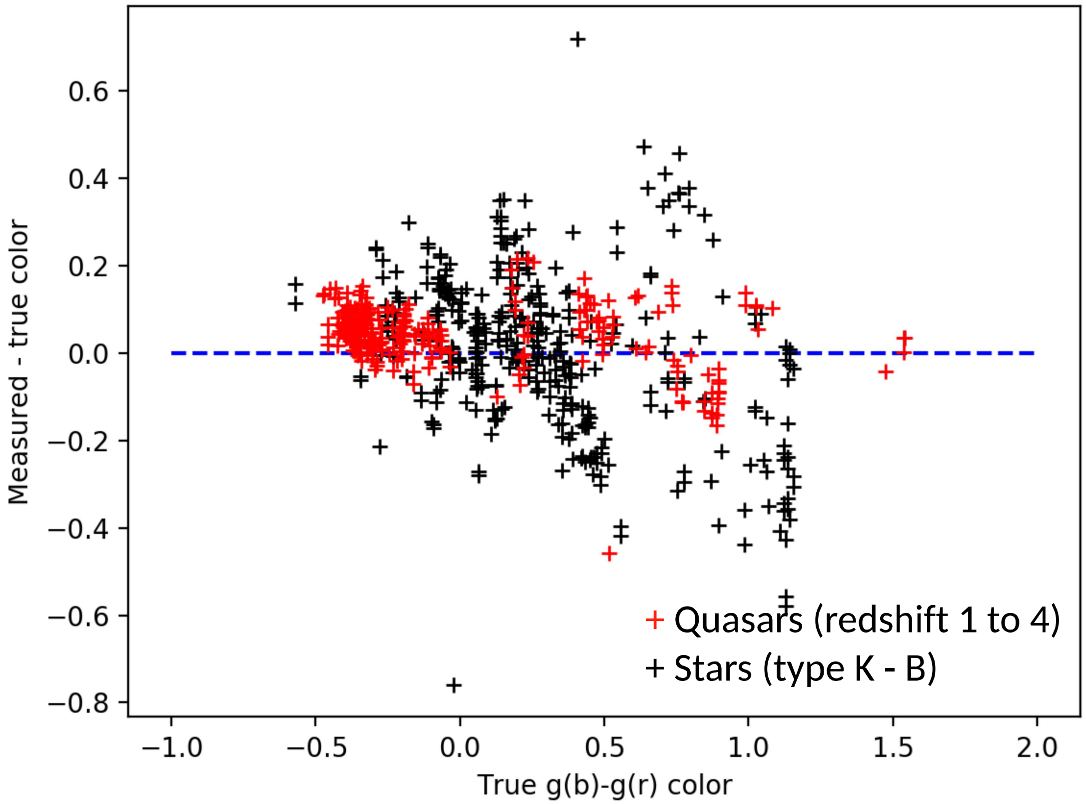
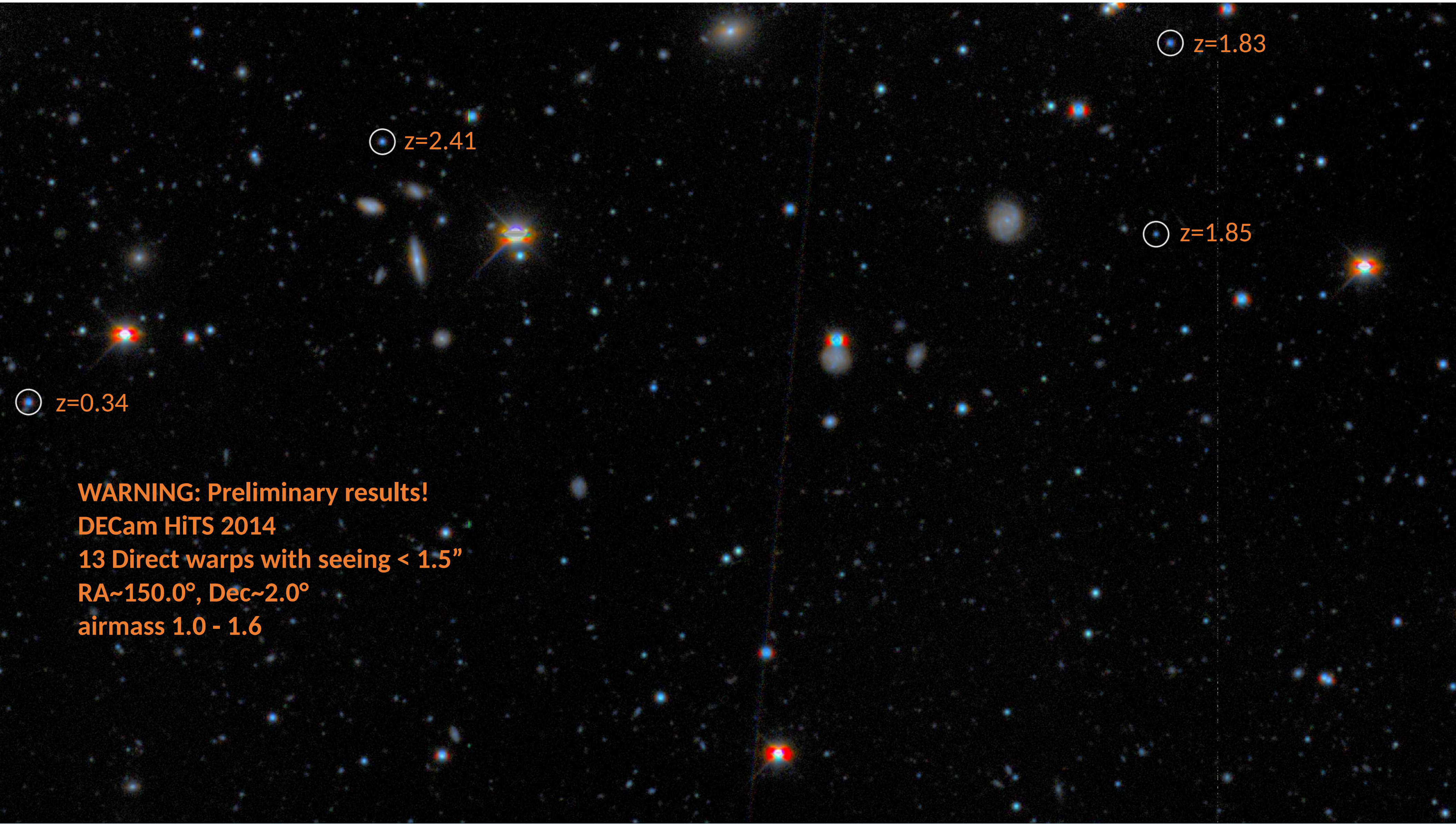



Turn on astrometric calibration:

- DCR shifts the apparent location of calibration stars
- The DCR model tries to fix the shift
- The recovered colors are shifted blue or red, depending on the color of the calibration stars


WARNING: Preliminary results!
DECam HiTS 2014
13 Direct warps with seeing < 1.5”
RA~150.0°, Dec~2.0°
airmass 1.0 - 1.6


z=2.41
z=1.83
z=1.85
z=0.34
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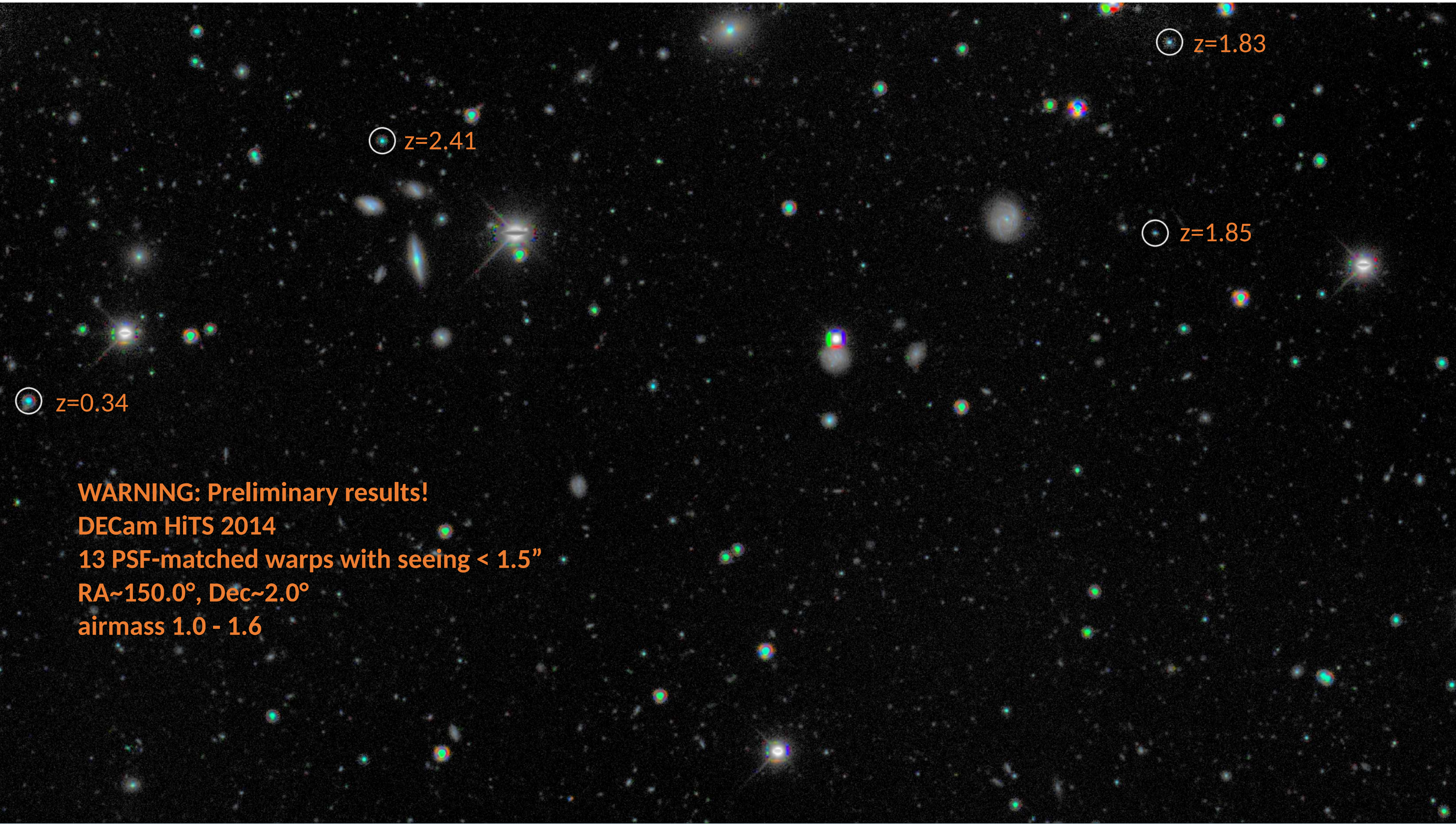

z=1.83
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- Currently tolerates a 50% range of seeing
- New science opportunities using single band spectra
- Ongoing investigations:
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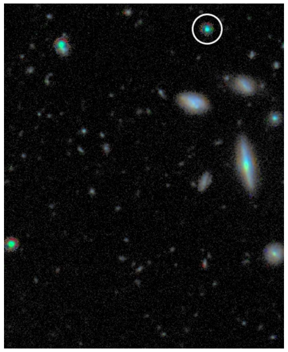

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# Extras

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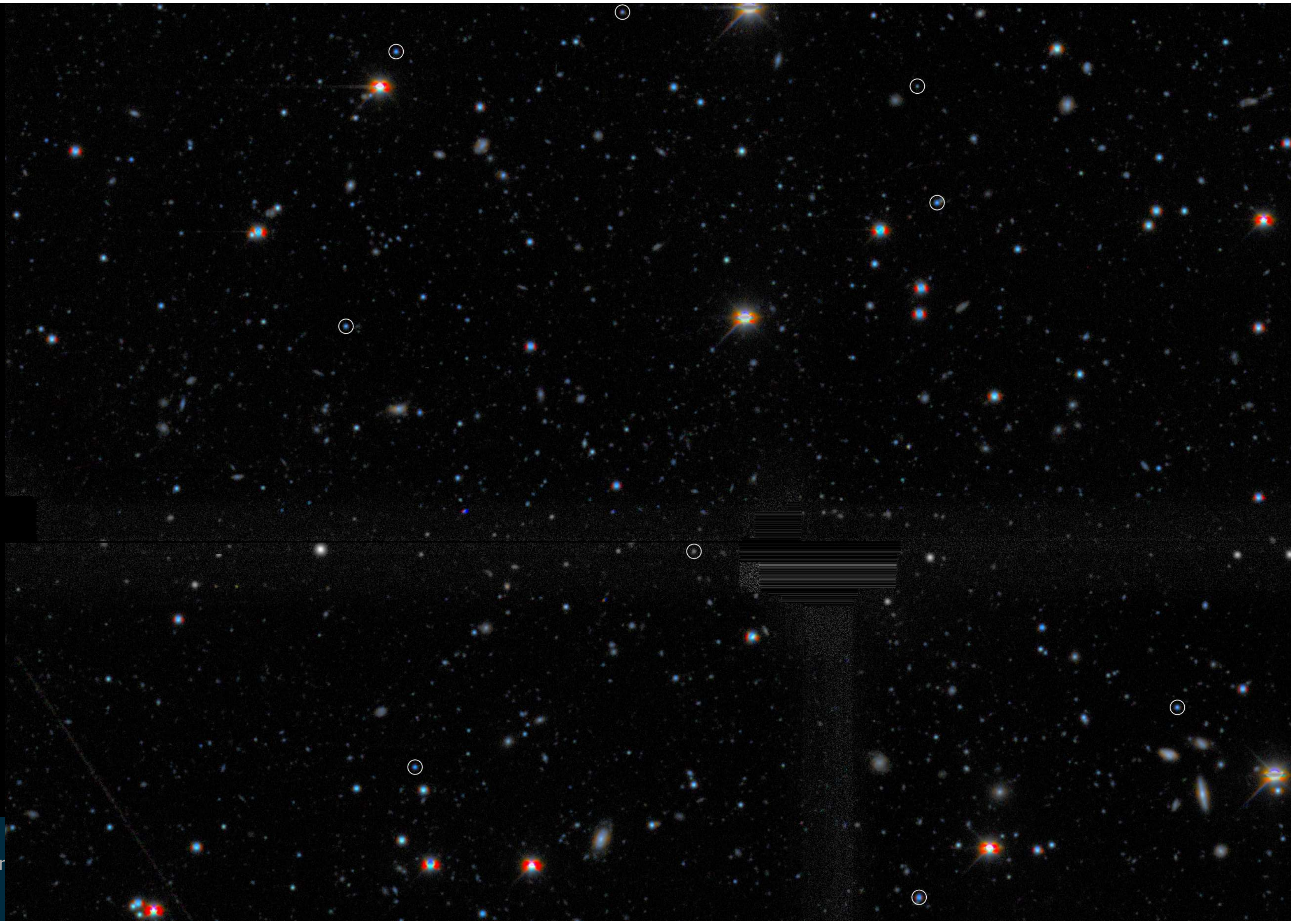

# Steps to building a DCR coadd

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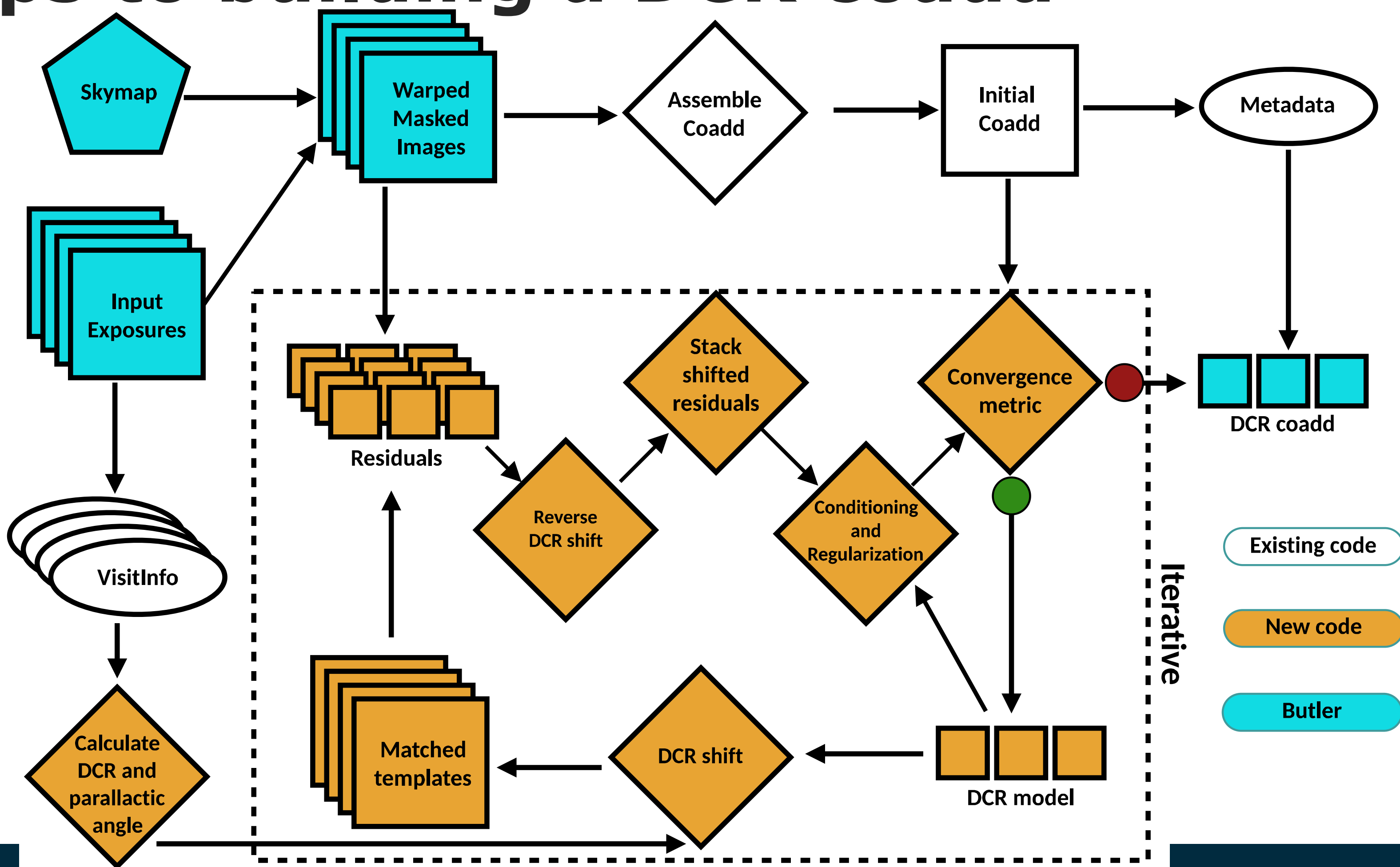
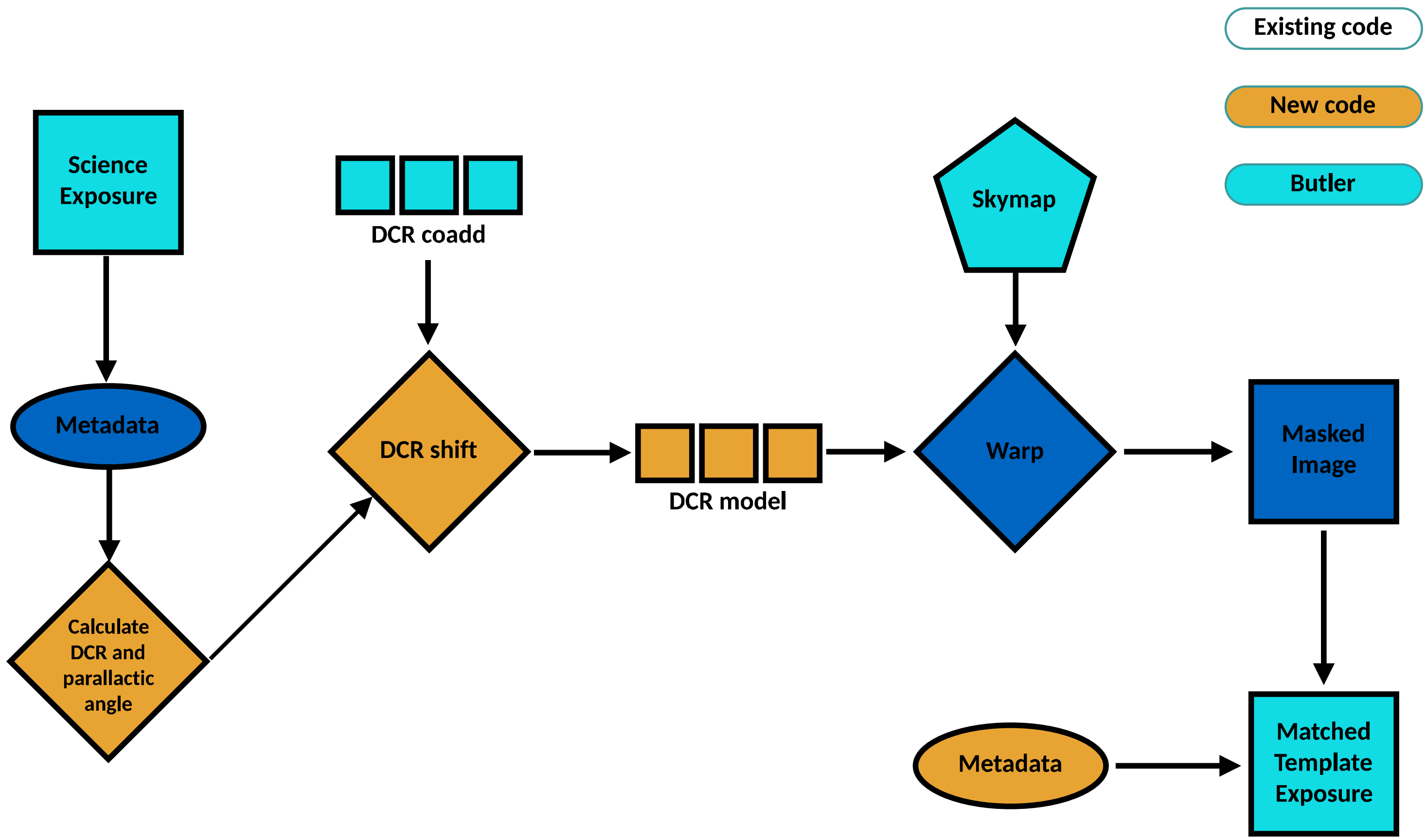


# Steps to building a DCR matched exposure

Rubin Observatory



# Accounting for Variable PSFs

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A work in progress!

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

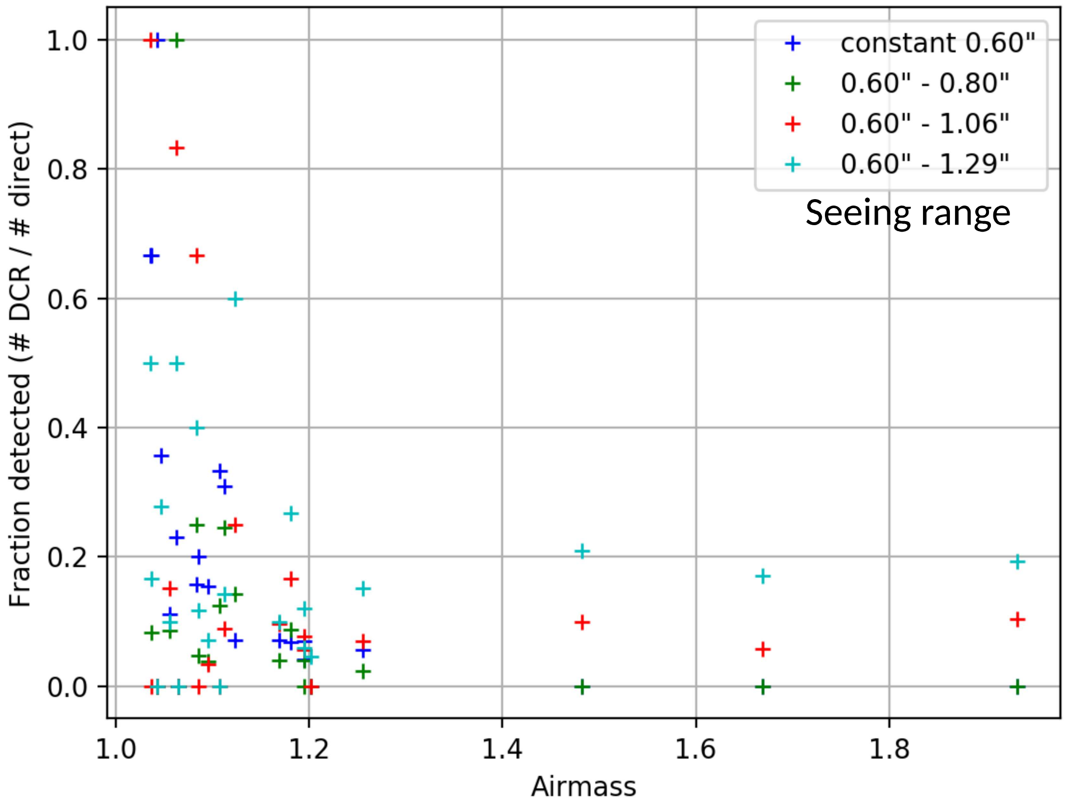
***P***: PSF of the sub-band models
***Q**$_i$*: Measured PSF of each image *i*

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*

# DCR image differences - fewer dipoles




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

# Testing the impacts of variable seeing

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Use OpSim feature-based scheduler to simulate observing conditions of one field 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