422 calibrated light-curves from the SNLS spectroscopic sample

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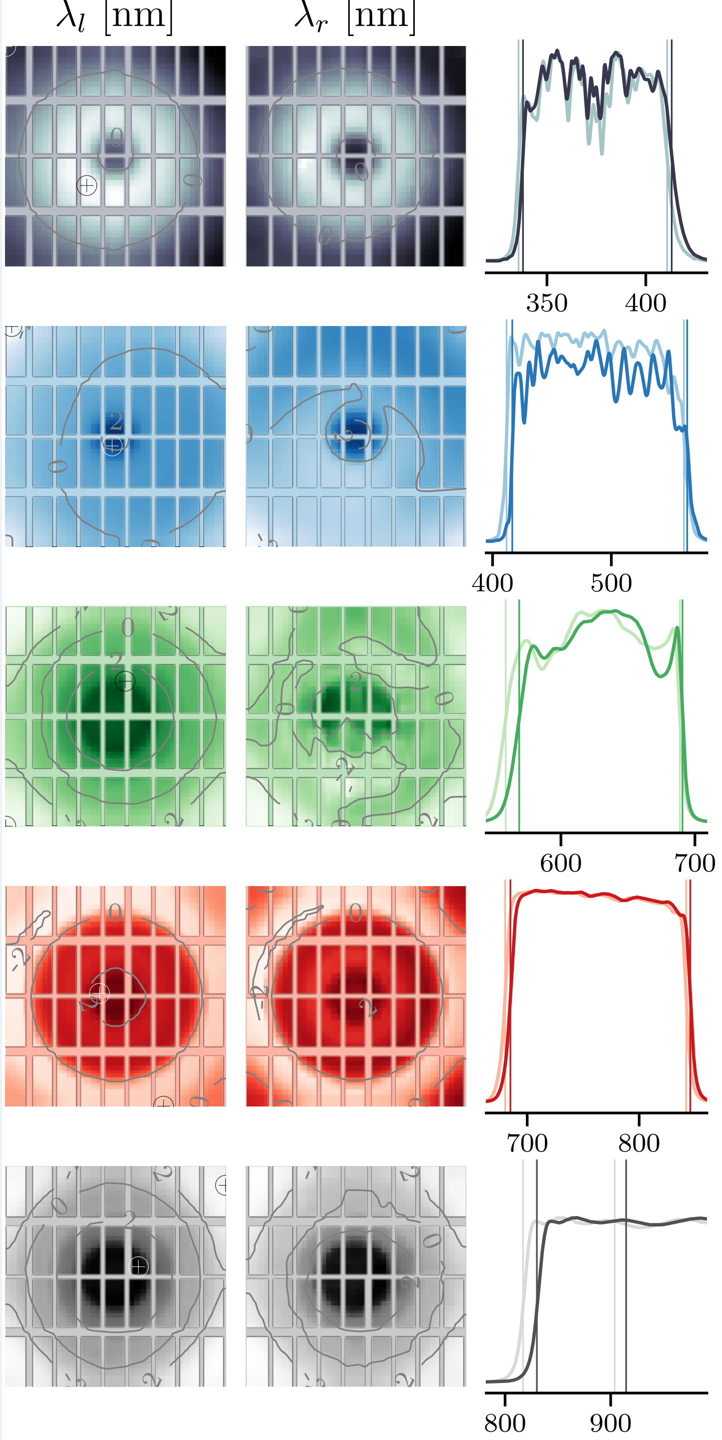
Motivation

- **Lemaitre compilation:** assemble ZTF low-z, SNLS, and HSC SNe Ia to minimize systematic uncertainties
- SNLS:
    - 140 new supernovae
    - Large spectroscopic sample $(0.1 < z < 1.0)$
    - Direct CALSPEC calibration in g r i z
- Previous calibration (B13) limited by:
    - Filter model relying on manufacturer witness samples
    - No direct measurement of the open (filter-free) instrument transmission
    - Concomitant standards requirement restricting calibration precision
- **This work:** new passband model + direct CALSPEC calibration + Gaia DR3 anchor → **< 5 mmag** in all bands
- 385 SNe Ia with SALT3 distances, 140 never published before

Ingredient 1: Comprehensive survey of filter transmissions

- MegaPrime filter set decommissioned in 2015, shipped to Lyon for a 2017 measurement campaign (Sassolas et al. 2018)
- Perkin-Elmer L1050 spectrophotometer: transmission at 0°, 5°, 10°, 15° incidence
- HR2000 cartography: 27×27 grid, **1 cm** sampling over the 26×26 cm filter
  - Well matched to the $\sim$**2 cm** beam averaging radius at the filter
- Wavelength calibration anchored on a didymium (WAV7) reference cell



Didymium reference spectrum

- Mean of 7 good-quality didymium scans (g and r bands)
- Cross-normalised to a common flux scale
- $\pm 1\sigma$ scatter band shown
- Absorption features at 471.9, 512.1, 680.7 nm used for calibration


Certificate of Calibration

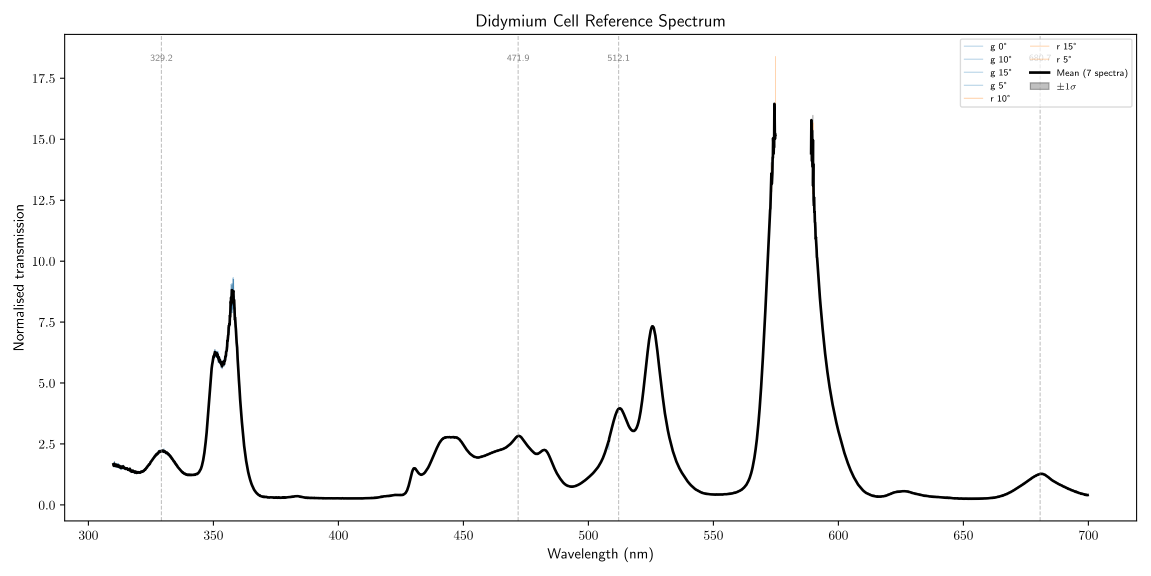
This certificate confirms that Didymium Glass WAV-7 Calibration Standard manufactured by Fireflysci Inc. was developed for ultra-violet and visible light (UV-VIS) bandwidths and its wavelength peaks are within the range of NIST benchmark values and are identified in the data-file: 430 WAV-7.csv

Fireflysci Premium Wavelength Calibration Filters *Serial No. 430*						
FFS Part No.	Passed QA	Detected Peak Values (nm)				
WAV-7	Yes	329.2nm	471.9nm	512.1nm	680.7nm	876.4nm
UV Absorbance		270nm	280nm	300nm	320nm	340nm
WAV-7	Yes	0.6187	0.5540	0.5319	0.3198	0.2936

Note 1: The certification was conducted with the appropriate spectrophotometer using 2nm spectral band-width
Note 2: Uncertainties of the certification are in full accordance with the NIST.
Wavelength Uncertainty: +/-0.2 nm, **Photometric Accuracy Uncertainty:** +/- 0.0024 AU.
Note 3: The measured wavelengths' peaks depend, among other factors, on the user's spectrophotometer's slit-width (spectral band-pass).
Note 4: This Certificate is immediately irrevocably void if the purchaser of this WAV-7 Calibration Standard passes (i.e. resells, etc) the standard to a third party.
Note 5: FFS WAV-7 Wavelength filter is made according to NIST SRM2009 guidelines
Note 6: Powder free gloves must be worn when handling calibration standards

FFS Part No.: WAV-7
Certificate No.: 1334
Test Date: June 1 2015

Fireflysci Inc.
1014 East 21 Street
Brooklyn NY 11210
347-441-4277
www.fireflysci.com



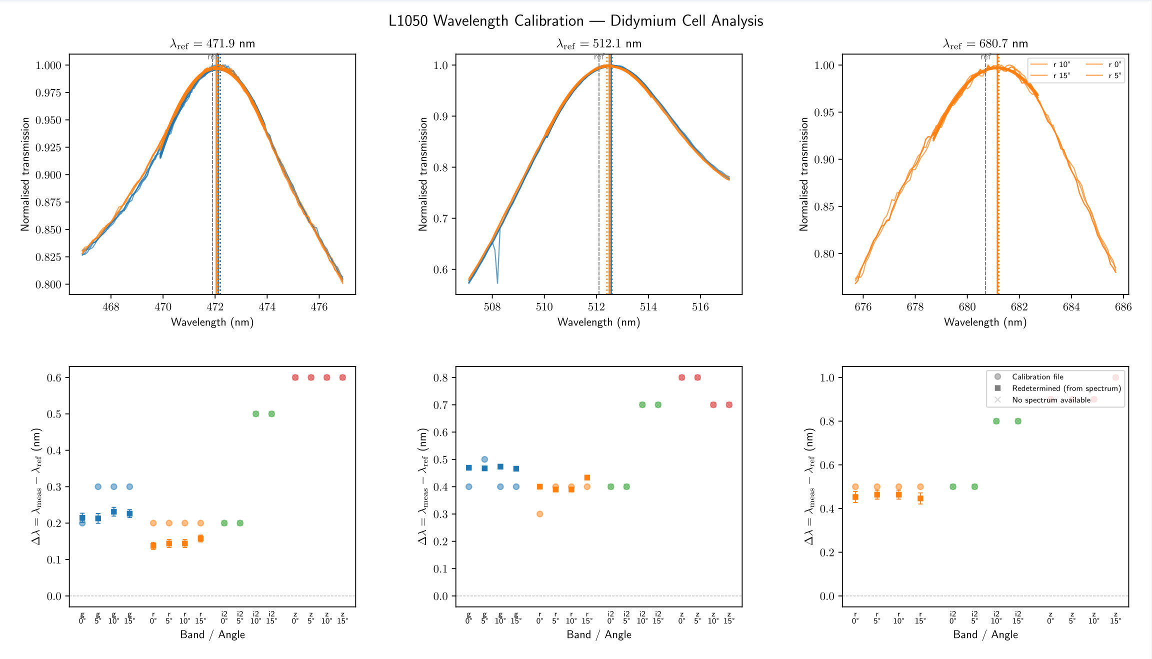
Wavelength calibration

- Didymium cell measured before each of the 4 angle measurements
- 3 absorption lines (471.9, 512.1, 680.7 nm) as wavelength reference

Per-band offsets (LMA file values):

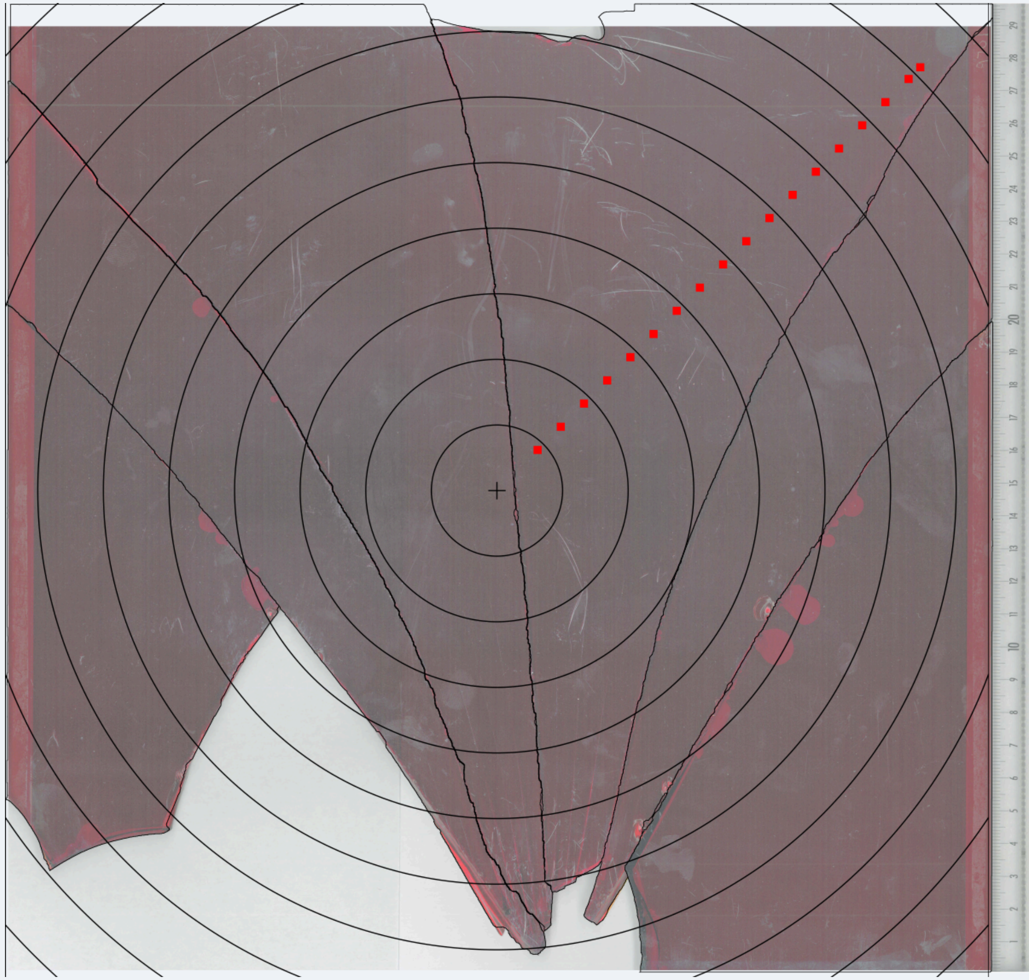
Band	Offset
g	0.358 ± 0.086 nm
r	0.358 ± 0.126 nm
i2	0.517 ± 0.195 nm
z	0.758 ± 0.138 nm

- Offset varies by **0.11 nm rms** → adopted as wavelength calibration uncertainty
- Cross-check (g+r, 24 lines): agrees within 0.015 ± 0.053 nm



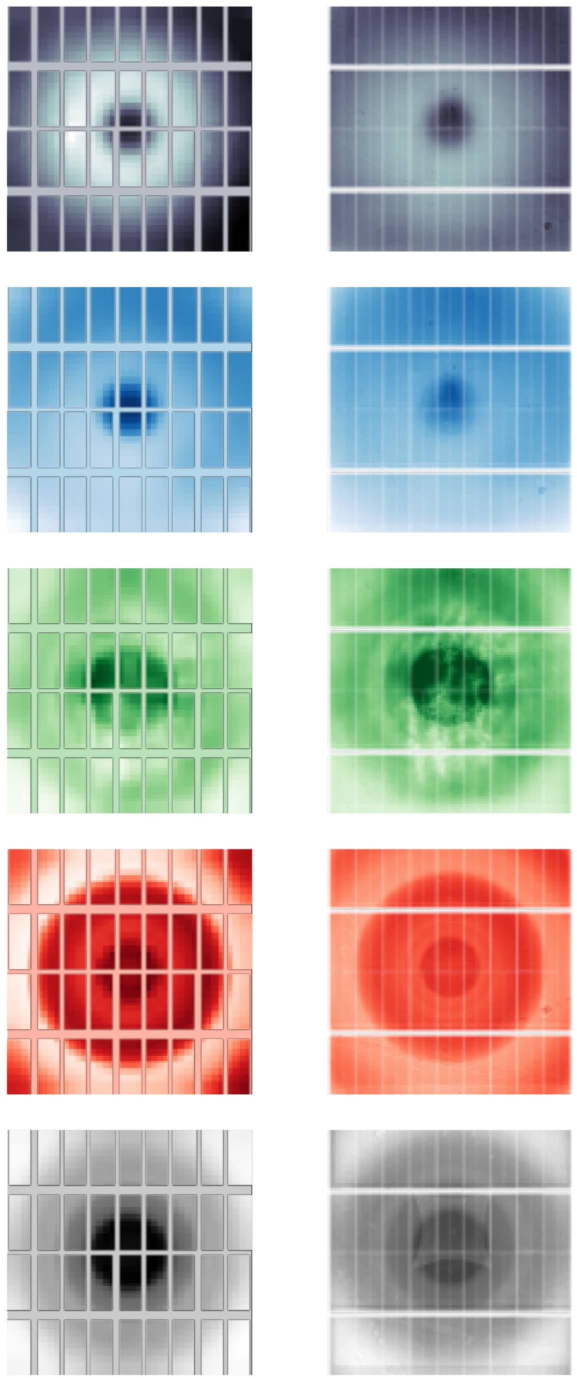
The broken i-band filter

- Original i filter broke in June 2007 $\rightarrow$ replaced by a slightly bluer i_2 in Oct 2007
- Most SNLS light-curves used the original i filter $\rightarrow$ high legacy value
- Pieces reconstituted; measured along a radius on the least altered piece
  - Radial symmetry assumed (consistent with on-sky measurements)
- Wavelength scale set retrospectively: i calibrated to match i_2 stellar measurements
  - Preferred shift: **2.2 nm bluer** (consistent with HR2000 calibration offset)



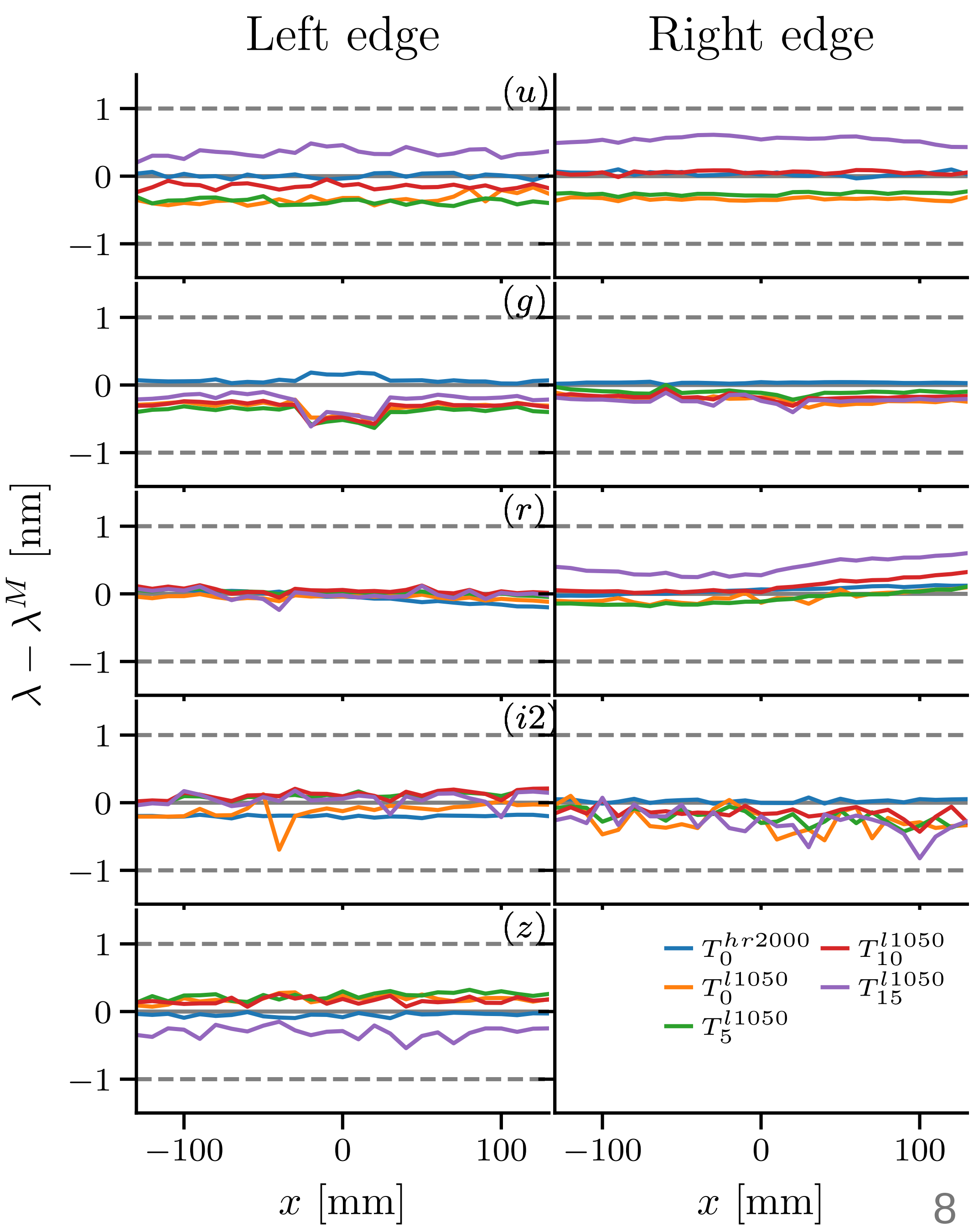
Filter orientation in the focal plane

- Filters are **not** rotationally invariant → orientation matters
- SNDICE2 LED maps of filter fronts confirm the LMA bench measurements
- Orientation resolved by comparing SNDICE2 transmission maps (right column) with LMA edge maps (left column)



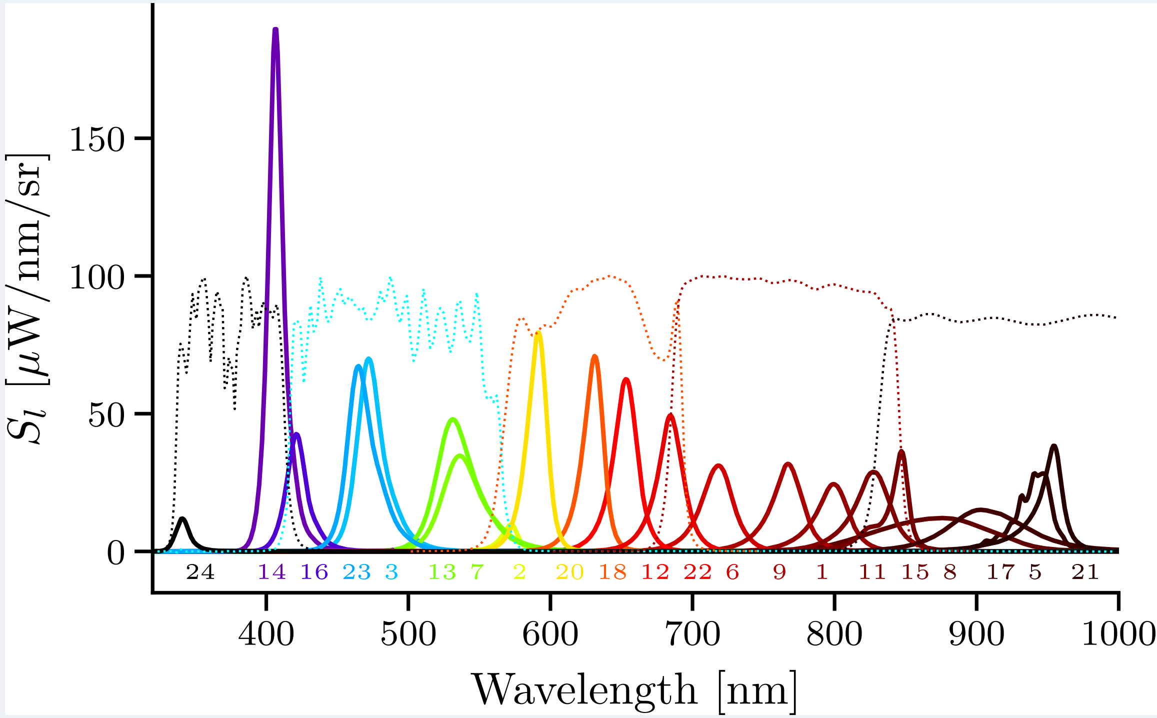
Synthesizing effective passbands

- Filter blueshift:
  $$T_\theta(\lambda) = T_0(\lambda/\sqrt{1-\sin^2\theta/n^2})$$
- Effective index $n(\lambda) = \bar{n} + k_n(\lambda - \lambda_0)$ fitted per filter
- Ghost correction:
  $$T_{\text{obs}} = T/(1 - R(1-T))$$
- Full-pupil numerical integration over $f/3.8$ CFHT beam
- Model agrees with measurements at **< 0.3 nm rms** in mean wavelength



Ingredient 2: In-situ telescope transmission

- SNDICE2: calibrated LED light-source installed at CFHT in Jan 2014
- 23 wavelength channels spanning 340–930 nm
- Projects a $\sim 1^\circ$ cone onto the primary mirror
- Data taken with dome closed, 31 nights
- Each LED spectrum calibrated on-bench (NIST photodiode + monochromator)

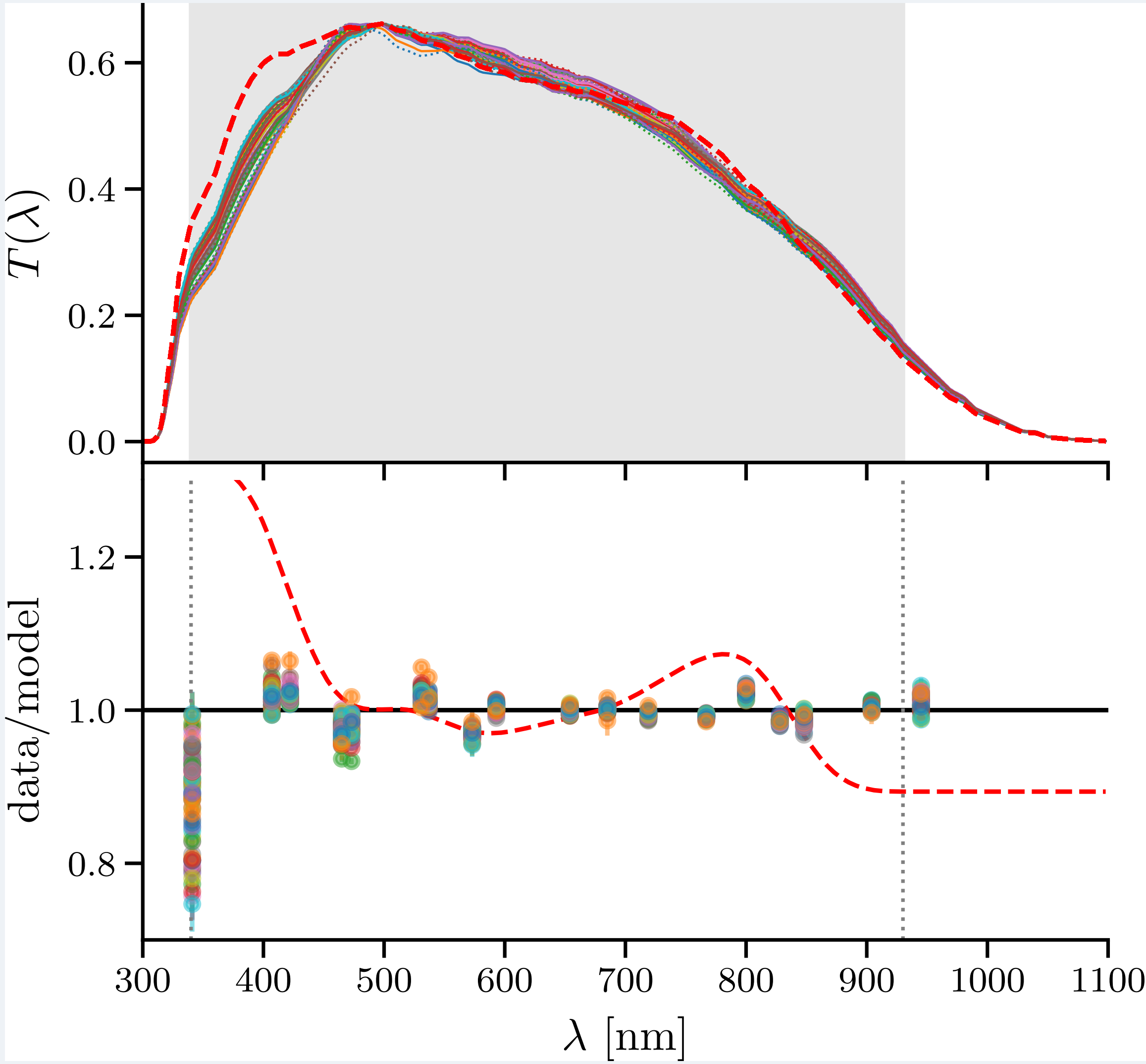


SNDICE2 results

- Fit per-amplifier correction $\kappa_a(\lambda)$ to expected transmission
- 18 usable LEDs, 10-knot cubic B-spline over 340–930 nm

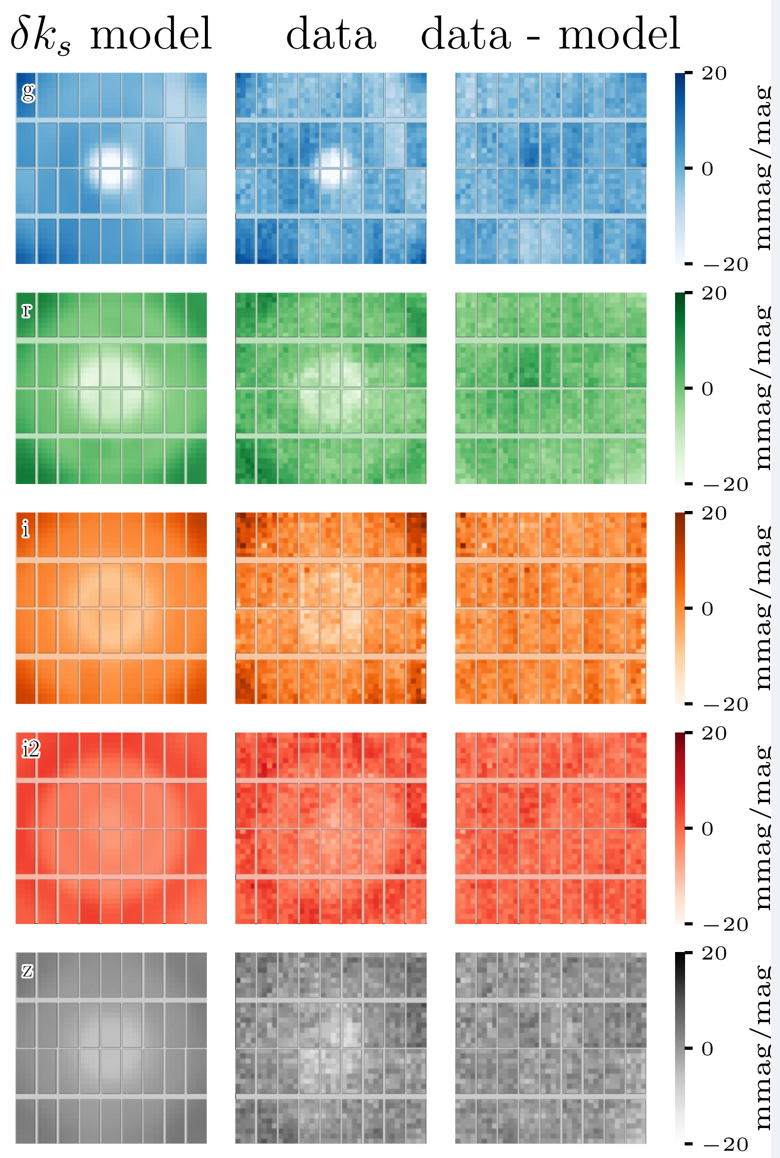
Key findings:

- Transmission at 420 nm: **14% lower** than assumed
- Transmission at 900 nm: **12% higher**
- Chip-to-chip dispersion: 3.7% at 420 nm (0.7% within a CCD)
- Residual systematics: ~ 0.6 nm rms (gri), 1.2 nm (z)



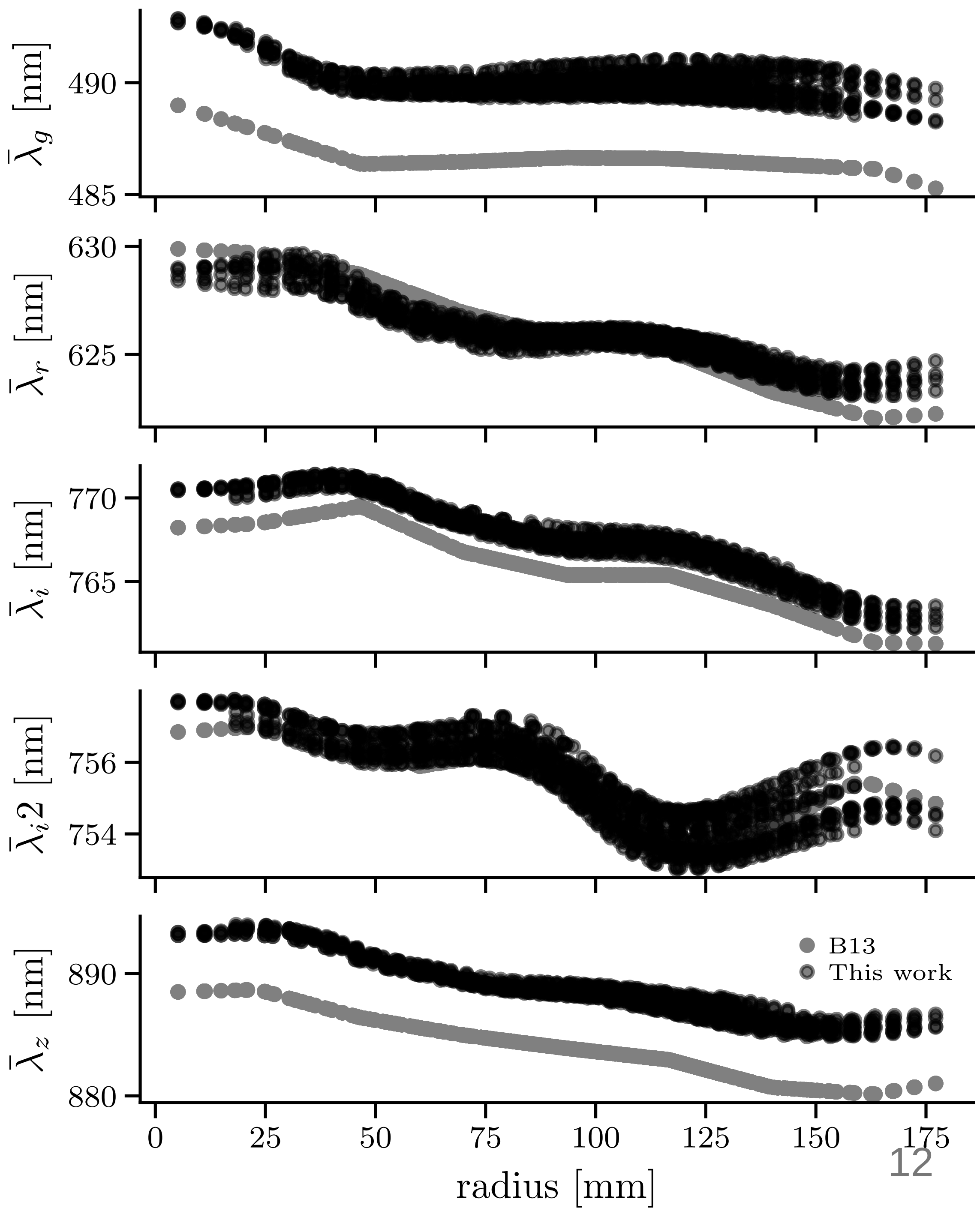
Consistency checks on stellar fields

- Predicted color terms vs measured on dense stellar fields
- RMS residuals at chip level: $2.6, 2.0, 1.7, 1.0, 1.2$ mmag/mag in gri_2z
- The new model solves the r-band inconsistencies that triggered the LMA campaign



Changes in the photometric system

- Old model assumed rotational symmetry (manufacturer's witness samples)
- New model reveals large 2D variations: g and z passbands shift by **up to 5 nm**
- The manufacturer curves were from witness samples, not the actual filters



Ingredient 3: Direct observations of CALSPEC standards

- 6 CALSPEC primary standards observed at CFHT over 2011–2015
- From 3–5 epochs (B13) to **~50 epochs per band**
- Aperture correction modeled as 2D polynomial across each sensor
- Same pipeline applied to standards, deep fields, and dense stellar fields

Fields	Stars	Dataset
6 CALSPEC fields	P330E, GD153, GD71, HZ4, HZ21, AGK81d266	~13000 images

Ingredient 4: Mapping the photometric response on dense stellar fields

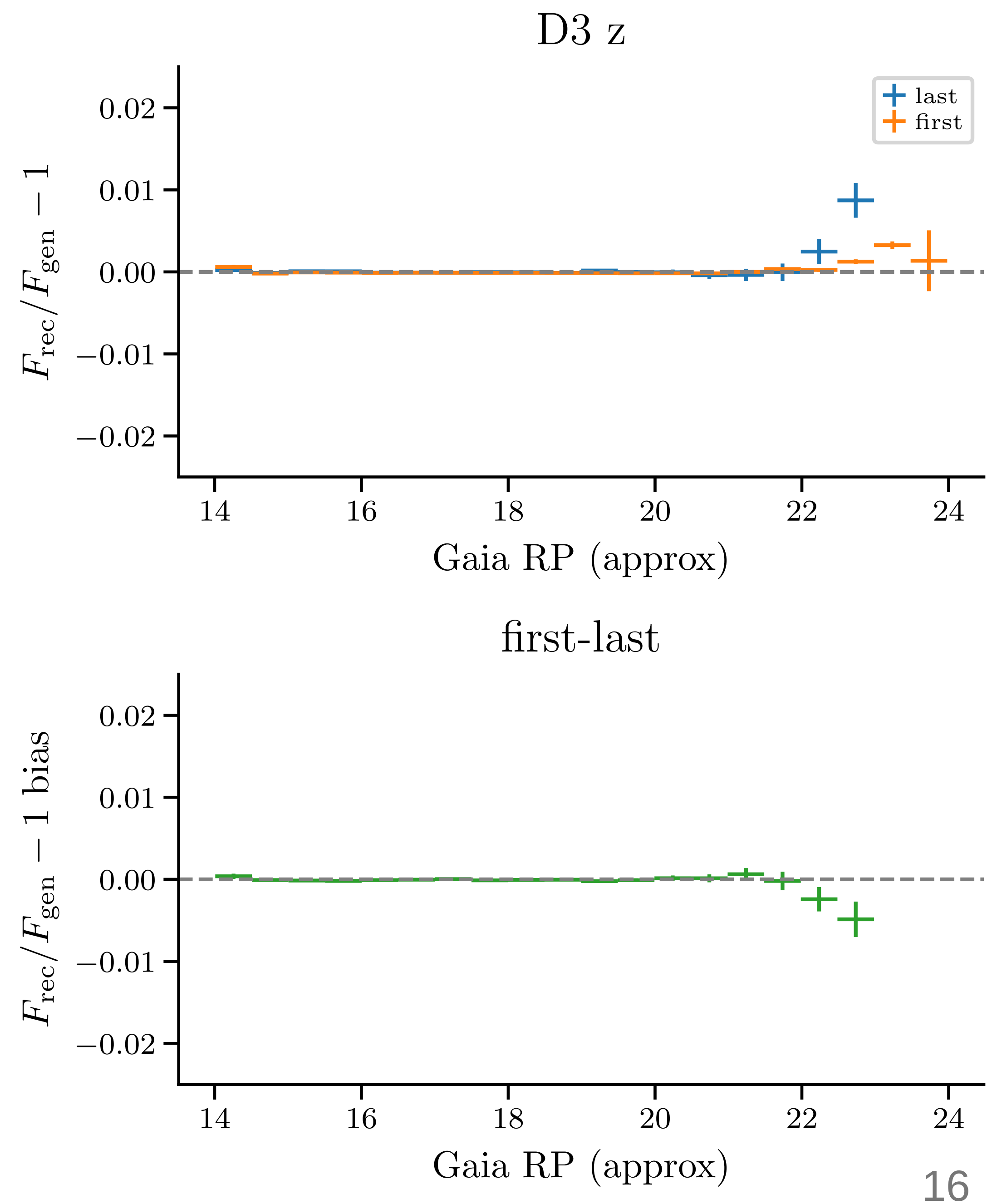
- Dithered sequences of Photo Grid and Photo Grid 2 observed **~twice a year** since 2003
- Model: $m_{s,x} = m_s + \delta(x) + C_x \cdot (BP - RP)$
  - $\delta(x)$: focal plane map of the photometric response (starflat)
  - C_x: local color transformation (predicted from passband model or fitted)
- Fitted separately per band and epoch → **88 independent determinations** across gri_2z
- Master maps produced for two periods: pre- and post-2007.5 (coincident with i-filter break)
- Already present in B13, but now **~twice more epochs** and a better passband model

Forced photometry and flux averaging

- Build average catalog of positions from all epochs, then **forced aperture photometry** at predicted positions
  - Circumvents selection bias — key improvement over B13
- Correct fluxes with the response map: $\phi_{s,t} = 10^{0.4\,\delta(x)} \times \phi^{\mathrm{raw}}_{s,x,t}$, then fit $\phi_{s,t} = \alpha_t \phi_s + n_{s,t}$
  - Noise model: $\sigma_b^2 + f^2\phi^2 + \phi/G$ ($f = 0.003$ mag floor, $G \sim 1.6$ e$^-$/ADU)
- Reject outliers: flag $p < 0.01$, drop exposures/stars with $> 20\%$ flagged
- **Deep fields split in two periods:**
  - Pre-2007.5: before i-filter break, no CALSPEC observations
  - Post-2007.5: very stable instrument, all CALSPEC standards
- Output: uncalibrated natural magnitudes $m_{s,f}$ per field/epoch

Linearity validation with MC simulations

- Inject synthetic perturbations into real forced-photometry catalogs
- Verify `averagephot` pipeline recovers input model without bias
- No significant bias in first or last epoch of field D3 (z-band)



Ingredient 5: Gaia DR3 as intermediary

- Previous calibration required **concomitant** observations of deep fields and standards
  - Atmospheric variations, different airmass & exposure → aperture corrections
- Gaia DR3 XP spectrophotometry breaks this degeneracy:
  - Compute synthetic MegaCam magnitudes from Gaia XP spectra for **all stars**
  - Determine relative field-to-field zero points from Gaia
  - Absolute scale set **exclusively by CALSPEC** (marginalizing over Gaia systematics)

The calibration model

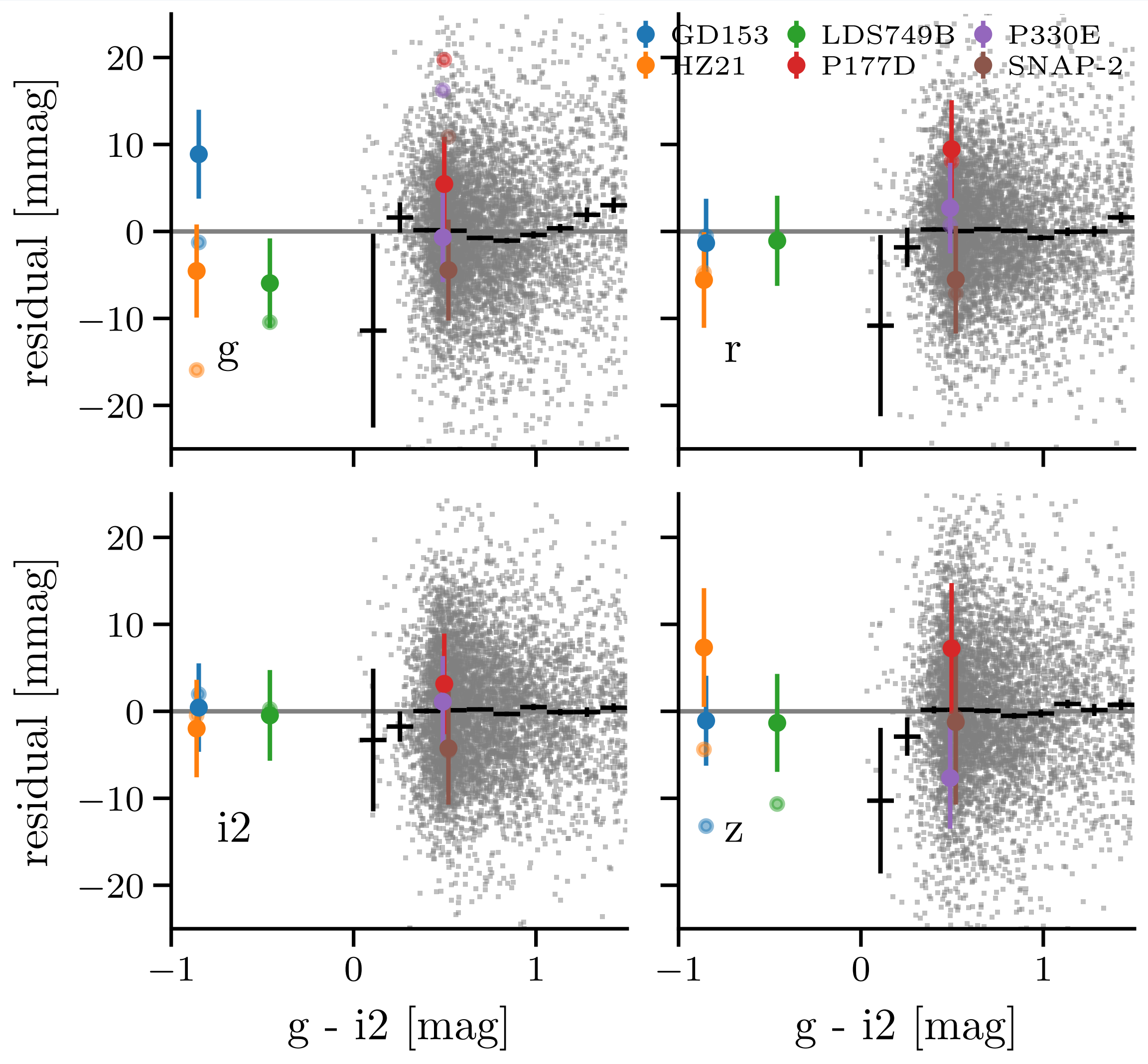
$$\tilde{m}_s - m_s = Z_f + \alpha(\tilde{g} - \tilde{i}_2) + f^{NL}(\tilde{m})$$

Term	Role
Z_f	Field zero point (target: 2.5 mmag precision)
α	Color term between Gaia and MegaCam
f^{NL}	Non-linearity correction (B-spline, 3 knots)
$\tilde{m}_s$	Synthetic magnitude from Gaia XP or CALSPEC

CALSPEC standards pin the absolute AB scale: $\tilde{m}_s^{\mathrm{calspec}} = m_s + Z_f$

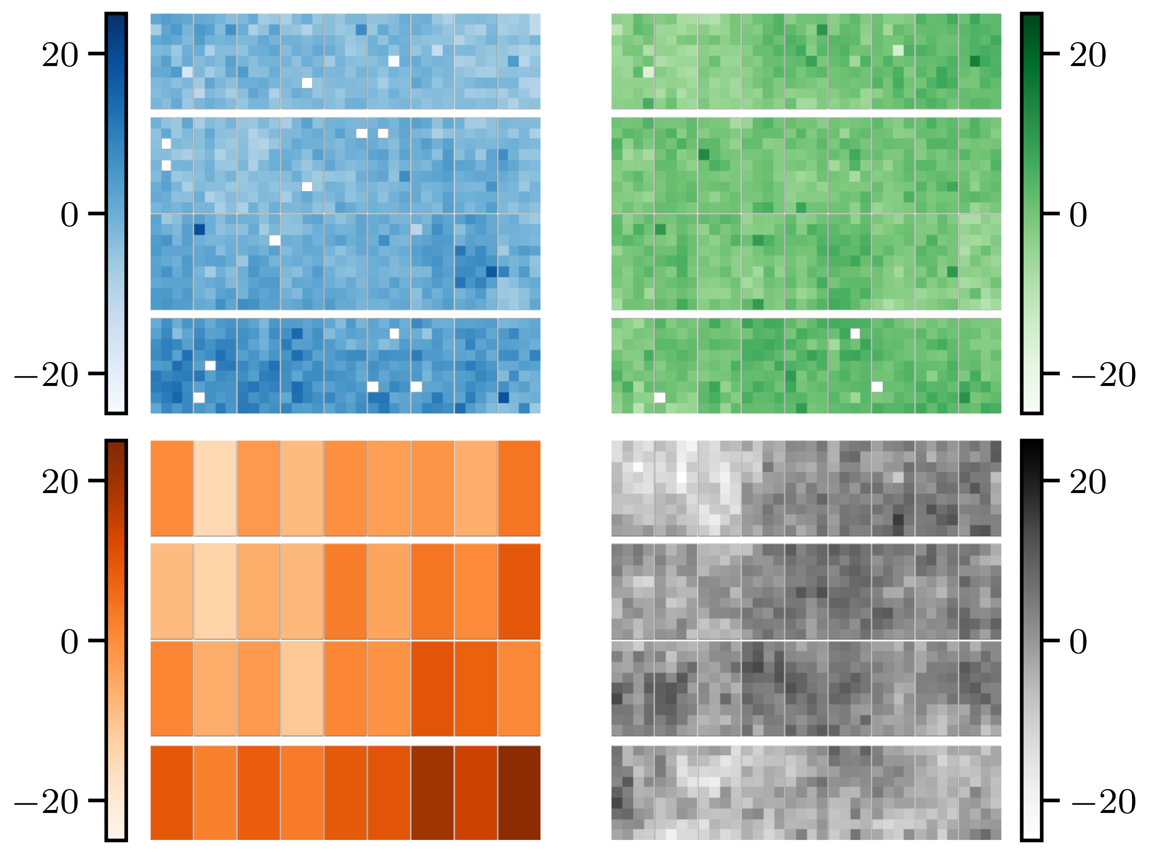
Calibration results

- **Statistical precision:** ~ 2.5 mmag per field
- **Systematic (non-uniformity):** ~ 3 mmag (dominant)
- **Filter systematics:** 0.5–1.3 mmag
- **Total uncertainty:** < 5 mmag in all bands



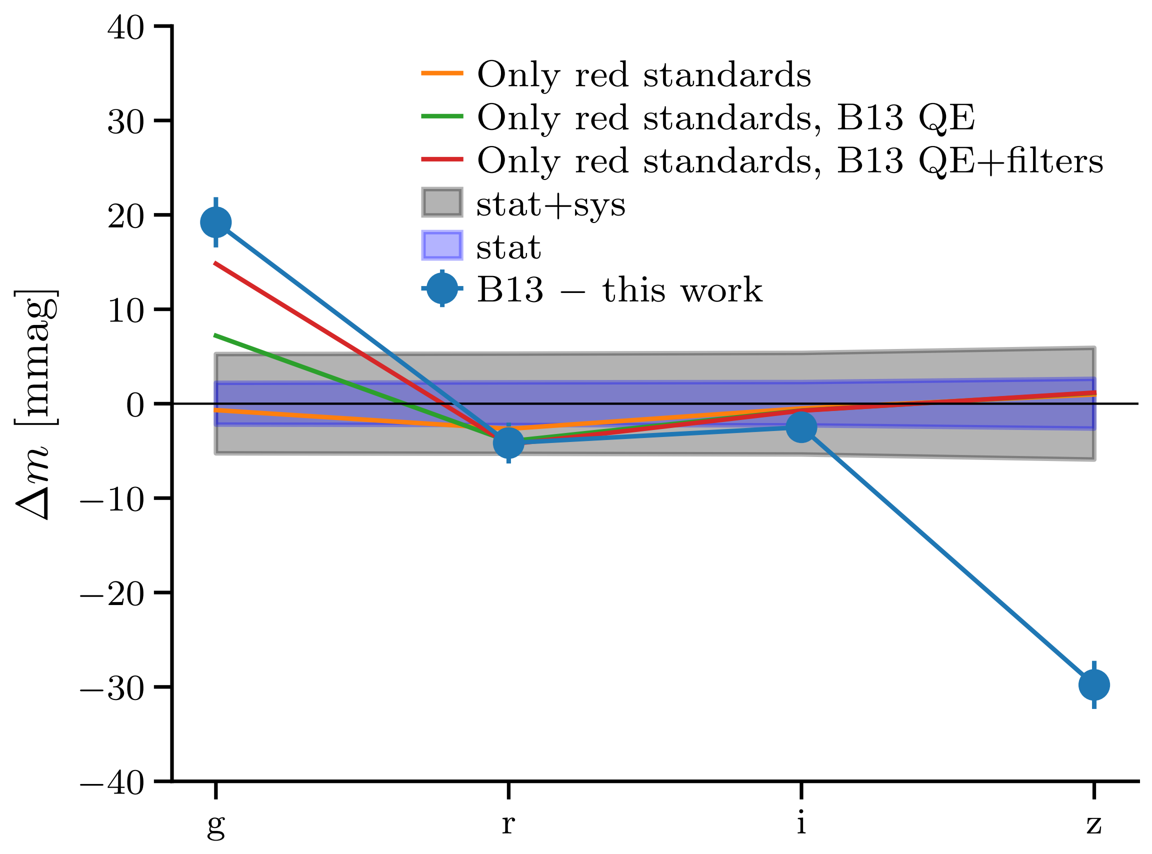
Internal consistency

- Survey split at the i-filter breaking (2007.5) → two independent calibration epochs
- Residual non-uniformities: $3.6, 2.0, 8.5, 4.5$ mmag CCD-to-CCD rms in $griz$
- Adopt **3 mmag** systematic from non-uniformity (post-2007.5)



Changes with respect to B13

- Largest revisions in g (~ 20 mmag bluer) and z (~ 30 mmag redder)
- Driven by: new filter measurements + SNDICE open transmission
- B13 z-band uncertainty underestimated by factor ~ 4

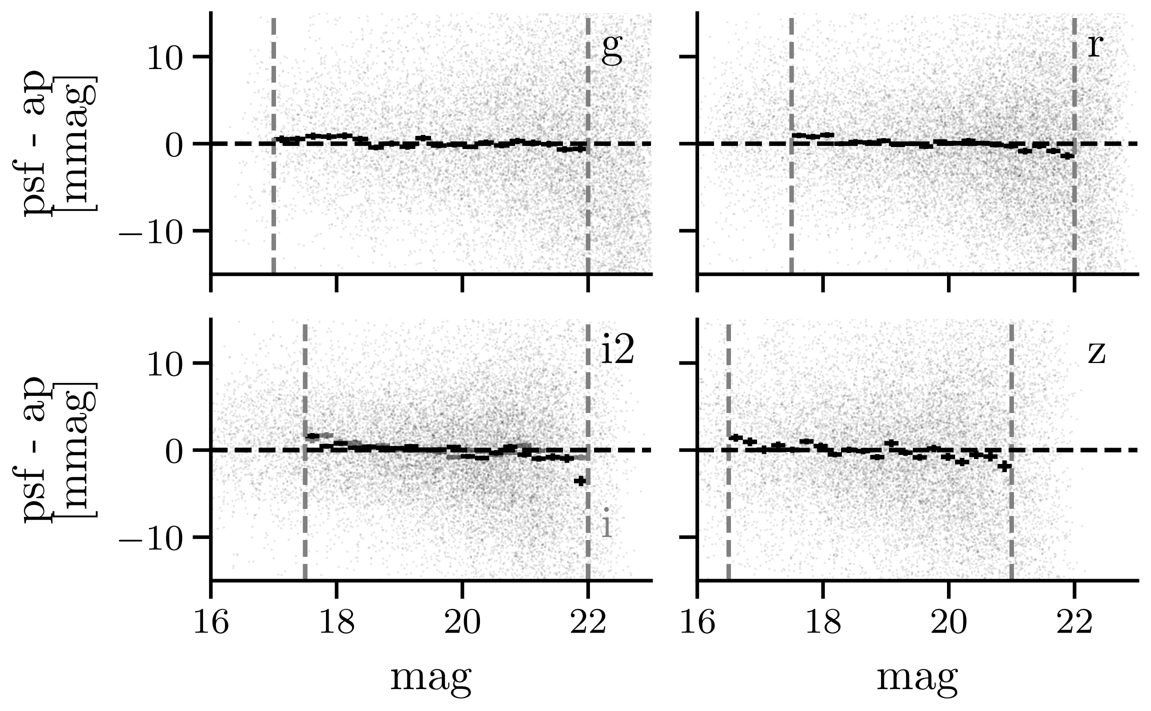


From stars to supernovae

- Scene-modeling photometry (SMP) applied to SNe **and** field stars
- Anchor SMP magnitudes to aperture catalogs

$$m_{\mathrm{psf}} = m_{\mathrm{ap}} + Z_{\mathrm{ccd}} + \alpha_b(g_{\mathrm{ap}} - i_{\mathrm{ap}}) + \gamma B$$

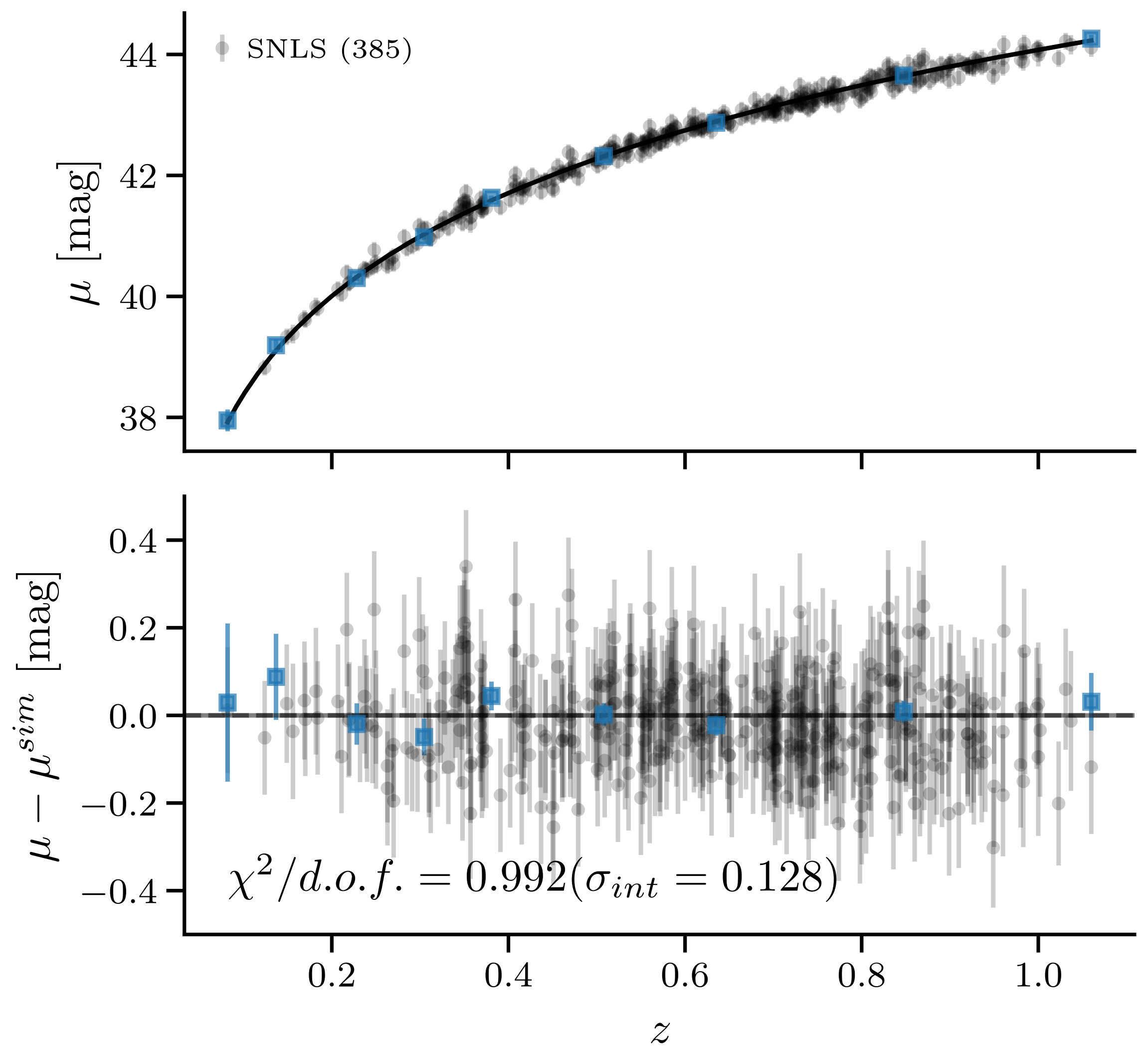
Term	Role
Z_{ccd}	Zero point per (field, CCD)
α_b	Chromaticity of PSF photometry
γB	Background contamination correction



The SNLS Hubble diagram

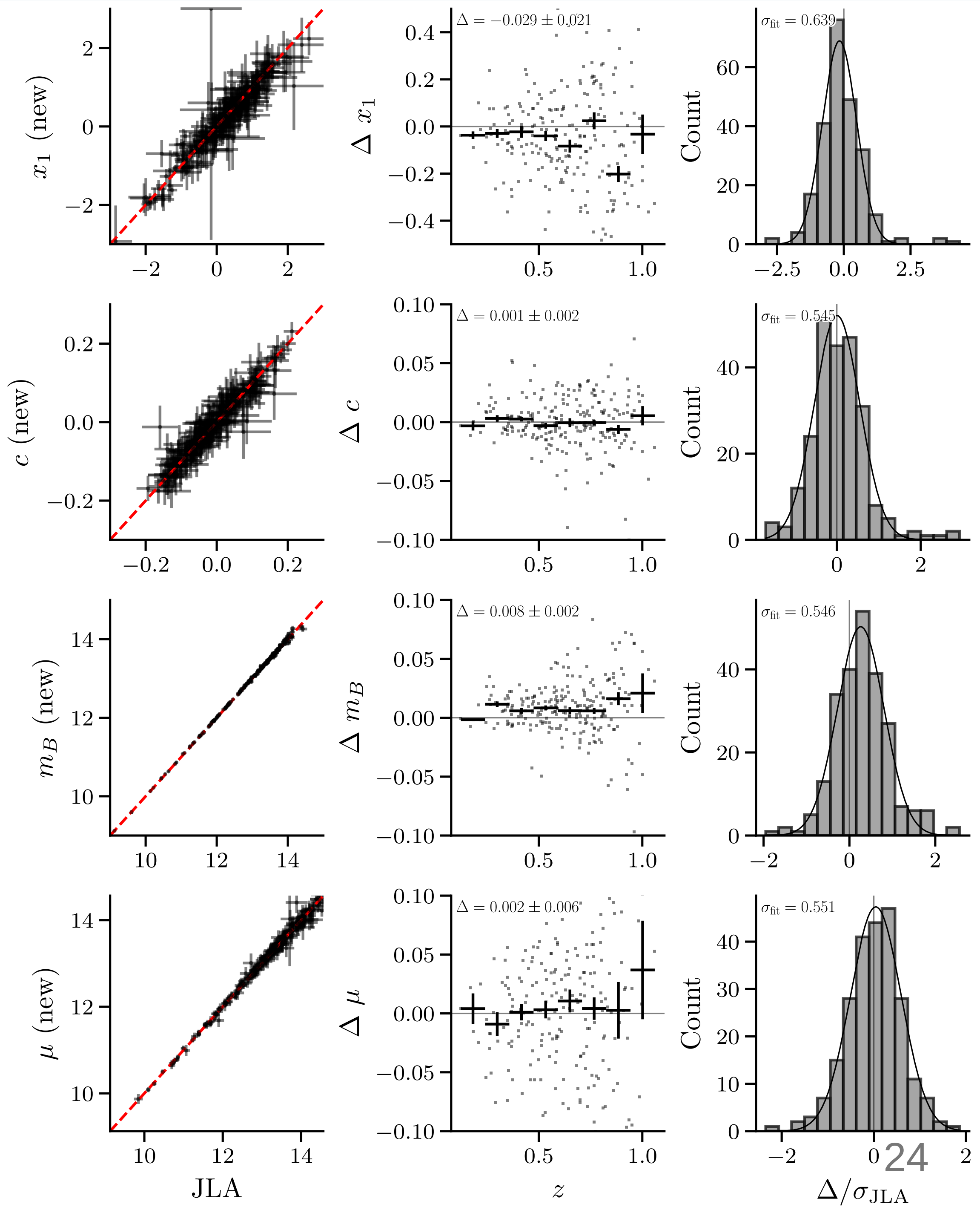
- **385 SNe Ia** pass quality cuts (Table 5 in paper)
- Intrinsic dispersion: $\sigma_{\text{int}} = 0.128 \pm 0.010$ mag
- No outliers at 3.5σ
- Sample covers $0.1 < z < 1.0$

Cut	Surviving
Successful SALT3 fit	422
χ^2, parameter-error & $\lvert c \rvert < 3$ cuts	—
All cuts	**385 (91%)**



Comparison with the JLA release

- 239 SNe in common with JLA
- Parameter shifts: $0.5\,\sigma_{\rm stat}$ (m_b, c), $0.6\,\sigma_{\rm stat}$ (x_1)
- Average distance modulus change: 0.008 ± 0.005 mag — **fortuitously small**
  - Partial cancellation: B13 relied on red standards with colors close to SN colors
  - But B13 z-band uncertainties were underestimated by $4\times$



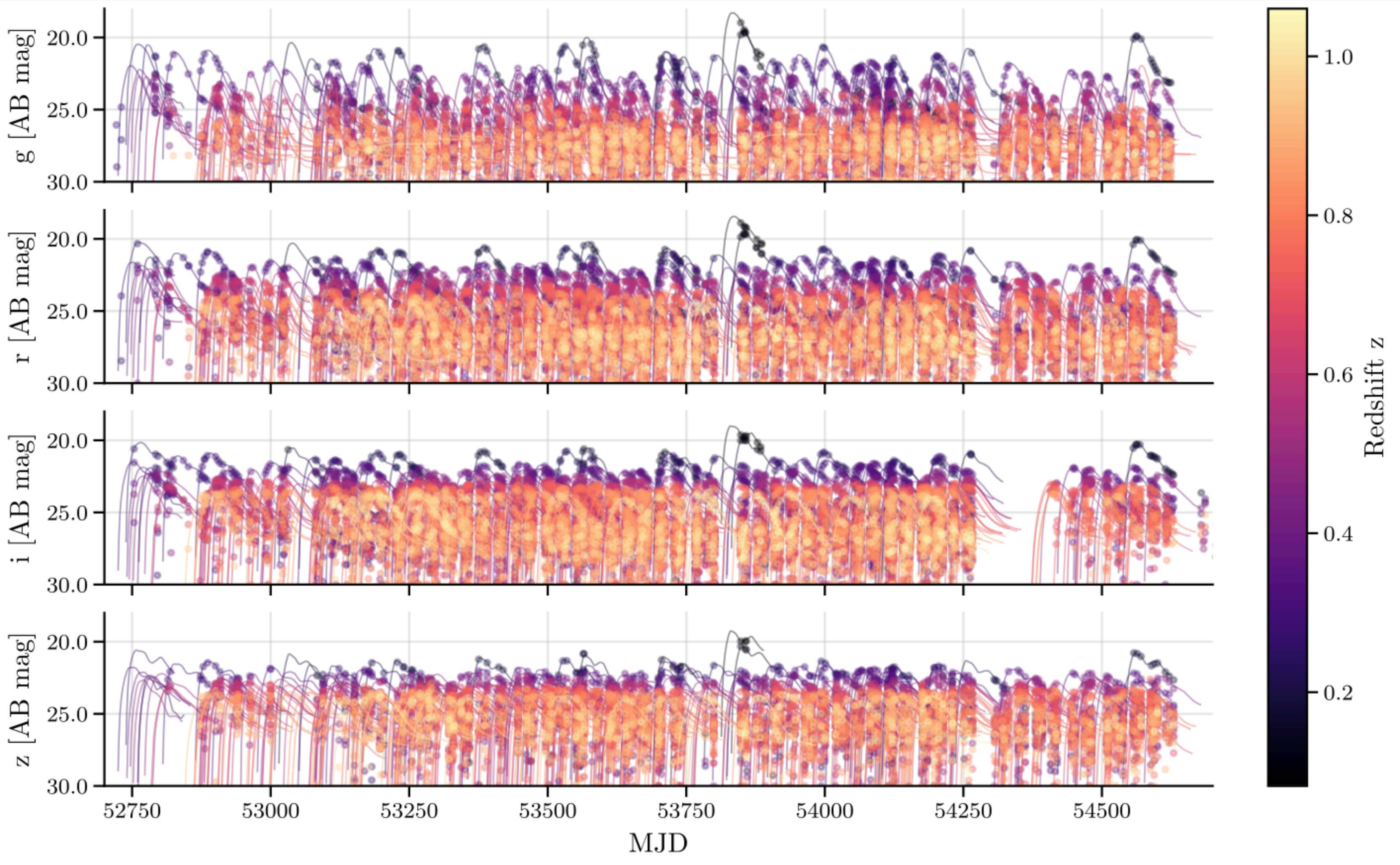
Conclusions

- **New passband model** for MegaPrime: sub-nm accuracy from LMA filter measurements + SNDICE in-situ transmission
- **Direct CALSPEC calibration** with ~50 epochs per band
- **Gaia DR3 uniformity anchor** tying deep and calibration fields to a common system
- **Calibration uncertainty < 5 mmag** in all bands (w.r.t. CALSPEC)
- **422 SNe Ia** released (385 passing quality cuts), 140 never published before
- Designed for the **Lemaitre compilation** — with ZTF low-z and HSC very high-z

Data products: gitlab.in2p3.fr/lemaitre/calib_snls

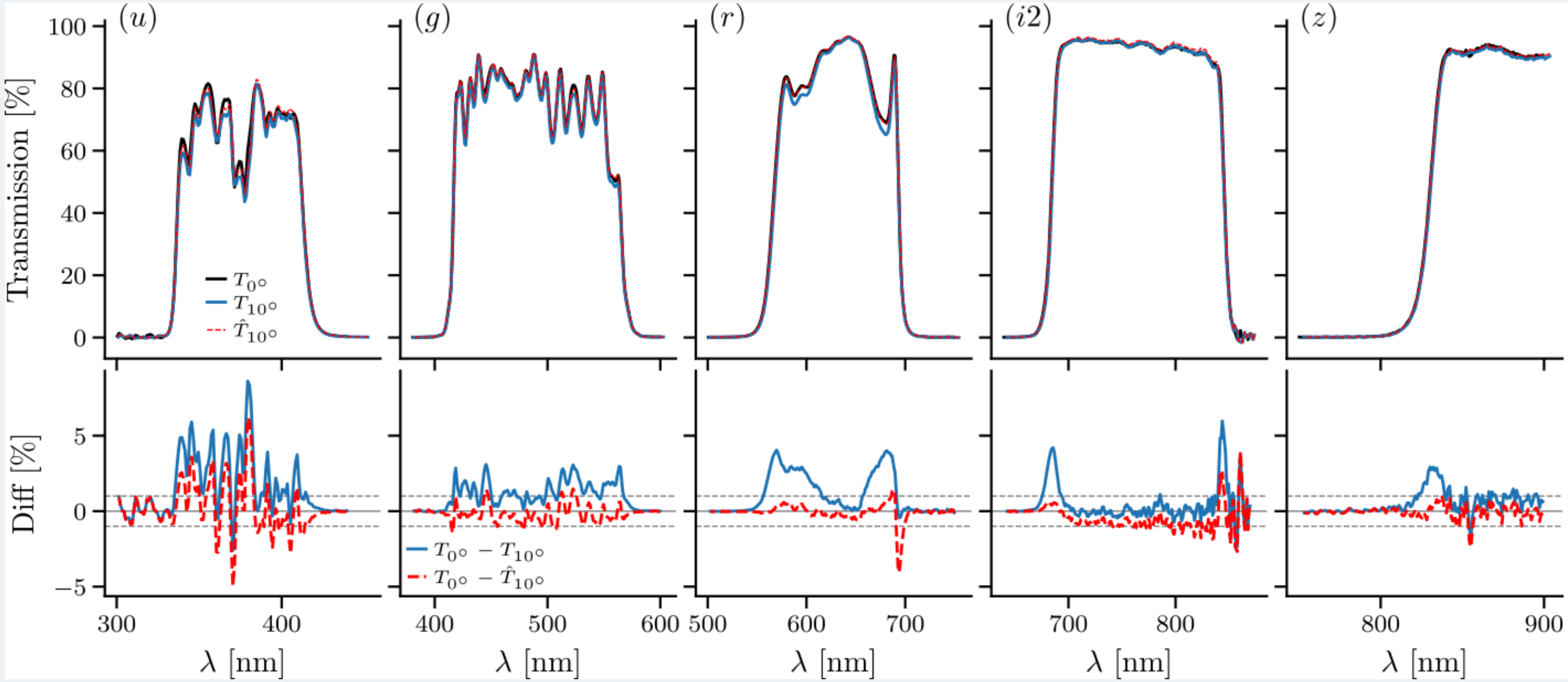
Backup: light-curve gallery

- 422 SNe Ia with successful SALT3 fits
- Multiband calibrated light-curves and best-fit models
- 3 spectroscopically identified SNe excluded for very low SNR



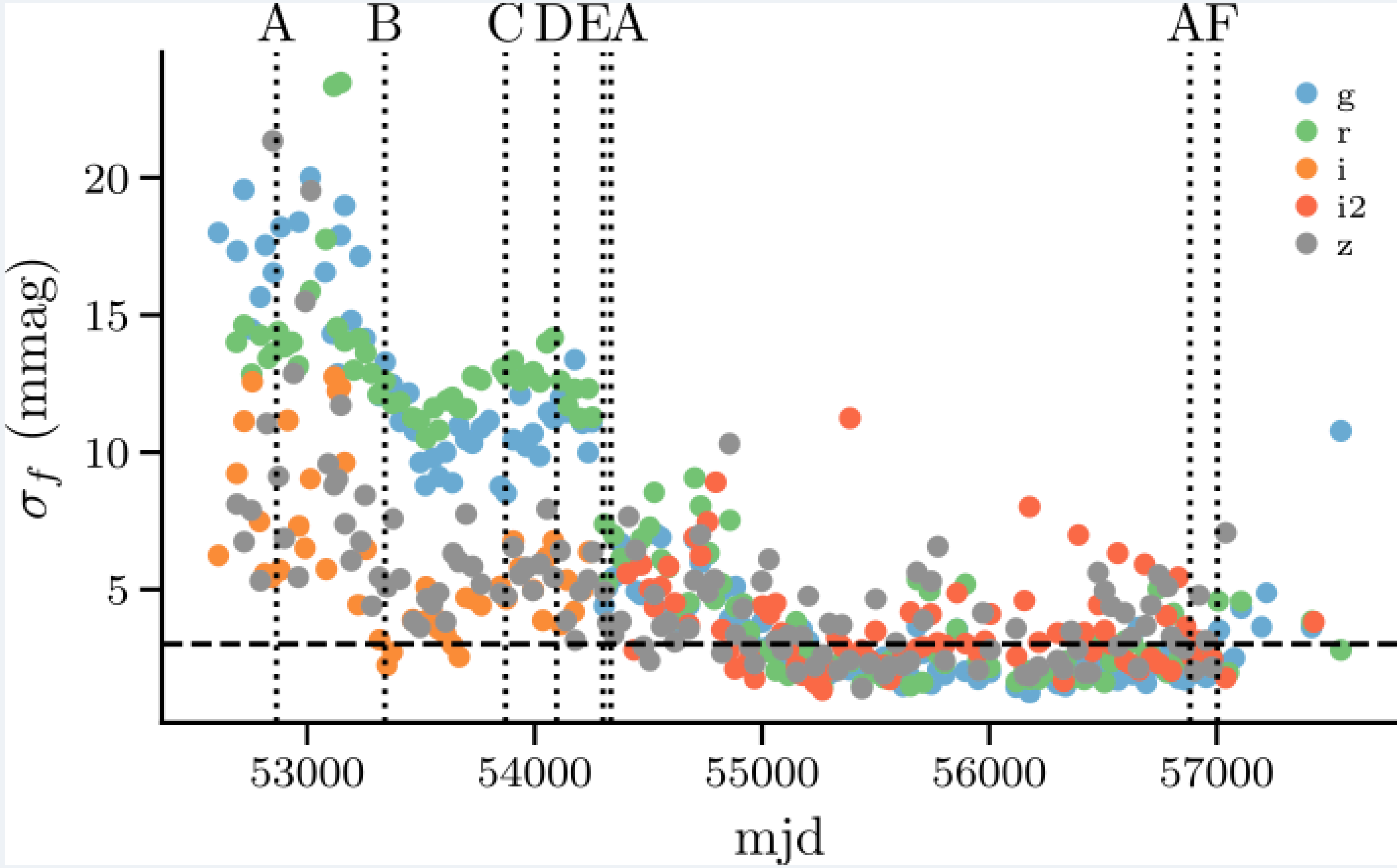
Backup: reflection boost correction

- Transmission measured at 10° incidence is blueshifted
- Residual corrected with a two-surface reflection model
- Separate reflectivity coefficients for fast and slow setups



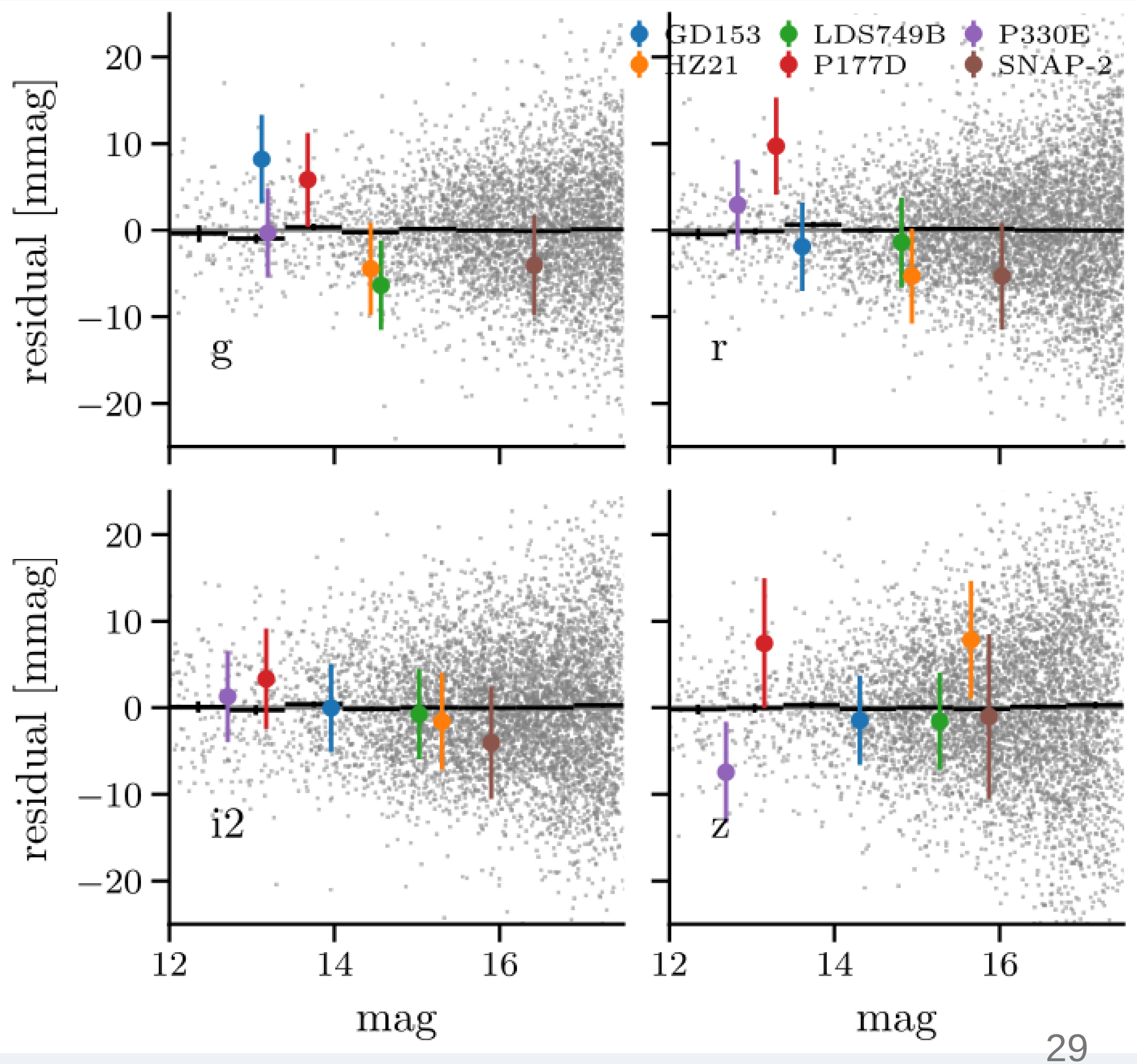
Backup: master flat-field stability

- RMS of per-run flats relative to the super-master flat
- Baseline: 3 mmag rms
- Marked events: recoating, lens flips, cleaning, filter break, coating degradation



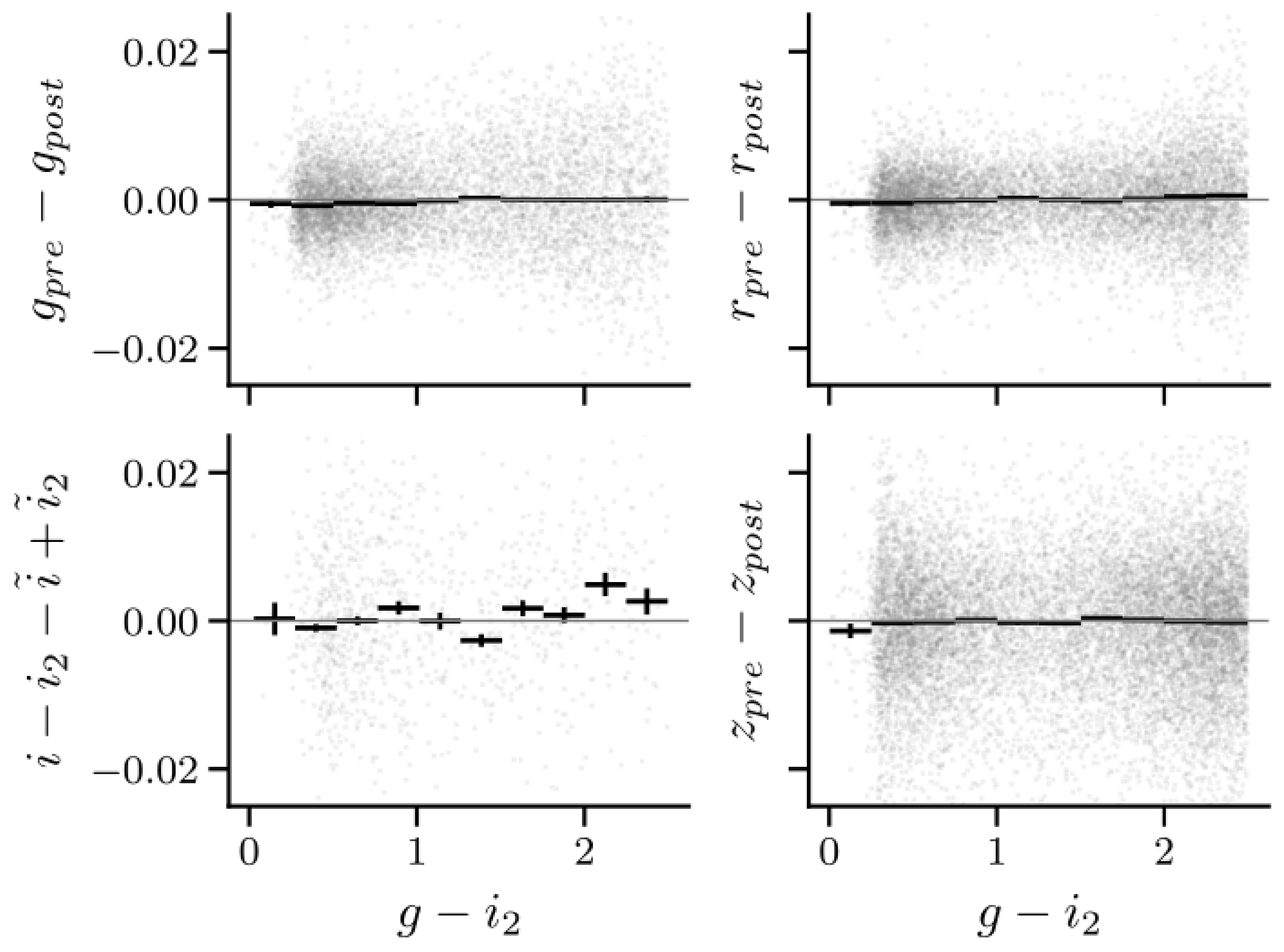
Backup: calibration residuals vs magnitude

- Residuals to the joint calibration fit in each band
- Checks for magnitude-dependent systematics
- Used to validate the exposure-time and non-linearity treatment



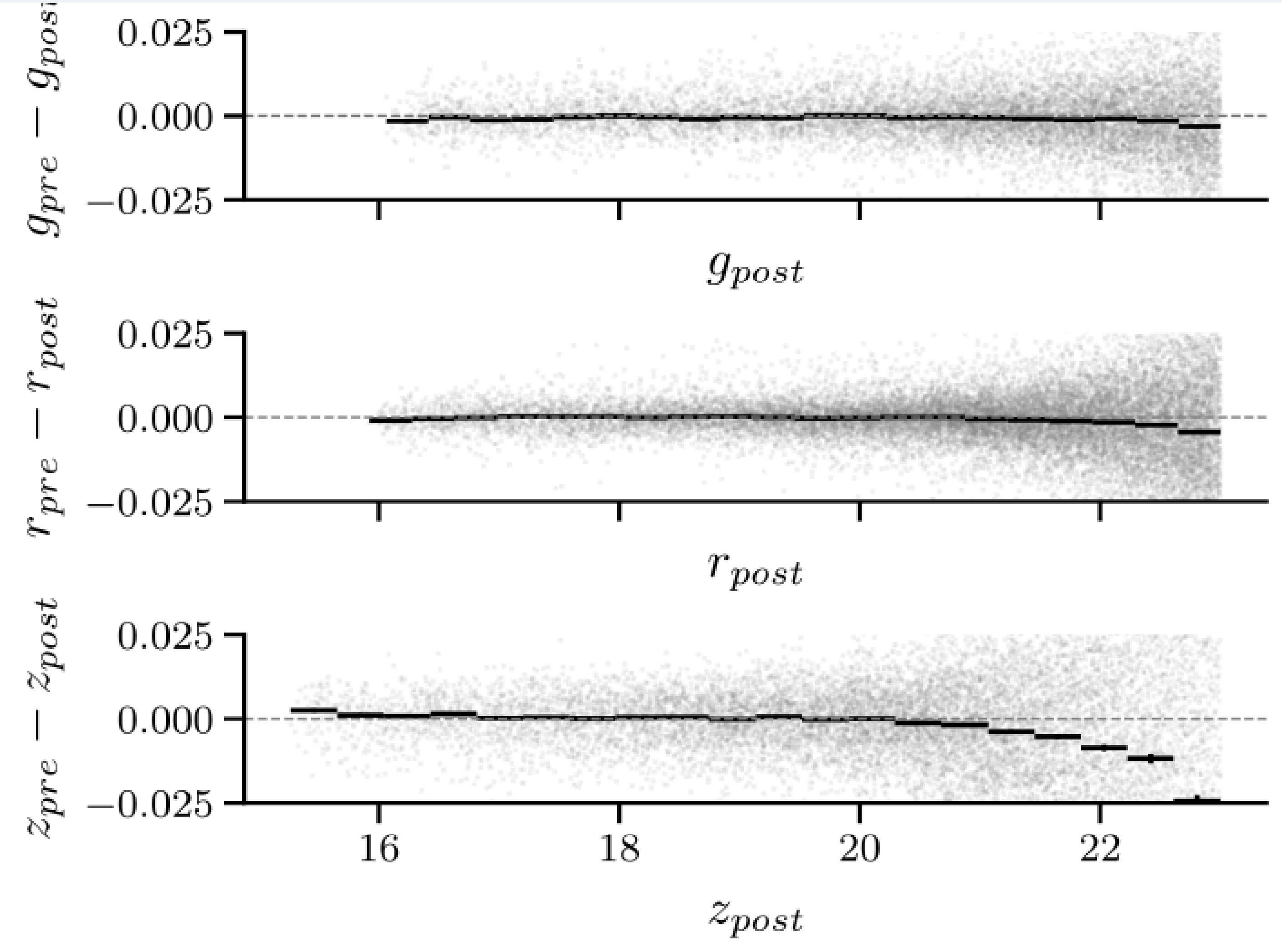
Backup: pre/post 2007.5 color terms

- Difference between pre- and post-2007.5 average magnitudes
- Compared as a function of color
- For i band, filter-change effect is subtracted



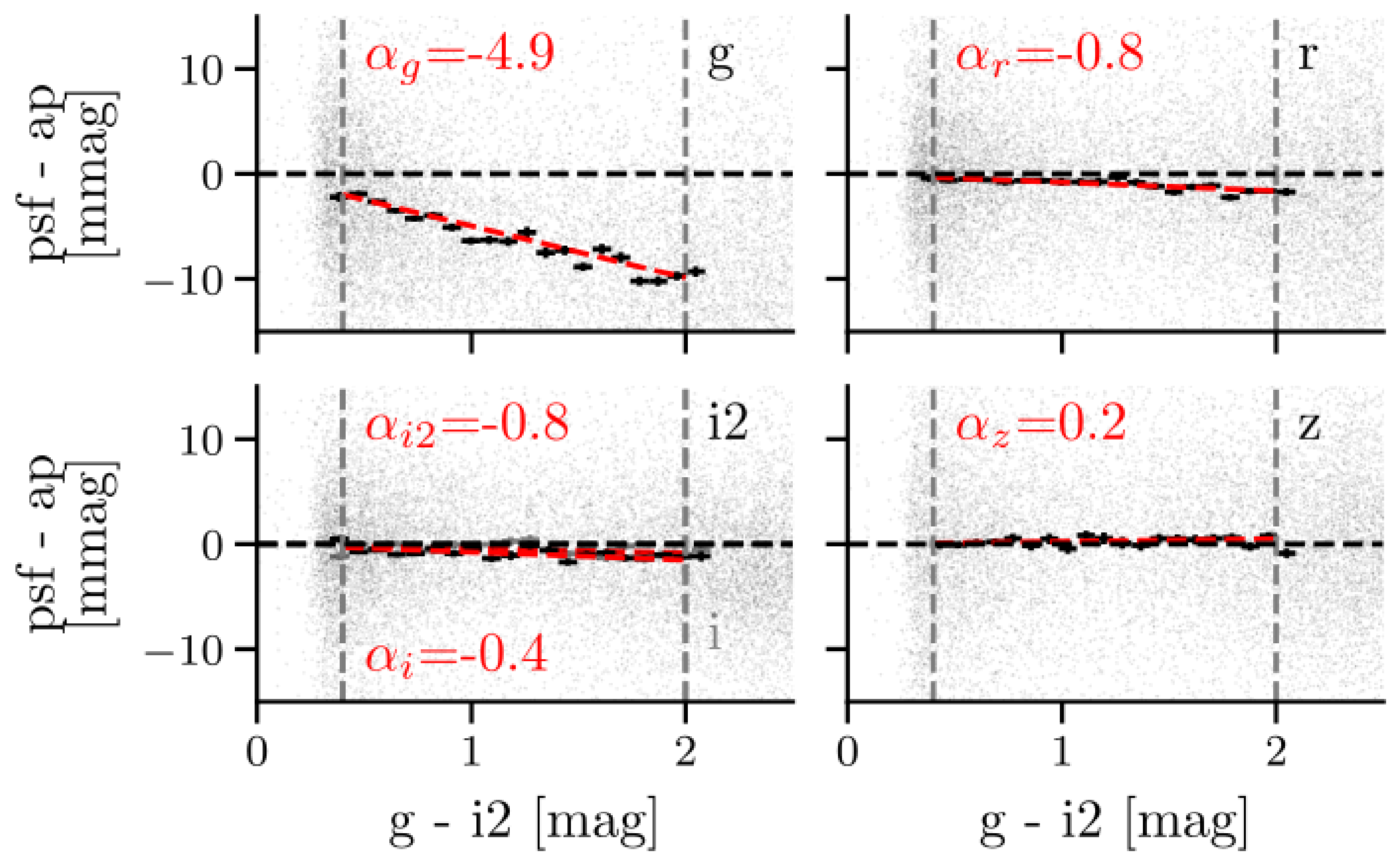
Backup: pre/post flux ratio

- Flux ratio between pre- and post-2007.5 catalogs
- Post-2007.5 data dominated by shorter 120 s exposures
- Probes flux-dependent calibration differences



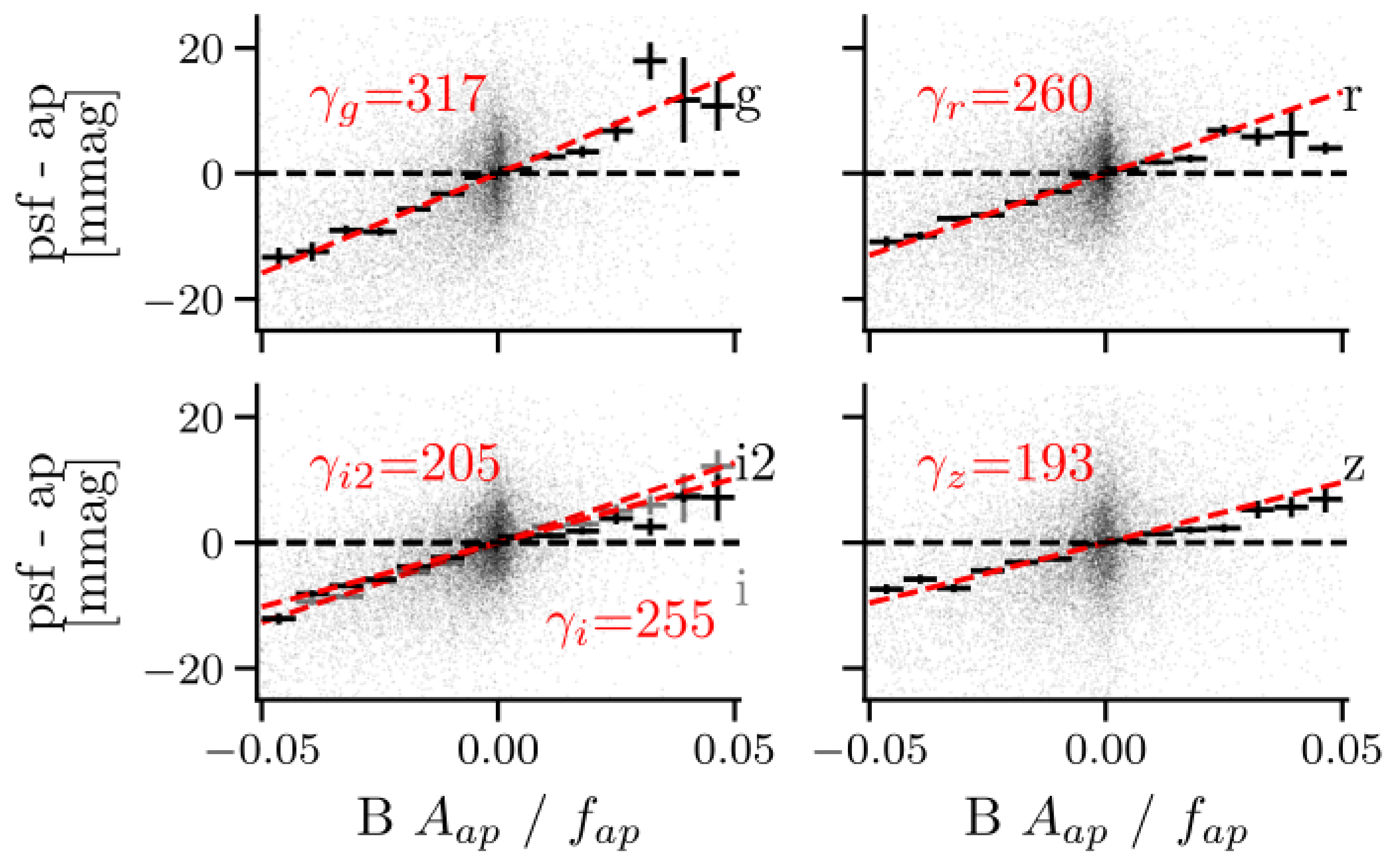
Backup: aperture vs PSF photometry, color

- Scene-modeling photometry compared with aperture photometry
- Dashed grey lines show the stellar color range used in the fit
- Checks color-dependent aperture corrections



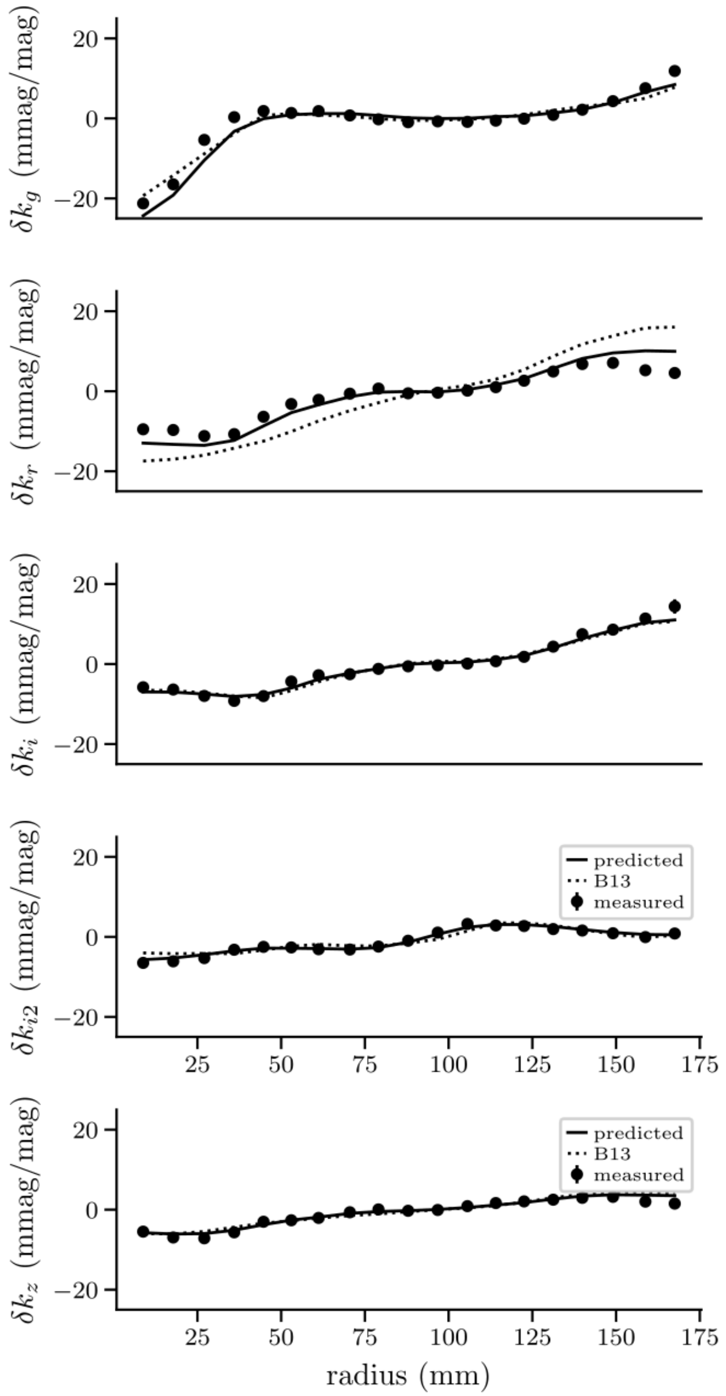
Backup: aperture vs PSF photometry, sky level

- Scene-modeling photometry compared with aperture photometry
- Plotted against local sky-level estimate
- Checks sky-subtraction dependence



Backup: radial color terms

- Center-to-edge stellar color differences on the MegaPrime focal plane
- Update of Figure 7 in B13
- Points: on-sky measurements; curves: model and previous transmission curves



Backup: HZ21 spectrum extrapolation

- Original HZ21 spectrum and extrapolated version used in the analysis
- Extrapolation covers the red end of the z filter
- Grey line shows the z-filter transmission curve