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A Draft Of An Idea of a Plan for Photometric Calibration

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DESC PCWG June 10th, 2022

Caveat

- This is a talk from me, Eli Rykoff, on my ideas for how we should be doing photometric calibration with LSST
- This is not fully fleshed out nor is it approved!
- We are drafting the formal plan for end-to-end calibration this summer. For realz.

- Also …
  - Please don’t ask me about u-band.

What is Photometric Calibration?

- “How bright is this object in physical units such as Jansky (10^{-26} W m^{-2} Hz^{-1})?”
  - Power per unit area per unit frequency
  - LSST calibrated flux units will be nanojansky

- Our instrument measures broadband fluxes over a range of frequencies
- This leads to … complications

Everything is Relative

- Measuring absolute fluxes is really quite difficult
  - Though all we need are 6 numbers (one for each band)

- 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.

Photometric Calibration in Two Easy Steps

- Step 1:
  - Combine measurements of stars, instrumental throughput, and atmosphere to estimate how to go from counts to nJy for an arbitrary SED object detected at a given location/time/filter.
- Step 2:
  - Apply this photometric calibration to all your objects in the survey.

Some Terminology

- 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

Step 1/N: ISR

- The Instrument Signature Removal (ISR) step is essential for removing instrumental features.
  - This talk is not going to focus on this, but it is a non-trivial issue with LSSTCam.
- The form of the output matters
  - **Fluence** images (report the total incident photons in each pixel) are for aperture fluxes
  - **Surface Brightness** images (report the mean surface brightness in the pixel) are for model fluxes
  - Differ by a factor of pixel area

Step 2/N: Measuring Stars

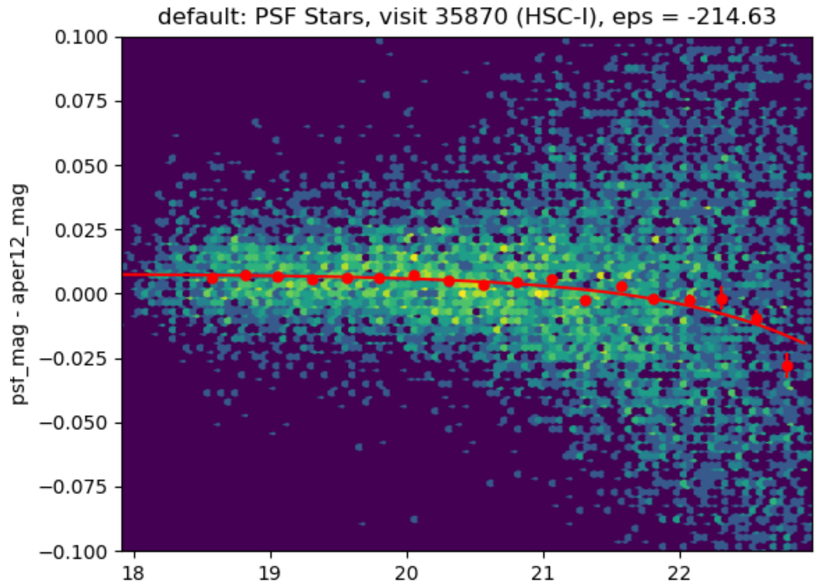
- How do we measure stars used to use for photometric calibration?
  - Can use a large, fixed aperture to measure flux
    - Pro: Insensitive to core of the PSF
    - Pro: A top-hat is a very simple model!
    - Con: Large aperture means lots of noise
    - Con: Large aperture is very sensitive to the local background
  - Could use PSF fluxes
    - Pro: Much less sensitive to local background
    - Con: A much more complicated model
  - Note that calibration issues from mis-estimated local background is a leading systematic in both DES and HSC calibrations.

Step 2/N: Measuring Stars

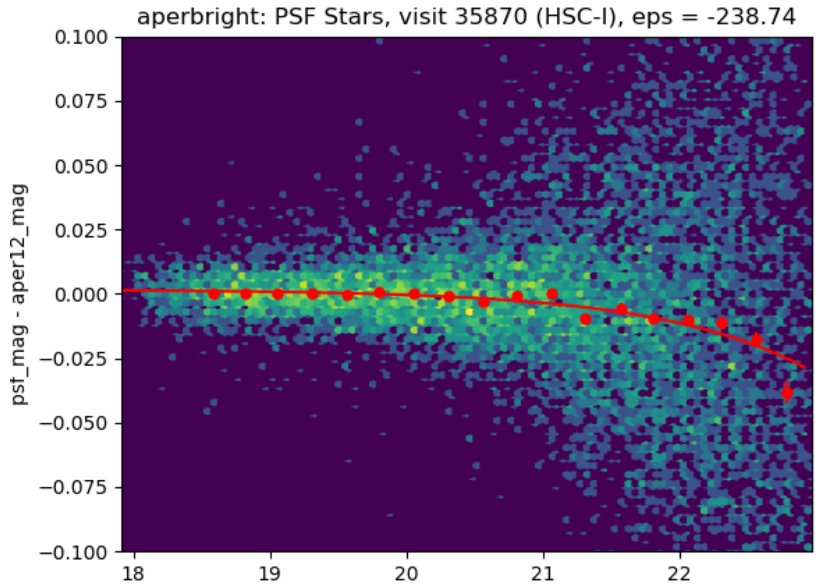
- An alternative: “compensated filters” (R. Lupton)
  - A fancy name for local background subtraction
  - Can be used with Gaussian filter or top-hat
  - If you do it right, then you get a lot of advantages without a noise penalty.
  - Nate Lust and I are working on this. Still not sure it’s going to work.
  - Need to think very clearly about “aperture corrections”

Step 3/N: Aperture Corrections

- 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
- But measuring this aperture correction map can go terribly awry.



Aperture Corrections computed with all stars



Aperture Corrections computed with bright stars

The Modeling Chain

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Star or Galaxy	SED measurements (CALSPEC, Gaia, templates, etc.)
Galactic Dust	Gaia, NIR, self-calibration
Atmosphere	AuxTel or self-calibration (FGCM)
Telescope / Filter	Collimated Beam Projector (CBP)
CCD	Collimated Beam Projector (CBP)

Types of Calibration Errors

- 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?

Computing Calibrated Flux

- 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:

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

Computing Calibrated Flux

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- 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

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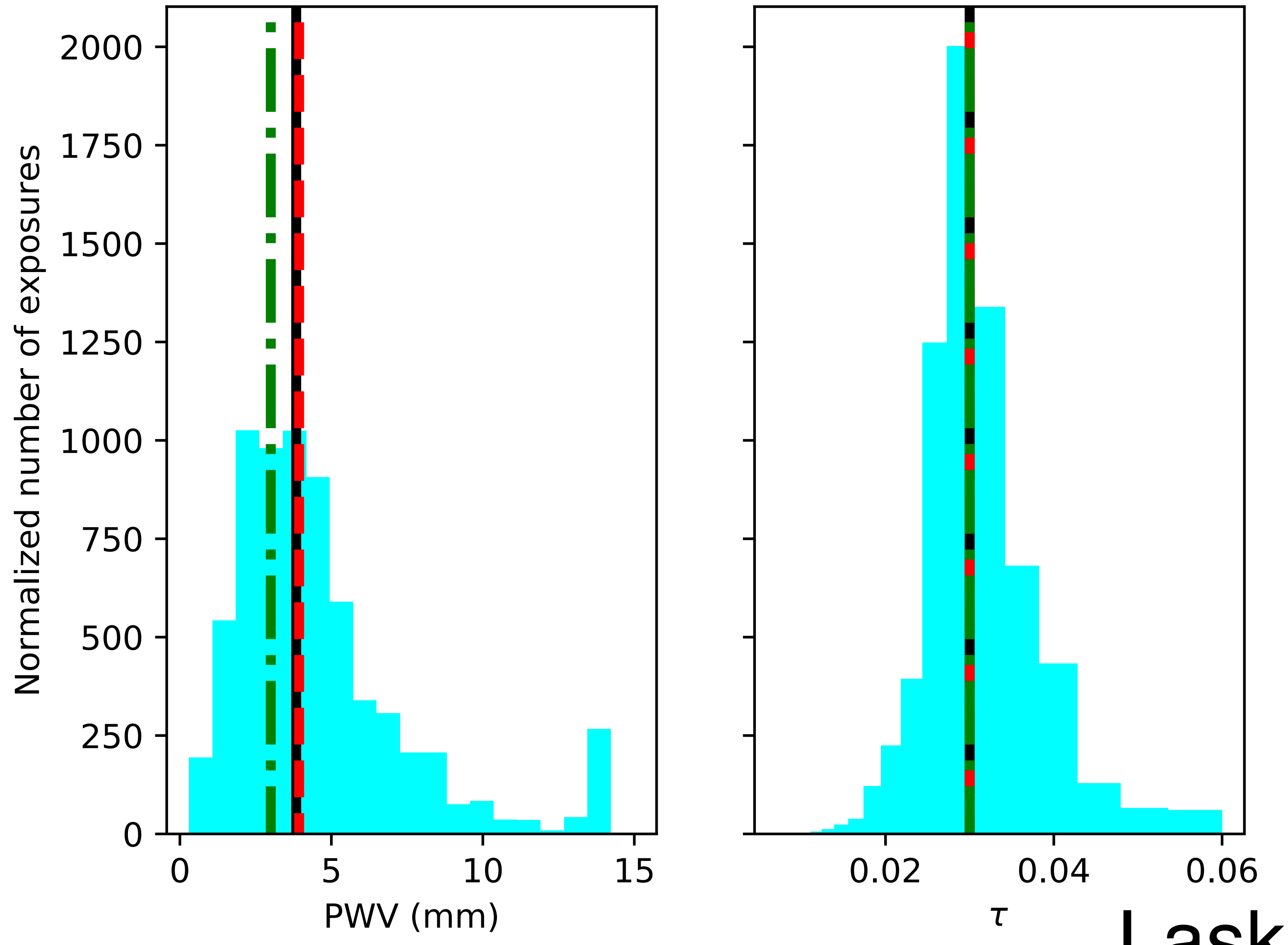
- If either the SED is the flat AB spectrum or the observed passband is the standard passband, the chromatic correction is 0.

- 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



Lasker+19

The Atmosphere

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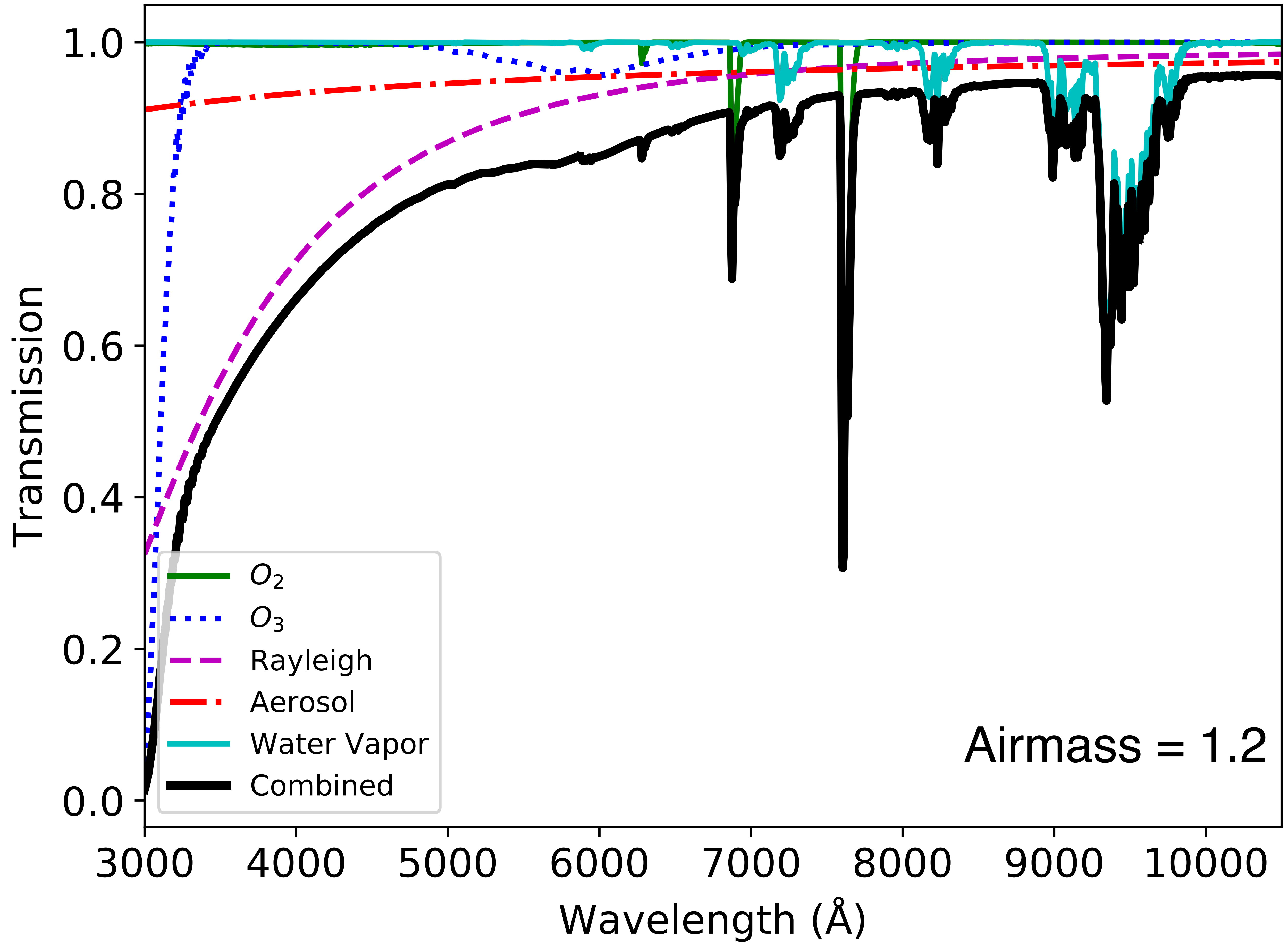
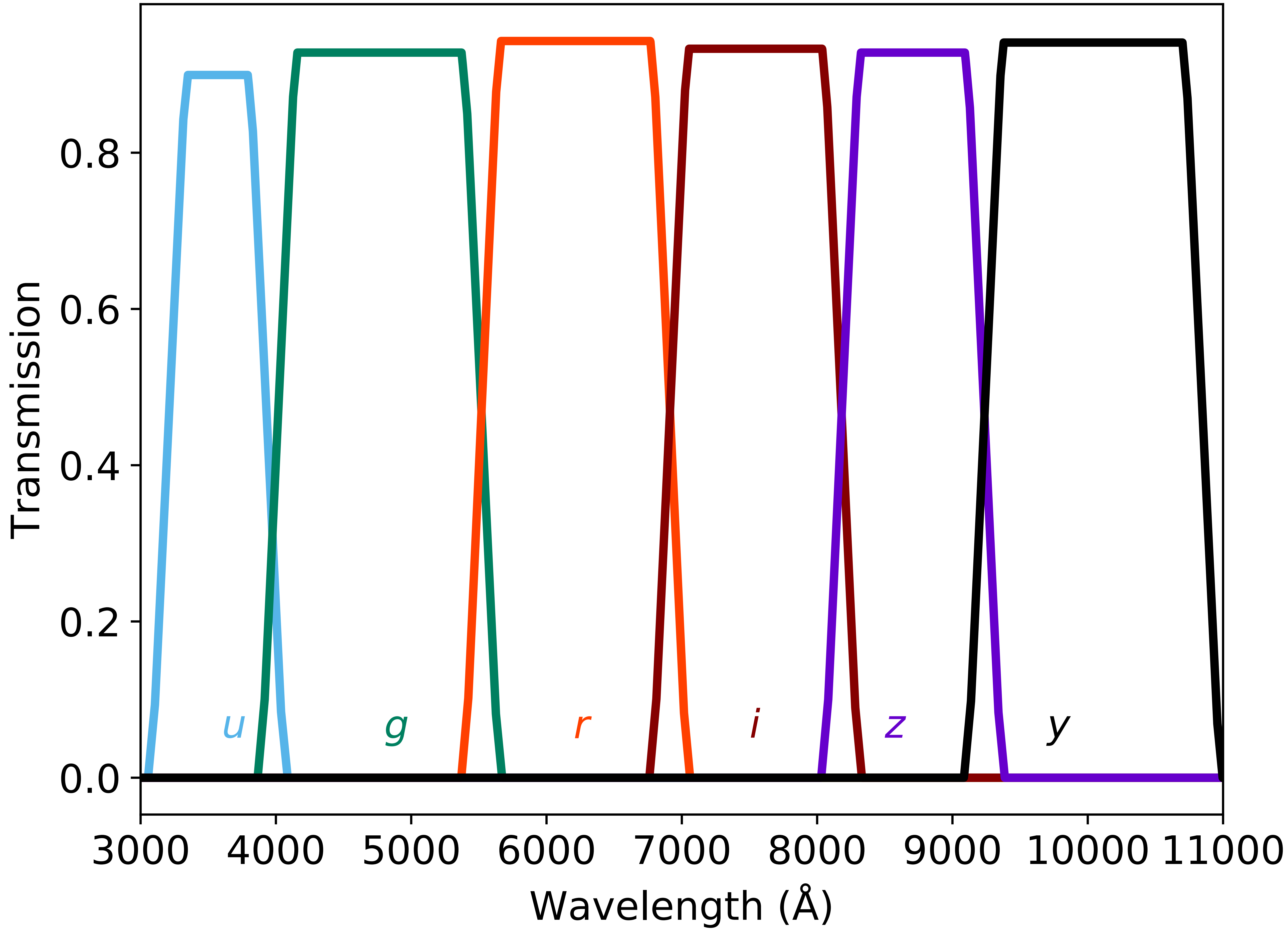
- The atmosphere is not clear … pesky molecules which give us air to breath and water to drink
- Choose a “standard atmosphere” to be as close to typical conditions as possible



The LSST Filters

- These are the nominal LSST filters



The LSST Passbands

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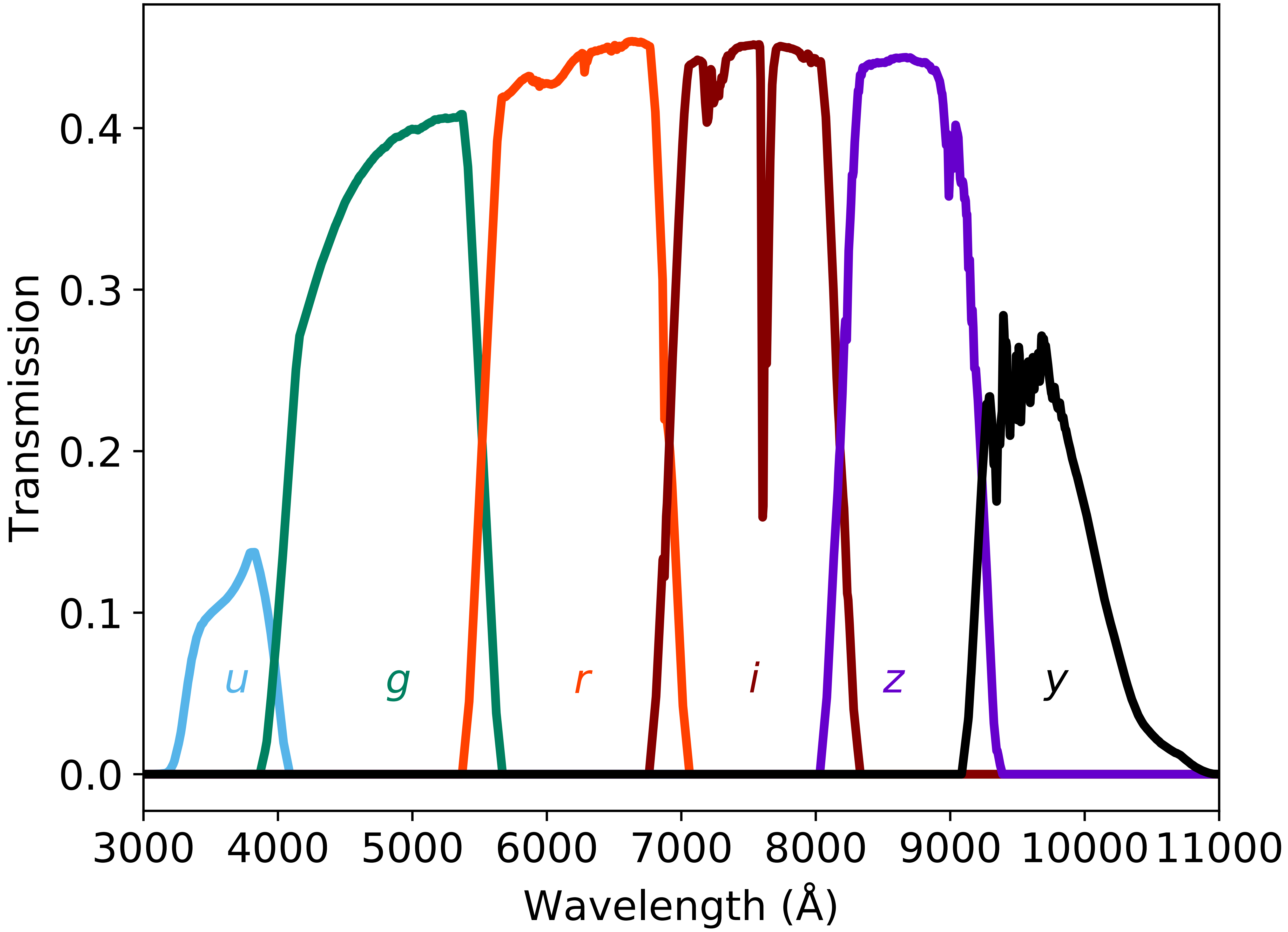
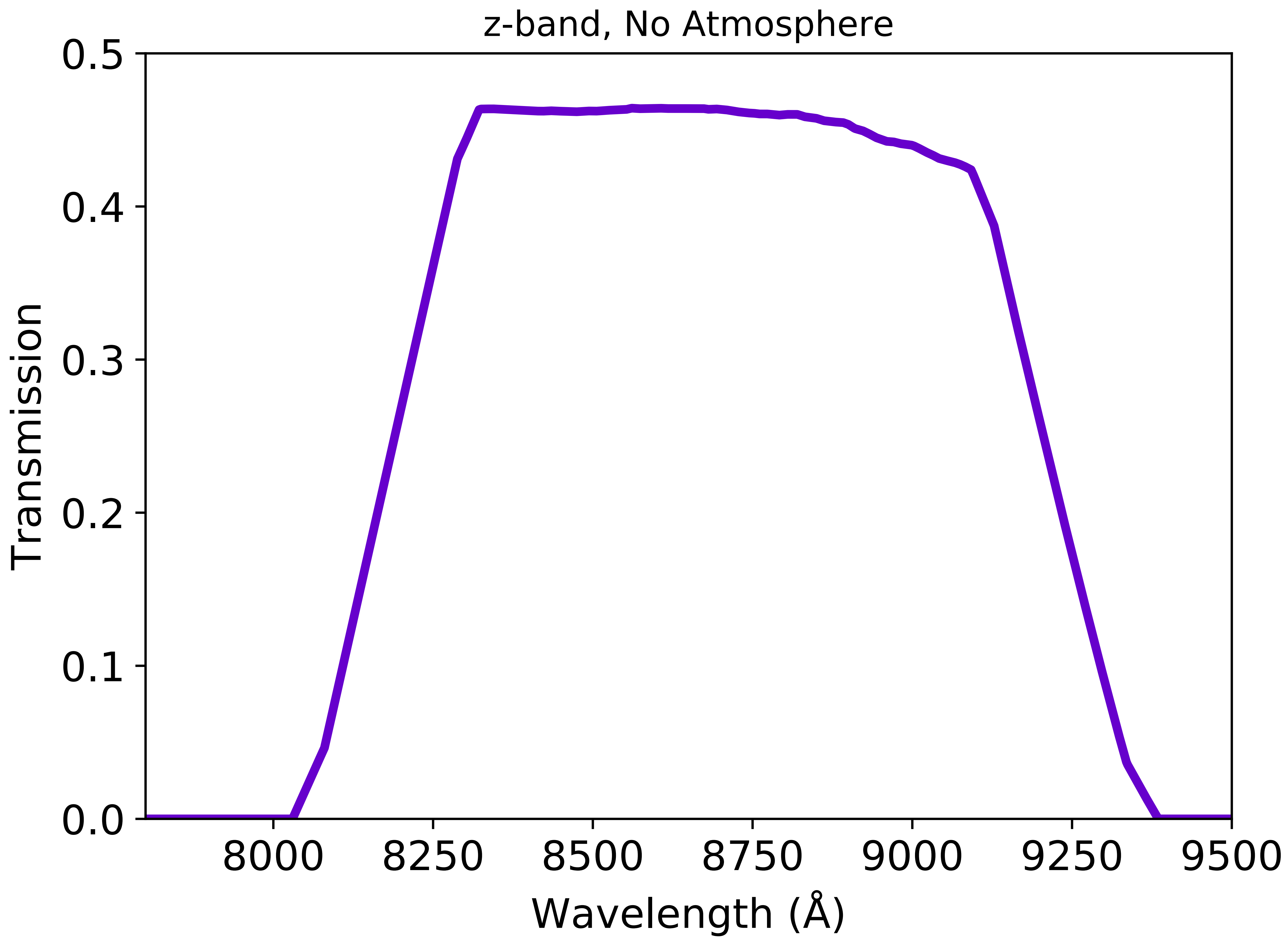
- These are the nominal LSST passbands (filter + mirror + lenses + ccds + atm)



Impact of the Atmosphere

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



Impact of the Atmosphere

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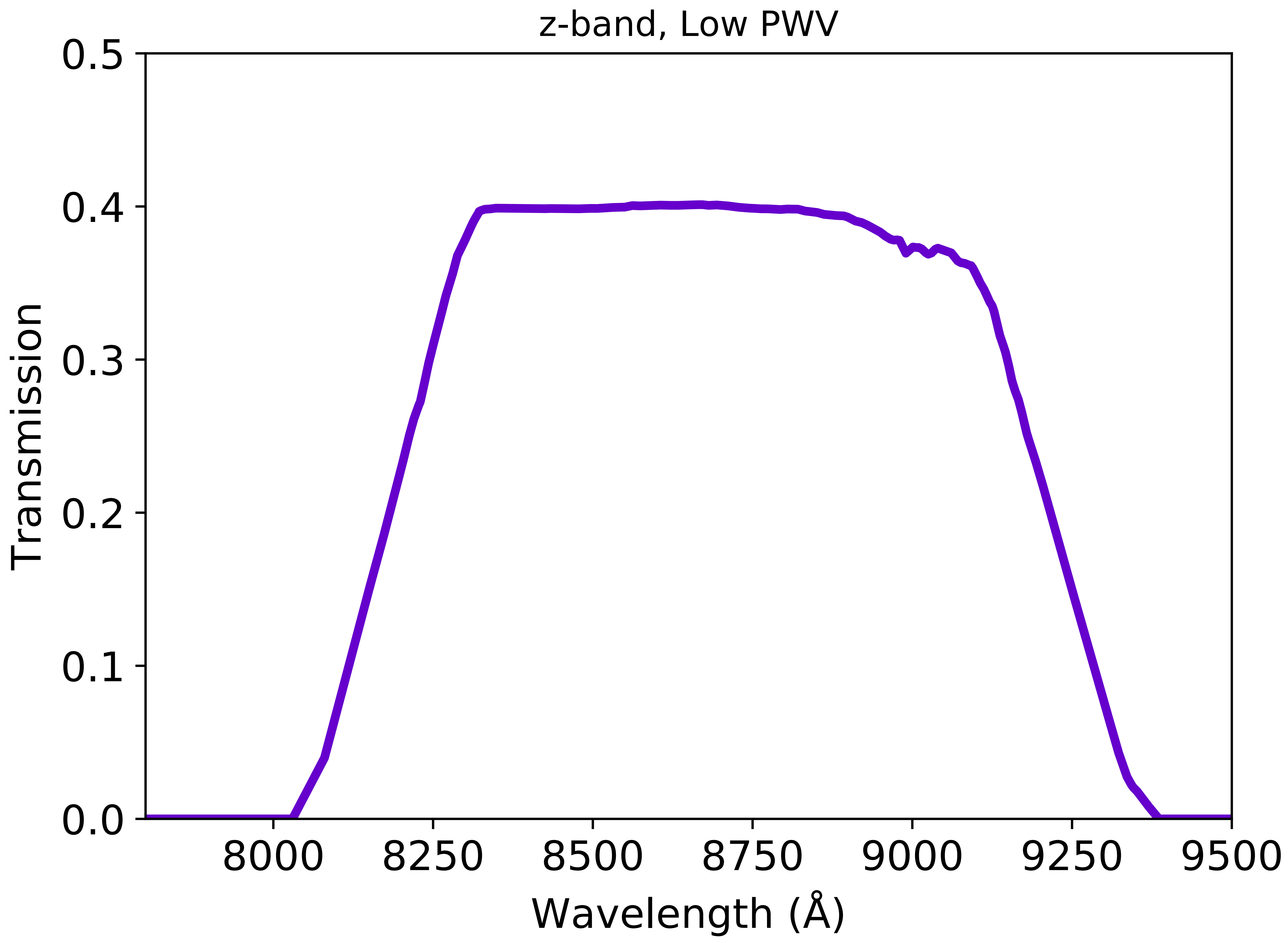
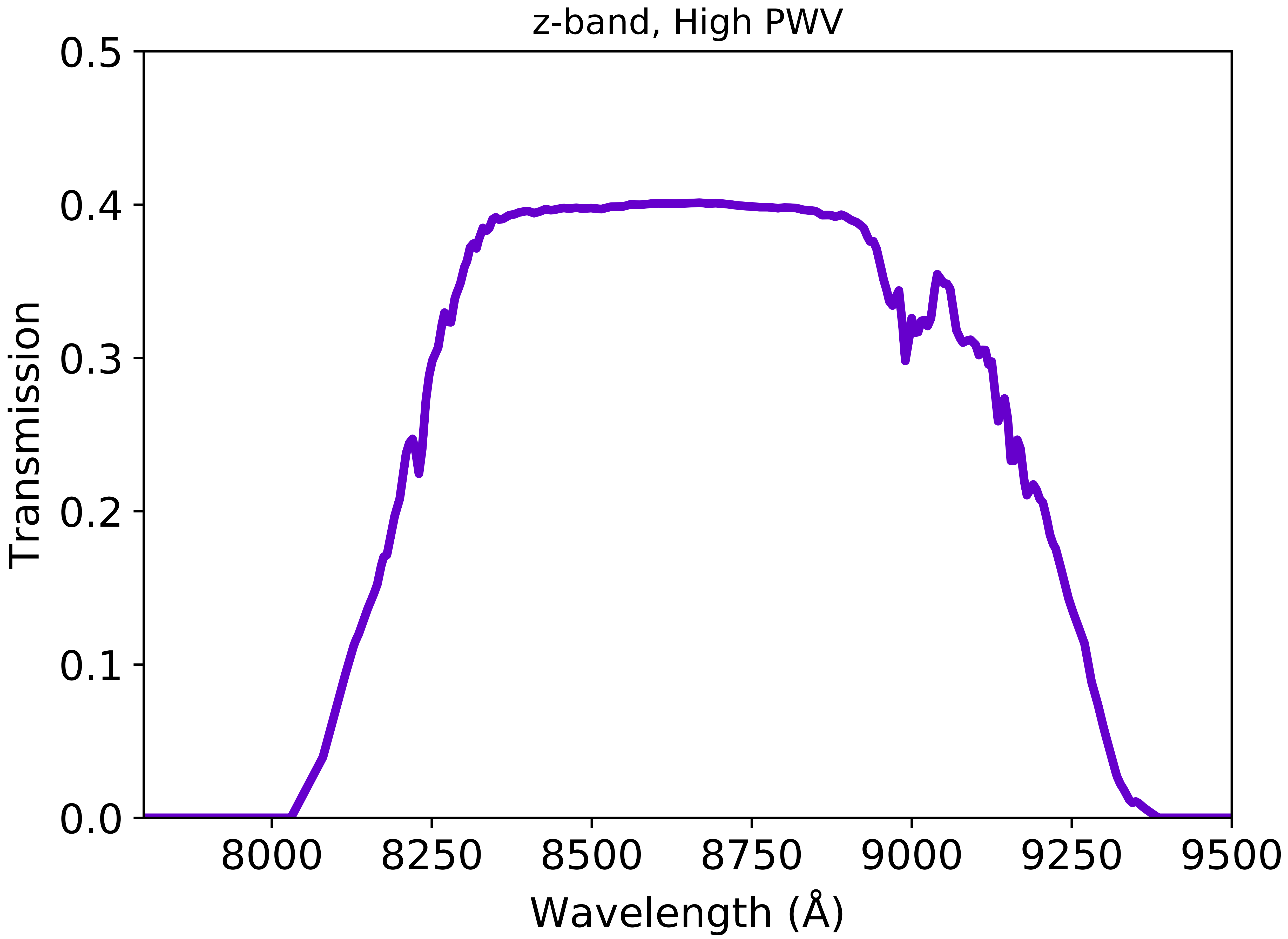
- If we add the atmosphere with a touch of water



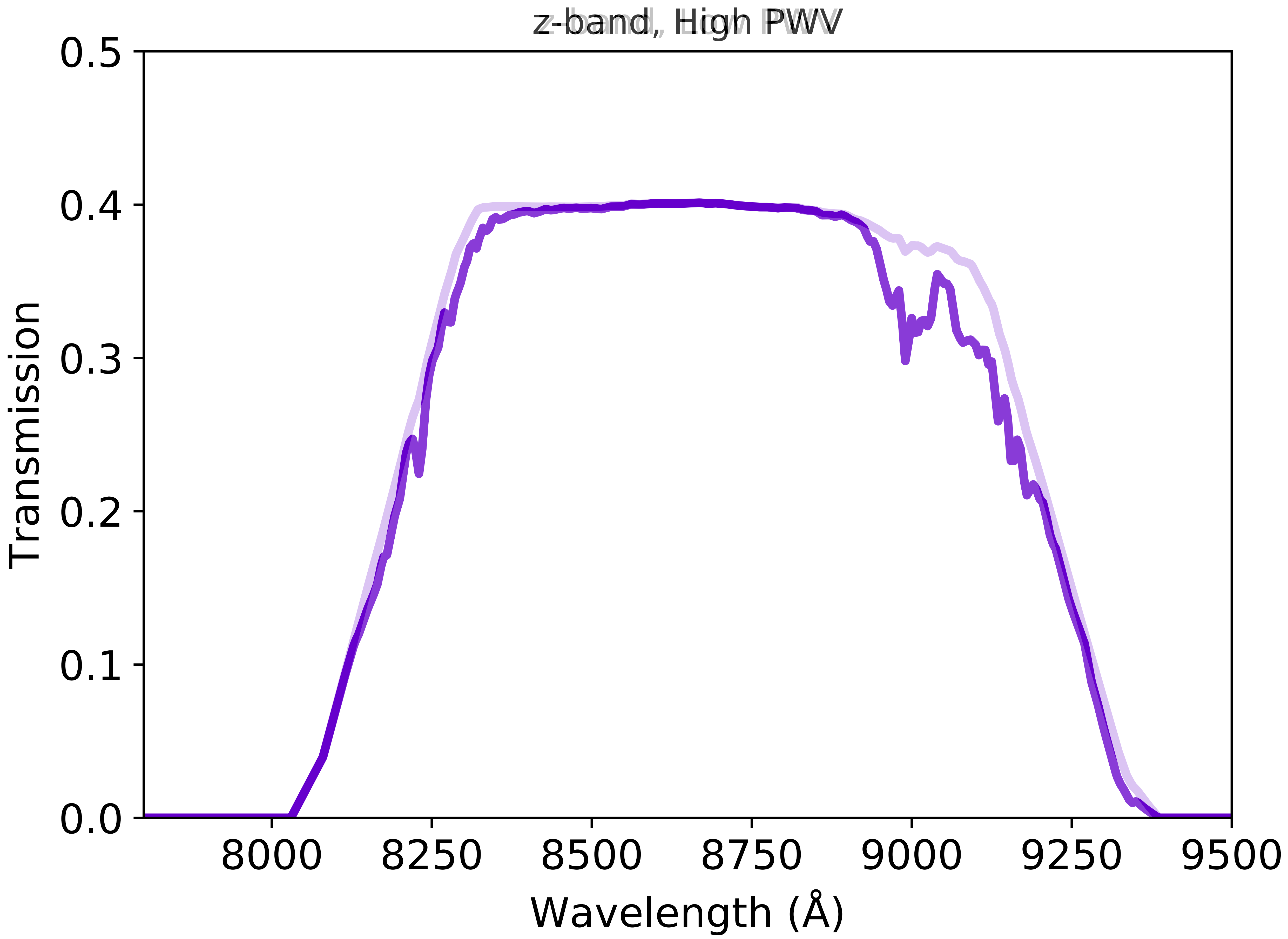
Impact of the Atmosphere

- If we add the atmosphere with a lot of water



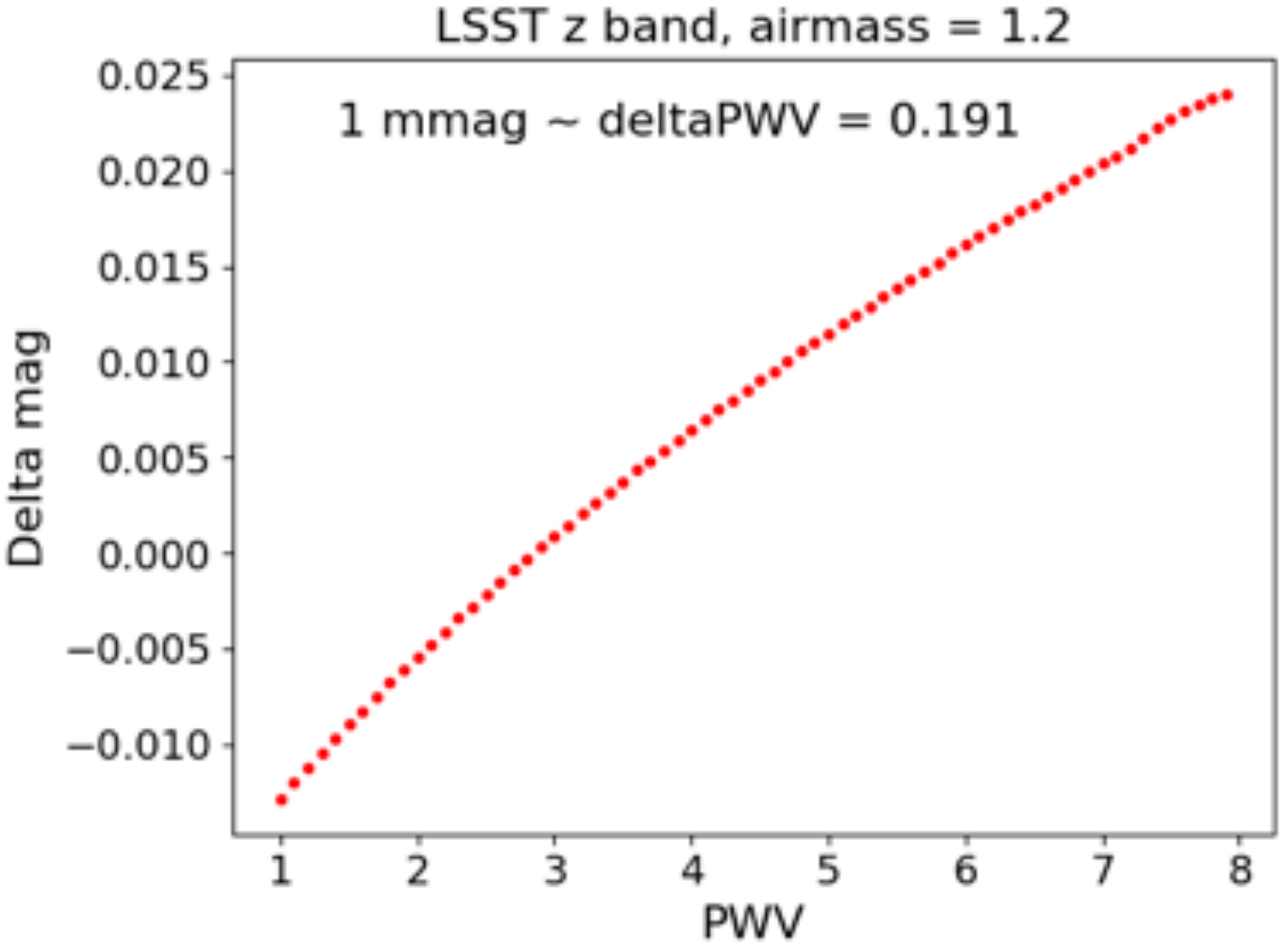
Impact of the Atmosphere

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



Impact of the Atmosphere

- 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

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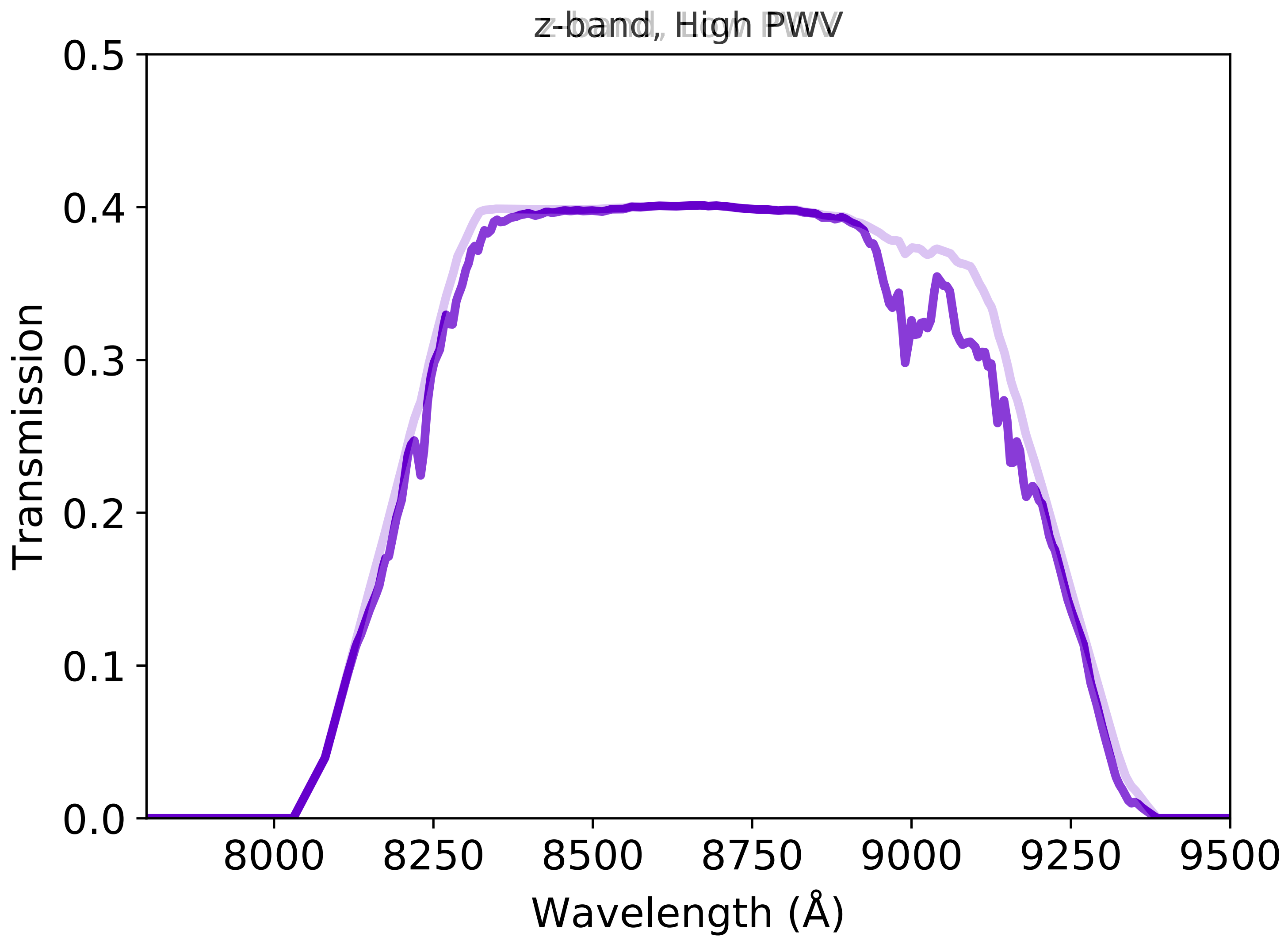
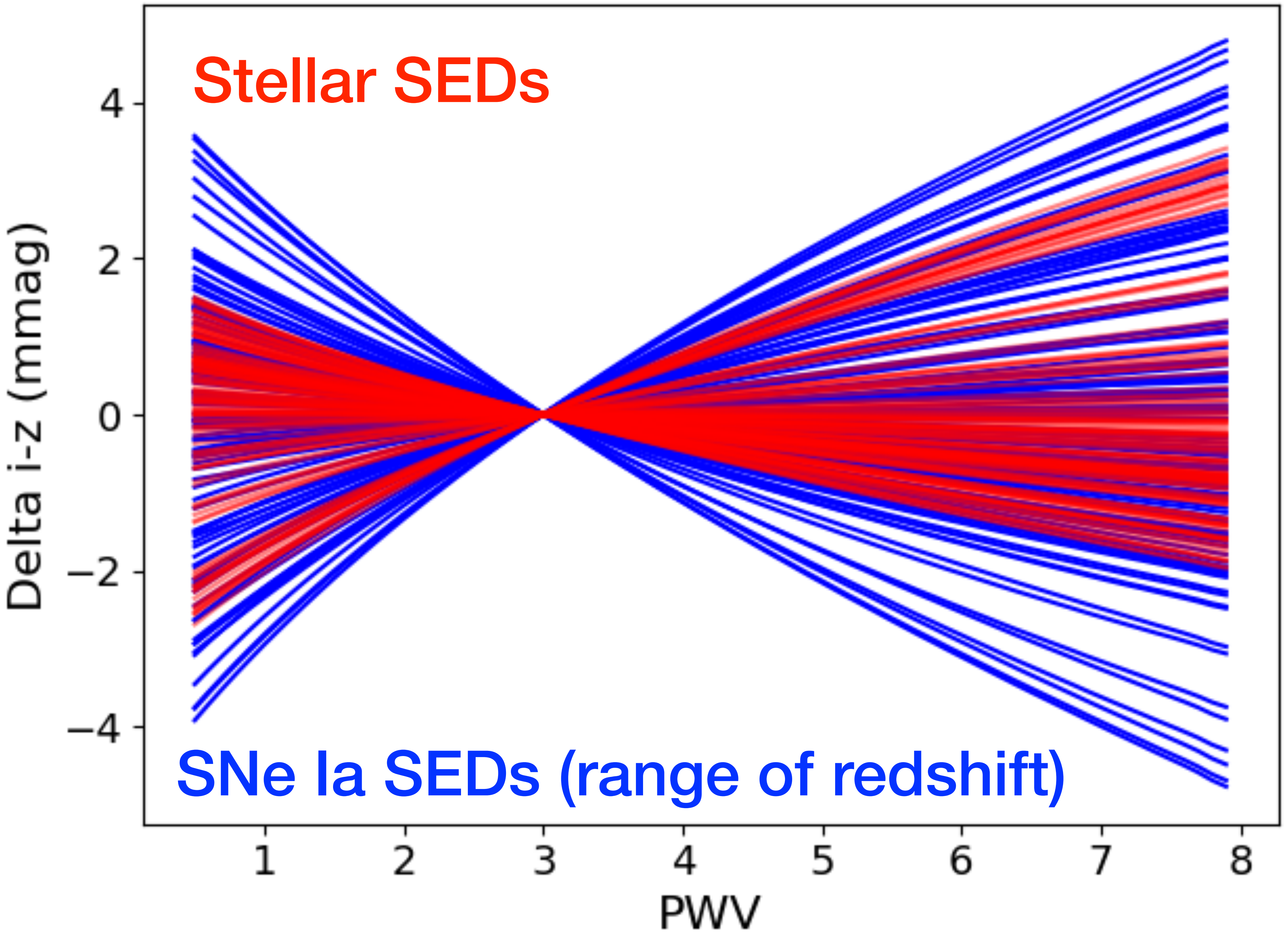
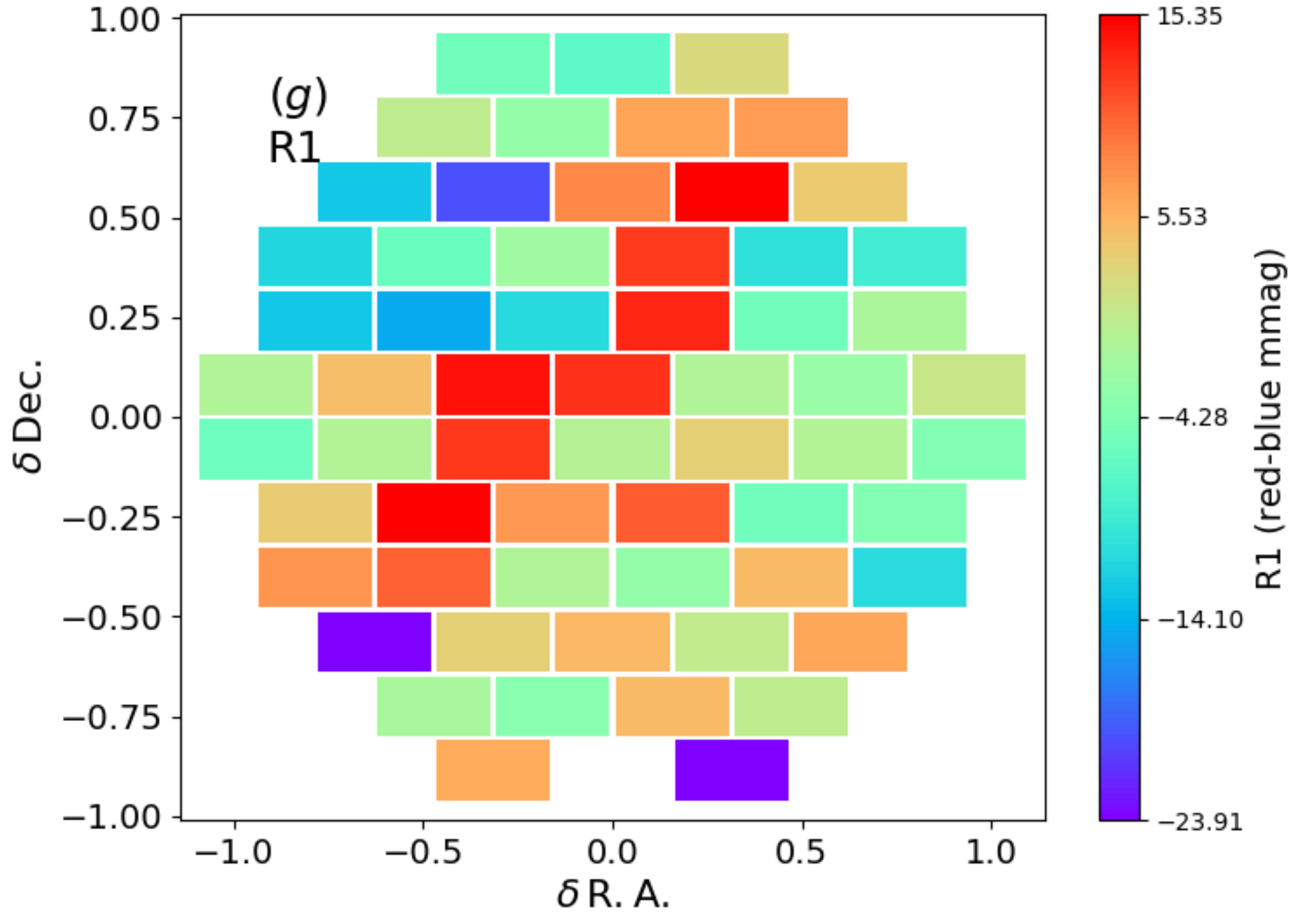
- Secondary impact is the chromatic effect. Mostly the red end of the z band is removed!
- Size of impact depends on the SED
- For SNe, need to know PWV at ~1 mm level



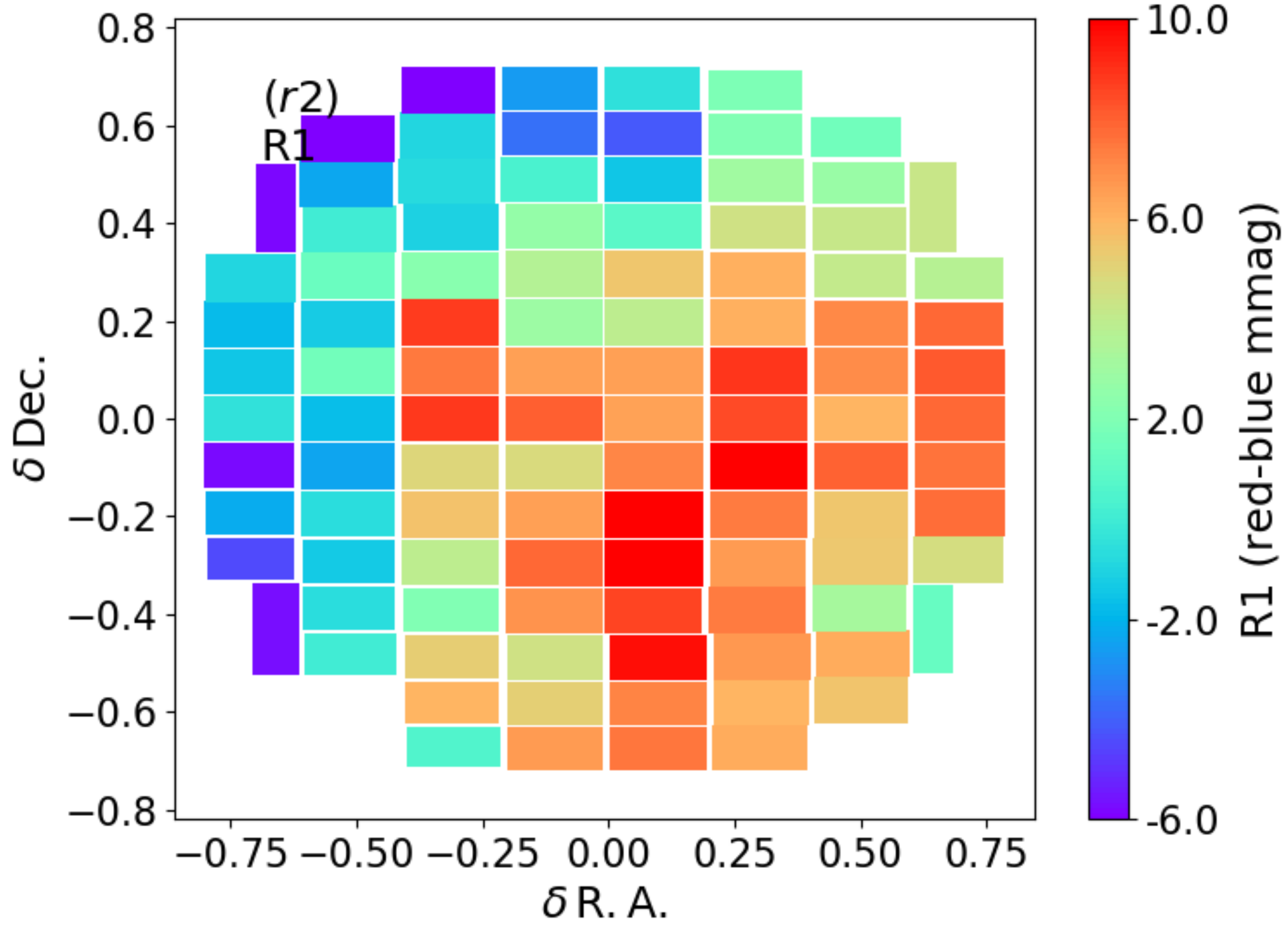


Impact of the Instrument

- We worry so much about the atmosphere … but the instrumental variations are much, much larger.
  - Chromatic effects of several percent from red to blue stars are common!



DECam g-band



HSC r-band (HSC-R2 filter)

Step 4/N: Modeling the Atmosphere

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- AuxTel will observe stars around the sky with low-resolution grating
  - Remove the star, fit the atmosphere
  - Goal is to transform atmosphere to the standard
  - Hopefully output components to describe modeled atmosphere as a function of time/position

- 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

- 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

Step 5/N: Modeling the Instrument

- Atmospheric throughput self-calibration is tractable because of the small number of parameters and predictable physical variations in the throughput

- Instrumental throughput self-calibration is not generally possible.
  - We only have broadband measurements of stars
  - Many degeneracies to go from here to throughput as a function of wavelength
    - Is that chromatic shift due to a being incorrect about the wavelength of the red end of the filter, or due to being wrong in the QE slope of the AR coating?
  - There is no substitute for scans

Step 5/N: Modeling the Instrument

- We need to know the QE of each detector (at least…) as a function of wavelength
- We need to know the variation of the filter throughput as a function of position (and it may vary both radially and azimuthally … and in surprising ways)
- We need to know the mirror reflectivity as a function of wavelength (and time!)
- In DES we used the DECal scans
  - In situ measurement of full system throughput
  - This is equivalent to the narrow wavelength flat-field scans planned for LSSTCam
  - Decomposing pupil ghosts, other throughput challenges with flats was non-trivial
- The collimated beam projector (CBP) is another way of getting the throughput (though limited by spot density).

Datasets

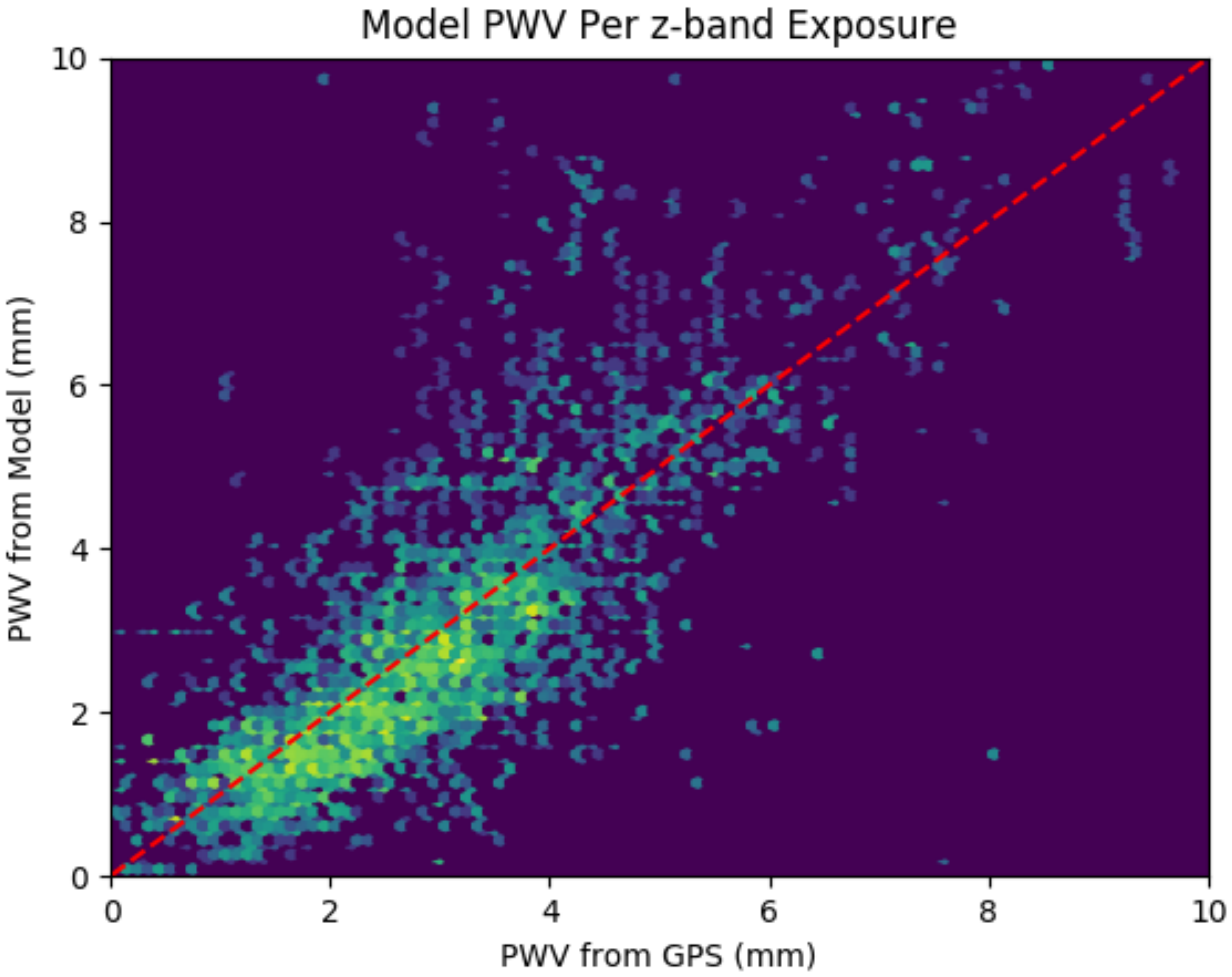
- FGCM has been run on DES Years 1-3 (“Y3”) and DES Years 1-6 (“Y6”)
  - Burke, Rykoff et al. (2018), and Rykoff, Burke et al. (in prep)

- FGCM has also been run on HSC PDR2 data (via https://github.com/lsst/fgcmcal)
  - Run on HSC S20a processing as part of HSC PDR3
  - Upcoming run on HSC PDR4

Testing PWV

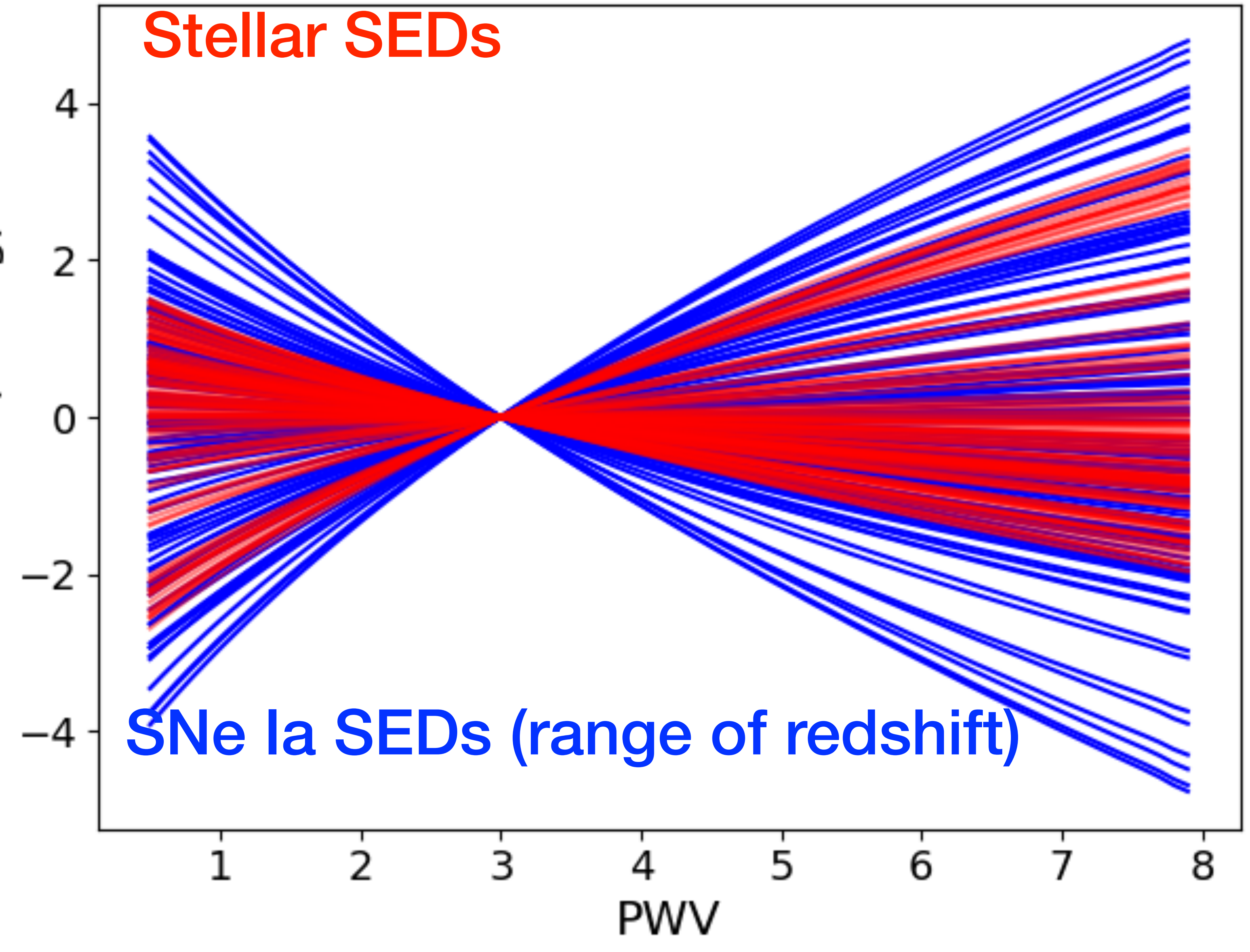
- For the first 4 years of DES, we had GPS measurements* of water vapor (not used in FGCM fit)
- There is good correlation per exposure
- Note that we do not care about the PWV for gri
- Good agreement in Y band as well (but noisier since the DES Y band is quite narrow)

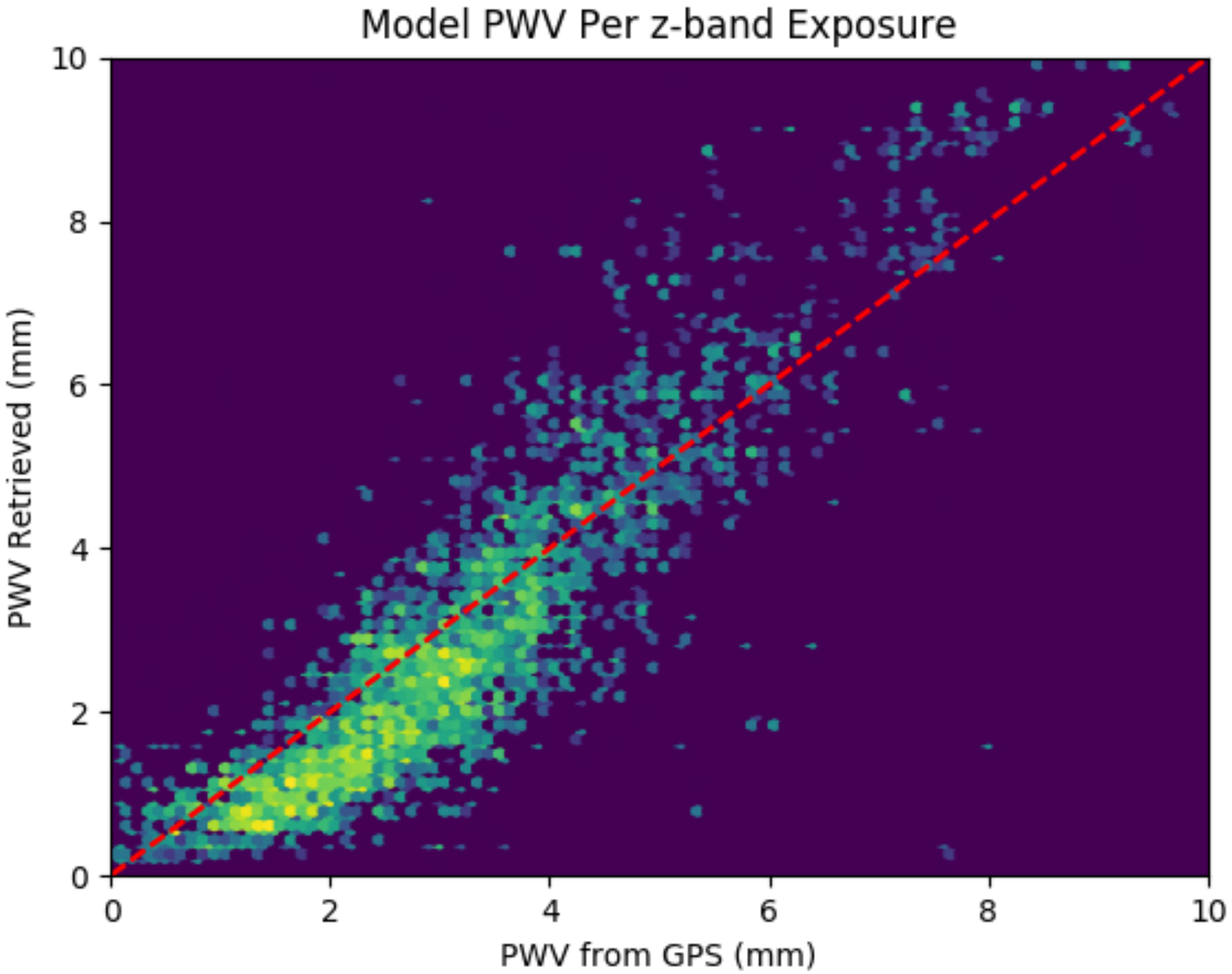
- *You can use GPS timing information to estimate the total water vapor in the atmosphere, by looking at the signal delay between different satellites



Testing PWV: The “Lupton Dream”

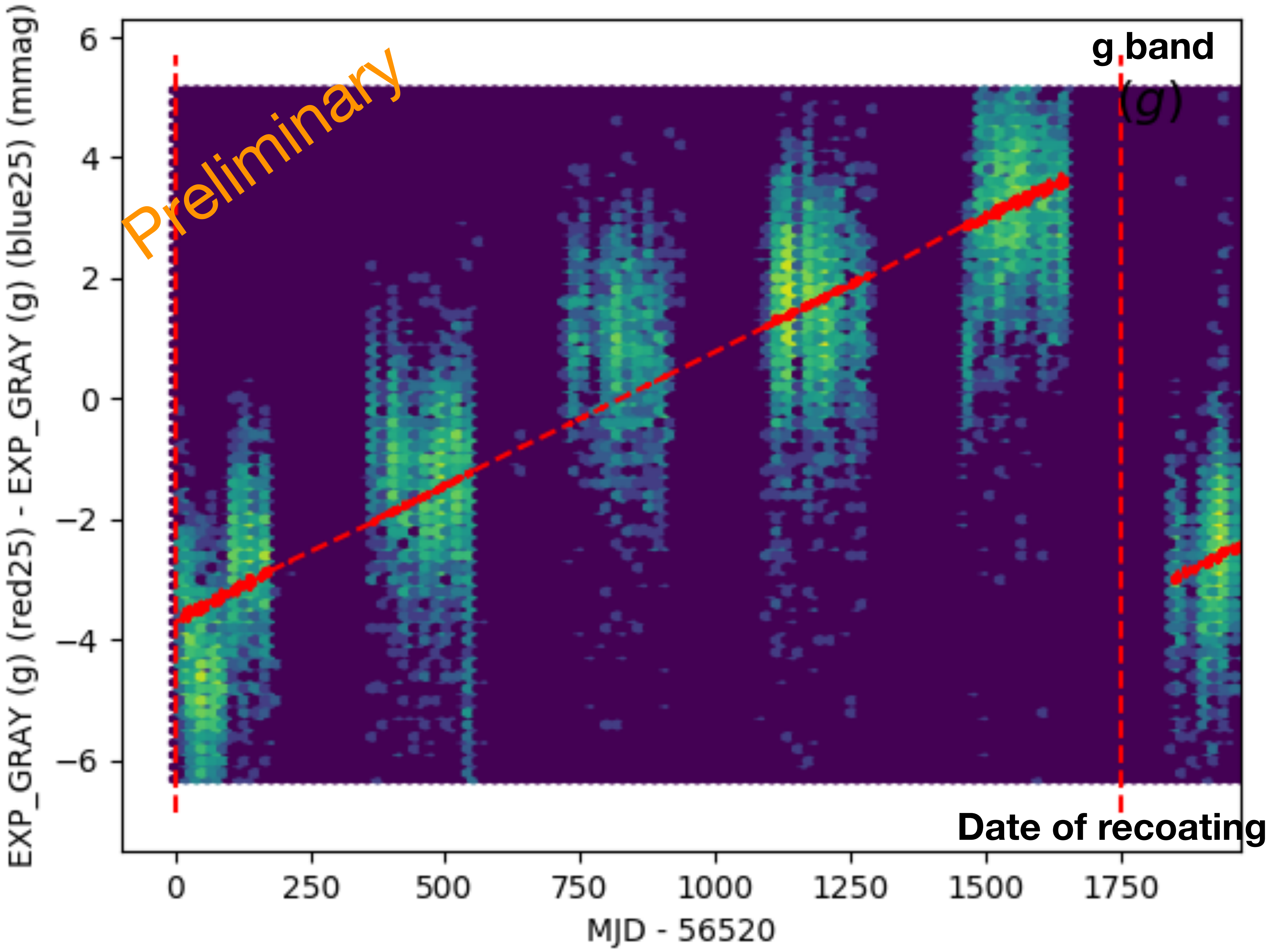
- Can we use the relative change in colors of red and blue stars at different levels of PWV to measure the PWV per exposure?
- Yes we can! Even in non-photometric conditions!





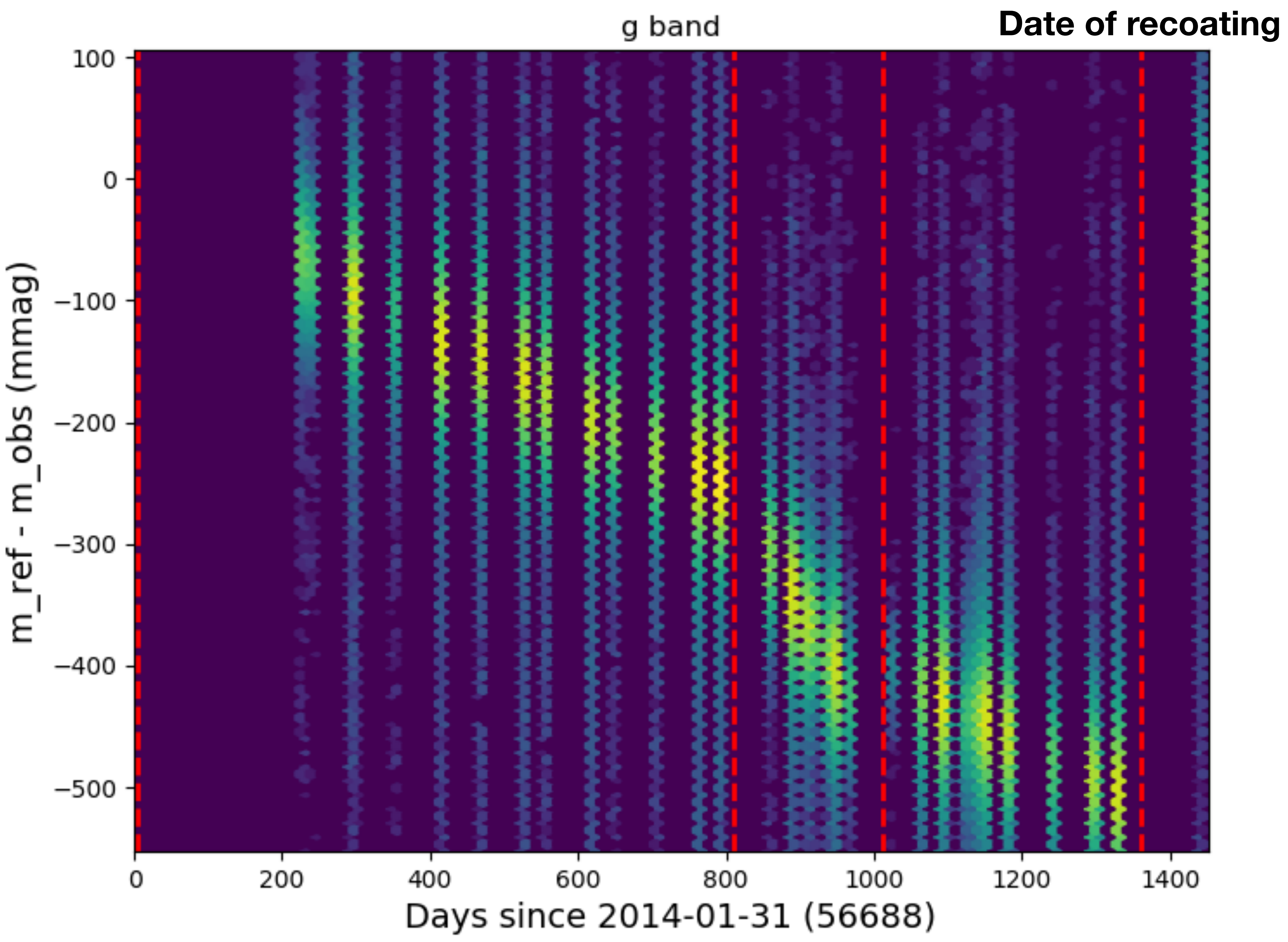
Temporal Variations in the Chromatic Passband

- 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



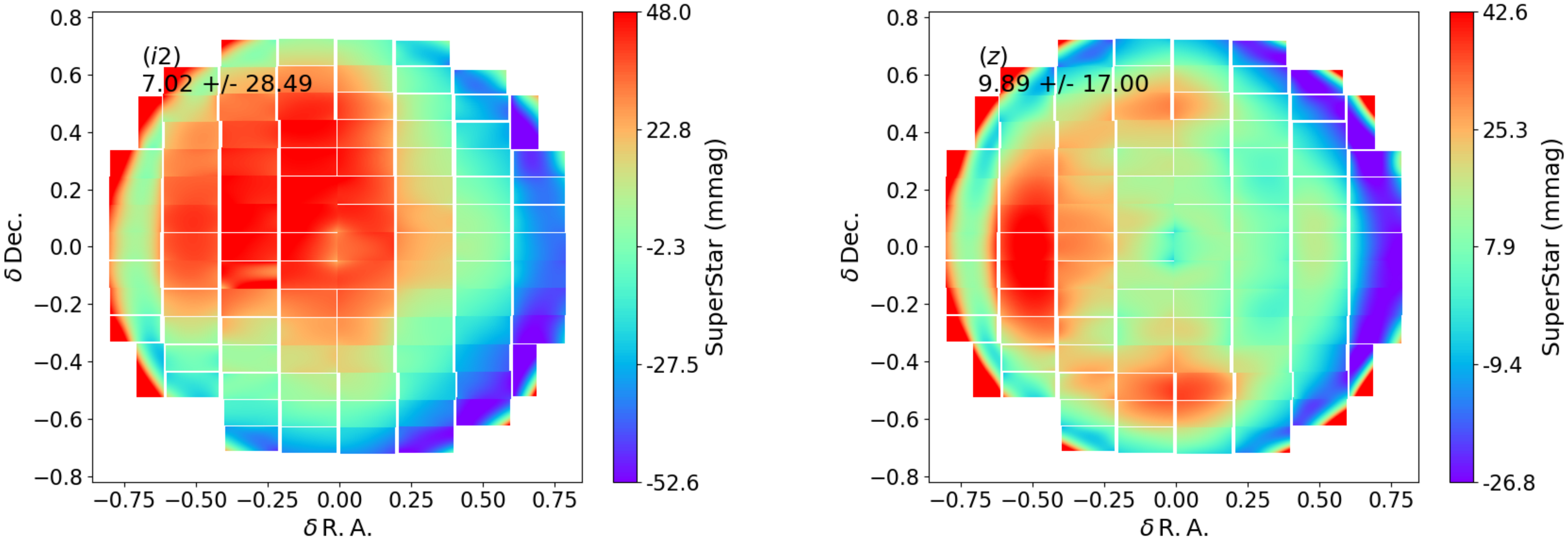
Temporal Variations in HSC Reflectivity

- 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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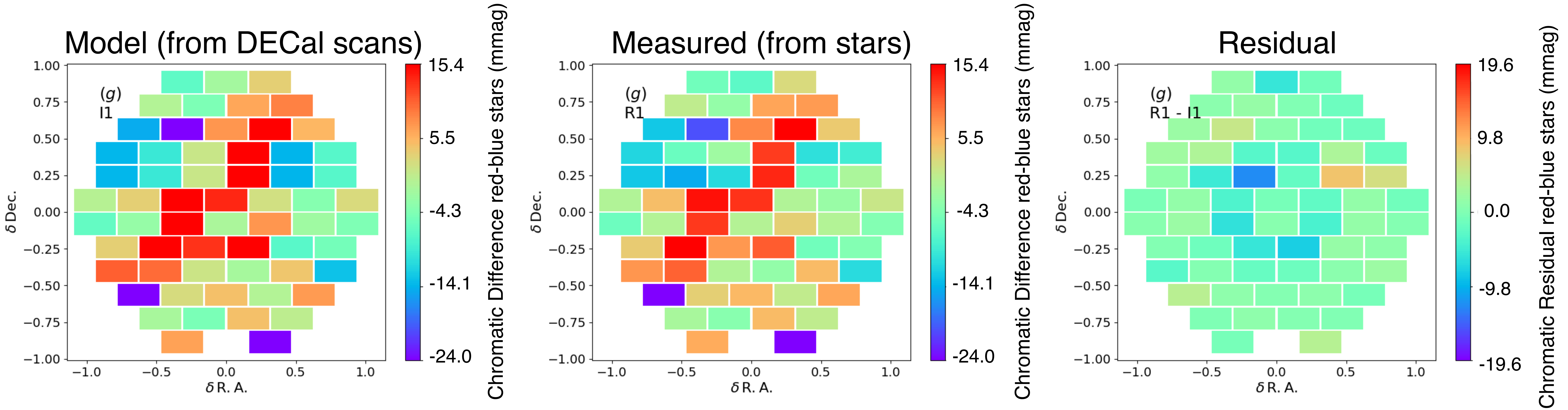

DES g-band

- 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

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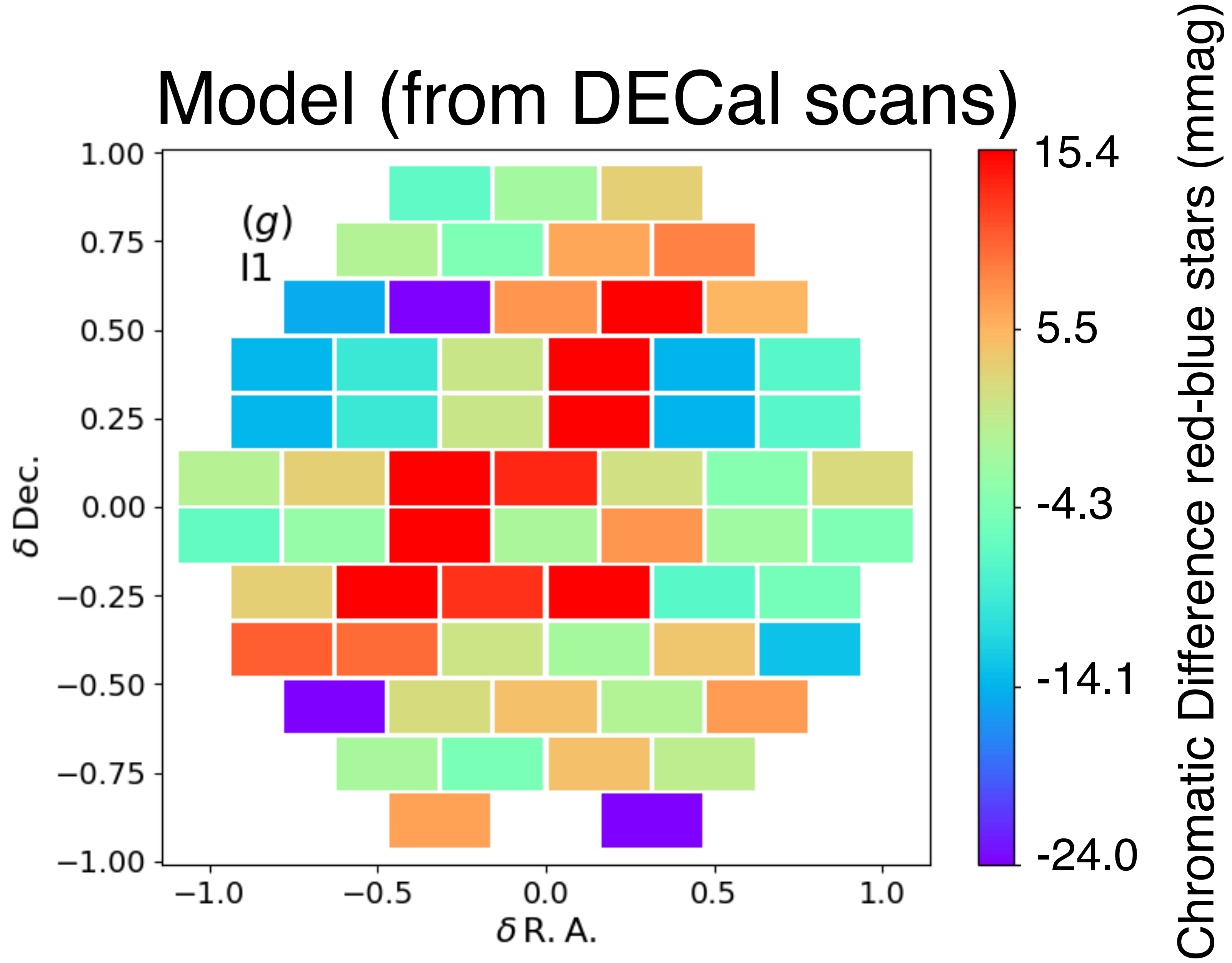
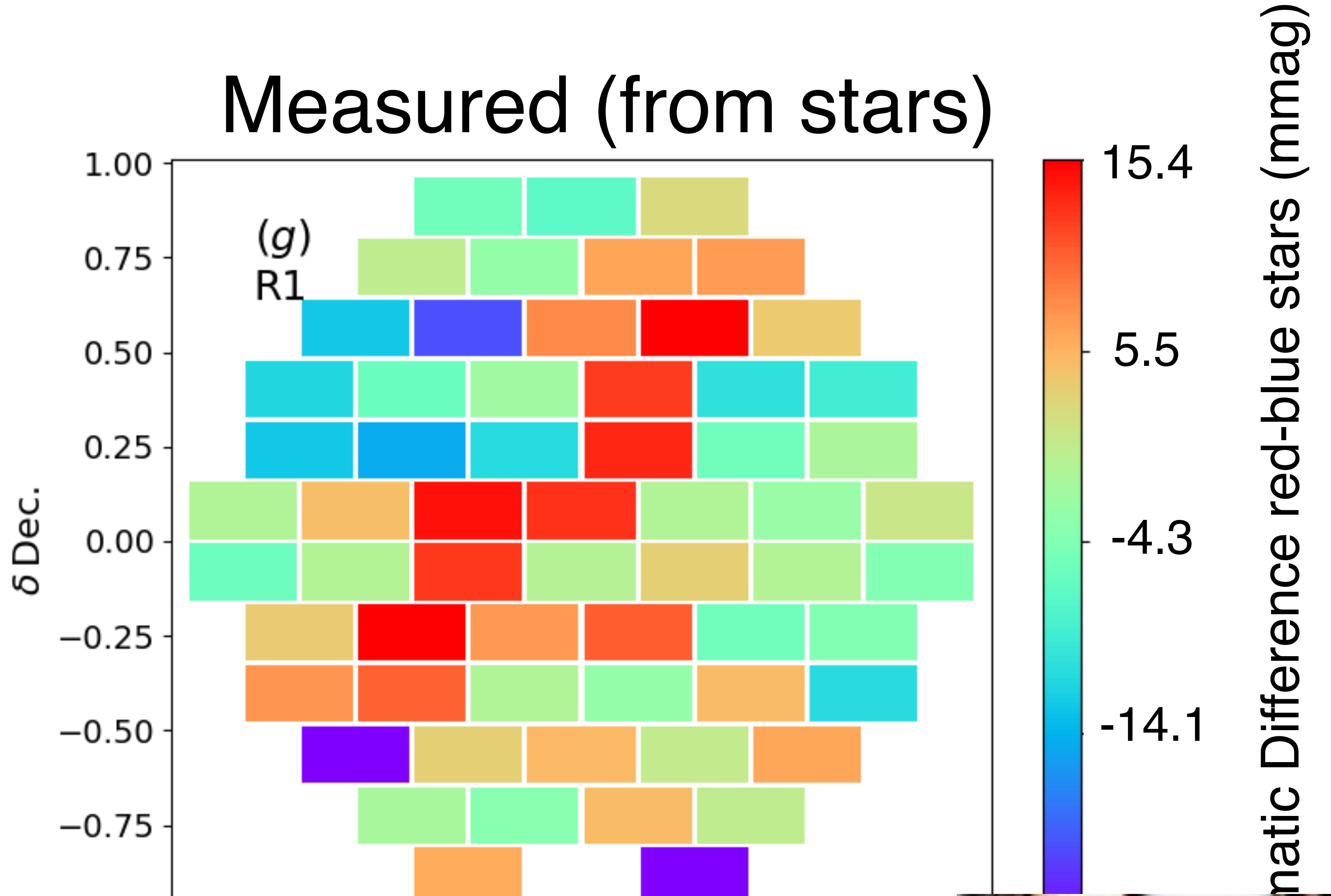
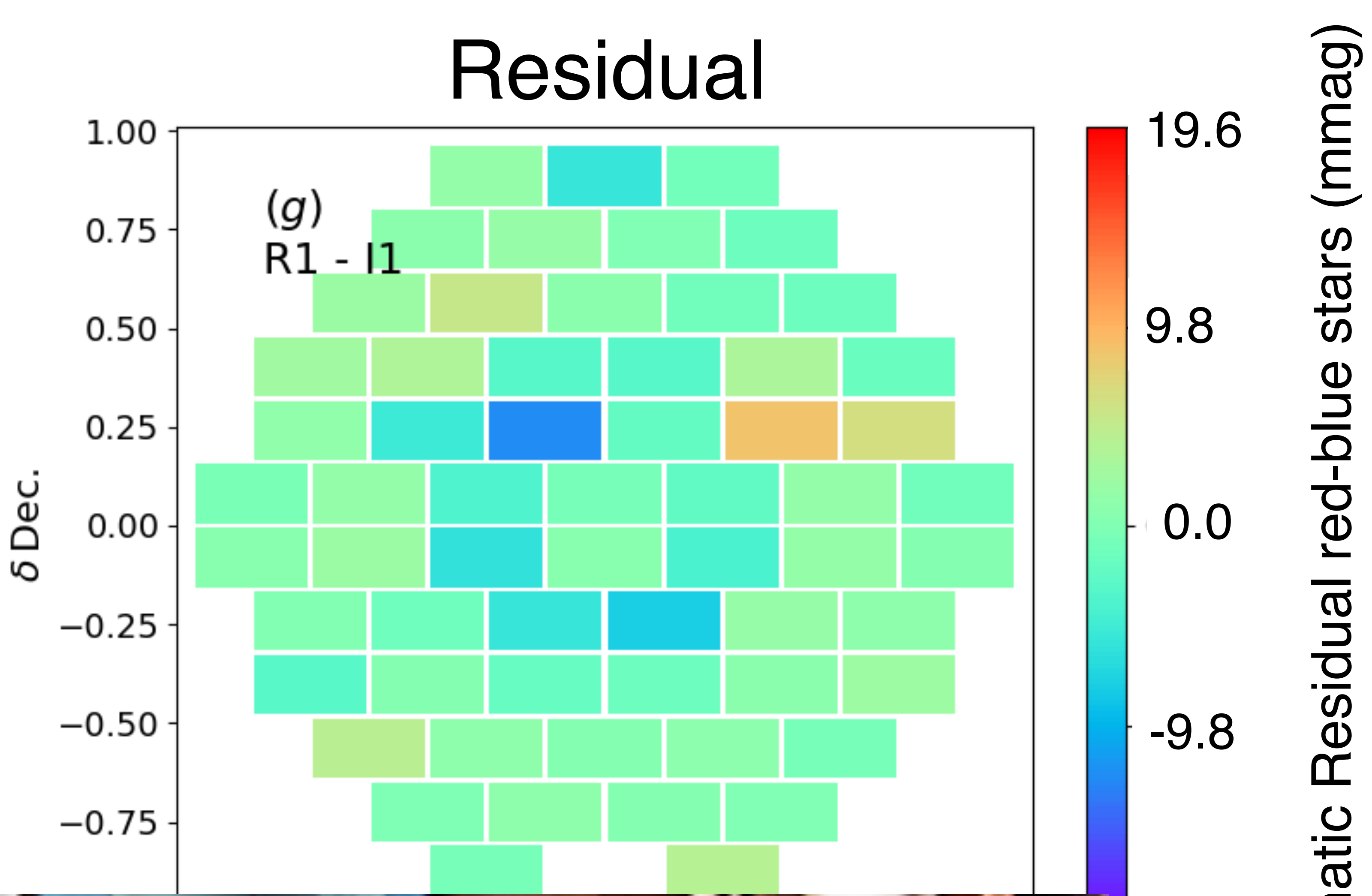
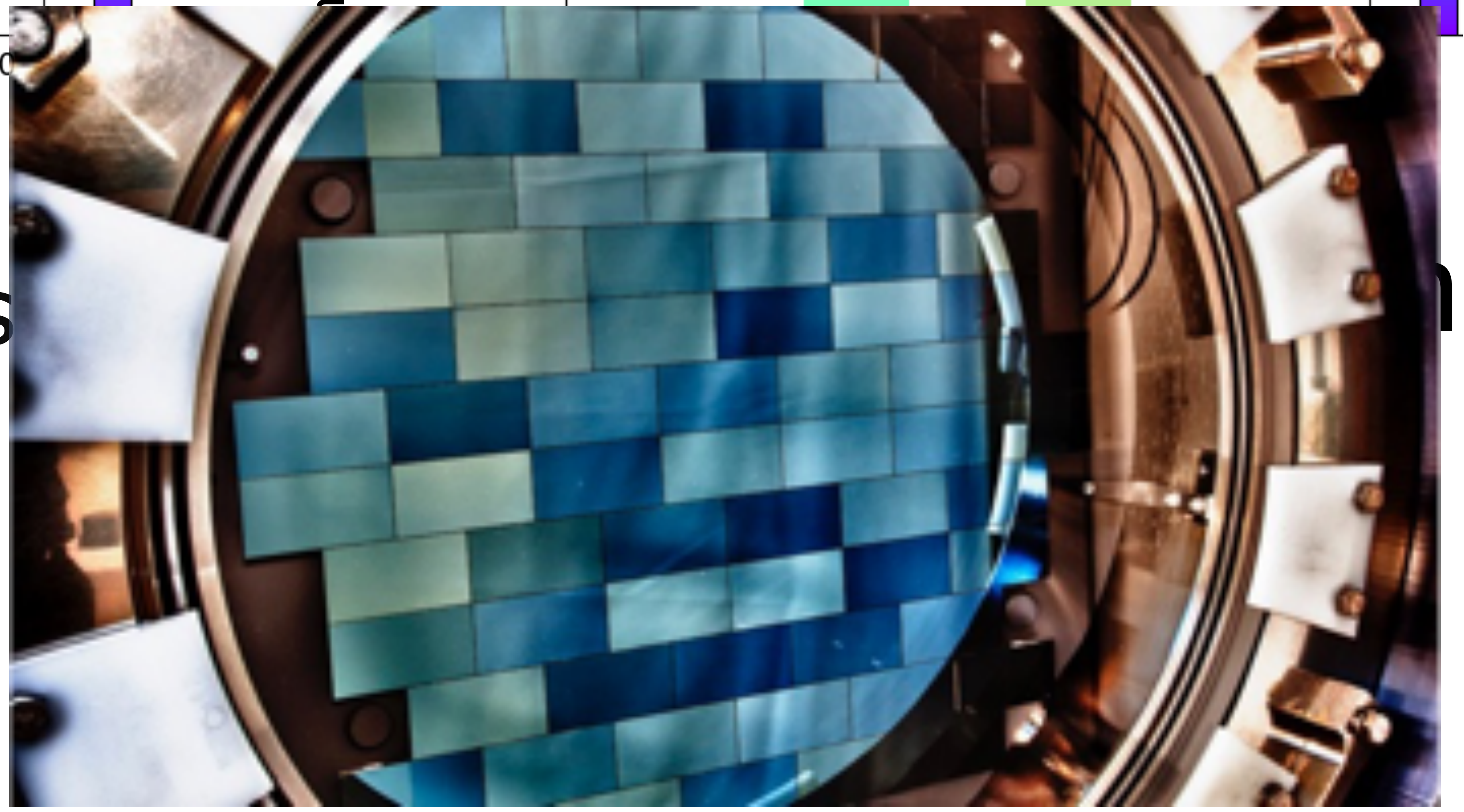

Model (from DECal scans)


Measured (from stars)


Residual



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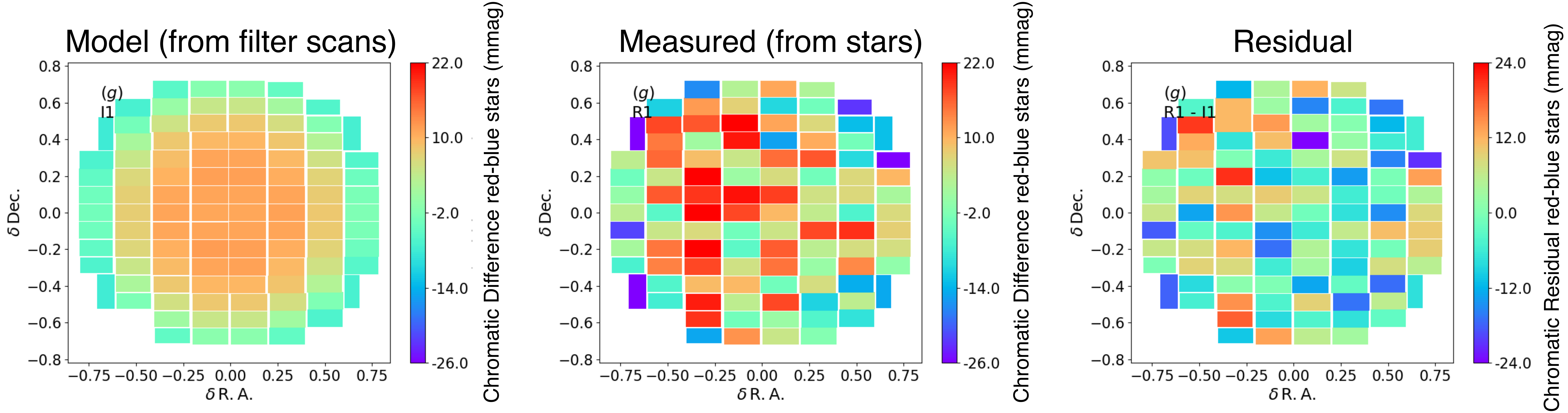
FGCM Can Test Throughput Measurements



Model (from filter scans)

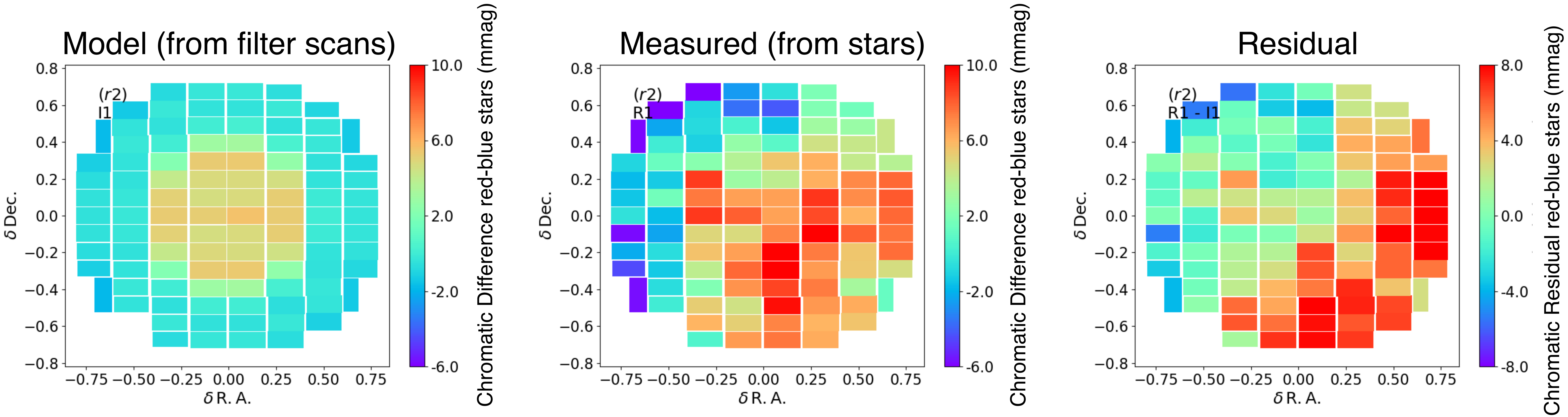
Measured (from stars)

Residual

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

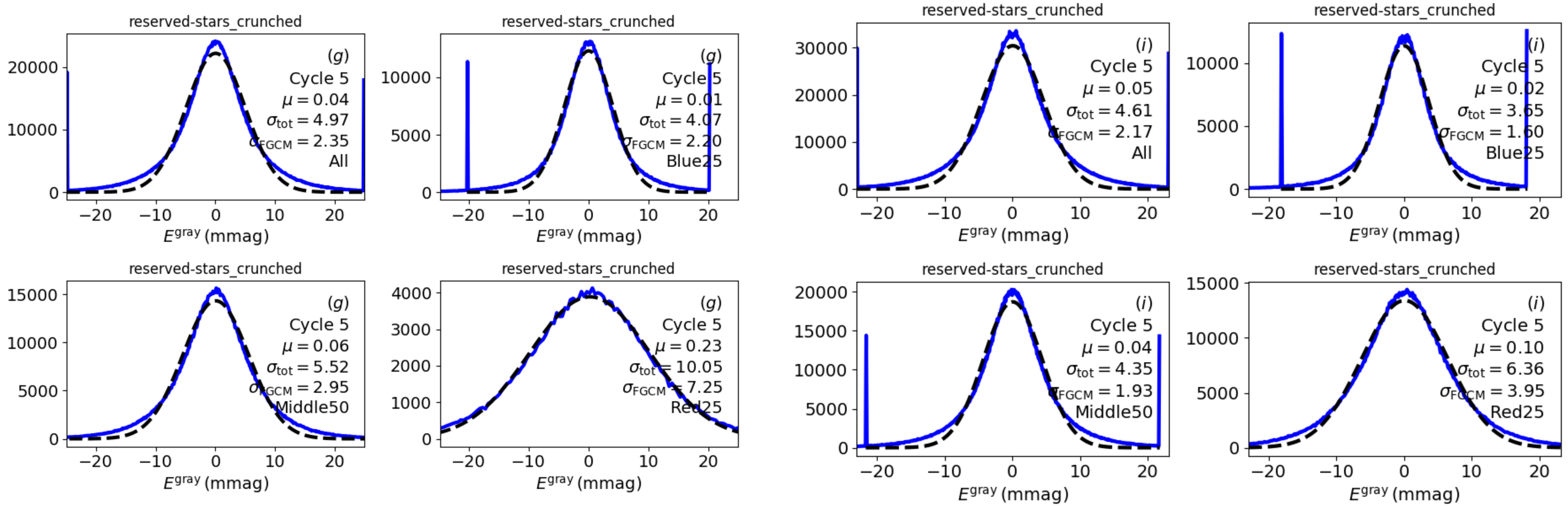


HSC r2-band

- 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

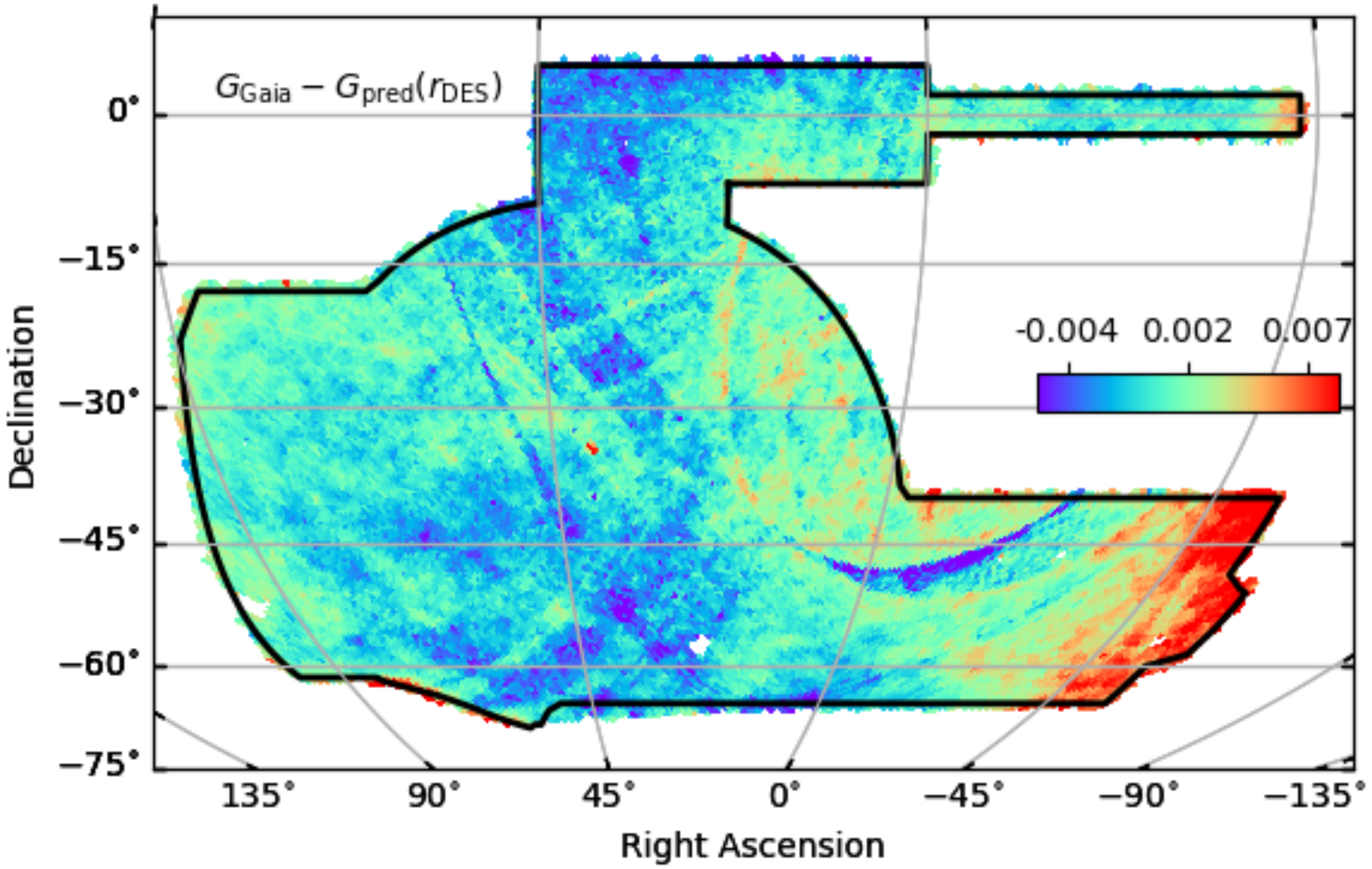
FGCM Repeatability (DES Y6)

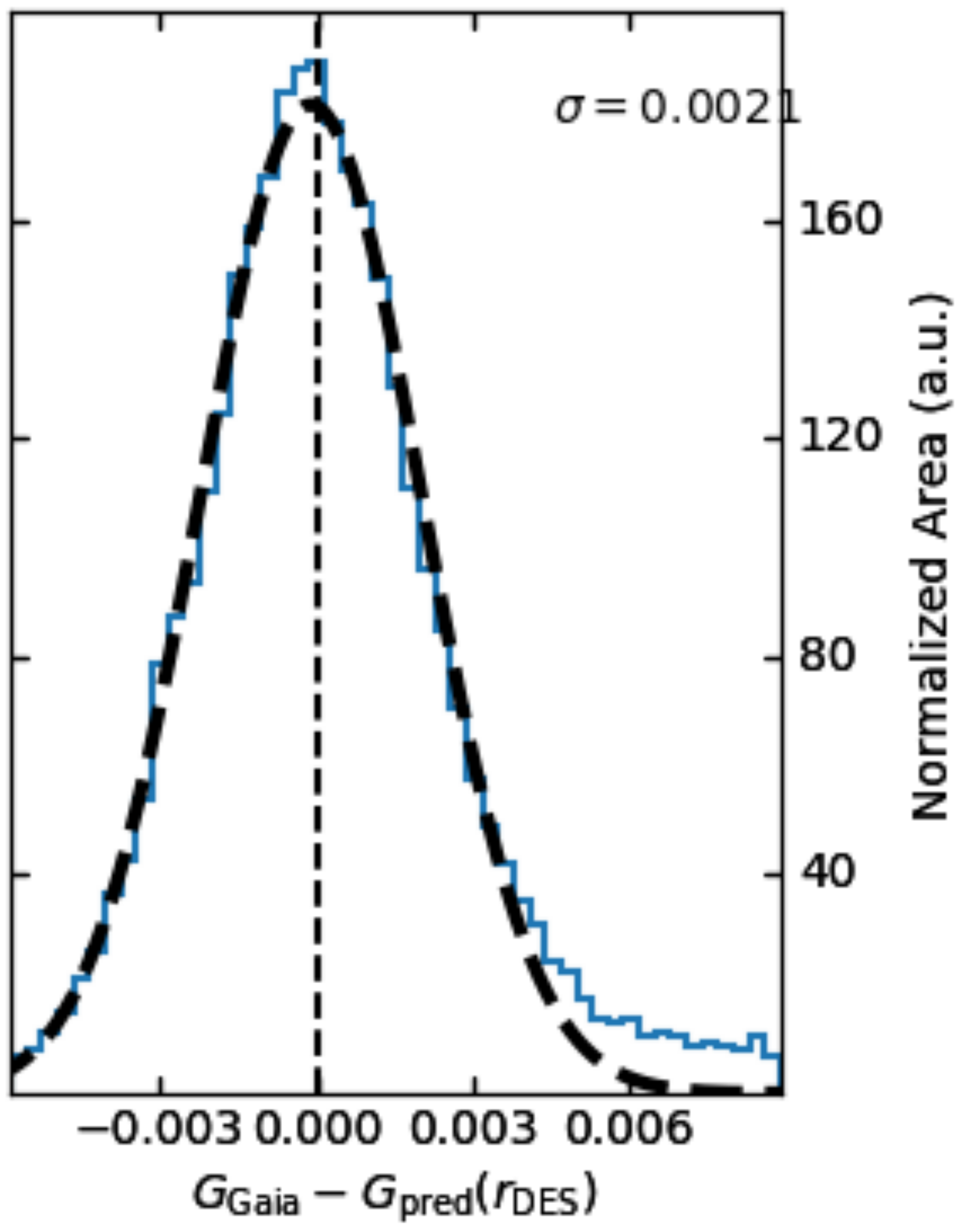
- 2-4 mmag repeatability for most bands / colors
  - Worst for reddest stars in g-band (unmodeled chromatic corrections)



FGCM Uniformity (DES Y6)

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





FGCM And AuxTel

- Multiple options to combine
  - Use AuxTel parameters as input to FGCM

  - Use AuxTel parameters as prior for FGCM

  - Use AuxTel and FGCM independently, use AuxTel as cross-check on FGCM

Step 6/N: Applying the Calibrations

- How to do this in the database … TBD
- The good news is that if you know an object SED then applying chromatic corrections at the catalog level just requires the weights of images that went into the coadd (see e.g. Sevilla-Noarbe et al. (2021), Appendix A.2)
- Cell-based coadds will make this a lot simpler
  - Every object in the cell shares the same inputs
  - Maybe wrong spatial scale in u-band
  - (Don’t ask me about u band)