Why might the DESC photometric calibration requirements keep you up at night?

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DESC Dark Energy School

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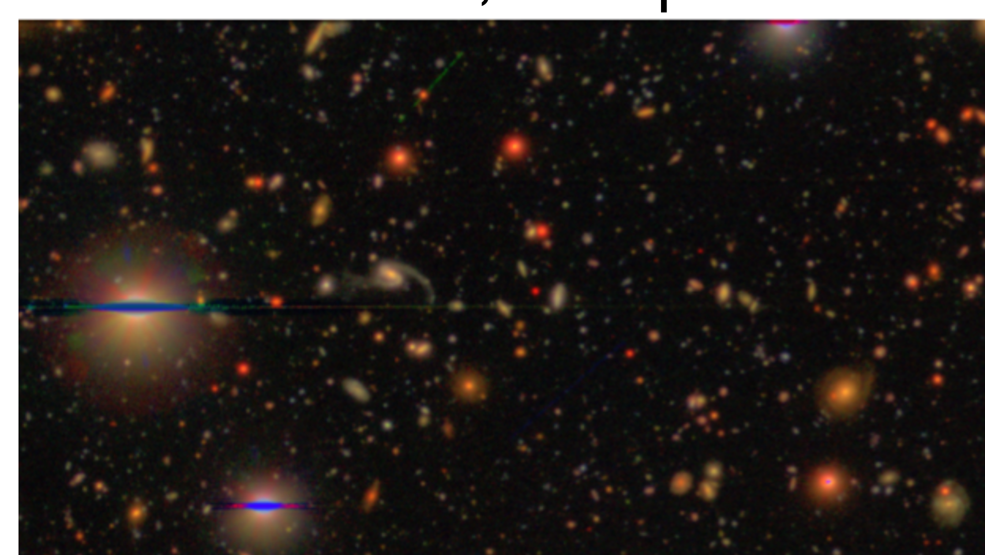
What LSST Will Give Us

- LSST will deliver an unprecedented amount of data
  - 100 - 250 visits (depending on band … and observing strategy, TBD)
  - A well-characterized instrument
- Exceptionally deep coadd catalogs after 1, 3, 6, 10 years
- Well-measured supernovae in the Wide-Fast-Deep (WFD) survey out to z~0.6 (depending on observing strategy…)
- Well-measured supernovae in the Deep Drilling Field Survey (DDS) out to z~1.0
- Other near real-time transients (not my concern)

Measuring Object Brightness

- See R. Lupton “How Bright is That Object?”
  - http://www.lsst-desc.org/DEschool#lupton
- Remove instrumental variations (“detrending” or “instrumental signature removal (ISR)).
- Measure the sky level (“pedestal”)
- Measure object counts, including deblending (oof), multi-band, multi-visit, handle PSF variation, chip edges, etc, etc…



gri true-color composite of COSMOS from HSC

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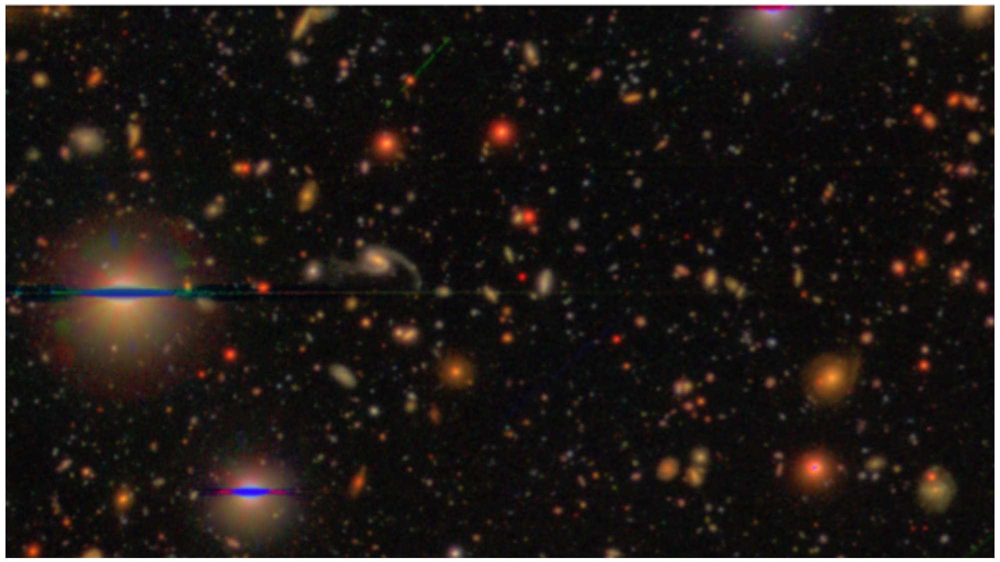
- Measure object counts, including deblending (oof), multi-band, multi-visit, handle PSF variation, chip edges, etc, etc…
- Assume these issues are handled perfectly by our DM friends and multiplicity of DESC task forces!



gri true-color composite of COSMOS from HSC

What is “Photometric Calibration”?

- Output of ISR is in units of “Analog-to-Digital Units” (ADU)
  - Counts that are measured from a signal that comes from an amplifier with gain g that is connected to a CCD that reads out photo-electrons produced by photons absorbed in the bulk silicon…
  - Please see all the wonderful work from the Sensor Anomaly Working Group (SAWG) for all the ways this can go wrong

What is “Photometric Calibration”?

- “How bright is this object in in physical units such as Jansky (10^{-26} $W\ m^{-2}\ Hz^{-1}$)?”
  - Power per unit area per unit frequency
  - Yes, Watts are $J\ s^{-1}$, and Hertz are s^{-1}, so we have a unit that is per second per Hertz…
  - LSST calibrated flux units will be nanojansky

- Our instrument measures *broadband* fluxes over a range of frequencies
  - This will lead to additional complications

Everything is Relative

- Measuring absolute fluxes is really quite difficult
- Most of our measurements are relative to something else
- Currently, we use CALSPEC standards measured by the Hubble Space Telescope
  - Above the atmosphere; good quality instrument; issues at the percent level (?!)
- Projects to put things on a NIST-calibrated scale

Some Terminology

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

What is a Millimagnitude?

- Although we measure fluxes (well … ADU), we astronomers use and quote values in magnitudes
  - Blame the ancient Greeks!
- Recall that

$$m = ZP - 2.5\log_{10}(f)$$

$$f = 10^{(m - ZP)/-2.5}$$

- What “change in flux” leads to a change of 0.001 mag (1 mmag)?

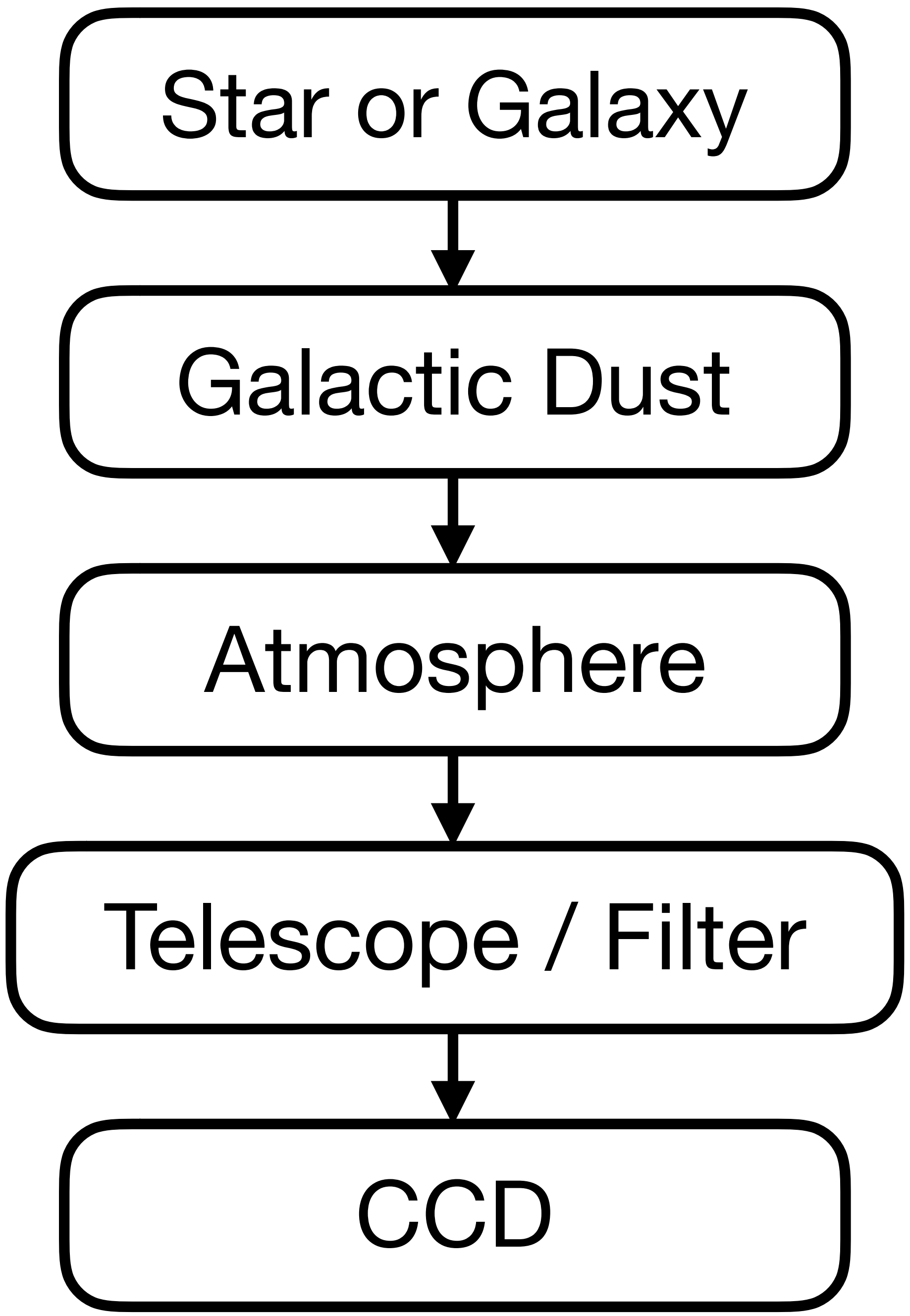
What is a Millimagnitude?

$$m_1 - m_2 = 0.001$$
$$m_1 - m_2 = (ZP - 2.5\log_{10}(f_0)) - (ZP - 2.5\log_{10}(f_1))$$
$$m_1 - m_2 = -2.5\log_{10}(f_0) + 2.5\log_{10}(f_1)$$
$$0.001 = -2.5\log_{10}\left(\frac{f_0}{f_1}\right)$$
$$\frac{f_0}{f_1} = 10^{0.001/-2.5} = 1.0009214$$

- This is a fractional change in flux
- Note that the fractional change is $0.001/(2.5/\ln(10))$

- Thus 1 mmag calibration means knowing relative flux changes at the sub-0.1%-level.

The Modeling Chain



SED measurements (CALSPEC, Gaia, Photo-*z* templates, etc …)

Gaia / NIR / self-calibration

Auxiliary Telescope (AuxTel) or self-calibration (FGCM)

Collimated Beam Projector (CBP)

Collimated Beam Projector (CBP)

The Modeling Chain

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

- Note that while most sources at high Galactic latitude are above the source plane, some WDs aren't

Dark Energy Science Probes

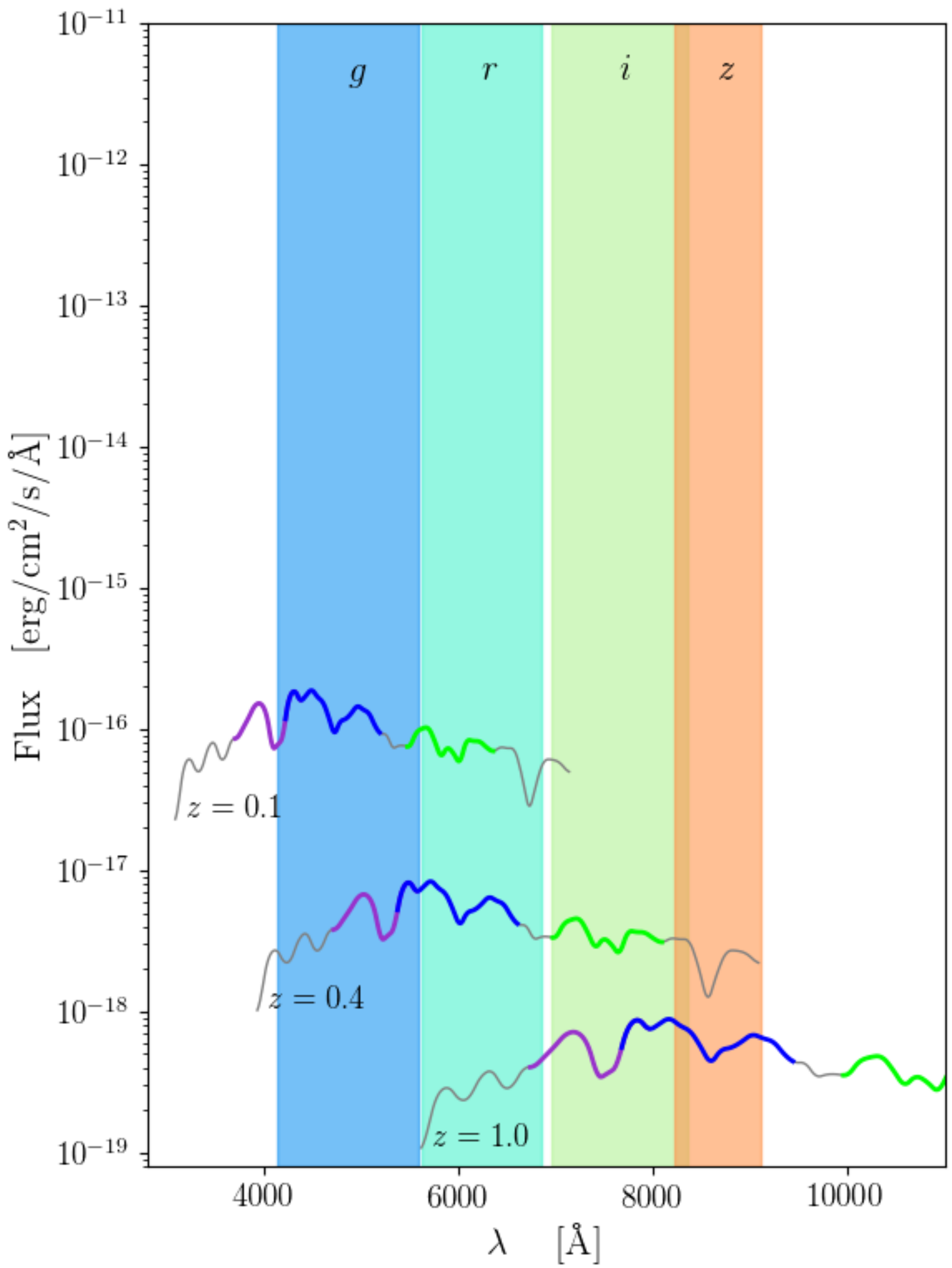
- Which probes care about photometric calibration?
- What part of photometric calibration do they care about?

Dark Energy Science Probes

- Large-scale structure
  - Via photo-zs, and counts of objects
- Clusters
  - Via photo-zs, red-sequence colors, counts of objects
- WL shears
  - Via photo-zs…
- Supernovae
  - Via distance modulus

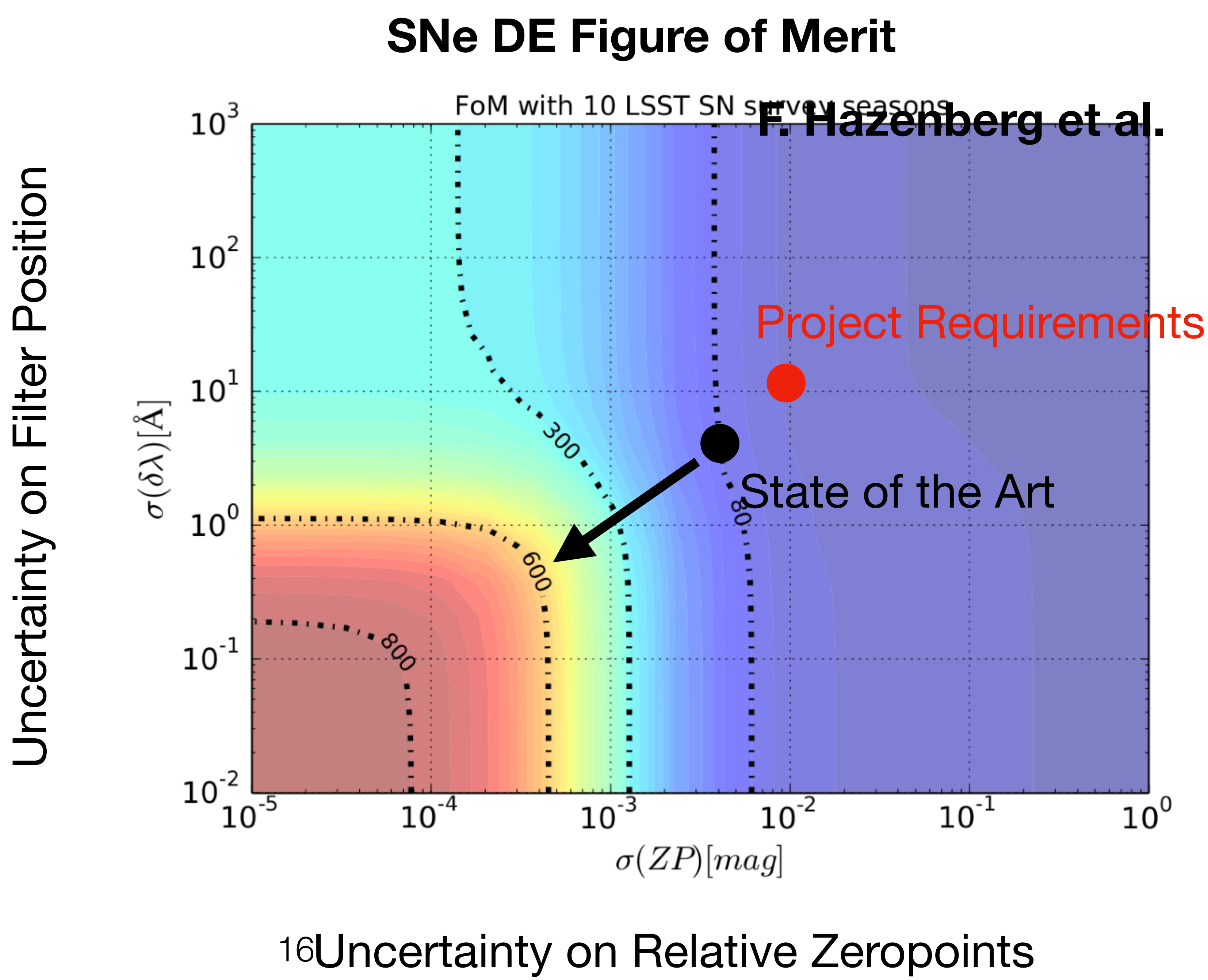
Supernova Cosmology

- Distances to low-z SNe rely on blue bands (g, r)
- Distances to high-z SNe rely on red bands (i, z)
- Must know band-to-band relative calibration at high precision or will falsely infer evolution in the SNe
- Must know filters very well



More Supernovae

- SNe drives the DESC SRD calibration requirements, beyond what LSST Project will promise
- Required to make LSST a Stage IV DE experiment (!)
- There are also a whole bunch of other SN systematics that must be conquered



Types of Calibration Errors

- Stability/Repeatability
  - If you return to an object later, do you get the same calibrated 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:

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

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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:

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

$$m_b^{\mathrm{obs}} = -2.5\log_{10}(\mathrm{ADU_b}) + 2.5\log_{10}(\Delta T) + 2.5\log_{10}(I_0^{\mathrm{obs}}(b)) + \mathrm{ZPT^{AB}}$$

$$I_0^{\mathrm{obs}}(b) \equiv \int_0^\infty S_b^{\mathrm{obs}}(\lambda)\lambda^{-1}d\lambda$$

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 ++ (2018) for details

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

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

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

Caution!

$$\delta_b^{\rm std} \equiv m_b^{\rm std} - m_b^{\rm obs} = 2.5\log_{10}(\mathbb{I}_0^{\rm std}(b)/\mathbb{I}_0^{\rm obs}(b))$$
$$+2.5\log_{10}\left(\frac{\int_0^\infty F_\nu(\lambda)\times S_b^{\rm obs}(\lambda)\times\lambda^{-1}d\lambda}{\int_0^\infty F_\nu(\lambda)\times S_b^{\rm std}(\lambda)\times\lambda^{-1}d\lambda}\right)$$

- The conversion from *observed* to *standard* magnitudes depends on SED ($F_\nu(\lambda)$) and observed passband ($S_b^{obs}(\lambda)$)

Exercise

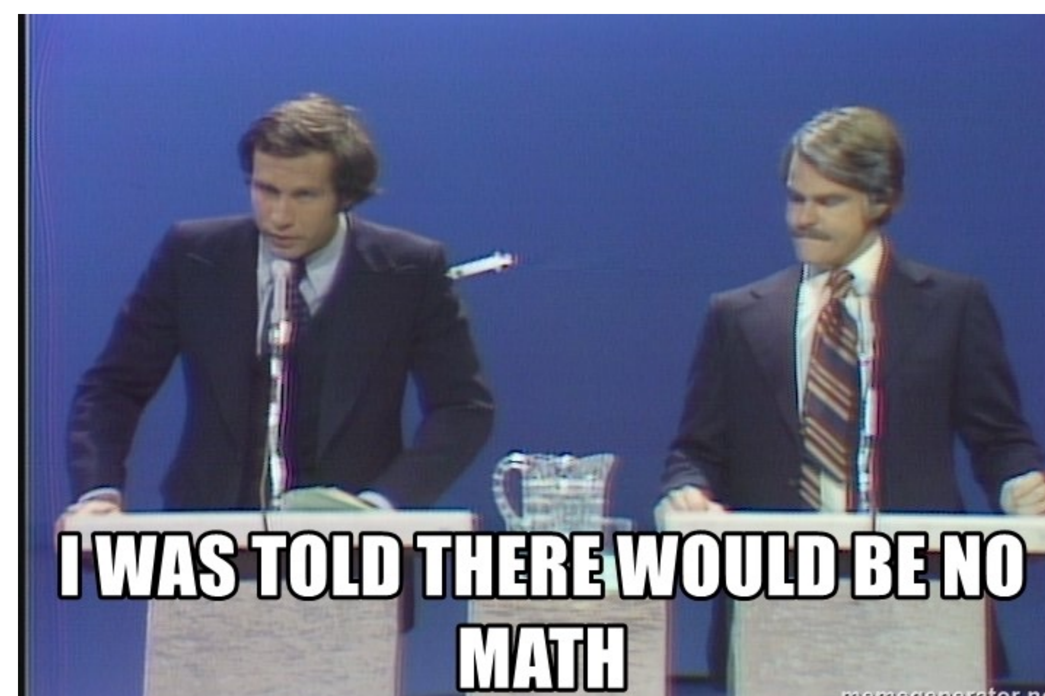
$$\delta_b^{\rm std} \equiv m_b^{\rm std} - m_b^{\rm obs} = 2.5\log_{10}(\mathbb{I}_0^{\rm std}(b)/\mathbb{I}_0^{\rm obs}(b))$$

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

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

- What is the typical magnitude change if $S_b^{\rm obs}(\lambda) = S_b^{\rm std}(\lambda)$?

- What is the typical magnitude change if $F_\nu(\lambda) = F_{AB}(\lambda)$?



Exercise

- What is the typical magnitude change if $S_b^{\text{obs}}(\lambda) = S_b^{\text{std}}(\lambda)$?
  - Replace “obs” with “std” in the equations above

$$\delta = 2.5\log_{10}\left(\frac{I_0^{\text{std}}}{I_0^{\text{std}}}\right) + 2.5\log_{10}\left(\frac{\int F_\nu S_b^{\text{std}}\lambda^{-1}d\lambda}{\int F_\nu S_b^{\text{std}}\lambda^{-1}d\lambda}\right)$$

$$\delta = 0 + 0 = 0$$

Exercise

- What is the typical magnitude change if $F_\nu(\lambda) = F_{AB}(\lambda)$?
    - F_{AB} is a flat spectrum (= 1)

$$\delta = 2.5\log_{10}\left(\frac{I_0^{\rm std}}{I_0^{\rm obs}}\right) + 2.5\log_{10}\left(\frac{\int F_{AB} S_b^{\rm obs}\lambda^{-1}d\lambda}{\int F_{AB} S_b^{\rm std}\lambda^{-1}d\lambda}\right)$$

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$$\delta = 2.5\log_{10}\left(\frac{I_0^{\rm std}}{I_0^{\rm obs}}\right) + 2.5\log_{10}\left(\frac{I_0^{\rm obs}}{I_0^{\rm std}}\right)$$

$$\delta = 0$$

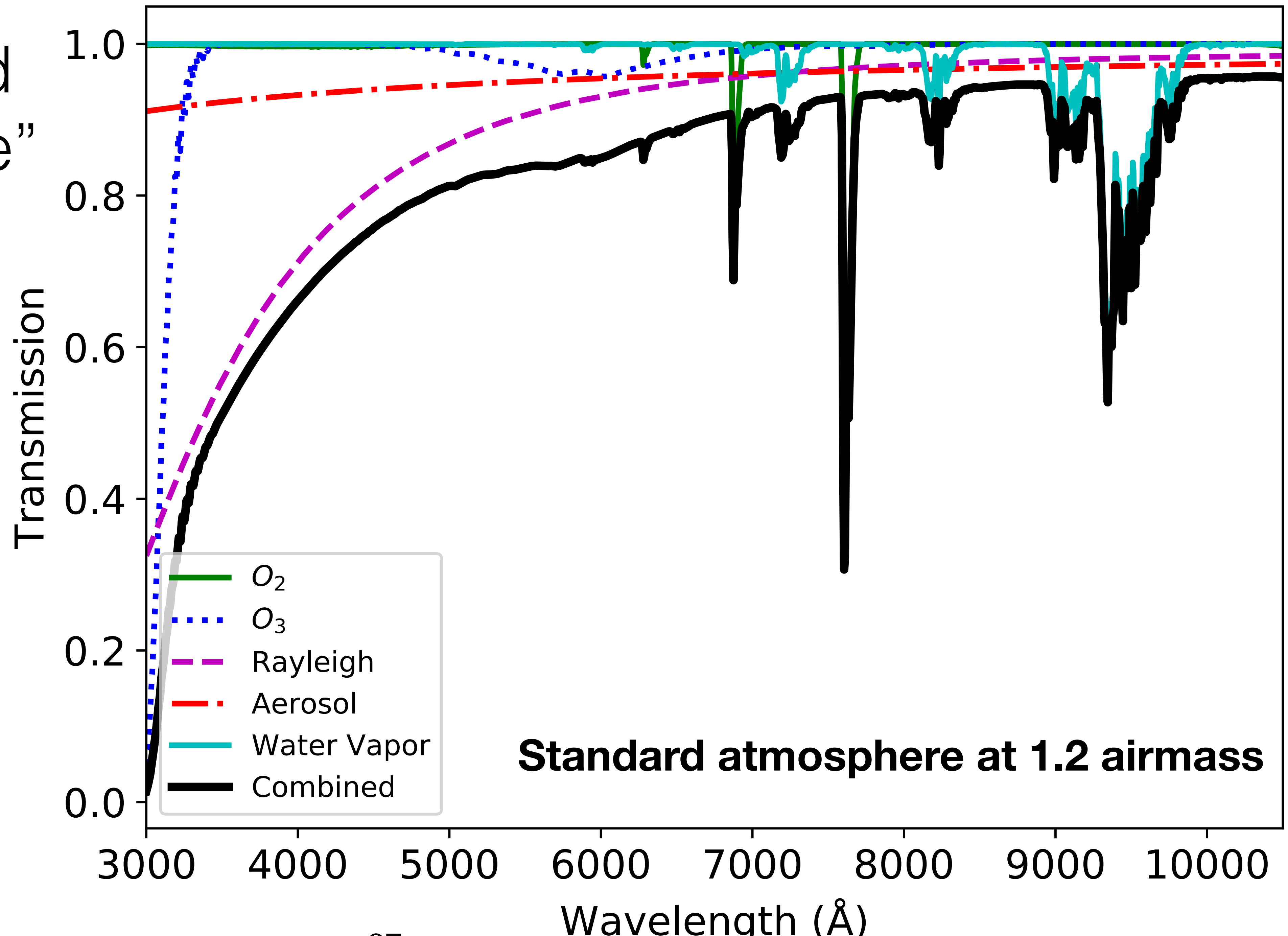
A-ha!

- If *either* the SED is the flat AB spectrum *or* the observed passband is the standard passband, the correction is 0!
- Choose your standard passband wisely!

- But … the further the passbands diverge, the greater the impact of different SEDs
  - Transferring calibrations from one survey to another at the mmag level is … challenging.

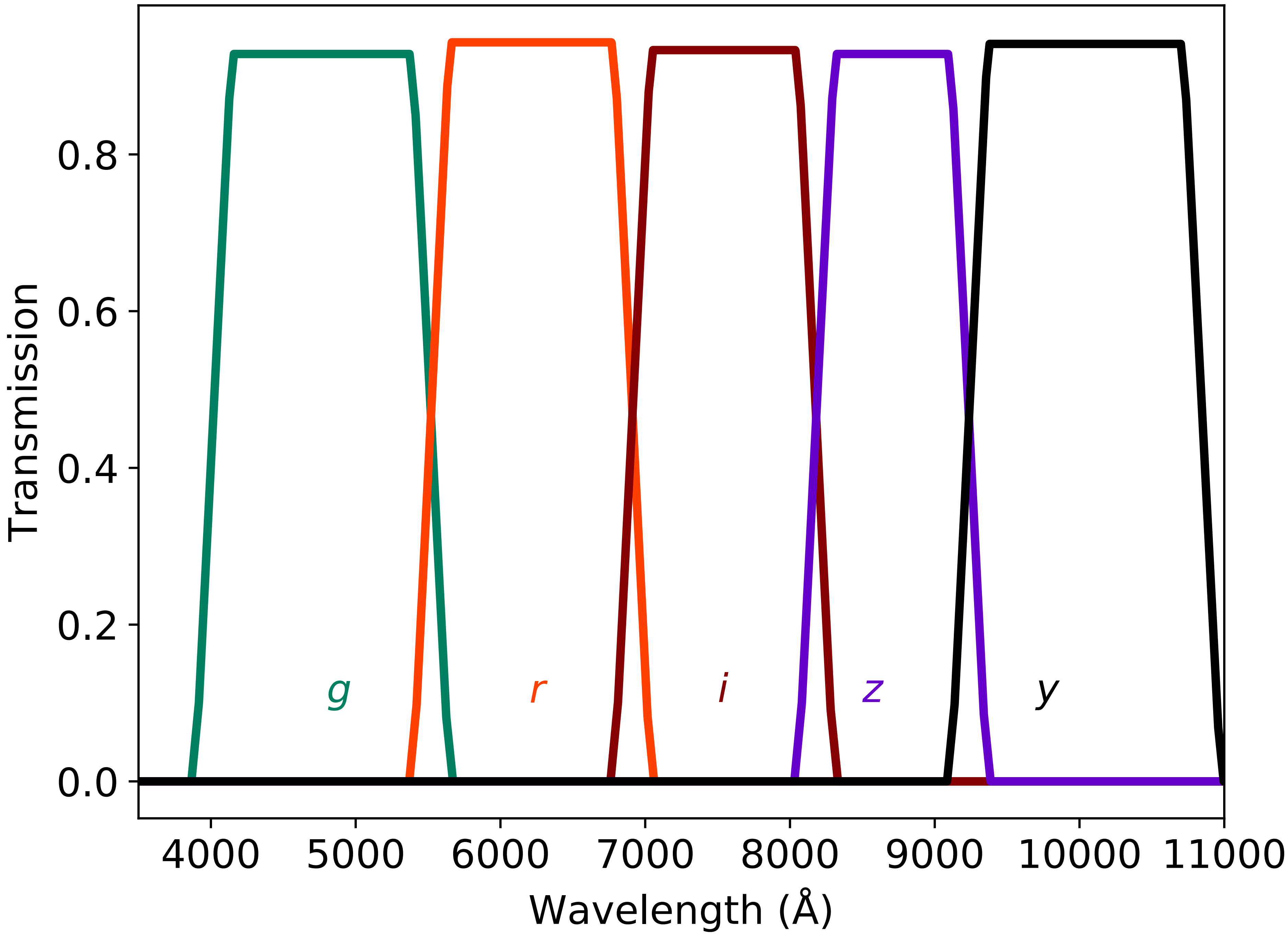
Atmosphere

- The atmosphere is not clear…and molecules scatter
- A “standard atmosphere” is chosen to be as close to typical conditions as possible



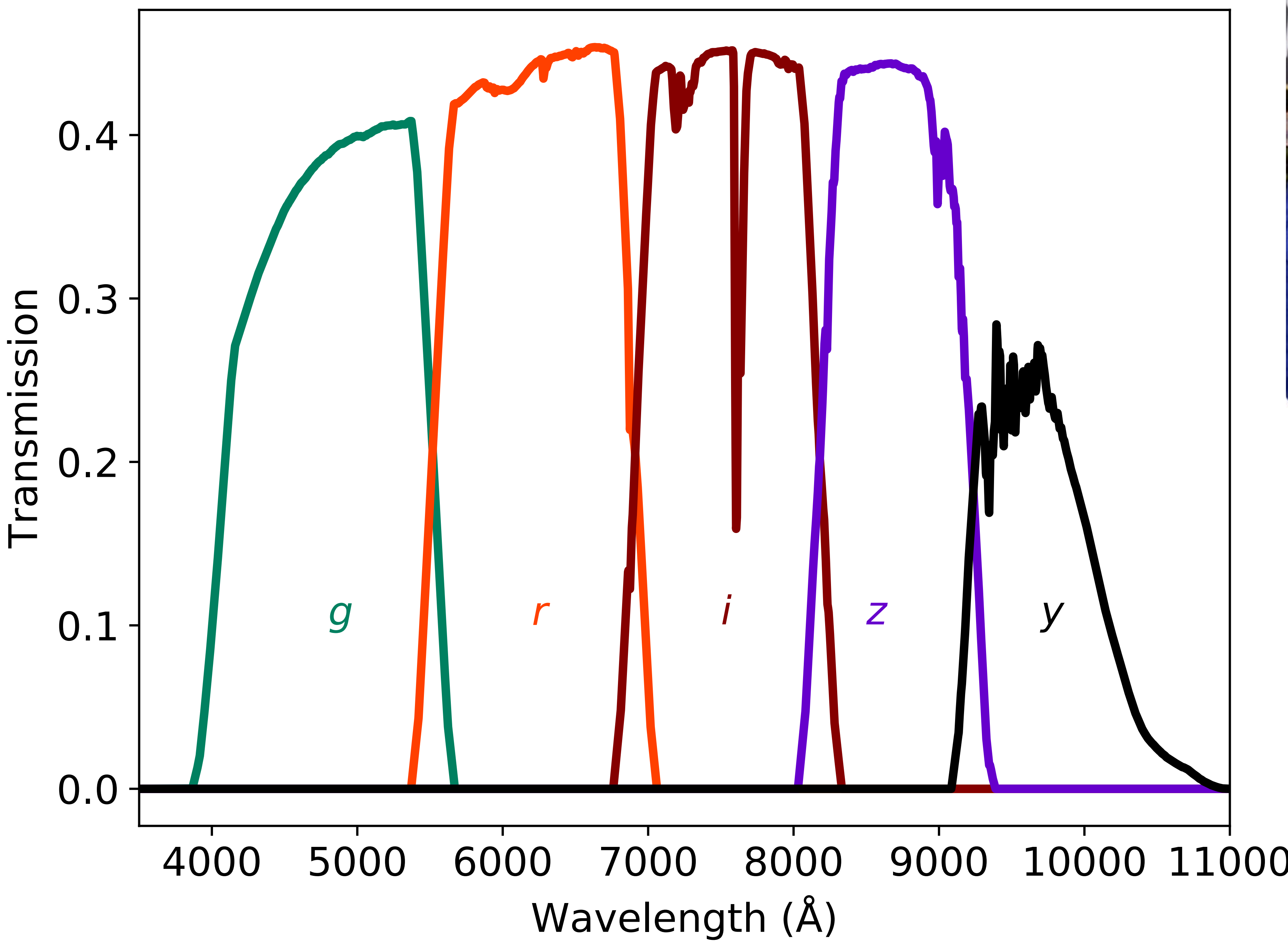
The LSST Filters

- These are the nominal LSST filters



The LSST Passbands

- These are the nominal passbands

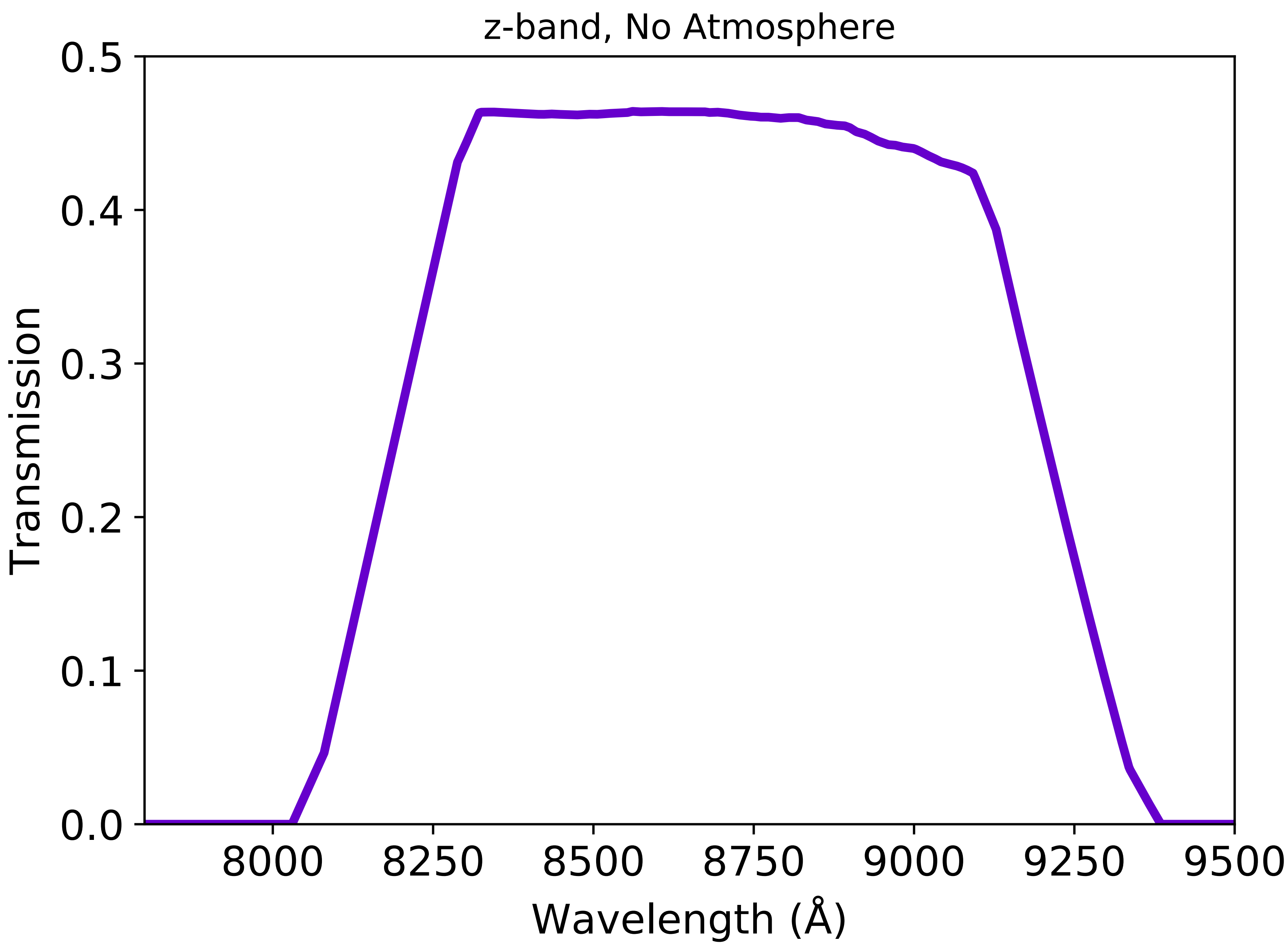


Just add water!
(and other atmospheric constituents)

Also don't forget about everything else in the way

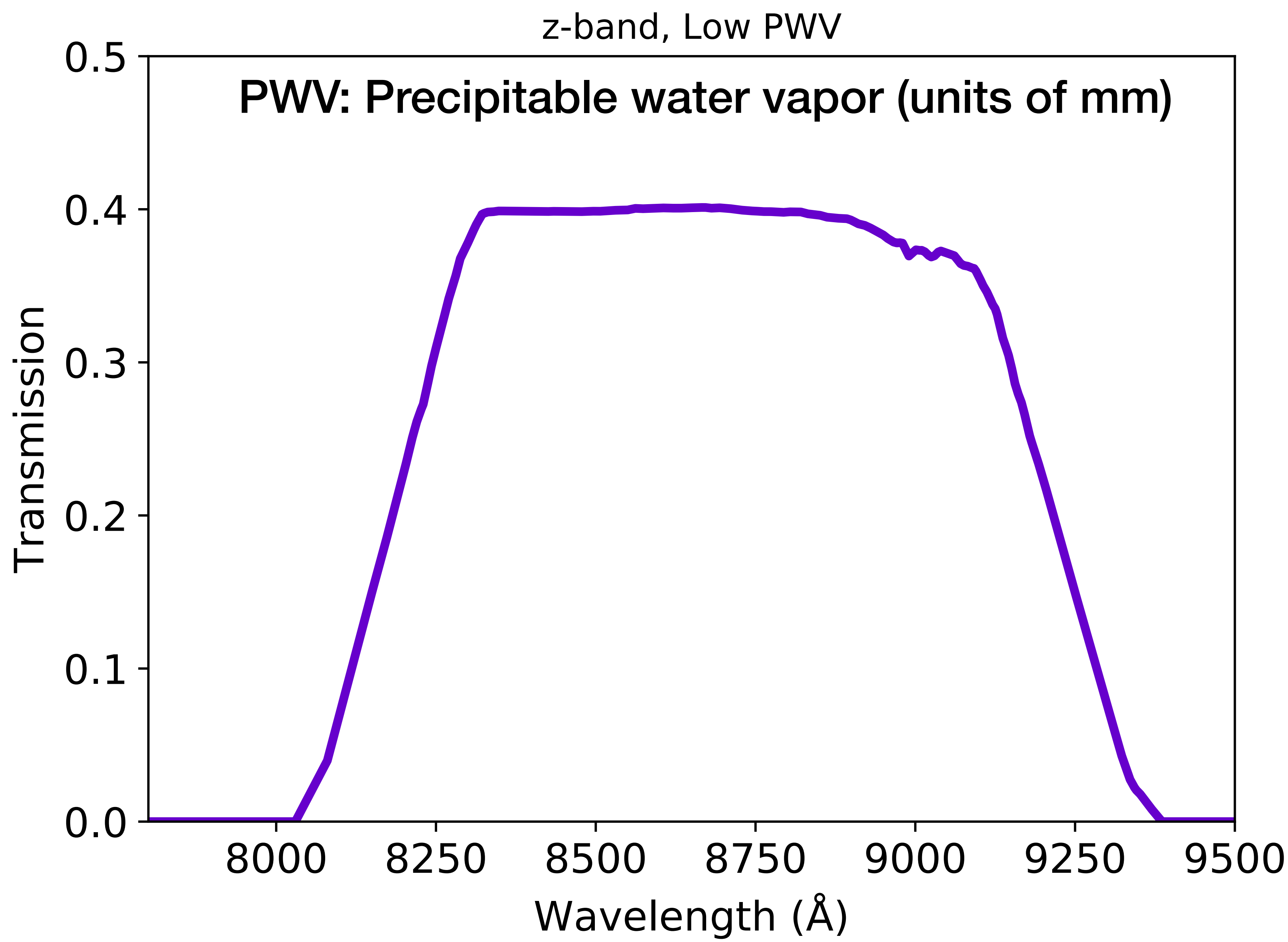
Impact Of The Atmosphere

- Here is the z-band (filter + hardware):



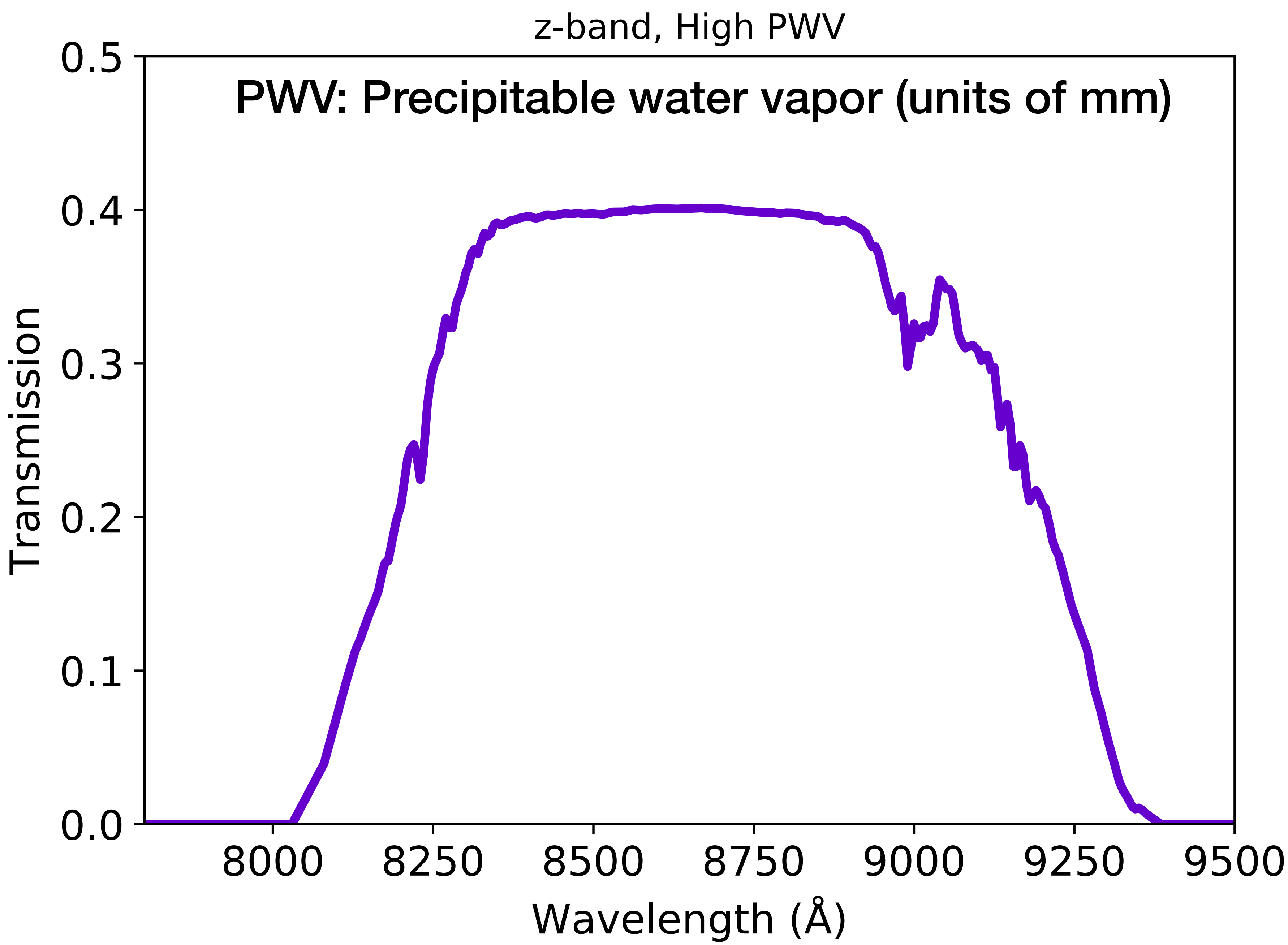
Impact Of The Atmosphere

- And if we add the atmosphere w/ a touch of water



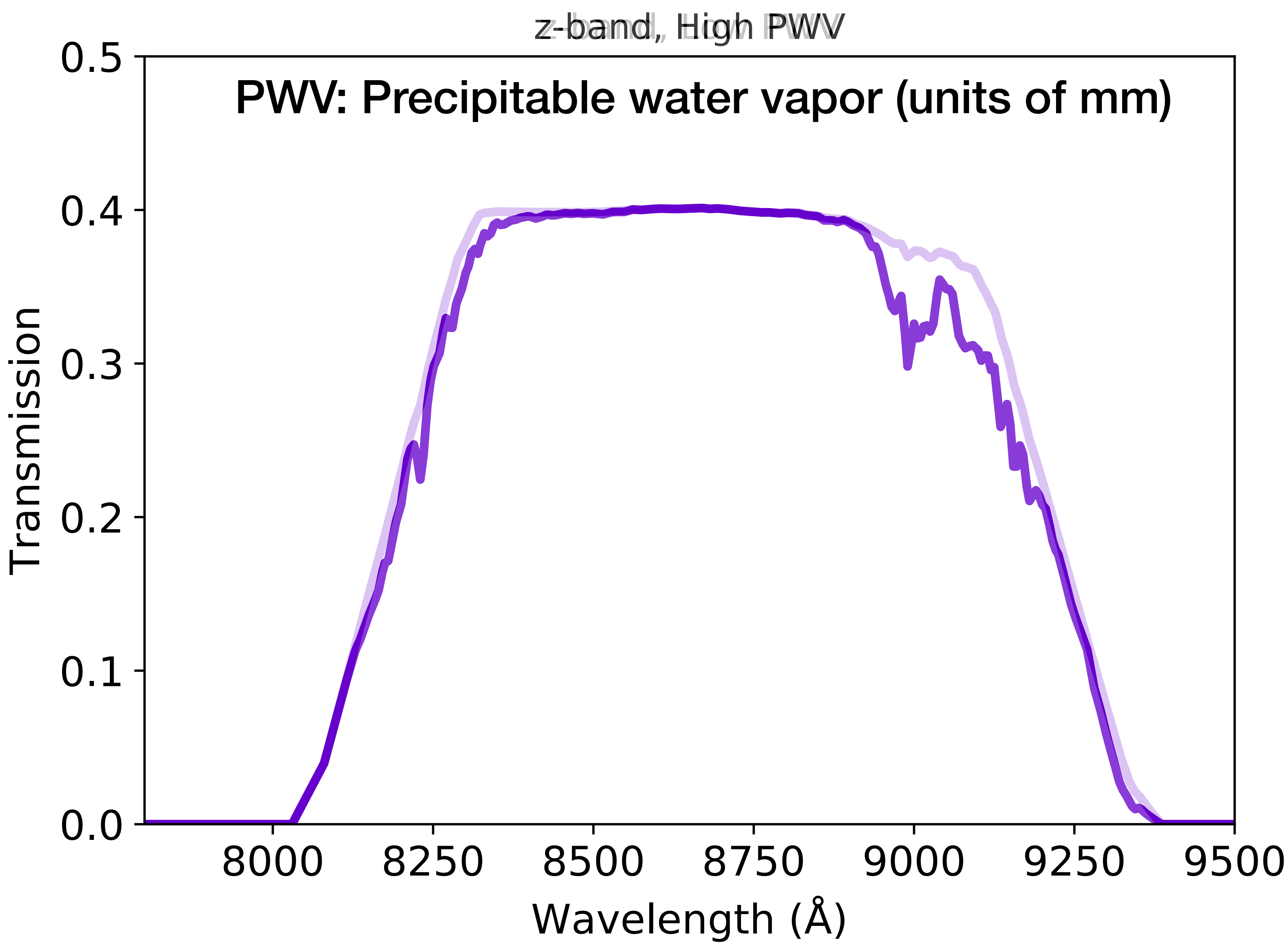
Impact Of The Atmosphere

- And if we add a bunch more water (still no clouds!)



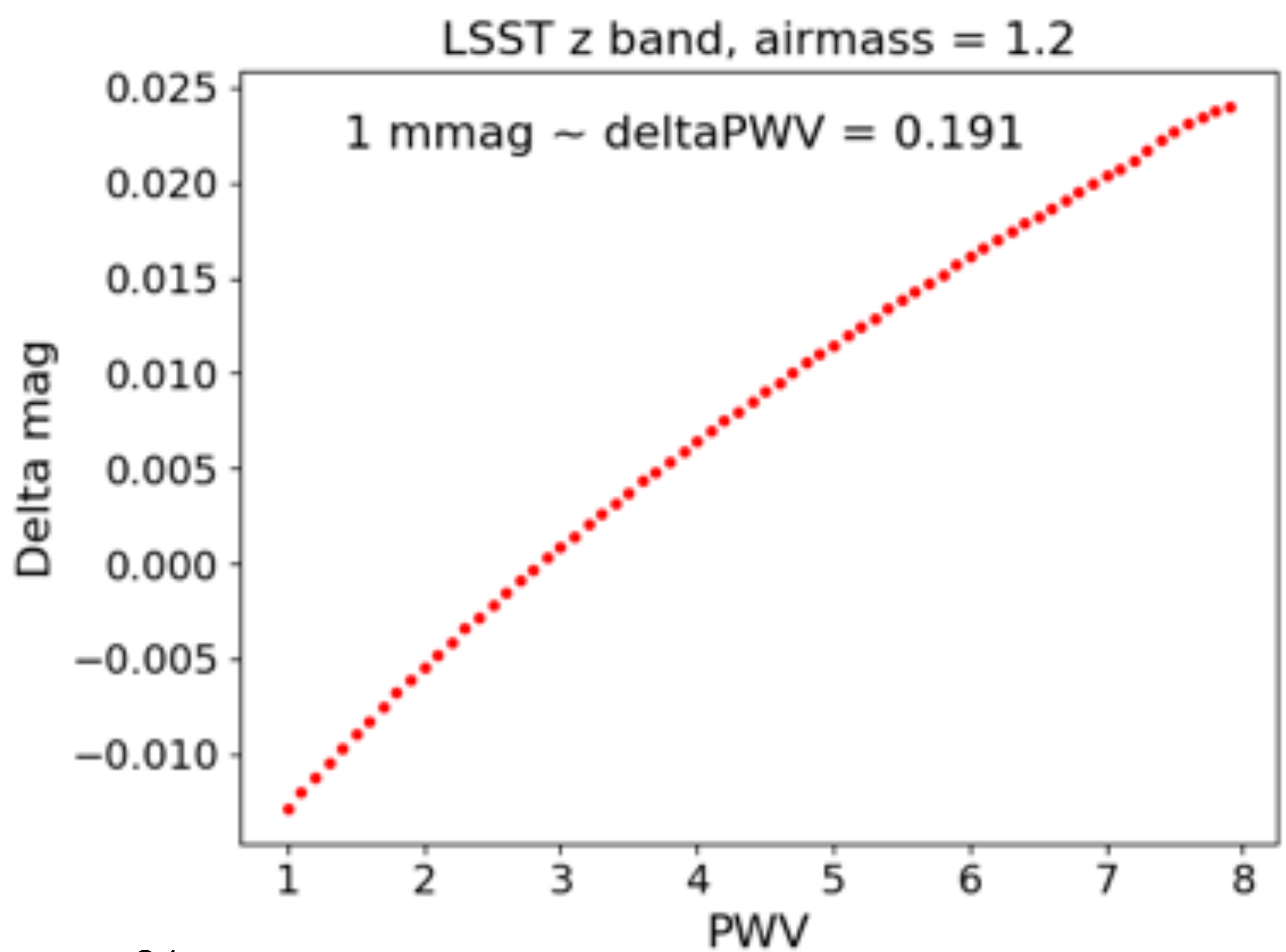
Impact Of The Atmosphere

- Let’s see that change



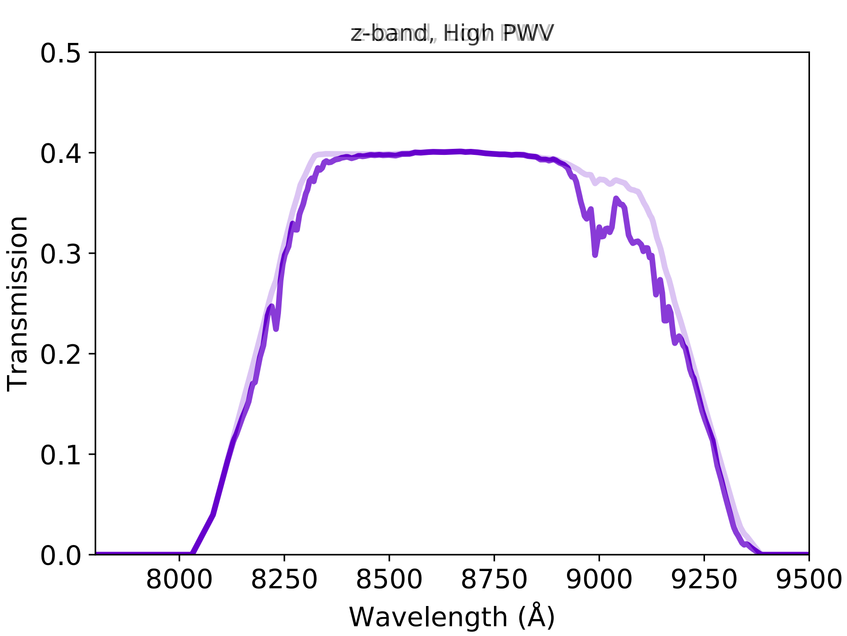
Impact Of The Atmosphere

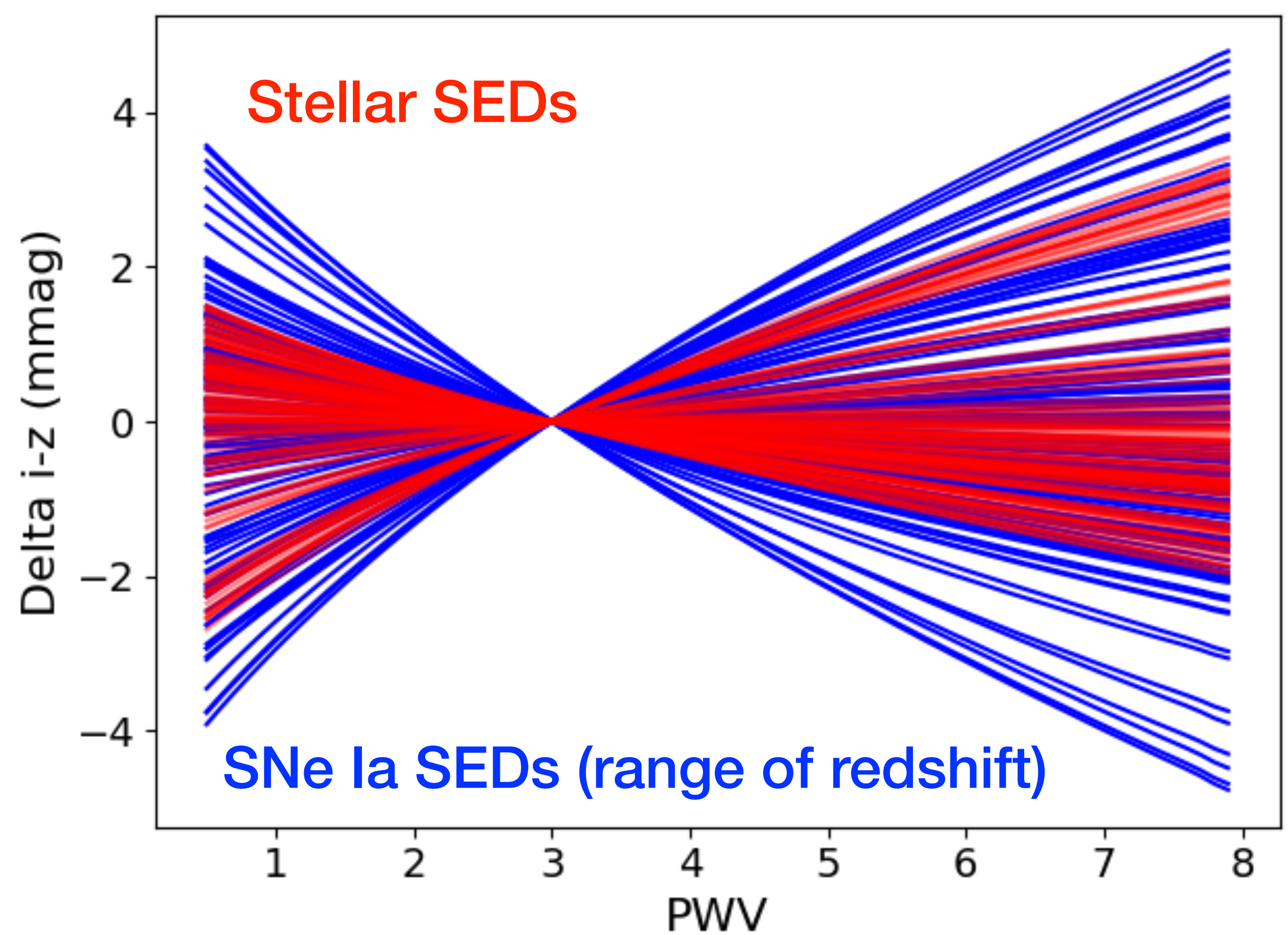
- Primary impact is the change in the overall throughput (transparency)
- To predict the throughput at mmag level, we need to know PWV at the ~0.2 mm level
- Satellite measurements are not well enough localized



Impact Of The Atmosphere

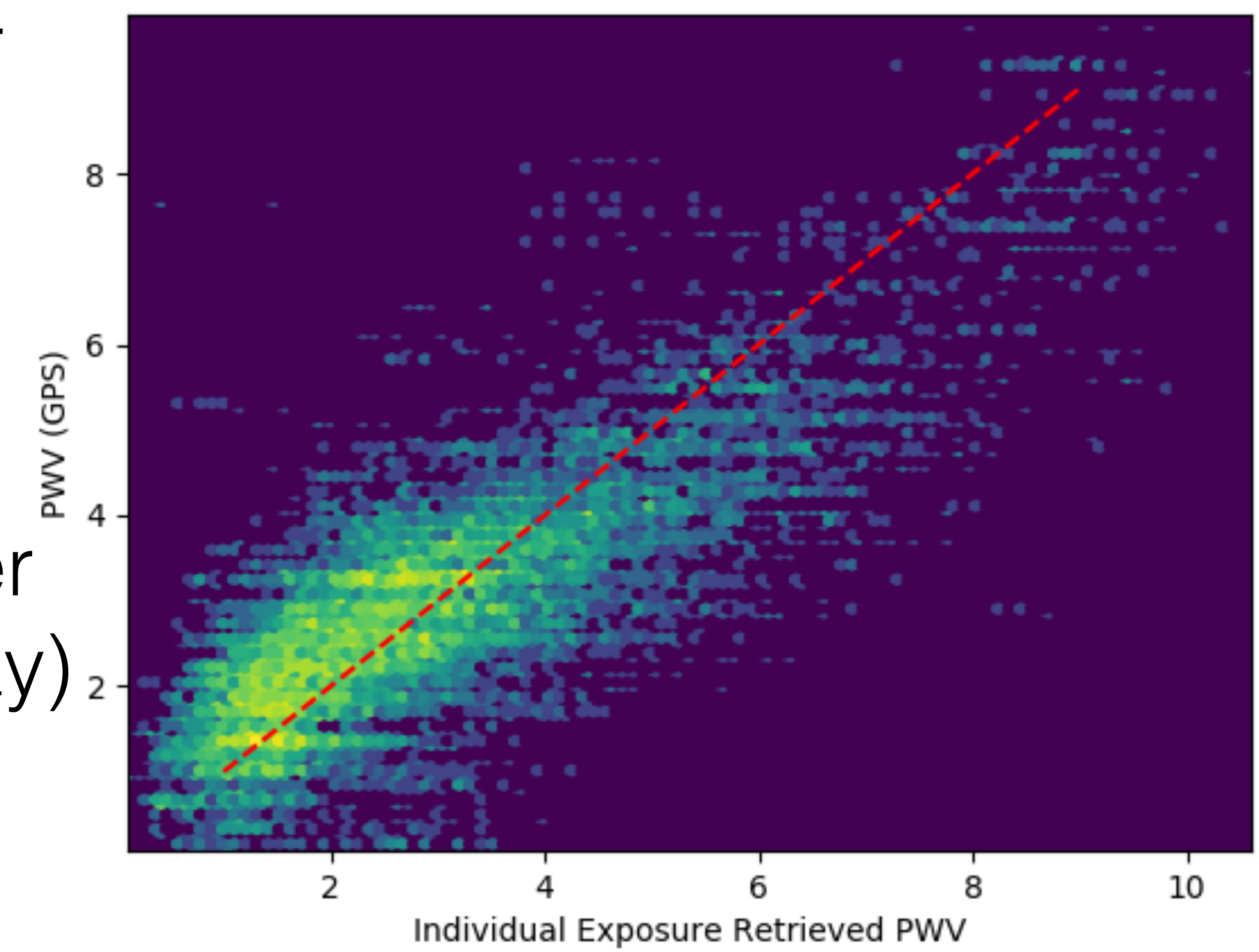
- Secondary impact is the chromatic effect. Mostly the red end of the z band is removed!
- Size of impact depends on the SED
- For SNe, need to know PWV at ~1 mm level





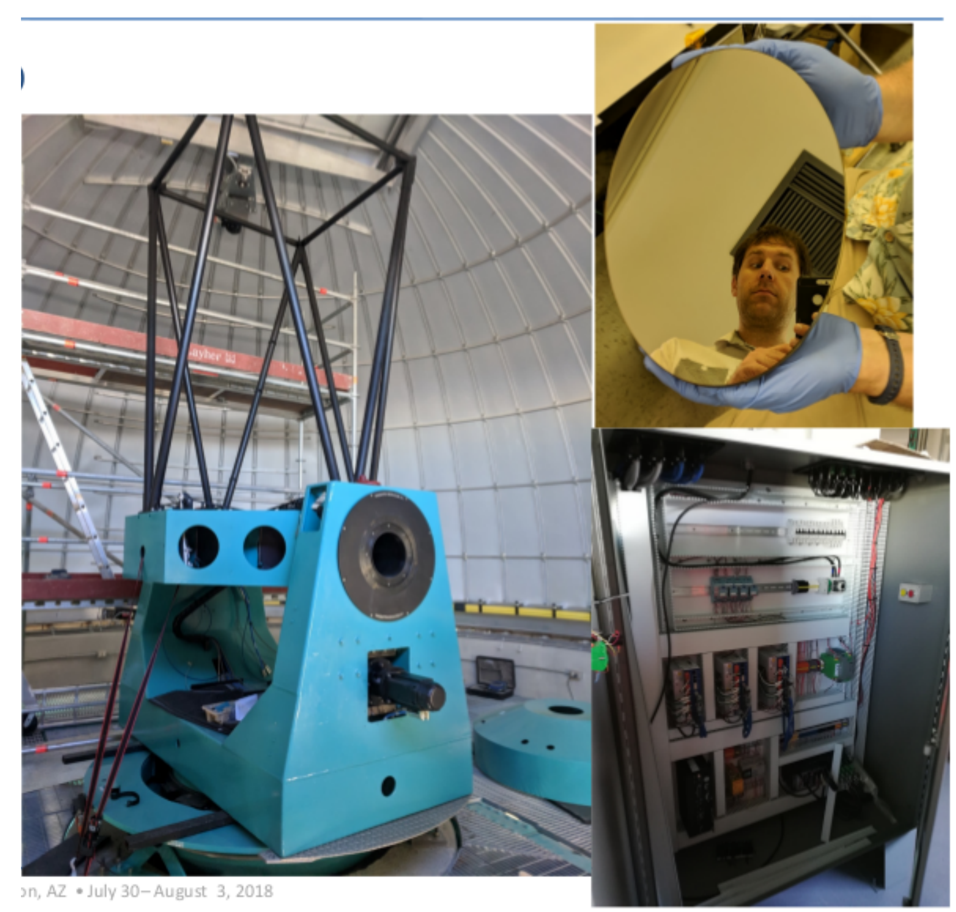
“Lupton Dream”

- Waitasec … can we use the relative change in magnitude of red and blue stars to estimate the PWV for each image?
- For DES, the answer is “yes”, though it’s a bit noisy
- Note that this only works in bands that are affected by water vapor (but that’s okay)



There Is Another Way…

- The Auxiliary Telescope (AuxTel)
- Monitor the atmospheric transmission along the line of sight
  - Low-resolution spectra of bright stars
- This will be the first LSST CCD on the sky!
  - Sensor characterization is ongoing…

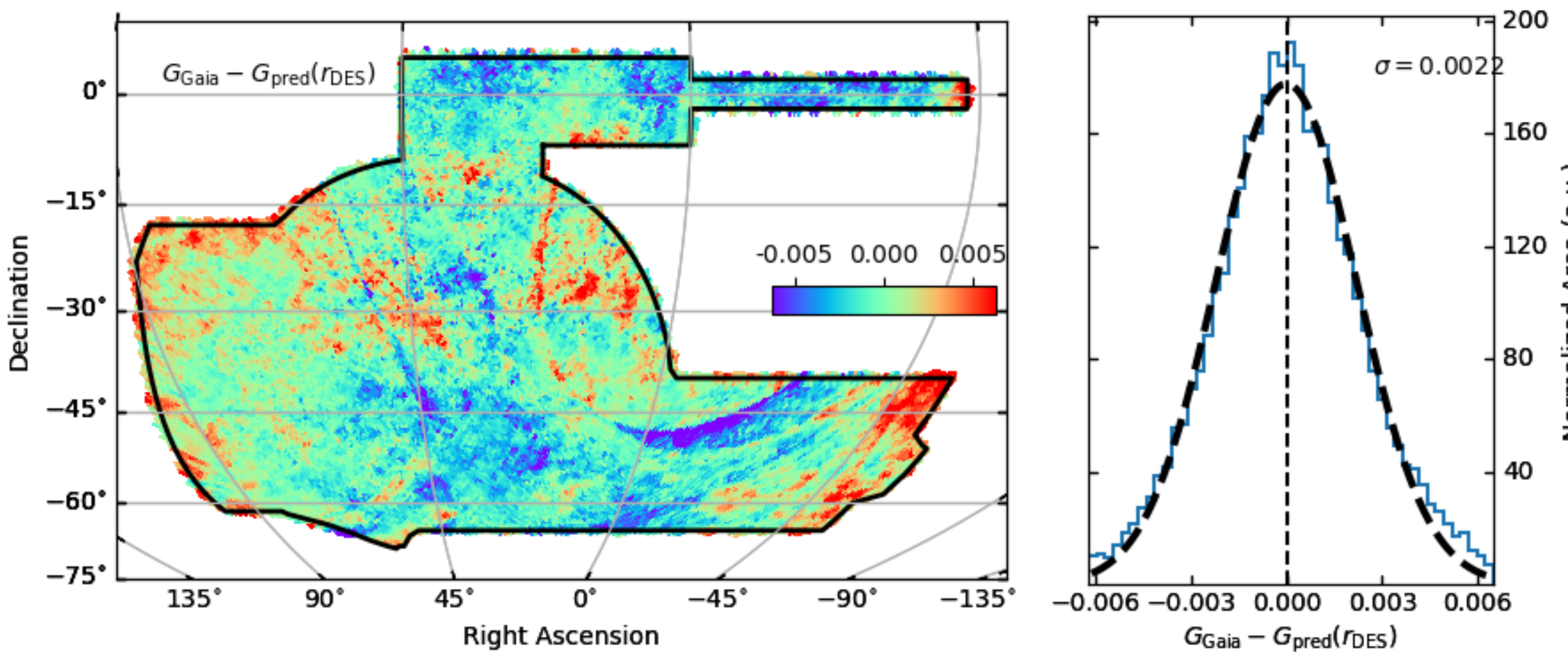


The Good News…

- Variations that have a measurable impact … have a measurable impact
- Tremendous power of self-calibration from broadband observations
- Forward Global Calibration Method (FGCM) constrains the atmosphere at <5 mmag level from stars alone in DES imaging data
    - Pushing down to 1 mmag is a challenge
    - But we have a decade of LSST imaging to do it!

Survey Uniformity

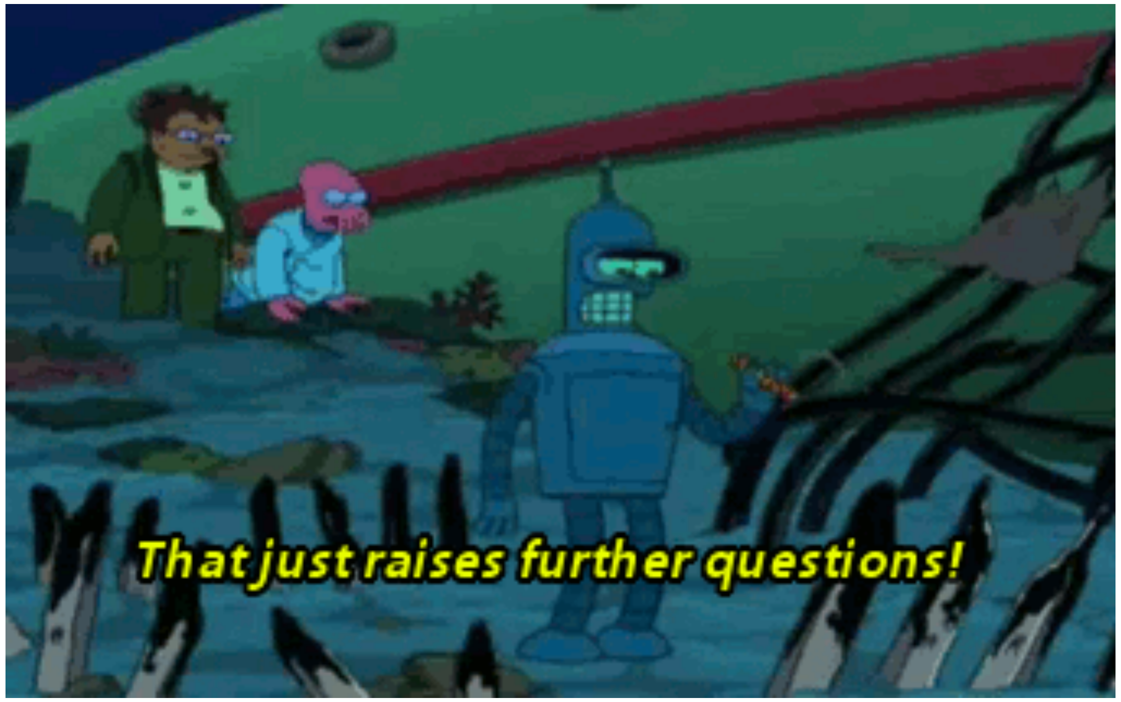
- Compare DES (self-calibration from FGCM) with Gaia DR2
- Gaia G band is very broad, so SED variation is significant — only works at high Galactic latitude



More Atmosphere

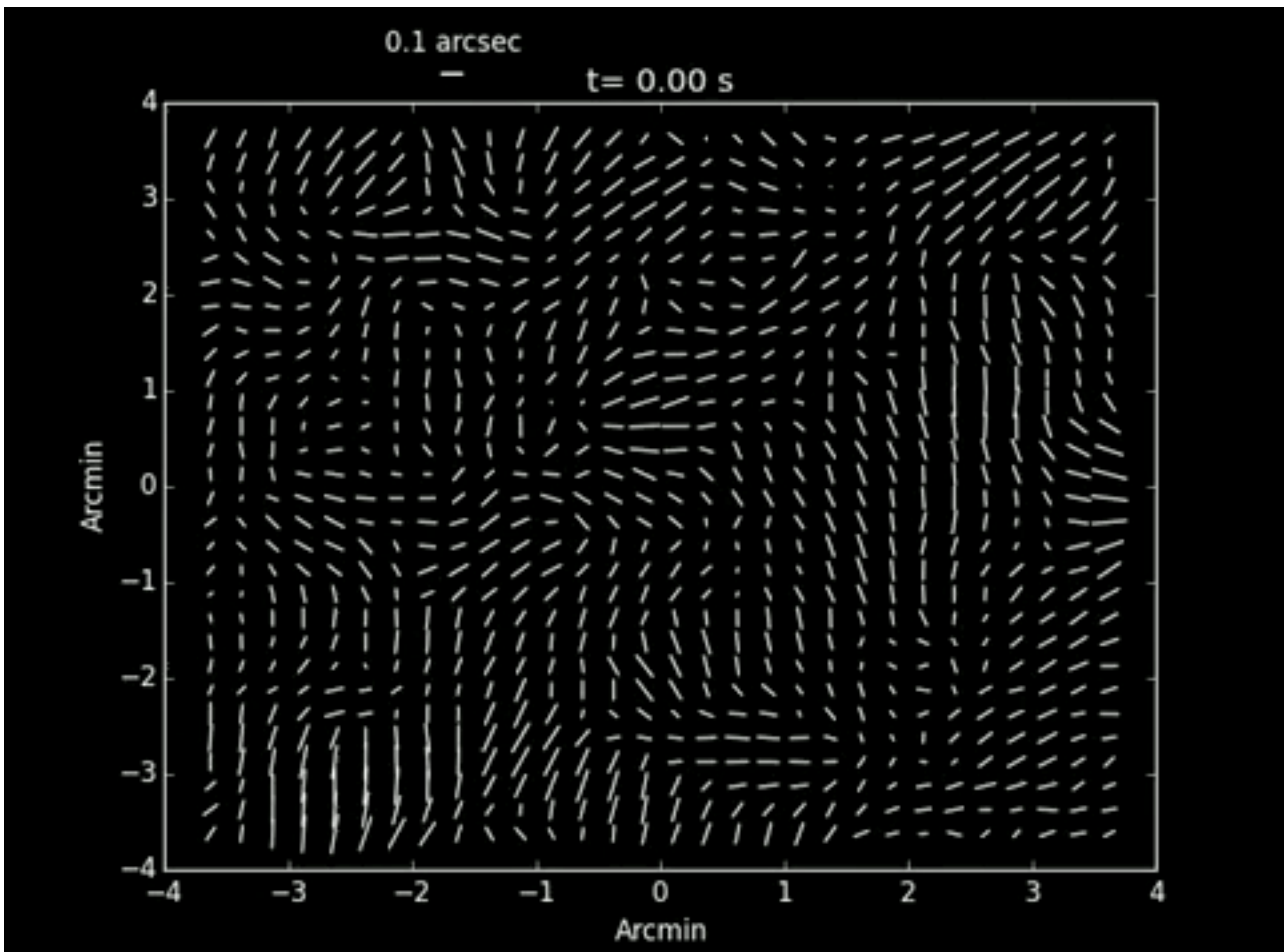
- From R. Lupton’s DESchool lesson
  - What pixel measurements should I make to find the number of counts in a bright star?
  - “Choose a largish circular aperture of radius R centered on the star, and add up all the pixel values”

- If only it were that simple



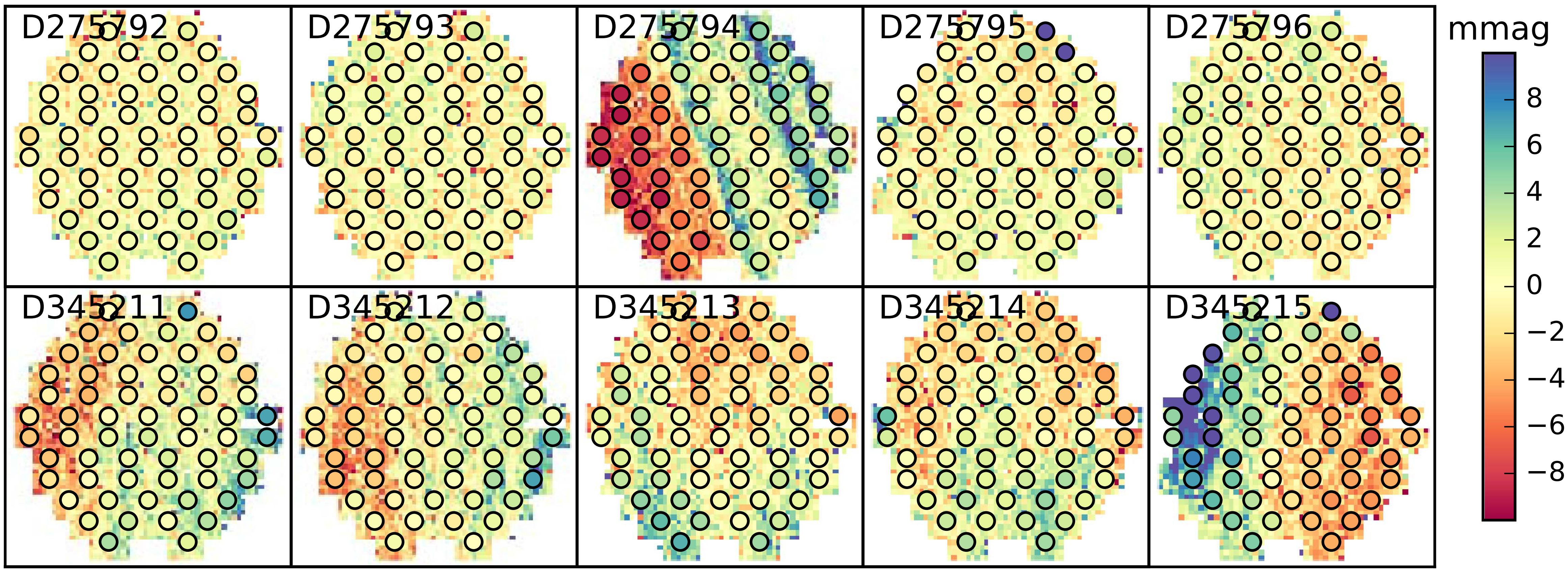
PSF Size Variations

- From Josh Meyer's DE School lesson in March, 2016:
  - Impact of atmosphere screens on PSF size/shape: https://youtu.be/xBFvKHkRmWQ



PSF Size Variations

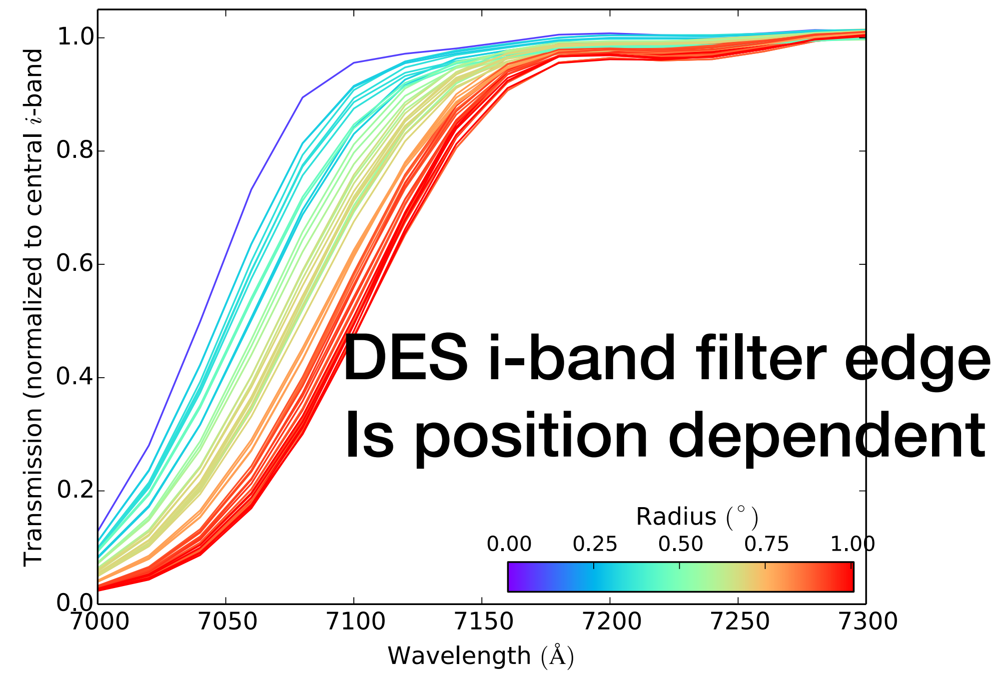
- PSF size variations lead to throughput variations!

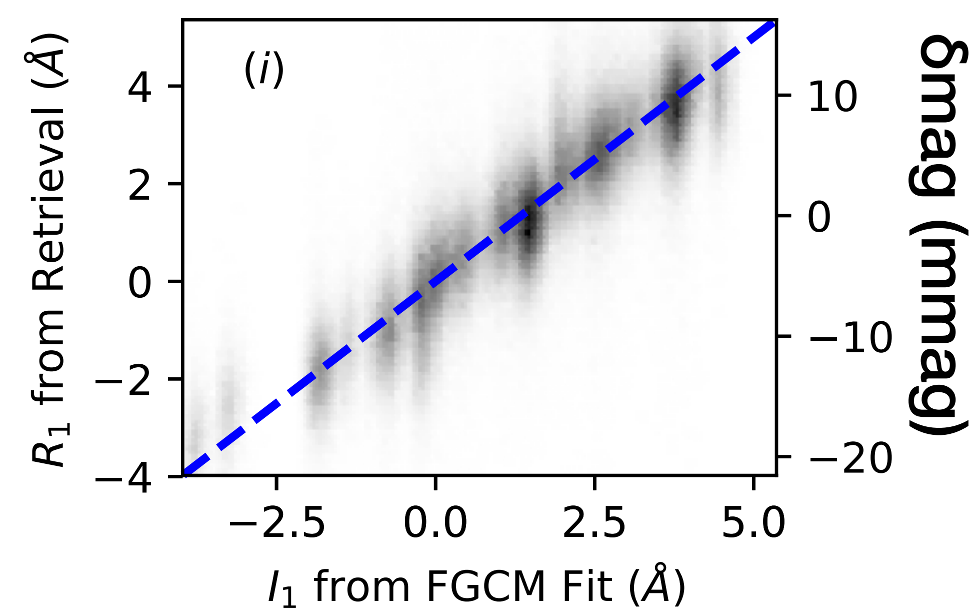


- “In summary, we find that all of the deviations above ≈1 mmag rms … on short timescales are plausibly attributable to spatial/temporal variations in aperture corrections.” Bernstein et al. (2018)

Impact of the Instrument

- So far, I've just asserted that we know the hardware.
- In the *i* band filter on the Dark Energy Camera, the blue edge is position dependent
  - Shift of ~5 nm (50 Å)
  - Leads to shifts of up to 3% between red and blue stars!





Questions

- What aspects of the system hardware do we need to know the throughputs?

- How would you measure these? If they need to be separated, how would you do it?

Questions

- What aspects of the system hardware do we need to know the throughputs?
  - Filters, lenses, mirrors, CCD quantum efficiency, all as a function of wavelength and position over the focal plane.

- How would you measure these? If they need to be separated, how would you do it?
  - In essence, the camera is a complete unit … need to know filters + everything else

The Collimated Beam Projector

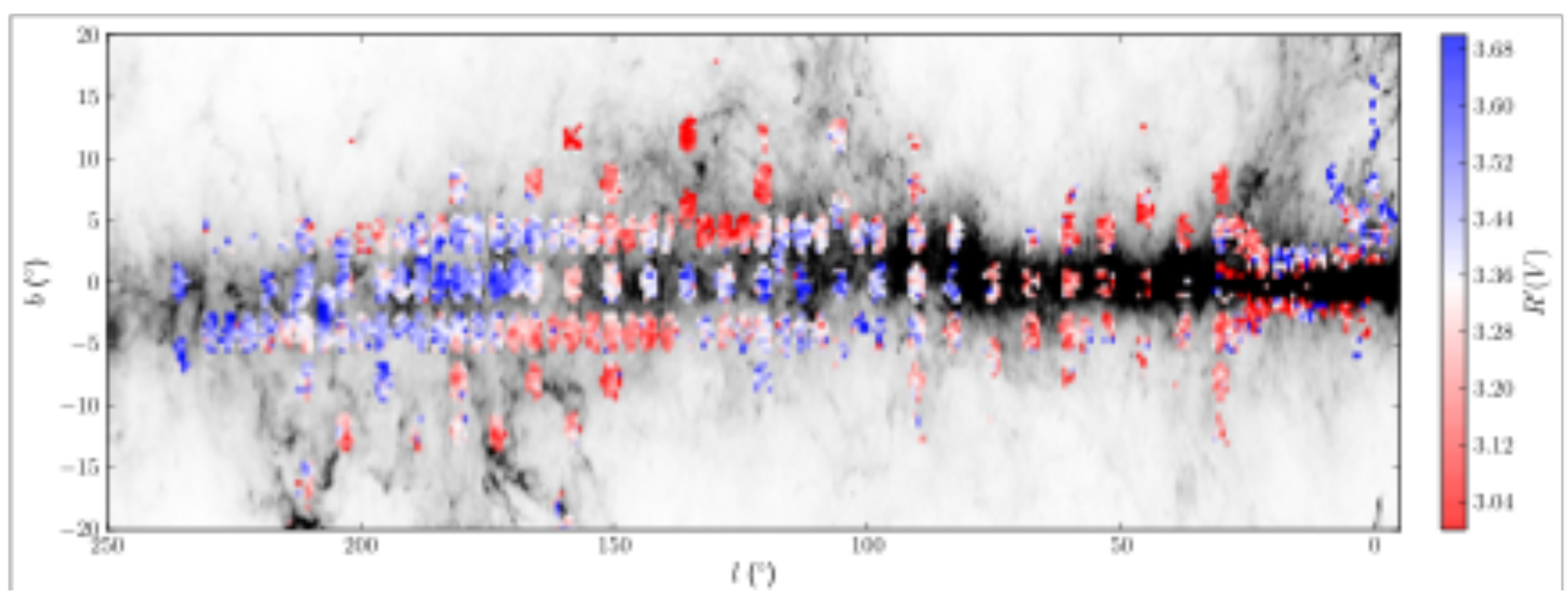
- It's a telescope … in reverse
- Mounted to edge of LSST dome
- Project monochromatic spots onto LSST focal plane
  - Requires a Class IV laser
- Traces relative throughput, ghosting, filter response, sensor QE…

Stubbs; Ingraham

One more thing…

The Milky Way (!)

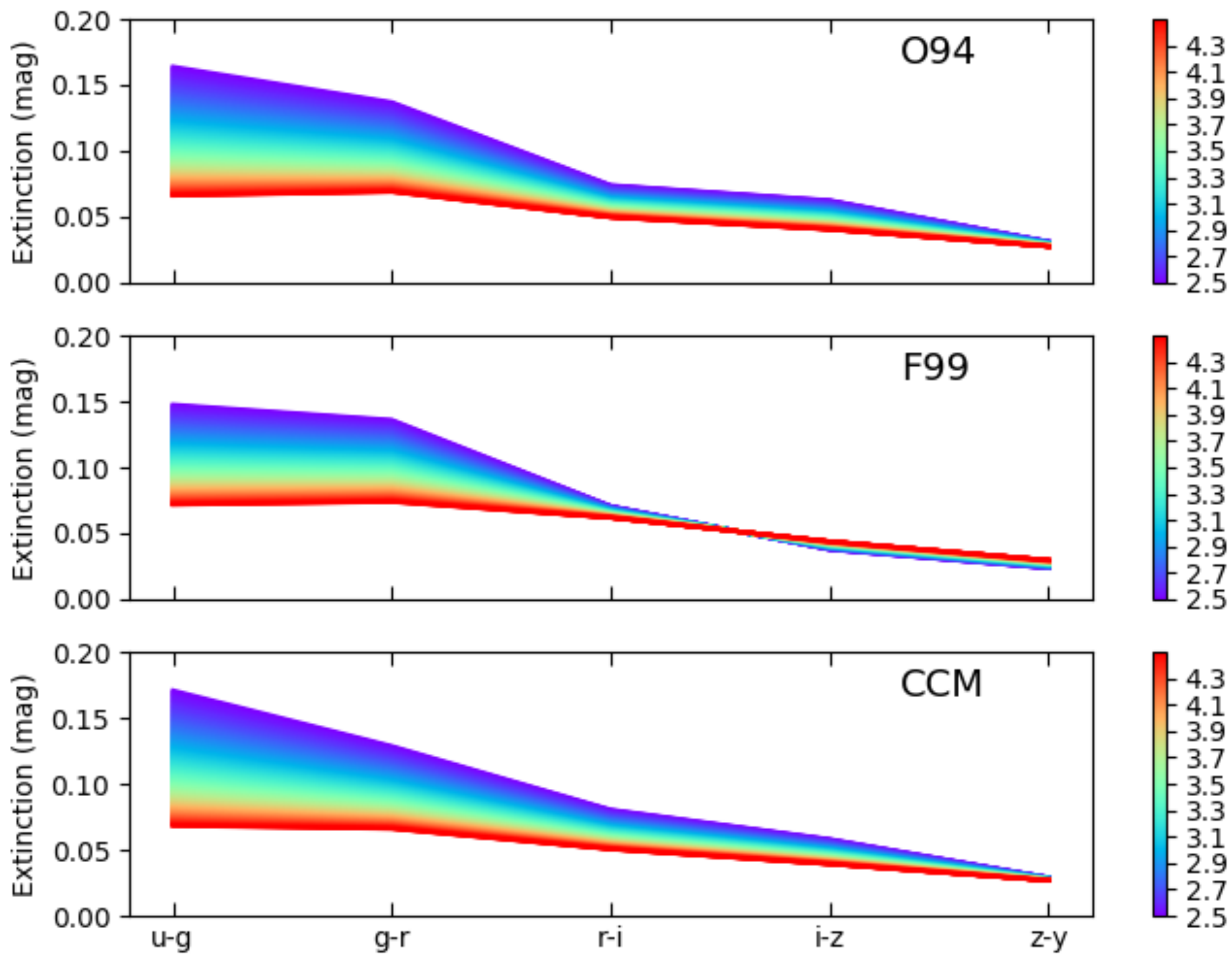
- On top of all this, we need to worry about Galactic reddening
  - Both the amount of reddening and the shape of the reddening law can vary over the MW
- Different assumptions about the reddening law (even if constant!) leads to percent-level differences over a significant fraction of LSST footprint

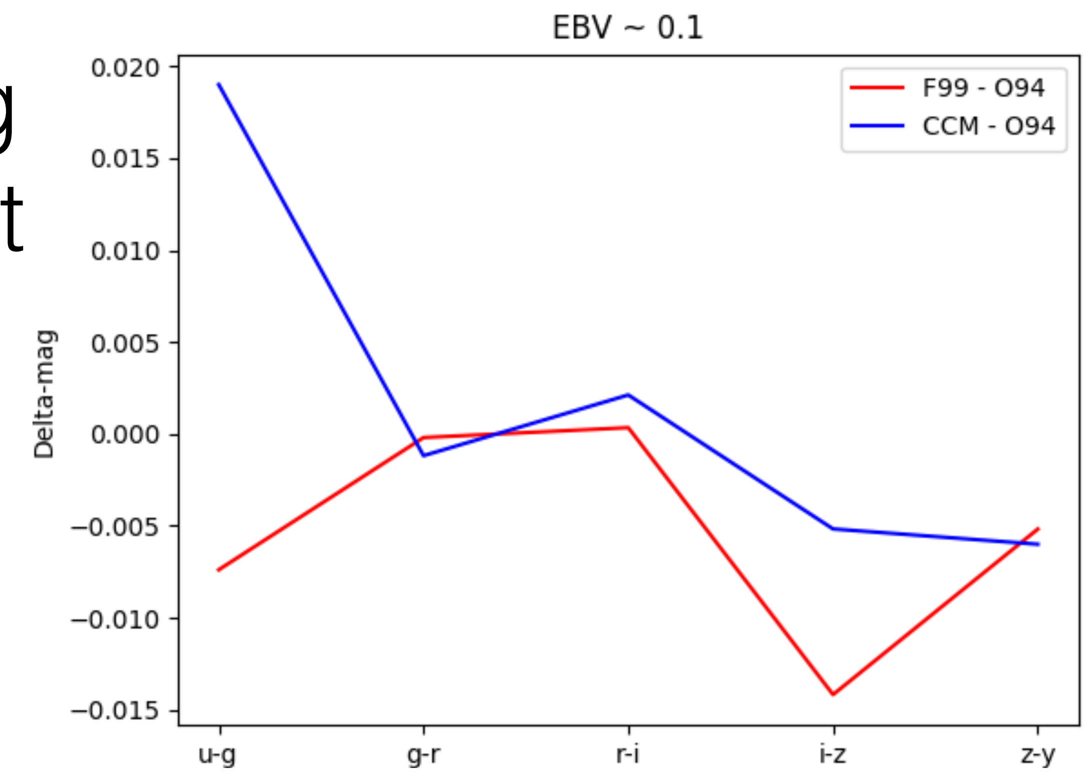


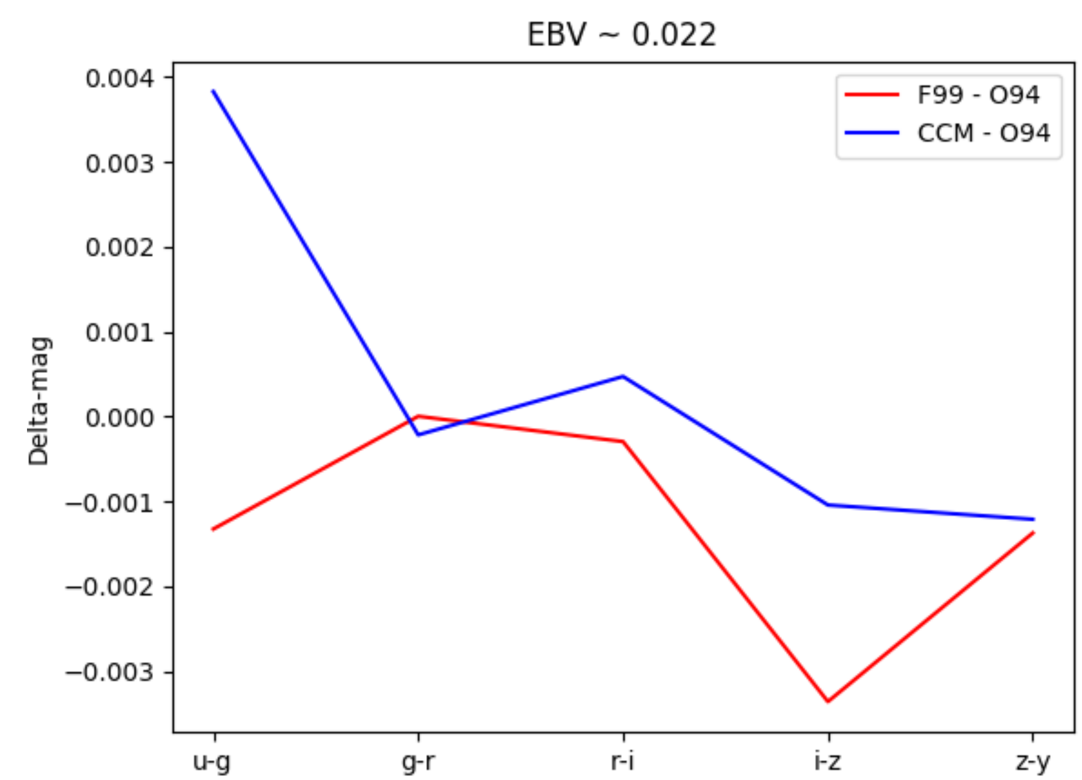
Schlafly++16

And the Reddening Law!

- Comparing reddening laws shows issues at the >mmag level (depending on amount of reddening)







Further Reading

- Survey strategy white papers
  - Lochner, et al: http://adsabs.harvard.edu/abs/2018arXiv181200515L
  - Scolnic et al: http://adsabs.harvard.edu/abs/2018arXiv181200516S
- LSST DESC SRD: http://adsabs.harvard.edu/abs/2018arXiv180901669T
- R. Lupton "How Bright is That Object?": http://www.lsst-desc.org/DEschool#lupton
- Burke, Rykoff++2018: http://adsabs.harvard.edu/abs/2018AJ....155...41B