Survey Uniformity and Atmosphere Modeling with Forward Global Calibration

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and the DES Calibrations Crew

LSST/DESC Calibration Workshop

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Outline

- What is FGCM?
  - See Burke, Rykoff+17 http://adsabs.harvard.edu/abs/2018AJ....155...41B and https://github.com/erykoff/fgcm
- Atmosphere and Instrumental Passbands
- The FGCM Fitting Procedure
- Calibration Errors
- Implementation in LSST

What is FGCM?

- The "Forward Global Calibration Method"
    - Solve the global calibration problem with a physical model of the atmosphere + instrument
    - Picking up on Stubbs & Tonry (2006)
    - Requires instrument throughput measurements
- Given a set of atmospheric parameters at any given time (under photometric conditions) we can predict the atmospheric extinction as a function of wavelength
    - Also need to know object SED (see e.g., Li+16)
- Once we know the atmospheric extinction, can predict fluxes of all the objects in an exposure

What is FGCM?

- Two step process
- Select exposures & stars suitable to obtain atmospheric model on nights of the survey
  - Multi-band solution
  - Assume atmospheric parameters vary slowly over the night
- Calibration stars are used to fit the zeropoint for all exposures in survey
  - Include chromatic corrections
  - Add non-photometric exposures (with increased error!)

Advantages of FGCM

- Forward model approach always leads to physically possible solutions
  - Allows physically-motivated non-linearities with airmass
  - No gray terms in the model means no runaway solutions
- Uses full range of star colors — increase the s/n and this is useful information!
- Instrumental transmission variations, plus possible evolution of passbands is properly incorporated
- Works best with more overlap in time and space (like übercal), and multiple bands per night is very useful

FGCM DES Y1-4

- FGCM paper (Burke++17) is based on DES Years 1-3
    - Old, fragile code
    - Issues with mis-measured out-of-band throughput
- Most result plots in this talk are from the newer solution incorporating DES Years 1-4
    - New, fancy, faster code
    - Better bandpass measurements
    - Avoid use of GPS water vapor
    - Aperture corrections and more!

The Atmosphere Model

- Atmospheric transmission can be described with a small number of parameters
  - Precipitable water vapor (PWV)
  - Aerosol Optical Depth (AOD) τ and α

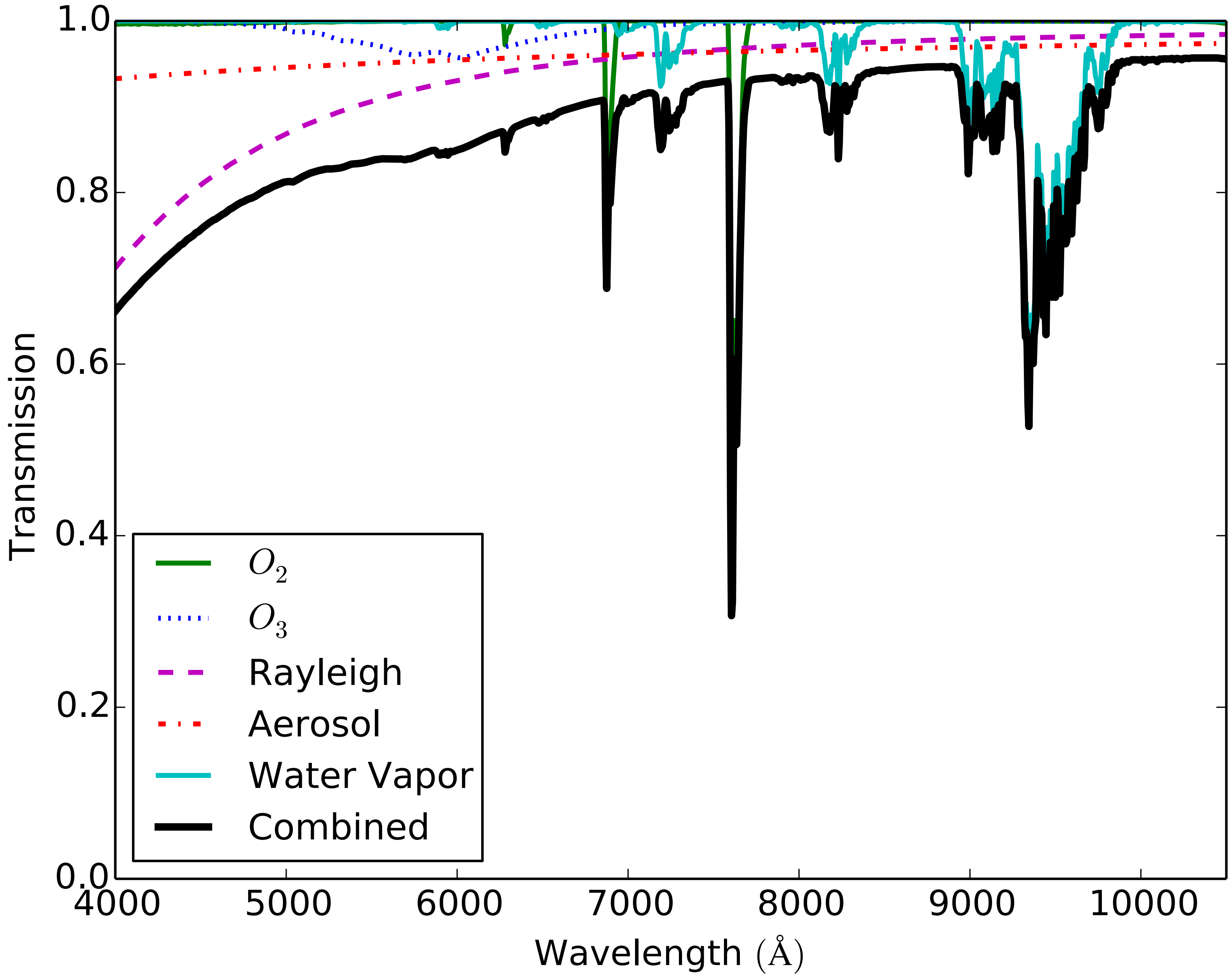
$$\tau(\lambda) = \tau_{7750} \times (\lambda / 7750\,\text{Å})^{-\alpha}$$

$$S_\tau(\lambda) = e^{X\tau(\lambda)}$$

  - Ozone (O_3)
  - Given zenith distance and barometric pressure, compute Rayleigh and O_2 using MODTRAN

Atmosphere Constituents

- The FGCM standard atmosphere model



Fit Parameters

- PWV varies linearly through the night
  - Could/should add quadratic term
- A single-constituent aerosol, with optical depth τ_{7750} that varies linearly through the night, and single α per night
- A single value for Ozone each night
- Plus airmass and site-monitored barometric pressure

Auxiliary Data

- Originally used PWV from GPS monitor (with additive/multiplicative biases)
  - Odd values, outliers, systematic problems led to worse performance
- DES also has auxiliary aTmCam system
- 4 narrow-band filters on 4 cameras
  - Continuously fit atmospheric parameters through night
- Have not been able to use as an input to help calibration
  - aTmCam not as stable as DECam, and thus adds more noise than signal

From ADUs to Fluxes

- The number of ADU depends on size of telescope, passband S_b^{obs} and SED of source $F_\nu(\lambda)$

$$\mathrm{ADU}_b = \frac{A}{g} \times \int_0^{\Delta T} dt \times \int_0^{\infty} F_\nu(\lambda) \times S_b(x,y,\mathrm{alt},\mathrm{az},t,\lambda) \times \frac{d\lambda}{h_{Pl}\lambda}$$

- Normalizing to the AB scale yields

$$m_b^{\mathrm{obs}} \equiv -2.5 \log_{10} \left(\frac{\int_0^\infty F_\nu(\lambda) \times S_b^{\mathrm{obs}}(\lambda) \times \lambda^{-1} d\lambda}{\int_0^\infty F^{\mathrm{AB}} \times S_b^{\mathrm{obs}}(\lambda) \times \lambda^{-1} d\lambda} \right)$$

- But what we really want is the magnitude through our “standard” atmosphere

$$m_b^{\mathrm{std}} \equiv -2.5 \log_{10} \left(\frac{\int_0^\infty F_\nu(\lambda) \times S_b^{\mathrm{std}}(\lambda) \times \lambda^{-1} d\lambda}{\int_0^\infty F^{\mathrm{AB}} \times S_b^{\mathrm{std}}(\lambda) \times \lambda^{-1} d\lambda} \right)$$

- See Fukugita+96, Lynne Jones, LSST Science Book, etc.

To The Standard!

- The difference between the observed passband and the standard passband is:

$$\delta_b^{\mathrm{std}} \equiv m_b^{\mathrm{std}} - m_b^{\mathrm{obs}} = 2.5 \log_{10}(\mathbb{I}_0^{\mathrm{std}}(b)/\mathbb{I}_0^{\mathrm{obs}}(b))$$

$$+2.5 \log_{10} \left(\frac{\int_0^\infty F_\nu(\lambda) \times S_b^{\mathrm{obs}}(\lambda) \times \lambda^{-1} d\lambda}{\int_0^\infty F_\nu(\lambda) \times S_b^{\mathrm{std}}(\lambda) \times \lambda^{-1} d\lambda} \right)$$

- With a normalization integral I_0

$$\mathbb{I}_0^{\mathrm{obs}}(b) \equiv \int_0^\infty S_b^{\mathrm{obs}}(\lambda) \lambda^{-1} d\lambda$$

- This correction depends on SED (color) of object
  - Each individual observation has its own bandpass which must be corrected

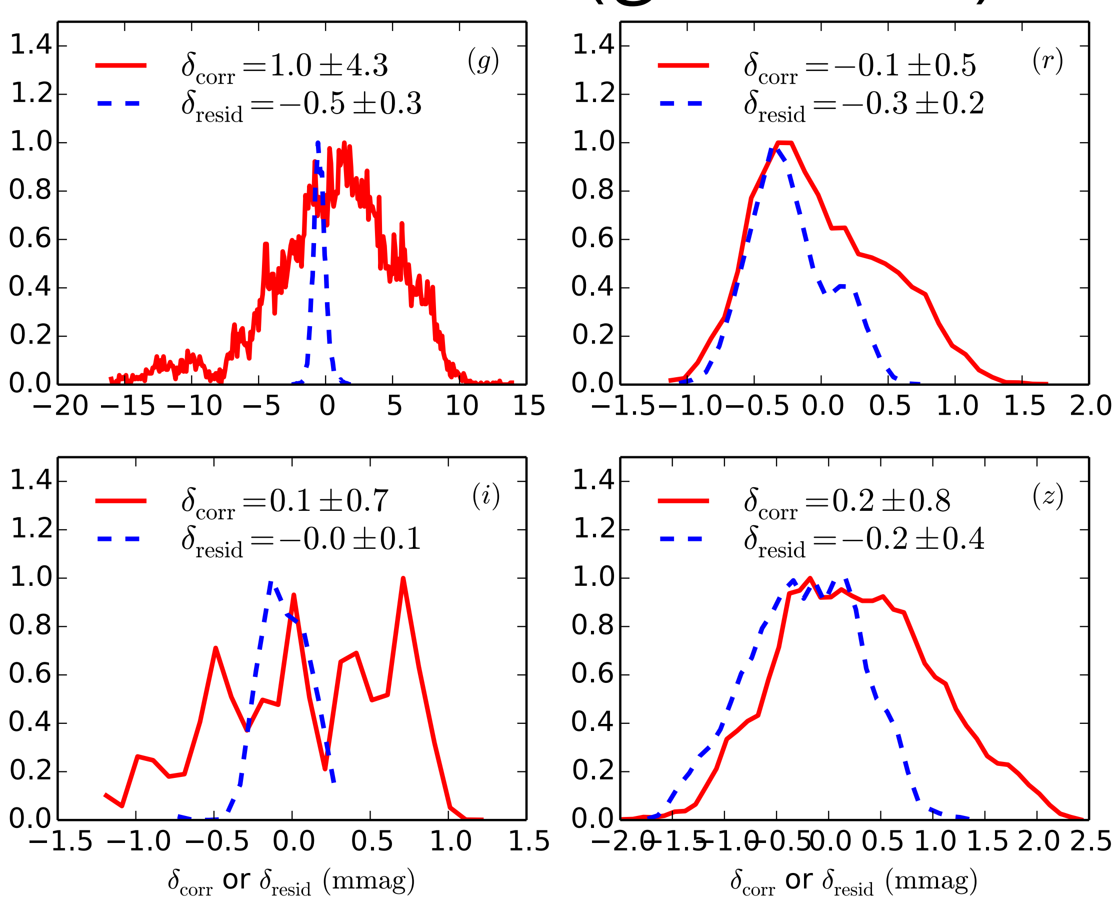
An Implementation Detail…

- All fits are performed with a linearized first-order approximation
  - Atmosphere + instrument transmissions are precomputed in a look-up-table (via MODTRAN)
  - Can run all of DES Y1-4 in ~24 hours on a 16 core machine with 128Gb of RAM
    - Often shorter than the database query+download…
- In the end, transmissions are computed for each exposure
  - Can be integrated with SN, galaxy, star SED
  - Linearized correction only really works with stars

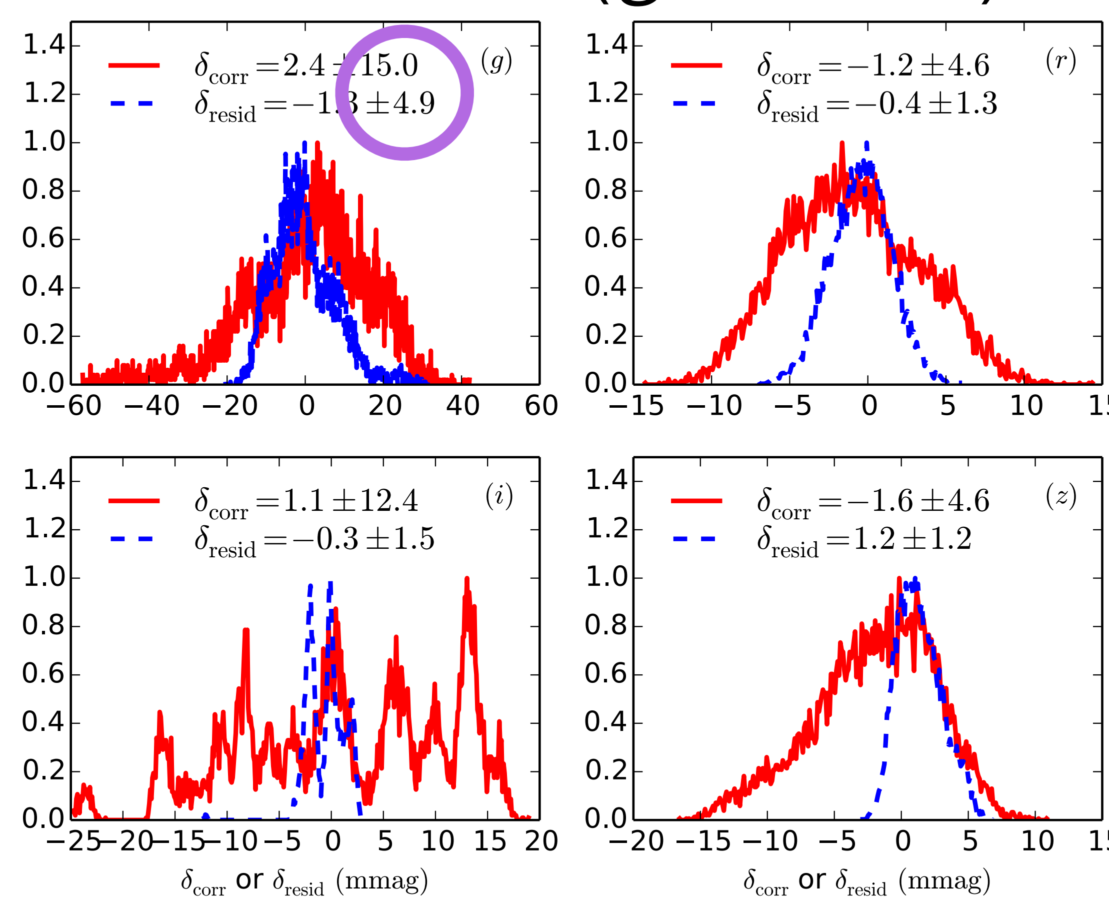
Chromatic Corrections

- Including instrumental and atmosphere effects, red histograms show the chromatic correction per exposure for stellar SEDs

Blue Stars (g-i ~ 0.5)



Red Stars (g-i ~ 3.0)



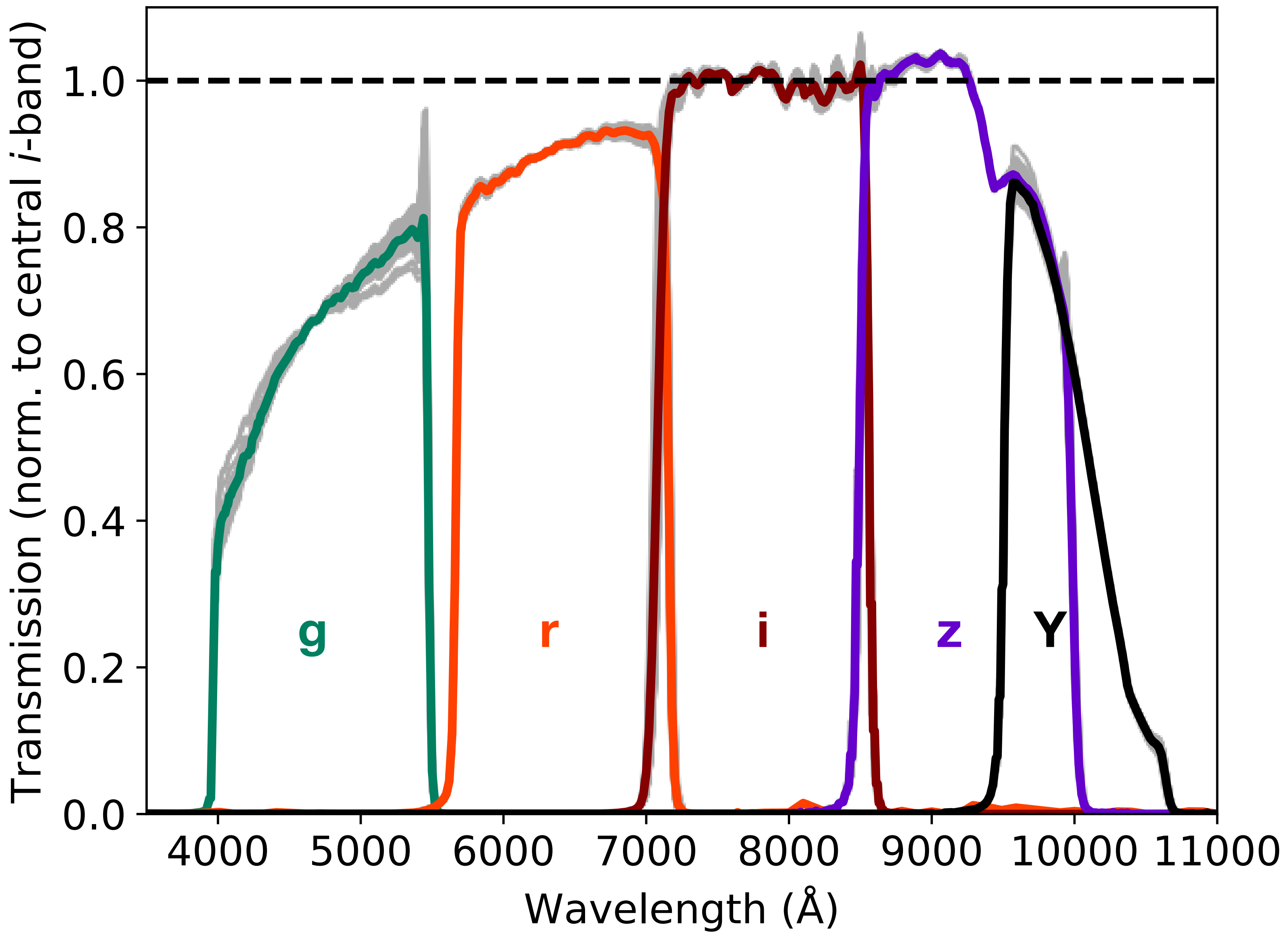
Instrumental Passband

- Instrumental effects (filter variations, anti-reflective coating differences, CCD QE differences) are as big or bigger than atmospheric effects

- Require (at least) CCD-by-CCD scans
  - For DES from the “DECal” system
  - For LSST from the CBP

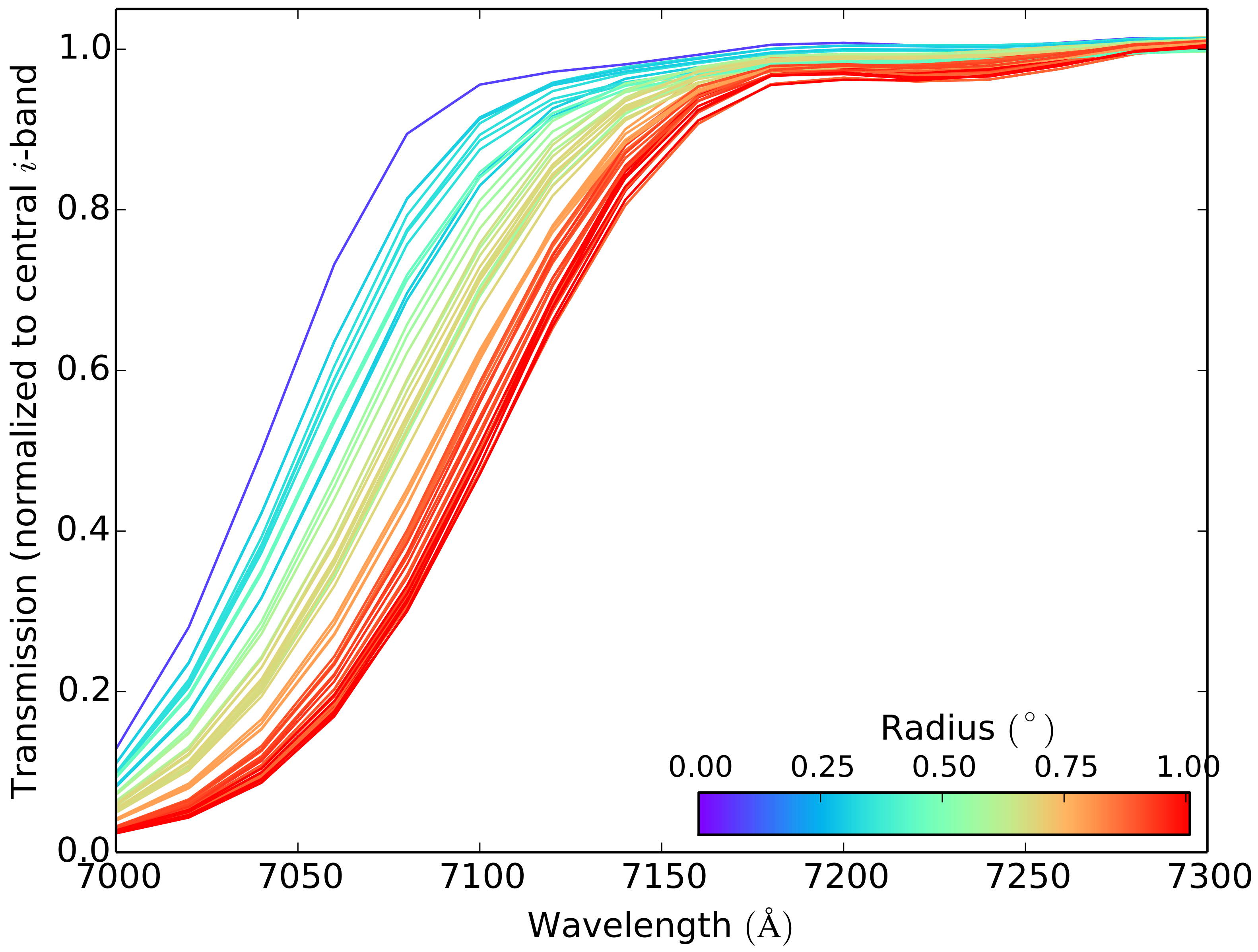
Filters+CCDs

- From the DECal monochromatic scans
  - g band especially variable from chip to chip



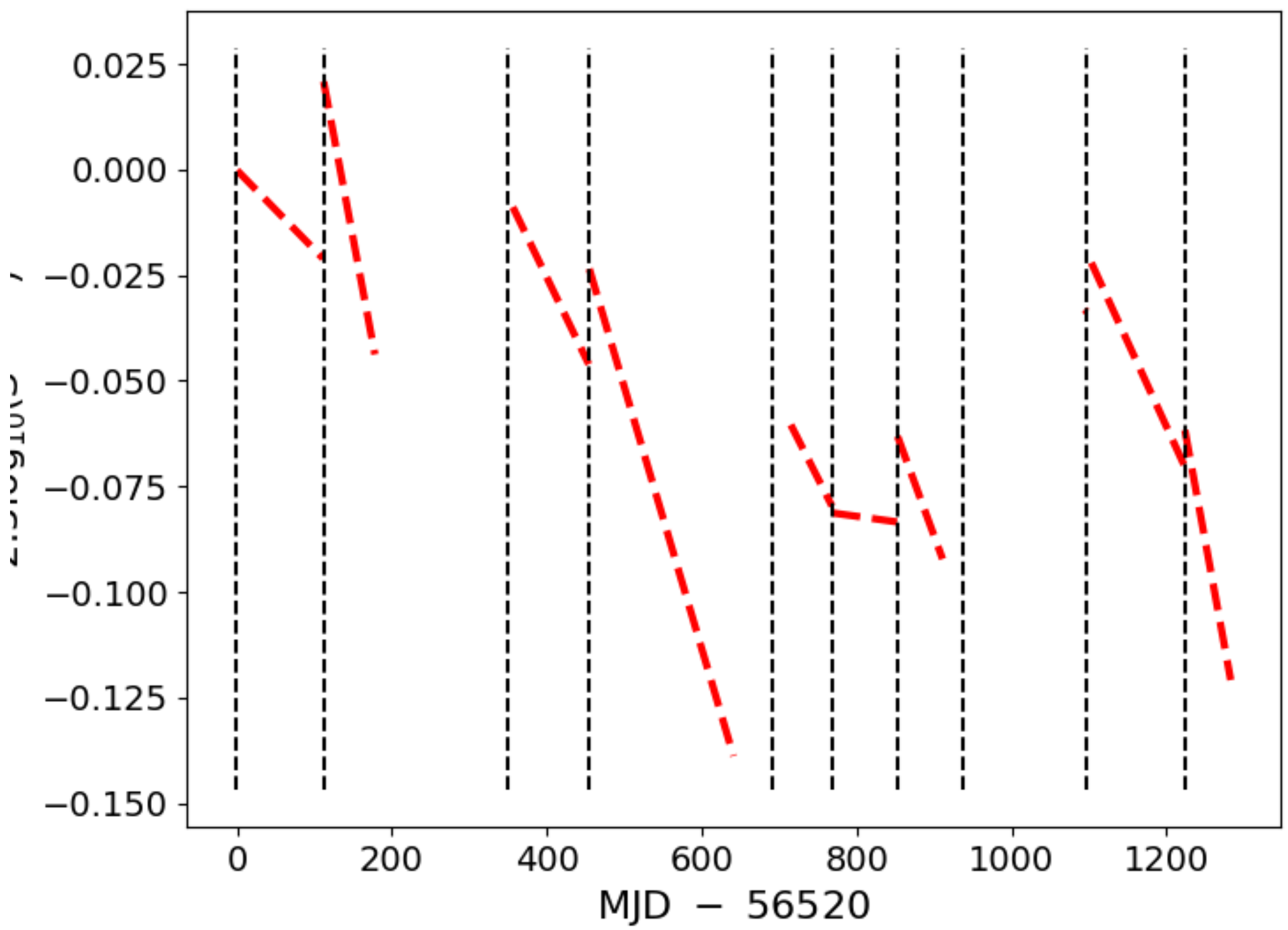
i band Radial Variation

- DECam *i* band filter has blue edge that varies with radius



Mirror + Corrector Dust

- Dust accumulates on mirror and corrector
  - Mirror washing a few times a year
  - Mirror to be re-aluminized summer 2018



The Fit

- Given atmospheric parameters and CCD response, correct each observation of each object from $m^{obs} \rightarrow m^{std}$
- Compute average magnitudes of each object

$$\overline{m_b^{\rm std}(j)} = \frac{\sum_i m_b^{\rm std}(i,j)\sigma^{\rm phot}(i,j)^{-2}}{\sum_i \sigma^{\rm phot}(i,j)^{-2}}$$

- Compute global χ^2

$$\chi^2 = \sum_{(i,j)} \frac{\left(m_b^{\rm std}(i,j) - \overline{m_b^{\rm std}(j)}\right)^2}{\sigma^{\rm phot}(i,j)^2}$$

- Recent update to code which models σ^{phot} as a function of FWHM, sky brightness, and $\langle m^{std} \rangle$

A Note on the Fit

- In our forward model formulation, we are not solving a system of linear equations
    - Use a non-linear solver (scipy.optimize.fmin_bfgs_b)
- Requires computation of $d\chi^2/dp$ for each parameter p
- Solving for these parameters (~6 times the number of nights) is efficient
    - Note that we have poor constraints on unimportant parameters on certain nights (e.g. nights with only g, r band we can't fit PWV well … nor do we need to)

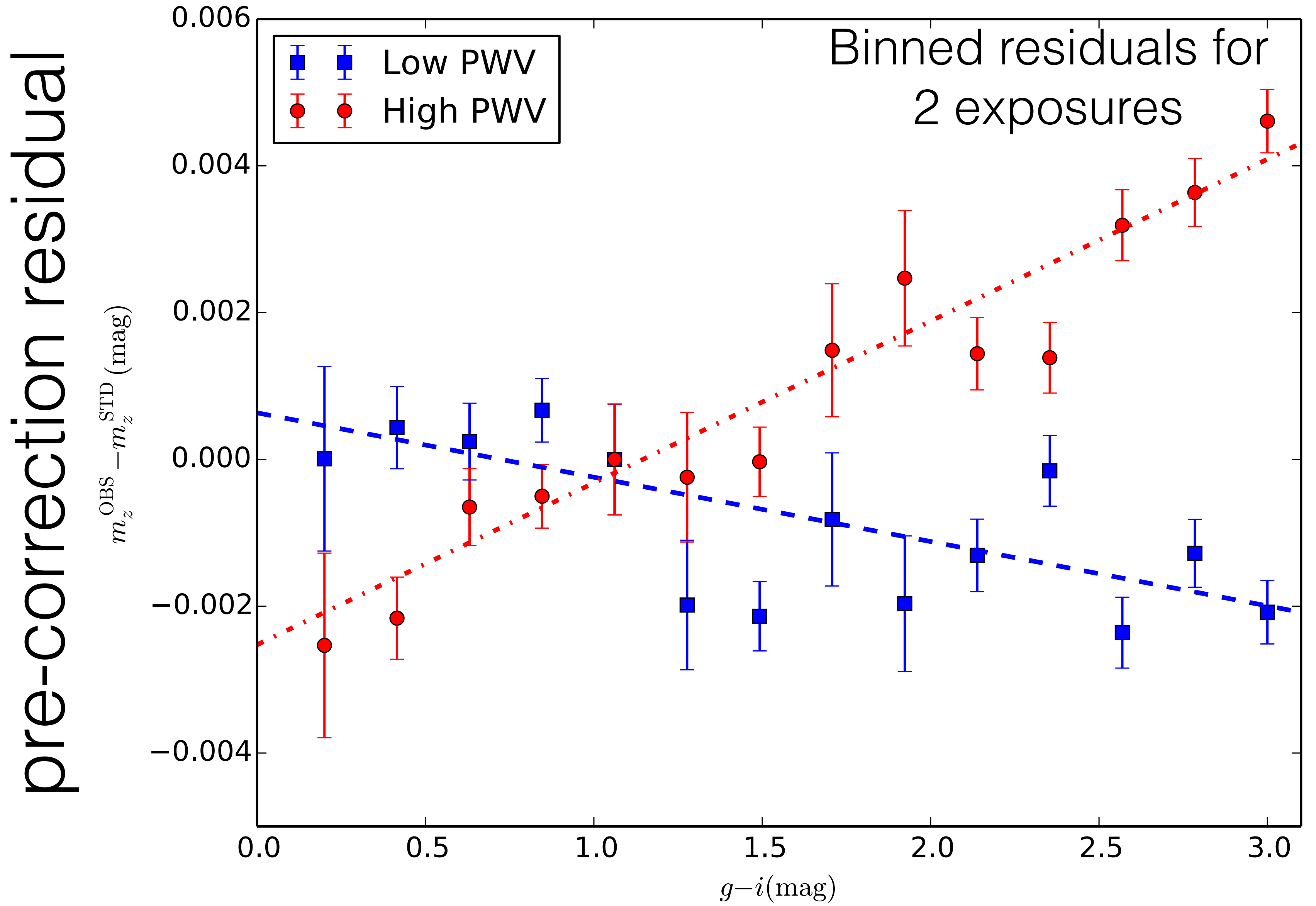
Chromatic Shifts

- To first order, the fit is sensitive to atmospheric extinction (I_0) to different components of atmosphere

- The fit is *also* sensitive to different color objects, and the response to different atmospheric components
  - PWV for DECam *z* and *Y* bands
  - Aerosols in *g* and *r* bands
  - Instrumental effects in all bands

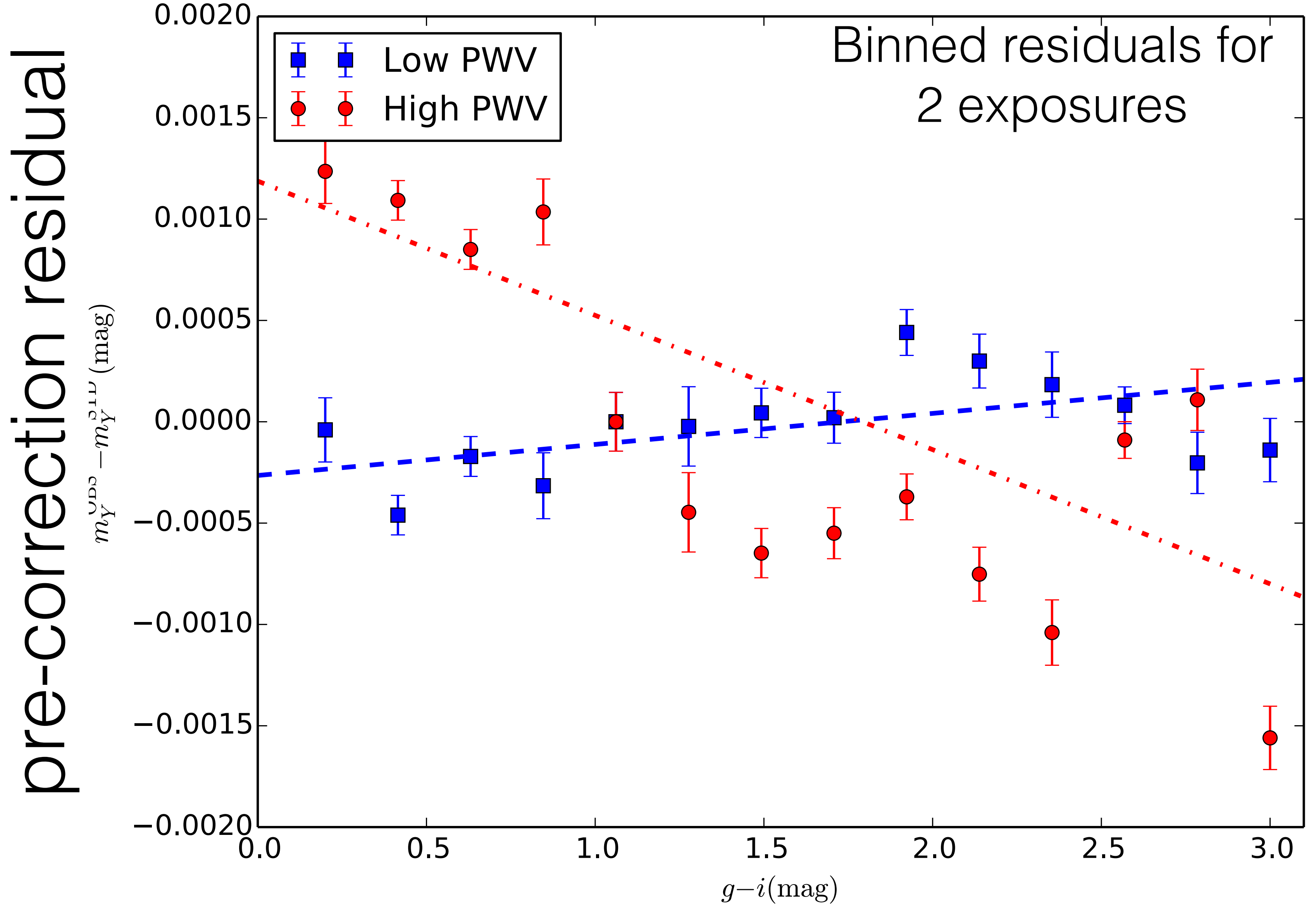
Water Vapor and *z*-band

- High PWV cuts the red end of the *z* band, so red and blue stars are shifted differently



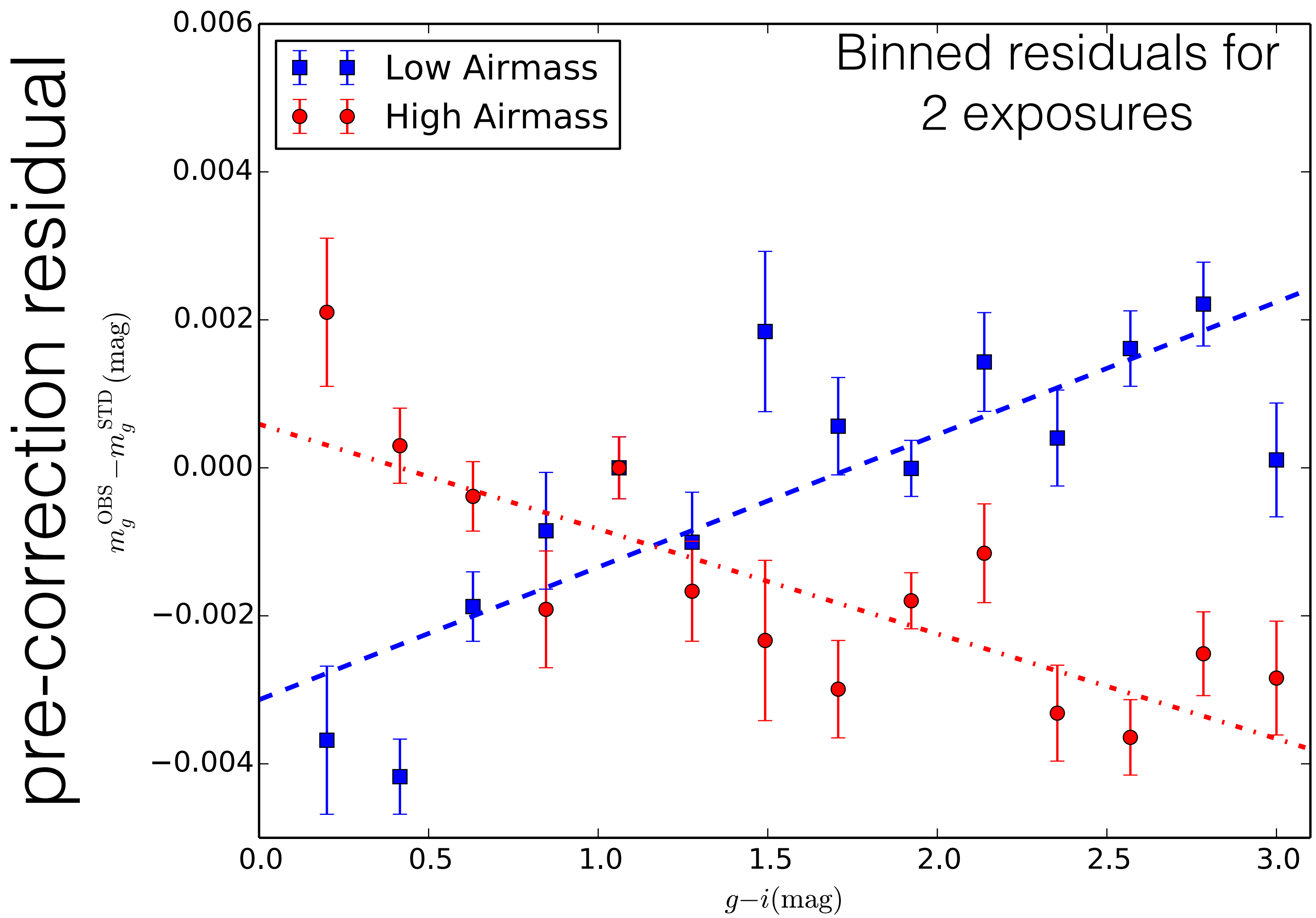
Water Vapor and *Y*-band

- High PWV cuts the blue end of the *Y* band, so red and blue stars shift the opposite way from *z*



Airmass and *g*-band

- High and low airmass have different Rayleigh terms, and different chromatic response in *g*



Photometric Selection

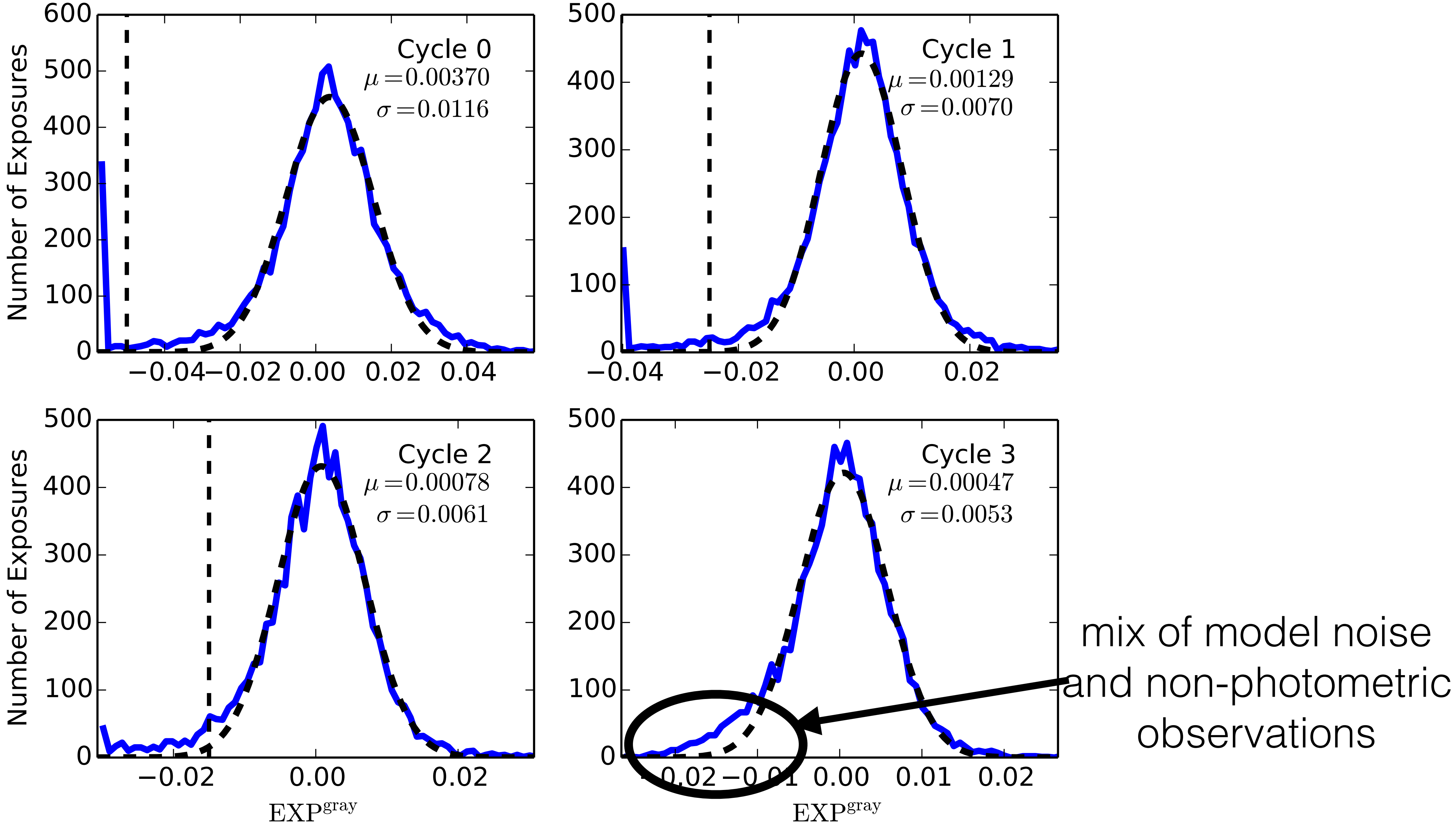
- As with any global calibration routine, a challenge is to select “photometric” observations

- Anything that is consistent with model is photometric
  - Fainter than model is non-photometric
  - Forward model approach constrains to physical solutions

- Fit model, reject non-photometric exposures, and refit

Photometric Selection

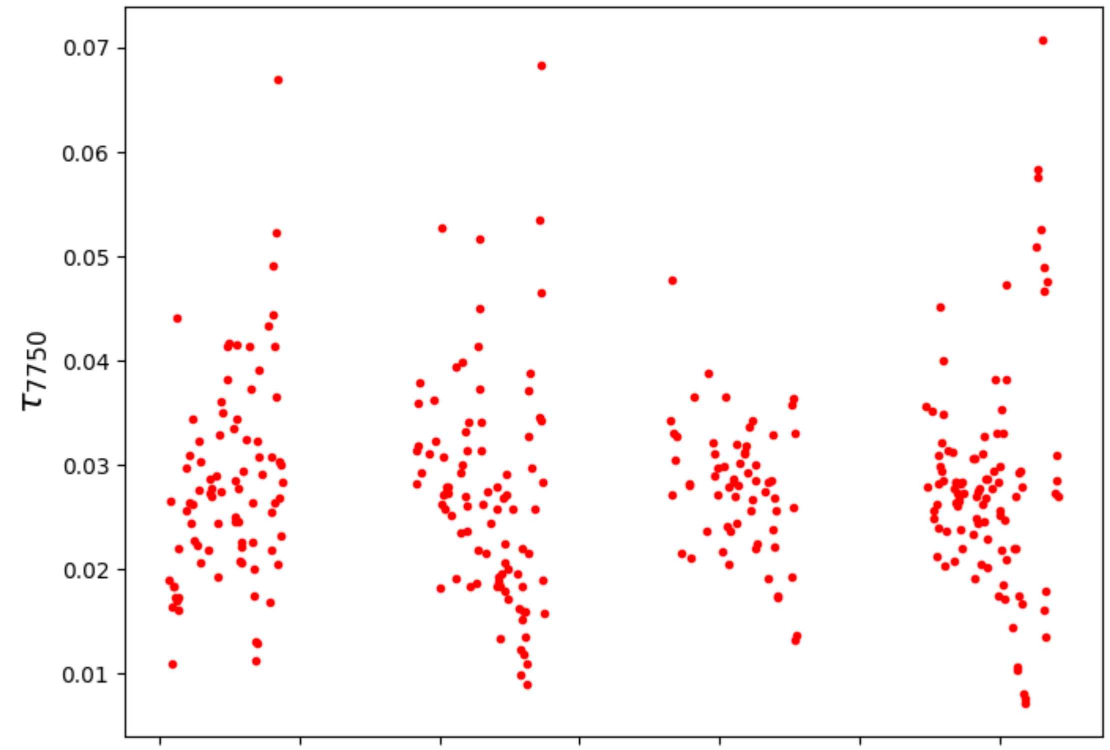
- Make cut progressively tighter at each fit “cycle”

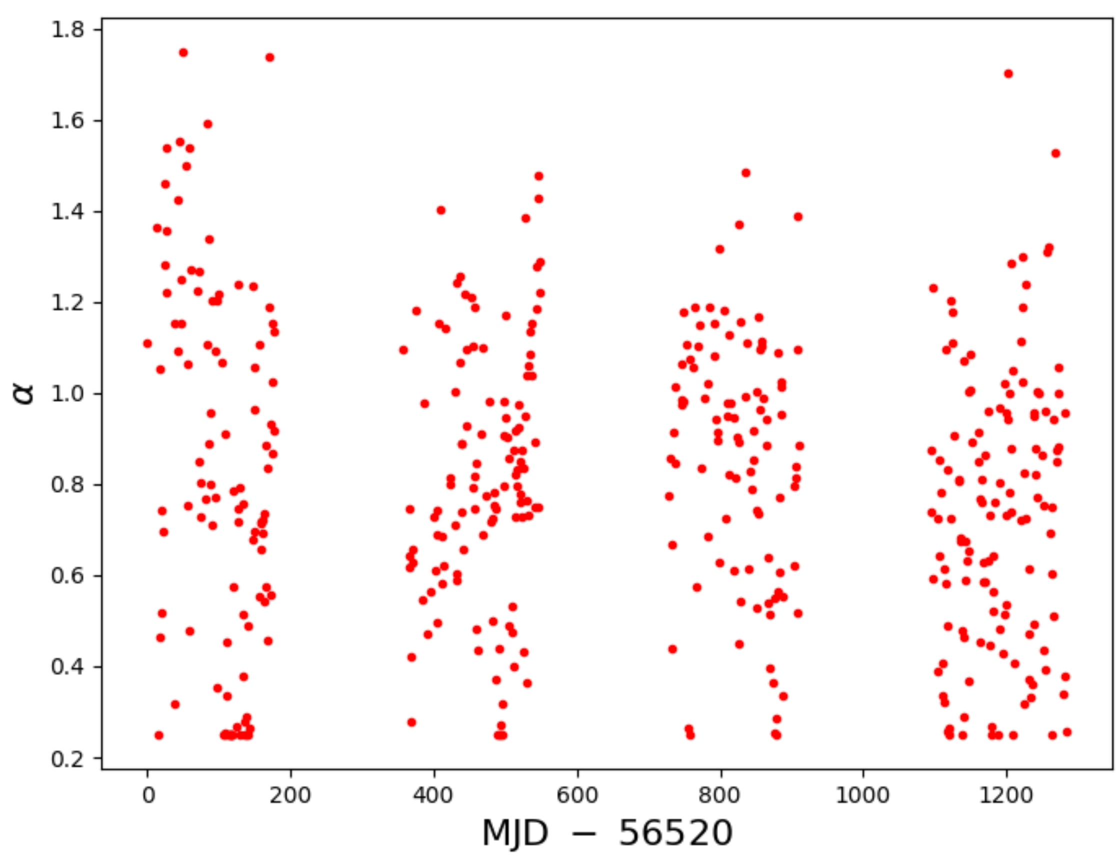


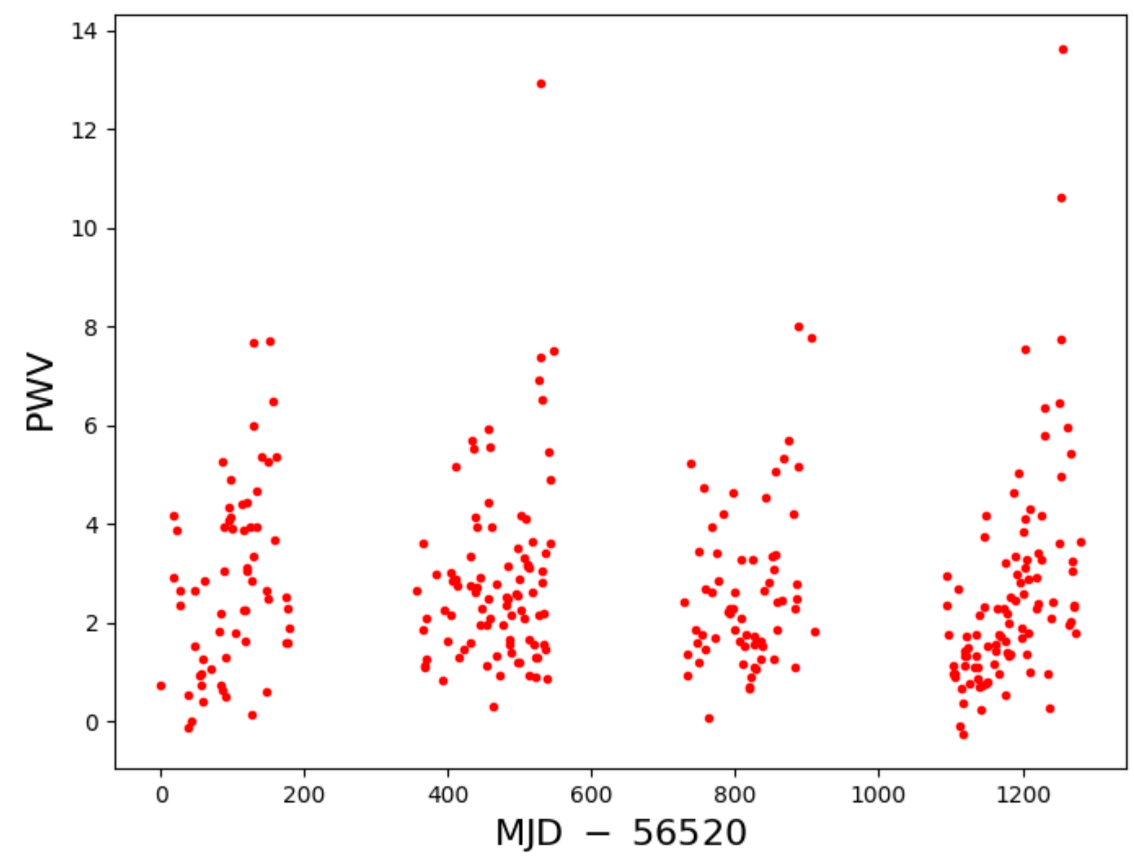
exposure avg. “gray” residual in i band

Atmosphere Fits

- Model parameters show seasonality
- Alpha is noisy

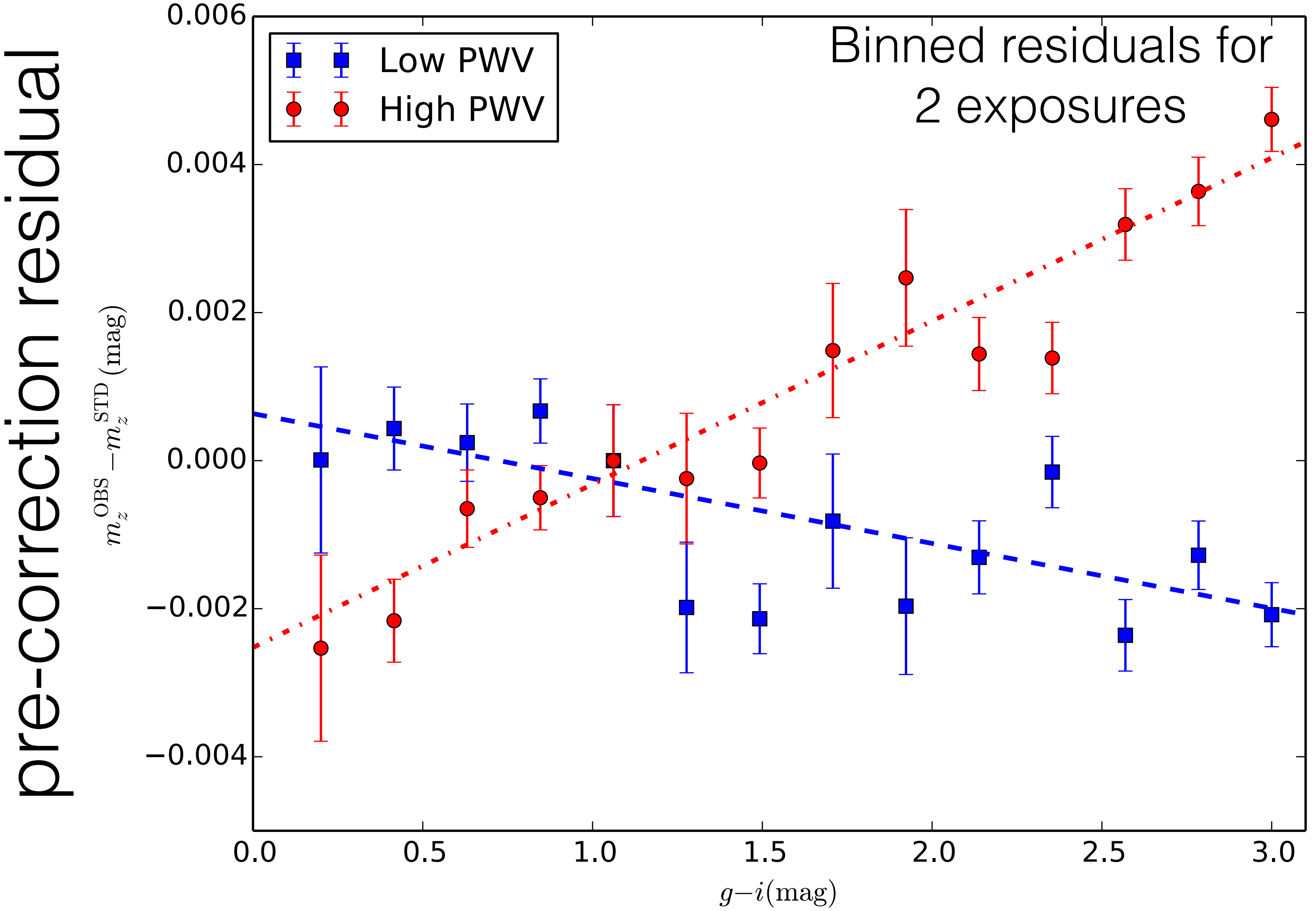






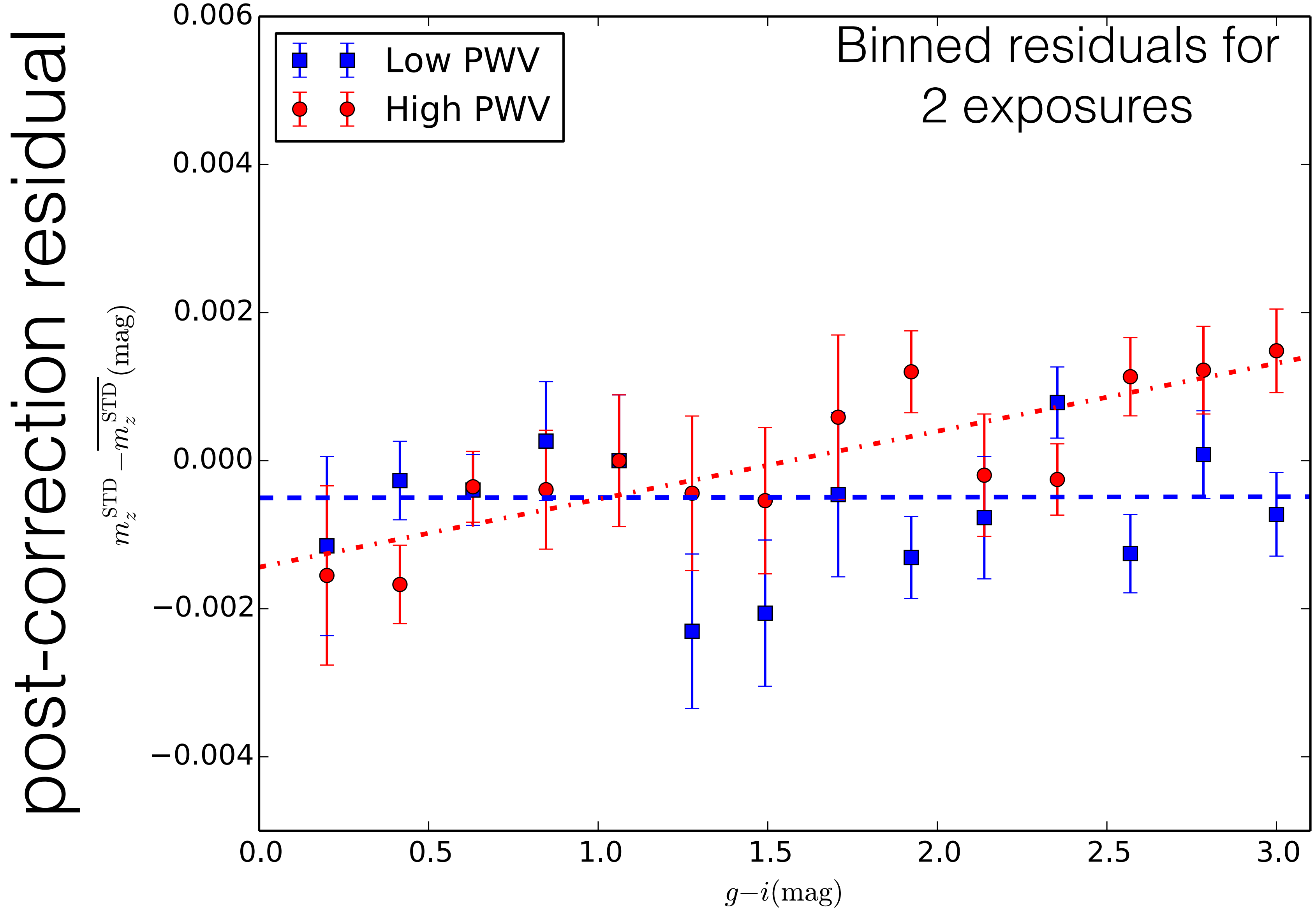
Water Vapor and *z*-band

- Before correction…



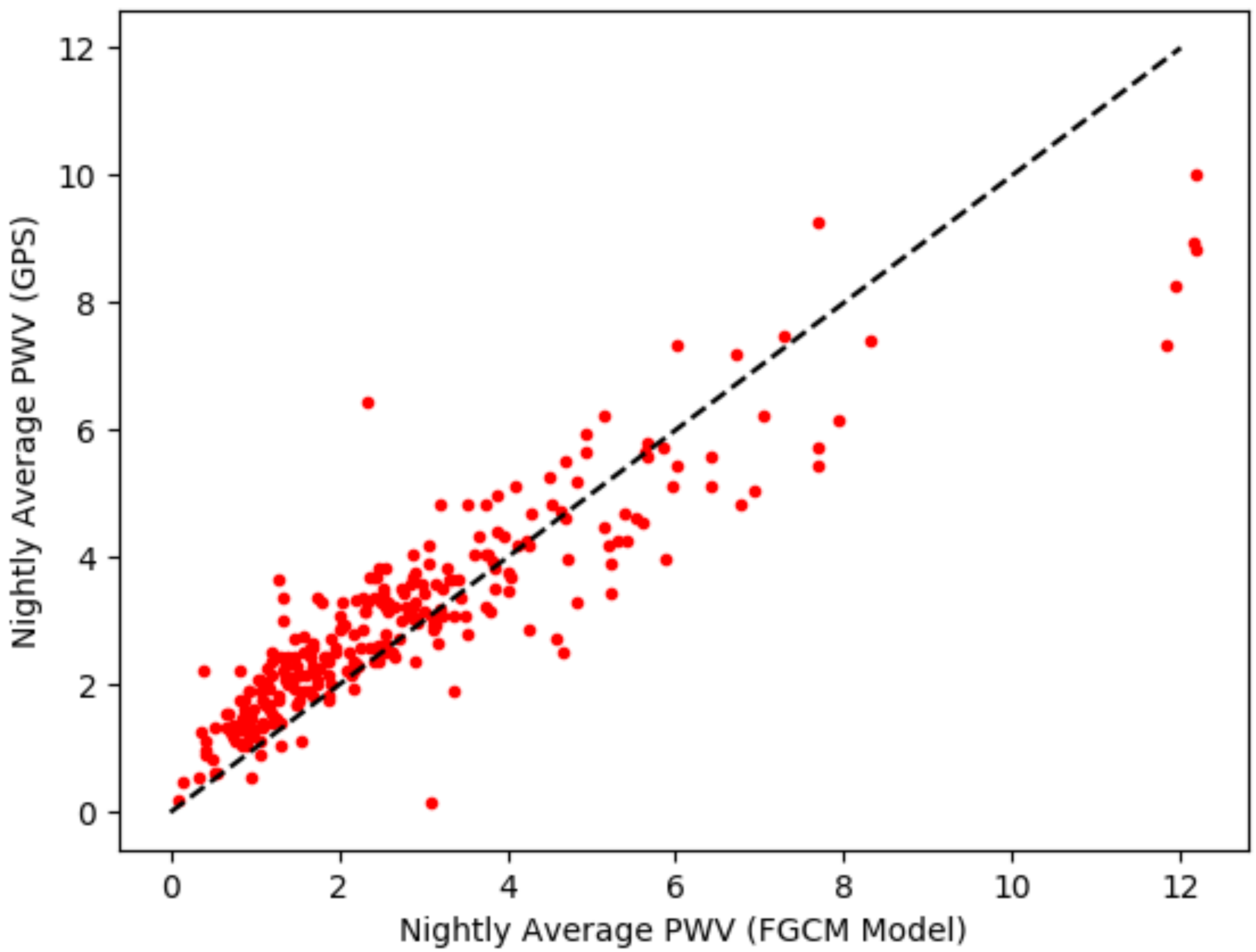
Water Vapor and *z*-band

- After correction…

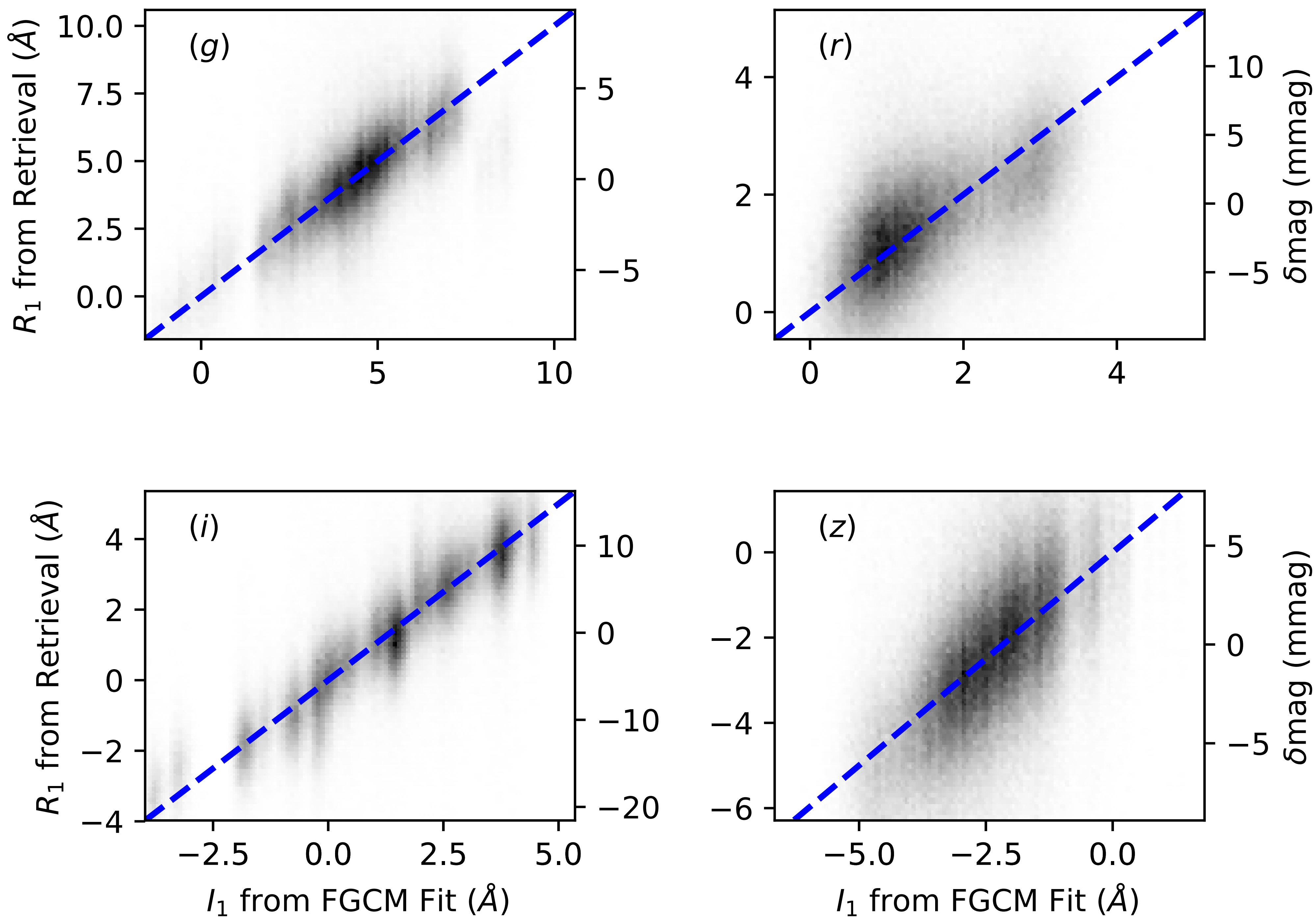


Water Vapor Checks

- We can test the current performance of the FGCM model with GPS water vapor data



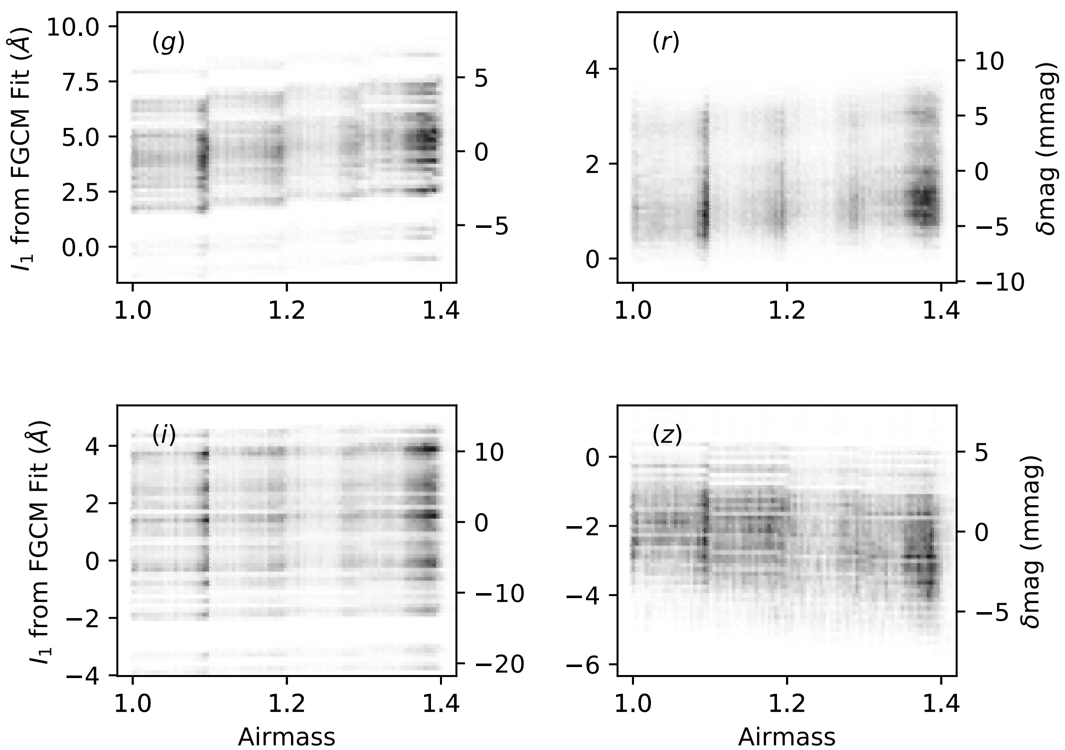
Global and Exposure Fits



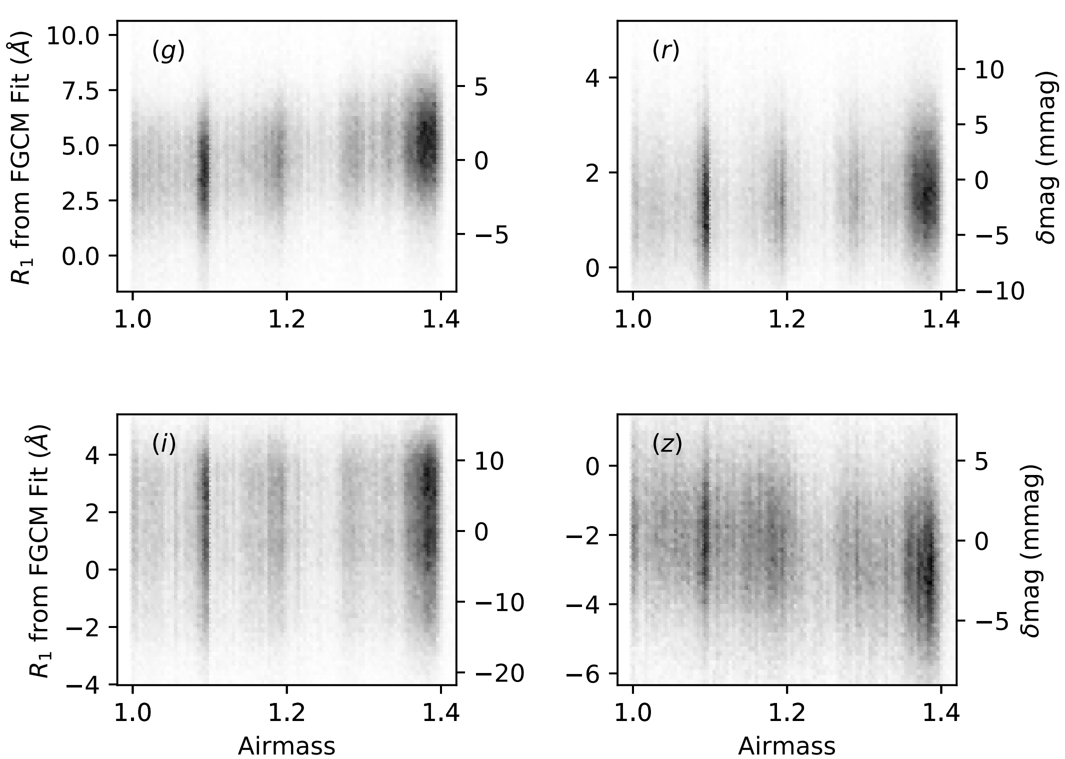
R1 is estimated from each exposure/ccd

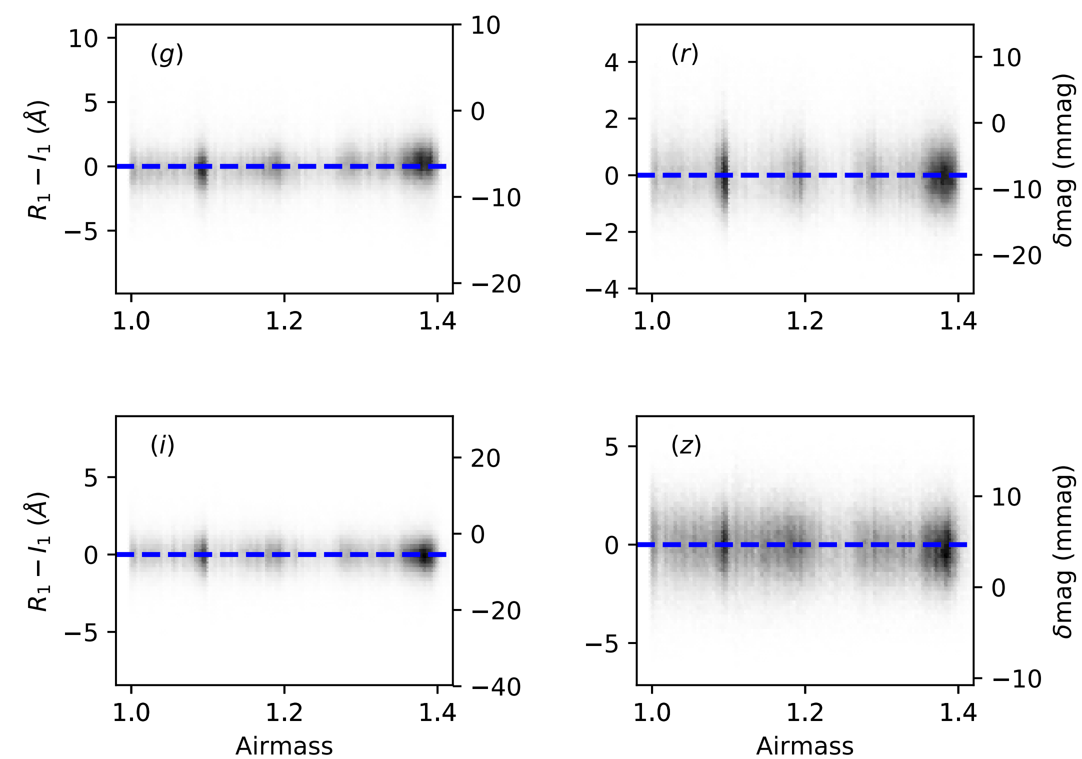
I1 is the linearized chromatic correction from fit

Airmass/Color Terms

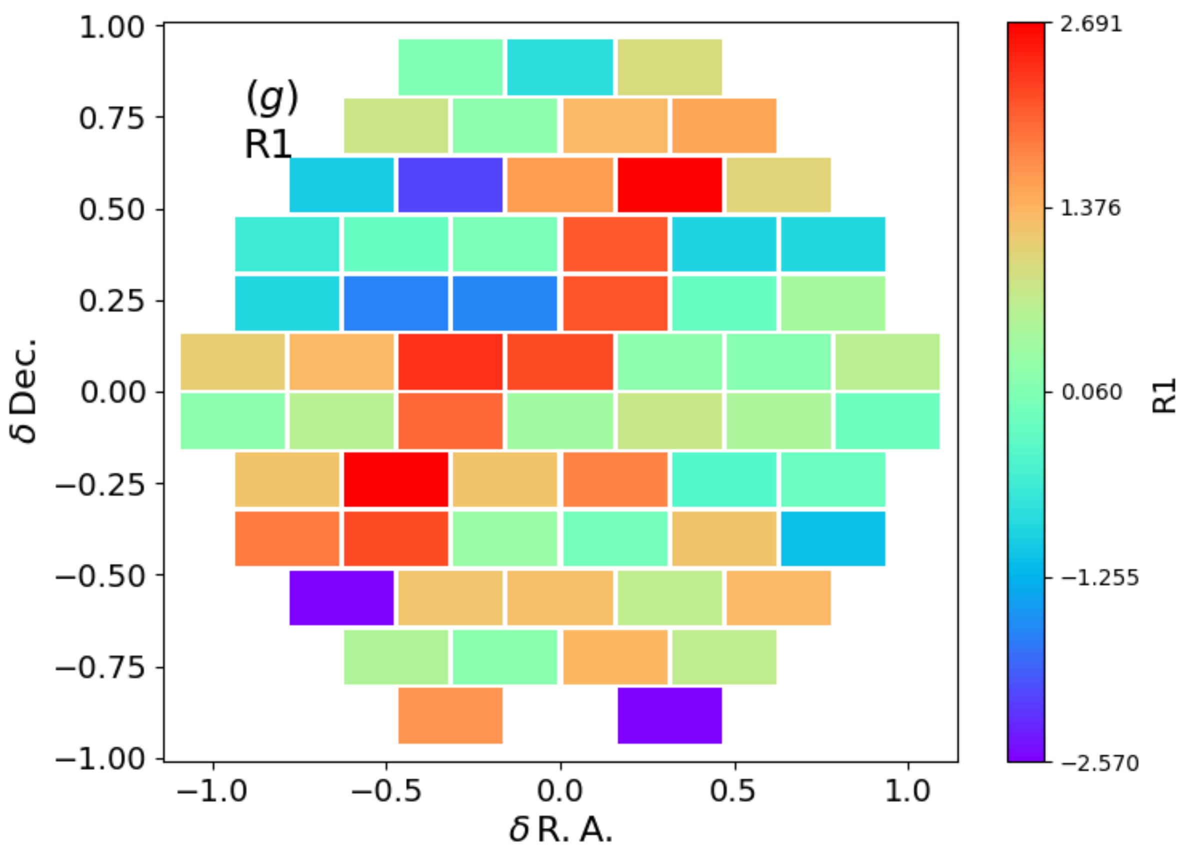


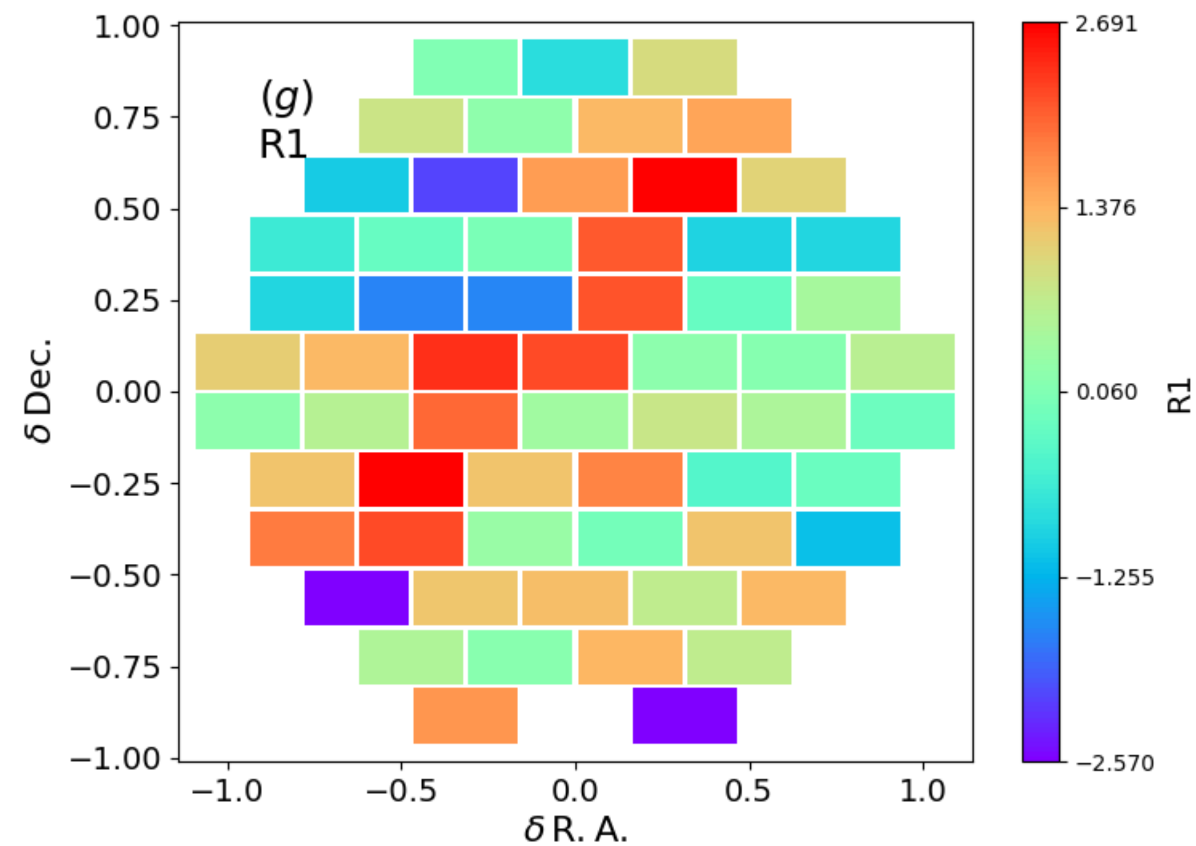
- FGCM predicts the color term as a function of airmass
  - It is not large!
  - But we do see it

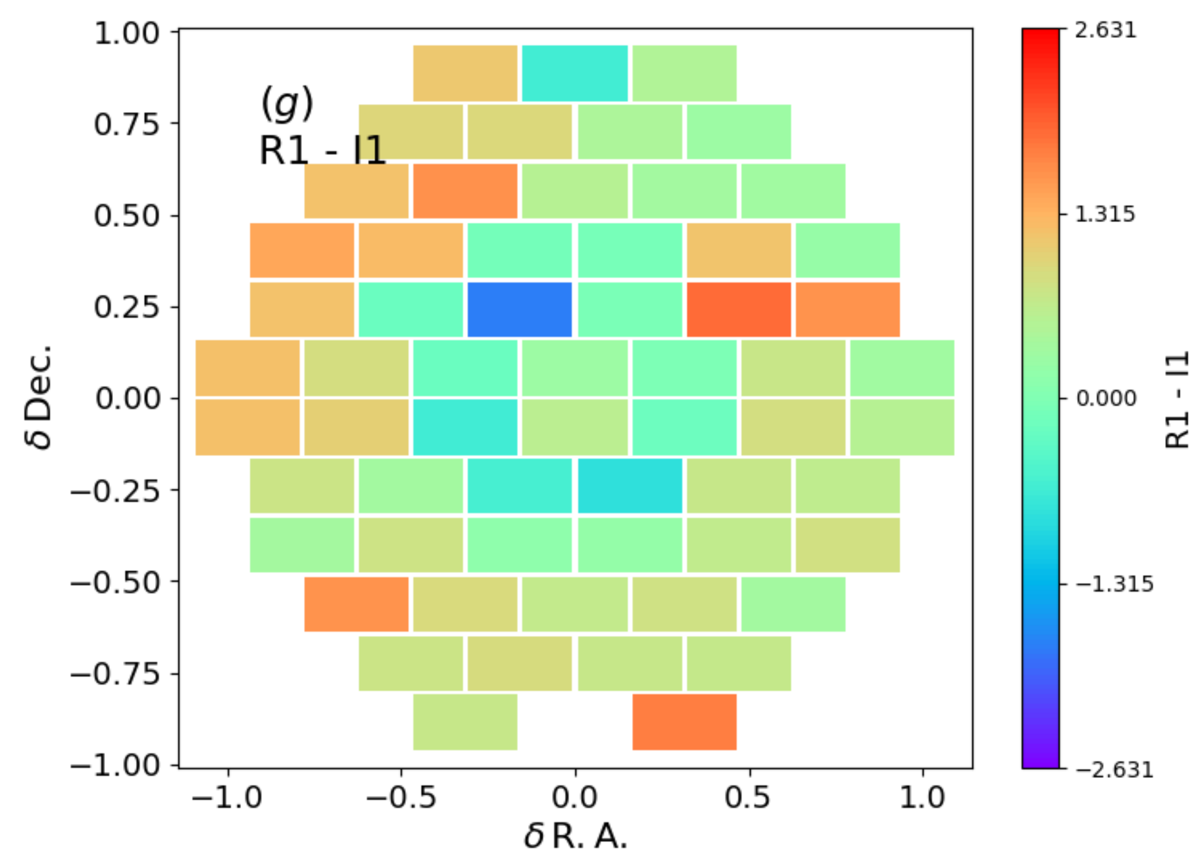




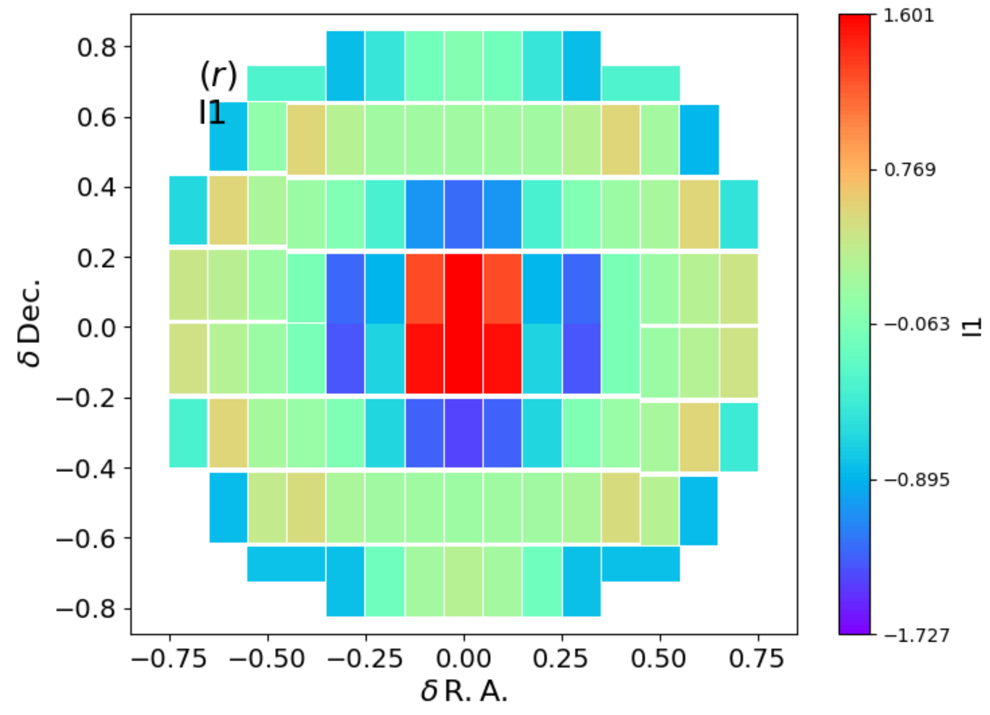
Checking for Throughput Errors

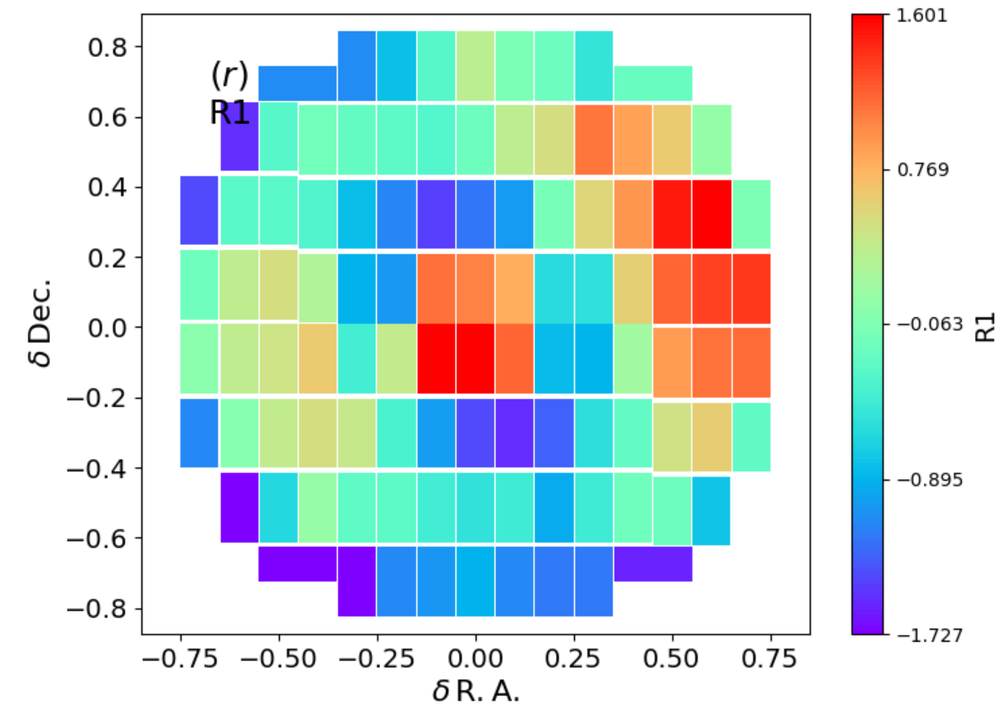




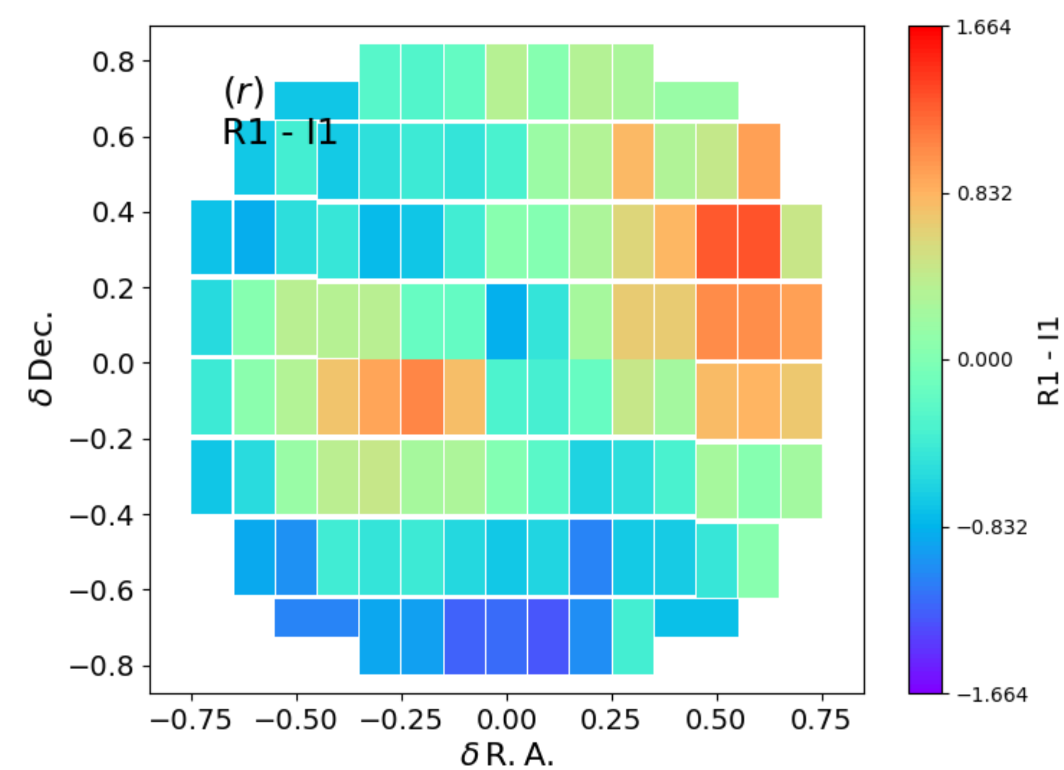


Checking for Throughput Errors (HSC)



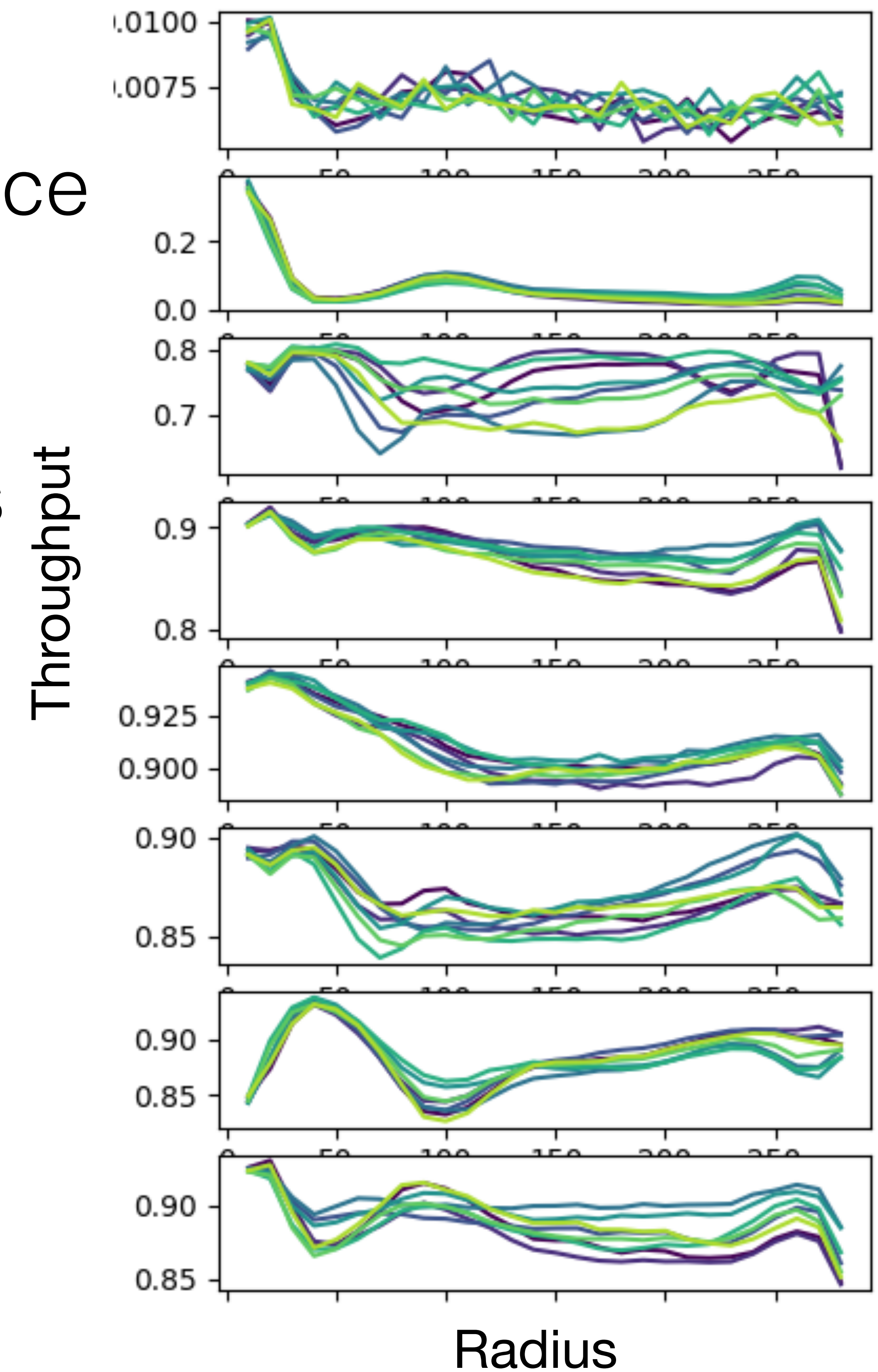


- HSC r-band: azimuthal dependence?

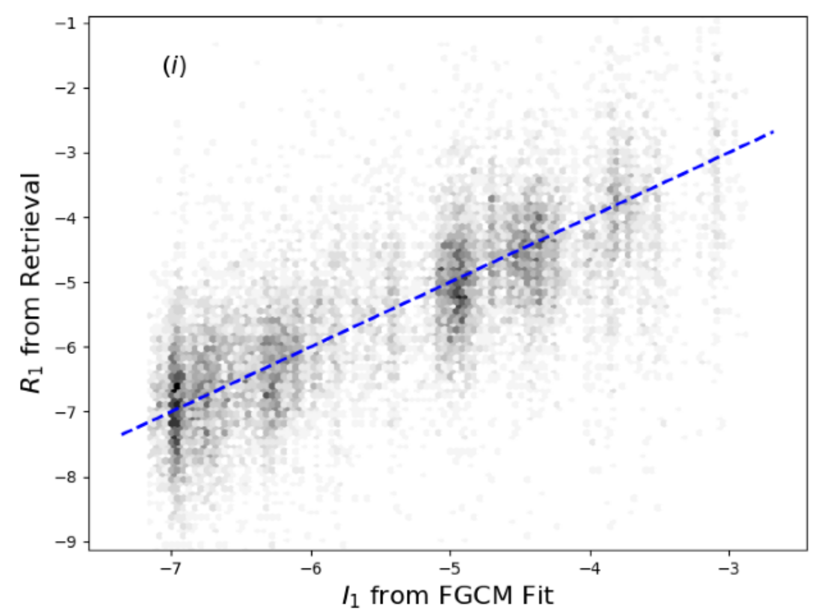


Checking for Throughput Errors (HSC)

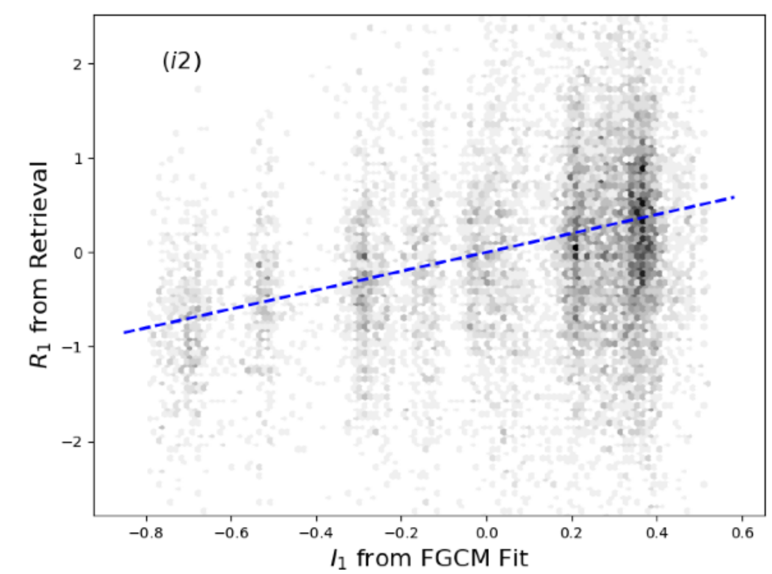
- Throughput in HSC r-band shows azimuthal dependence (especially at filter edges)
- Currently, the transmission curve in DM stack assumes azimuthal symmetry



HSC i and i2 bands

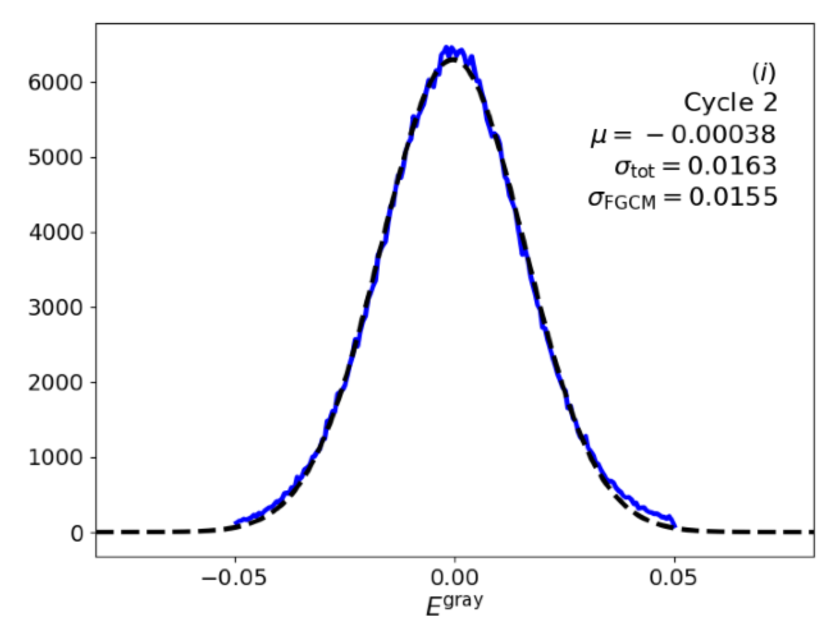


Chromatic Term from Model



Chromatic Term from Model

- Natively cross-calibrate i and i2 bands
- No noticeable difference in statistics

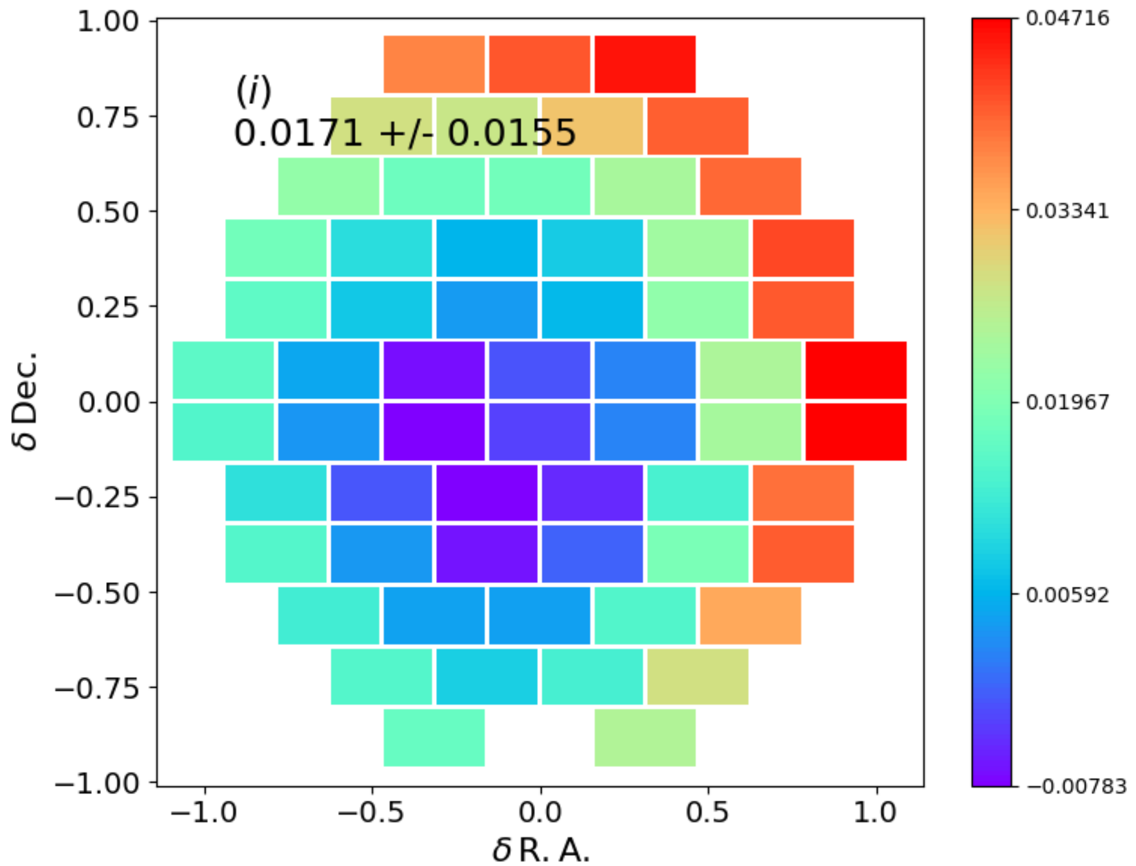


Additional Model Parts

- Superstar Flats
- Aperture Corrections
- Temporal correlations
  - Not actually part of the model, but interesting

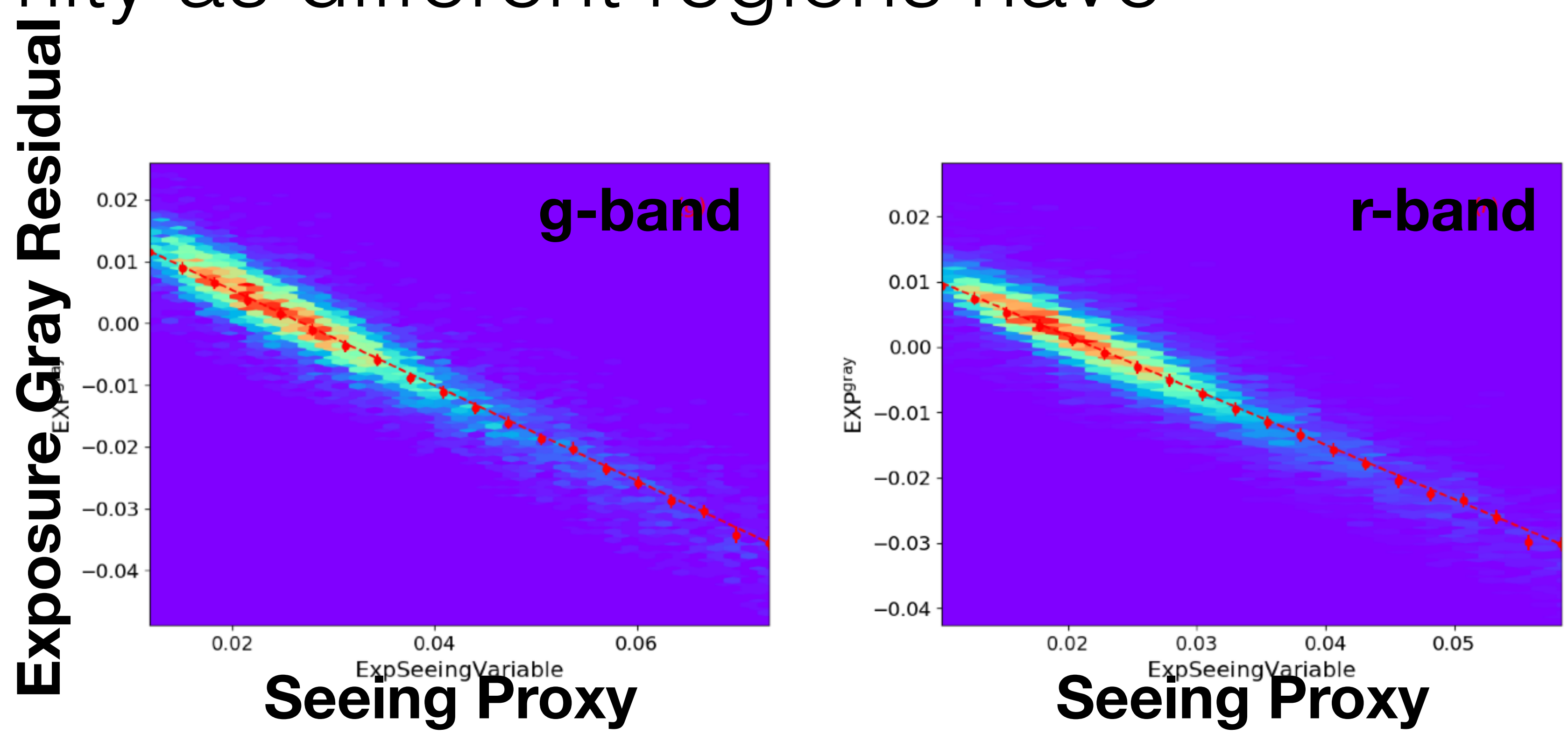
SuperStar Flats

- DES has a starflat calculation (Bernstein++)
  - Computed in dense, dithered star fields
  - Overall linear term ambiguity, and no chromatic terms
- In the wide-field survey we have many, many observations
  - Look for common modes. Currently ccd-by-ccd in DES, can fit 2nd order polynomial.



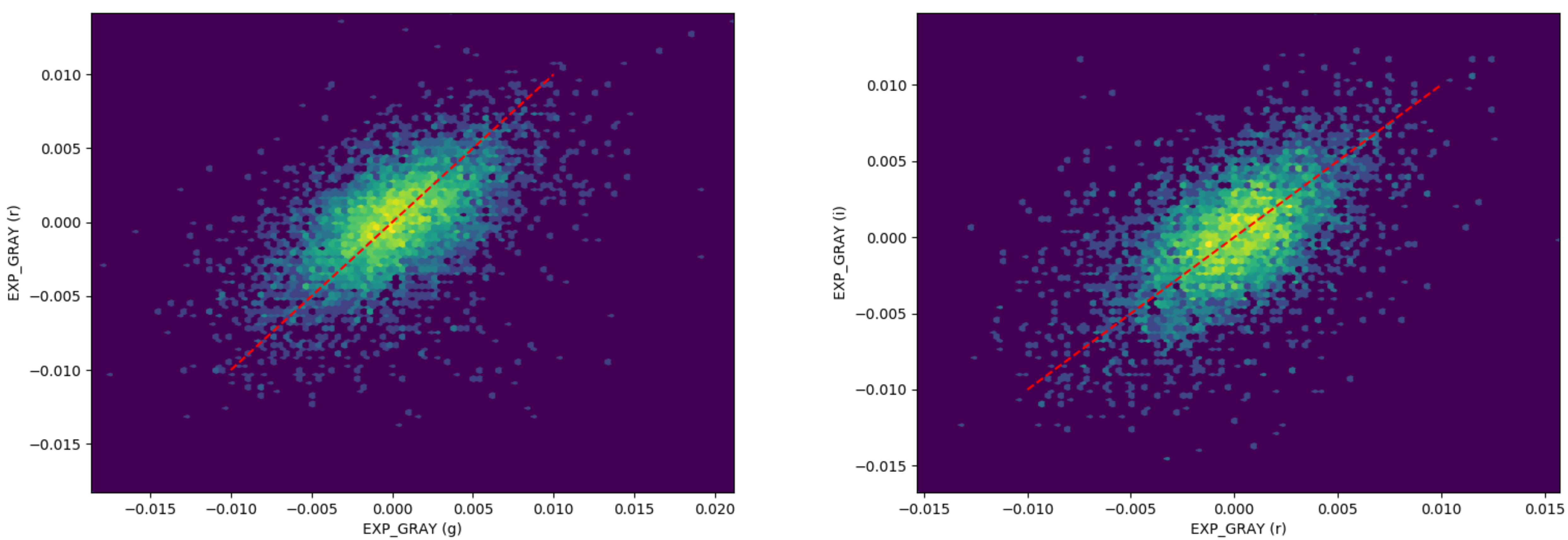
Aperture Corrections

- With a forward model approach, can measure residuals that are not part of instrument/ atmosphere model
- Fit linear model at the end of each fit cycle
    - Converges very rapidly
- Matters to uniformity as different regions have different seeing distribution



Temporal Correlations

- There is an additional gray residual in observations taken within ~10-15 minutes
  - Beyond the model, if one observation is a bit dim the next one is likely to be as well
  - High altitude cirrus?

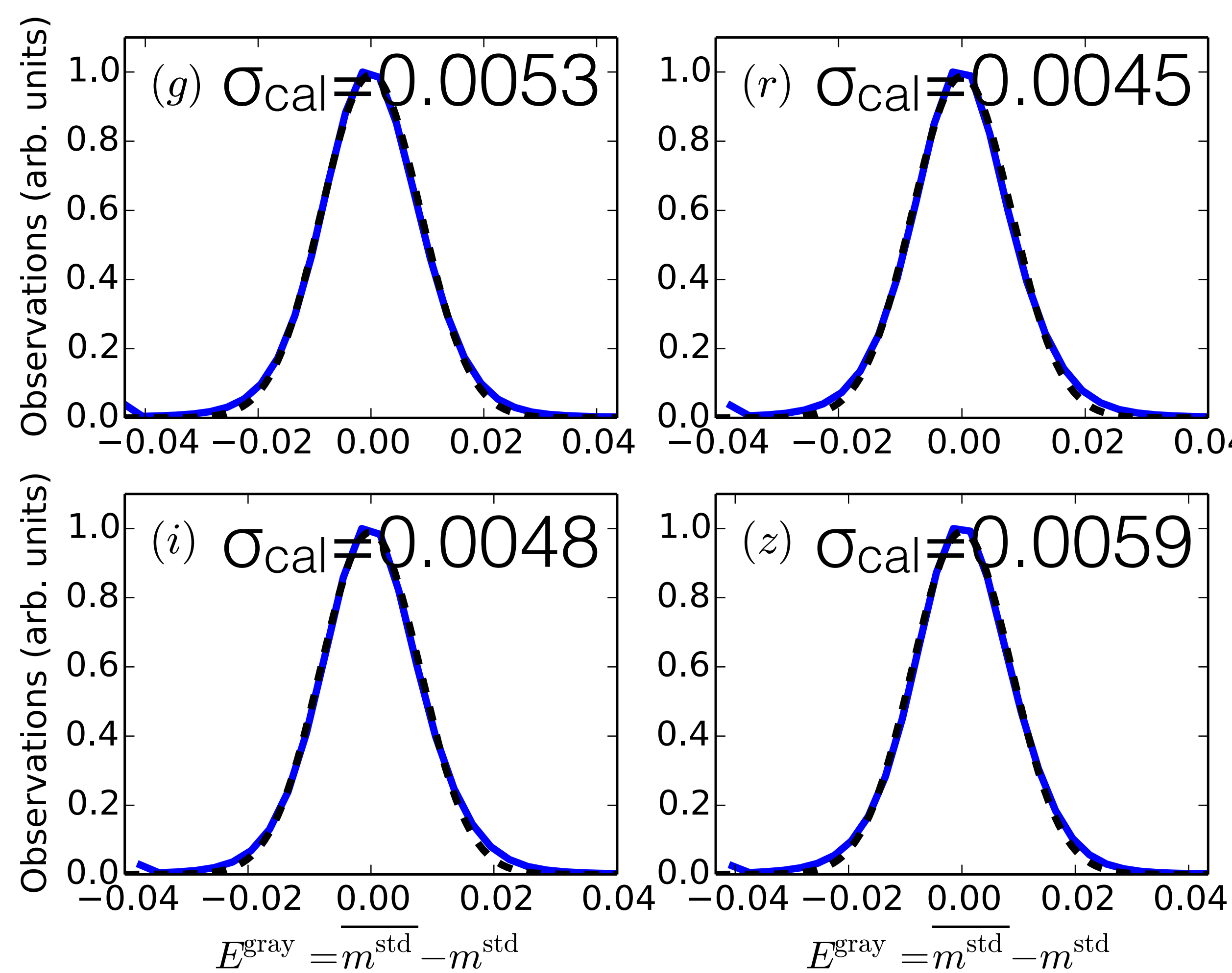


Calibration Errors

- Stability/Repeatability
  - If you return to an object
- Uniformity
  - If you go to another point in the survey footprint
- Chromatic
  - If you move to a different object SED

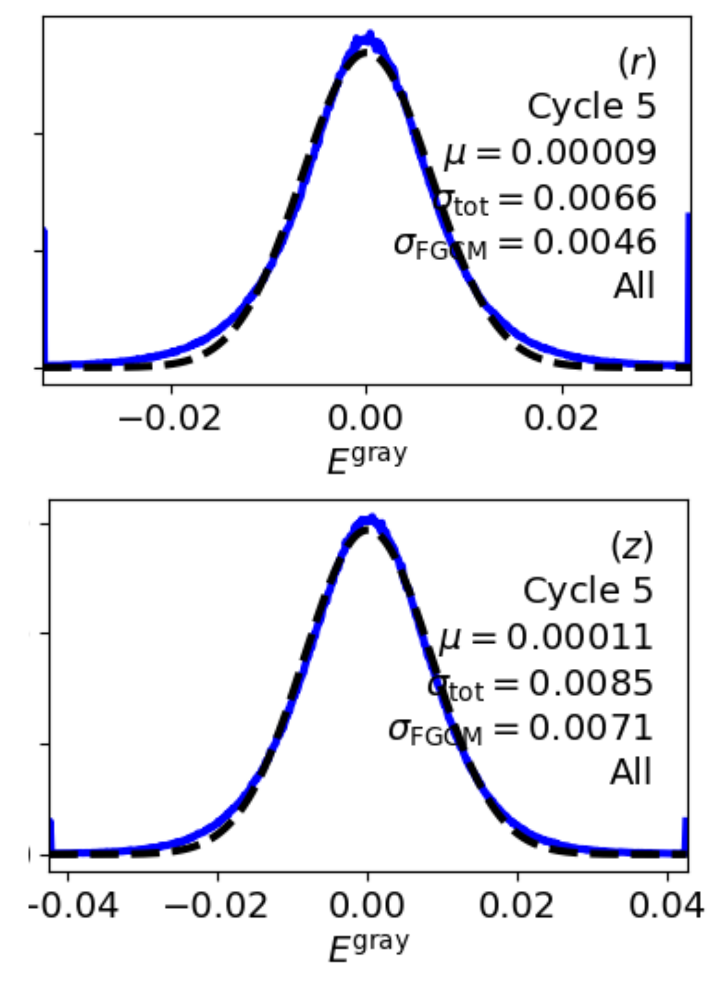
Repeatability (griz)

- For all observations of all objects in the fit, what is the intrinsic RMS?
- ~5-6 mmag
- These are straight model residuals
- Assume: each tiling is independent
- Yields the variance of the parent distribution of the random errors of calibration fit
- $(\delta \text{FGCM})^2 \sim (5\text{-}6\ \text{mmag})^2$



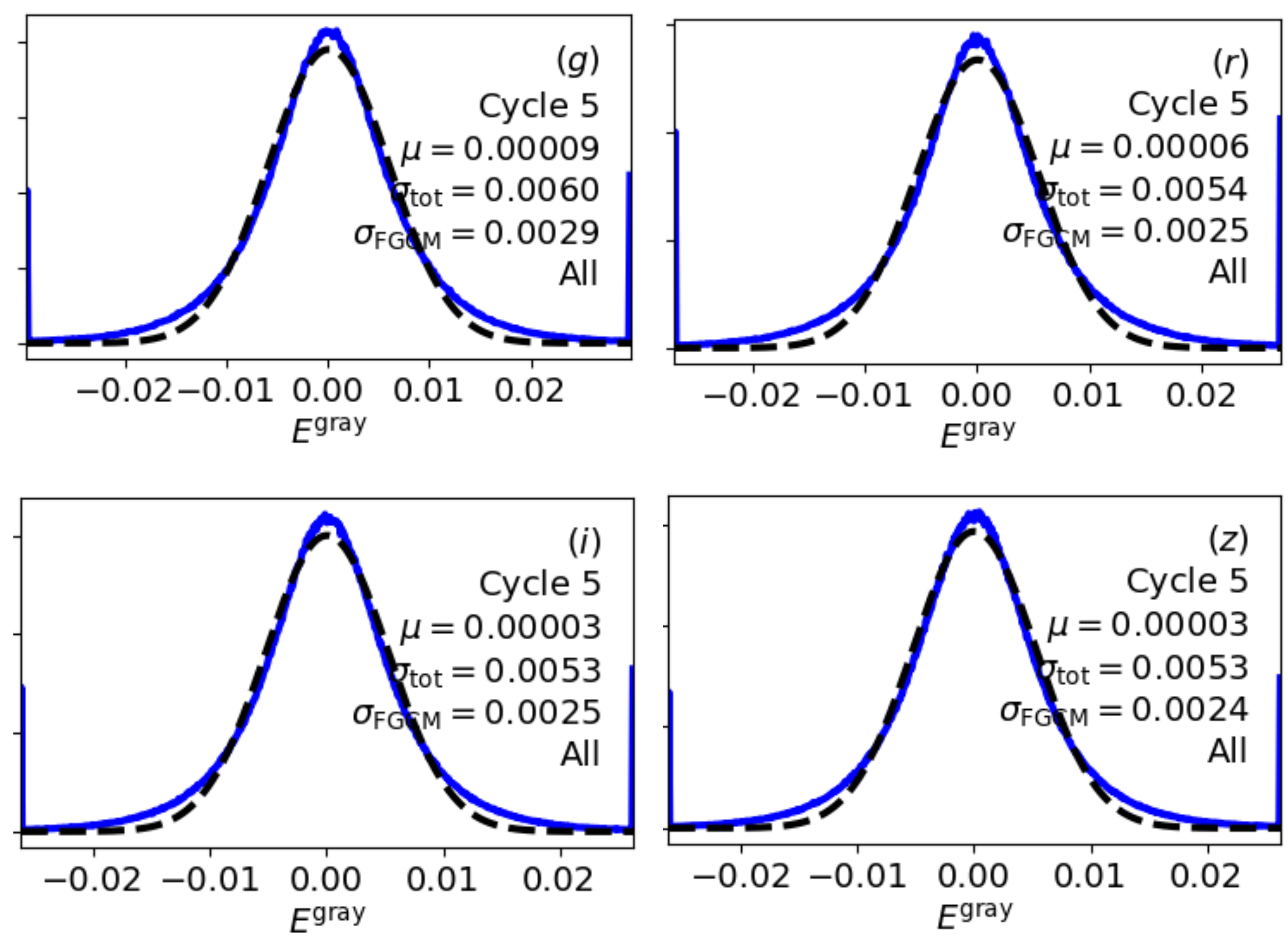
Repeatability (griz)

- For all observations of all objects in the fit, what is the intrinsic RMS?
- ~4-7 mmag
- These are straight model residuals
- Assume: each tiling is independent
- Yields the variance of the parent distribution of the random errors of calibration fit
- $(\delta\text{FGCM})^2 \sim (4\text{-}7\ \text{mmag})^2$



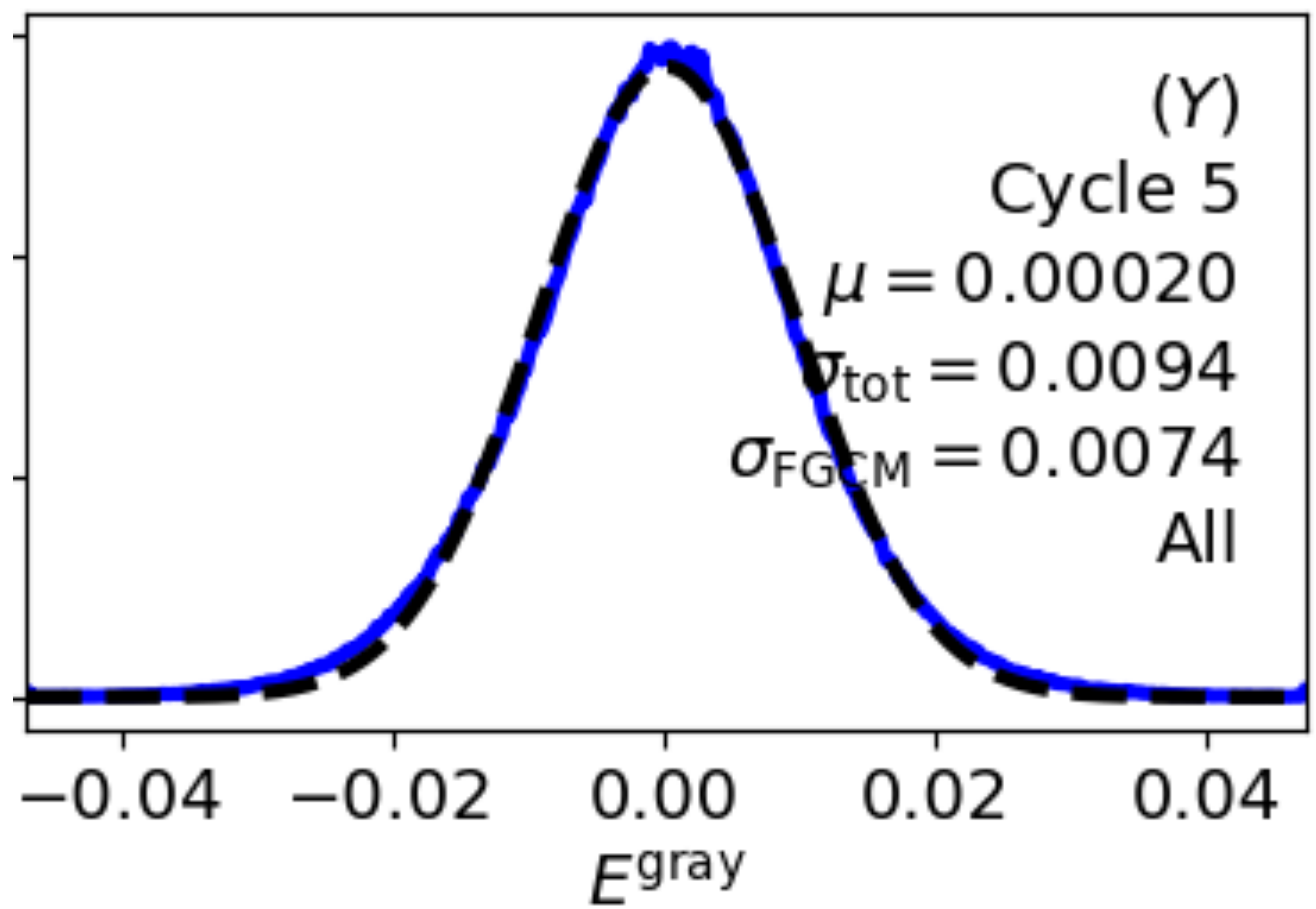
Repeatability (griz)

- The very last step is the “CCD crunch”
  - A single gray ZP correction is applied to each CCD relative to the mean calibrated stars
  - Not part of the model
- Yields local, final repeatability, but not true intrinsic model quality
- $(\delta \mathrm{FGCM}_{crunch})^2 \sim (<3\ \mathrm{mmag})^2$



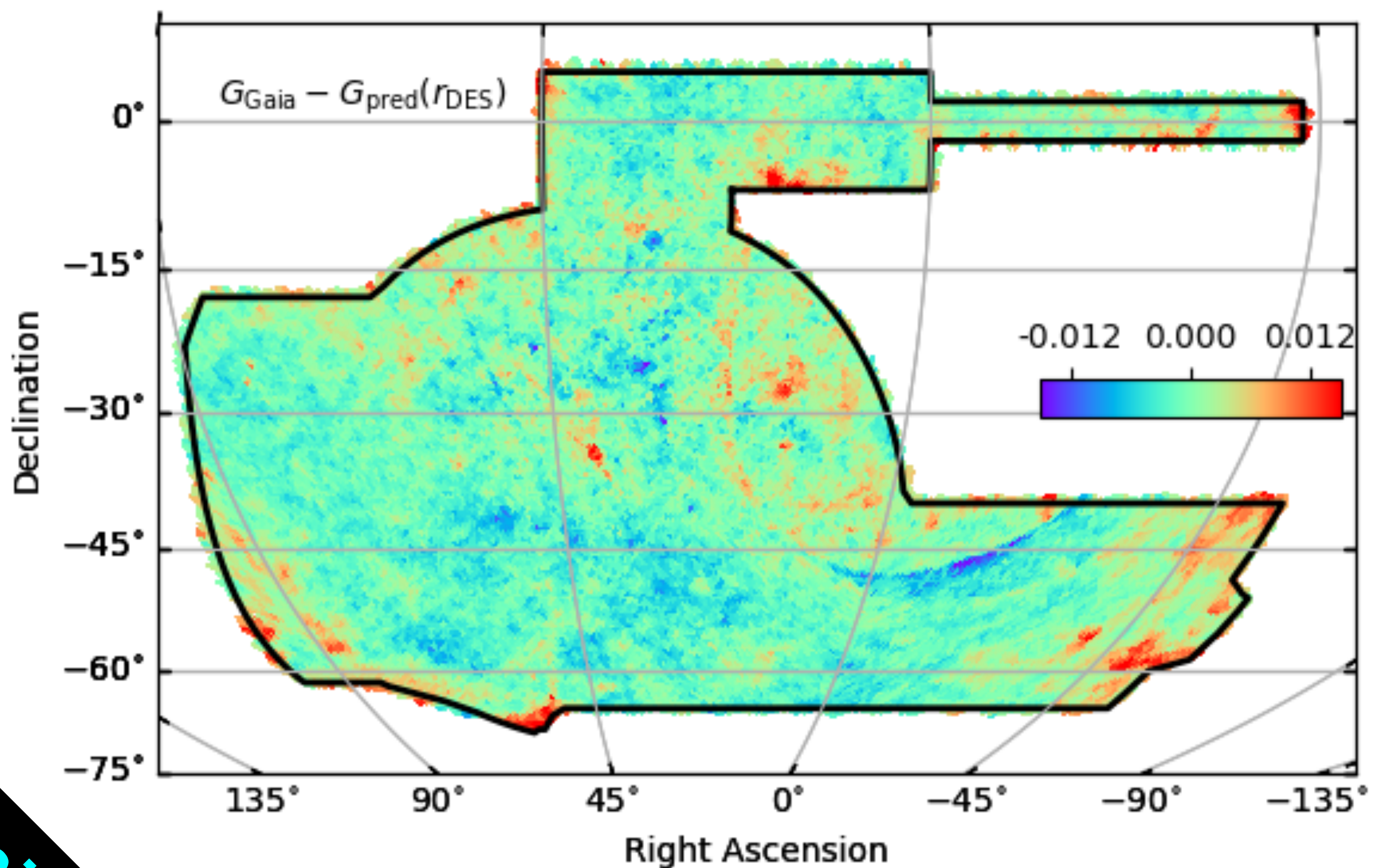
Repeatability (Y)

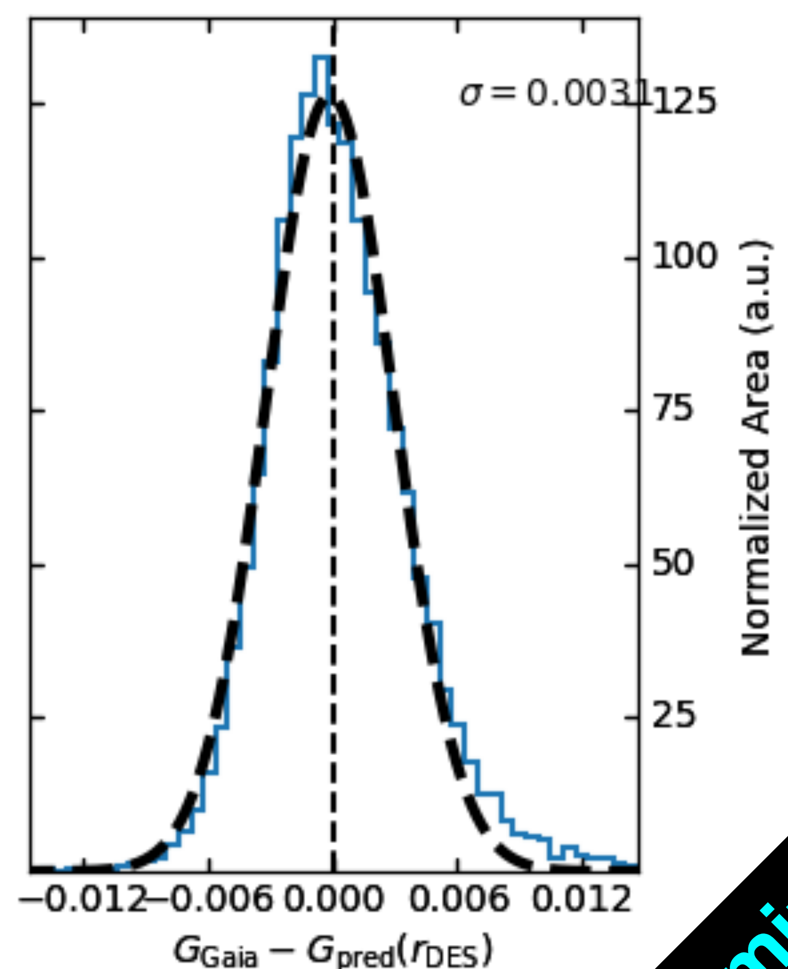
- We do not use Y band in our fit. It is “dead-reckoned”
- We think we know the atmosphere from the other bands… do we? (yes)



Comparing to Gaia

- …see my other slides…
- RMS of 3.1 mmag uniformity for r_{DES} vs G_{DR2}





Preliminary

Preliminary

FGCM and the LSST Stack

- FGCM has been integrated with the LSST stack
  - So far not part of mainline distribution (will change soon)
  - Only works with HSC and obs_subaru so far (only package with transmission curve support)
- A major limitation (currently) is collating all the star data
  - Each visit/ccd pair has a flat fits file that must be read in and good sources selected
  - This is not fast; database access in the future?
- Outputs atmosphere transmissions per exposure, plus zeropoints

LSST Baseline Plans

- Use spectrophotometry from Gaia to synthesize LSST griz as reference over large scales
  - u+y are still TBD
- LSST jointcal to solve per-band gray extinction coefficients
  - AuxTel to supply atmosphere transmission for chromatic terms
  - Works on overlapping images on patches/tracts
  - Allows flexible polynomial fits for intra-CCD variation of throughput

FGCM LSST Plans

- Originally thought of as useful for QA and redundancy
- Might be able to solve current issues with jointcal photometry
- Designed to incorporate auxiliary atmosphere data from instruments like AuxTel
  - Though DES performance is better without GPS or aTmCam
  - Require a very stable photometric telescope

FGCM LSST To-Do

- Currently does not use any reference catalog information
  - Can be extended to make use of Gaia spectrophotometry
  - Some R&D here
- Currently produces 1 zeropoint per CCD
  - Extension to higher order is possible
  - Need to ensure fits are valid

Extra Slides

Linear Approximation

- You should — if you can — integrate the corrections given S_b^{obs} and SED of source $F_\nu(\lambda)$
  - This is impractical for fitting
- Do a first-order expansion of the SED

$$F_\nu(\lambda) = F_\nu(\lambda_b) + F_\nu^{'}(\lambda_b)(\lambda - \lambda_b)$$

$$F_\nu^{'}(\lambda) = \frac{dF_\nu(\lambda_b)}{d\lambda}$$

$$\mathcal{F}_\nu^{'}(\lambda_b) \equiv F_\nu^{'}(\lambda_b)/F_\nu(\lambda_b)$$

Linear Approximation

- Substituting in, the correction factor is now:

$$\delta_b^{\mathrm{STD}} \approx 2.5\log_{10}(\mathbb{I}_0^{\mathrm{STD}}/\mathbb{I}_0^{\mathrm{obs}}) + 2.5\log_{10}\left(\frac{\int_0^\infty (1+\mathcal{F}'_\nu(\lambda_b)\times(\lambda-\lambda_b))\times S_b^{\mathrm{obs}}(\lambda)\times\lambda^{-1}d\lambda}{\int_0^\infty (1+\mathcal{F}'_\nu(\lambda_b)\times(\lambda-\lambda_b))\times S_b^{\mathrm{STD}}(\lambda)\times\lambda^{-1}d\lambda}\right)$$

- And the corrected magnitude is

achromatic extinction

$$m_b^{\mathrm{STD}} = -2.5\log_{10}(\mathrm{ADU}) + 2.5\log_{10}(\Delta T) + 2.5\log_{10}(\mathbb{I}_0^{\mathrm{obs}}) - 2.5\log_{10}\left(\frac{1+\mathcal{F}'_\nu(\lambda_b)\mathbb{I}_{10}^{\mathrm{obs}}(b)}{1+\mathcal{F}'_\nu(\lambda_b)\mathbb{I}_{10}^{\mathrm{STD}}(b)}\right) + \mathrm{ZPT}^{\mathrm{AB}}.$$

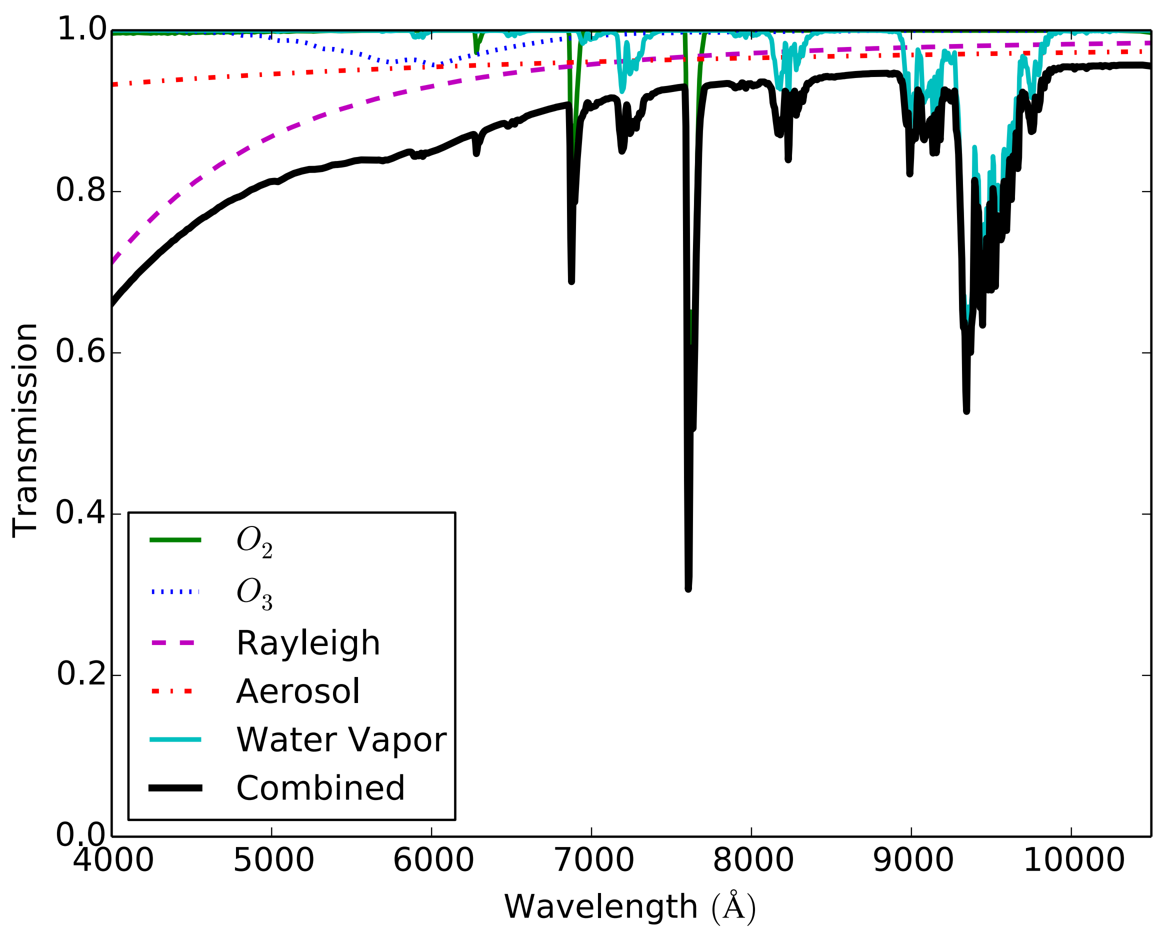
chromatic correction

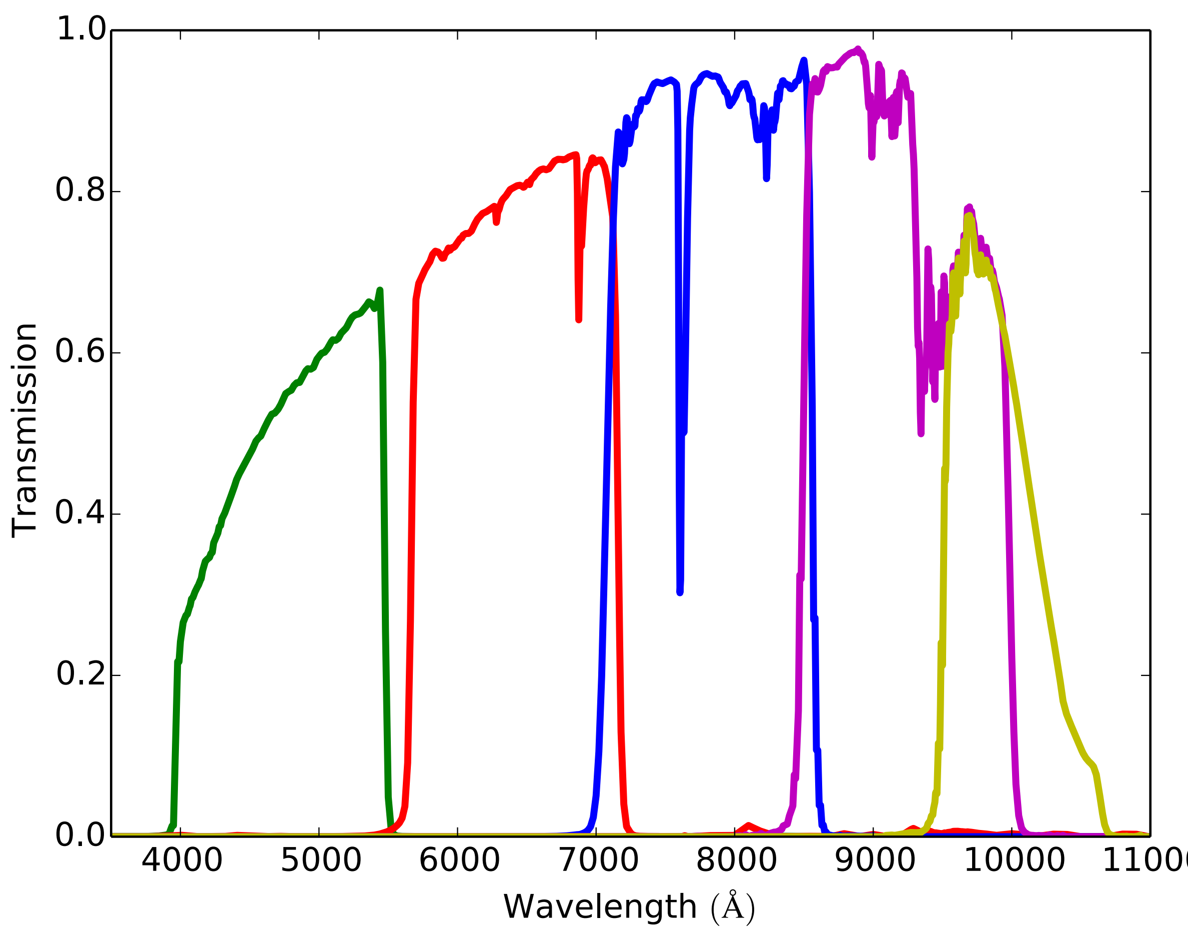
$$\mathbb{I}_{10}^{\mathrm{obs}}(b) \equiv \frac{\mathbb{I}_1^{\mathrm{obs}}(b)}{\mathbb{I}_0^{\mathrm{obs}}(b)}$$

$$E^{\mathrm{gray}}(i,j) \equiv \overline{m_b^{\mathrm{STD}}(j)} - m_b^{\mathrm{STD}}(i,j)$$

Water Vapor & *z*-band

- The water vapor cuts off the red end of the DECam *z*-band
    - Much less so the LSST *z*-band, and very much the blue end of the LSST *y*-band

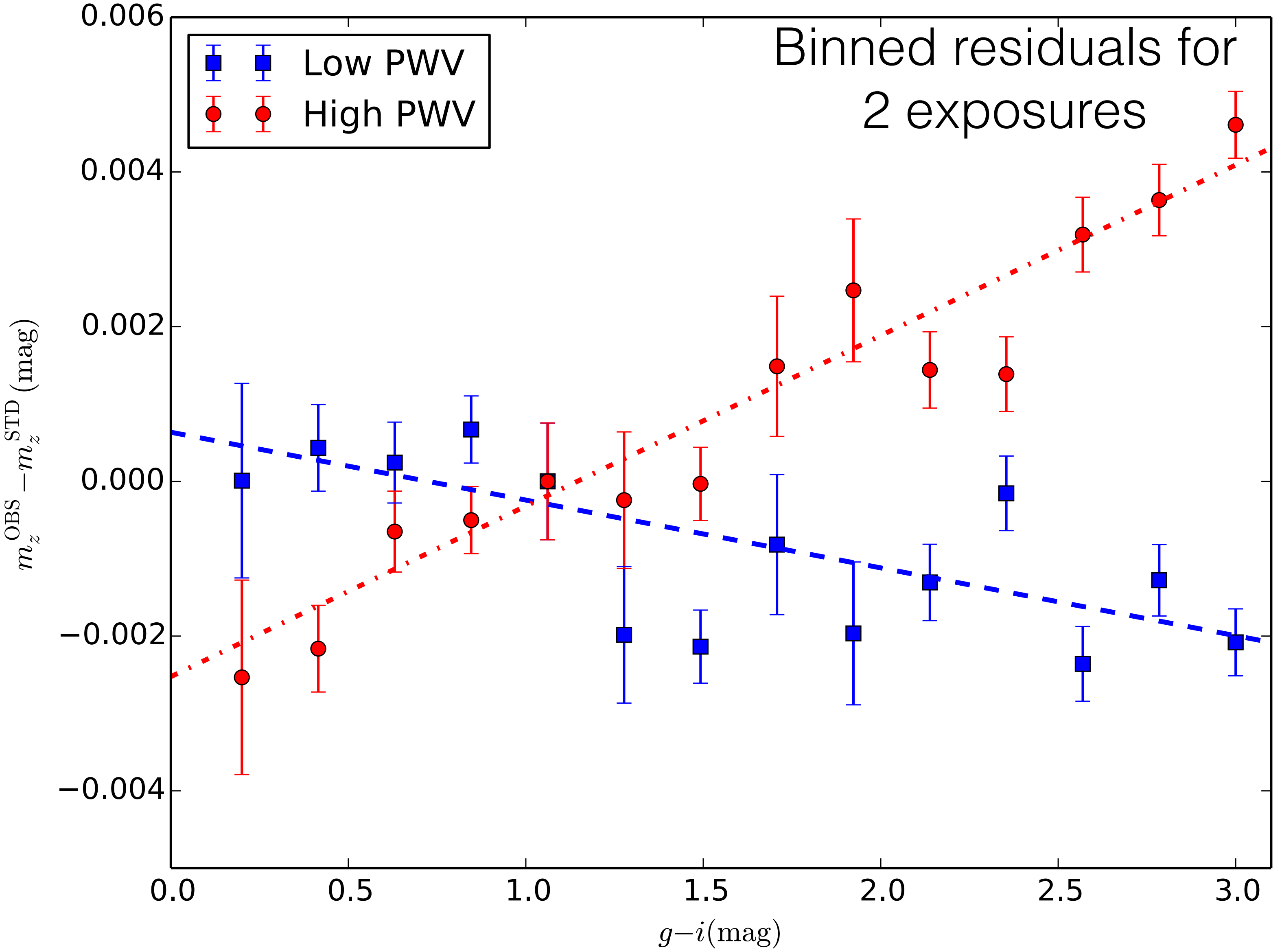




Water Vapor and *z*-band

- Before any chromatic correction, there is a PWV-dependent color term

pre-correction residual

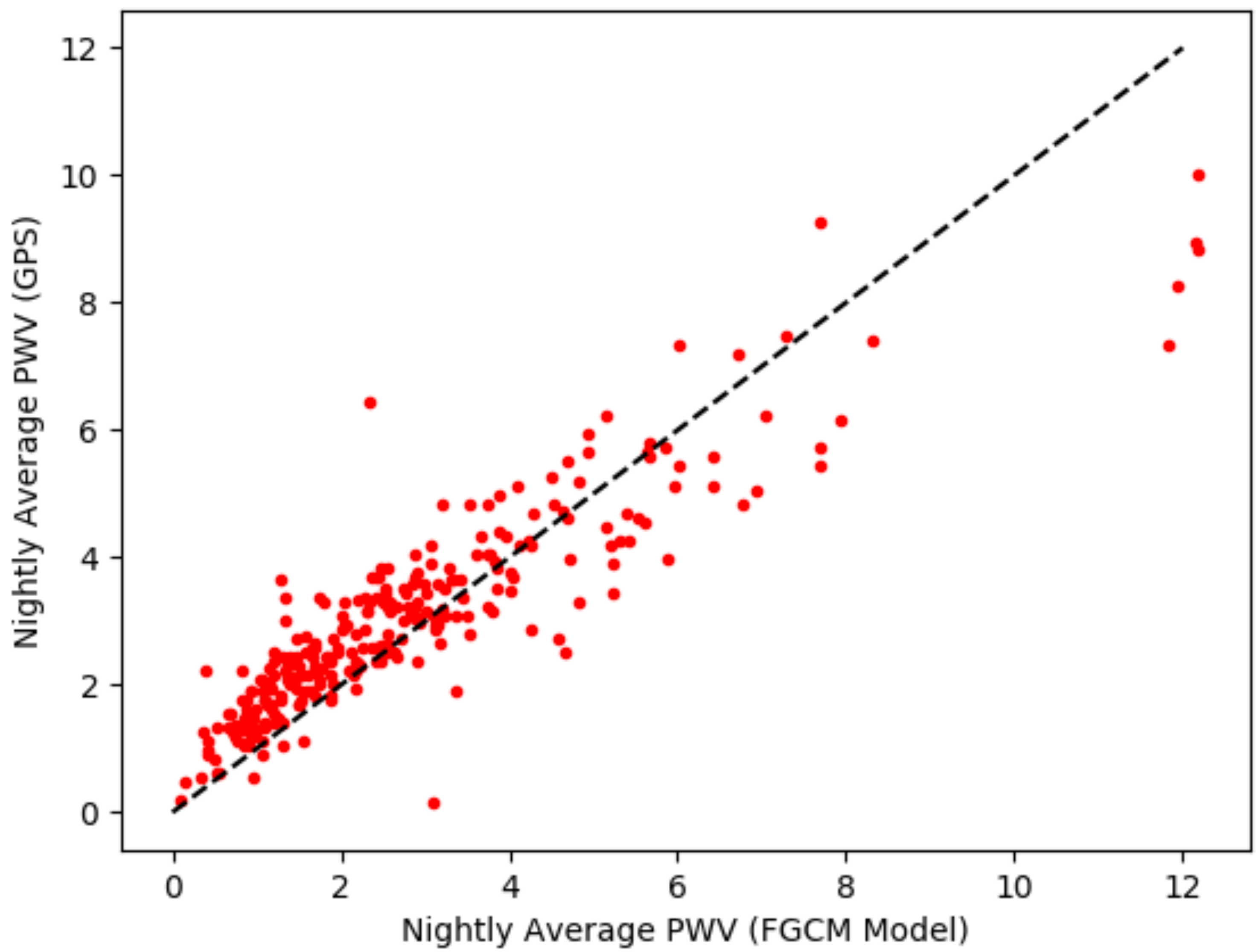


How to Model PWV

- In the current FGCM model, the precipitable water vapor has an intercept and slope per night
  - Signal primarily in z-band
  - Affects overall throughput (extinction) and color
  - Extinction could be due to aerosols, non-photometricity, etc, while color effect is unambiguous
- Can we model PWV directly from the color shifts? (This is what I call the “Lupton Dream”)
- Note that PWV primarily affects *z*-band, and so we only really need to model it for *z*-band!

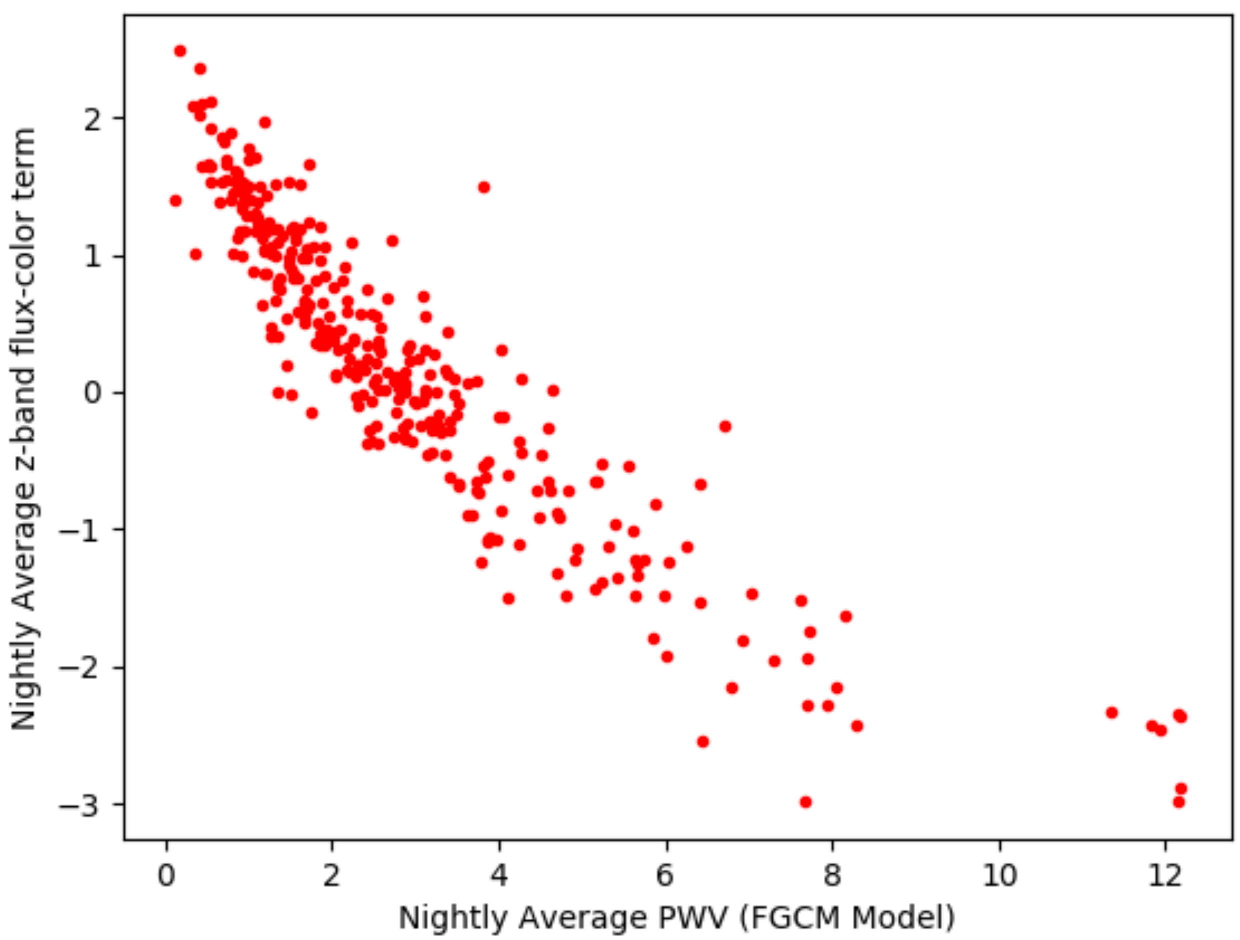
Testing the FGCM Model

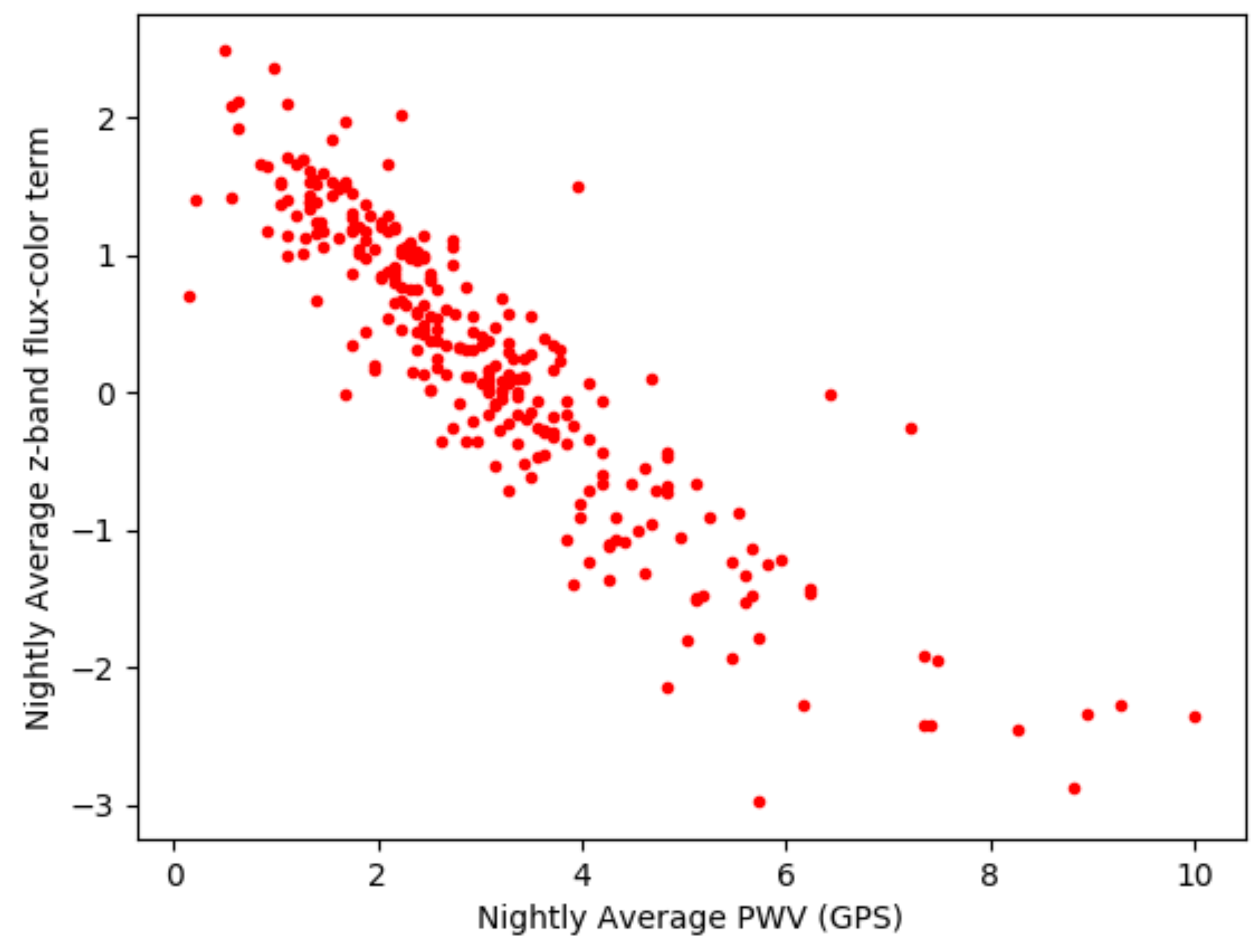
- First, we can test the current performance of the FGCM model with GPS water vapor data



Testing the Color Terms

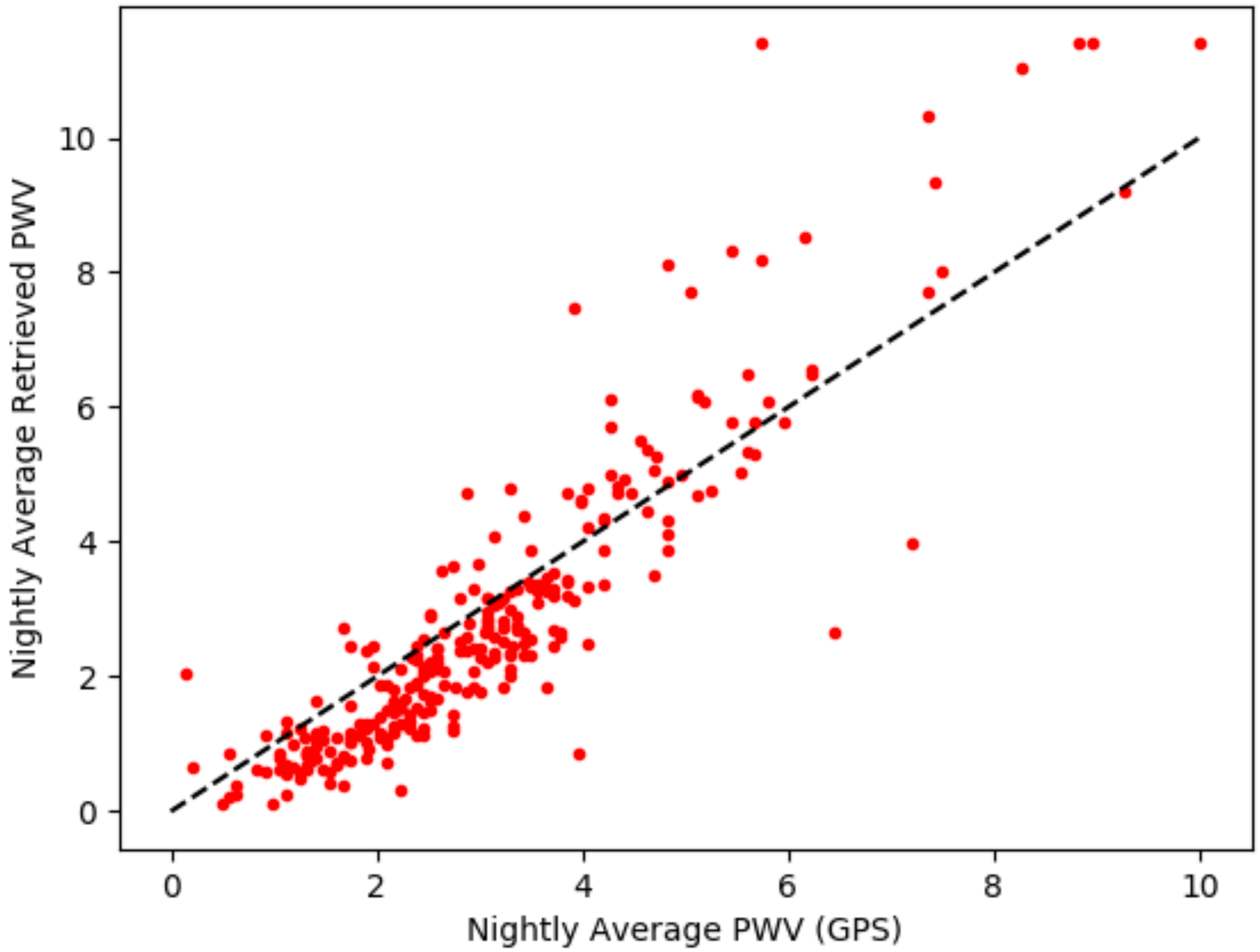
- Next, looking at the nightly average FGCM flux-color term
  - This “retrieved” quantity (R1) is not part of the model, but is a post-processing diagnostic





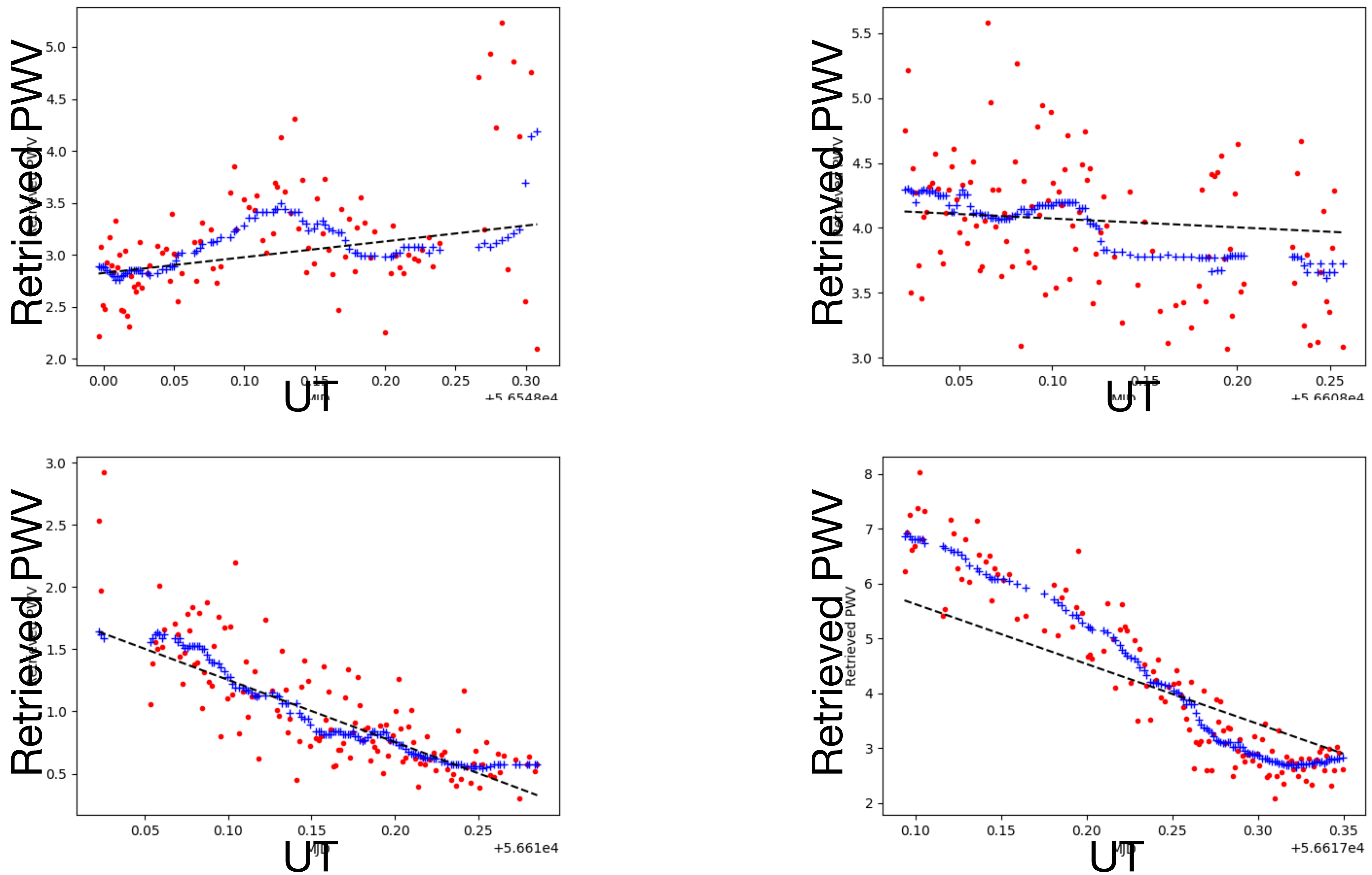
Inverting R1

- We can invert R1 to get a “retrieved PWV” from the required color corrections to the data
  - Correlates well with GPS PWV



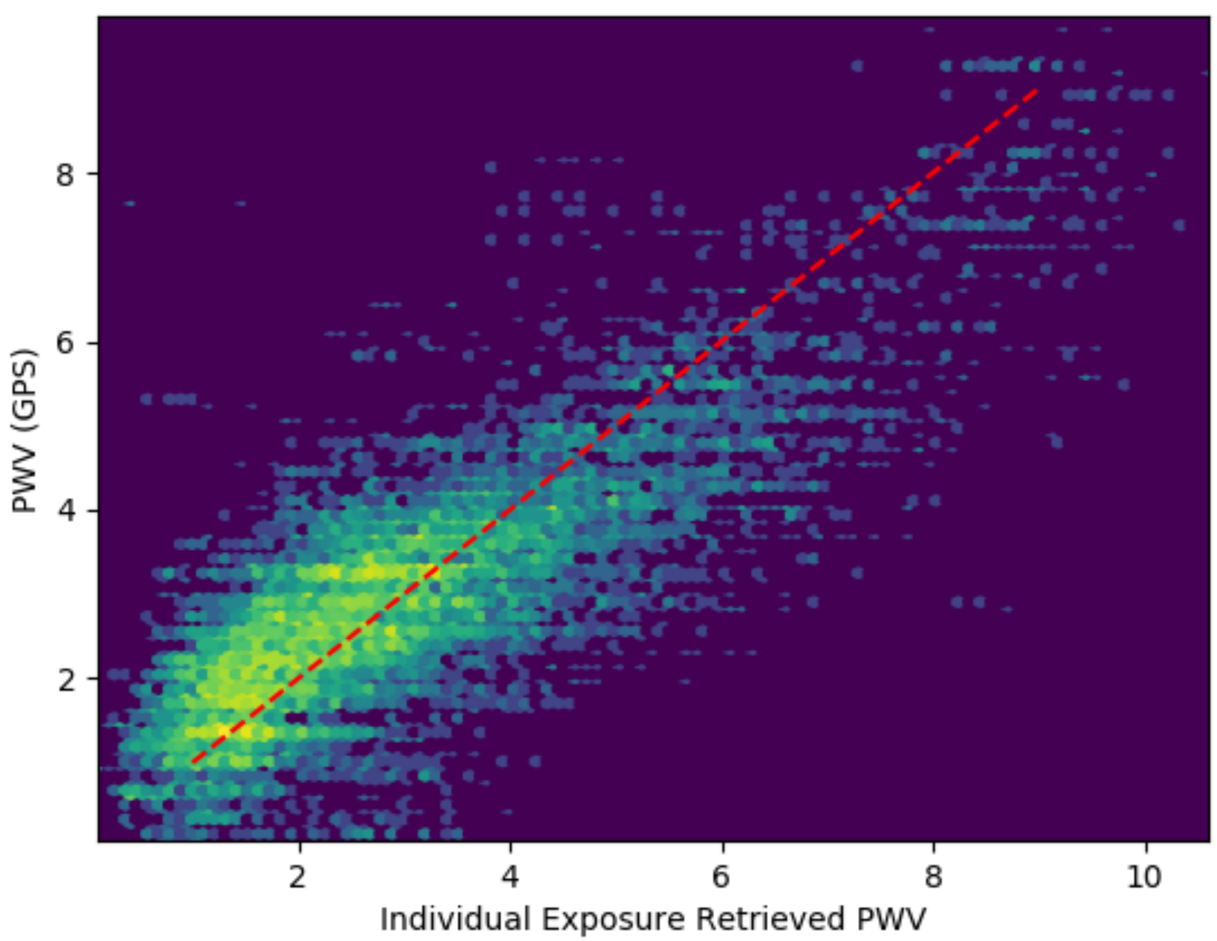
Intra-Night Variability

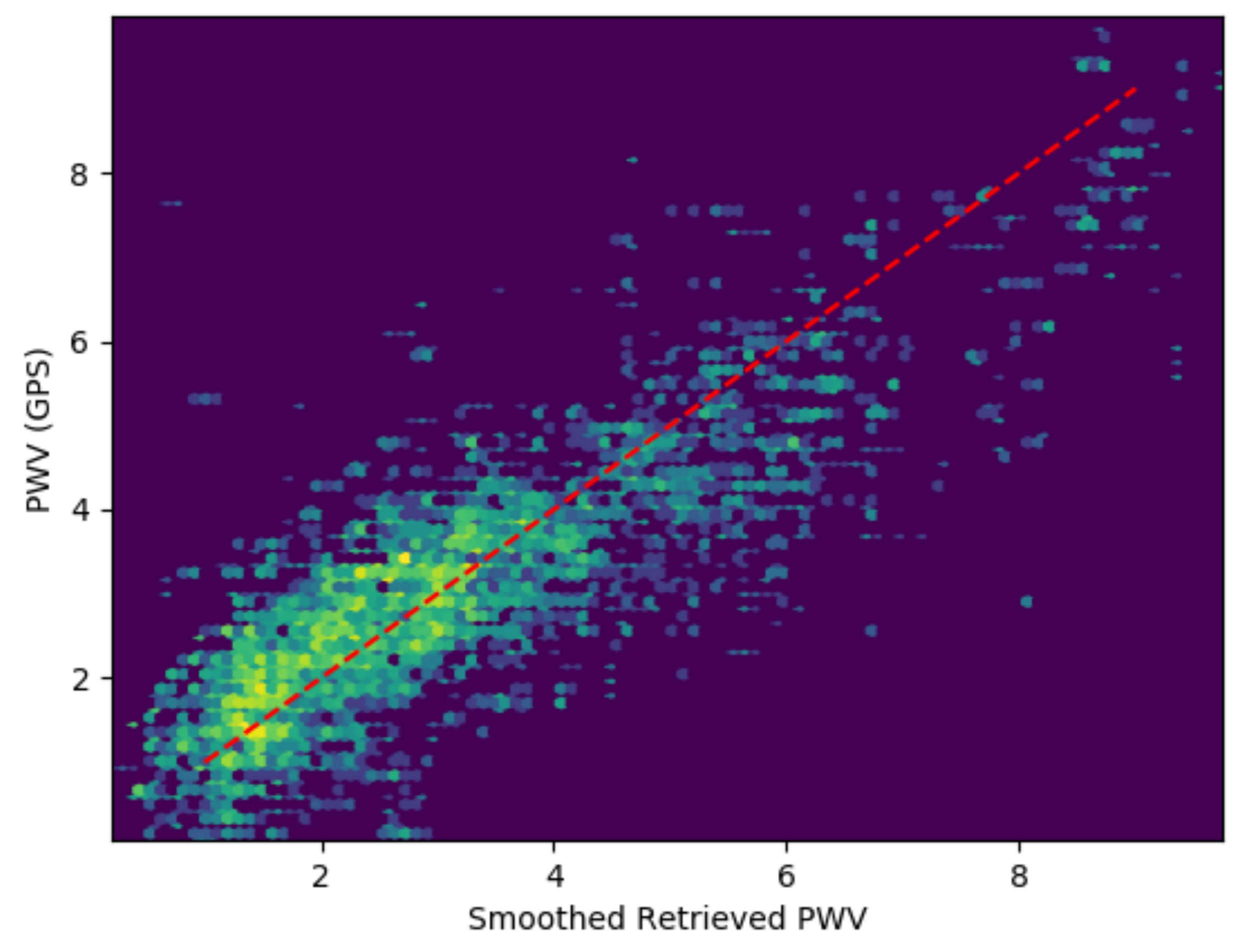
- The RPWV value can vary a lot through the night



RPWV and GPS

- RPWV correlates with GPS
- Though still a lot of scatter even after smoothing
- Noise in the GPS measurements or other offsets?





FGCM Flowchart