Rubin Observatory

“Photometric Calibrations”

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“SLAC”

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What is Photometric Calibration?

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- ISR will convert ADU (DN) to photons (see Robert’s talk)

- Background/Sky correction will discard sky photons and leave source photons (see Yusra’s talk)

- Photometric calibration converts source photons to nanoJansky for broadband filters
  - Answering “how bright is this object in physical units”, e.g. 1 Jy = 10^{-26} W m^{-2} Hz^{-1}
  - (Well, actually …)

Everything is Relative

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- Measuring absolute fluxes is really quite difficult
  - An STSci meeting on this topic was postponed to a later date
- Most of our measurements are relative to something else
- Currently, we use CALSPEC spectrophotometric standards measured by the Hubble Space Telescope
  - Above the atmosphere; quality instrument; issues at percent level?
  - Depends on dA white dwarf models and/or precision spectrophotometry
- Absolute calibration is not the subject of this talk
  - We can get to a nJy-like scaling.

Some Terminology

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- A "filter" is an optical element that selects a specific frequency range
  - A filter + the instrument + the atmosphere defines a "passband" or "band"
- A "gray correction" is an achromatic adjustment that affects all all frequencies / bands equally
  - Clouds are assumed to be "gray". But they are not spatially constant!
  - Dust accumulation on mirrors/lenses is also (probably) gray.
- A "chromatic correction" depends on the object spectral energy distribution (SED)
  - Most everything depends on SED

Types of Calibration Errors

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- Stability/Repeatability
  - If you return to an object later, do you get the same calibrated “top-of-atmosphere” flux?
- Uniformity
  - If you go to a different part of the survey, and look at a star with the same SED/distance, do you get the same calibrated flux?
- Chromatic
  - If you compare stars of different colors, do you get a consistent ADU → flux transfer?

The Modeling Chain

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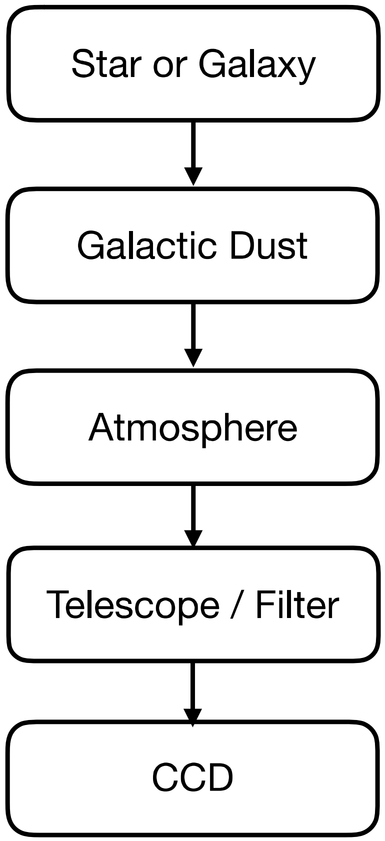

SED measurements (CALSPEC, Gaia, templates, etc.)

Gaia, NIR, self-calibration

AuxTel or self-calibration (FGCM)

Collimated Beam Projector (CBP)

Collimated Beam Projector (CBP)

Computing Calibrated Flux

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- The number of ADU detected by the CCD depends on the size of the telescope, the "observed" passband, and the spectral energy distribution (SED) of the source

- We then have to integrate all the photons that hit the detector:

Observed passband

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

Source SED

Computing Calibrated Flux

- It is convenient to measure relative to the "AB system"
  - Flat-spectrum in $F_\nu(\lambda)$ (Fukugita et al. (1996)):

$$AB_\nu \equiv -2.5 \log_{10} F_\nu(\mathrm{erg\,s^{-1}\,cm^{-2}\,Hz^{-1}}) - 48.6$$

- We then define the observed "top-of-atmosphere" magnitude relative to the AB system:

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

Computing Calibrated Flux

- One of our goals is to convert an observed magnitude (with a passband that varies with time and position) to a standard magnitude (so that the SNe and photo-z folks don't have to worry about all the unique passbands in the survey)
- See Burke, Rykoff et al. (2018) for details

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

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

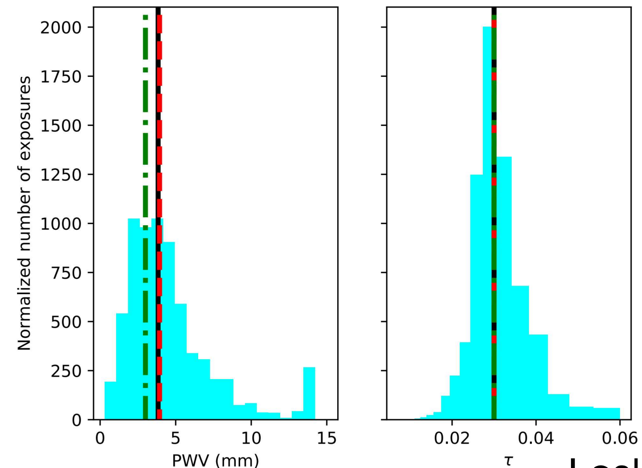
$$\mathbb{I}_0^{\mathrm{obs}}(b) \equiv \int_0^\infty S_b^{\mathrm{obs}}(\lambda)\lambda^{-1}d\lambda$$

Choose Your Standard Wisely

- If either the SED is the flat AB spectrum or the observed passband is the standard passband, the chromatic correction is 0.

- The further the passbands diverge, the greater impact of different SEDs
  - Particular challenges include CCD quantum-efficiency (E2V and ITL chips) and water vapor variations

- Choose a standard passband as close to the “typical” observing conditions as possible



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The Atmosphere

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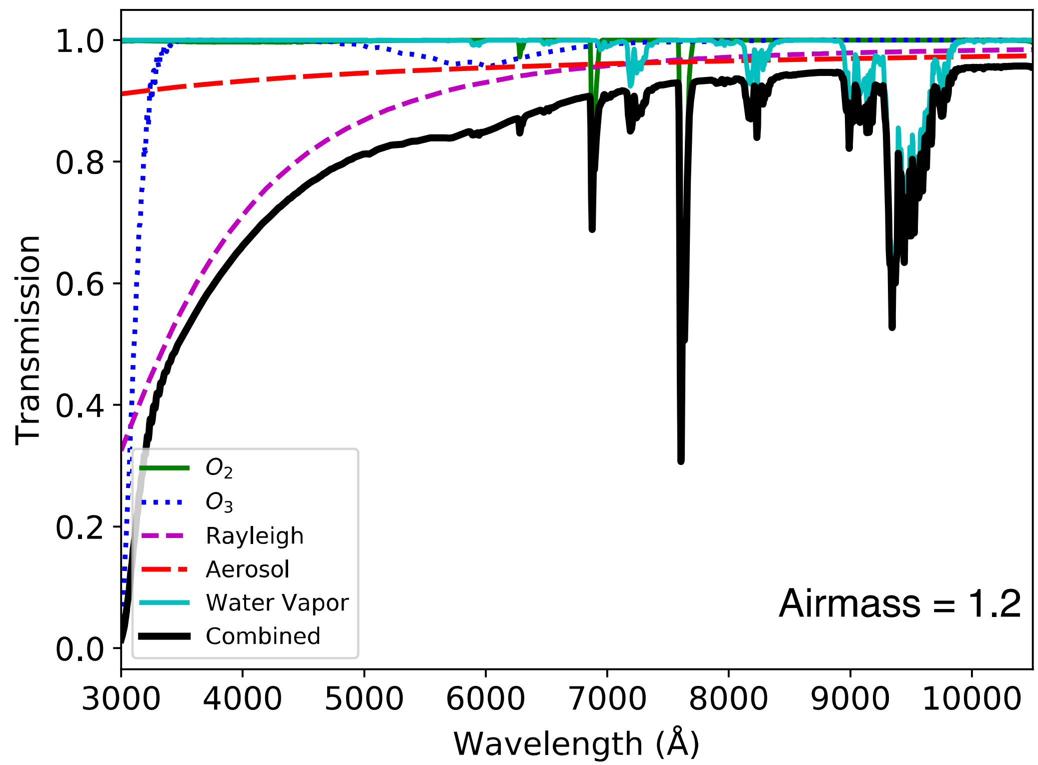
- The atmosphere is not clear … pesky molecules which give us air to breath and water to drink

- Choose a "standard atmosphere" to be as close to typical conditions as possible



The LSST Filters

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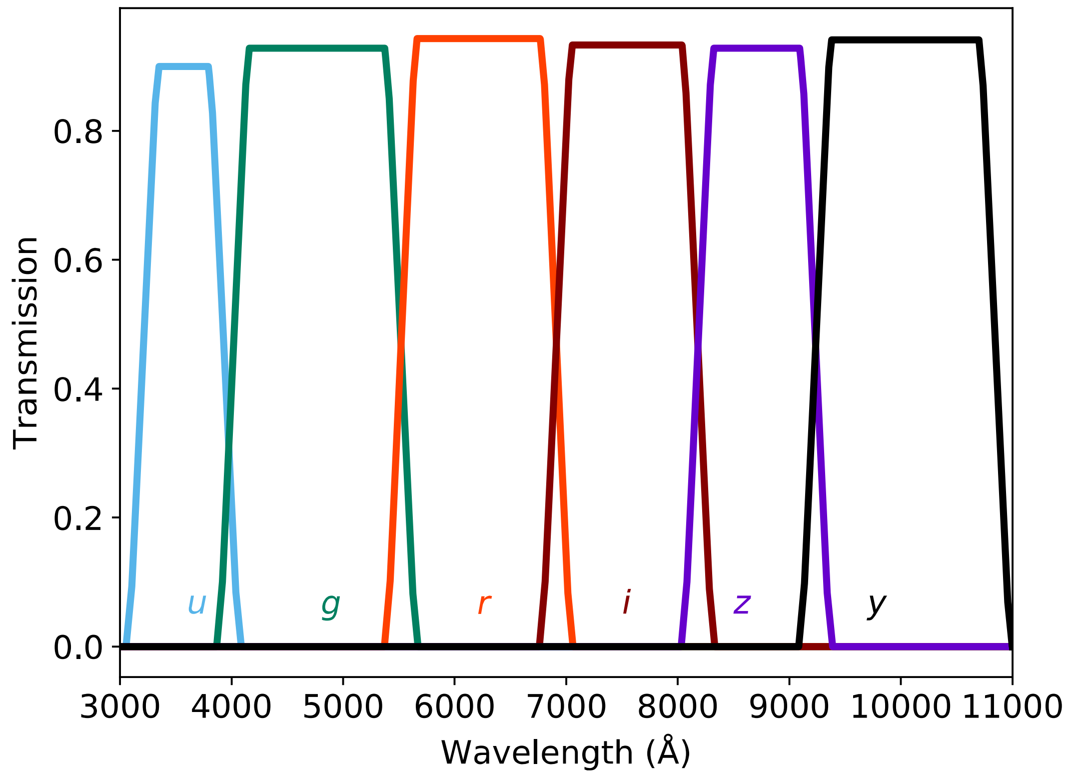
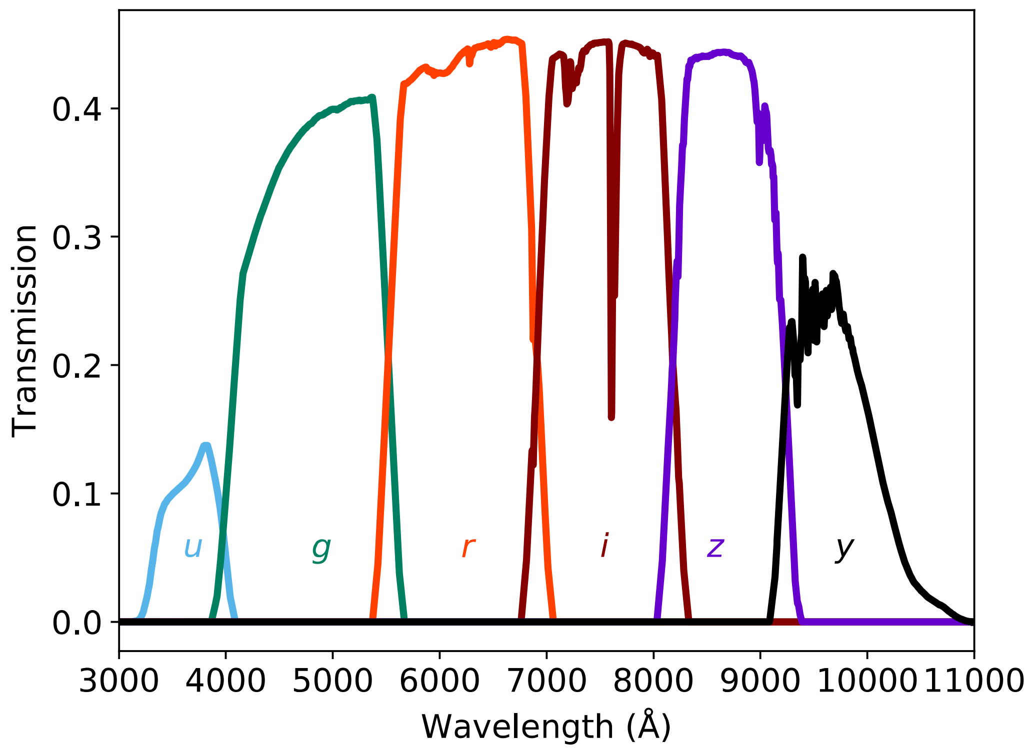
- These are the nominal LSST filters



The LSST Passbands

- These are the nominal LSST passbands (filter + mirror + lenses + ccds + atm)



Impact of the Atmosphere

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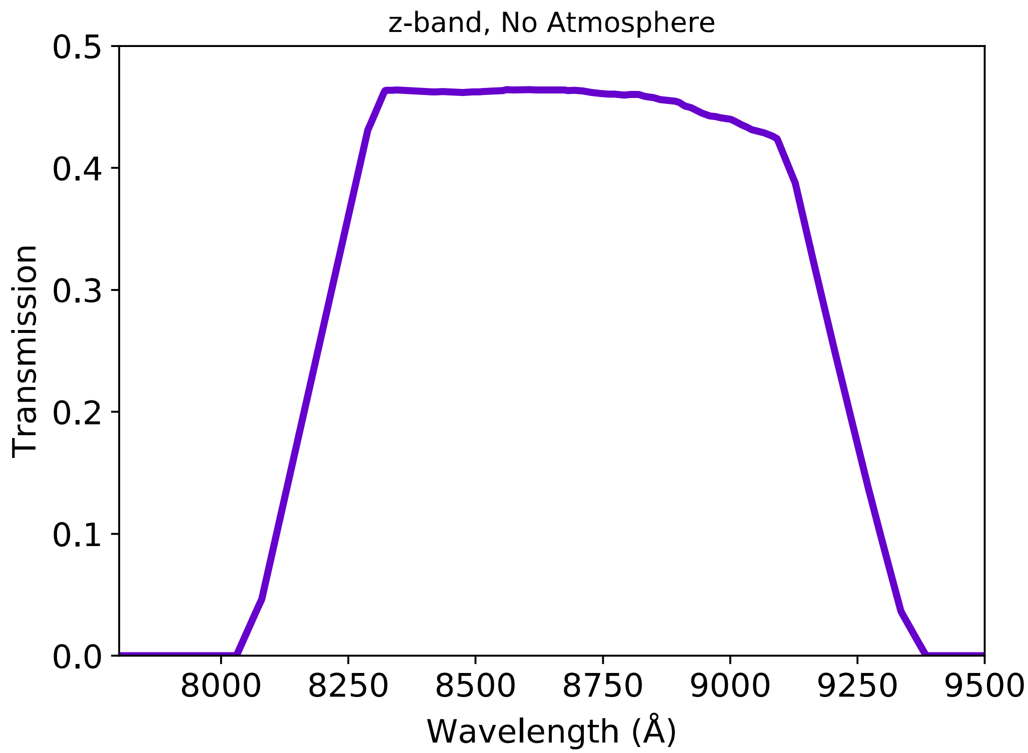
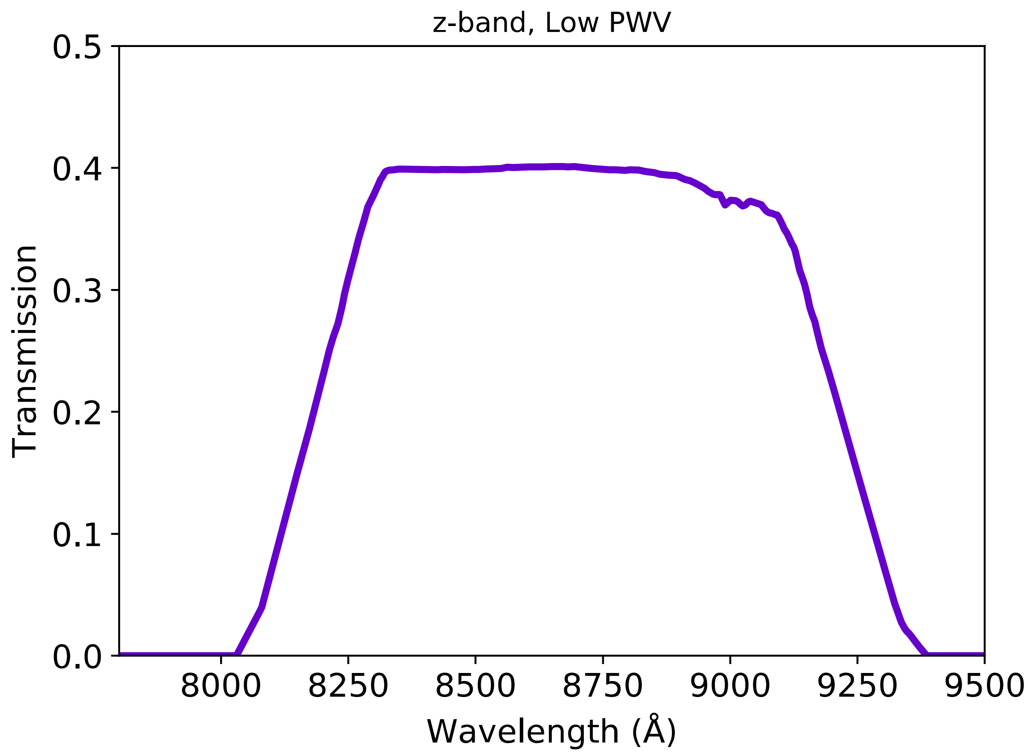
- Here is the z-band (filter + instrument)



Impact of the Atmosphere

- If we add the atmosphere with a touch of water



Impact of the Atmosphere

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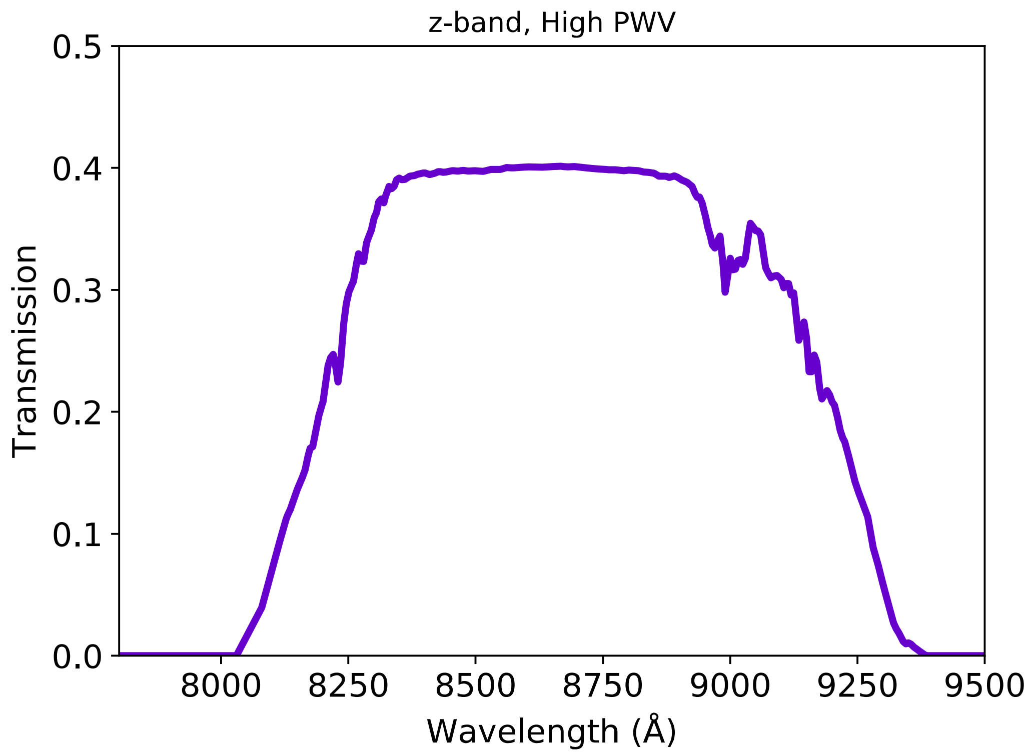
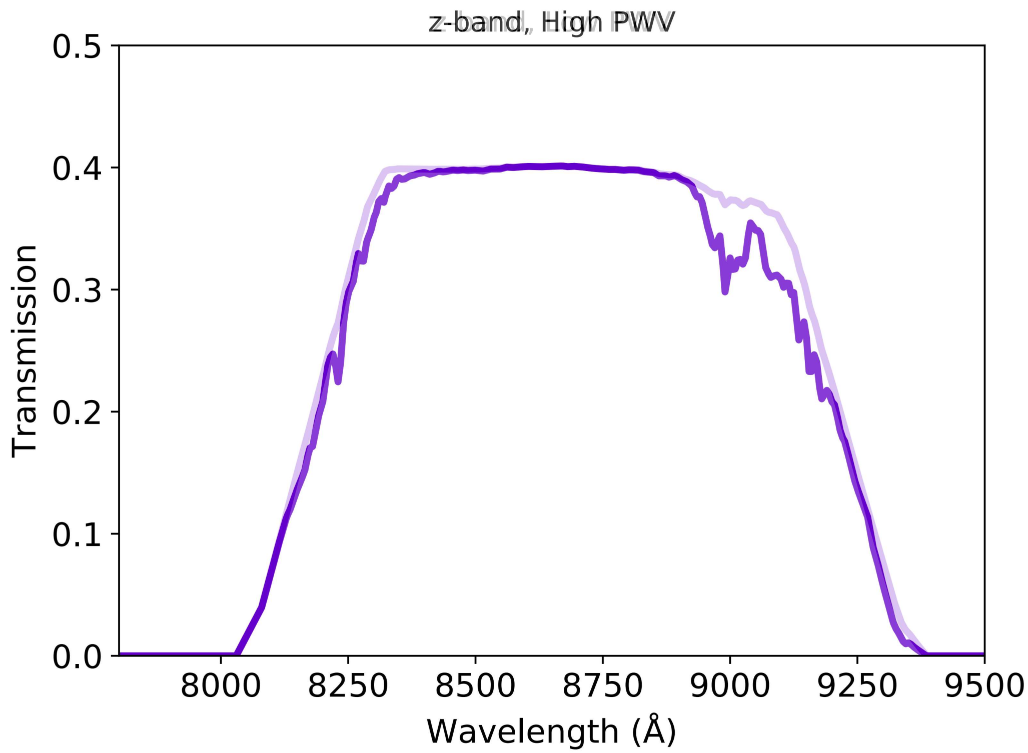
- If we add the atmosphere with a lot of water



Impact of the Atmosphere

- And we overlay the two — water vapor cuts out red end of z band (and blue end of y band)



Impact of the Atmosphere

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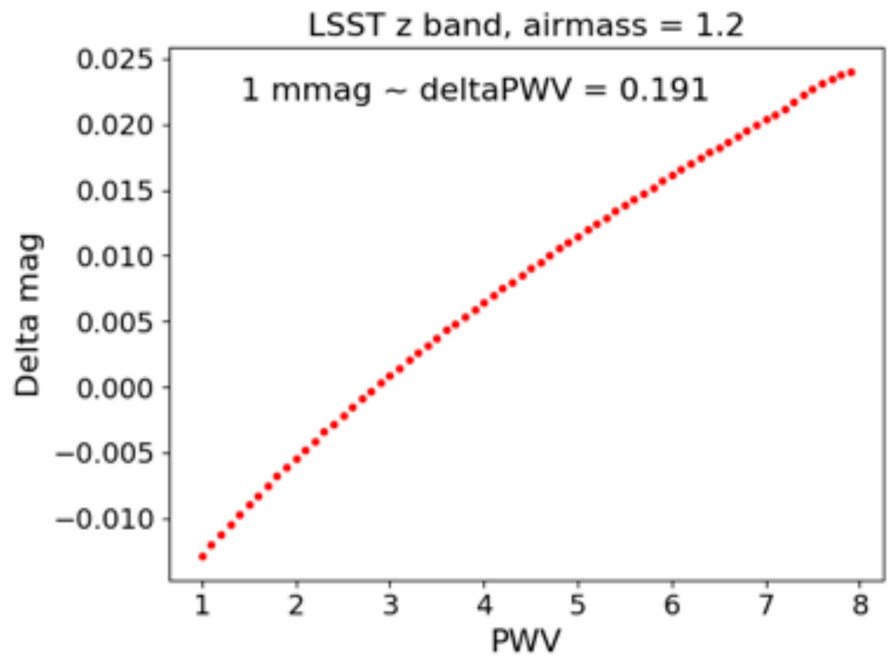
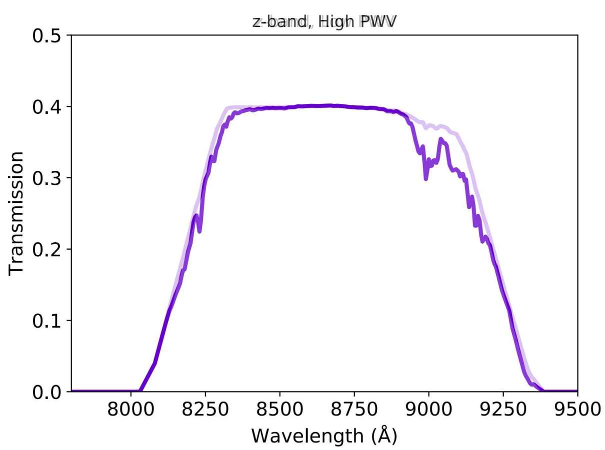
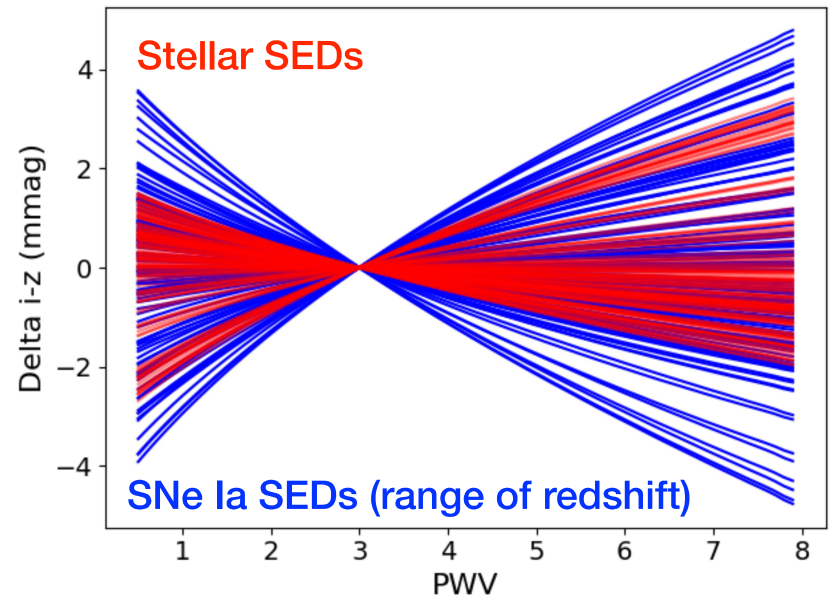
- Primary impact is the change in the overall throughput (transparency)
- To predict the total throughput at mmag level, we need to know PWV at the ~0.2 mm level
- This is degenerate with with any gray/opacity measurements so is not critical



Impact of the Atmosphere

- Secondary impact is the chromatic effect. Mostly the red end of the z band is removed!
- Size of impact depends on the SED
- For SNe, need to know PWV at ~1 mm level





Modeling the Atmosphere

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- AuxTel will observe stars around the sky with low-resolution Ronchi grating (see Robert's talk)
  - Remove the star, fit the atmosphere
  - Goal is to transform atmosphere to the standard (not necessarily know the individual components)

- Self-calibration via the Forward Global Calibration Method (FGCM)
  - Solve the global calibration problem with a physical model of the atmosphere + instrument
  - Picking up on Stubbs & Tonry (2006)
  - See Burke, Rykoff et al. (2018)

FGCM in a Nutshell

- Any variation in the atmosphere that has an observable effect … has an observable effect
  - This is the key to self-calibration
- 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 et al. 2016)
- Once we know the atmospheric extinction, can predict fluxes of all the objects in an exposure
- Works for “photometric observations” — those that are consistent with the atmosphere model

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

The FGCM Atmosphere Model

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- Use MODTRAN for atmospheric modeling
  - Goal is to get things to a standard, not necessarily to delve into the atmospheric physics
- The FGCM parameters
  - Precipitable Water Vapor (PWV)
  - Aerosol Optical Depth (AOD) normalization and slope
  - Ozone
- Given zenith distance and barometric pressure, we can additionally compute O2 and Rayleigh scattering from MODTRAN

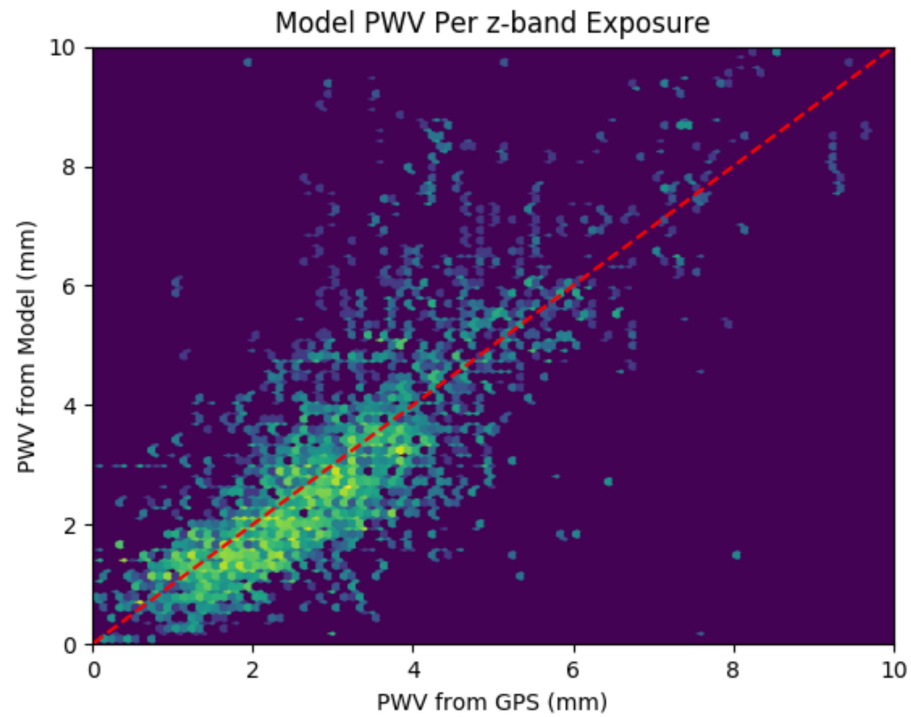
Datasets

- FGCM has been run on DES Years 1-3 ("Y3") and DES Years 1-6 ("Y6")
  - Burke, Rykoff et al. (2018), and Rykoff, Burke et al. (in prep)

- FGCM has also been run on HSC PDR2 data (via https://github.com/lsst/fgcmcal)
  - Currently running on HSC S20a processing

Testing PWV

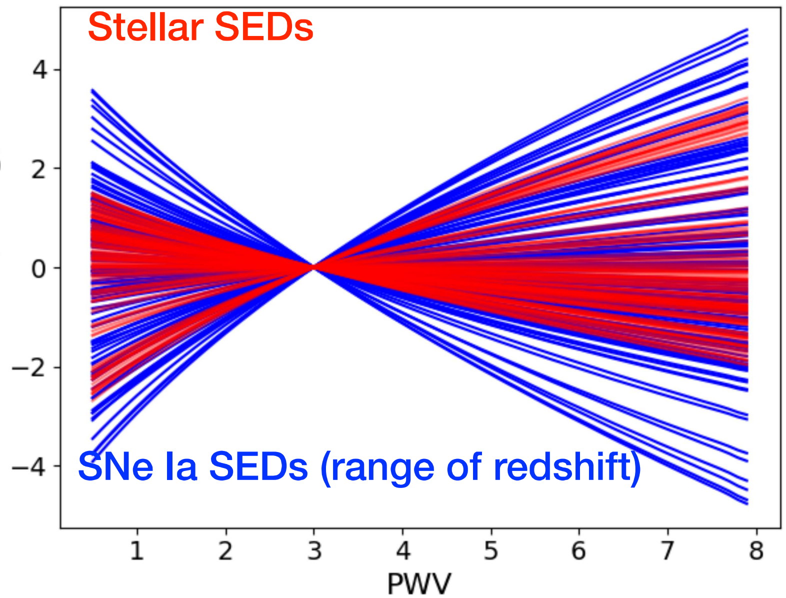
- For the first 4 years of DES, we had GPS measurements* of water vapor (not used in FGCM fit)
- There is good correlation per exposure
- Note that we do not care about the PWV for gri
- Good agreement in Y band as well (but noisier since the DES Y band is quite narrow)

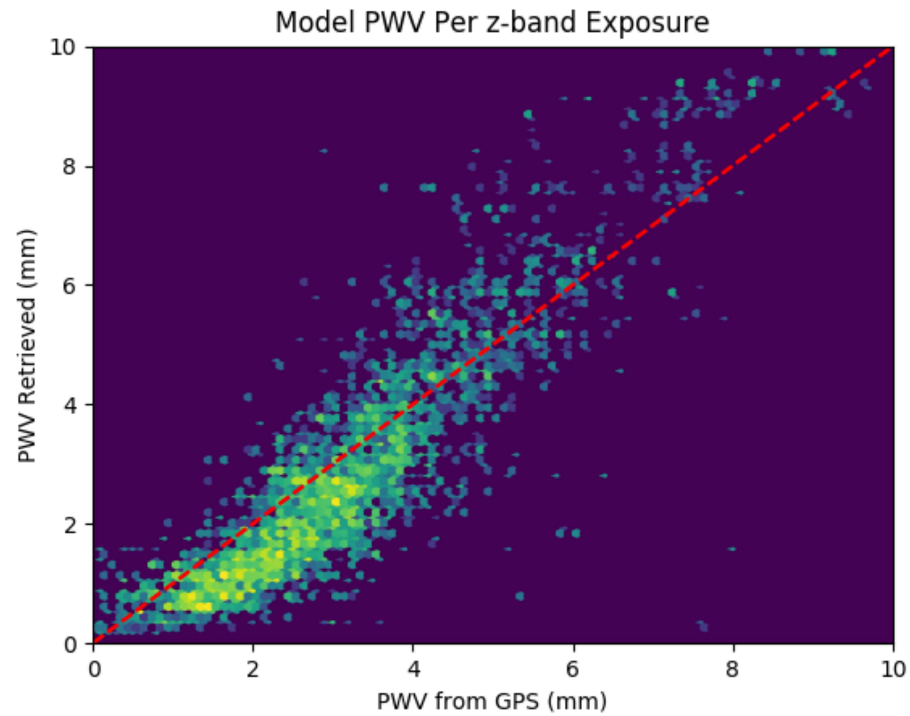


- *You can use GPS timing information to estimate the total water vapor in the atmosphere, by looking at the signal delay between different satellites

Testing PWV: The “Lupton Dream”

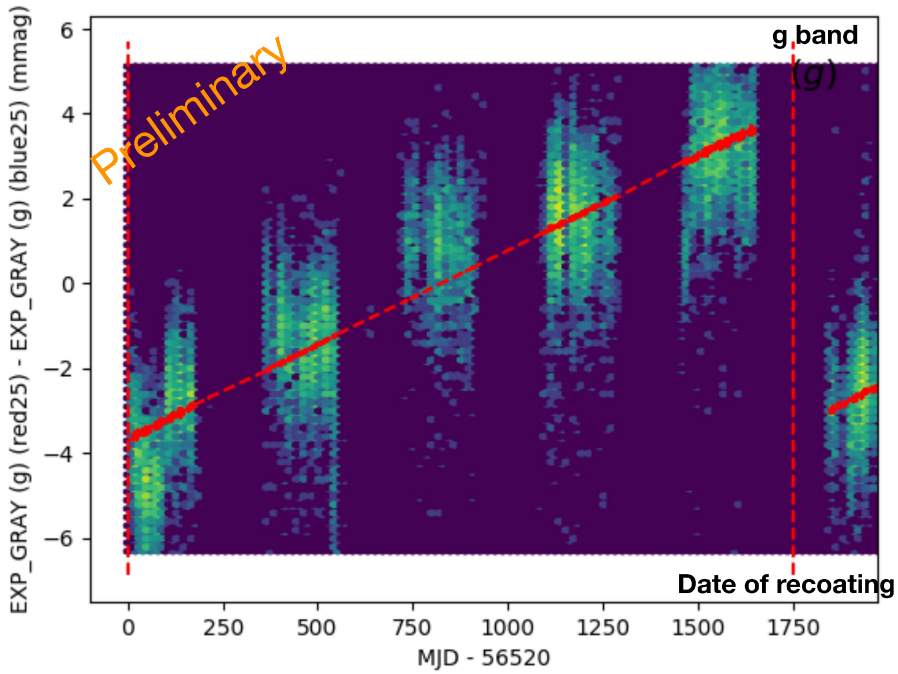
- Can we use the relative change in colors of red and blue stars at different levels of PWV to measure the PWV per exposure?
- Yes we can! Even in non-photometric conditions!





Temporal Variations in the Chromatic Passband

- In DES we looked at 6 years of chromaticity residuals
- Compare residuals of red stars to blue stars per exposure
- This is molecular degradation of the mirror surface
  - No amount of washing can clean this
  - Leads to a several mmag residual in the g-band over 5 years



Temporal Variations in HSC Reflectivity

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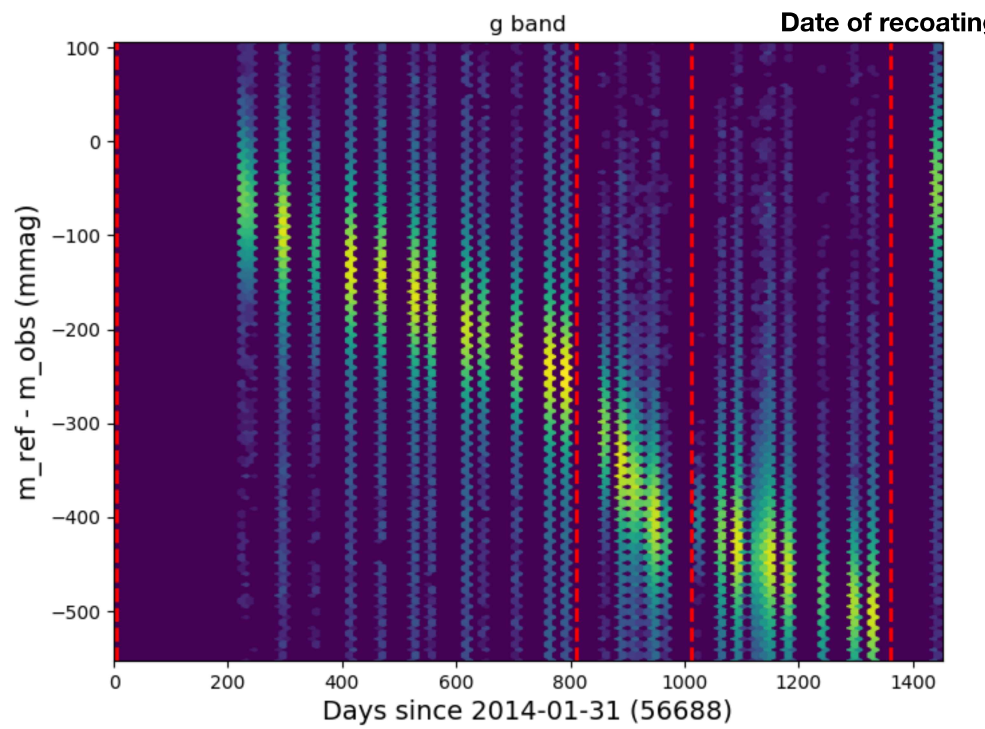
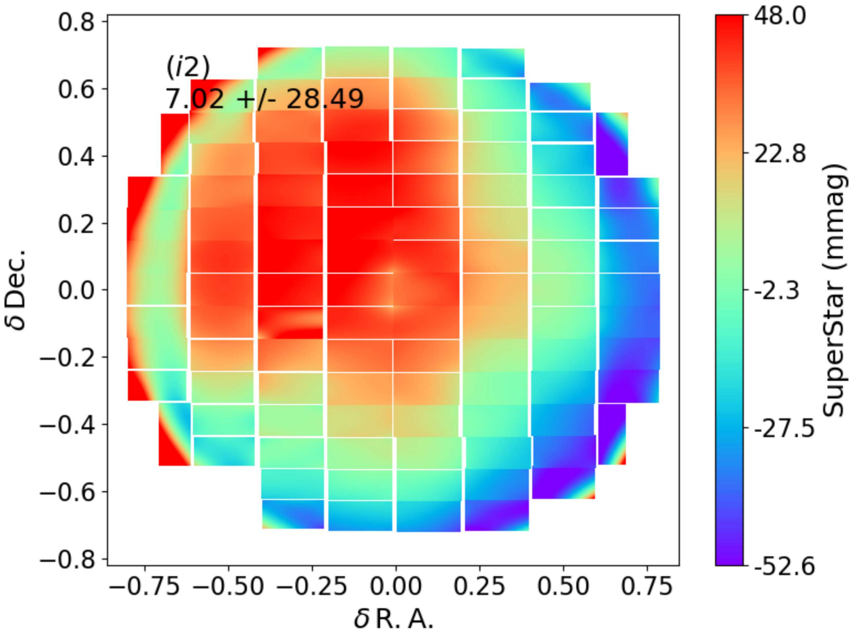
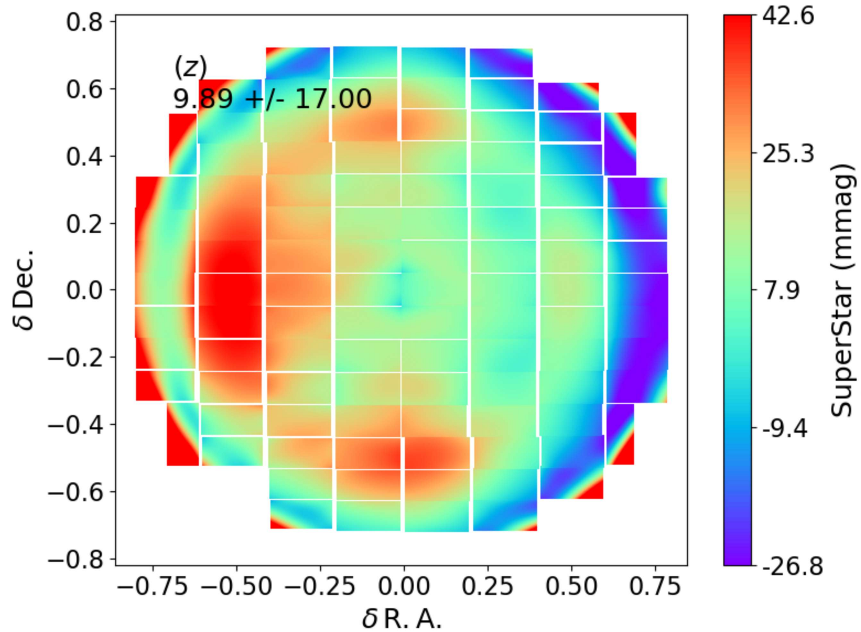
- Plot the raw comparison between observed (uncorrected) magnitudes and PS1 magnitudes
  - Reference stars are not required for FGCM fit, but can be used
- Over several years, a ~50% reduction in throughput before recoating (!)
- A period of several months with a more rapid decline (seen in all bands)
  - Corresponds with increased activity from Kilauea
  - Impact of “vog” (volcanic fog)?



FGCM Can Measure Illumination Corrections

- A “star flat” normalizes the response of the instrument to focused light
  - Plots are after removing pixel area variation as predicted by WCS





FGCM Can Test Throughput Measurements

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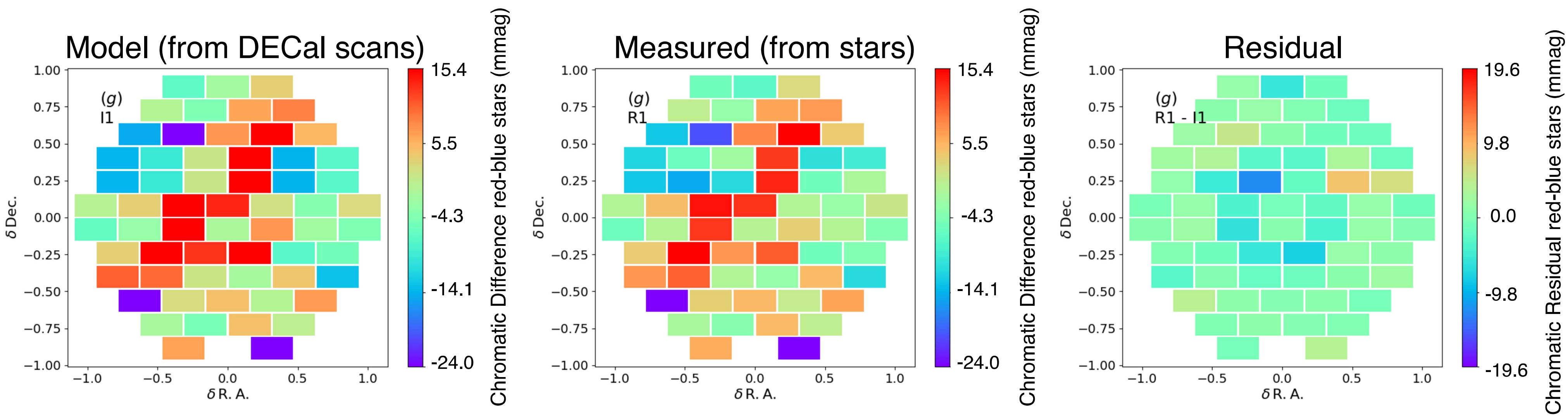
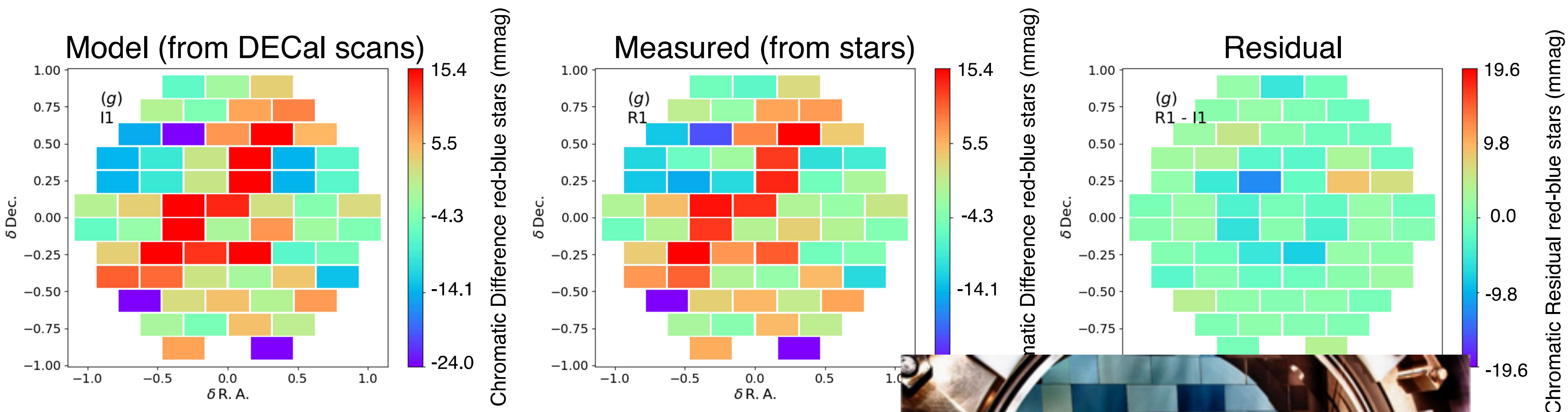
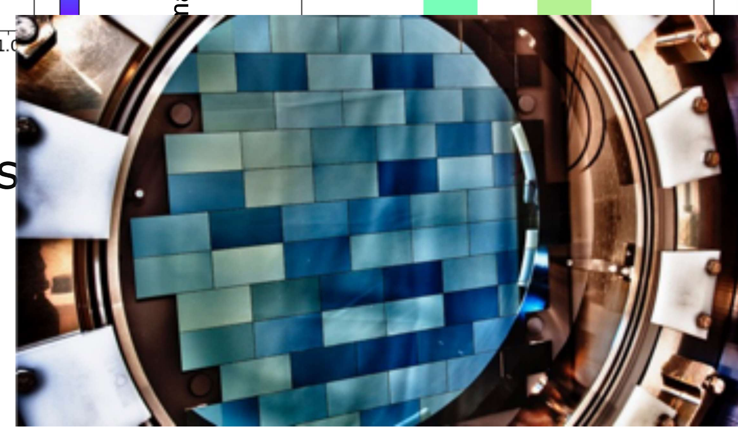


DES g-band

- Units are chromatic shift from blue to red stars
- Residuals are due to varying QE (typically AR coating in g band)

FGCM Can Test Throughput Measurements





- Units are chromatic shift from blue to red stars ... nd
- Residuals are due to varying QE (typically AR coating in g band)

FGCM Can Test Throughput Measurements

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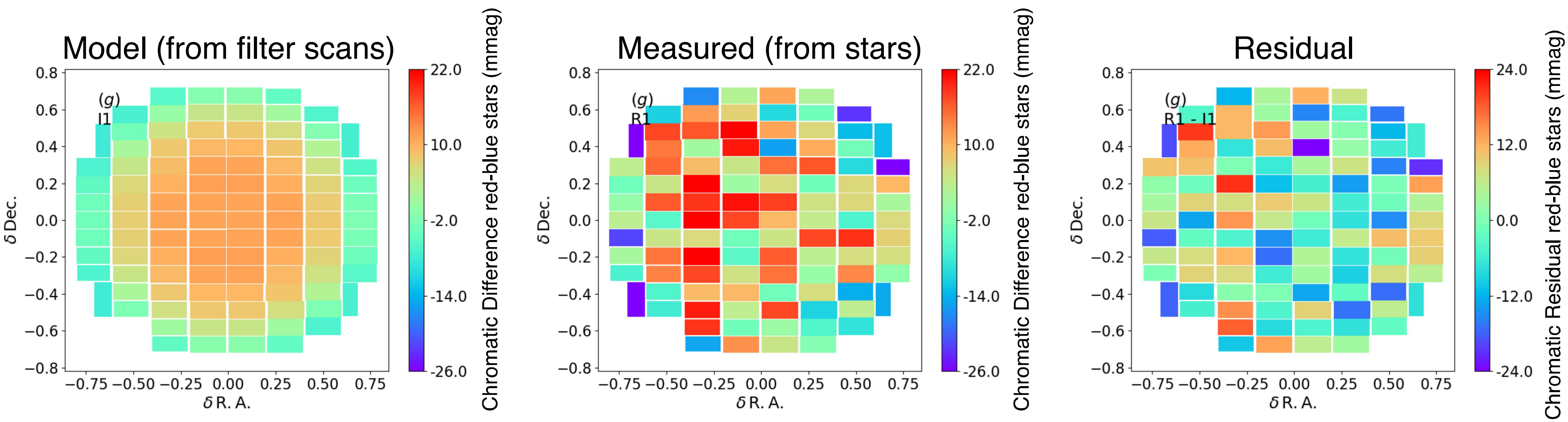
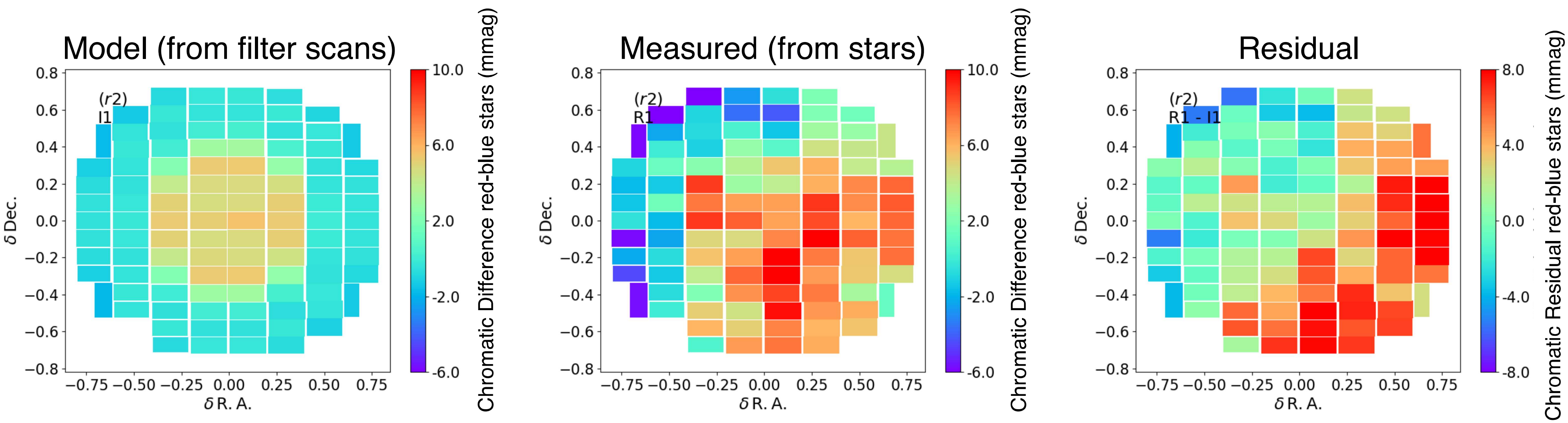


HSC g-band

- Units are chromatic shift from blue to red stars
- Residuals are due to varying QE (typically AR coating in g band)

FGCM Can Test Throughput Measurements



HSC r2-band

- Units are chromatic shift from blue to red stars
- There is azimuthal dependence of filter throughput
  - Seen in filter scans, not supported in stack yet

FGCM Repeatability (DES Y6)

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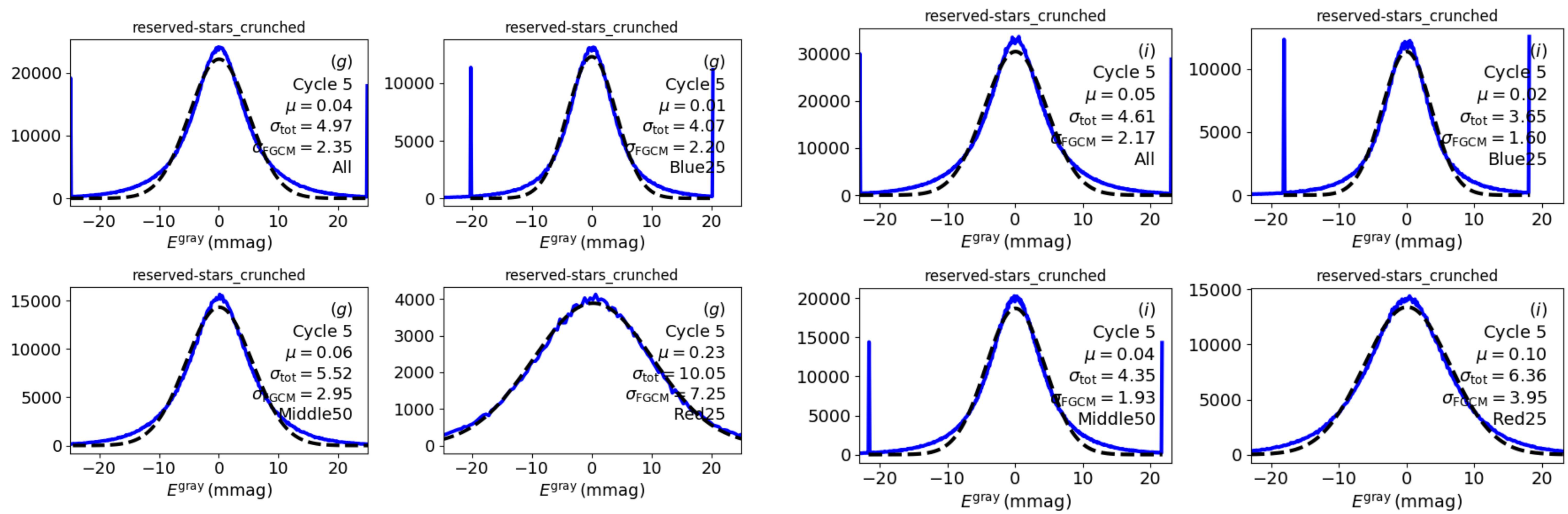
- 2-4 mmag repeatability for most bands / colors
  - Worst for reddest stars in g-band (unmodeled chromatic corrections)



FGCM Uniformity (DES Y6)

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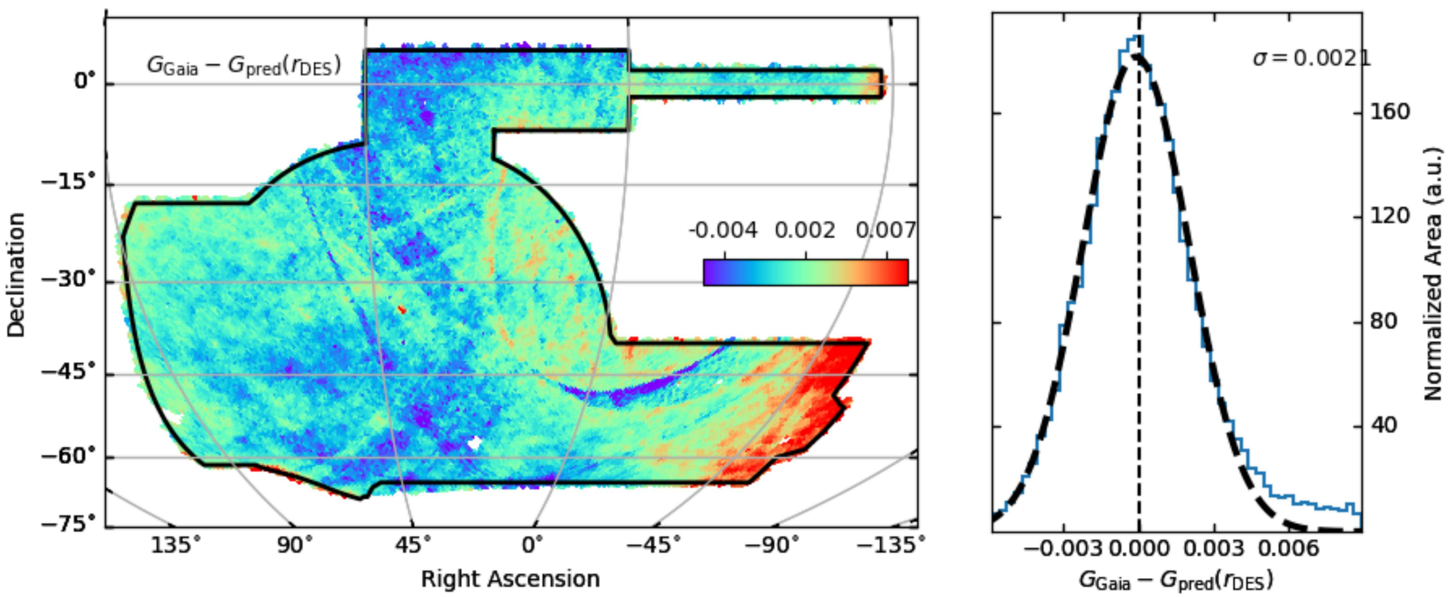
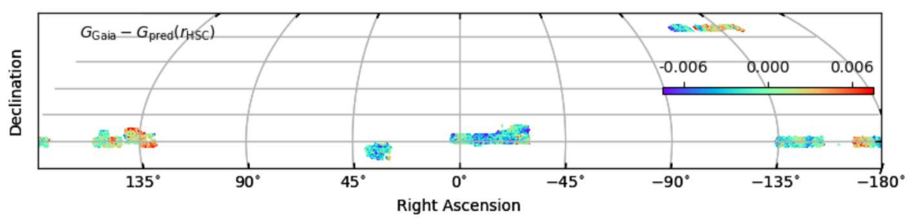
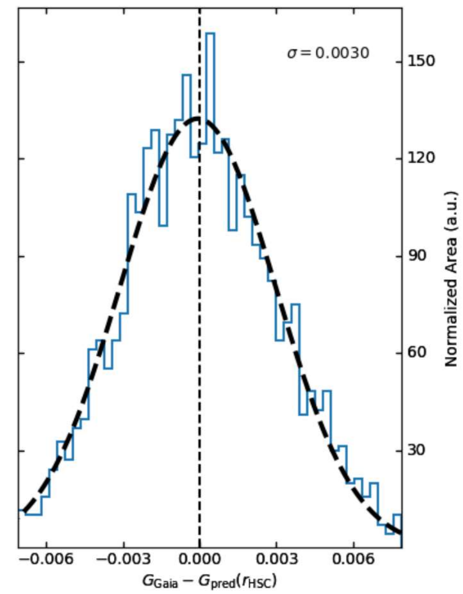
- Compare to Gaia GDR2
  - Synthesize Gaia G using (weighted) g+r+i+z
- Consistency at 2.1 mmag



FGCM Uniformity (HSC PDR2)

- Run without reference stars, 3.0 mmag uniformity
- Enough observations of deep fields to tie separated wide fields together
- Thankfully, LSST will not observe like this…





Wait … What are we calibrating?

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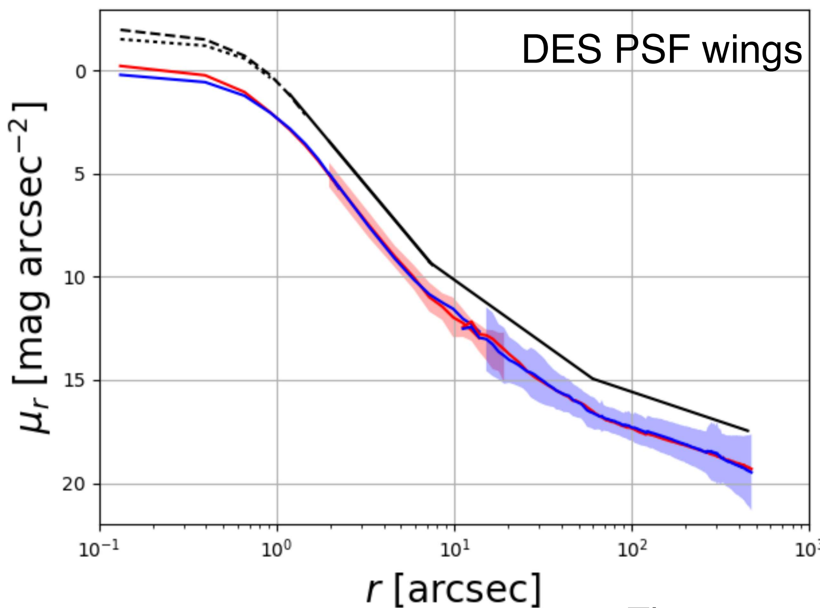
- Traditionally use a largish (12 pixel radius for HSC) aperture for calibrations
  - These are correct for "fluence" images (number of photons incident on the pixel) vs a surface brightness image (differ by a factor of pixel area)
- Not all the flux from the stars falls into this aperture!
- What are the implications? How do we correct for this?
- Aperture corrections!
  - Unfortunately, this is not a uniquely defined concept…

“Aperture Corrections” (Of the First Kind)

- Our best stellar and galaxy photometry is based on PSF-convolved fluxes
- The PSF extends to infinity…
- Should we correct our aperture fluxes to infinity?
- Could use a curve-of-growth…
- This is very difficult and very noisy to compute how it varies on short spatial and temporal scales!



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“Aperture Corrections” (Of the Second Kind)

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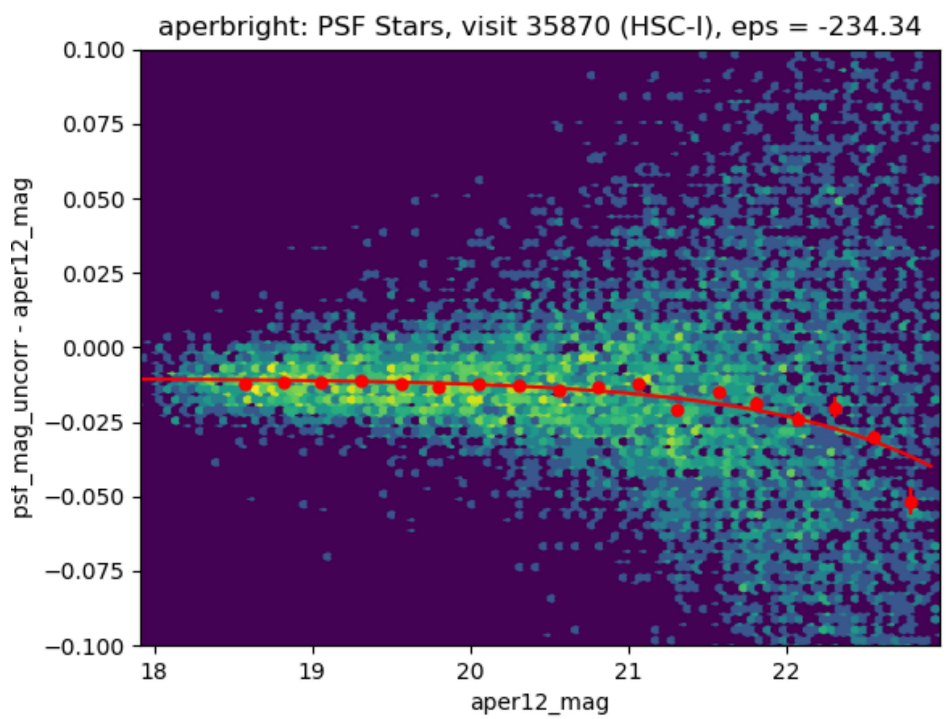
- But all our measurements are relative!
- If we measure our primary calibration stars (e.g. CALSPEC) with the same 12 pixel aperture we only need to know the flux *within this aperture*
- So we empirically compute an “aperture correction map” to convert PSF/Cmodel/etc fluxes to the same normalization as our calibration fluxes for well-measured stars
- This accomplishes the same goal as the curve-of-growth but avoids pesky infinities
- Note that these aperture correction maps are applied to all stack coadd quantities that rely on PSF models!

"Aperture Corrections" (Of the Second Kind)

- Summarize the full focal-plane difference between PSF and aper mags on a single HSC image

Offset because of different normalization



Curved because of sky/background issues

"Aperture Corrections" (Of the Second Kind)

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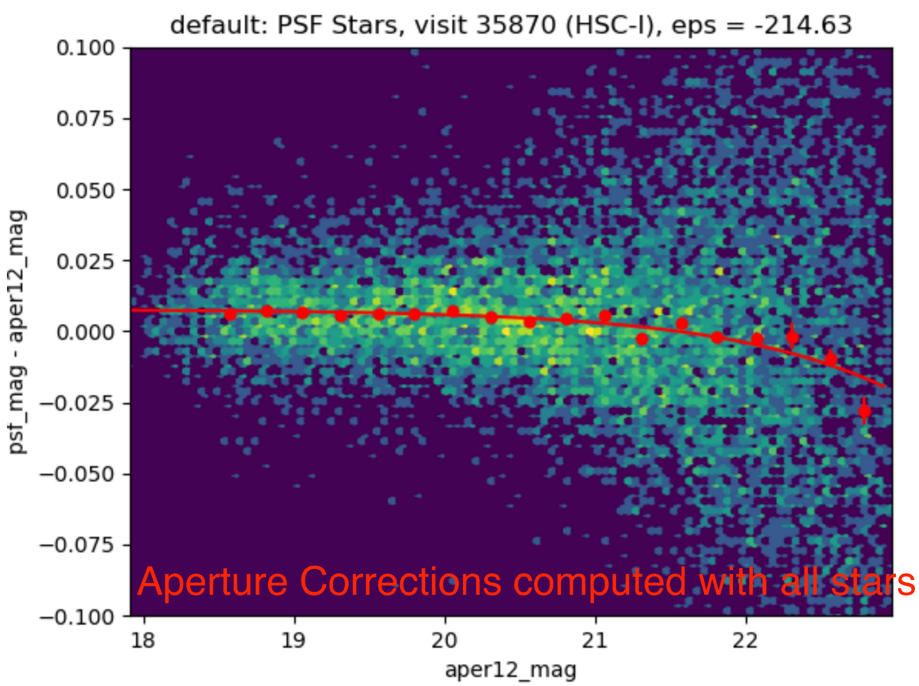
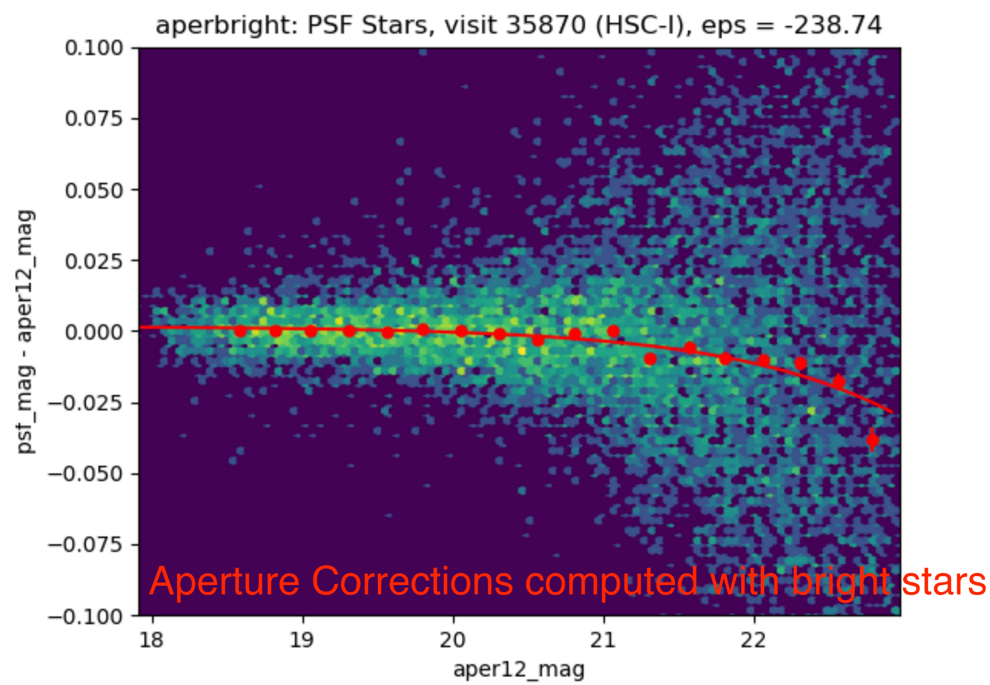
- We must be careful in how we compute the aperture correction map
- If we do not get background correct, all stars should not be equally weighted





“Aperture Corrections” (Of the Second Kind)

- Is this method optimal?
  - No.

- I believe we know more about the PSF variations (as imperfect as this knowledge is) than to rely on fully empirical corrections

- We plan on exploring this further

“Aperture Corrections” (Of the Third Kind)

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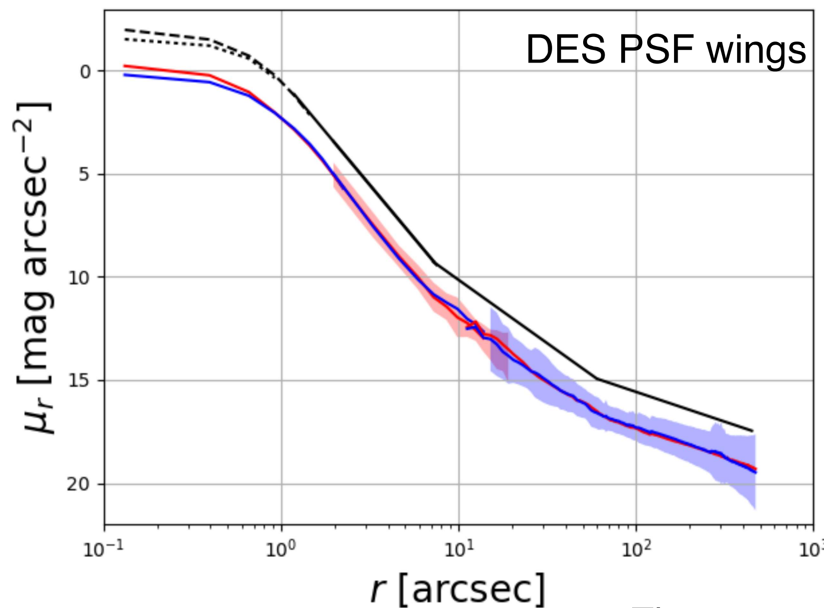
- We calibrate with a 12 pixel (2.4” radius) aperture …
- As the wings of PSF change then more light will go into and out of this aperture.
- The FGCM model must account for this.
  - See also Bernstein et al. (2018), and Gary’s talk from this morning



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"Aperture Corrections" (Of the Third Kind)

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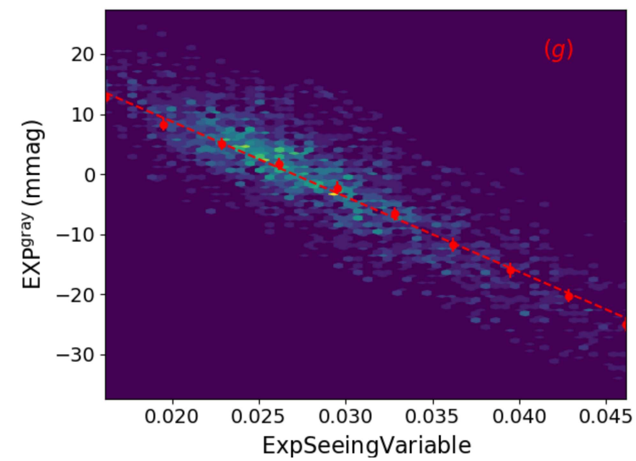
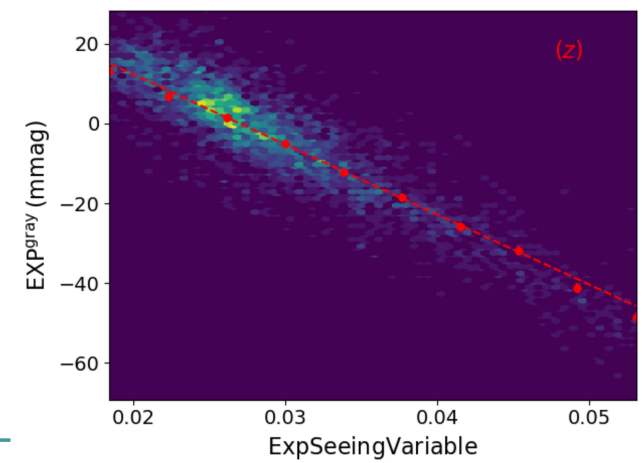
- Compute median of mag in 17 pix aper - 12 pix aper
- Photometric residual is strongly correlated!
- Primary source of apparent "non-photometricity"
    - This can be modeled!

In summary, we find that *all* of the deviations above ≈1 mmag rms from a static response function plus secant airmass law on short timescales are plausibly attributable to spatial/temporal variations in aperture corrections. The A_t statistic measured from bright stars is an accurate predictor of these aperture corrections, so on a typical half-hour stretch of clear-sky observations we can homogenize the exposure zeropoints to ≈1 mmag, and if we have sufficient stellar data in an exposure to map out variation of A_t across the FOV, we could reduce any intra-exposure inhomogeneity to similar level.





Conclusions

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- In order to get calibrations to the 5 mmag level (project) or 1 mmag level (DESC) requirements we must know
  - Instrumental throughput (CBP)
  - Atmosphere (AuxTel / FGCM)
  - Throughput variations (FGCM)
- In DES we are <5 mmag
  - Without using external reference catalogs
  - Gets easier with more overlap in space and time (yay LSST!)
- Aperture corrections and PSF modeling remain issues!