“Forward Global Calibration” of the Dark Energy Survey

Eli Rykoff, Dave Burke
and the DES Calibrations Crew

LSST Calibrations Meeting

June 14th, 2017

Outline

- What is FGCM?
  - See Burke, Rykoff+17 http://arxiv.org/abs/1706.01542
- Atmosphere and Instrumental Passbands
- The FGCM Fitting Procedure
- Calibration Errors
- 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)
- 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
  - Include non-photometric exposures (with increased error!)

The Atmosphere Model

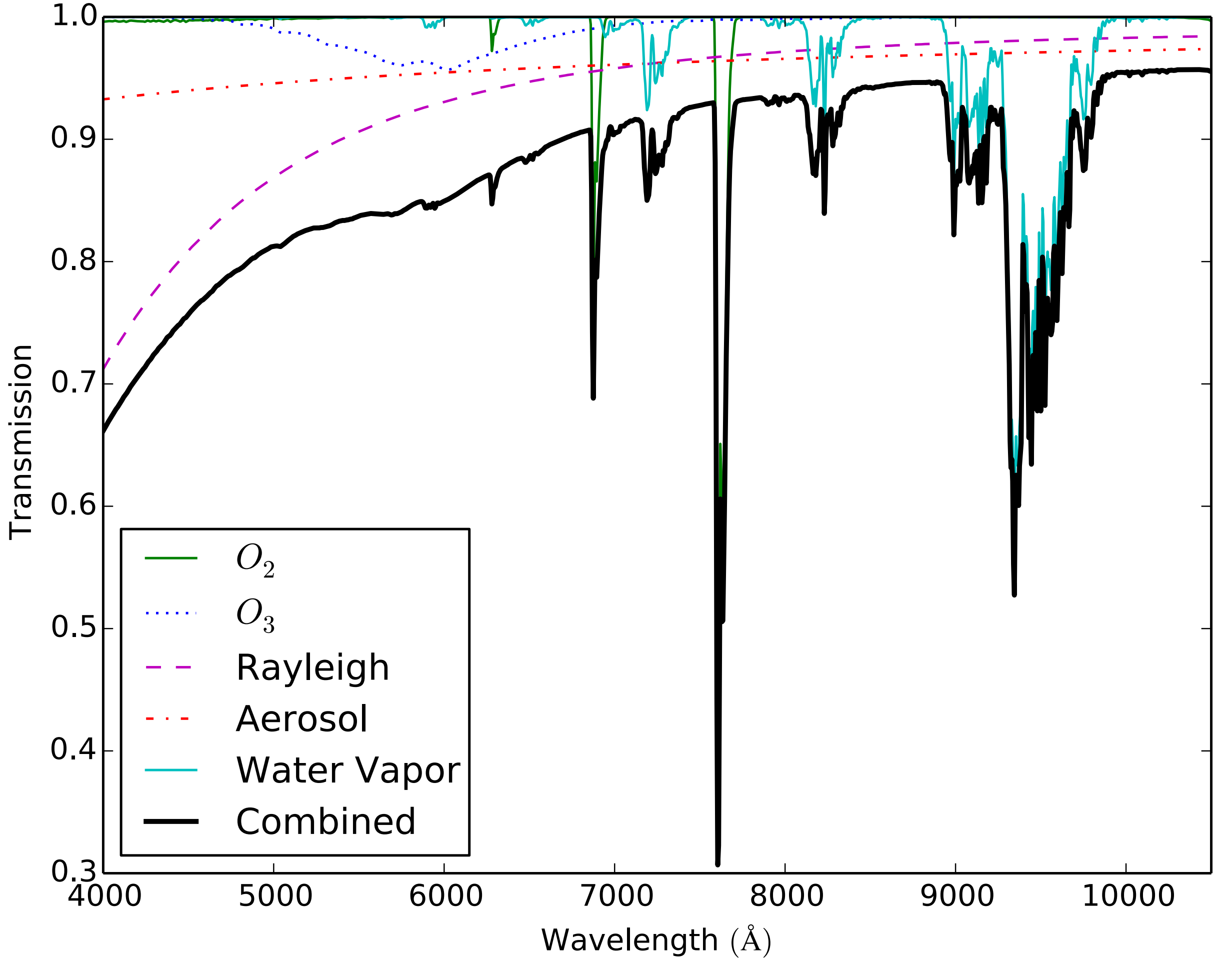
- Atmospheric transmission can be described with a small number of parameters
  - Precipitable water vapor (PWV)
  - Aerosol Optical Depth (AOD) τ and α

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

  - 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

- We use PWV from the GPS monitor system
  - With a global multiplicative and additive bias
- 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

- DES also has auxiliary aTmCam system
- 4 narrow-band filters on 4 cameras
  - Continuously fit atmospheric parameters through night
- Did not use for DES Year 1-3 because of some problems with the parameters
  - Working on improved calibration of aTmCam… promising so far.

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

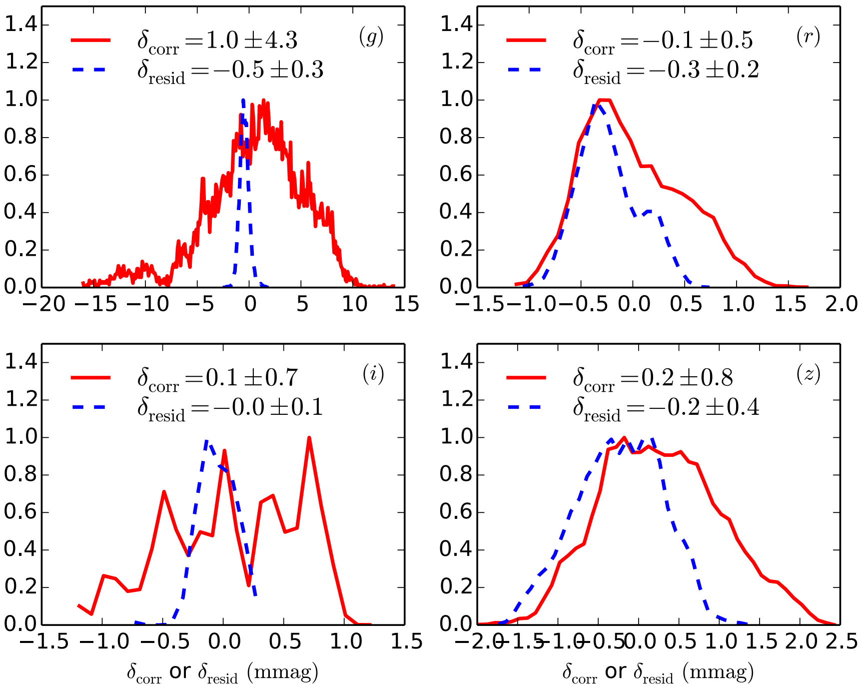
$$\mathbb{I}_0^{\mathrm{obs}}(b) \equiv \int_0^\infty S_b^{\mathrm{obs}}(\lambda)\lambda^{-1}d\lambda$$

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

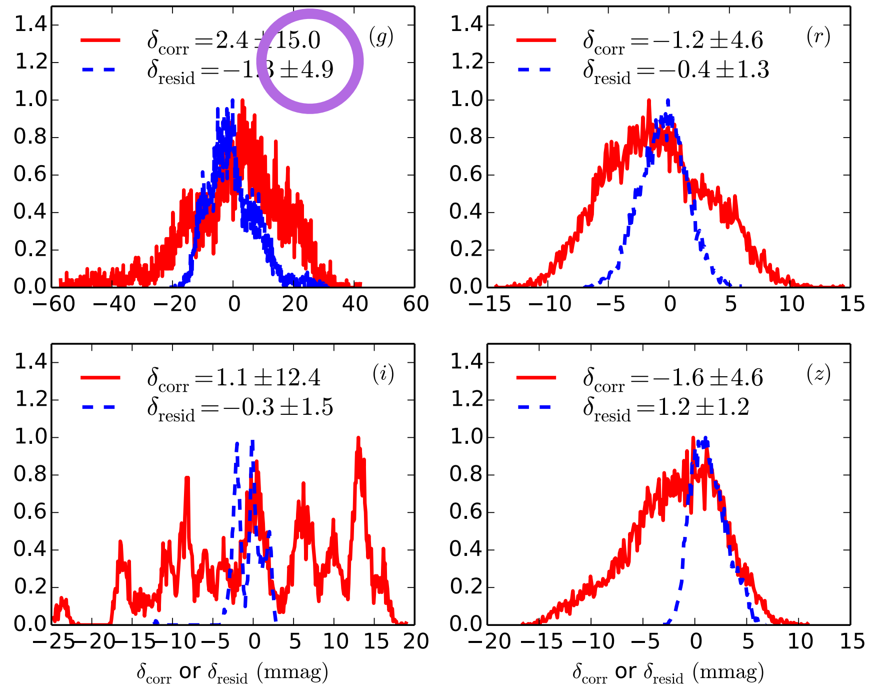
Chromatic Corrections

- 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)



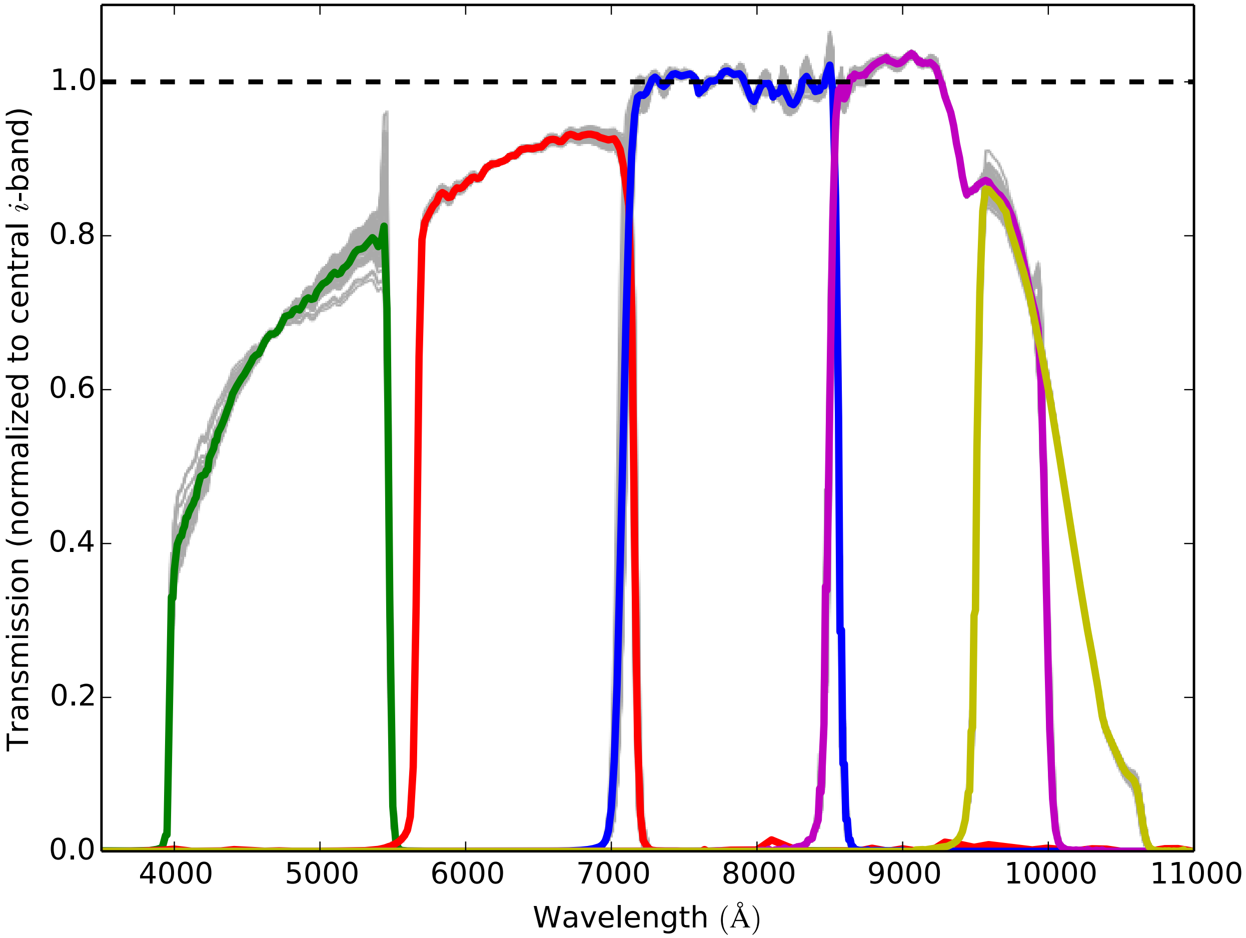
Instrumental Passband

- 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)

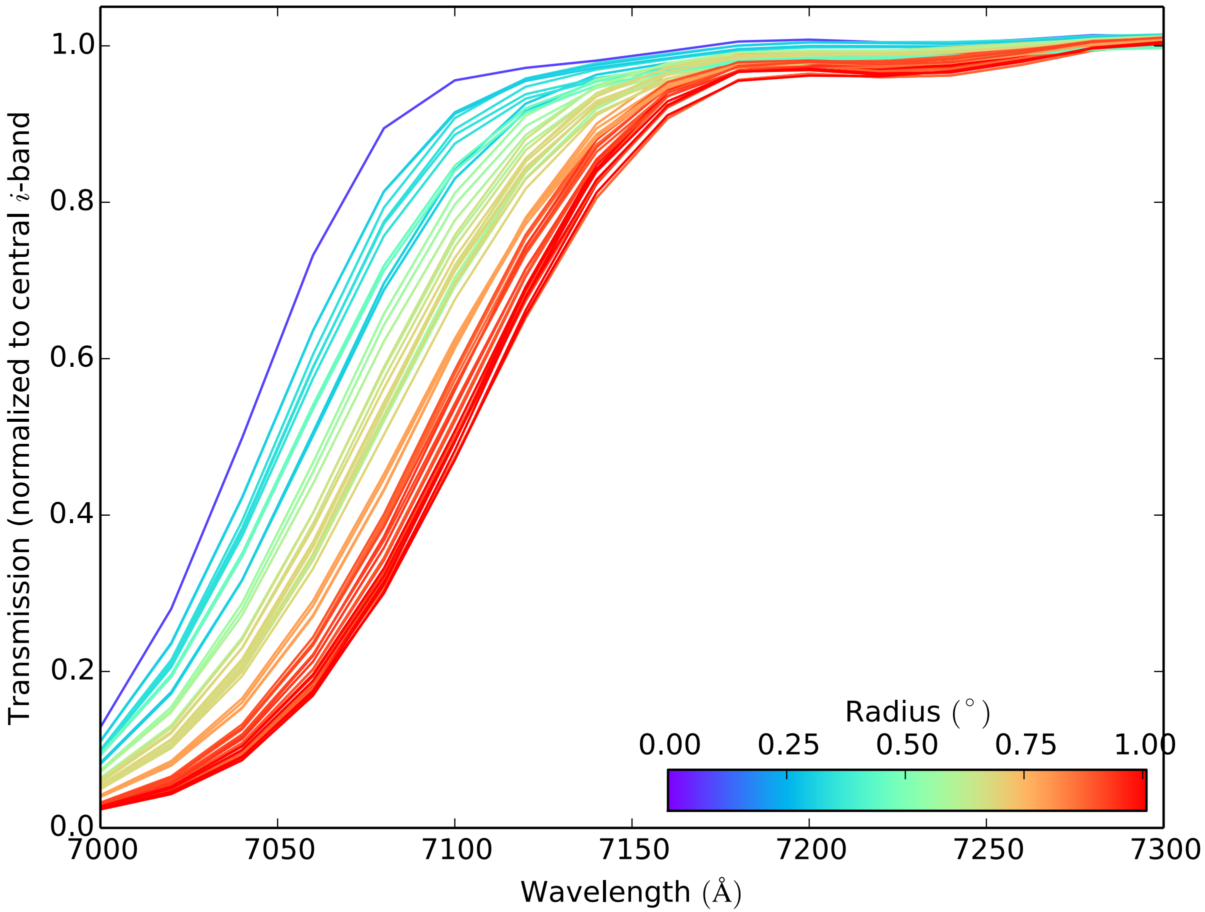
Filters+CCDs

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



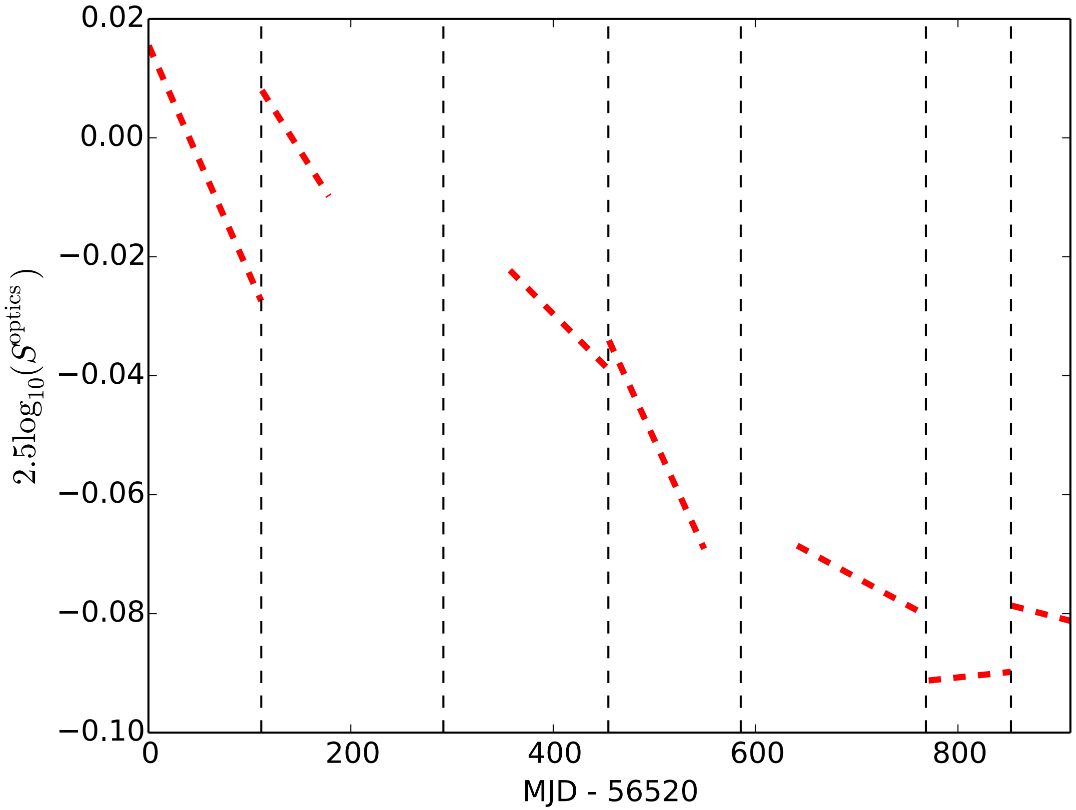
i band Radial Variation

- 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 2017



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

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

- Compute global χ^2

$$\chi^2 = \sum_{(i,j)} \frac{\left(m_b^{\mathrm{STD}}(i,j) - \overline{m_b^{\mathrm{STD}}(j)}\right)^2}{\sigma^{\mathrm{phot}}(i,j)^2 + (\sigma_0^{\mathrm{phot}})^2}$$

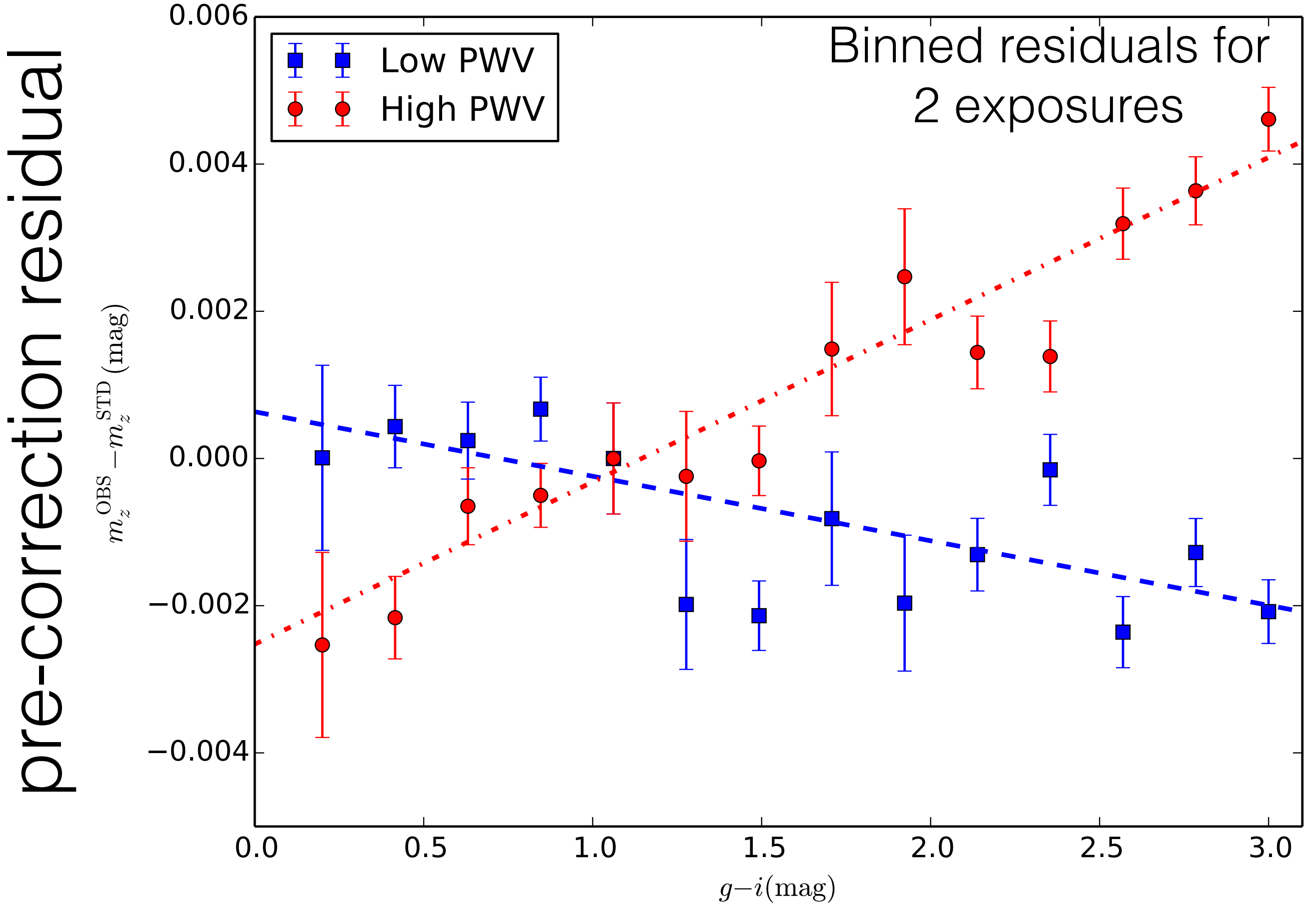
Chromatic Shifts

- 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 *z* and *Y* bands
  - Aerosols in *g* and *r* bands
  - Instrumental effects in all bands

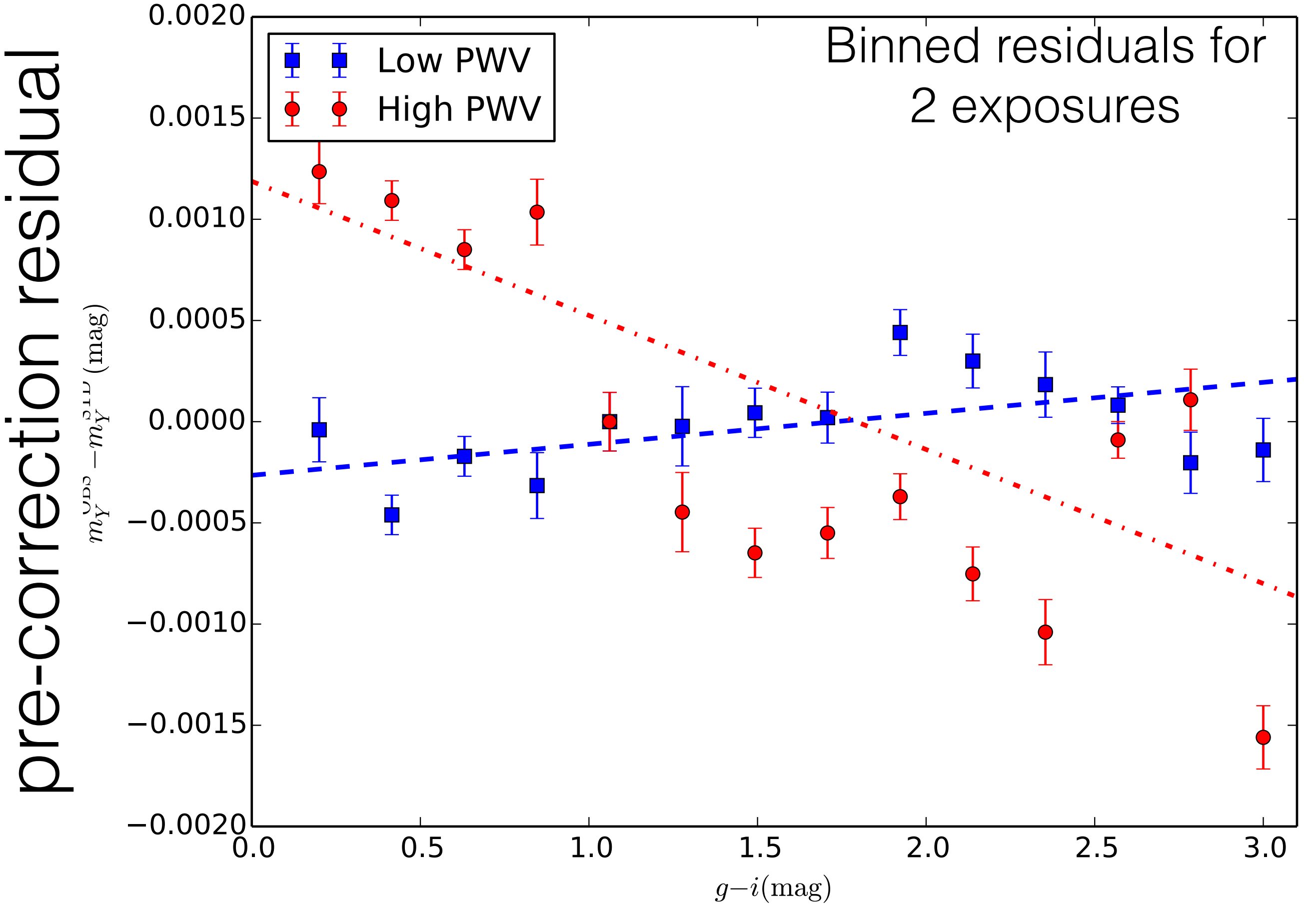
Water Vapor and *z*-band

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



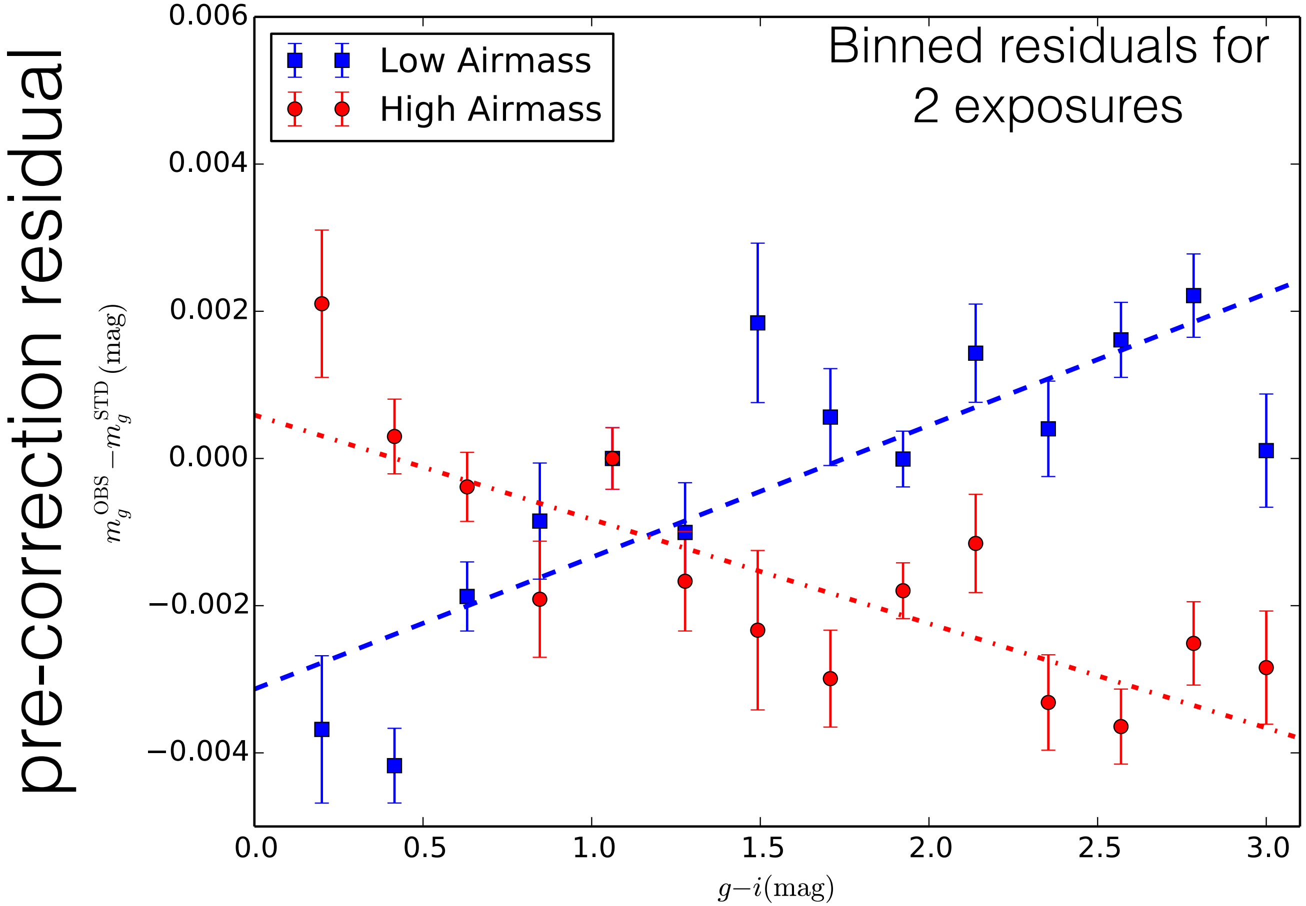
Water Vapor and *Y*-band

- 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*

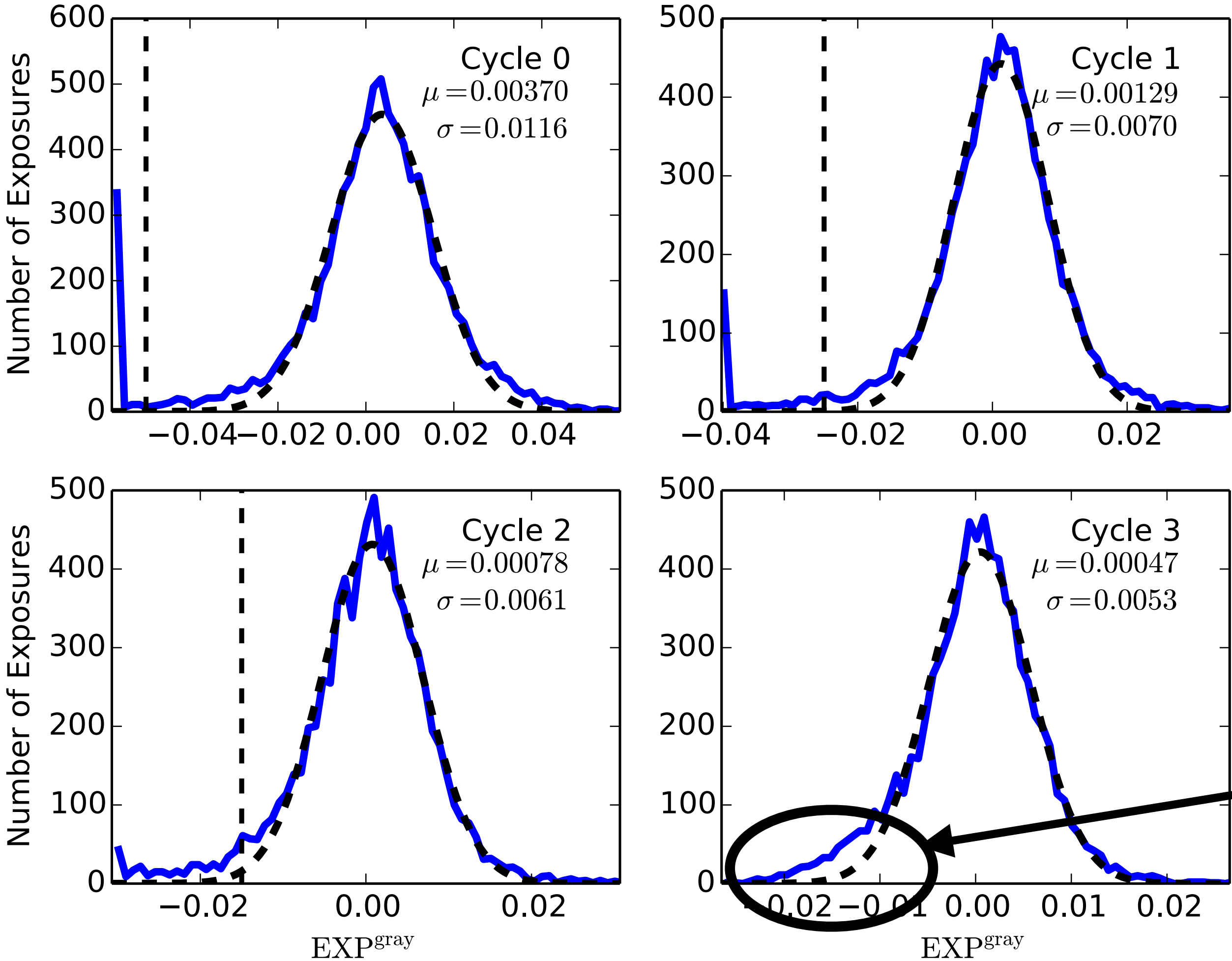


Photometric Selection

- 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”

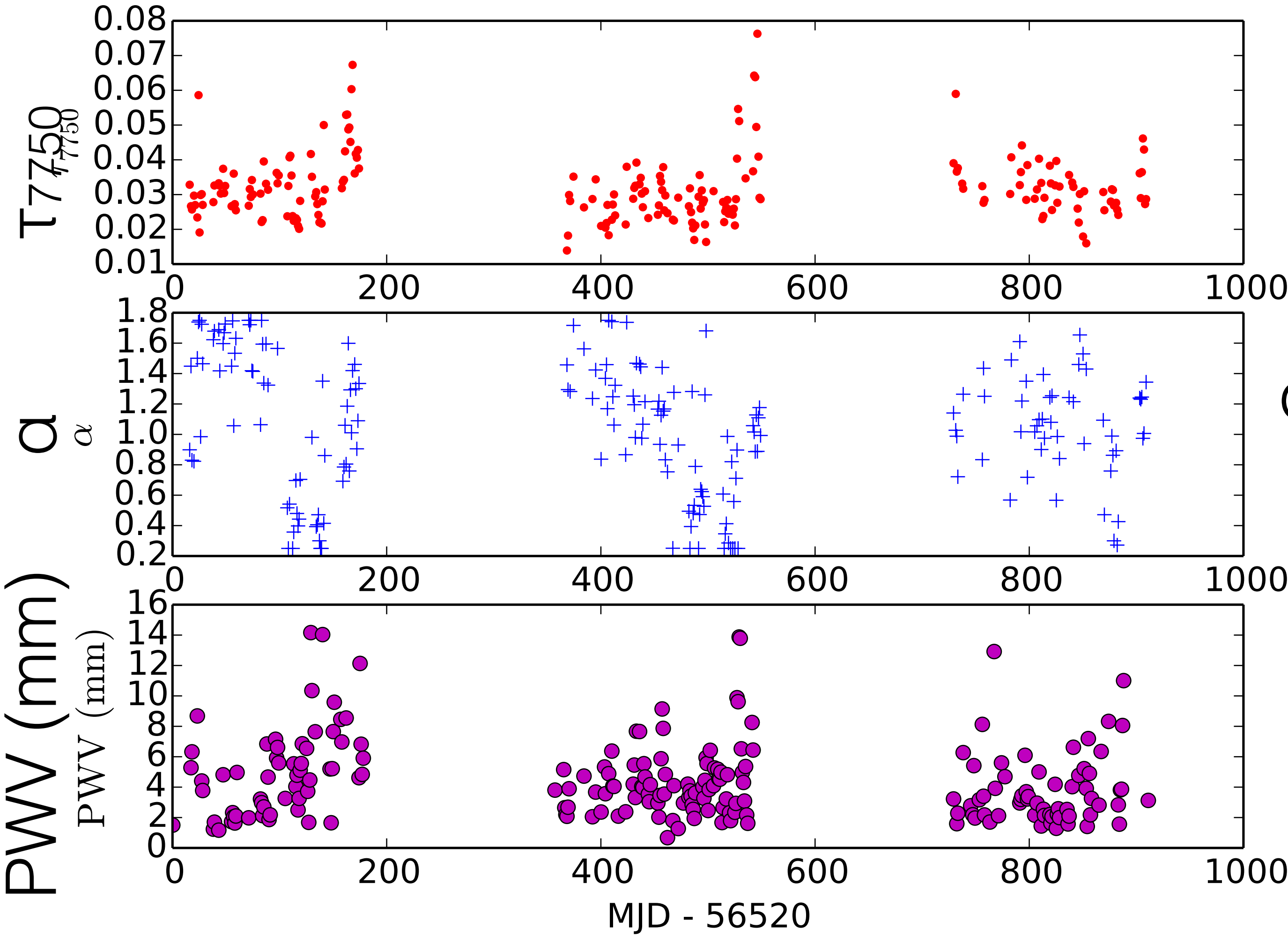


mix of model noise and non-photometric observations

exposure avg. “gray” residual in i band

Atmosphere Fits

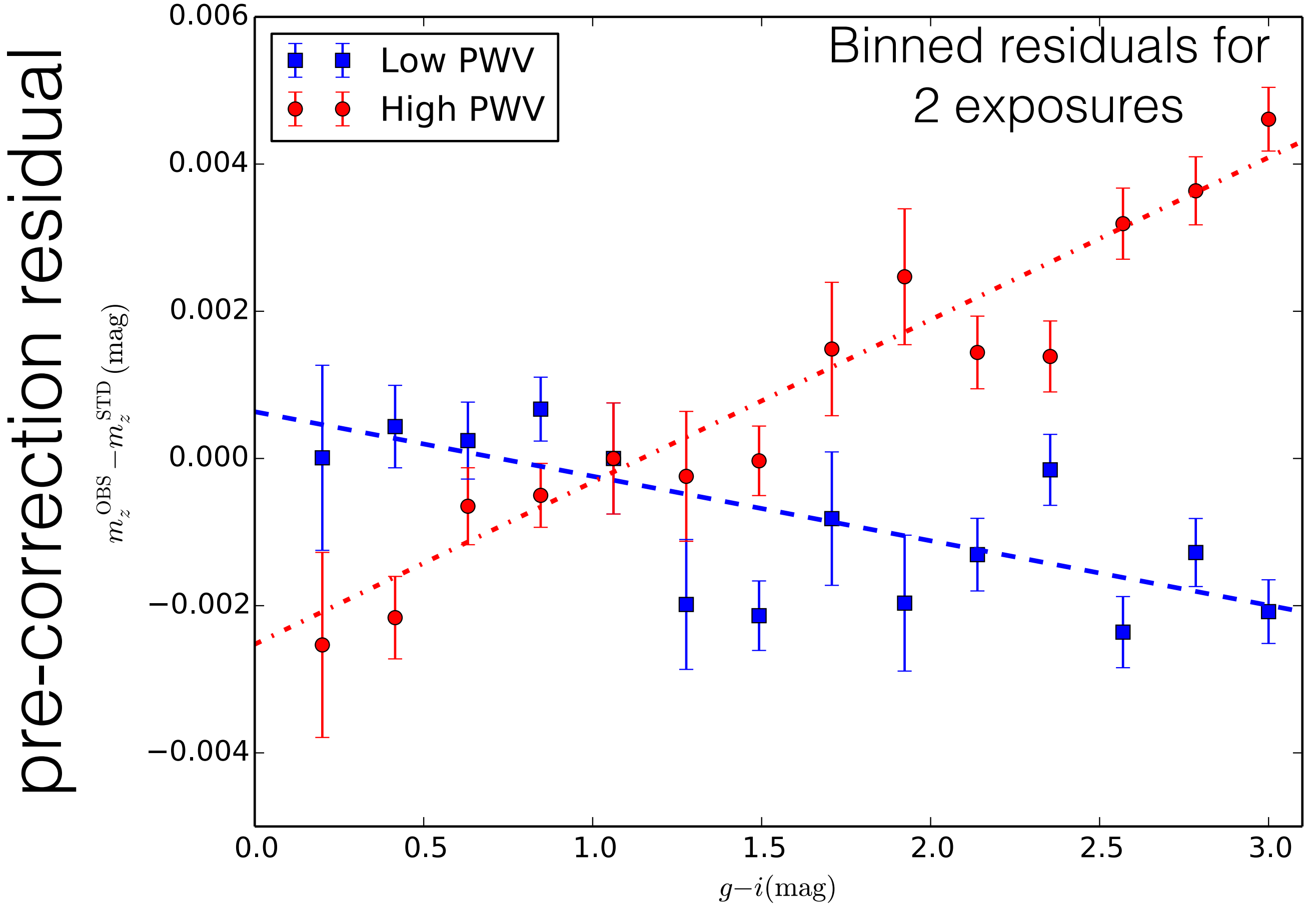
- Model parameters show seasonality



α is very noisy

Water Vapor and *z*-band

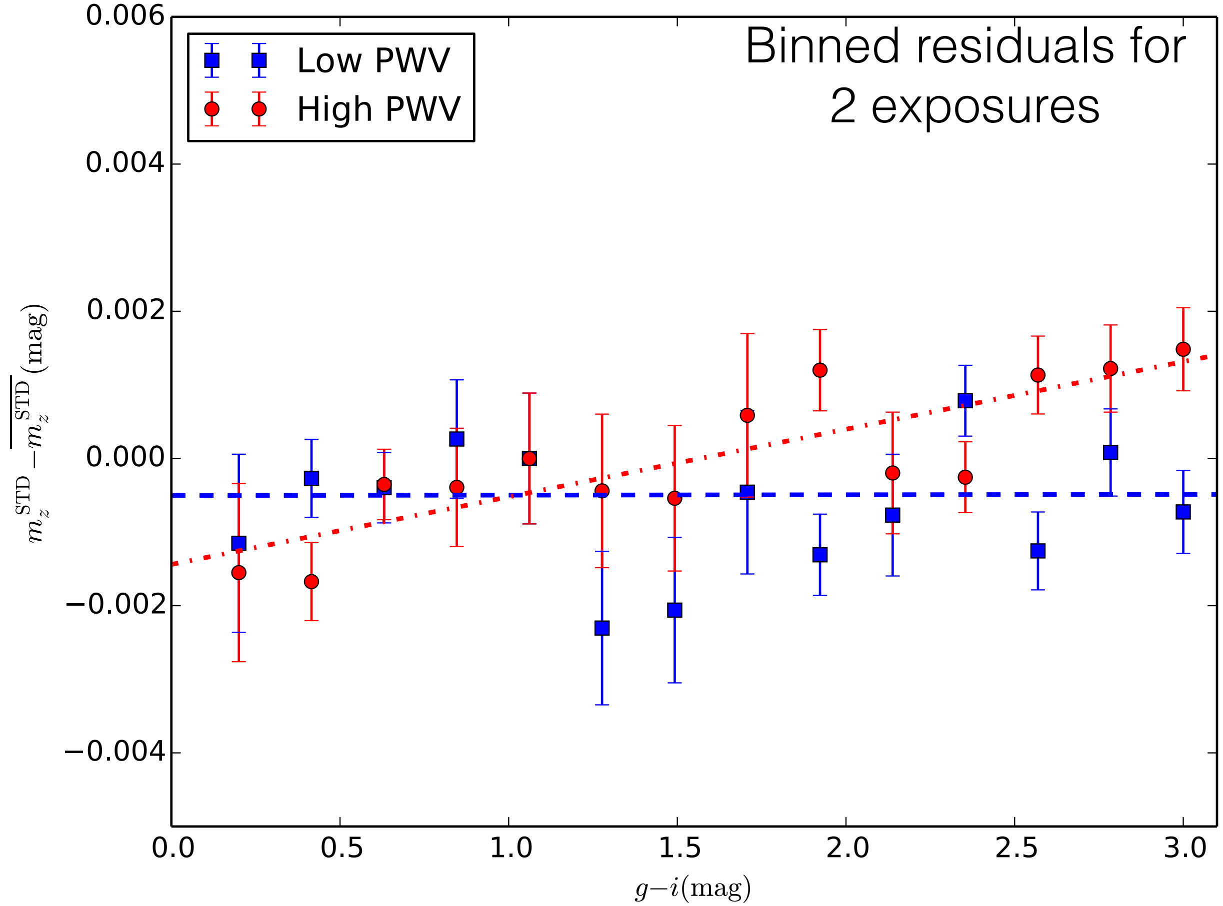
- Before correction…



Water Vapor and *z*-band

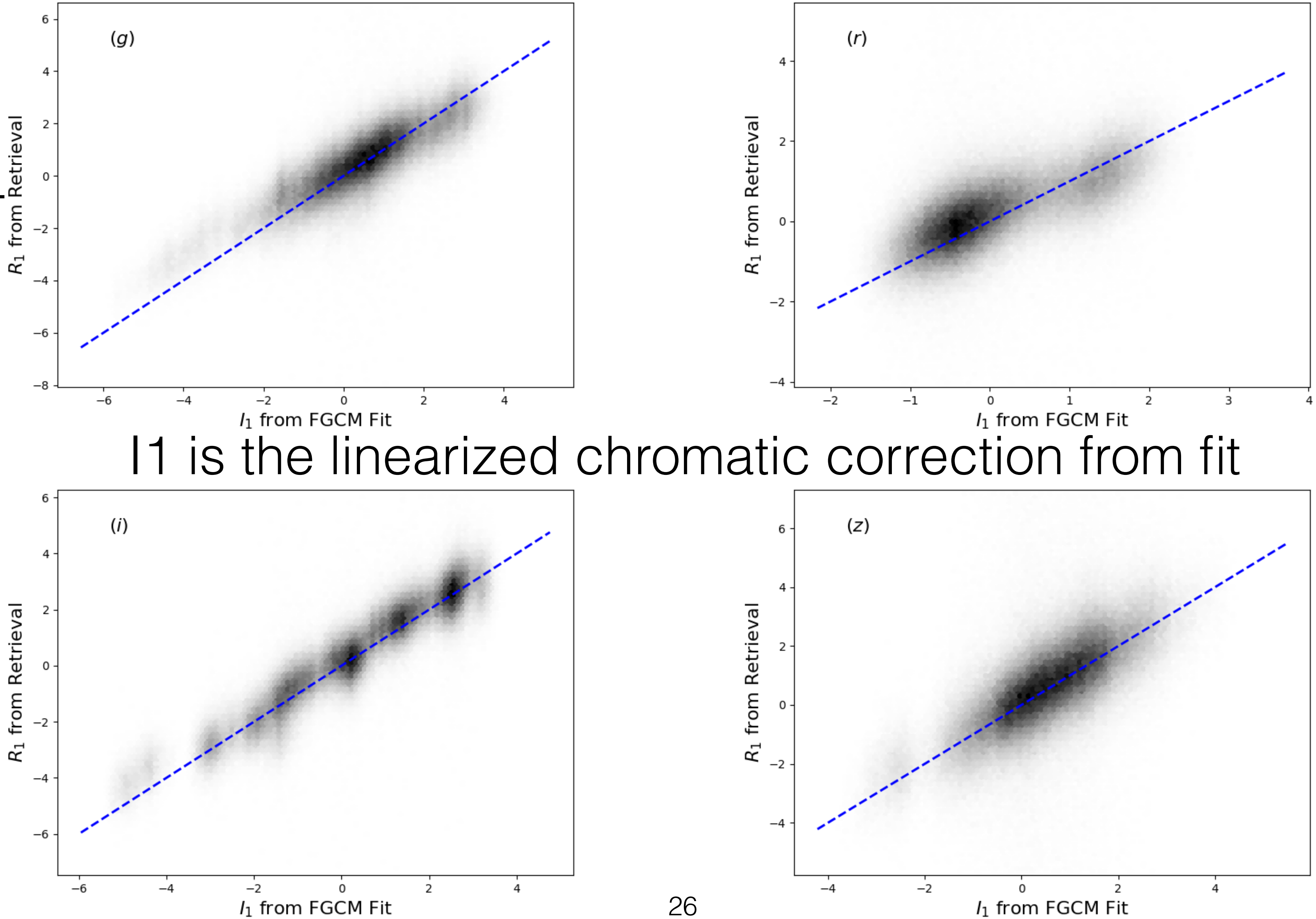
- After correction…

post-correction residual



Global and Exposure Fits

R1 is estimated from each exposure/ccd



I1 is the linearized chromatic correction from fit

Calibration Errors

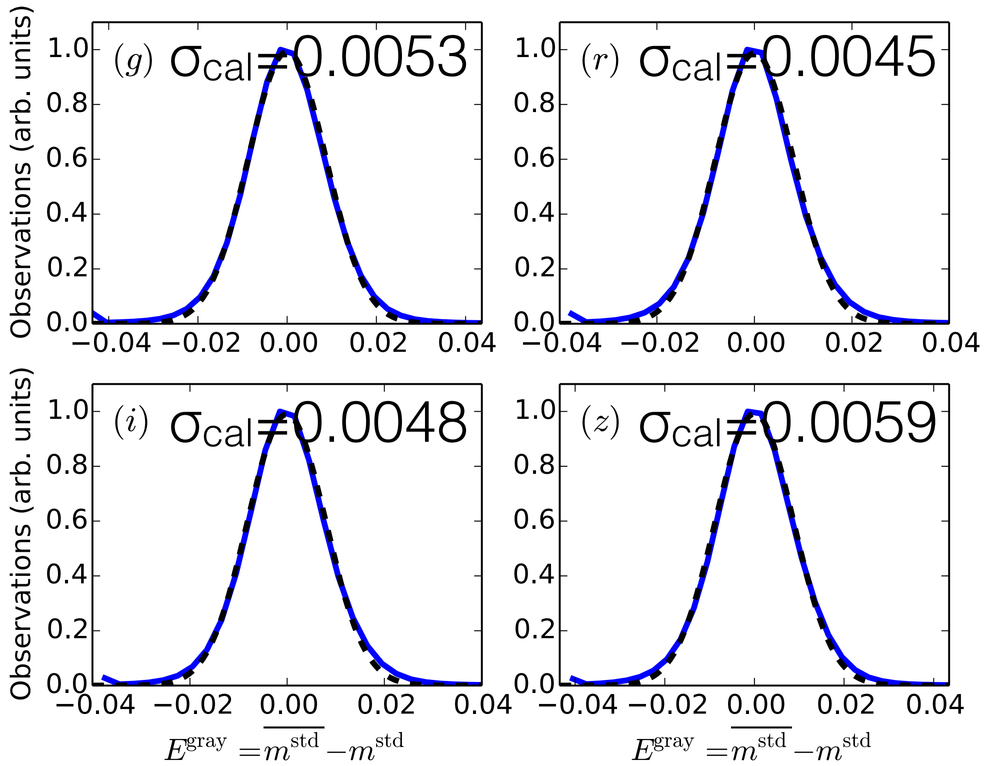
- Stability/Repeatability
  - If you return to an object

- Uniformity
  - If you go to another point in the survey footprint

- Chromatic
  - If you move to a different object SED

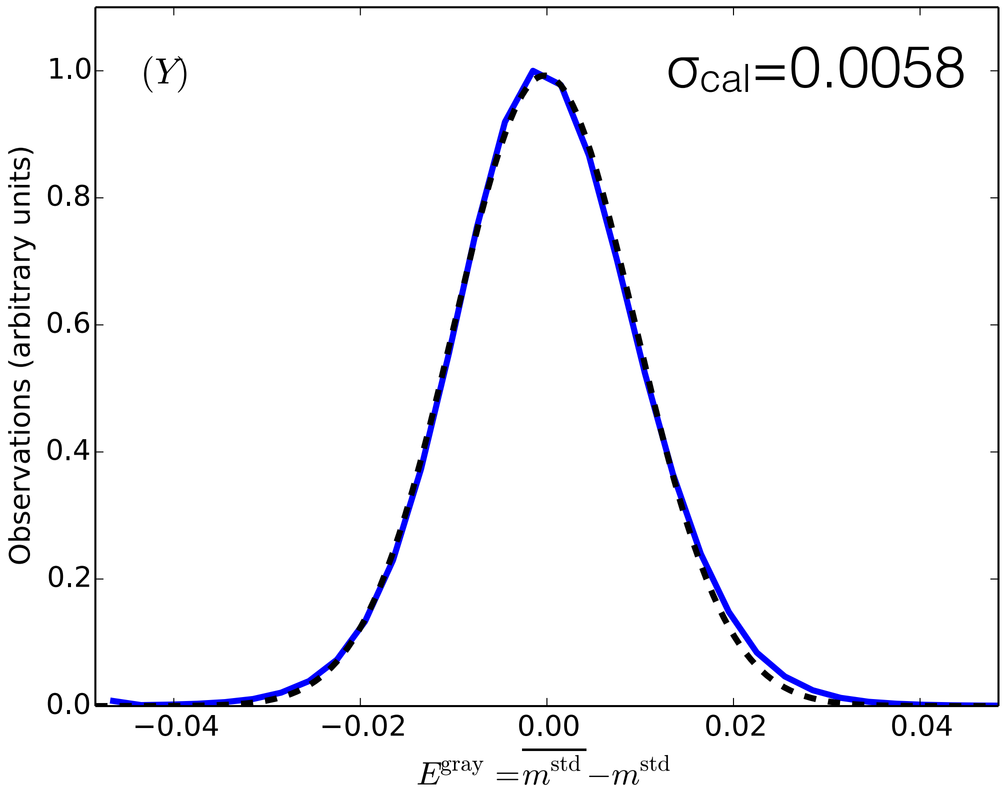
Repeatability (griz)

- 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
- $(\delta\text{FGCM})^2 \sim (5\text{-}6 \text{ mmag})^2$



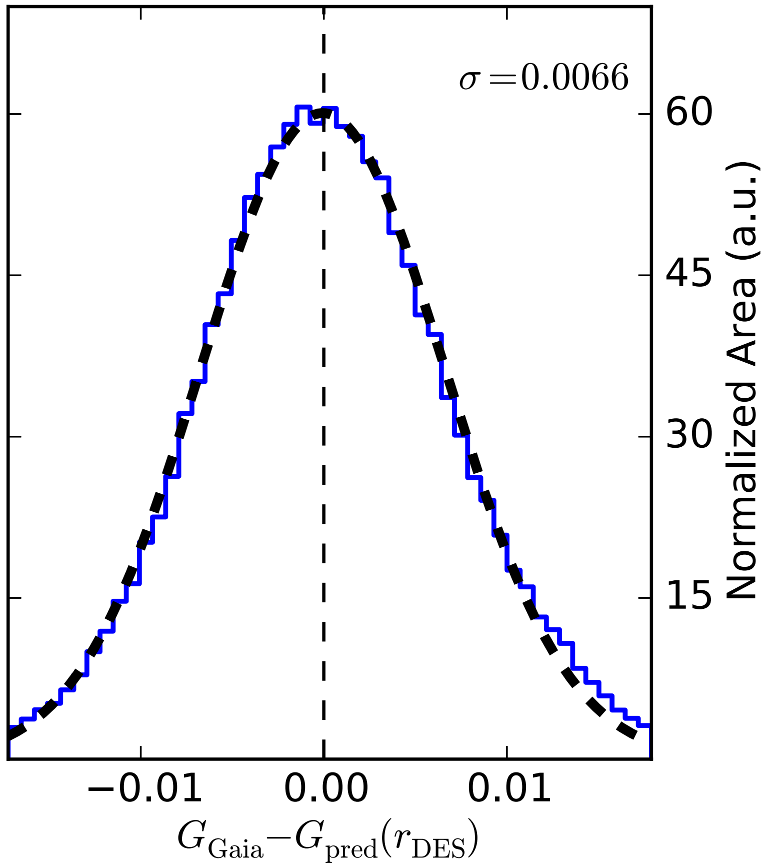
Repeatability (Y)

- 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)

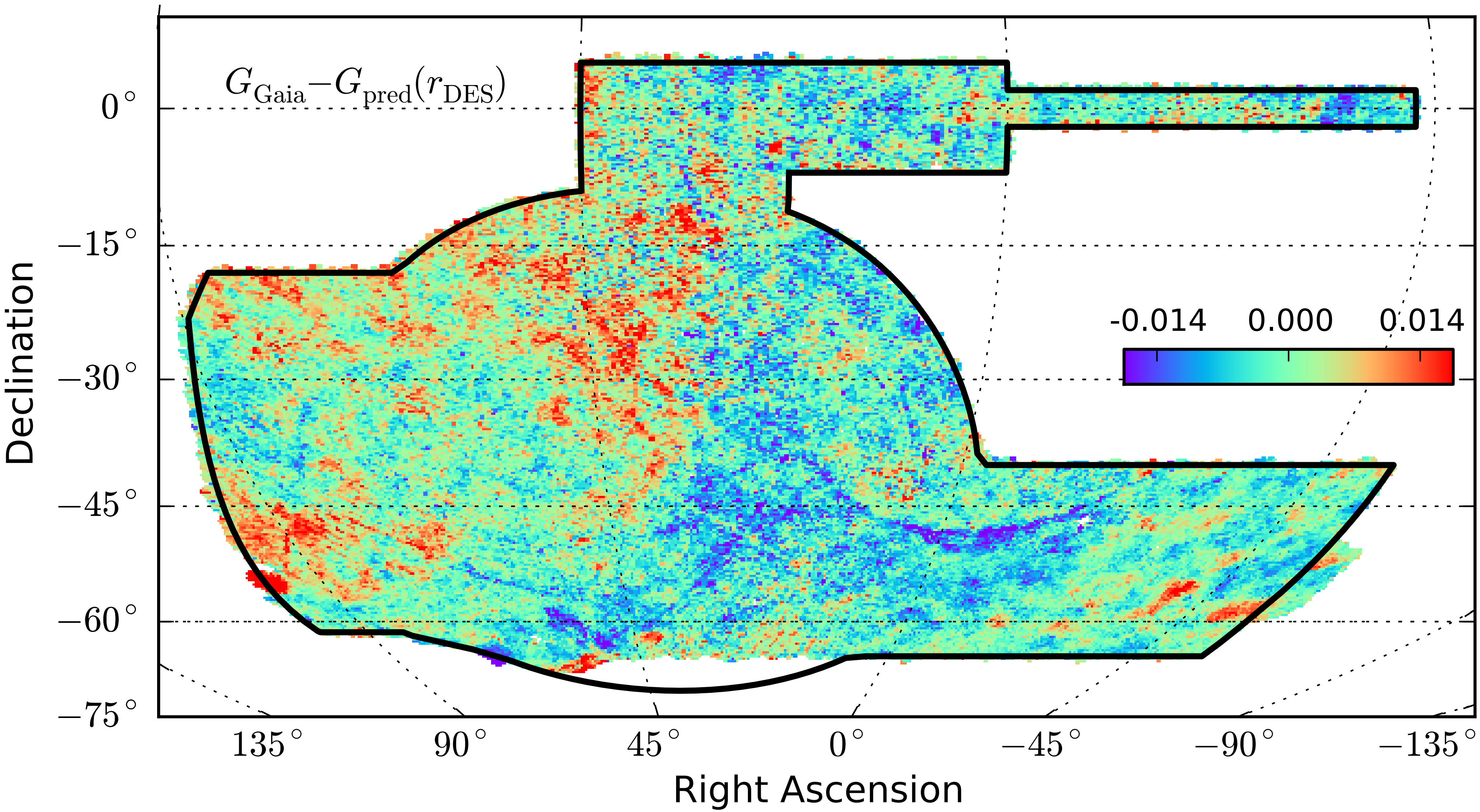


Comparing to Gaia G

- Consistent with 5-6 mmag uniformity over 5000 deg^2 footprint
- Very broad Gaia G band tricky to compare to



Comparing to Gaia G



LSST

- QA and redundancy! (obvious)
- Robert's dream of measuring (e.g.) PWV directly from each image affected by PWV
  - We have the signal … but it is noisy
  - Smooth over what timescale?
- Aerosol signal is trickier…
- Given Gaia spectrophotometry, we can short-circuit parts
  - Known SED of every (brighter) source
  - Use apparent star colors as more direct measure of atmospheric parameters (as above)

Updates

- Add aperture correction term (necessary for DES photometry)
- Updated model interpolation
- Repeatability down to 3-4 mmag in gri
  - Need more PWV improvements for *z*, *Y*
- Completely refactored code >10x faster
  - 3 years of DES in <24 hours using 20 cores
- Being incorporated into LSST stack
  - Code to be made public “soon”

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

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

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

Computing Zeropoints

- The FGCM fit yields a set of standard star magnitudes from good, photometric exposures
- To compute a CCD zeropoint:

model zp

$$ZP = < \overline{m_j^{\mathrm{STD}}} - (m_{ij}^{\mathrm{obs}} + \mathbb{I}_0 + \mathrm{chrom} + \mathrm{superstar} + \ldots) >$$

- Where I_0 is the integrated atmosphere extinction; we have a chromatic correction that depends on star color; a “superstarflat” correction
- The residual between the zeropoint and the predicted model zeropoint is $\mathrm{CCD}^{\mathrm{gray}}$

Computing Zeropoints

- The “gray” corrections are assumed to have no chromatic terms
  - Clouds, dome occultations, other effects
  - Errors in atmosphere and unmodeled effects: this will be an incorrect assumption
- 90% of DES exposures taken on nights with atmospheric solution
  - The rest have only instrumental chromatic corrections
- Apply to all CCDs
  - Effect of “compressing” the repeatability plots
  - This is a fit artifact, and we do not believe the (2-3 mmag) errors that result from this.

Aperture Effects

- We only recently looked at fit residuals with PSF FWHM
  - This is an issue that increases our noise
- Implementing an afterburner correction for DES Year 3; properly fit in new versions of code

Grav Residuals with Seeing