THE DARK ENERGY SURVEY

Chromatic Corrections for Broadband Photometry

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Fermilab

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PACCD2016, BNL

DES Calibration Group
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Outline

- Broadband Photometry and Dark Energy Survey
- Variation of the System Response in the Instrument and Atmosphere
- Chromatic Errors —> Chromatic Corrections
- Plan for DES Photometry Calibration

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Broadband Photometry

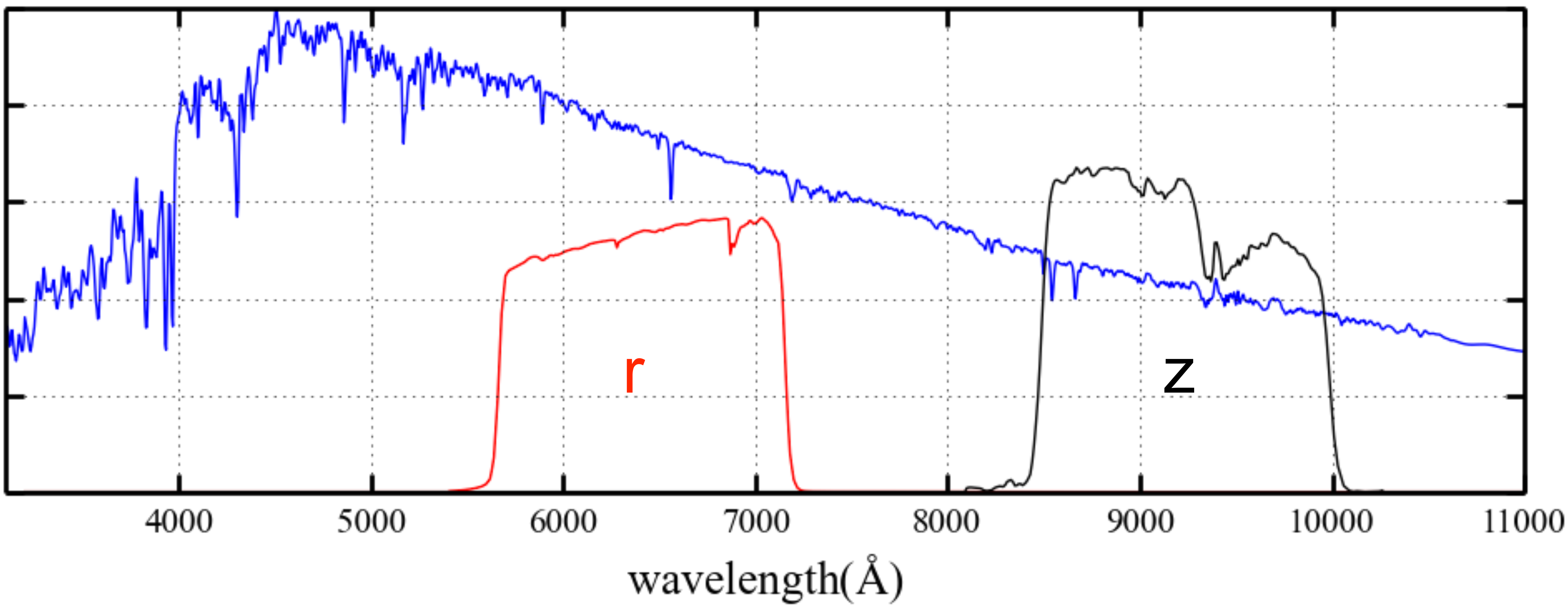
- Measurements of the brightness of objects
- Top-of-Atmosphere (TOA) magnitude of an object as observed by a given bandpass

- AB magnitude:

$$m = -2.5 \log_{10} \frac{\int F_\nu(\lambda) S_b(\lambda) \lambda^{-1} d\lambda}{\int S_b(\lambda) \lambda^{-1} d\lambda} - 48.60$$

- $F_\nu(\lambda)$ — Spectral Energy Distribution (SED), ergs/cm^2/s/Hz
- $S_b(\lambda)$ — System response, dimensionless, b = ugriz, etc.
- **Photometry: Average of an SED weighted by the system response**

G star SED

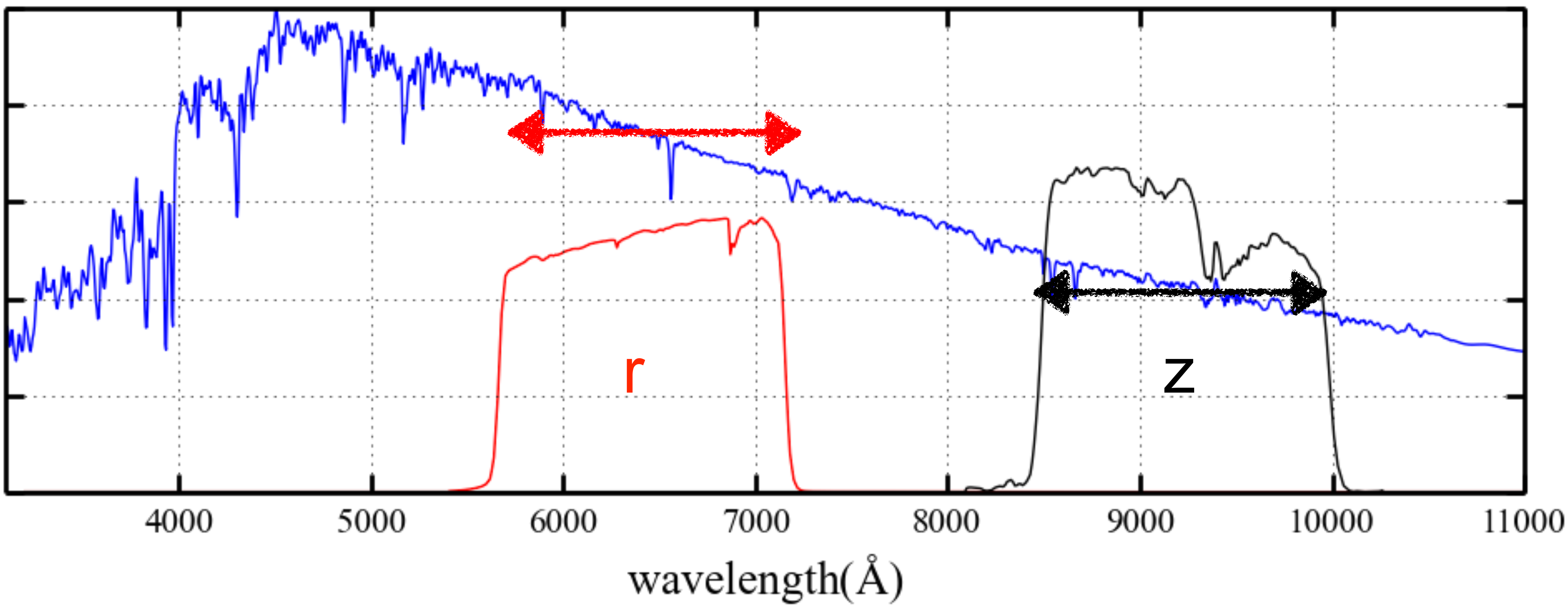


$$S_b(\lambda) = S^{atm}(\lambda) \times S_b^{inst}(\lambda)$$

system response

instrumental throughput + atmospheric transmission

G star SED



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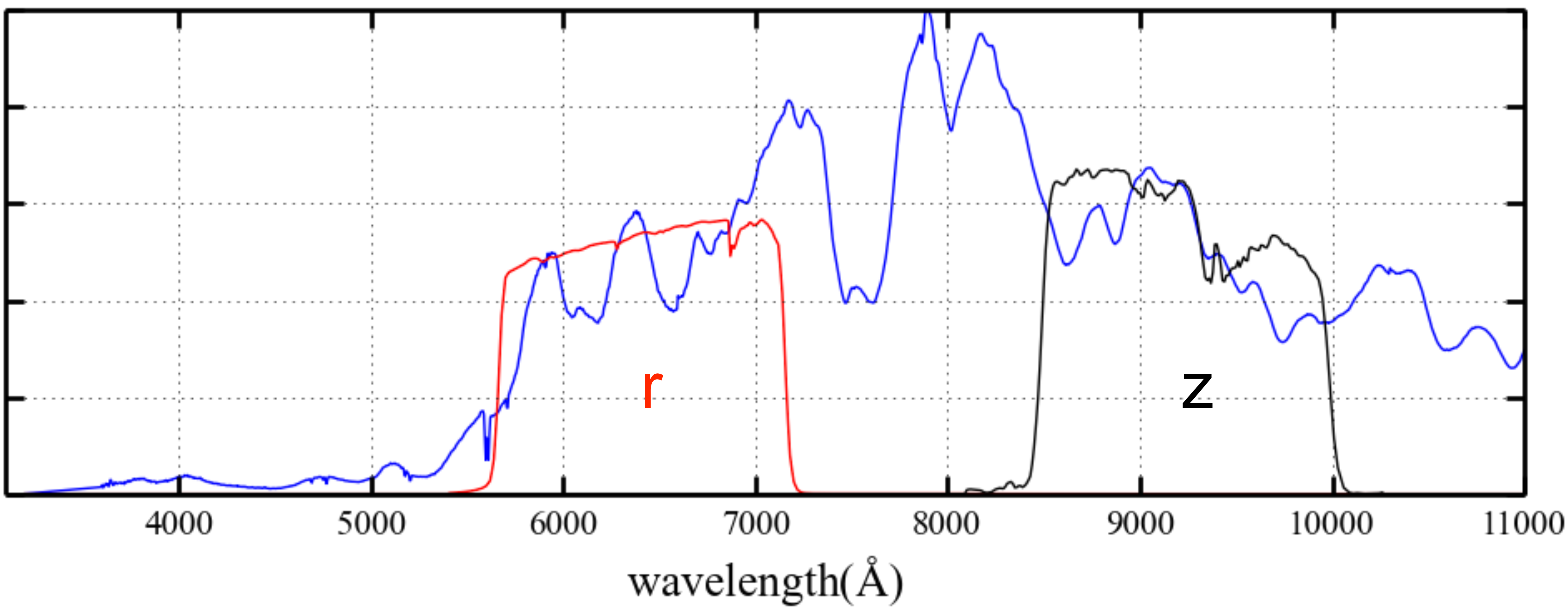
SN Ia at z = 1



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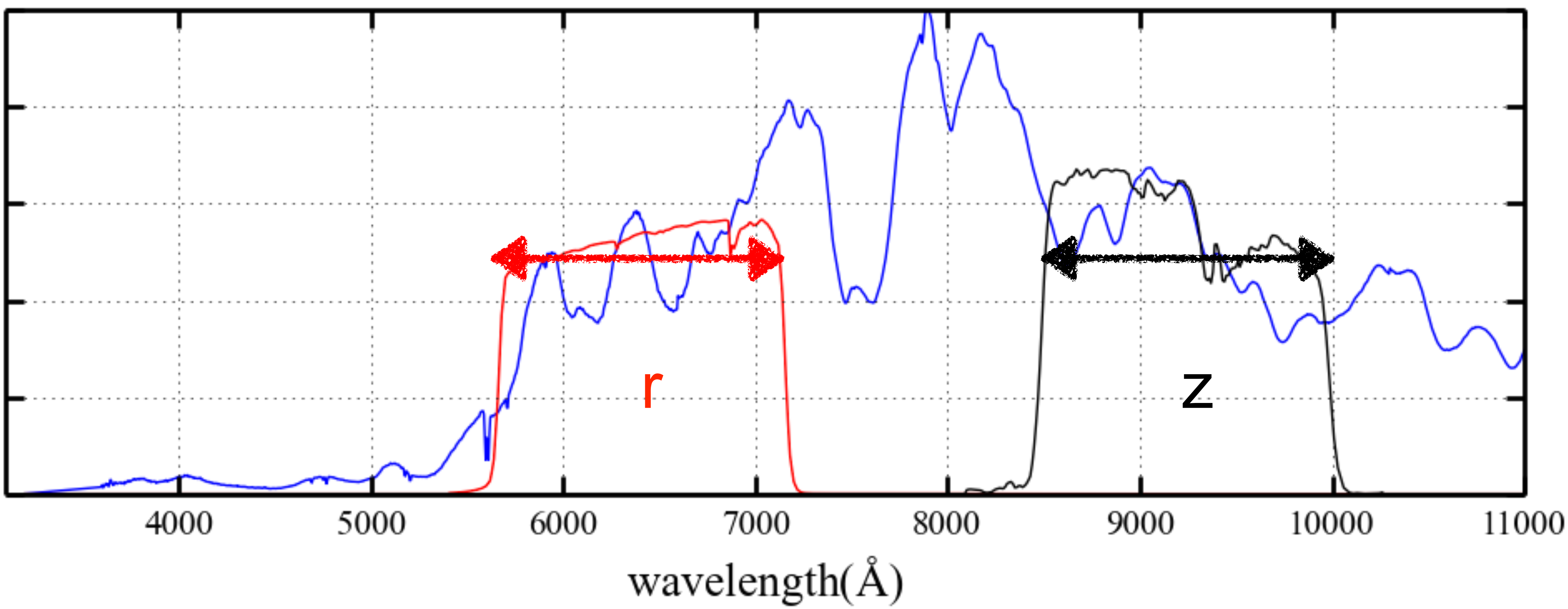

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Broadband Photometry

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- Magnitude depends on the system response $S_b(\lambda)$
  - Photometry System — natural system for one survey
- Color transformation between photometry systems

Johnson-Morgan-Cousins to SDSS

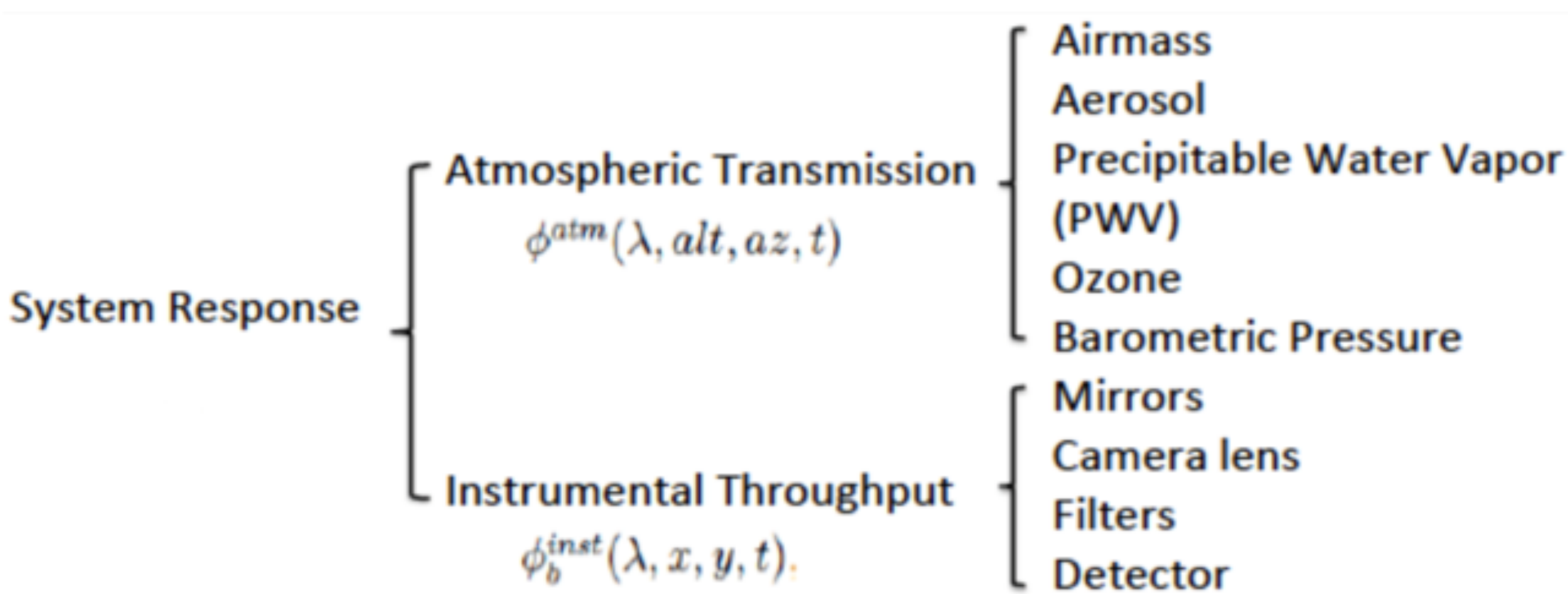
TRANSFORMATIONS BETWEEN $UBVR_CI_C$ AND $u'g'r'i'z'$

Magnitude/Color	Observed	Synthetic[a]
$UBVR_CI_C$ to $u'g'r'i'z'$		
g'	$= V + 0.54(B-V) - 0.07$	$= V + 0.56(B-V) - 0.12$
r'	$= V - 0.44(B-V) + 0.12$	$= V - 0.49(B-V) + 0.11$
r' for $V-R < 1.00$	$= V - 0.81(V-R) + 0.13$	$= V - 0.84(V-R) + 0.13$
r' for $V-R \geq 1.00$	...	$= V - 0.84(V-R) + 0.13$
$u'-g'$	$= 1.33(U-B) + 1.12$	$= 1.38(U-B) + 1.14$
$g'-r'$	$= 0.98(B-V) - 0.19$	$= 1.05(B-V) - 0.23$
$r'-i'$ for $R-I < 1.15$ ...	$= 1.00(R-I) - 0.21$	$= 0.98(R-I) - 0.23$
$r'-i'$ for $R-I \geq 1.15$ ...	$= 1.42(R-I) - 0.69$	$= 1.40(R-I) - 0.72$
$r'-z'$ for $R-I < 1.65$...	$= 1.65(R-I) - 0.38$	$= 1.59(R-I) - 0.40$
$r'-z'$ for $R-I \geq 1.65$...	None observed	$= 2.64(R-I) - 2.16$

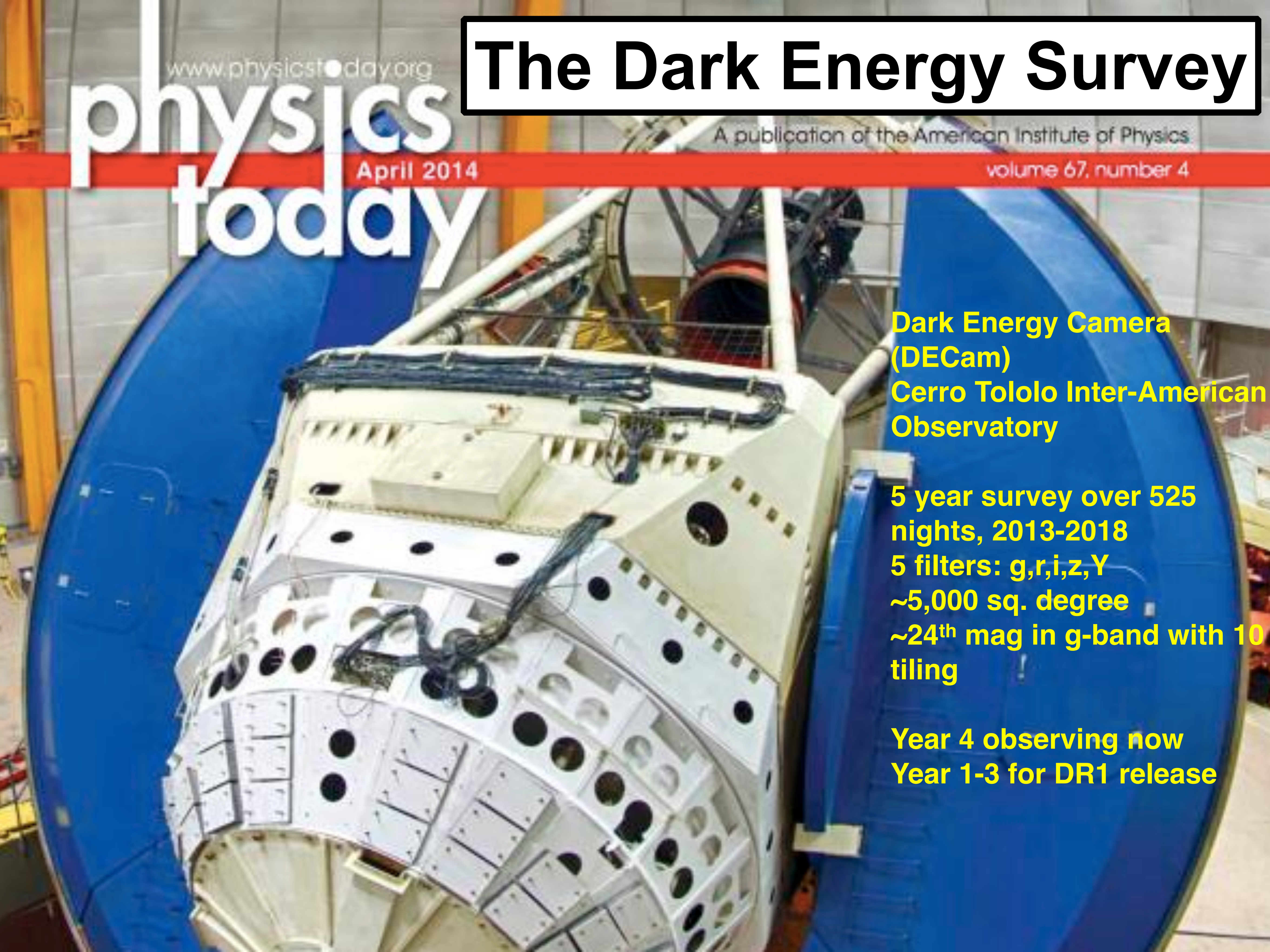
Smith et al. 2002

Photometric calibration

- Übercal calibration:
  - Grey-term correction with repeat measurements of stars
  - Zeropoint only; No color-term applied
- However….
- System response also varies within one survey
  - From exposure to exposure
  - From CCD to CCD
  - Atmospheric transmission — time and airmass
  - Instrumental throughput — position (and time)



The Dark Energy Survey



Dark Energy Camera (DECam)
Cerro Tololo Inter-American Observatory

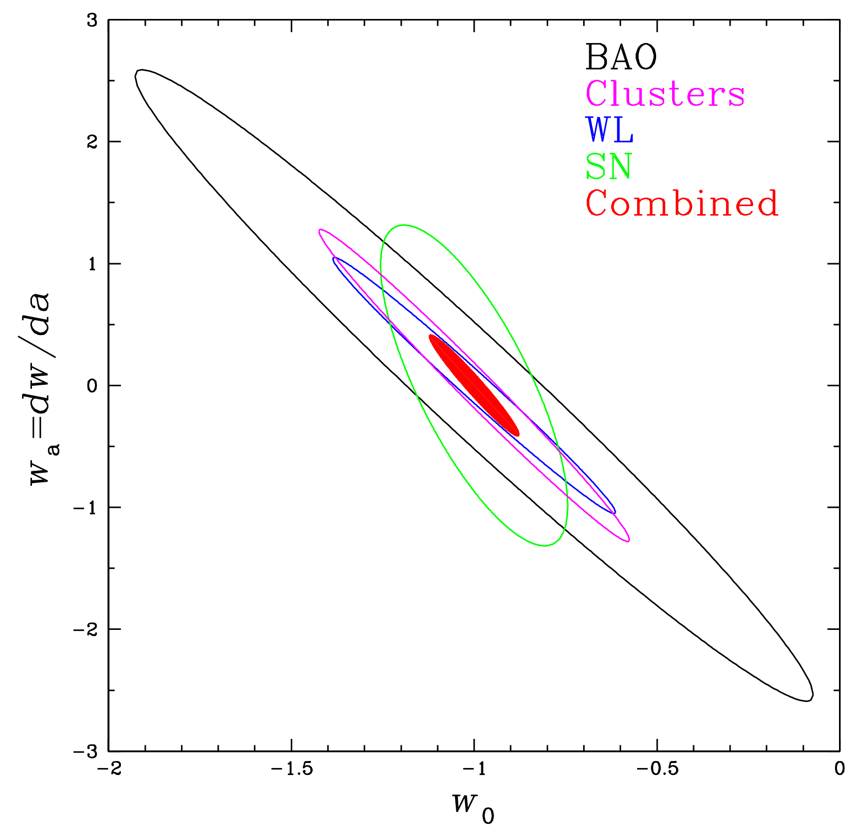
5 year survey over 525 nights, 2013-2018
5 filters: g,r,i,z,Y
~5,000 sq. degree
~24th mag in g-band with 10 tiling

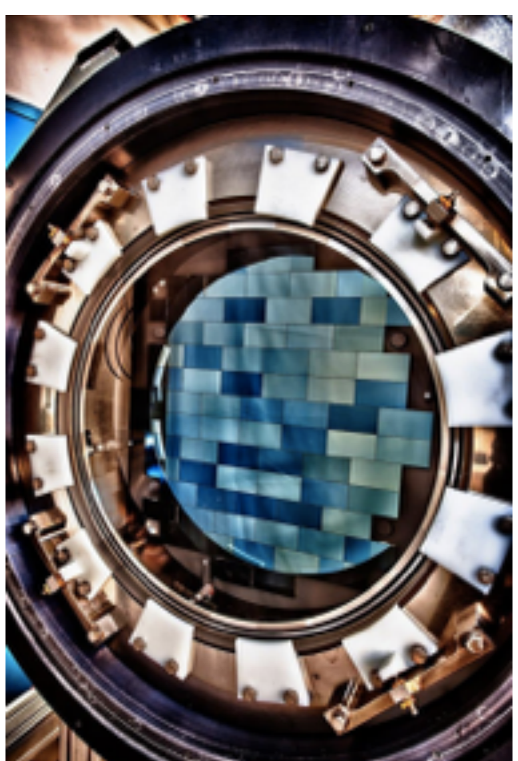
Year 4 observing now
Year 1-3 for DR1 release

The Dark Energy Survey (DES)

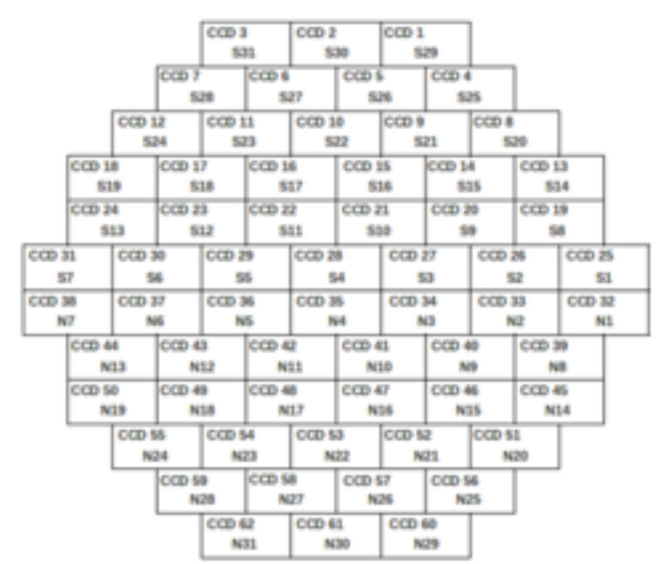
- Constrain the Dark Energy Equation of State with:
  - Supernova
  - Weak Lensing
  - Large Scale Structure
  - Galaxy Clusters

Forecast





- DECam
  - 62 2k x 4k CCDs
  - 570 megapixel camera
  - < 20s readout time
  - ~3 deg^2 field-of-view
  - Unprecedented sensitivity



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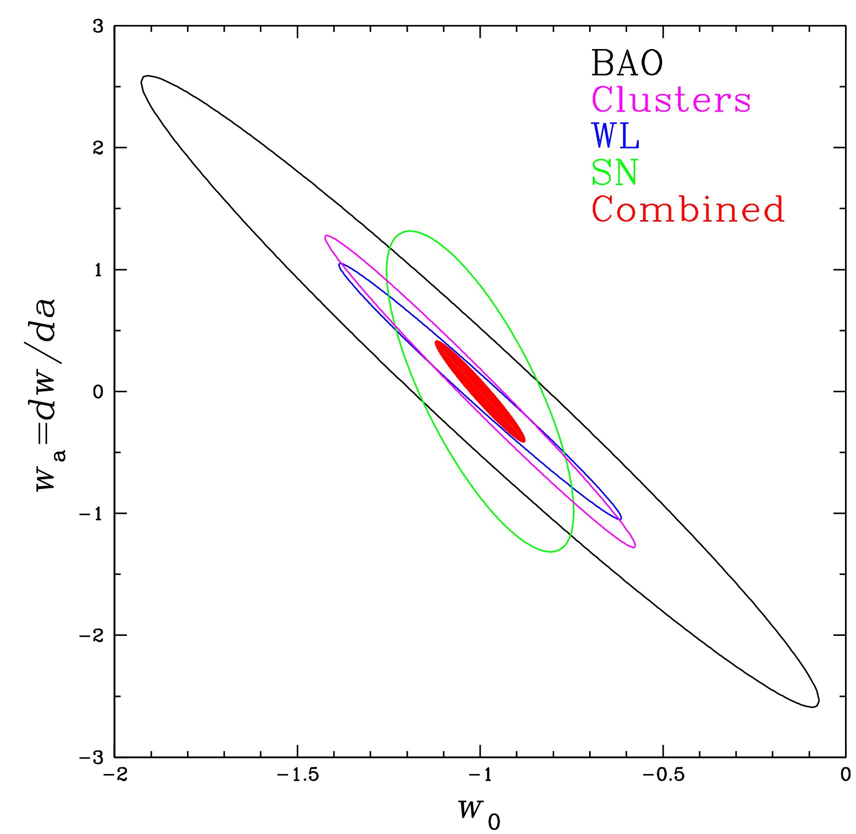

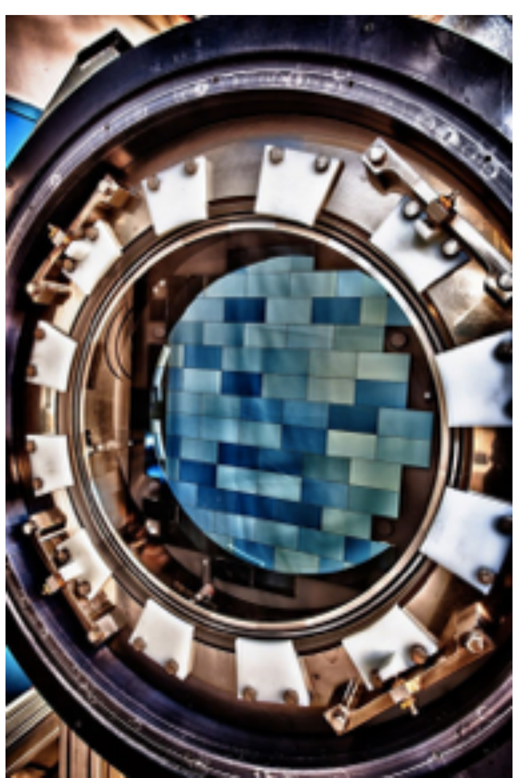

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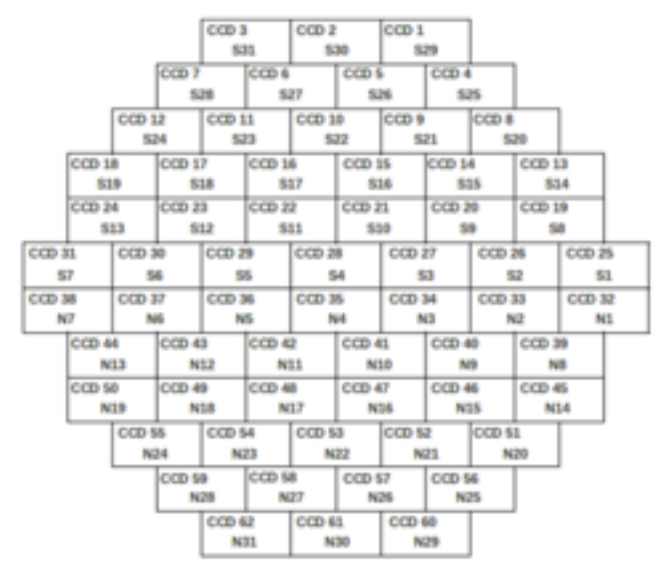
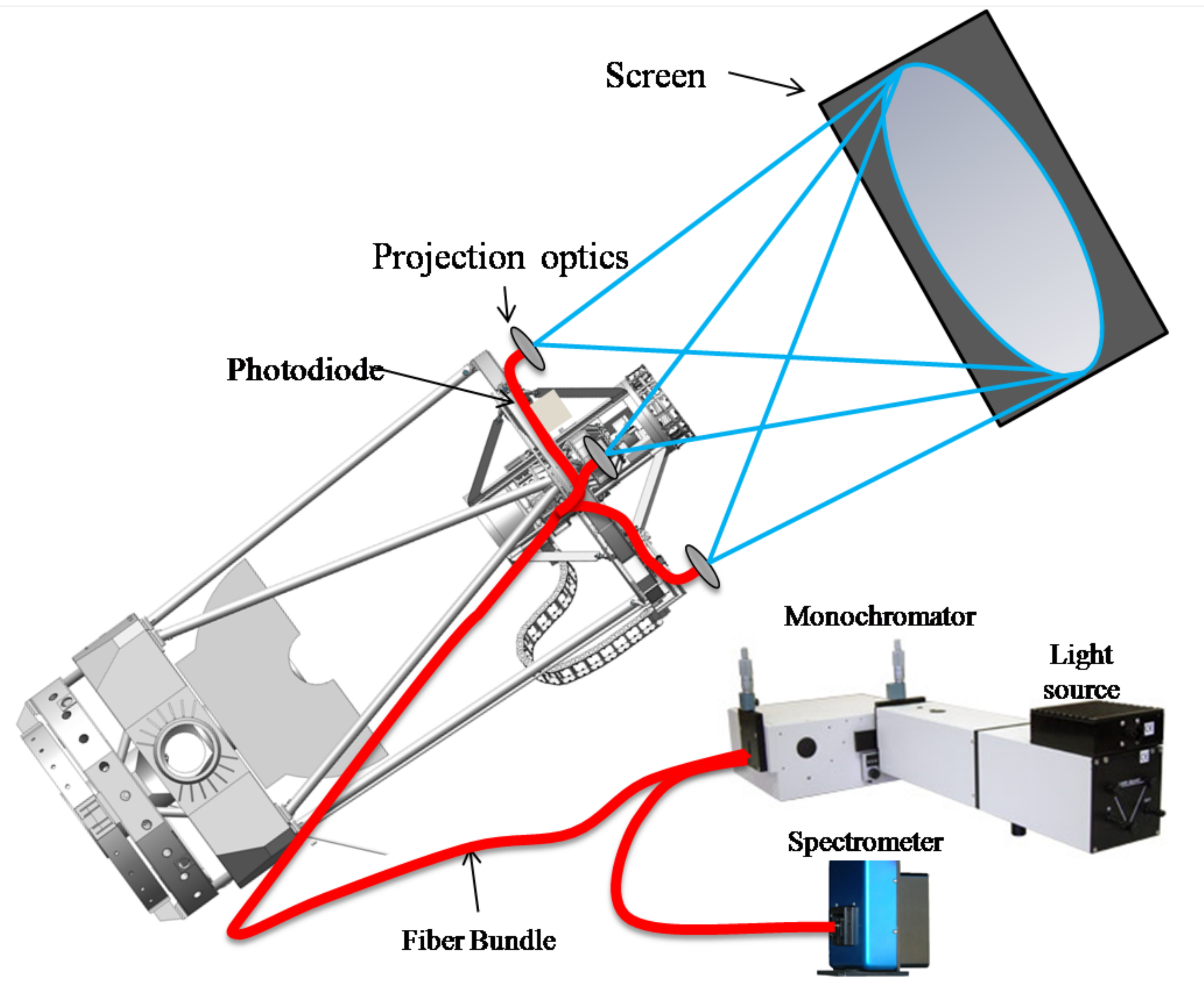


DECal

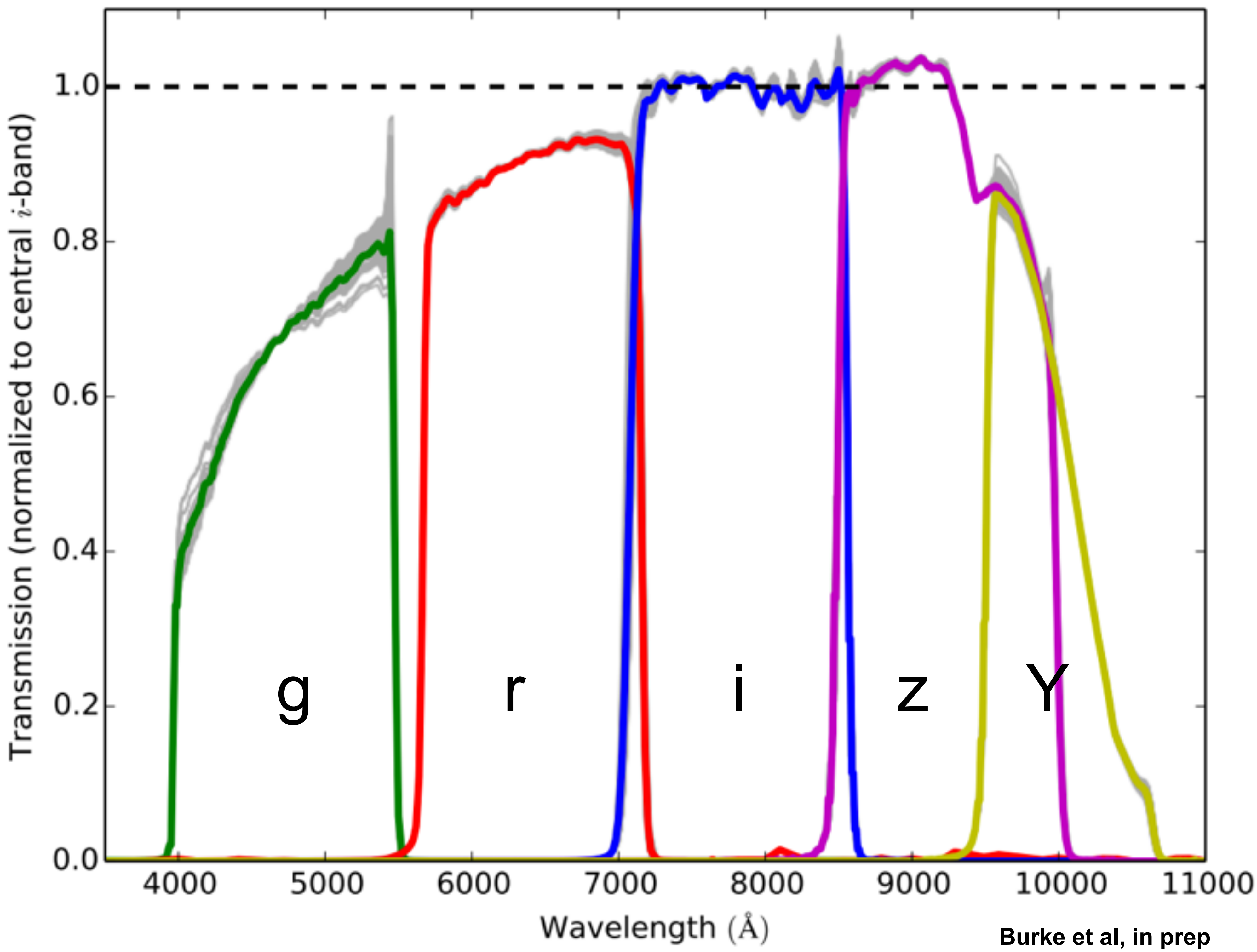
Spectroscopic calibration system for DECam



Rheault et al. 2014, SPIE **Marshall et al, in prep**

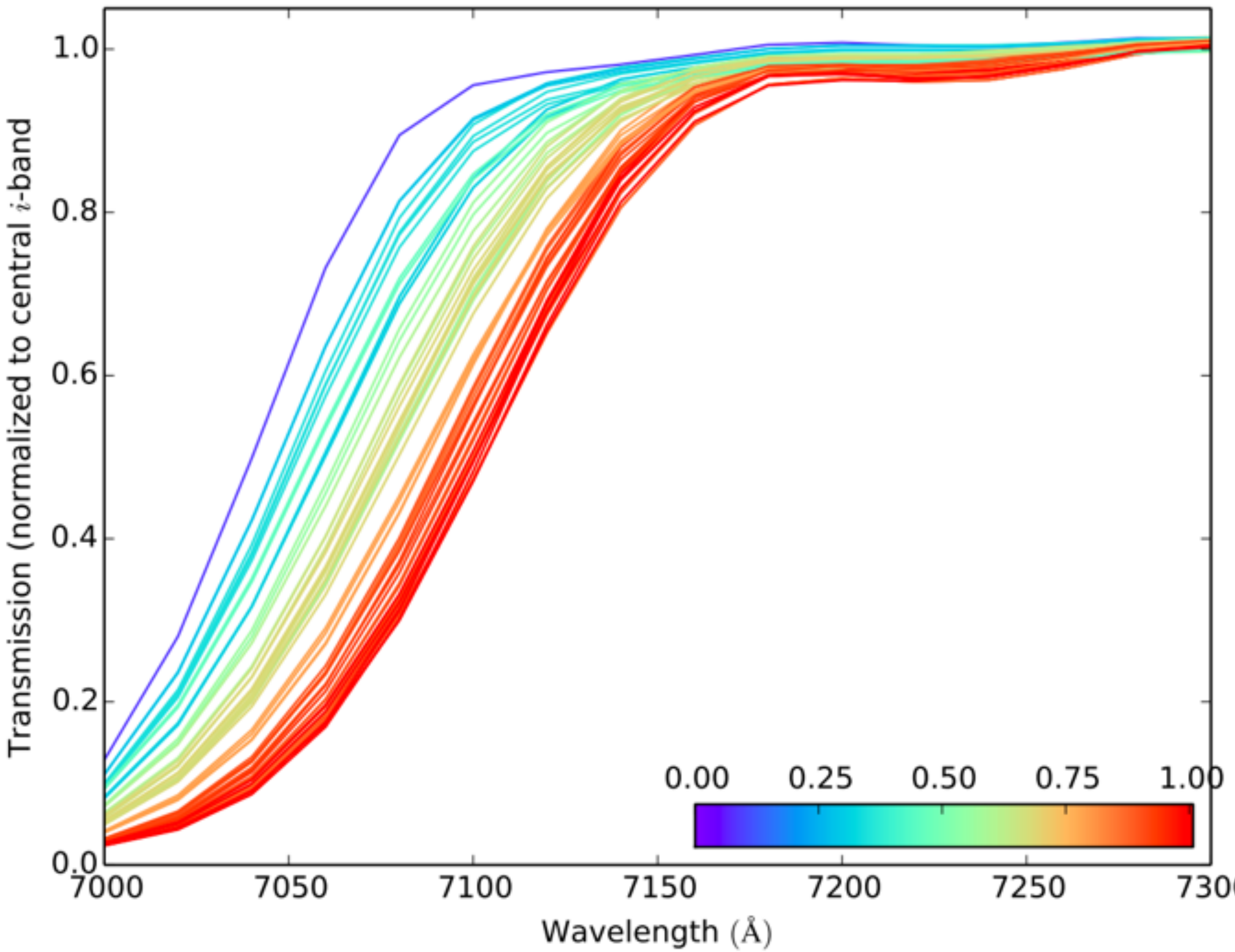
- Monochromatic light:
  - 2nm width (1-10nm)
- Coarse scan:
  - out-of-band light inspection
  - 300-1000 nm for each filter
  - 10 nm in step
- Fine scan:
  - throughput measurement
  - +/- 50 nm around each filter
  - 2nm in step
- Frequency
  - only scan during cloudy nights
  - (dome light leaking at Blanco!)
  - ~2 hr per band, about 3 filter per night
  - depend on weather but roughly 2 full sets per year

DES Instrumental Throughput



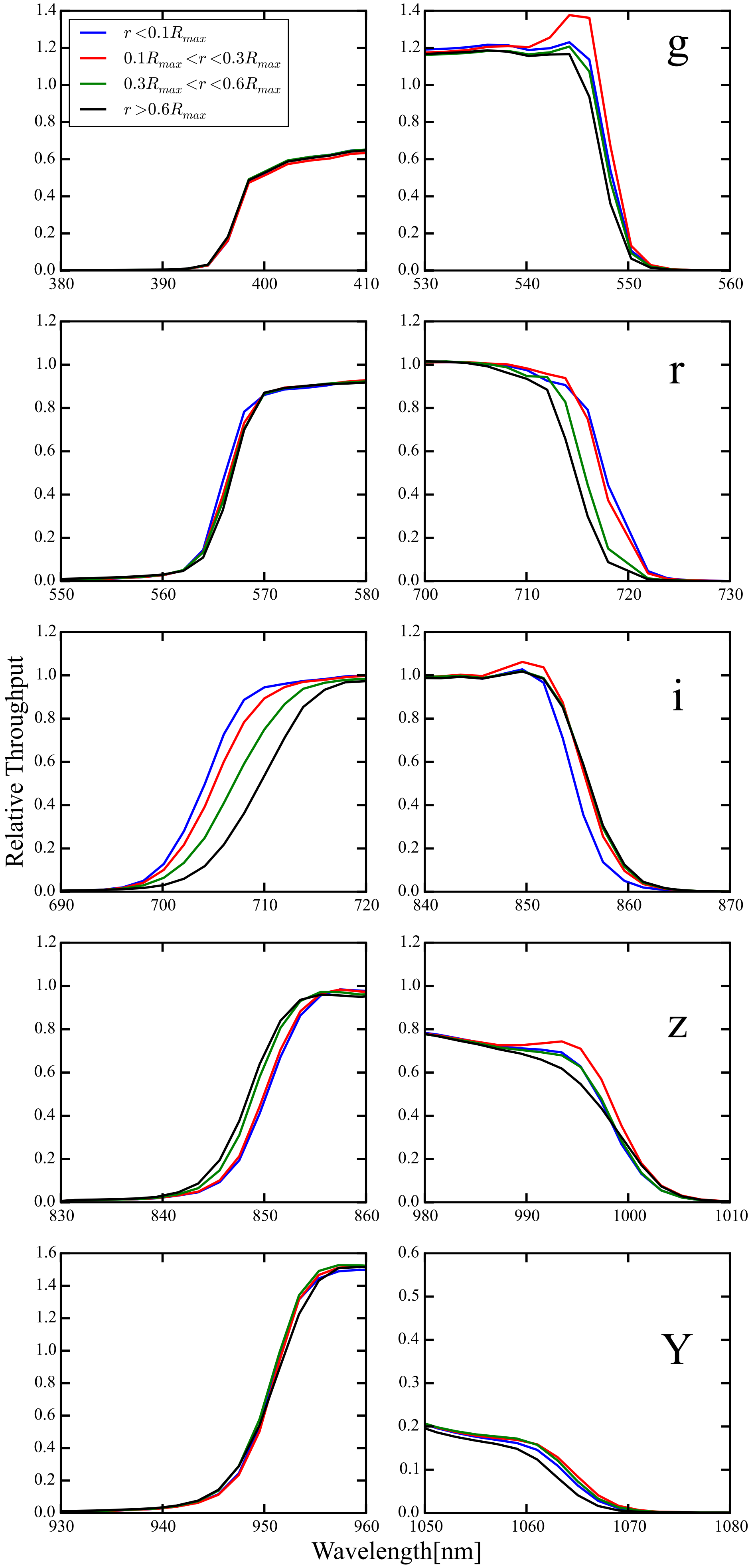
Burke et al, in prep

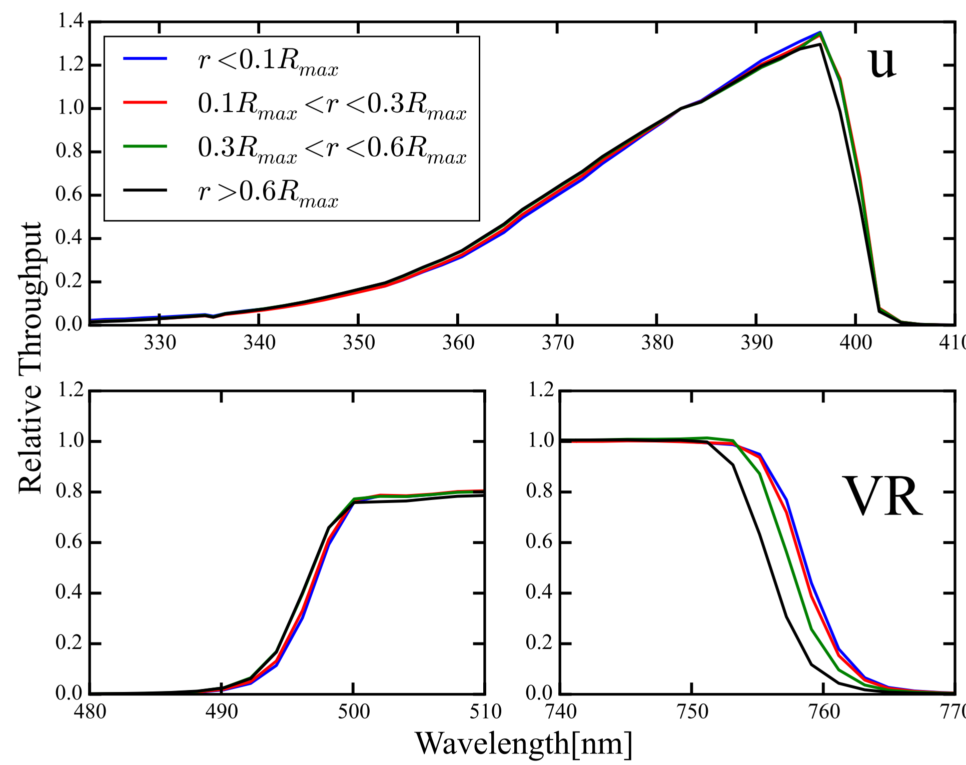
Radial Variation in i-band



Burke et al, in prep

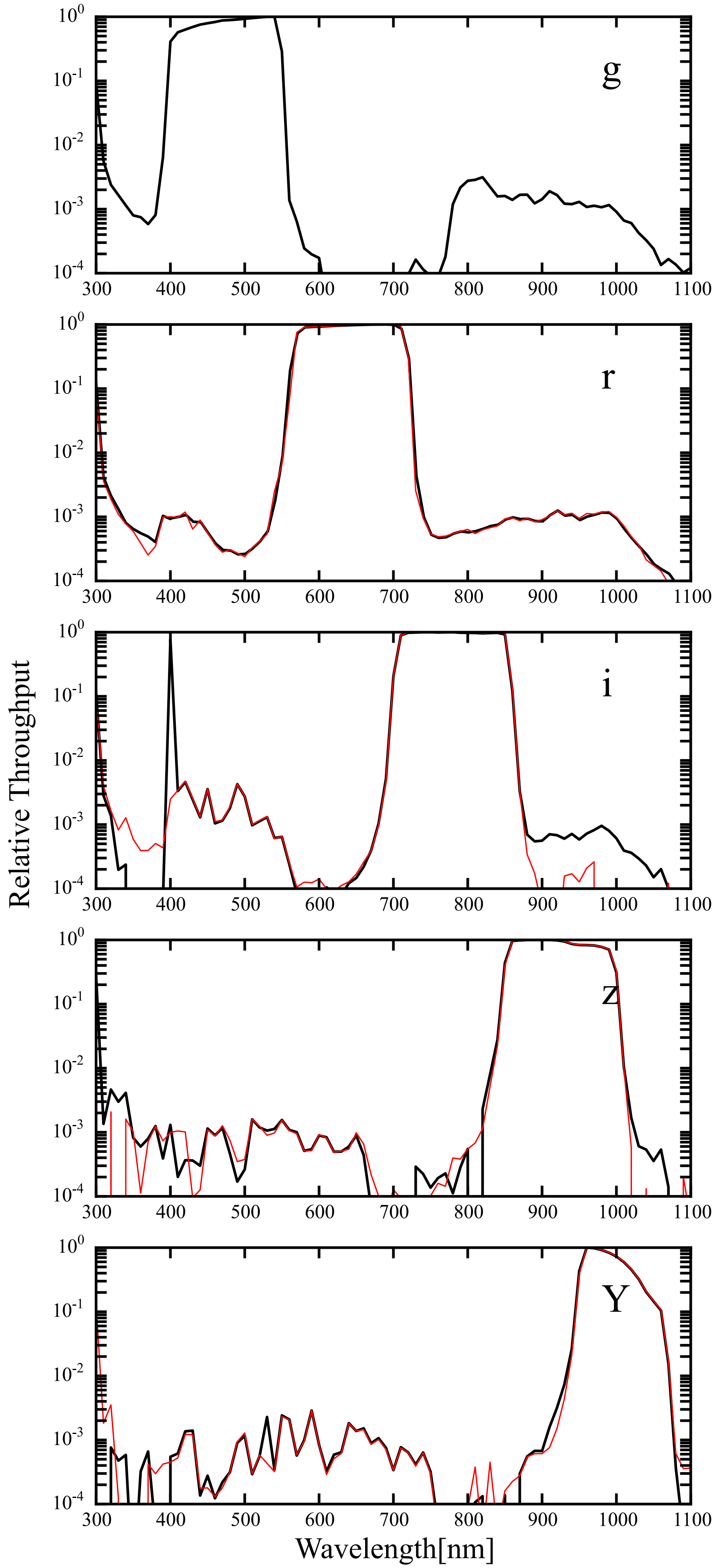
Throughput at different radii

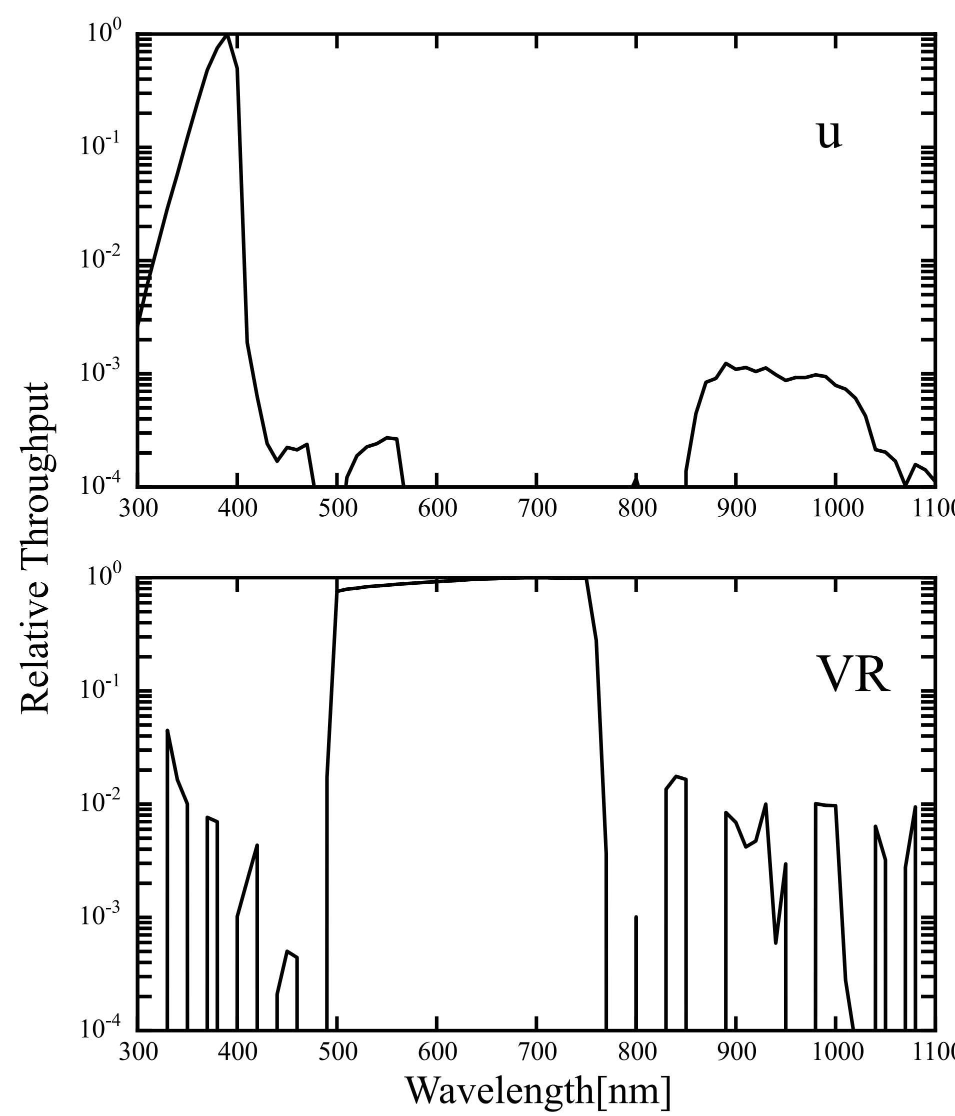




Marshall et al, in prep

out-of-band light

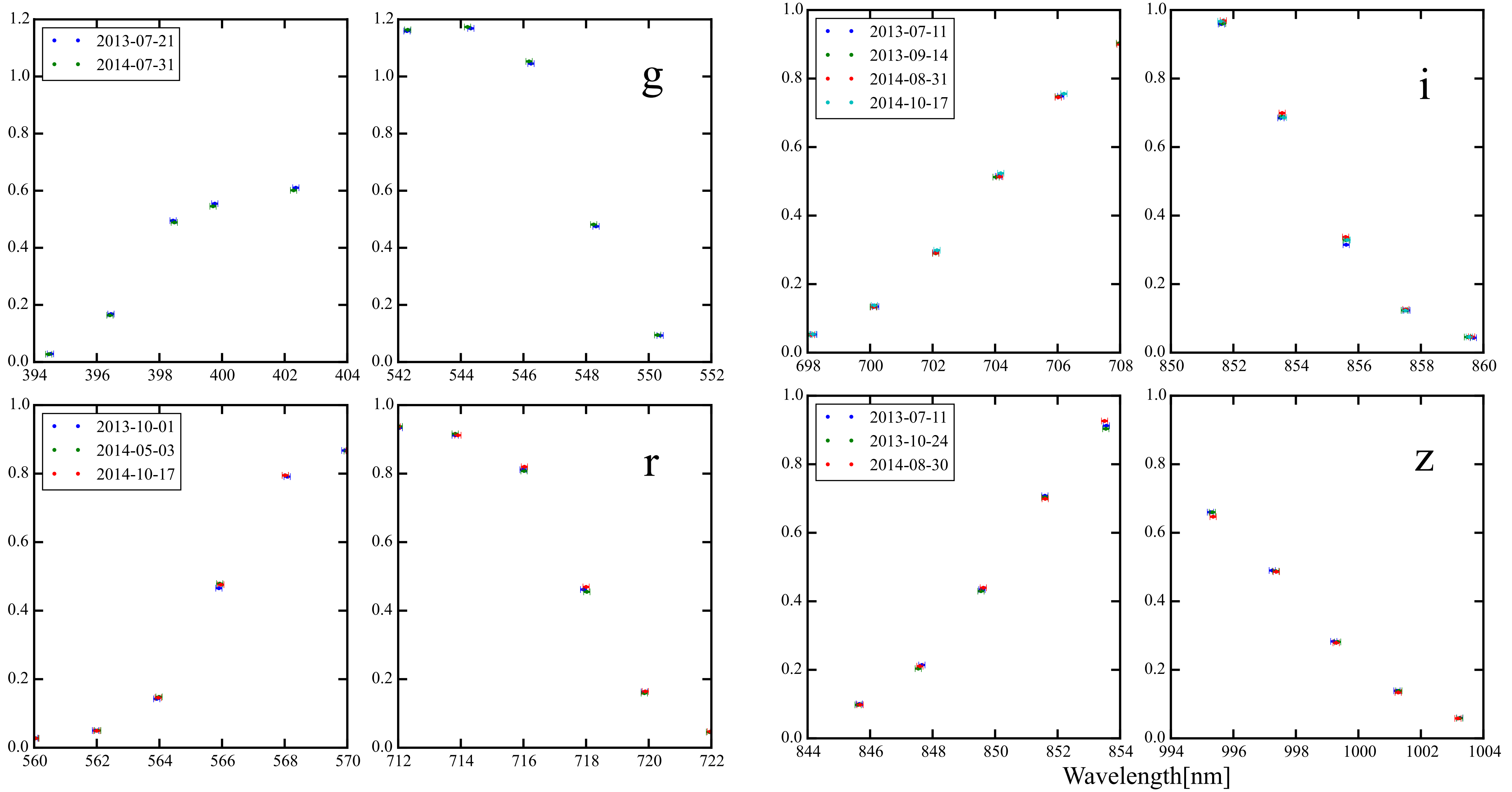




Marshall et al, in prep

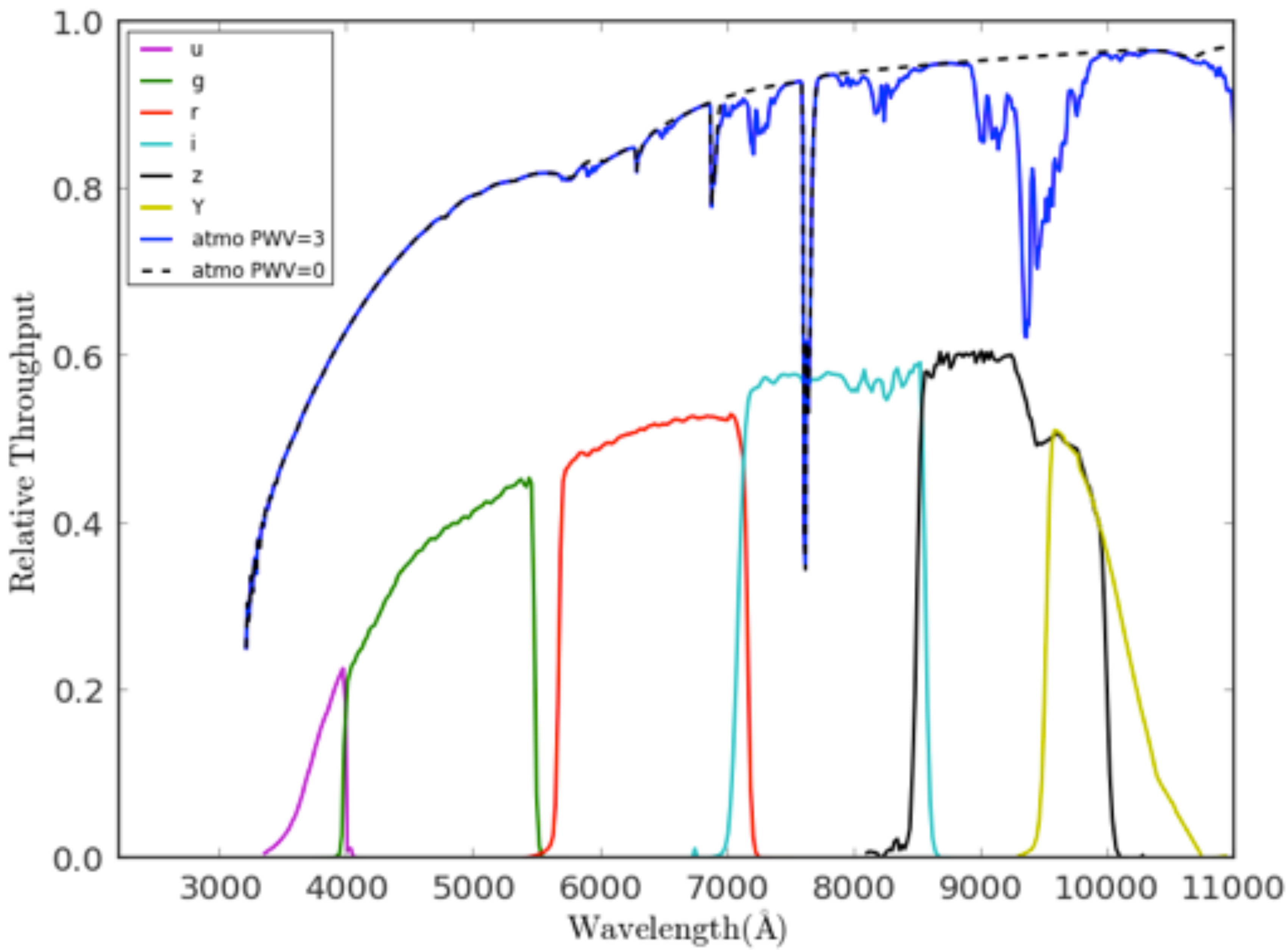
Instrumental Throughput Variation Over Time

- **Throughput vs. time — no difference monitored**



Marshall et al, in prep

Atmospheric Transmission Variation Over Time



Li et al. 2014, SPIE

Precipitable Water Vapor (PWV) mainly affects DES z and Y band

Auxiliary systems to monitor the variation in the atmosphere.

- aTmCam
- GPSMon

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Systematic Chromatic Errors

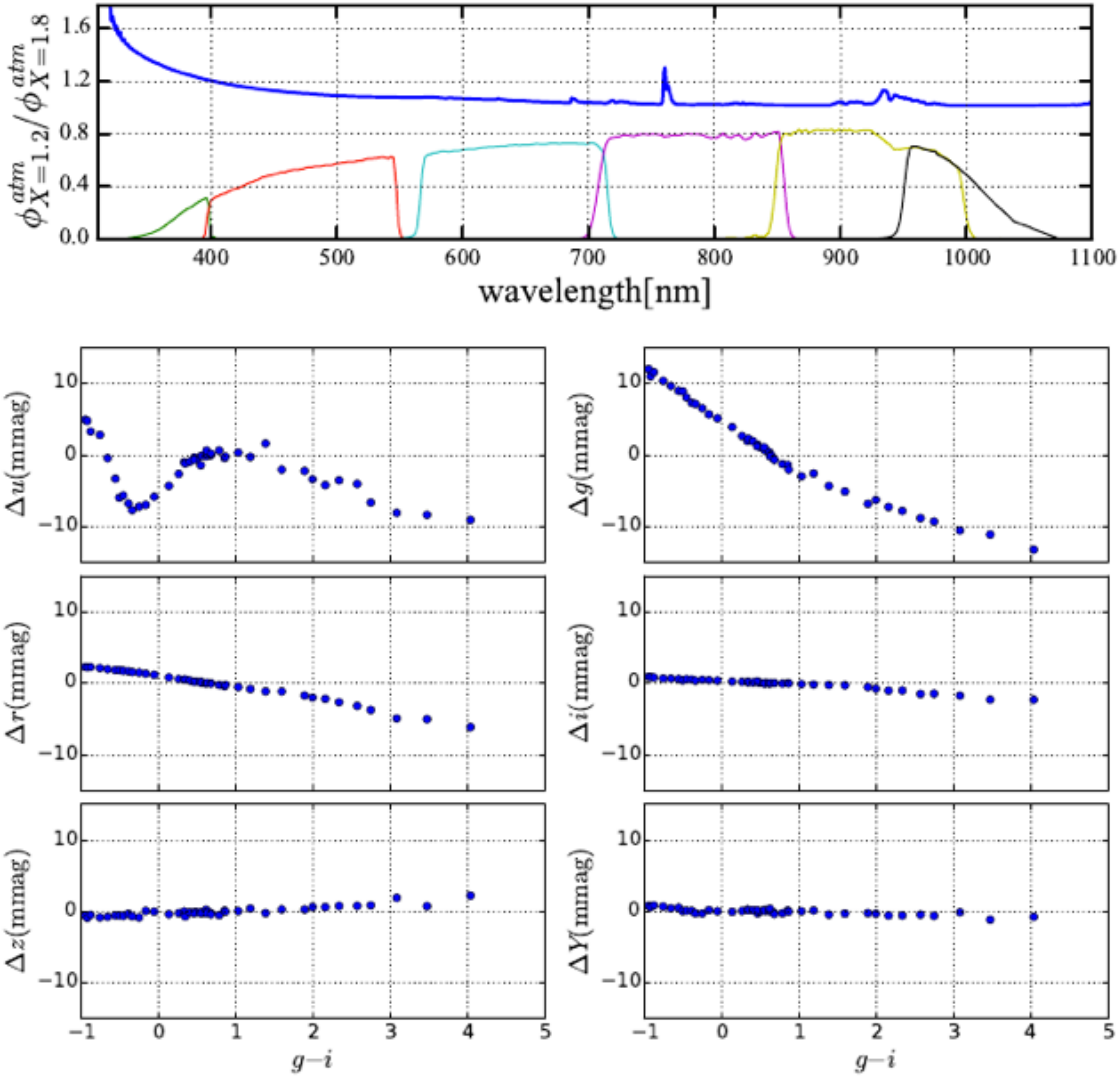
- When the system response deviates from a **standard system response**, this variation will introduce **systematic chromatic errors (SCE)** that depend on source colors.

- Not only **grey-term calibration**, but also **chromatic correction** needed in one survey.

- An assessment of SCE in DES is given in Li+2016

$$\Delta m = -2.5\left[\log_{10}\frac{\int_0^\infty F_\nu(\lambda)\phi^{atm}(\lambda)\phi_b^{inst}(\lambda)\lambda^{-1}d\lambda}{\int_0^\infty F_\nu(\lambda)\phi_{ref}^{atm}(\lambda)\phi_{b,ref}^{inst}(\lambda)\lambda^{-1}d\lambda} - \log_{10}\frac{\int_0^\infty F_\nu^{ref}(\lambda)\phi^{atm}(\lambda)\phi_b^{inst}(\lambda)\lambda^{-1}d\lambda}{\int_0^\infty F_\nu^{ref}(\lambda)\phi_{ref}^{atm}(\lambda)\phi_{b,ref}^{inst}(\lambda)\lambda^{-1}d\lambda}\right]$$

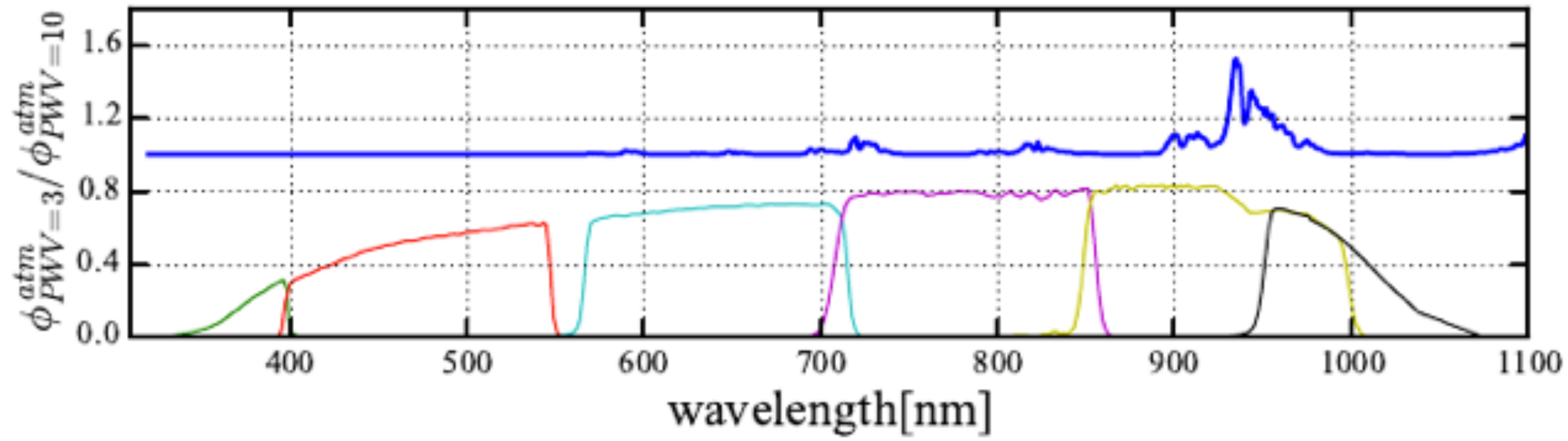
SCE on stars for airmass change from 1.2 to 1.8

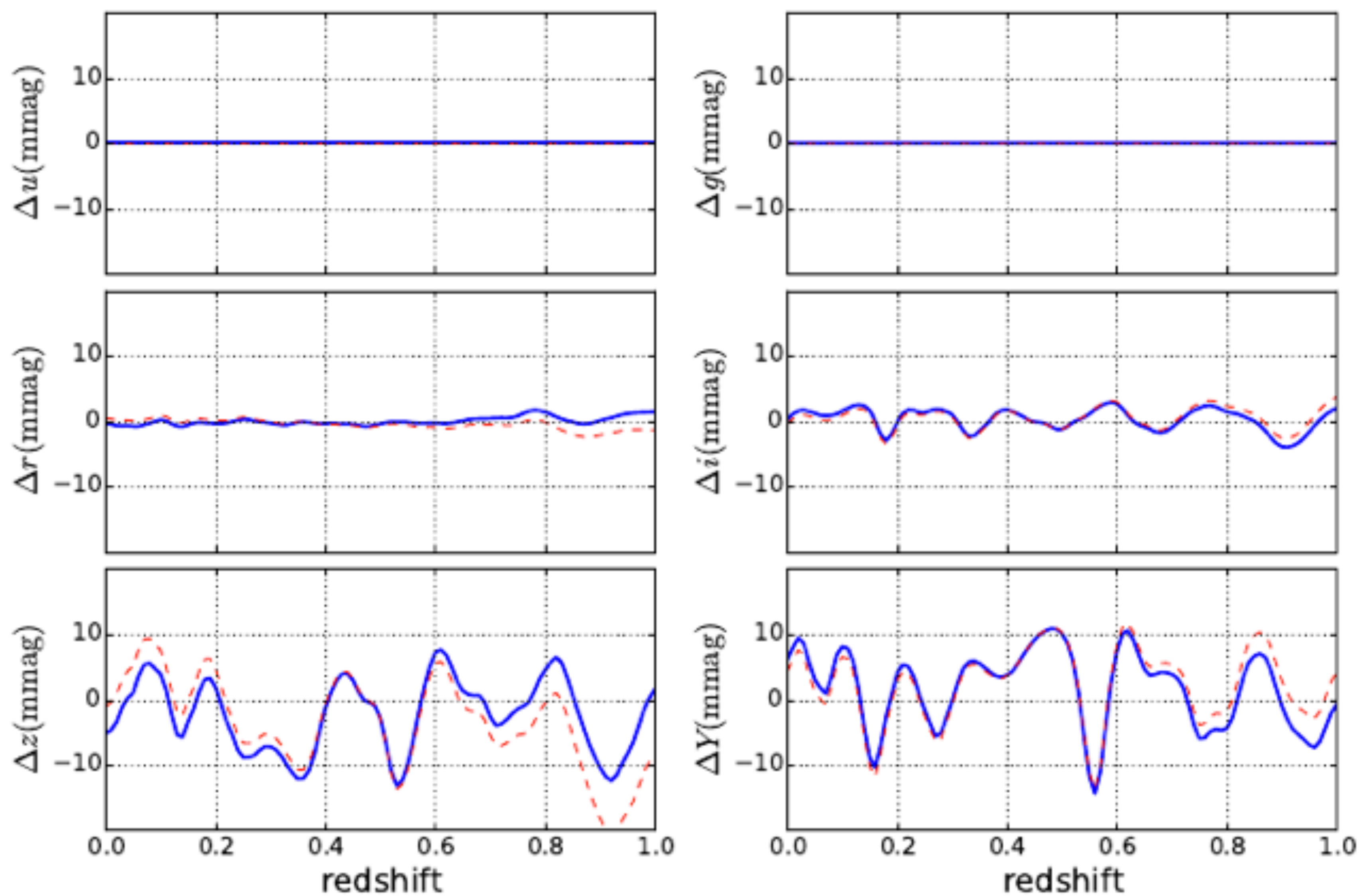


Li et al. 2016

2nd-order atmospheric extinction term

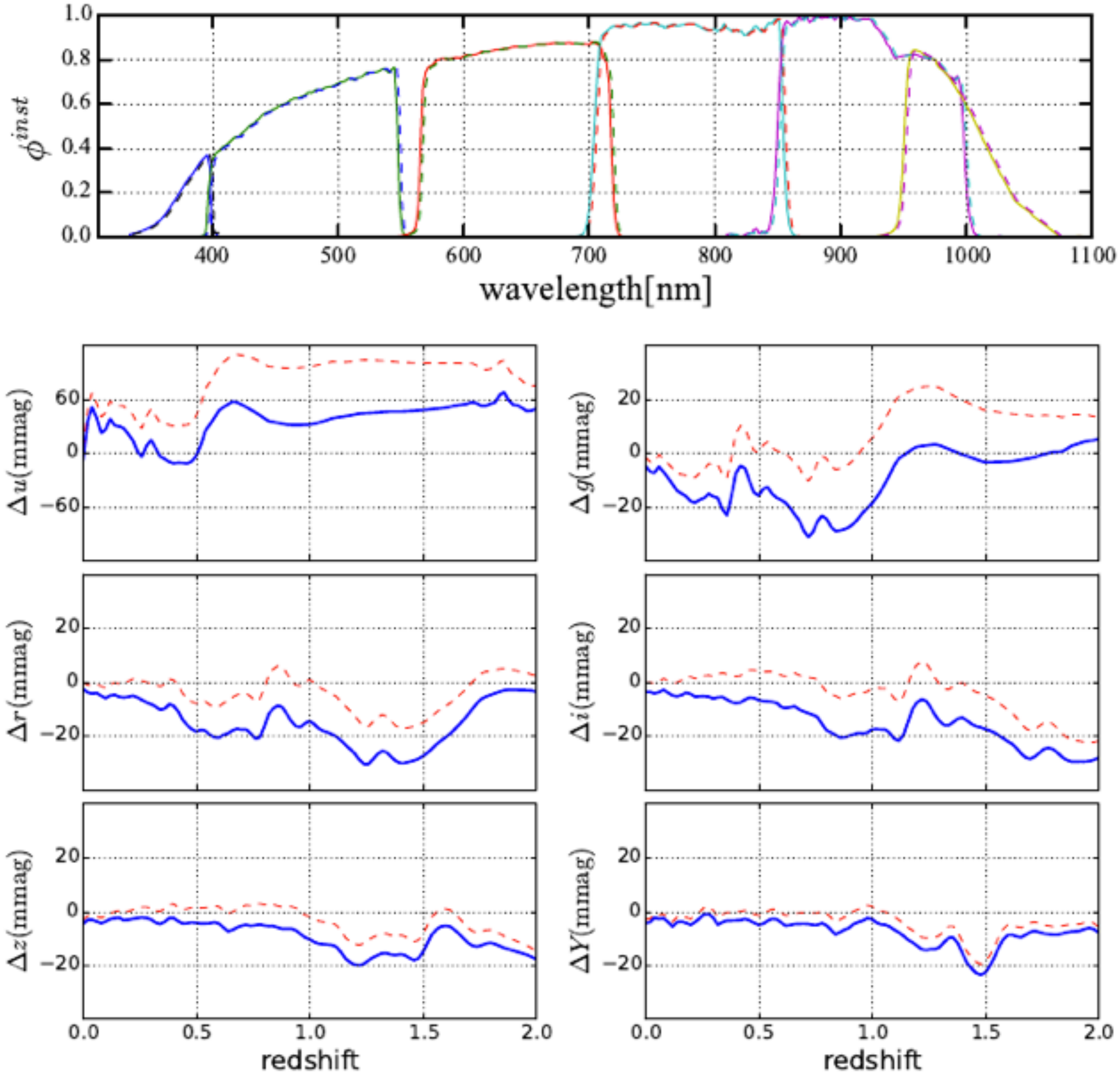
SCE on SNIa for PWV change from 3mm to 10mm





Li et al. 2016

SCE on elliptical galaxy for 2nm shift in the instrumental throughput



Li et al. 2016

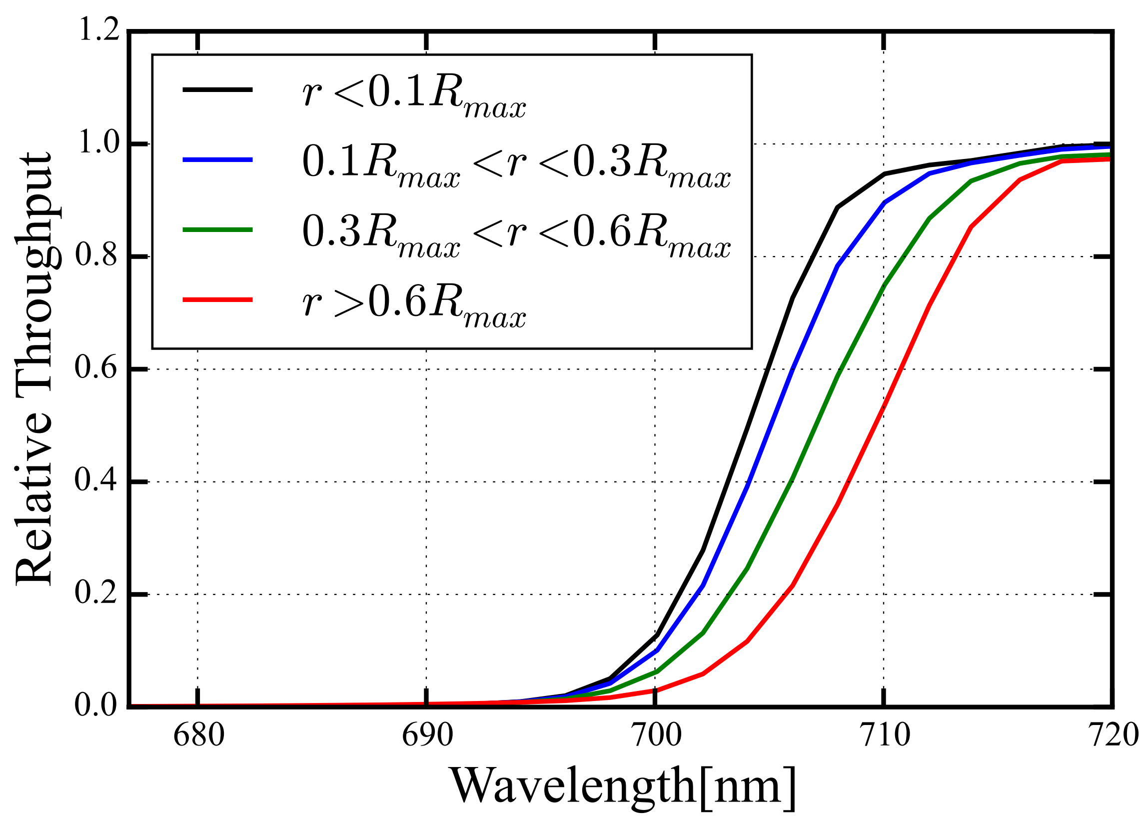
Compare to DES data

Correct SCE caused by the variation in the instrumental throughput

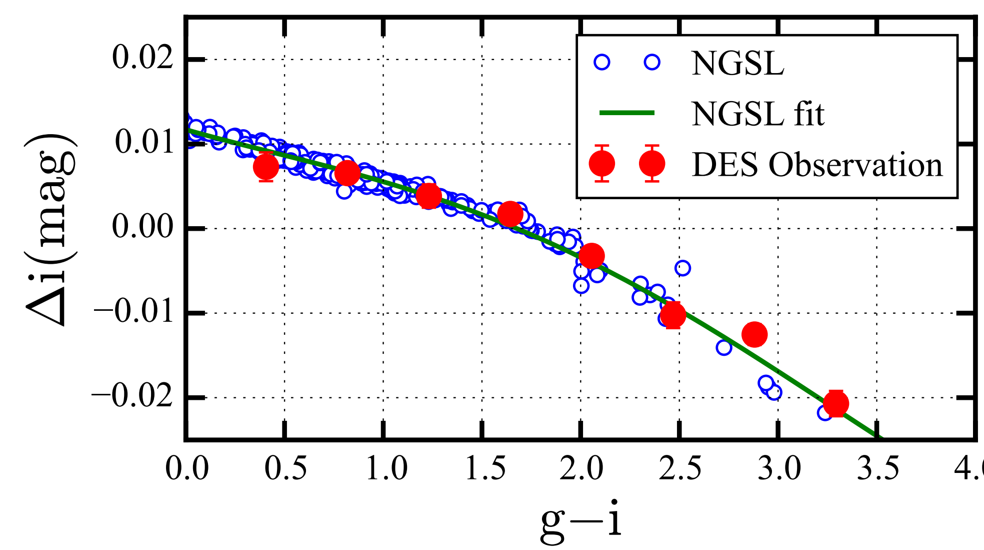
Li et al. 2016

DECal scan results in i-band

r < 0.1Rmax vs. r > 0.6 Rmax



Marshall et al. in prep



Before correction: SCE > 20mmag
After correction: SCE < 3mmag

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  - Year 3 internal data release
  - Forward Global Calibration Method
  - Chromatic Corrections

Forward Global Calibration Method

- Define a standard system response
- Minimize the difference of the repeat measurements of stars
- Measurements of instrumental throughput and atmospheric transmission from auxiliary systems
- For a given CCD on a given exposure
  - — one **zeropoint** and one **system response**
  - — zeropoint is derived w.r.t a G-type star
- Zeropoint for every exposure+CCD used for image coadd
- Additional chromatic corrections needed for every object

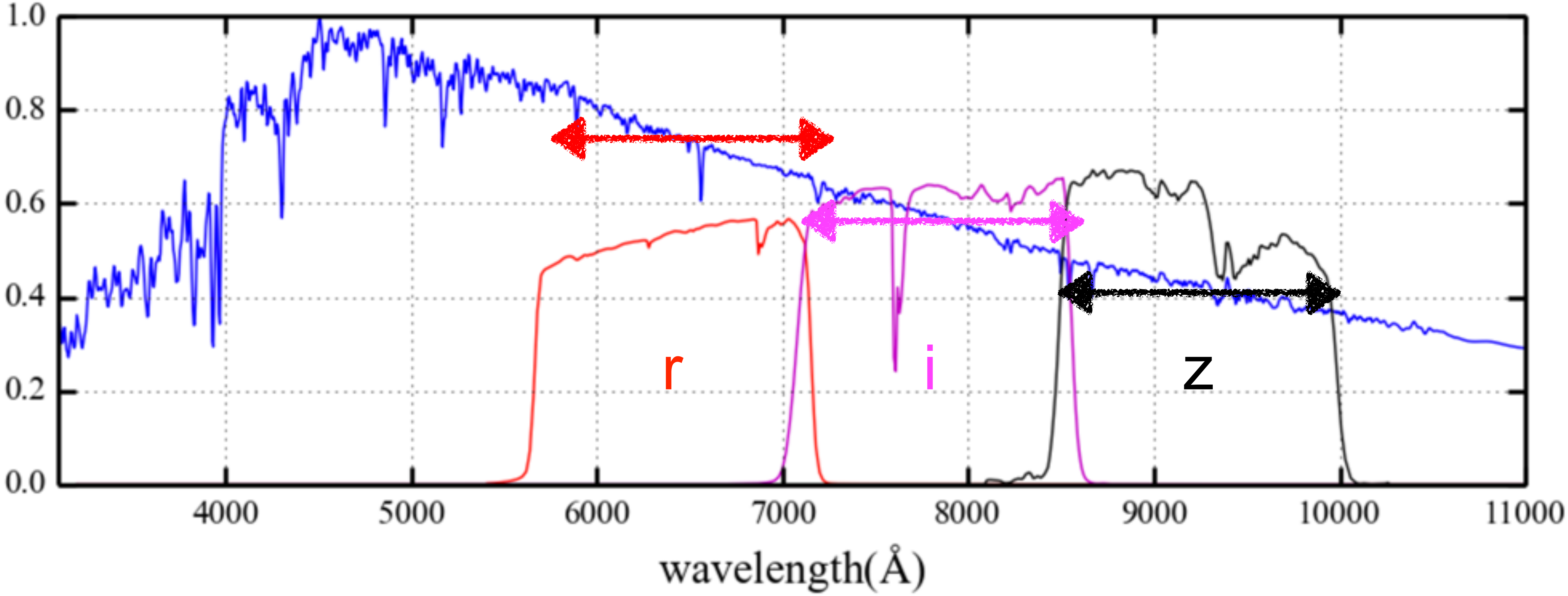
Burke et al. in prep

Chromatic Correction Task Force

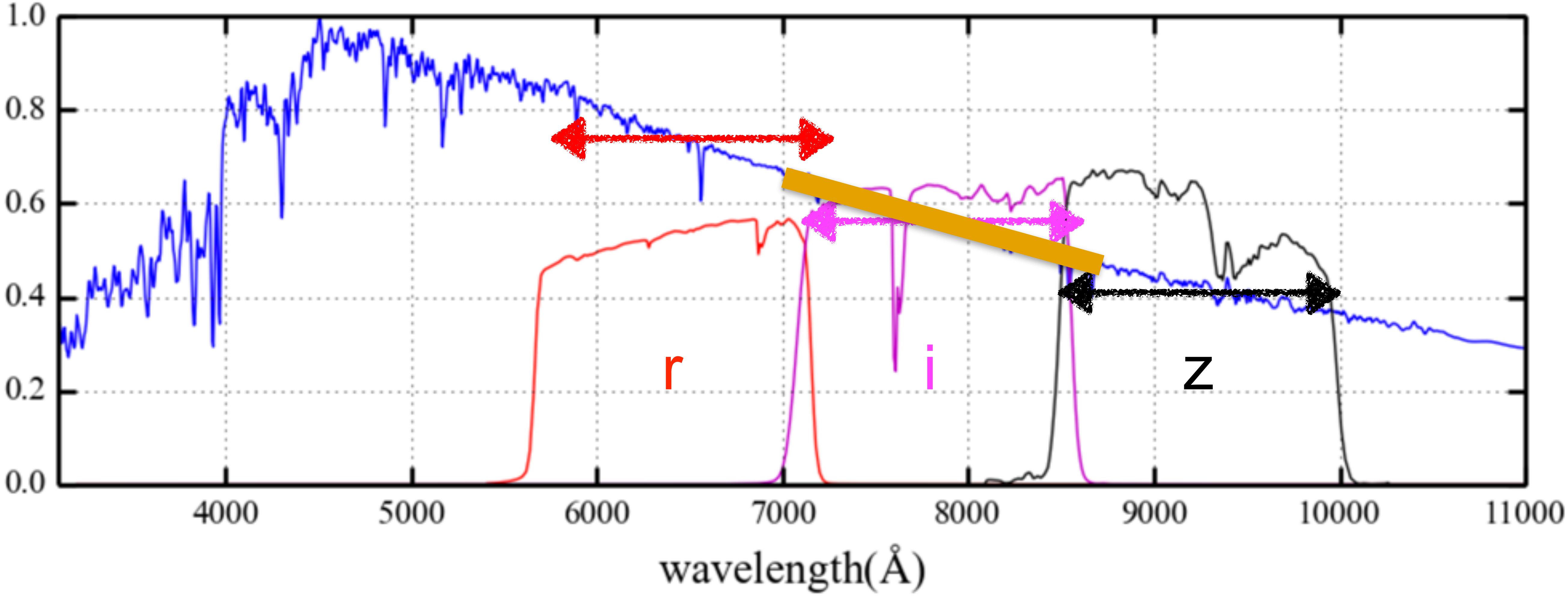
- Chromatic corrections are derived for every object in every single epoch exposure
  - Stars: First order chromatic correction
  - Galaxies: Not determined yet
    - effects on photo-z
  - Supernova: Full integrated chromatic correction

- Corrections from multiple exposures are weighted-averaged as the final chromatic corrections in the coadd catalog

G star SED


1.0
0.8
0.6
0.4
0.2
0.0
4000
5000
6000
7000
8000
9000
10000
11000
wavelength(Å)
r
i
z

G star SED



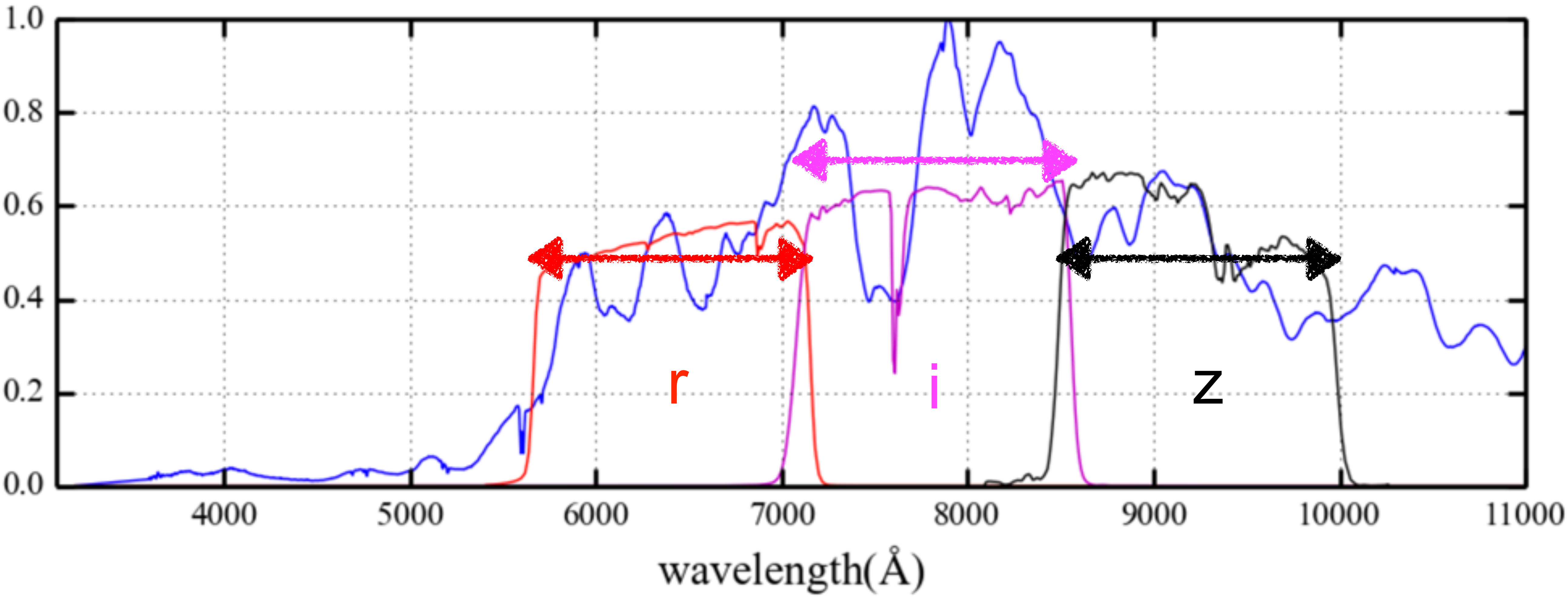
First-order chromatic correction

- First order approximation on the SED based on the color

Pros: fast computation, no SED needed

Cons: first order approximation

SN Ia at z = 1



Full integrated chromatic correction

Pros: more accurate if the input SED is correction

Cons: more computation power; need an SED

Conclusions

- System response change from one exposure to another, and from one CCD to another
  - **even within one CCD — future work!**
- This variation will introduce systematic chromatic errors that cannot be calibration with grey-term only corrections.
- A forward global calibration method is needed take care both the grey-term correction (zeropoint) and chromatic corrections.