# ZTF Photometric Calibration Status and Plans

Andrew Drake
on behalf of the ZTF Calibration Team

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## Further details at:

http://web.ipac.caltech.edu/staff/fmasci/ztf/ztf_pipelines_deliverables.pdf

http://www.oir.caltech.edu/twiki_ptf/bin/view/ZTF/Calibration

http://nesssi.cacr.caltech.edu/ZTF/Web/Calib.html

# ZTF Photometric Calibration

## Current Calibration.

Select set of PS1 photometric calibrators for each field/quadrant

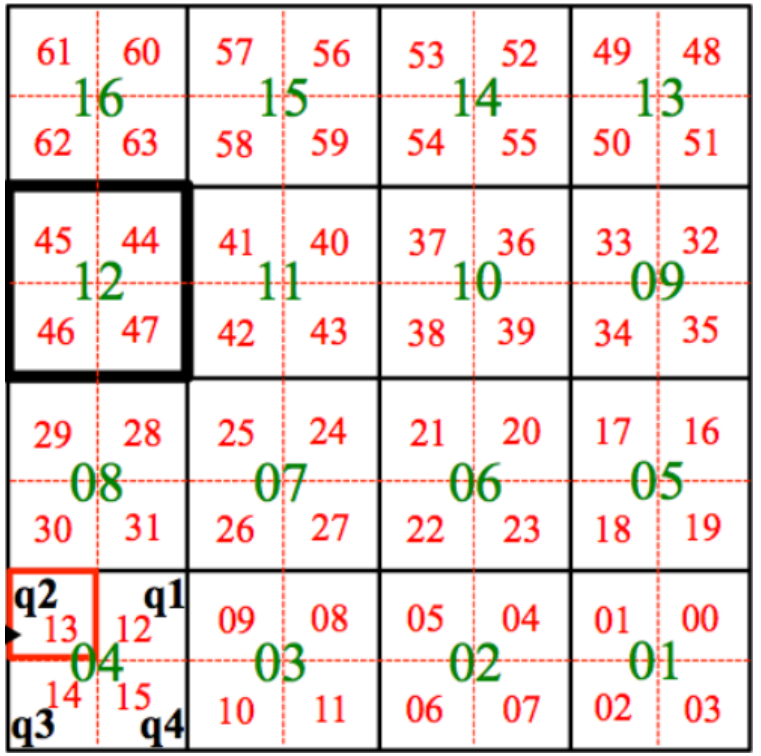
$$m_{cal} = m_{inst} + ZP_f + c_f\left(m_1^{PS1} - m_2^{PS1}\right),$$

Fit for colour coeff $C_f$ and zero point $ZP_f$, using *ZTF* $g$, $r$, $i$ instrumental magnitudes ($m_{inst}$) and m1,m2 among PS1 colours g,r,i,z.
eg.

$$g^{PS1} - g = ZP_g + c_g(g^{PS1} - r^{PS1})$$

$$r^{PS1} - r = ZP_r + c_r(g^{PS1} - r^{PS1})$$

$$i^{PS1} - i = ZP_i + c_i(r^{PS1} - i^{PS1})$$




Masci et al. 2018 ZSDS

Further details, see ZSDS section 6.5 (Masci et al.):

http://web.ipac.caltech.edu/staff/fmasci/ztf/ztf_pipelines_deliverables.pdf

# Current Status of PSF photometry

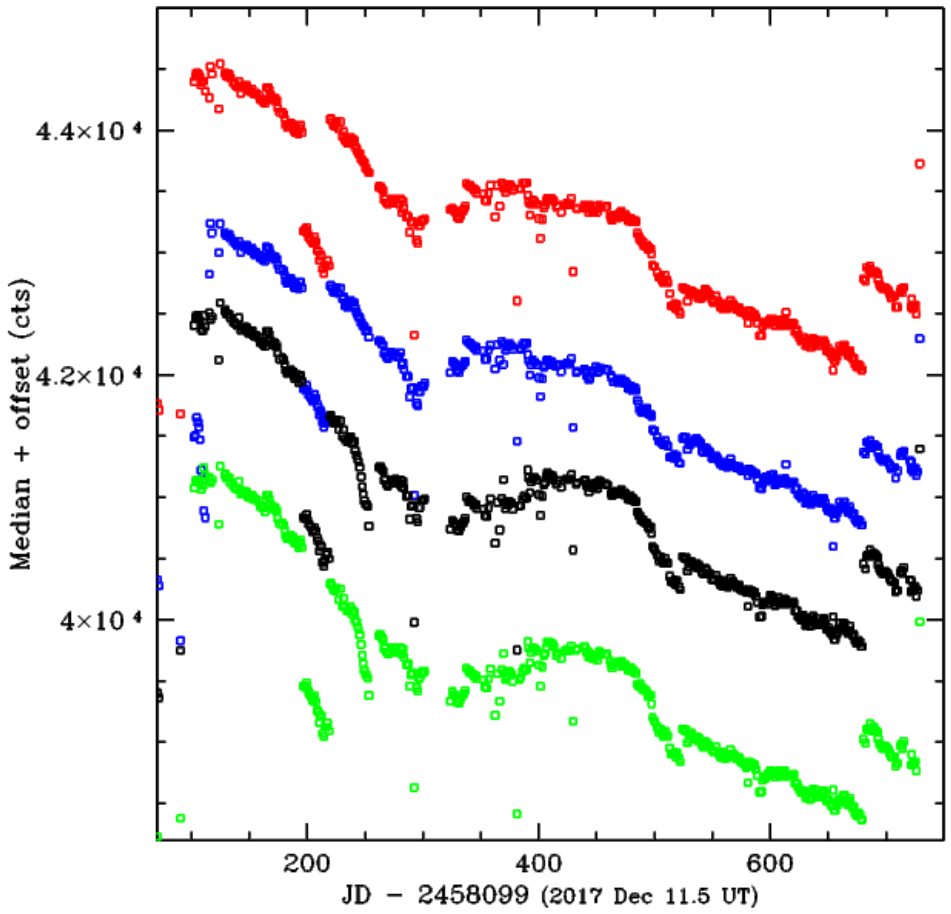
- ZTF g,r-band photometric error limits
  - Individual observations raw RMS ~2-5%
  - Calibrated individual obs. vs PS1, RMS ~1.2-1.8%
  - Calibrated median object mags vs PS1, RMS ~0.7% (mag < 18.5)

- Currently observe small (< 2%) systematics with:
  - Source colour, magnitude, location, airmass, reddening, skylevel, number of calibrator stars, and with time.

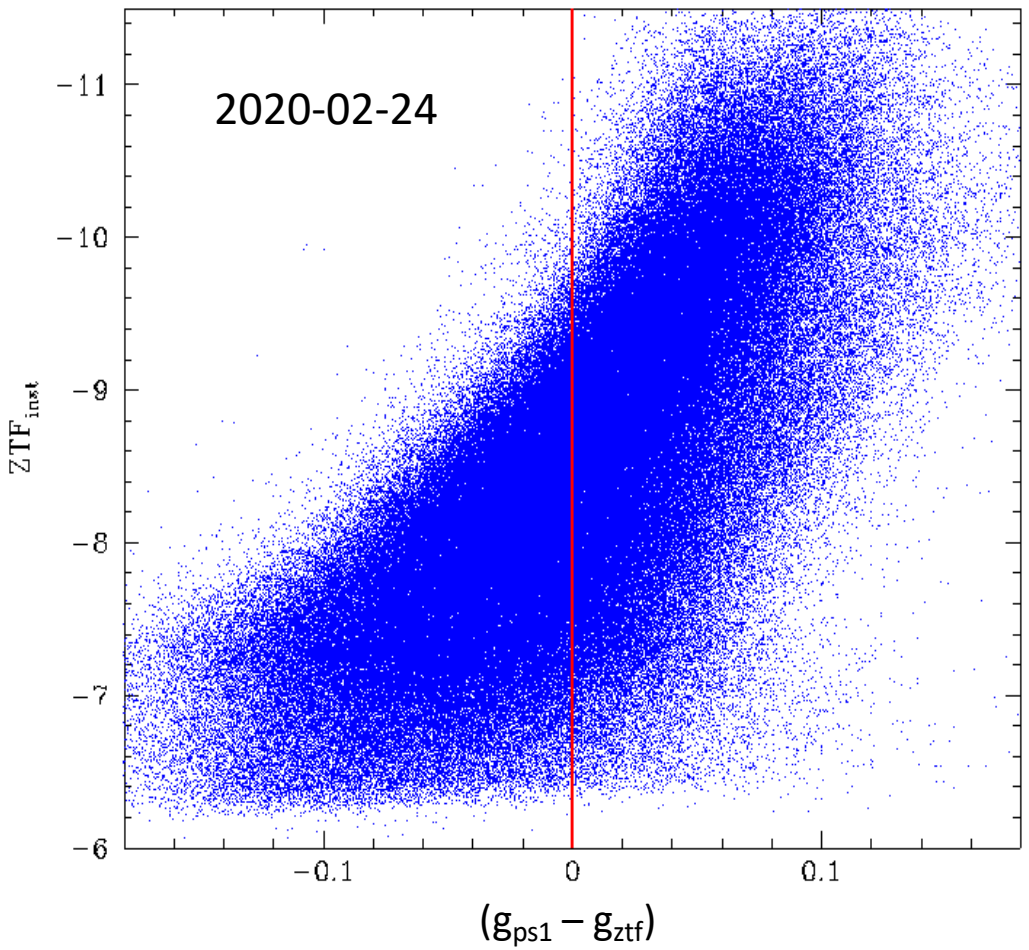
# Sources of Uncertainty

- Instrumental
  - Uncertainties in filter and CCD response
  - Dust accumulation
  - Instrument changes (CCD linearity, timing, readout)
  - Malfunctions (shutter errors, etc.)
- Software
  - PSF model inaccuracies, biases
  - Incomplete modelling (spatial variations, etc.).
- Observational Conditions
  - Seeing, skylevel, airmass
  - Clouds, varying atmospheric components.
- Calibration Data
  - Phot. uncertainties in calibrators
  - Reddening uncertainties

# Instrumental variations

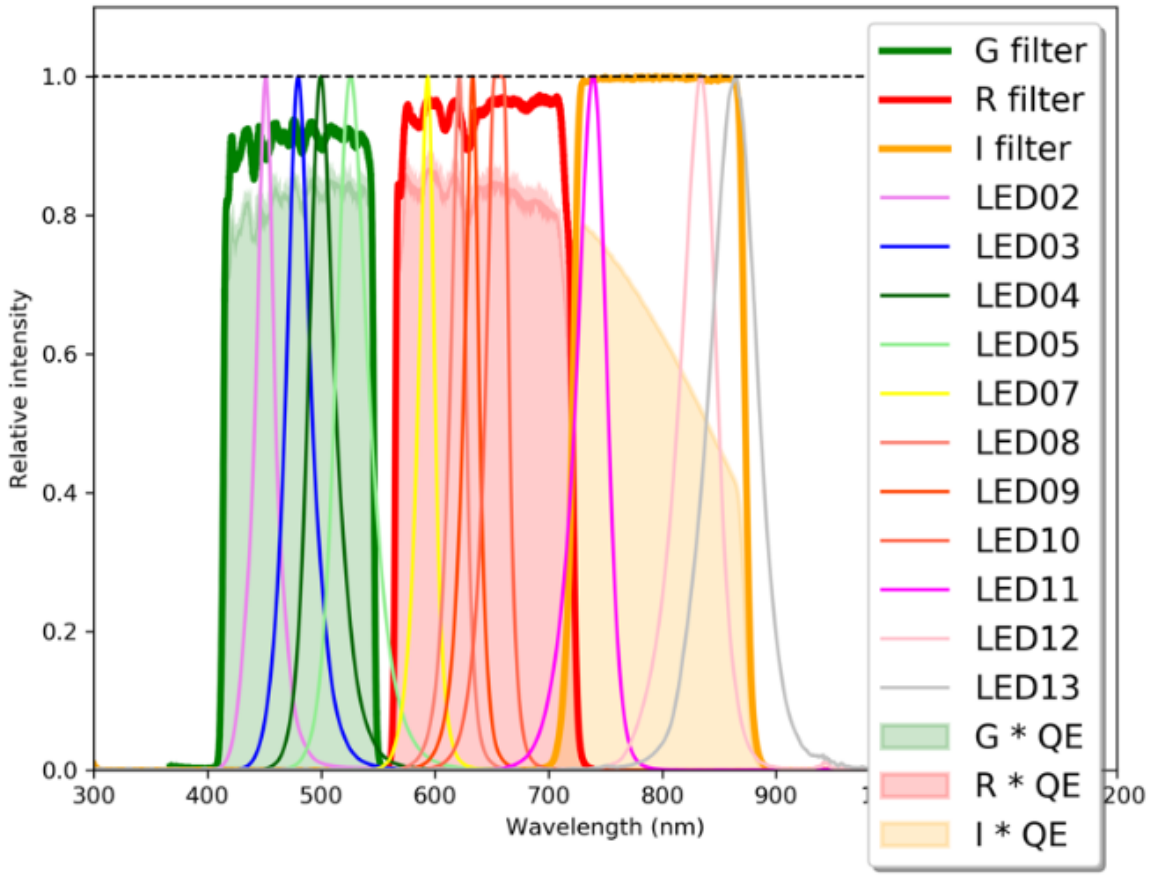



Variation in g-band median flatfield values over time, due to dust and instrumental changes.




ZTF CCD6 instrumental magnitude vs g-band residuals

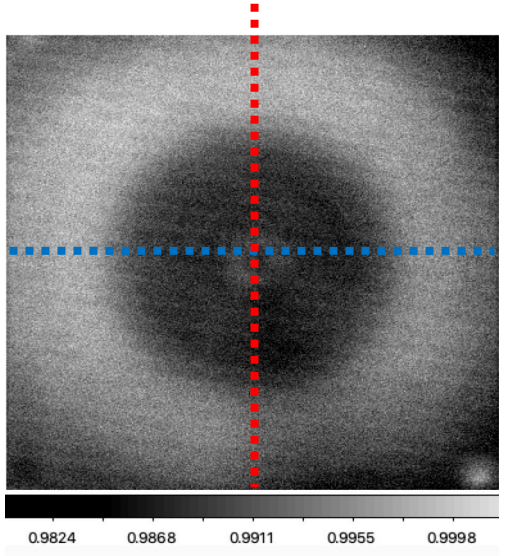
# Colour response from LED flats

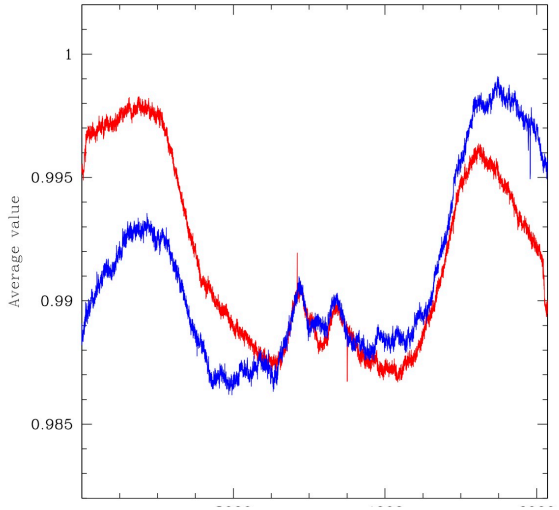



ZTF filter bandpasses and normalized flatfielding LED spectra (Rosnet et al. 2020).

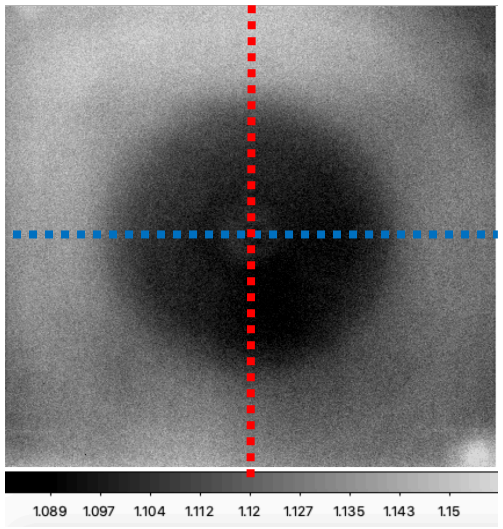
# Spatial variation of CCD colour response

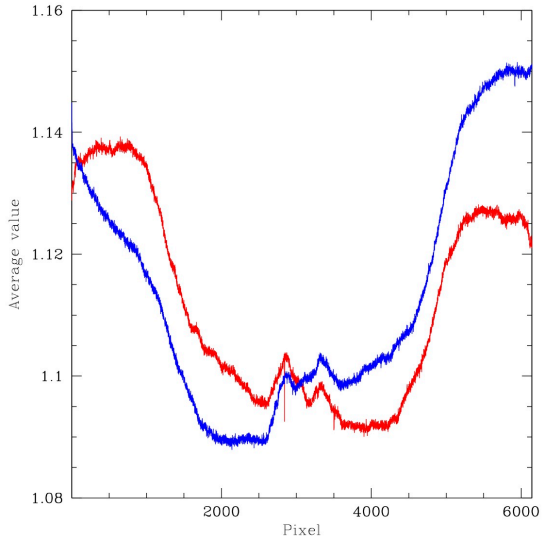
R-band CCD colour dependence based on ratio of 594 and 653nm LED flats.



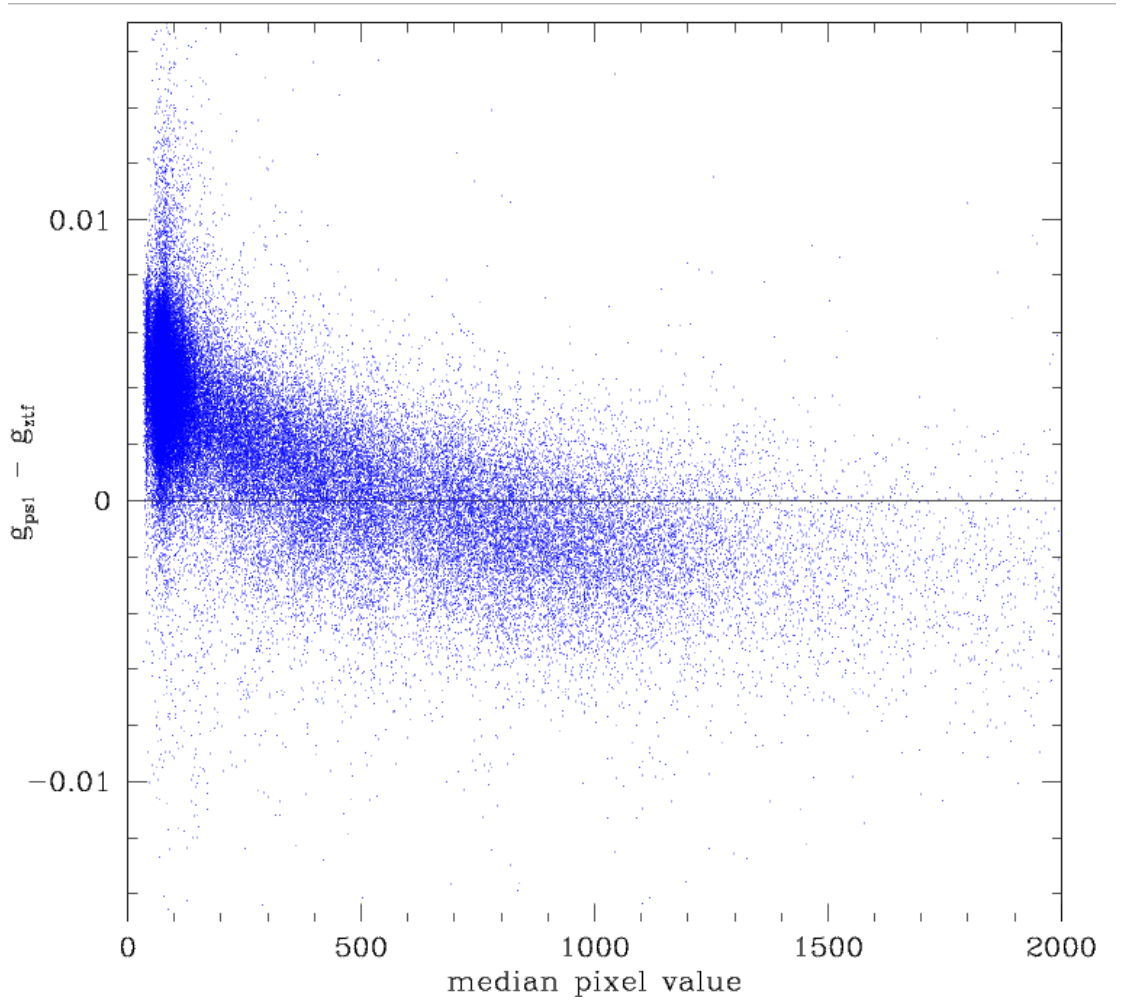



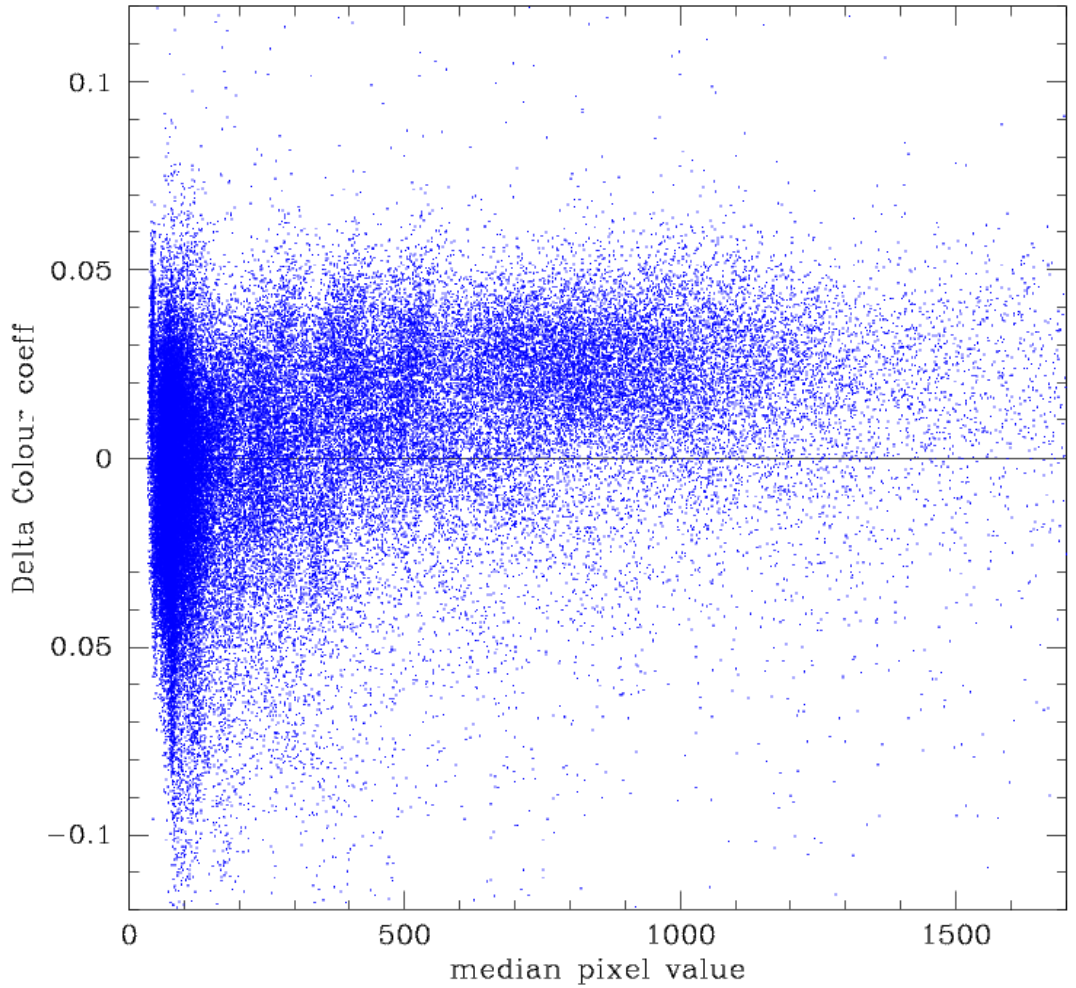

I-band CCD colour dependence based on ratio of 740 and 864nm LED flats.



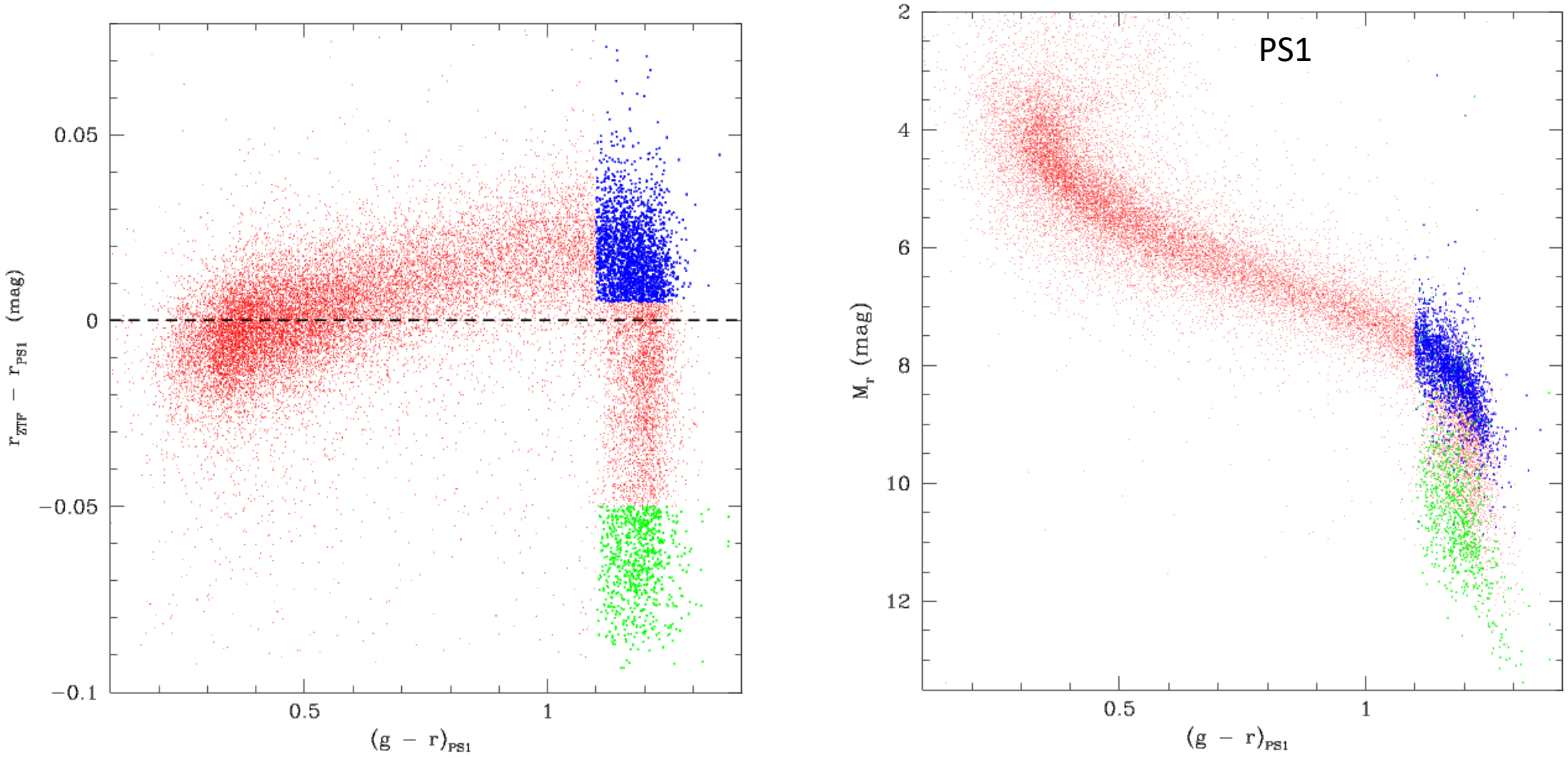
# g-band residuals depend on skylevel



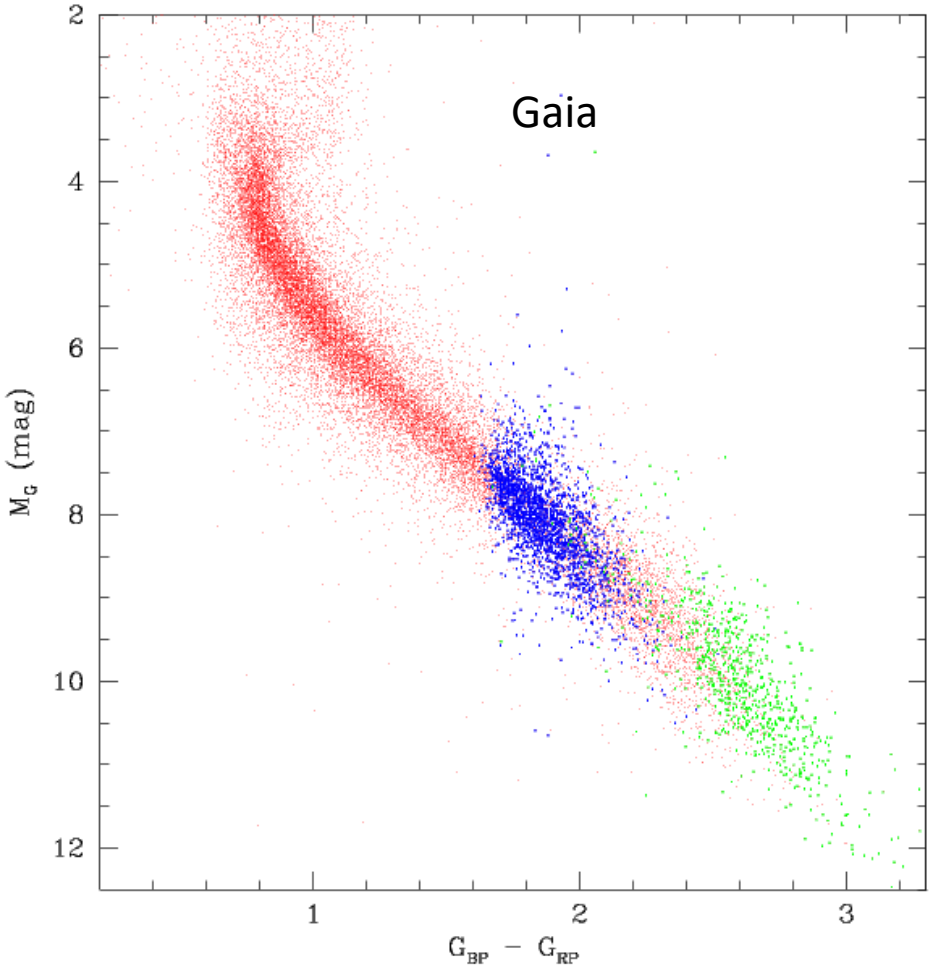

Photometric residuals in g-band wrt PS1 for sources with g < 18.5 and 600 < ncat < 3000.

# r-band residuals depend on source colour

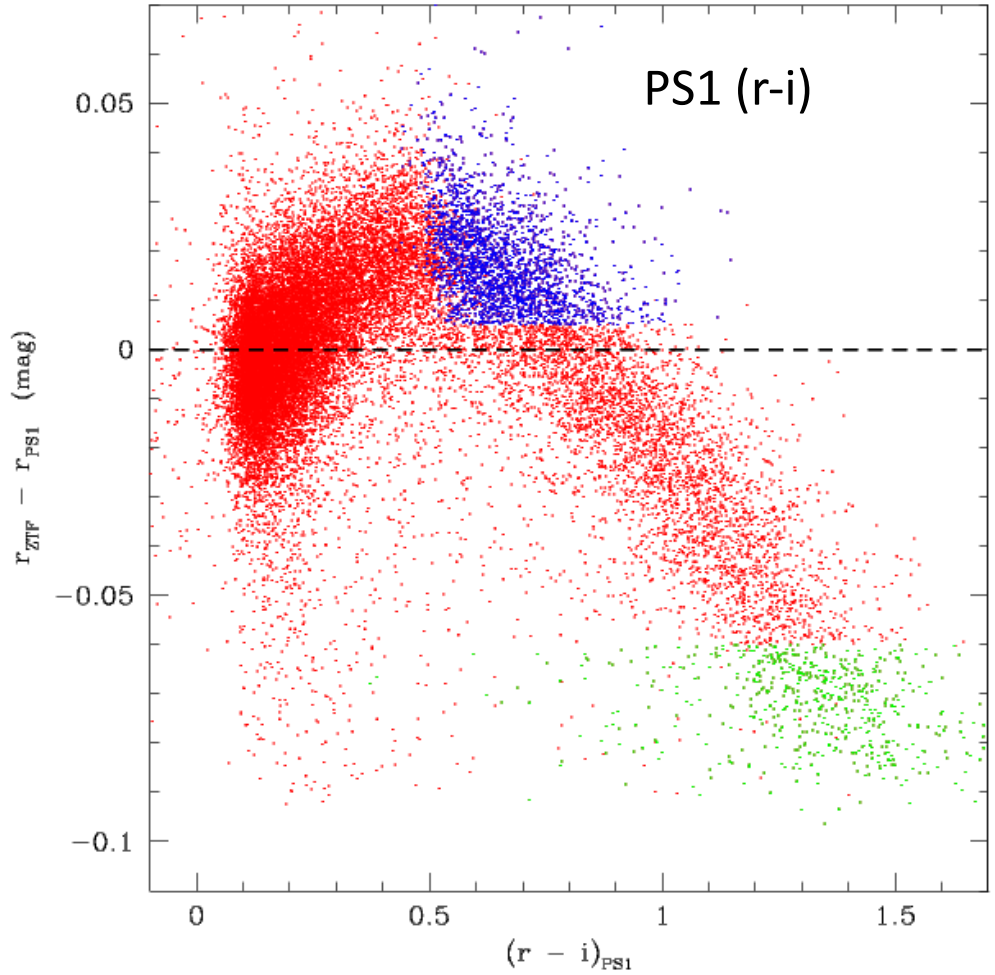



Photometric residuals in ZTF r-band wrt PS1 for bright sources in a halo field

# Stars with poor calibration

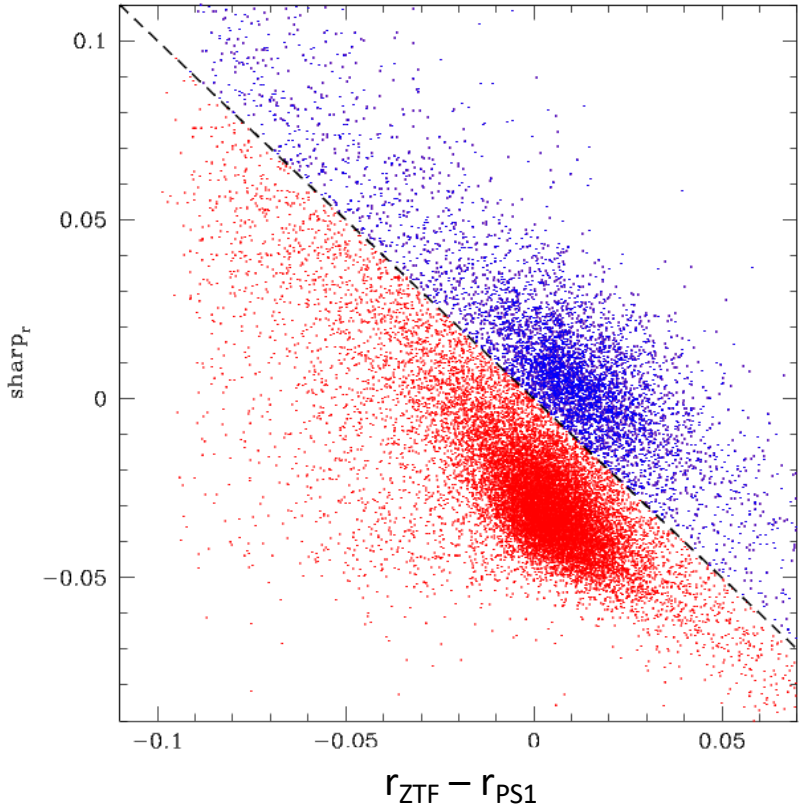


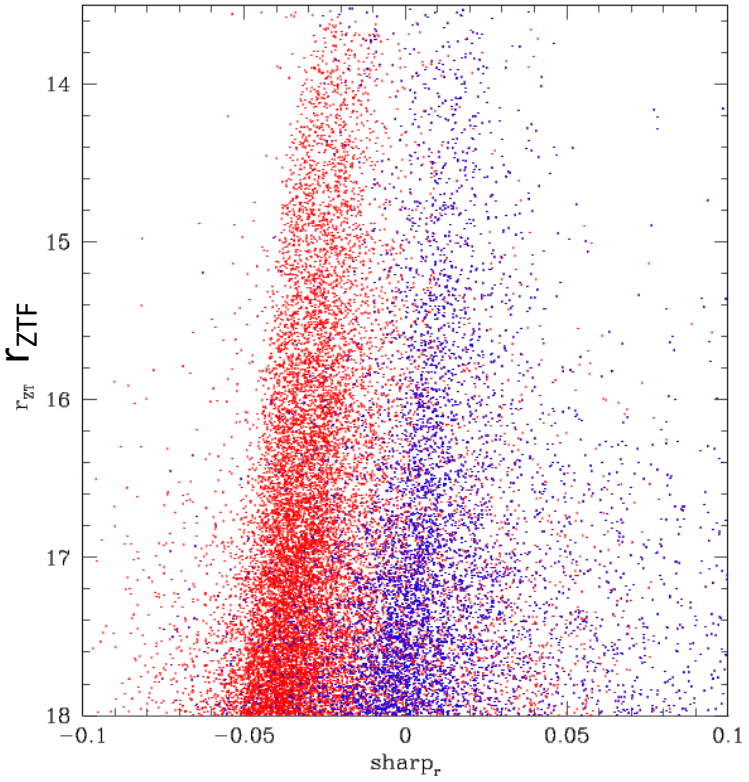

CMDs from ZTF and Gaia photometry for the same halo ZTF field

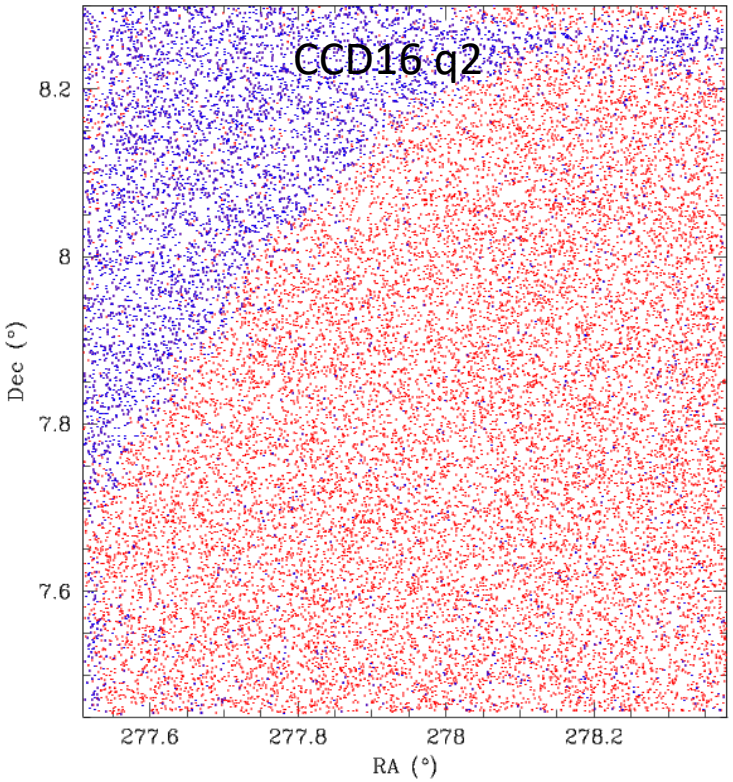



For r-band, sources with PS1 g-r > 1.2 can be calibrated using their r-i colours.

# PSF variations with mag and x,y



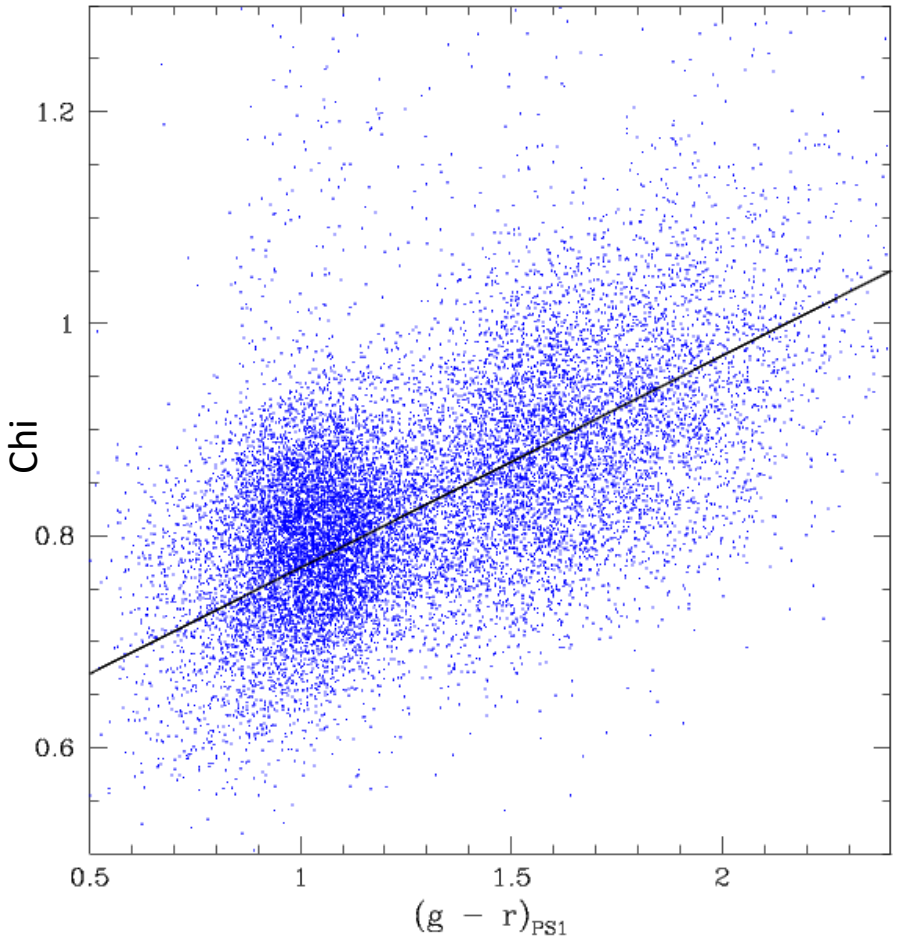

PSF shape variations traced by sharpness

Spatial variations in sharpness

*sharpness* = $FWHM^2_{obs}$ - $FWHM^2_{model}$

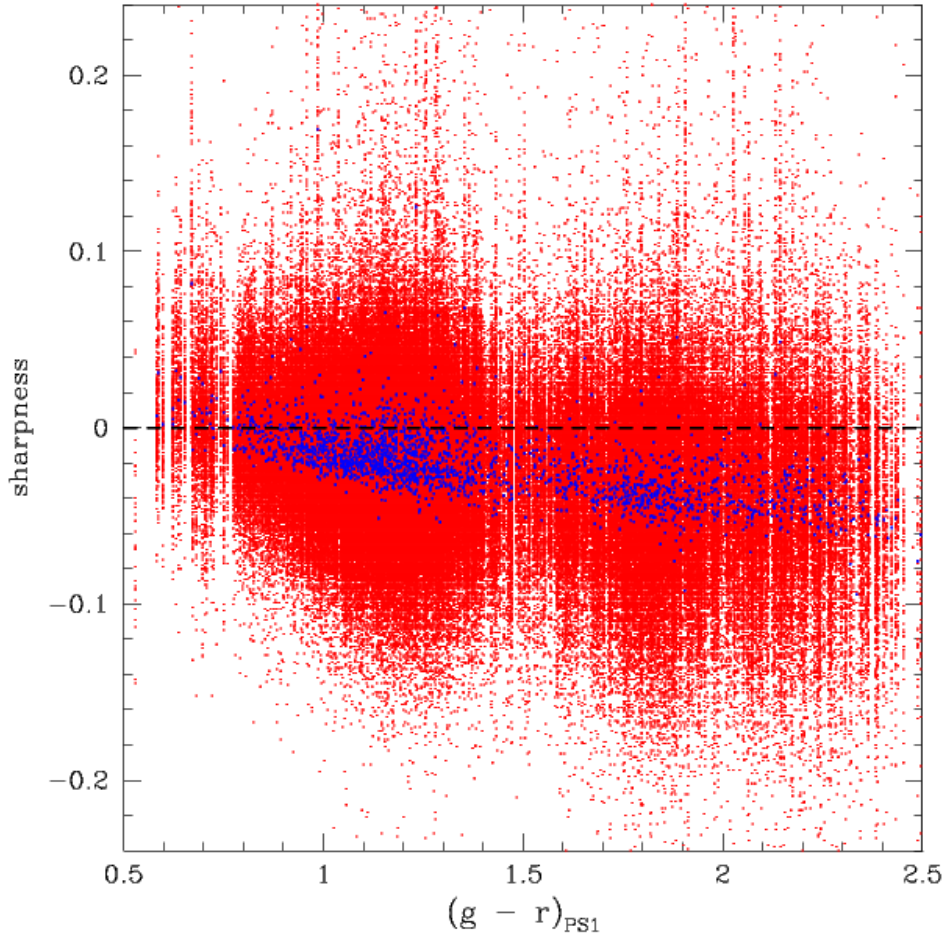
# PSF colour dependence

PSF shape variations (traced with chi) with colour



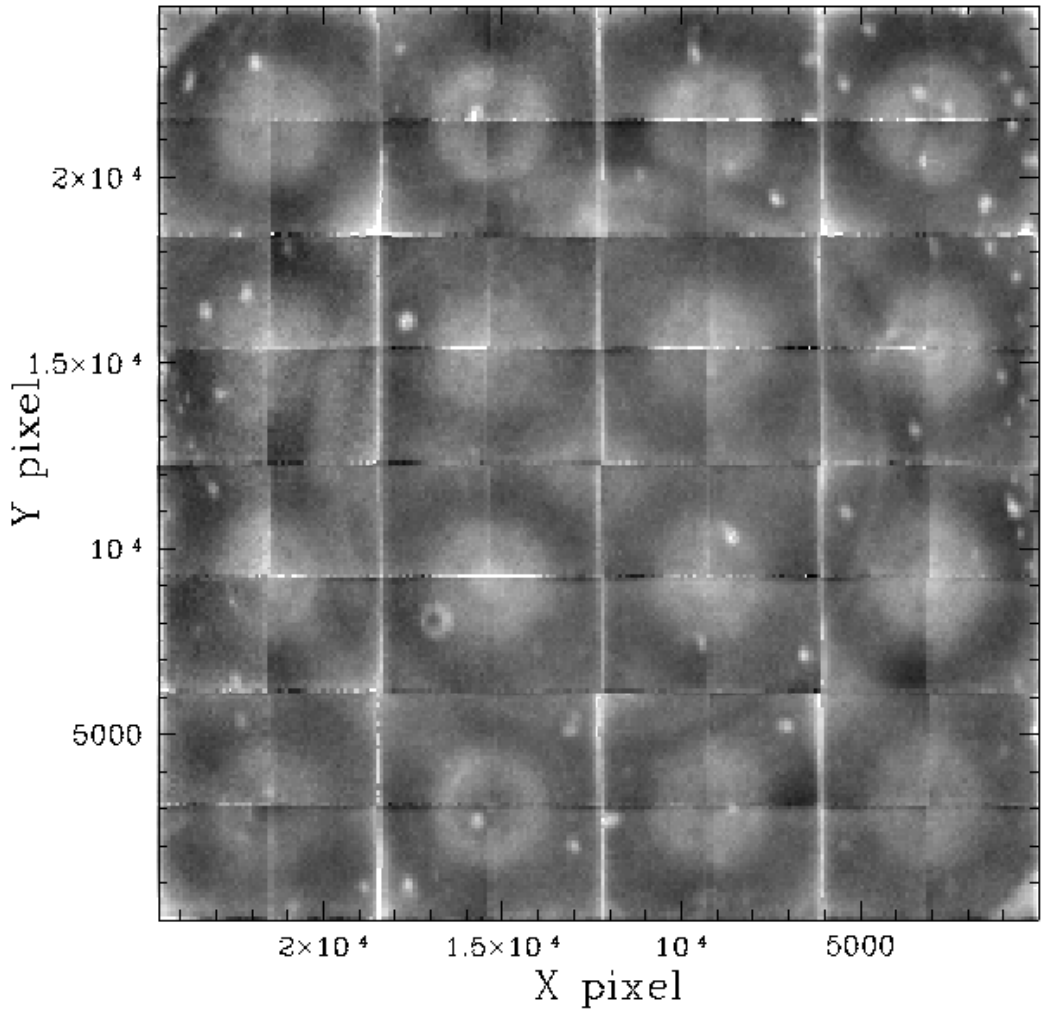

Chi = (PSF fit RMS)/(readnoise predicted RMS)

PSF shape variations (traced with sharpness) with colour

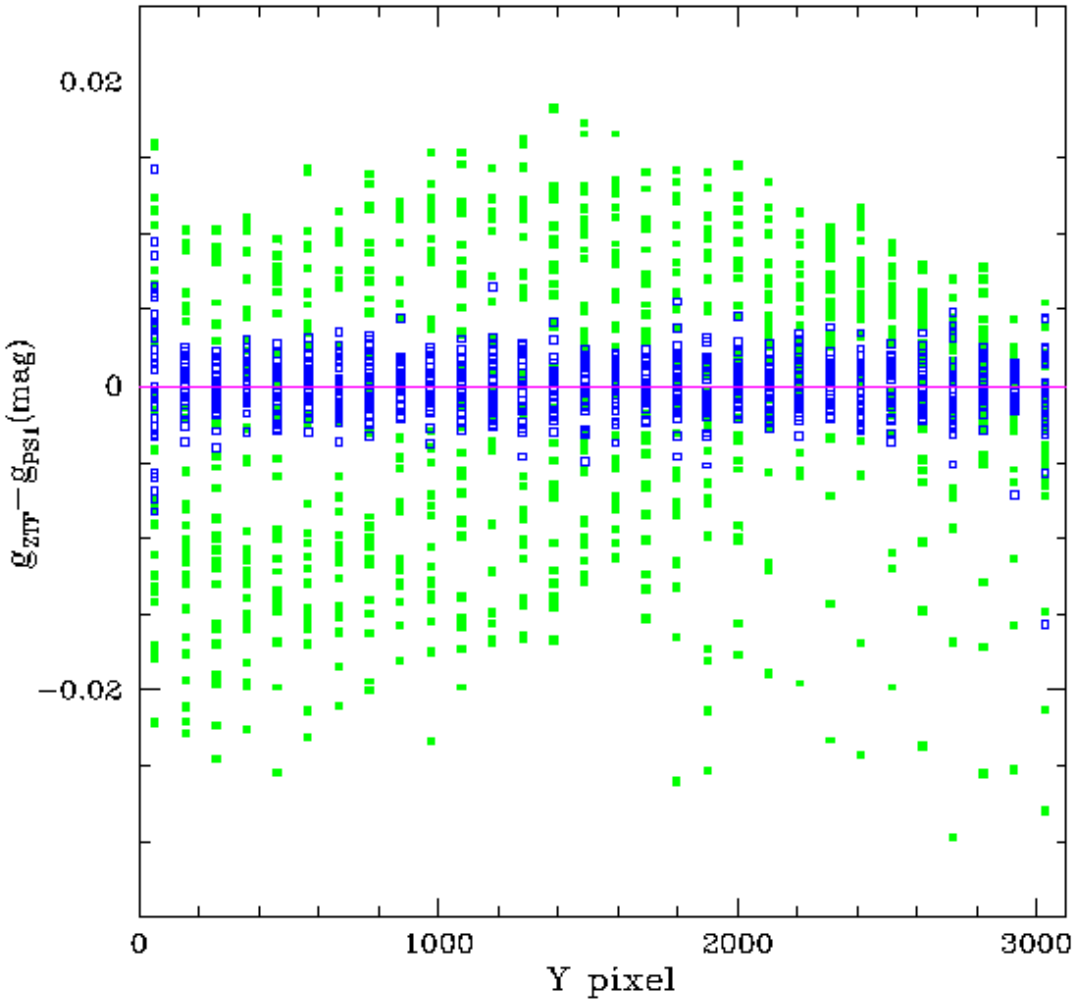



*sharpness = $FWHM^2_{obs}$ - $FWHM^2_{model}$*

# Spatial photometric residuals



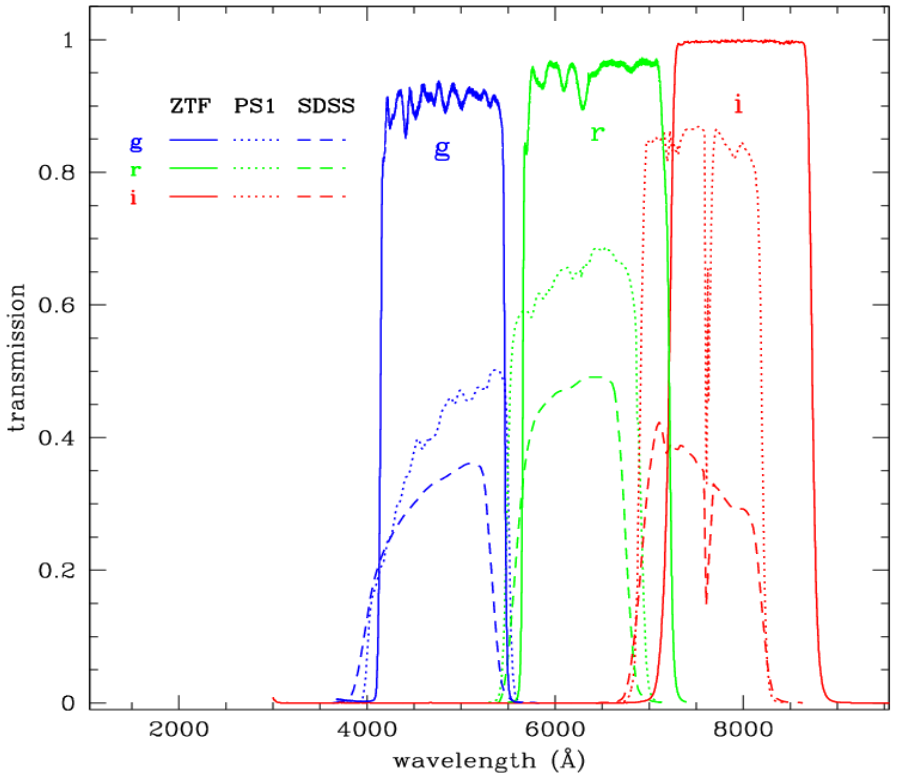

Photometric residuals for ZTF Camera in g-band




Quadrant spatial structure (green), fit residuals (blue)

# Current calibration error sources

- PSFs variations with colour, magnitude and location are poorly modelled.
- Calibration is only performed on a per quadrant basis.
  - =>Trends with skylevel in g-band for sparse fields due to lack of calibrator stars.
- Current model does not account for intra-quadrant variations with airmass or reddening.
- ZTF calibrated to PS1, but filter differences lead to errors.
  - => High RMS for red sources in r-band.
- Issues with scattered light and long-term stability.
- Strong spatial phoometric residual structure.
- Overscan, crosstalk, ghost artifacts in early ZTF data.




Ref. Ngeow et al. (2019)

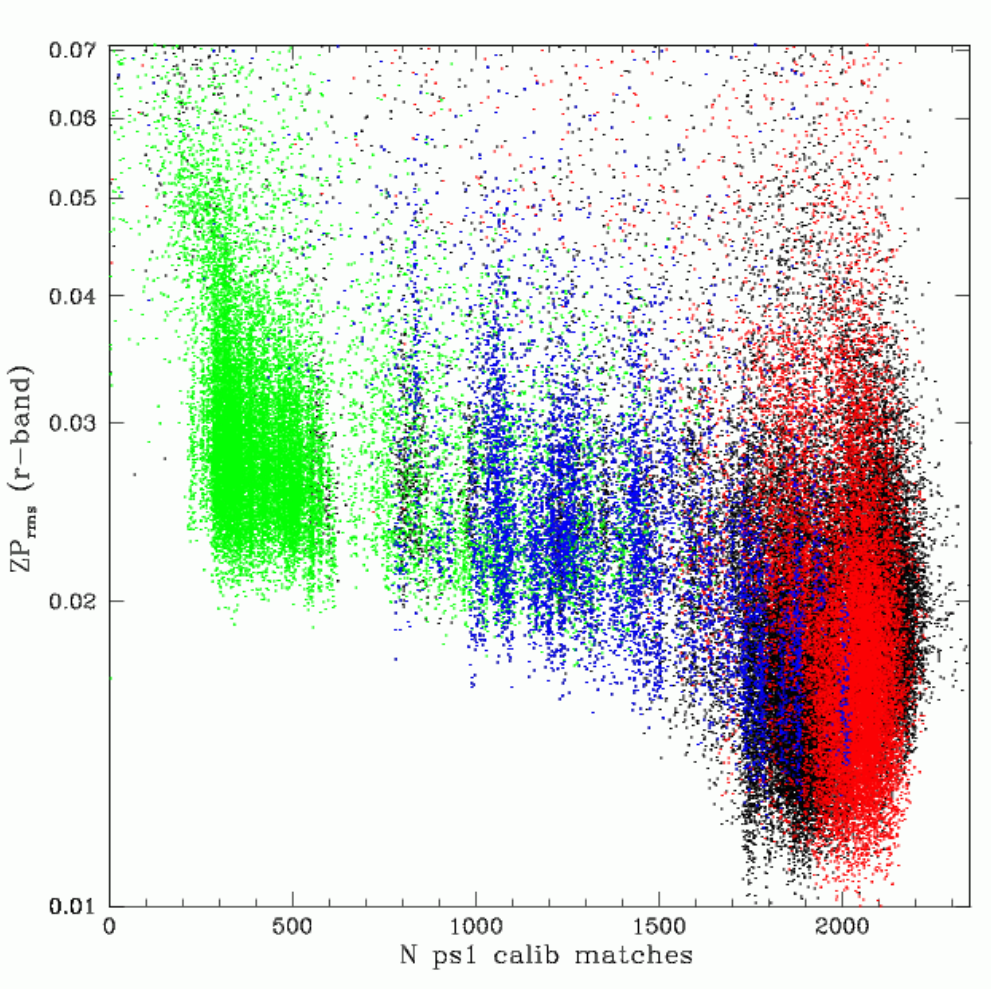
# Steps towards a ZTF Ubercalibration (Zubercal)

## Current ZTF calibration:

Single ZP and colour coefficients fit on a per frame basis.
Variations in airmass, reddening, and spatial structure not fit.
Limited by no. of calibration stars within quadrant.

## Zubercal approach:

Calibrate all frames taken on a night simultaneously.
Increase number of calibrator by a factor of a few hundred.
=> Better account for spatial and temporal variations and dependencies.
=> Possibly extend across full CCDs, or full FoV.




Colours represent different Galactic latitudes.

# ZTF Photometric Calibration

Current calibration: $m_{cal} = m_{inst} + ZP_f + c_f\left(m_1^{PS1} - m_2^{PS1}\right),$

A more complete description: $m_{cal} = m_{inst} + ZP_f + c_1(m_1\text{-}m_2) + c_2 X + c_3 X(m_1\text{-}m_2) + c_4 E_{bv} + c_5 UT + c_6 f(x,y) + \ldots$

Extinction with Airmass

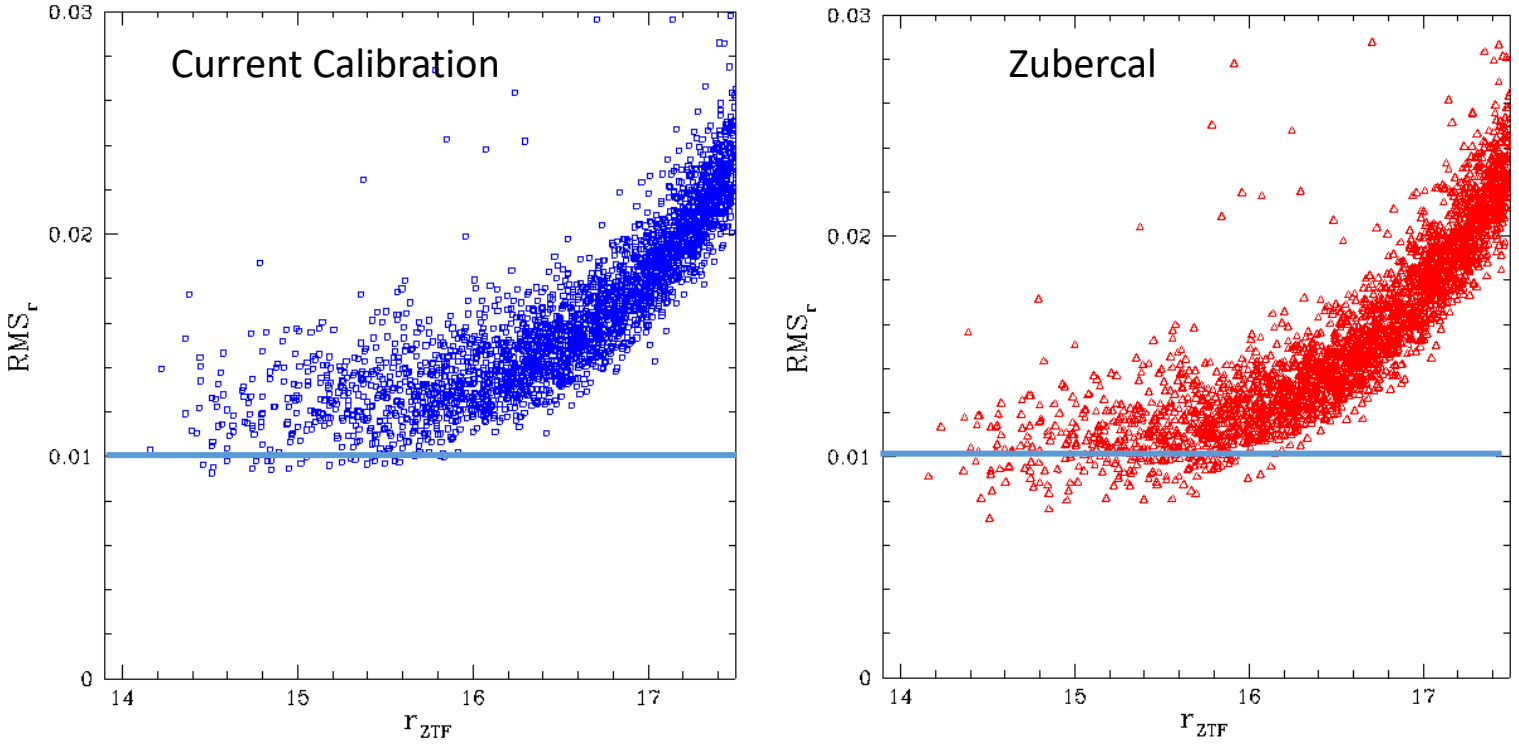
Colour dependence of extinction

Reddening

Time dependence

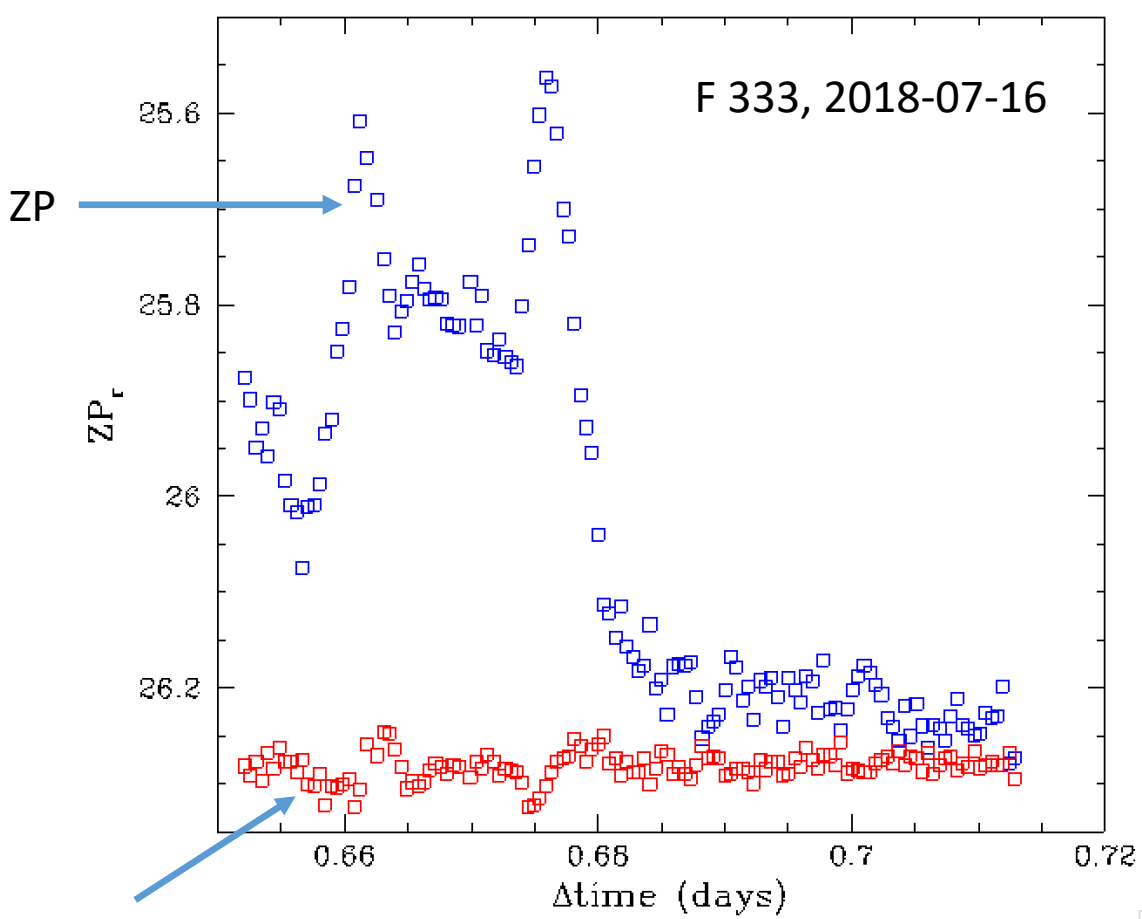
Spatial dependence

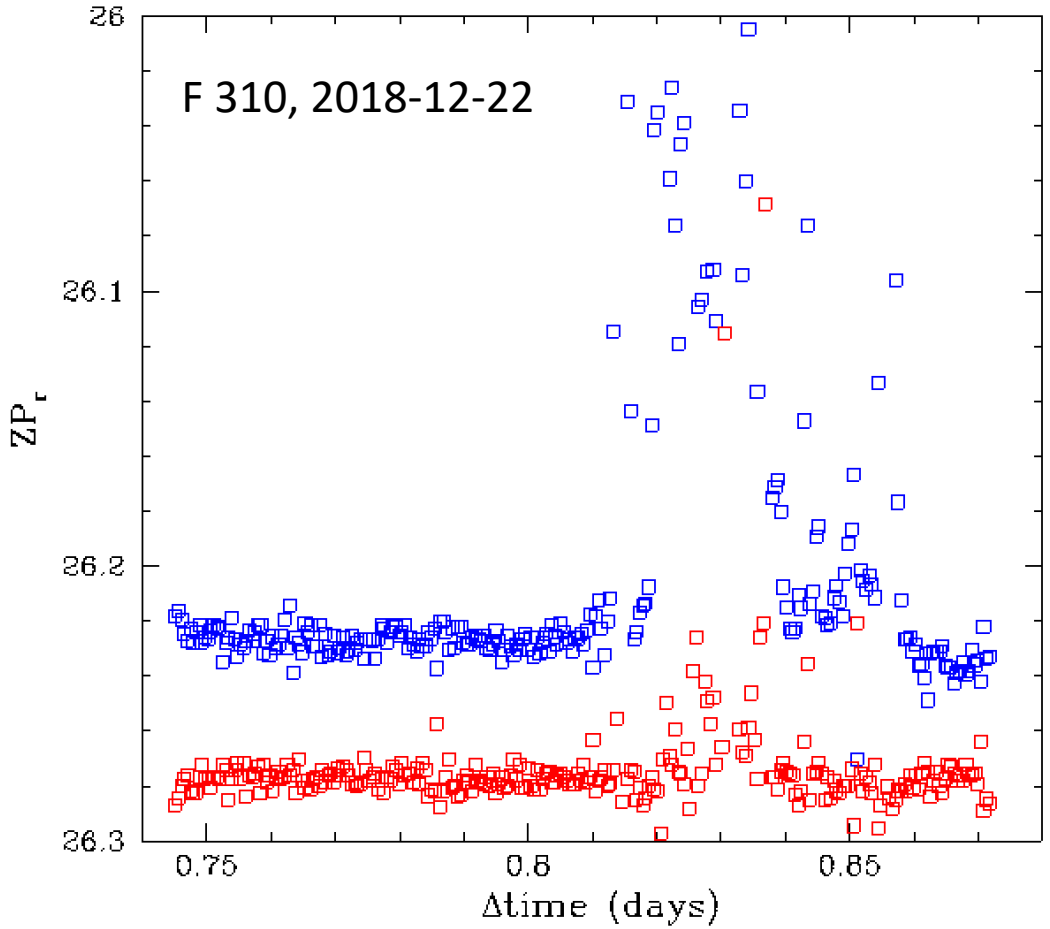
Data from fields 614 and 661 observed on 2019-11-13



# Varying observational conditions

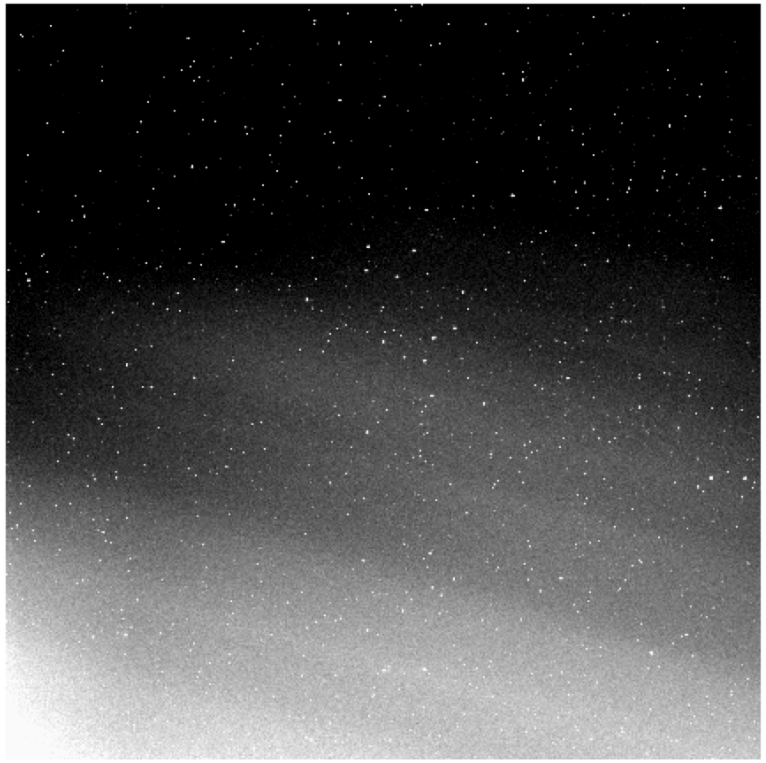
Time dependence based on fields observed on hundreds of times a night.

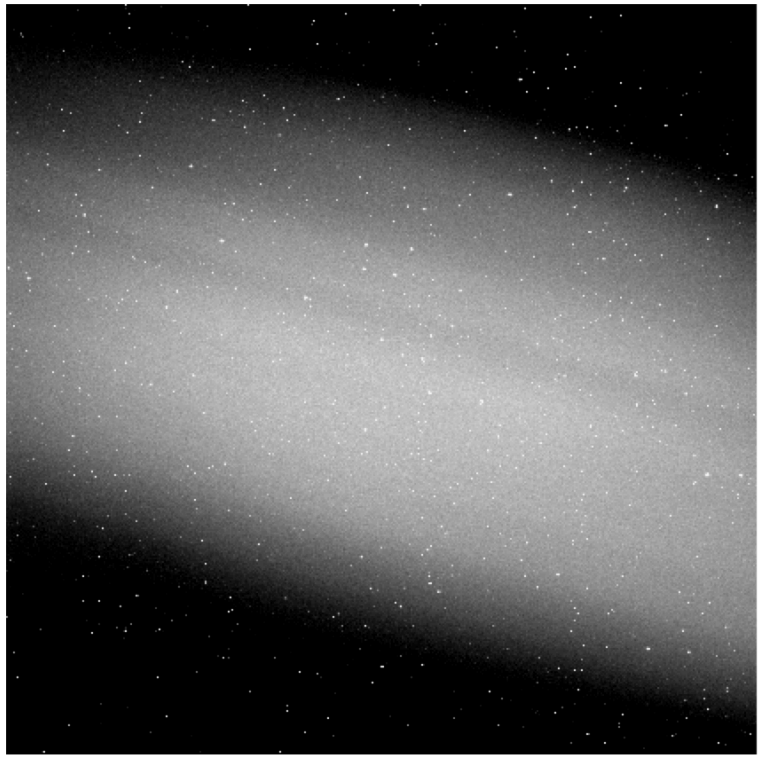


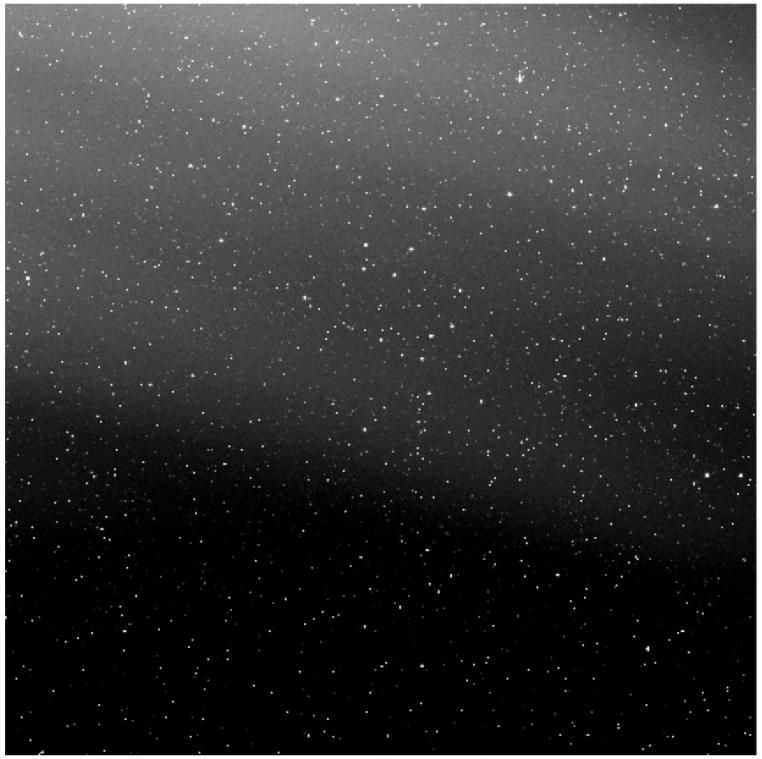



# Varying observational conditions

Three images of F310 taken in sequence during ~2 min on 2018-12-22.

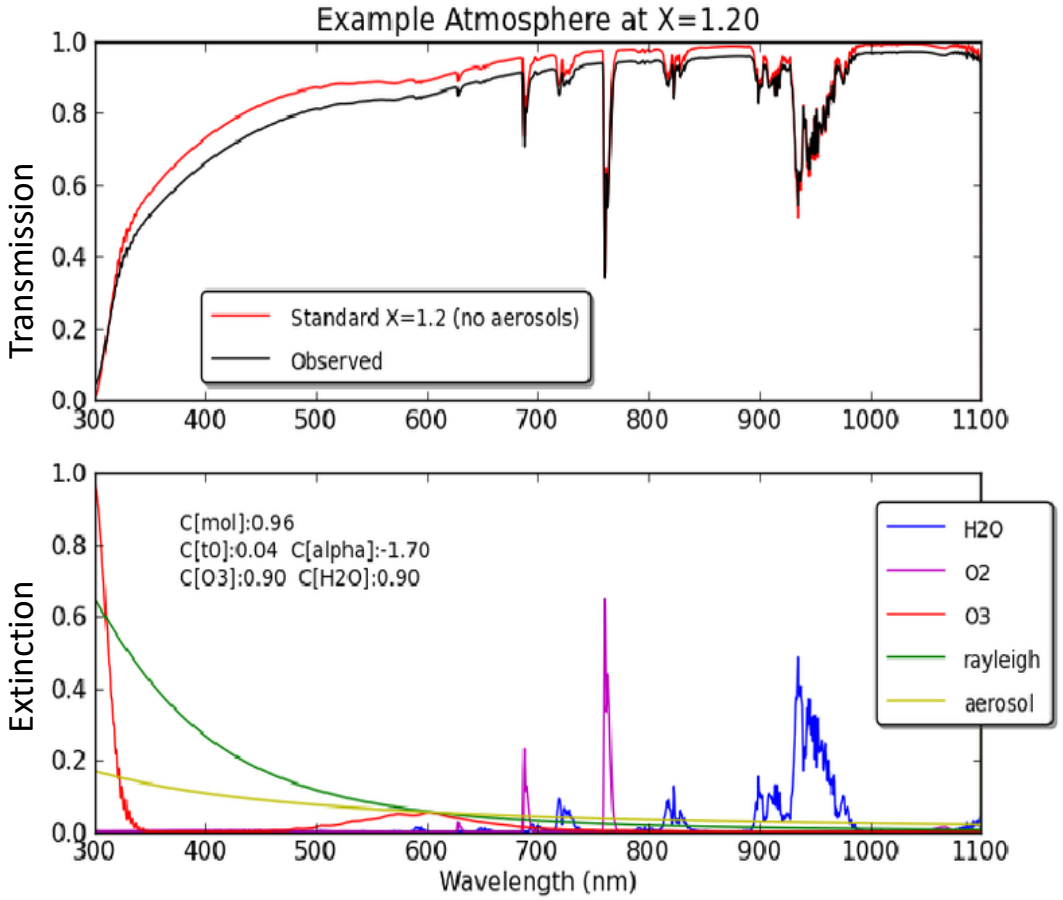


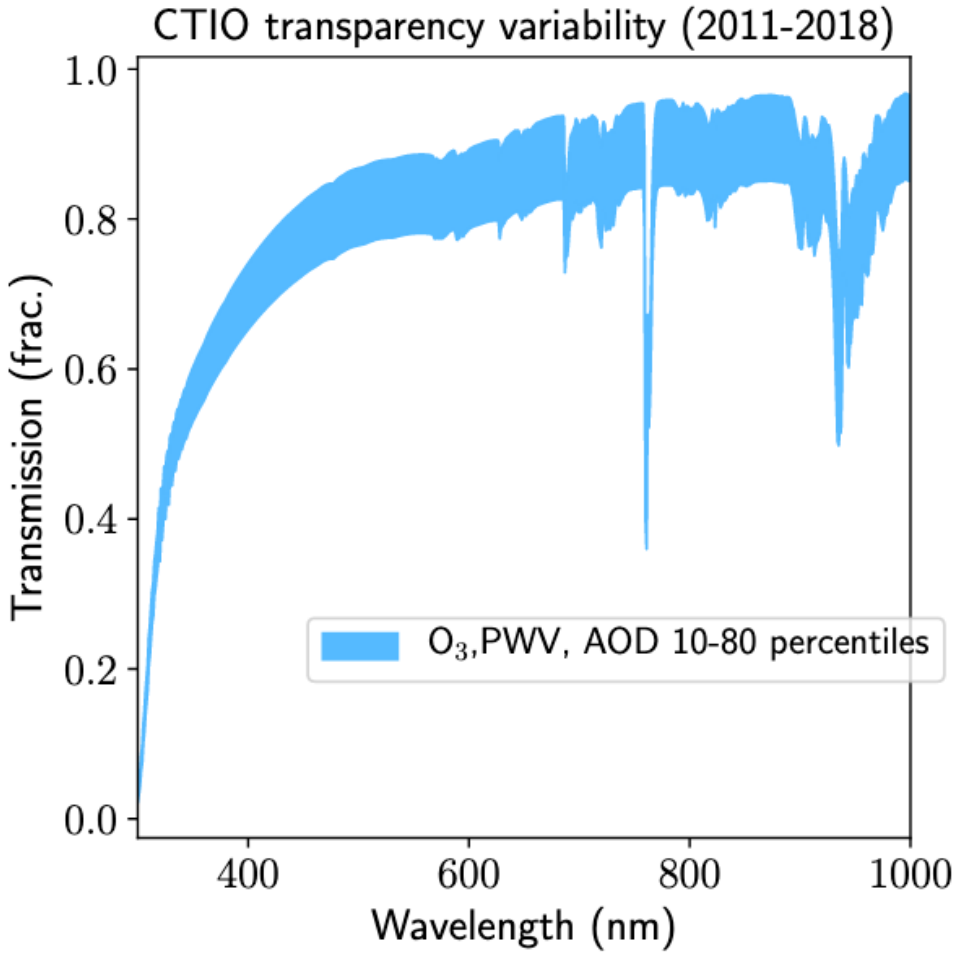




# Atmospheric components

Atmospheric components and variations with wavelength measured  for atmospheric components (Aerosol optical depth, AOD 550nm), Precipitible Water Vapor (PWV), O3 (Ozone))  (Guyonnet et al.~2019).



# Photometric System Modelling

Problem: ZTF does not have a dedicated photometric monitoring telescope (c.f. SDSS, LSST, etc.), and …

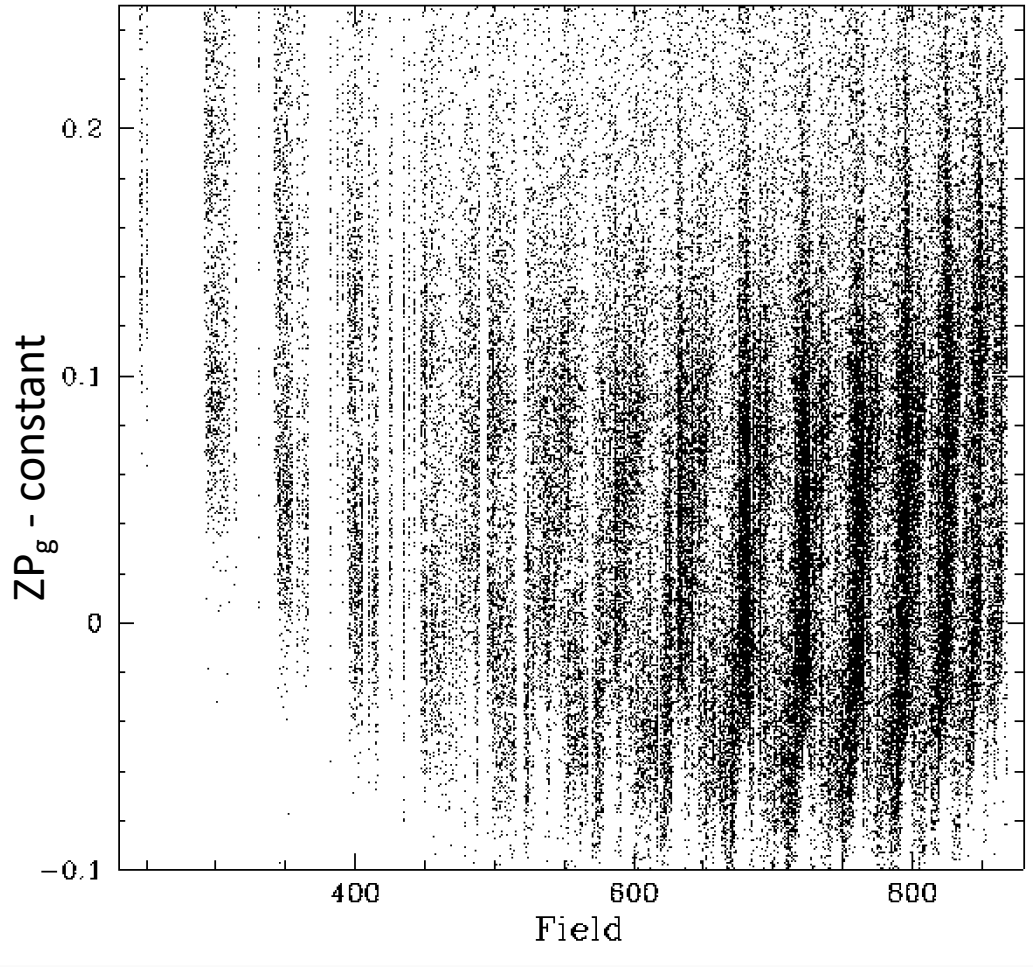
Zero-point scatter (mmag) for images in delay range.

| band | $T < 1\text{hour}$ | $1\text{hour} < T < 1\text{day}$ | $1\text{day} < T < 10\text{day}$ |
|---|---|---|---|
| $u$ | 20.9 | 27.4 | 30.9 |
| $g$ | 10.7 | 17.9 | 25.2 |
| $r$ | 19.7 | 17.9 | 26.3 |
| $i$ | 12.6 | 15.8 | 21.5 |
| $z$ | 7.6 | 15.4 | 30.0 |

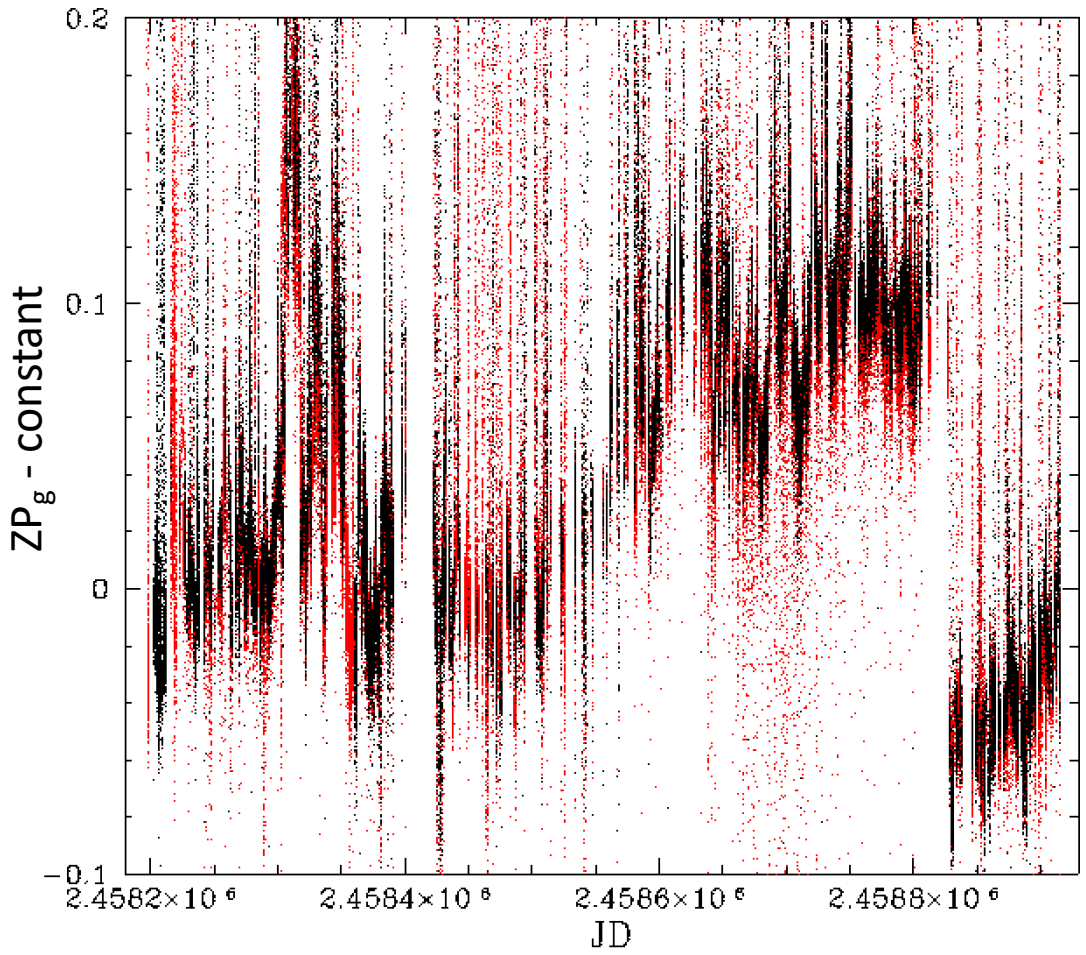
Transparency variations from Magnier et al. (2008)

However: If we can accurately model the ZTF photometric dependencies, we can estimate transparency for each observation.

# Variations in ZTF Zero Points

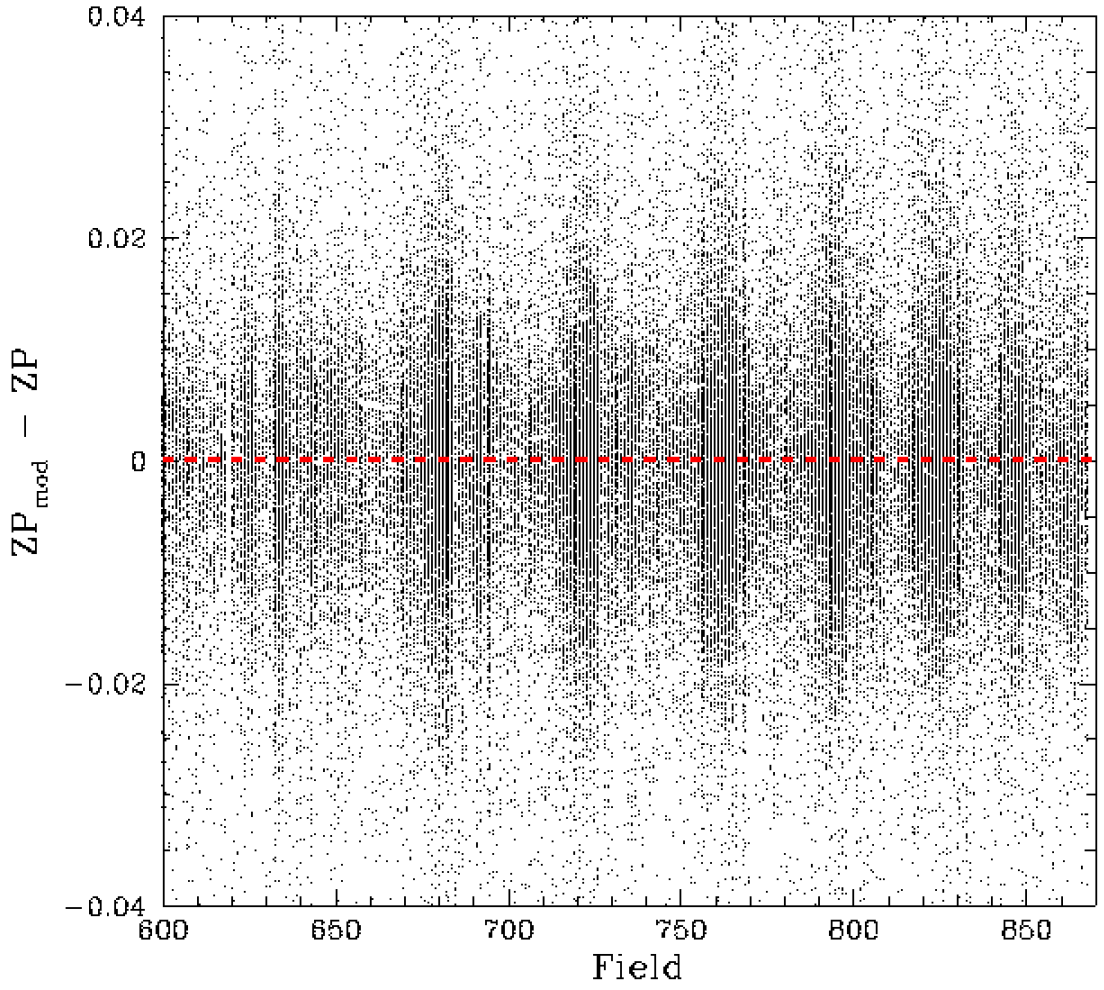



Field dependence

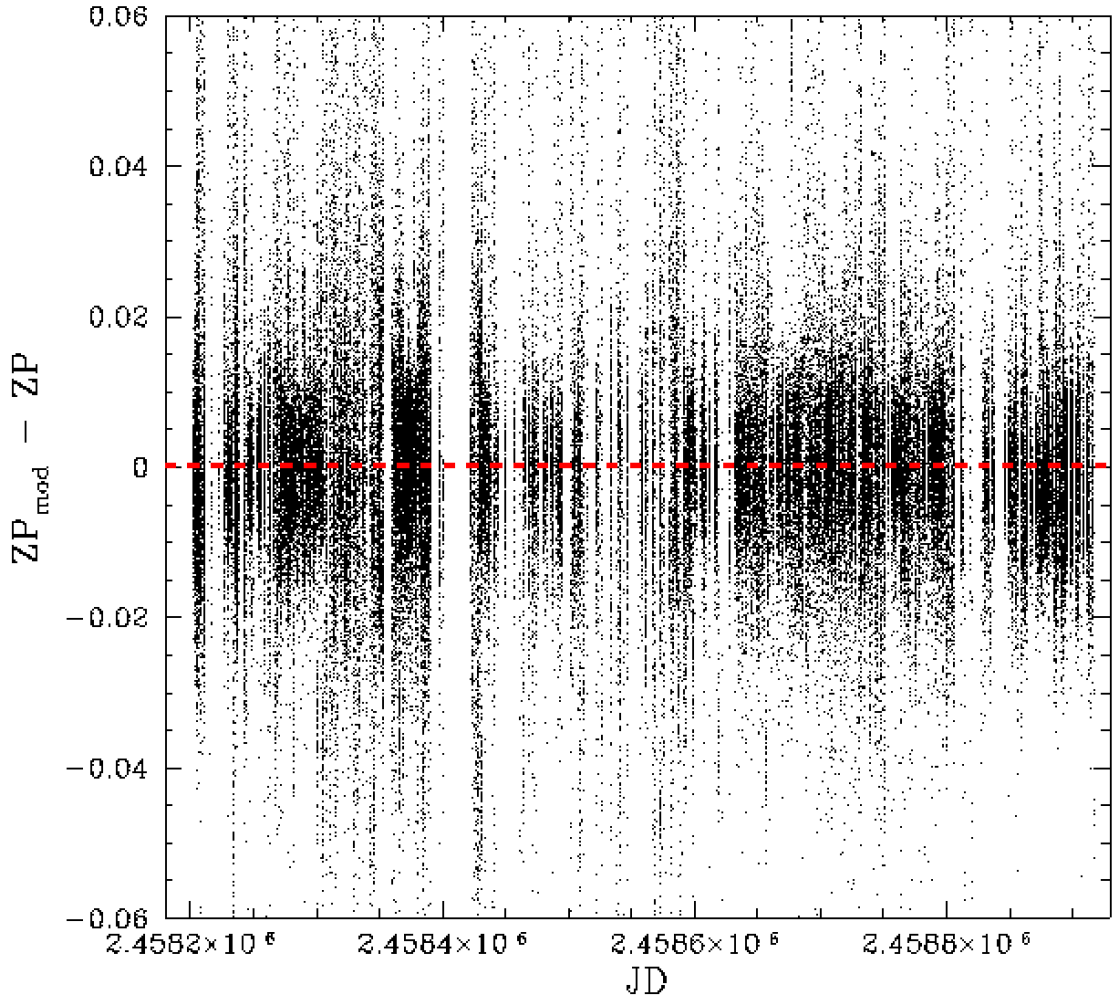



Time dependence

# Current Accuracy of ZP Modelling




Field dependence




Time dependence

# Additional Work by Calibration Group

- LED flats in SED weighted combinations.
- Unfiltered vs filtered flat comparison (to account for scattered light).
- CCD depth and charge diffusion modelling.
- Spatial PSF modelling with PIFF
- Spectrophotometric calibration via monochrometer (DePoy et al.)
- Alternate photometric catalogue testing:
  Gaia EDR3, Dec 2020, (1.8 billion sources, 1mmag at G=17, 5mmag at G=20).

Weekly meeting Fri. 8:30am: https://zoom.us/j/951591406