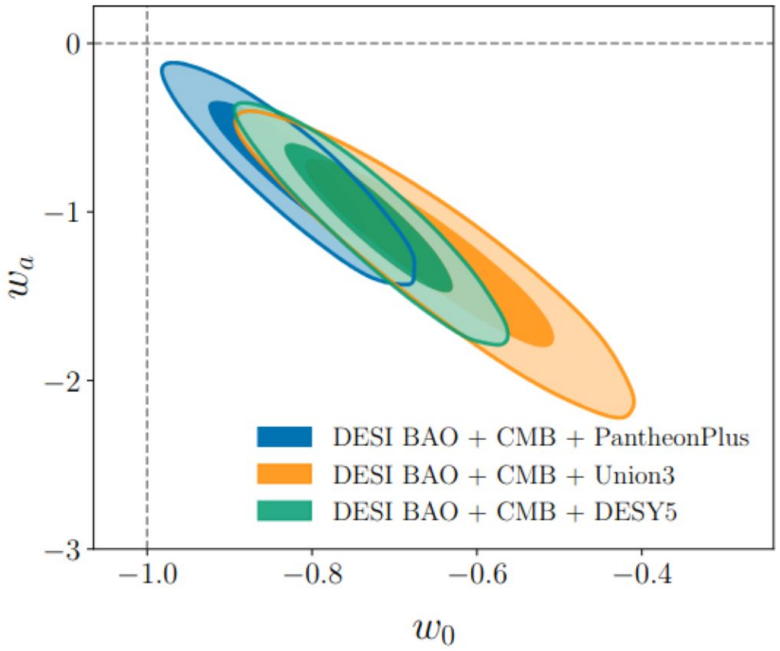
Testing Dark Energy with Type Ia Supernovae

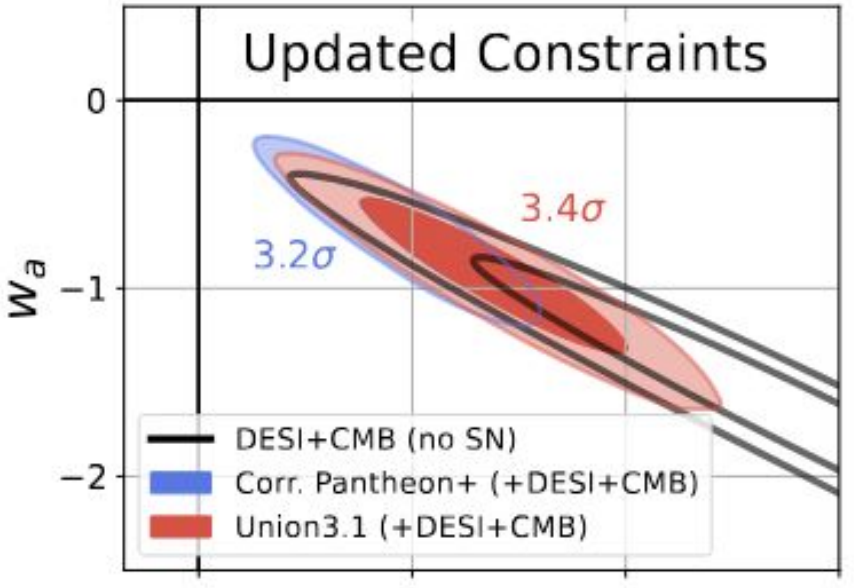
N. Regnault

LPNHE
PARIS

Context

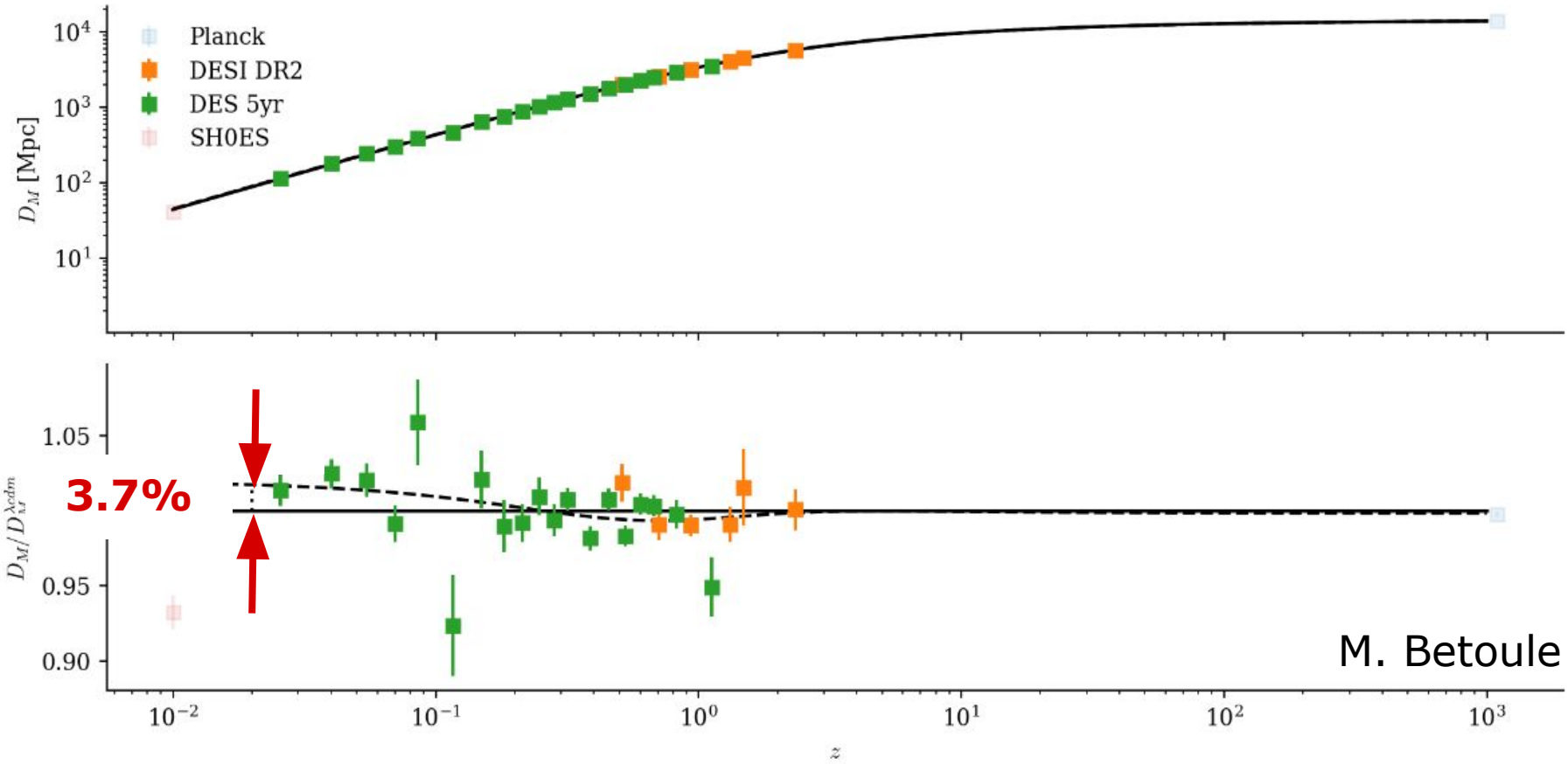


DESI DR2, 03/2025



(Union3.1, Hoyt et al, 2025)
See also: (DES-dovekie, Popovic et al, 2025)

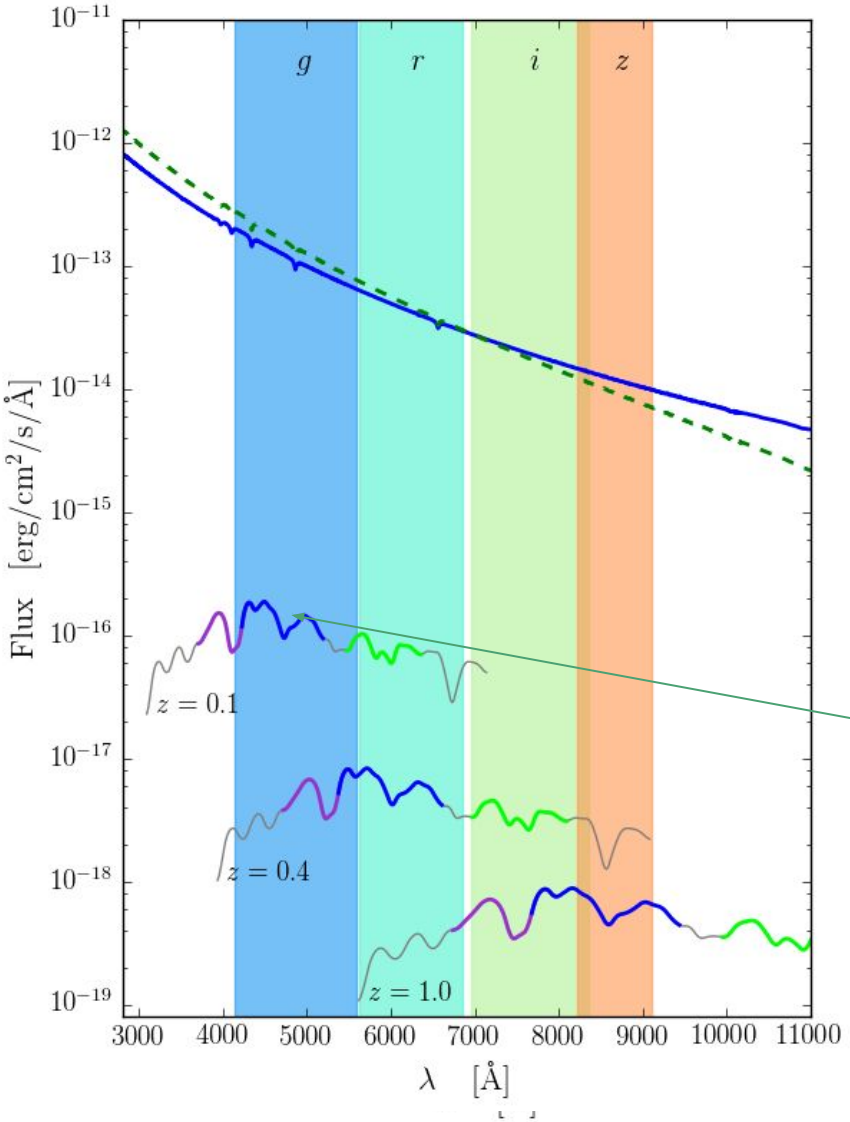
The w-wa tension in the Hubble diagram



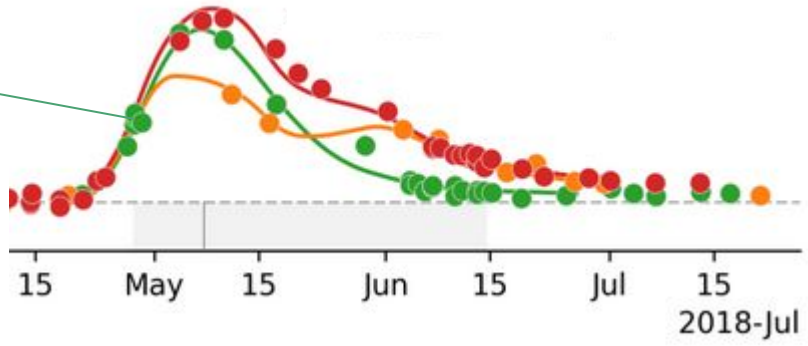
… a differential 3.7% effect between low and high-z

→ target accuracy: 0.5%

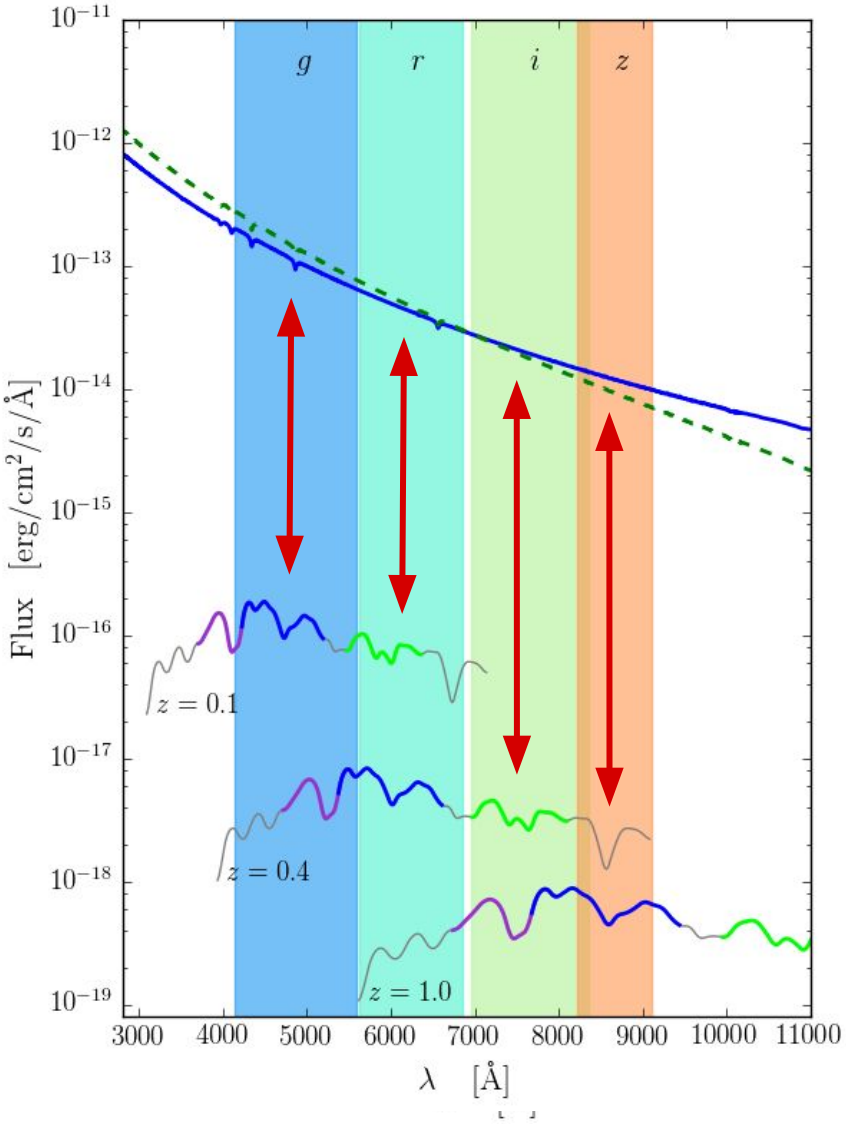
The essence of the measurement



- An empirical SN SED model
  - Trained from survey data
  - *To infer rest-frame fluxes and colors from observer frame measurements*

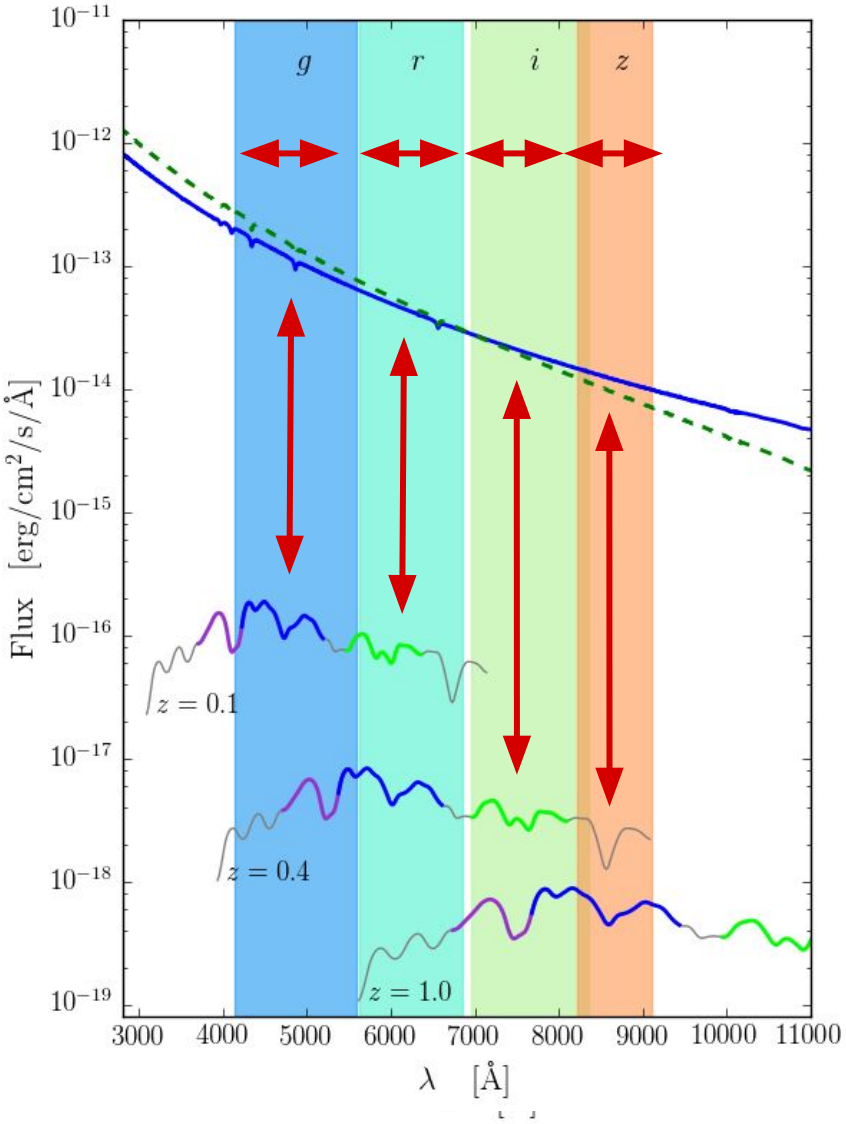


The essence of the measurement



- An empirical SN model
  - Trained from survey data
- Relative band calibration. Relies on
  - Primary flux standard
  - Flux metrology chain
  - Control of instrument(s) linearity

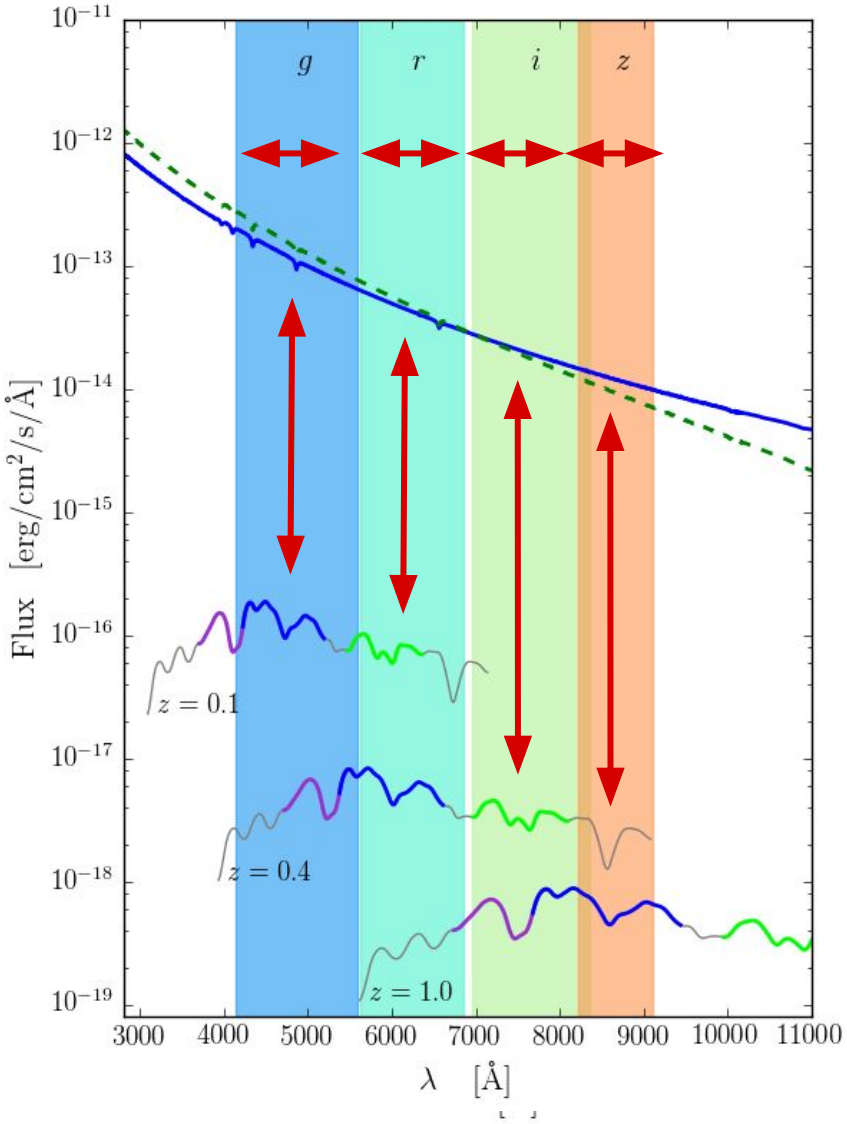
The essence of the measurement



- An empirical SN model
  - Trained from survey data
- Relative band calibration. Relies on
  - Primary flux standard
  - Flux metrology chain
  - Control of instrument(s) linearity
- Models of the survey(s) bandpasses
  - To predict SN fluxes from SN model
  - To calibrate each bandpass from primary flux standard(s)
  - *Filter uncertainties hit twice (!)*

Primarily a flux metrology experiment

The essence of the measurement



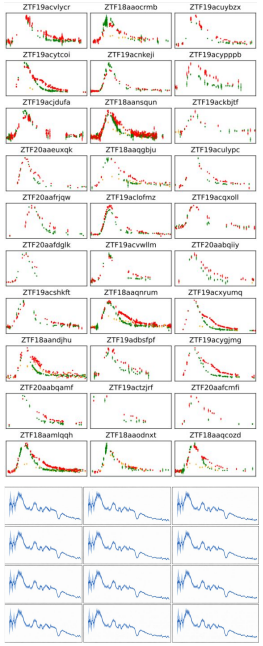
Primarily a flux metrology experiment

Of course, Other issues:

- Probe
  - Evolution
- Foregrounds / astrophysical biases
  - Galactic dust
  - Galactic evolution
  - Galactic structures vs. SN properties
- Analysis
  - Selection effects
  - Data curation

Modeling & cosmology chain

Dataset | **SN model** | **SN parameters** | **Standardized distances** | **Cosmology**



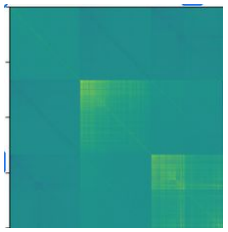
Calibration

Bandpasses

Model training

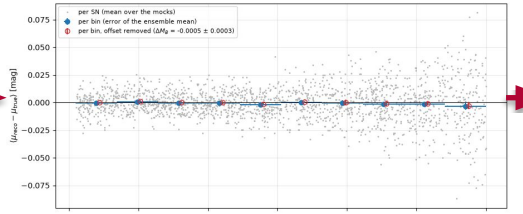
Light-curve fitting

$$\begin{pmatrix} \begin{pmatrix} x_{0,1} \\ \vdots \\ x_{0,N} \end{pmatrix} \\ \begin{pmatrix} x_{1,1} \\ \vdots \\ x_{1,N} \end{pmatrix} \\ \begin{pmatrix} c_1 \\ \vdots \\ c_N \end{pmatrix} \end{pmatrix}$$

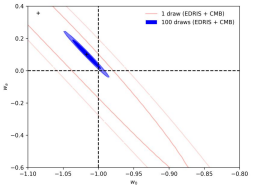


Covariance

$$\mu = m - \mathcal{M} + \alpha\, x_1 - \beta\, c + \Delta_{\text{host}}$$



Hubble residuals



$w_0 - w_a$

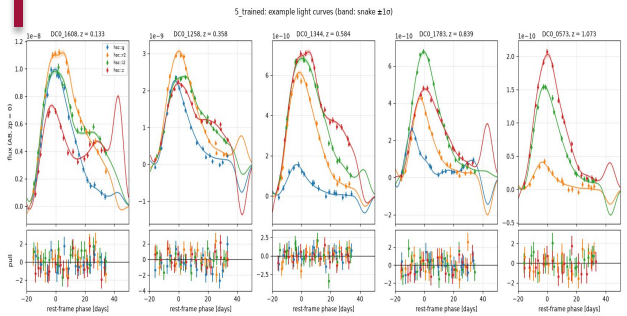
Data | Training & fitting | Parameter inference | Distance inference | Constraints

Example: a perfect 2000 SN survey

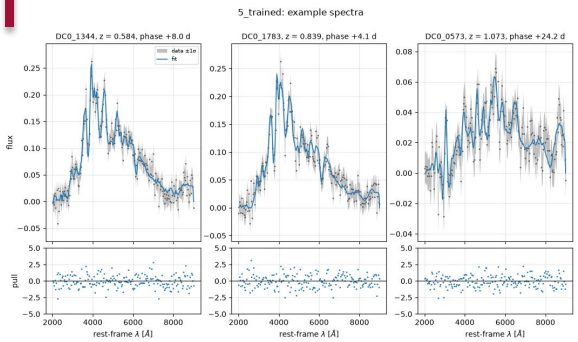
2000 SNe · 0.02 < z < 1.1 · 4 bands (g, r, i, z) · 1 spectrum / SN

Dense light-curve sampling, one instrument — injected through the full analysis chain

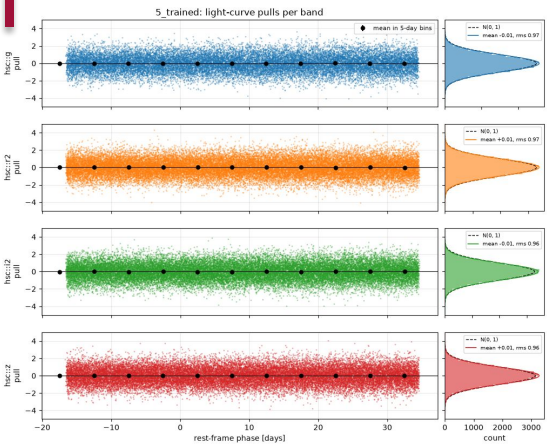
Light-curve fits



Spectral fits

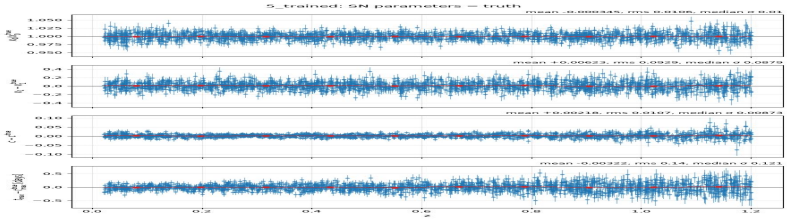


Photometric residuals



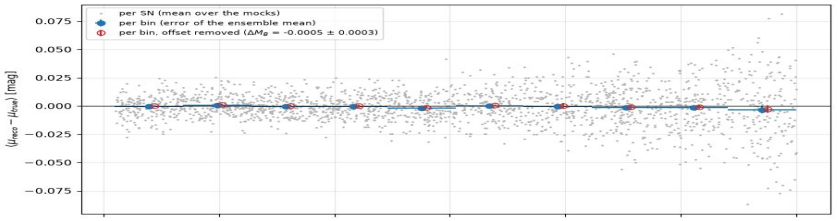
Inferred SN parameters

Fitted parameter residuals versus redshift



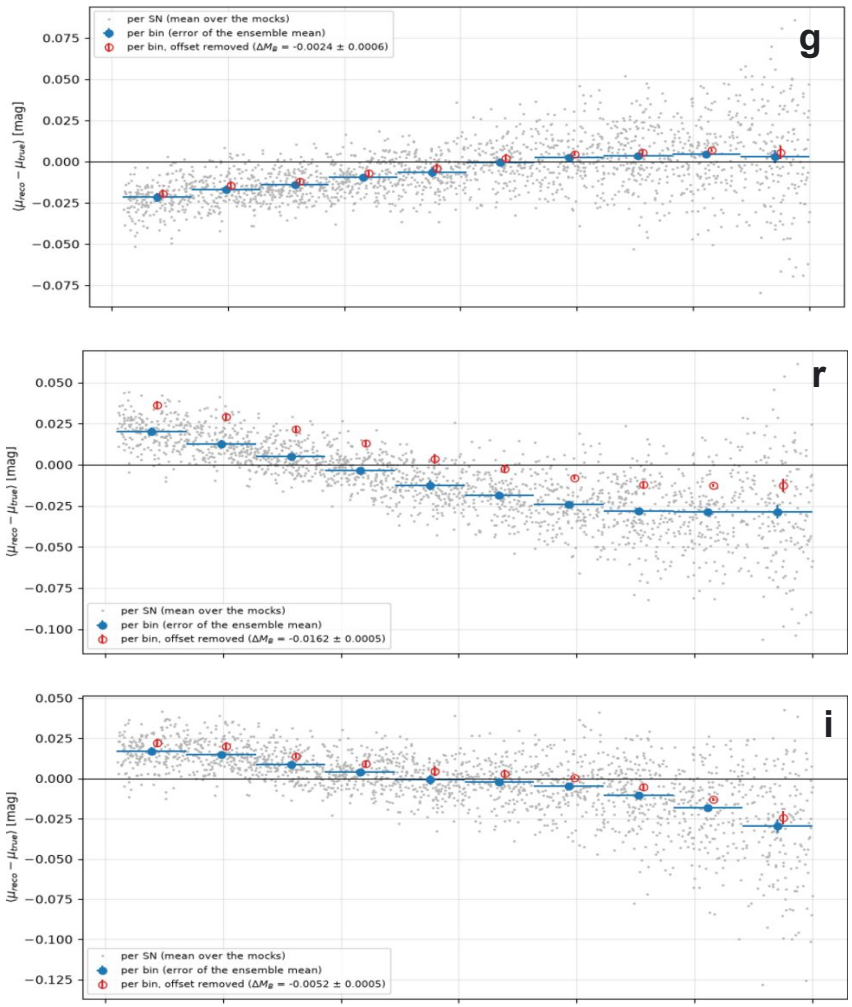
Standardized distances

Distance residuals after standardization

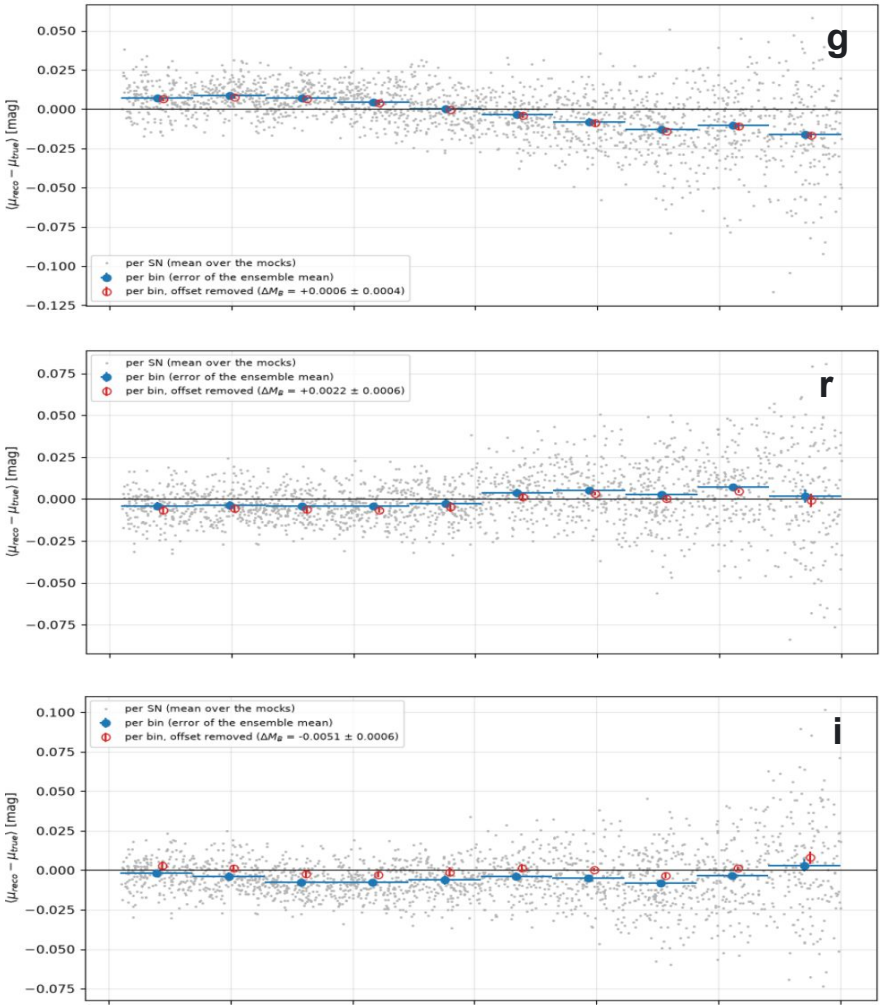


Calibration shifts induce structured Hubble residuals

Flux calibration · 10 mmag



Filter position · 1 nm



Calibration error modes

Small changes in calibration produce coherent, redshift-dependent distance shifts.

10 mmag

flux zero-point shift

1 nm

filter central-wavelength shift

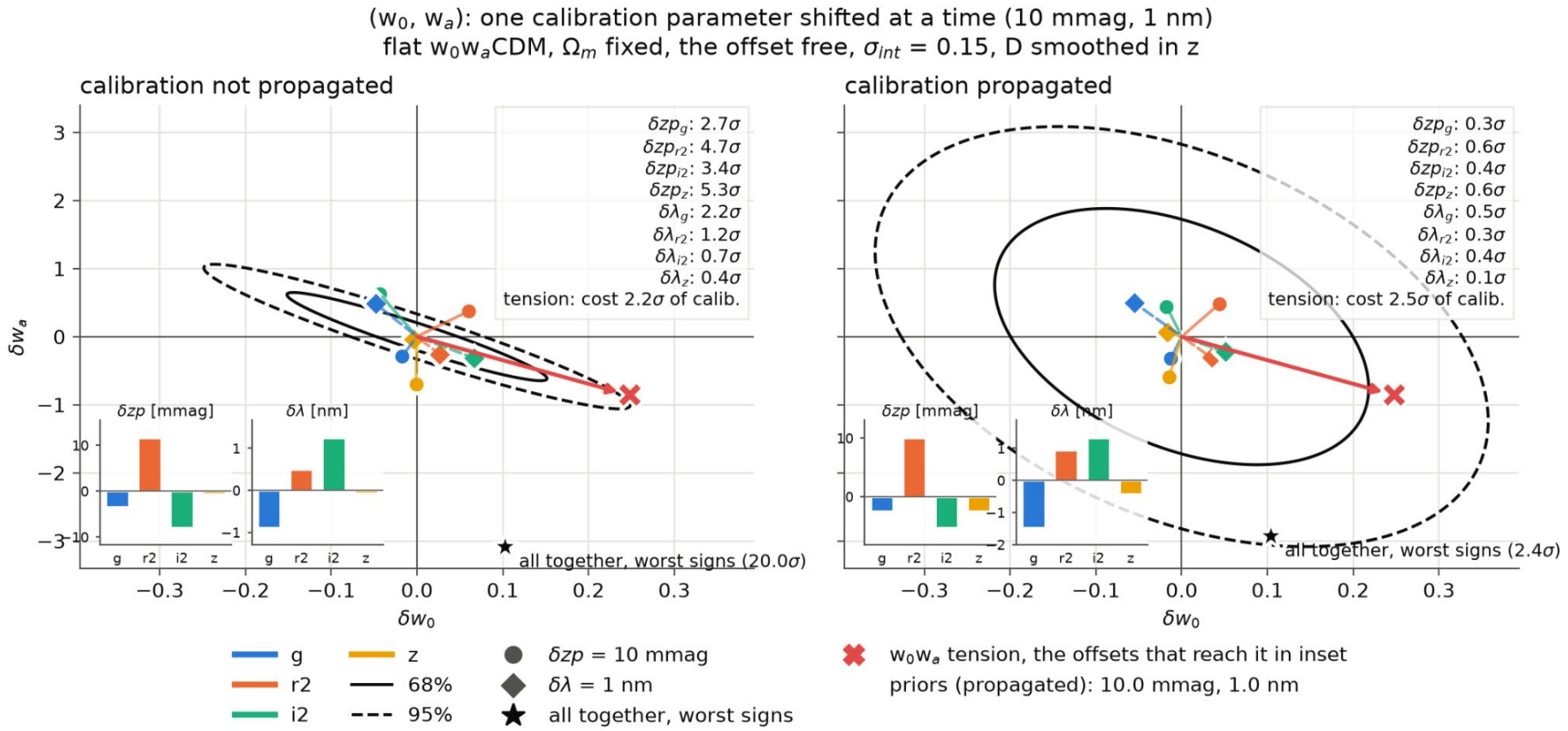
The resulting modes can be comparable in amplitude to the w_0–w_a signal in the Hubble diagram.

Next: propagate the calibration shifts into cosmological constraints.

Impact on the w_0–w_a plane · current calibration

10 mmag zero points · 1 nm bandpass shifts

STATE OF THE ART

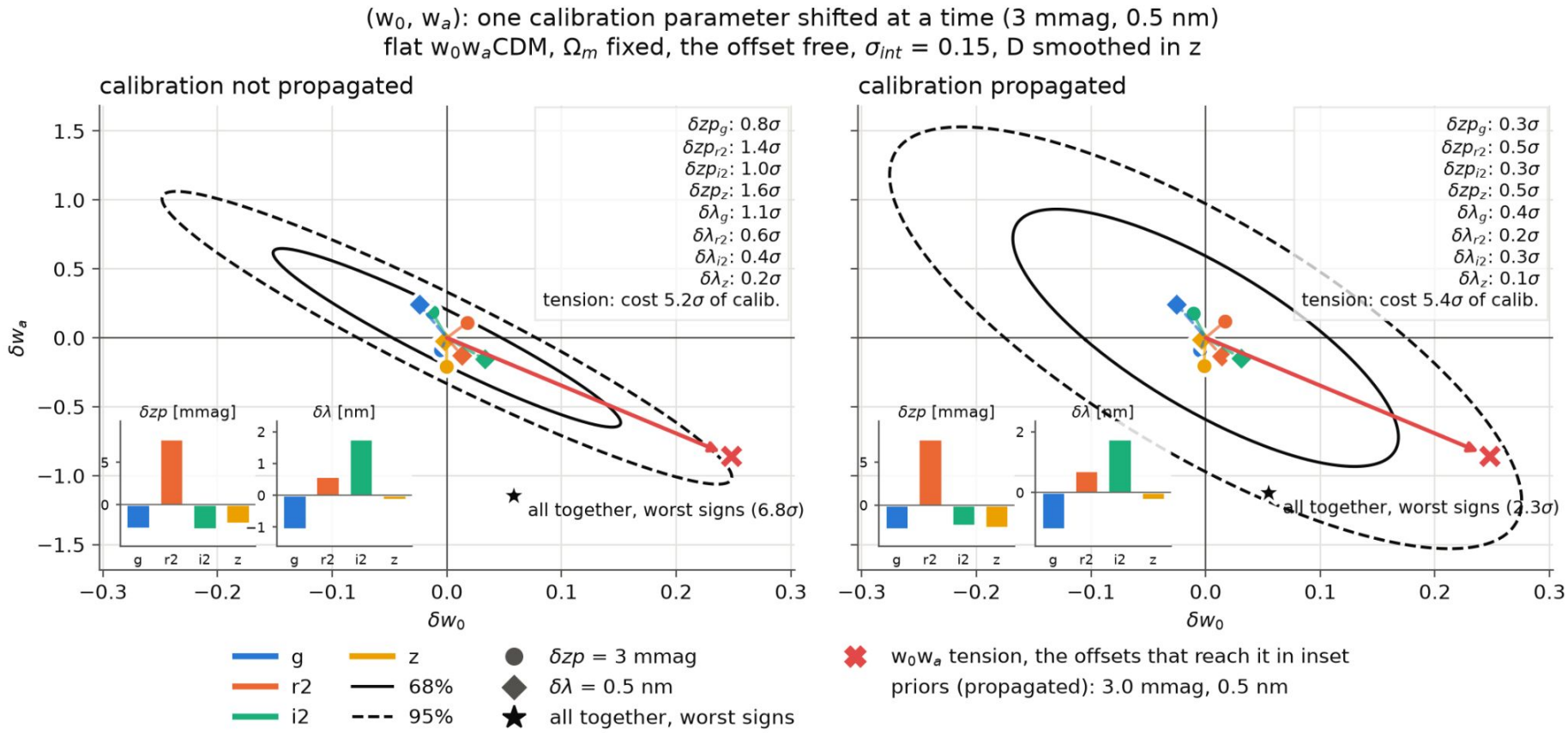


Left: calibration not propagated Right: calibration propagated

Impact on the w_0–w_a plane · target calibration

3 mmag zero points · 0.5 nm bandpass shifts

TARGET (CONSERVATIVE)



Left: calibration not propagated Right: calibration propagated

Calibration accuracy sets the robustness of w_0–w_a

Calibration errors can reproduce an apparent dynamical dark-energy signal.

CURRENT CALIBRATION

σ(zp) ≈ 10 mmag

σ(δλ) ≈ 1 nm

≈ 2.2σ

calibration offset can mimic the w_0–w_a tension

TARGET CALIBRATION

σ(zp) ≈ 3 mmag

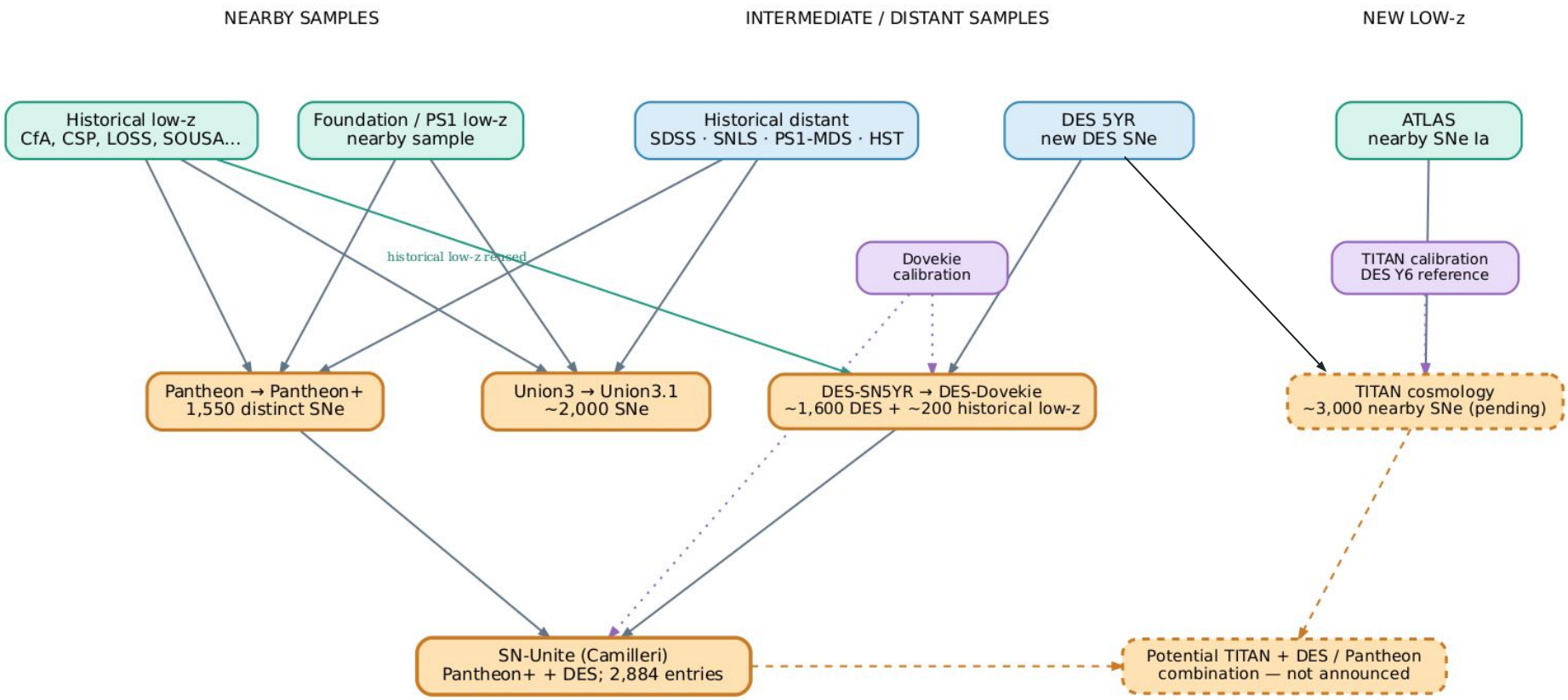
σ(δλ) ≈ 0.5 nm

> 5σ

calibration offset required to mimic the same tension

Precision calibration is a prerequisite for an independent dark-energy test.

Historical compilation & the Titan path



Union & Union3.1

Union3 → Union3.1

~2,000 SNe from largely historical surveys

Same observations; updated host-galaxy properties

Homogeneous stellar-mass estimates

Cosmological consequence

Low-z / high-z distance offsets reduced

DESI + CMB + Union preference: ~3.8σ → ~3.4σ

Not an independent SN sample

Takeaway: analysis choices matter at the ~10–30 mmag level.

Hoyt et al. (2026), Union3.1

Pantheon+

Pantheon+ (2022)

1,550 distinct SNe Ia

1,701 light curves

Historical low-z + Foundation/PS1 low-z + SDSS, PS1-MDS, SNLS and HST

Calibration baseline

Fragilistic cross-survey calibration

Overlaps strongly with Union3 and DES low-z

A different analysis ≠ independent observations

Takeaway: most “independent” compilations reuse the same nearby SNe.

Scolnic et al. (2022); Brout et al. (2022)

DES-5yr & Dovekie

Dovekie: calibration changes

Filter shifts (relative to Fragilistic):

PS1 g: **−30 Å**; SNLS griz: **+30 Å**

Some historical bands: up to ±70 Å

Adopted 1σ filter uncertainties:

DES griz: 5, 5, 10, 30 Å

DES ZP uncertainties: 2–3 mmag

DES result: updated distances

SN-only Ωm: 0.352 → 0.330

Evolving Dark Energy preference: 4.2σ → 3.2σ

Not a calibration-only test:

SALT3 retrained; selection and CMB also changed.

Large filter revisions ≠ a coherent 1σ calibration mode aligned with w_0–w_a.

Popovic et al. (2025, 2026), Dovekie / DES-Dovekie

SN-Unite

SN-Unite (Camilleri 2026)

2,884 SN Ia entries

Combines Pantheon+ and DES-SN5YR

Extended Dovekie calibration; SALT3.UNITE

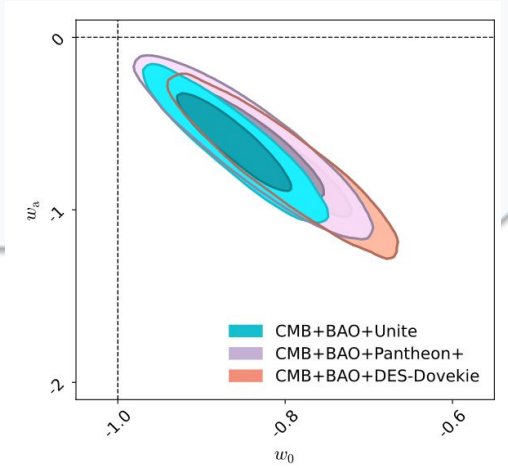
Unified host masses and bias corrections

What changes?

Pantheon+ vs Unite low/high-z offset: ~20 mmag

Much of it traced to host-mass and dust/population modelling

W0wa preference: ~3.1σ (maximum likelihood)



Takeaway: improved consistency, not a new independent data set.

Camilleri et al. (2026), Supernovae Unite

TITANS

TITAN / ATLAS: large new low-z sample

~3,000 SNe targeted for cosmology in DR1

ATLAS “cyan” / “orange” wide filters

Effective cyan shifts: +50 to +100 Å

Derived from stellar color terms

ZP/spatial corrections: several–tens of mmag

Calibration, not yet cosmology

Residual calibration metrics:

~9 mmag (cyan), ~5 mmag (orange)

Not yet a SN Hubble-diagram covariance

DES Y6 stellar calibration reference

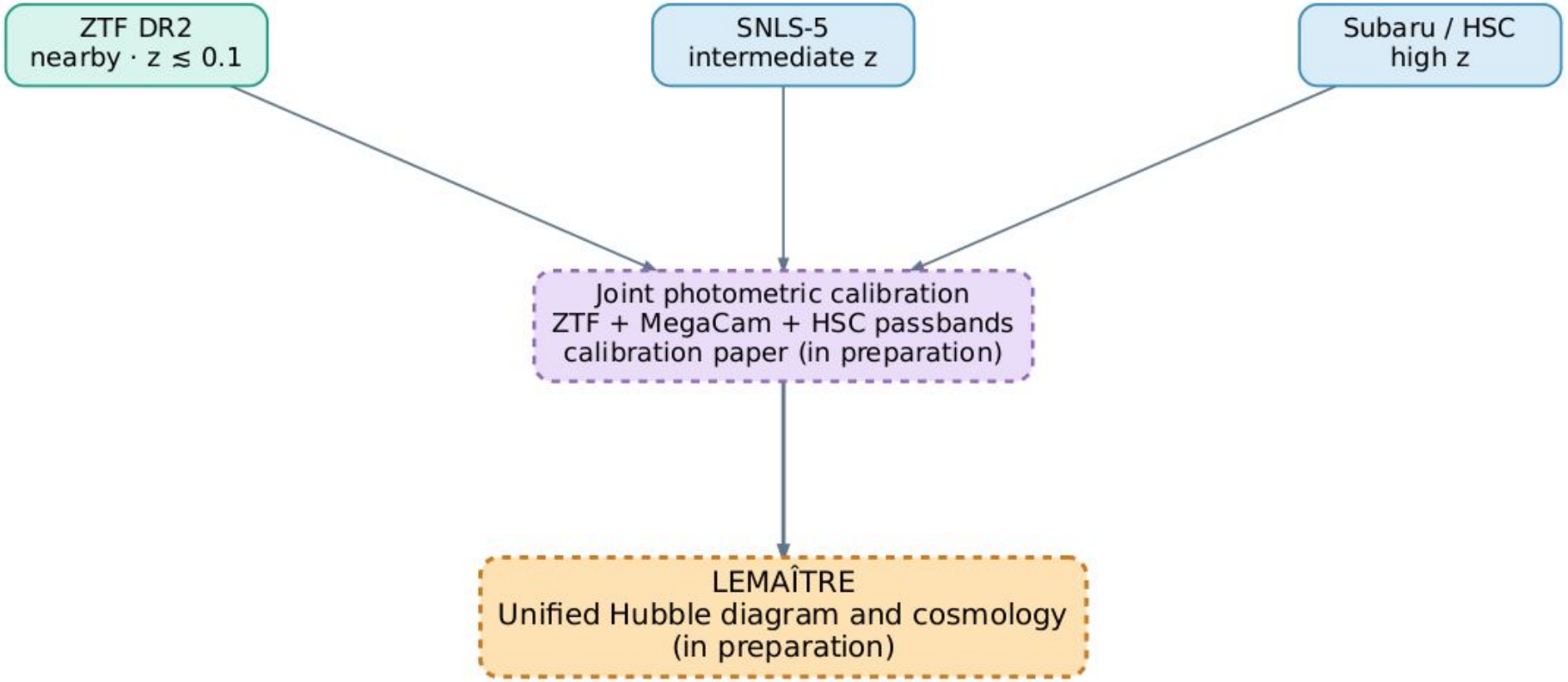
Future cosmological combination not yet established

The measured slopes, and therefore implied filter shifts are most pronounced for cyan where we find each chip should be shifted by 50 - 100 Å in the same direction. Although this initially sounds substantial, given how broad the ATLAS filter bands are this is comparable to shifting a DES or PS1 band by 25 - 50 Å, which has been shown to be necessary in some cases (e.g., PS1-g; Scolnic et al. 2015). While the exact cause of the observed chromatic effect is unknown (e.g., change in quantum efficiency, filter degrading, calibration issue) our phenomenological approach is efficient at removing

Large nearby sample; filter shifts are effective, not direct passband metrology

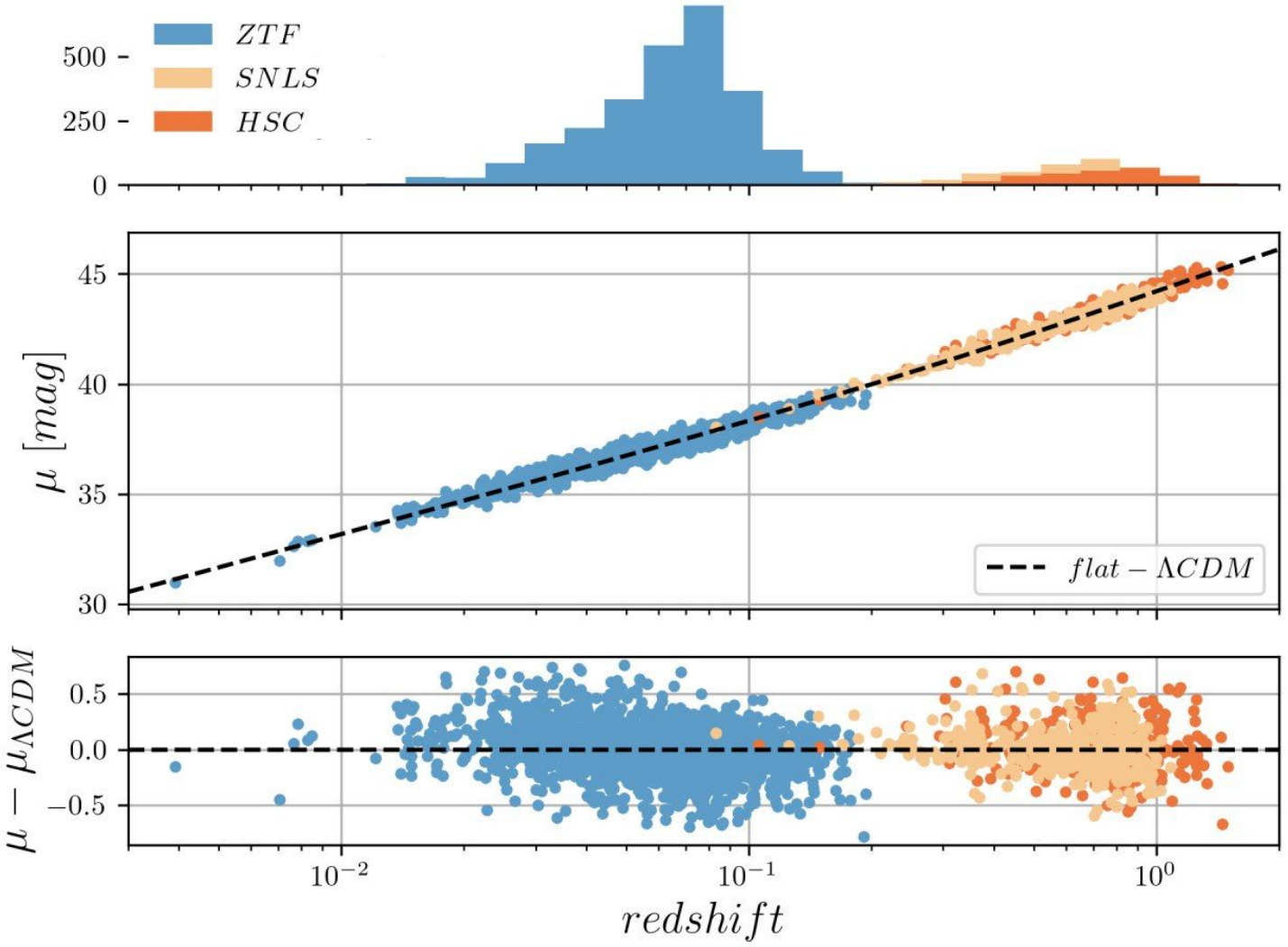
Marlin et al. (2026), TITAN DR1 calibration; cosmology analysis forthcoming

The Lemaitre project



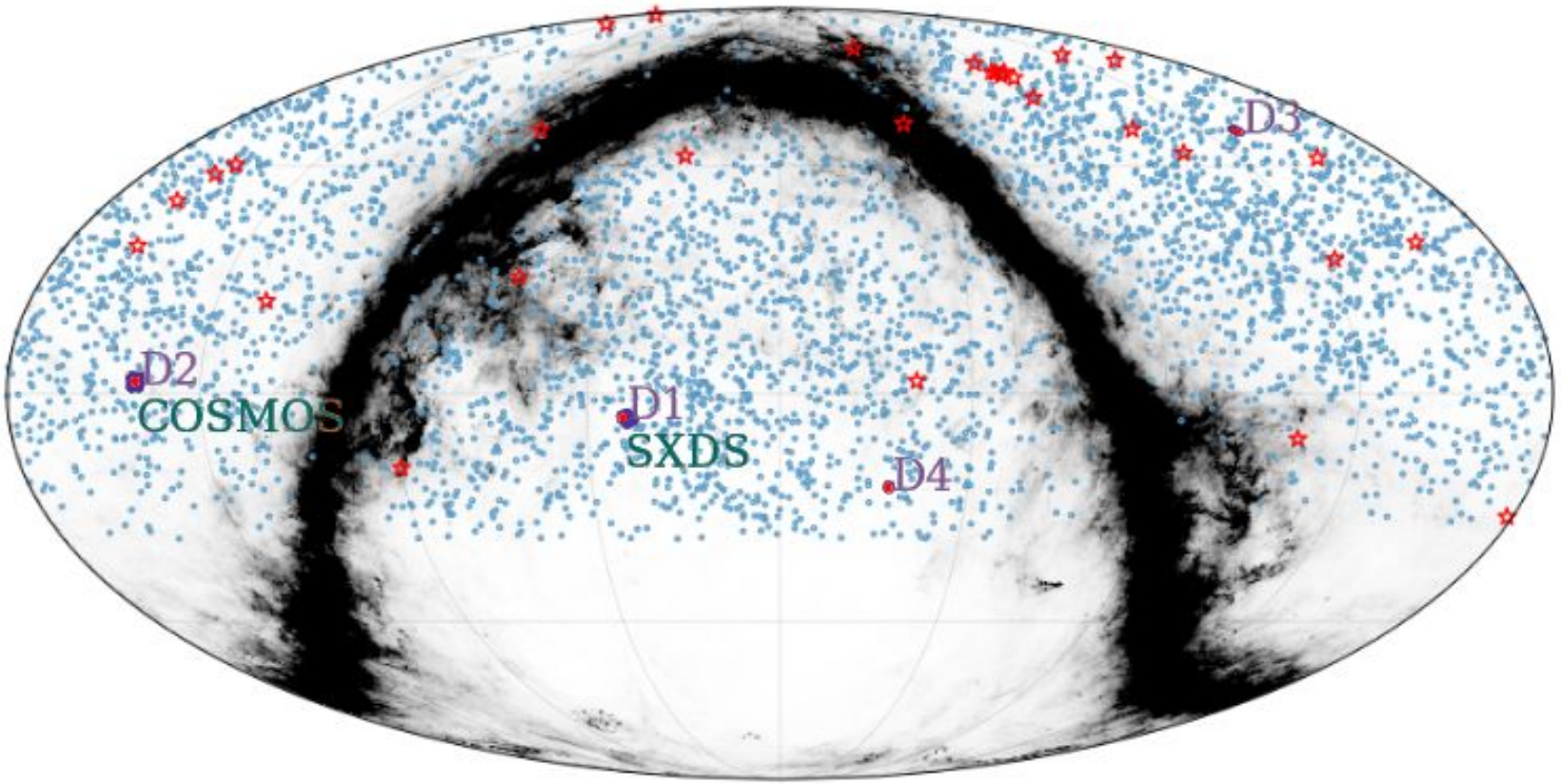
Latest Extended Mapping of Acceleration with an Independent Trove of Redshifted Explosions

The LEMAÎTRE Hubble diagram



The Lemaître sample — one Hubble diagram

Independent observations from the nearby to the high-redshift Universe



- ZTF DR2 supernovae
- CALSPEC standards observed by ZTF
- SNLS fields · D1–D4
- Subaru/HSC fields · COSMOS, SXDS

Zwicky Transient Facility



Three complementary SN Ia samples

Different redshift ranges, one unified analysis and calibration chain

NEARBY

ZTF DR2

≈ 3,000

2018–2020 · Northern sky

High-cadence light curves

Spectroscopic classification

Volume-limited to z < 0.06

INTERMEDIATE

SNLS-5

171

SNLS years 4–5 · MegaCam

Unpublished SN sample

High-quality multiband photometry

Bridges low and high z

DISTANT

Subaru / HSC

≈ 300

Two seasons · Two deep fields

g, r, i, z, Y observations

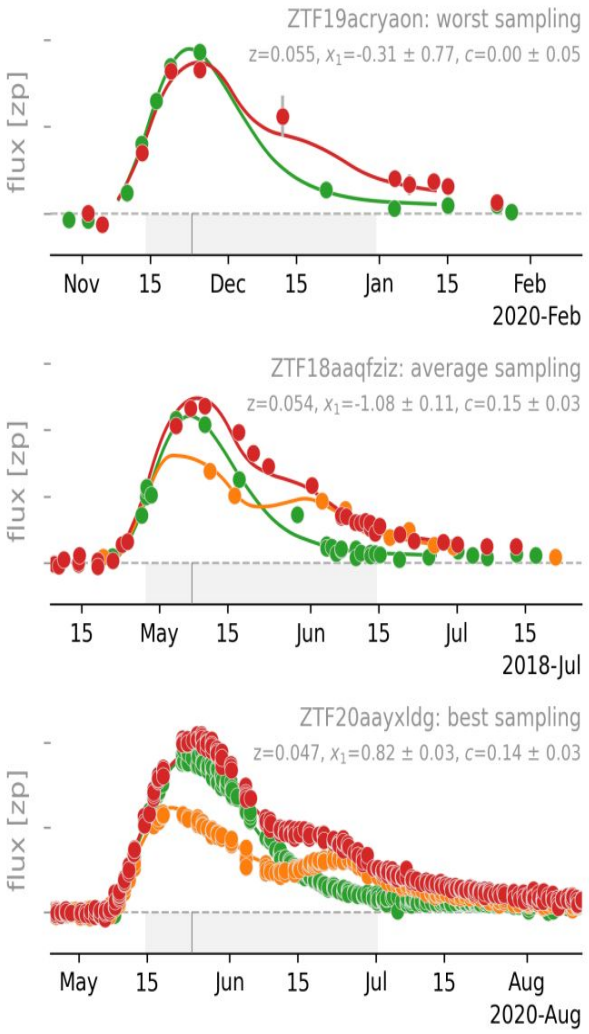
Median redshift ≈ 0.8

Extends beyond z ≈ 1

Core asset: independent SN observations spanning the acceleration transition.

ZTF DR2 — a new low-z regime

Dense, homogeneous light curves from a spectroscopically identified survey



3,628 spectroscopic SNe Ia

≈ 2,670 after light-curve cuts

High cadence and broad phase coverage

Simple spectroscopic selection (g < 18.5)

Volume-limited subset at z < 0.06

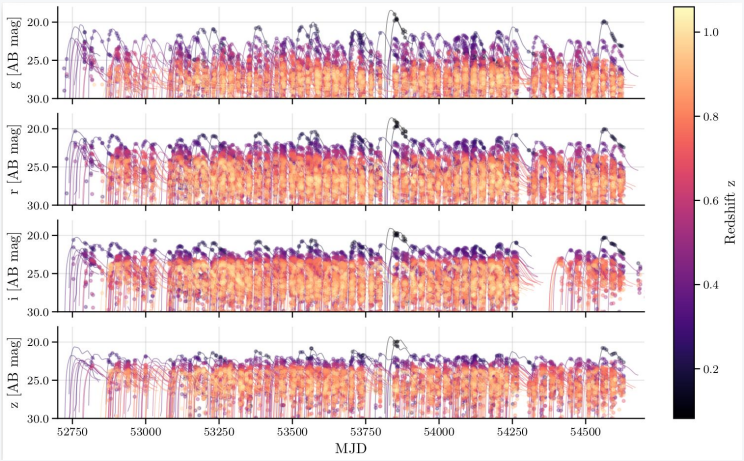
Rigault et al. · ZTF DR2

DR2 release: https://ztfcosmo.in2p3.fr/papers

SNLS-5 and HSC — the redshift lever arm

Two complementary samples connect the nearby Universe to z > 1

SNLS-5 · 171 SNe

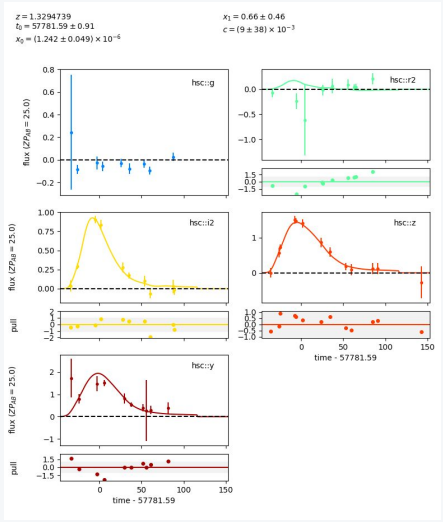


SNLS light-curve ensemble

Years 4–5 of SNLS

MegaCam filter metrology; direct CALSPEC calibration

Subaru / HSC · ~300 SNe



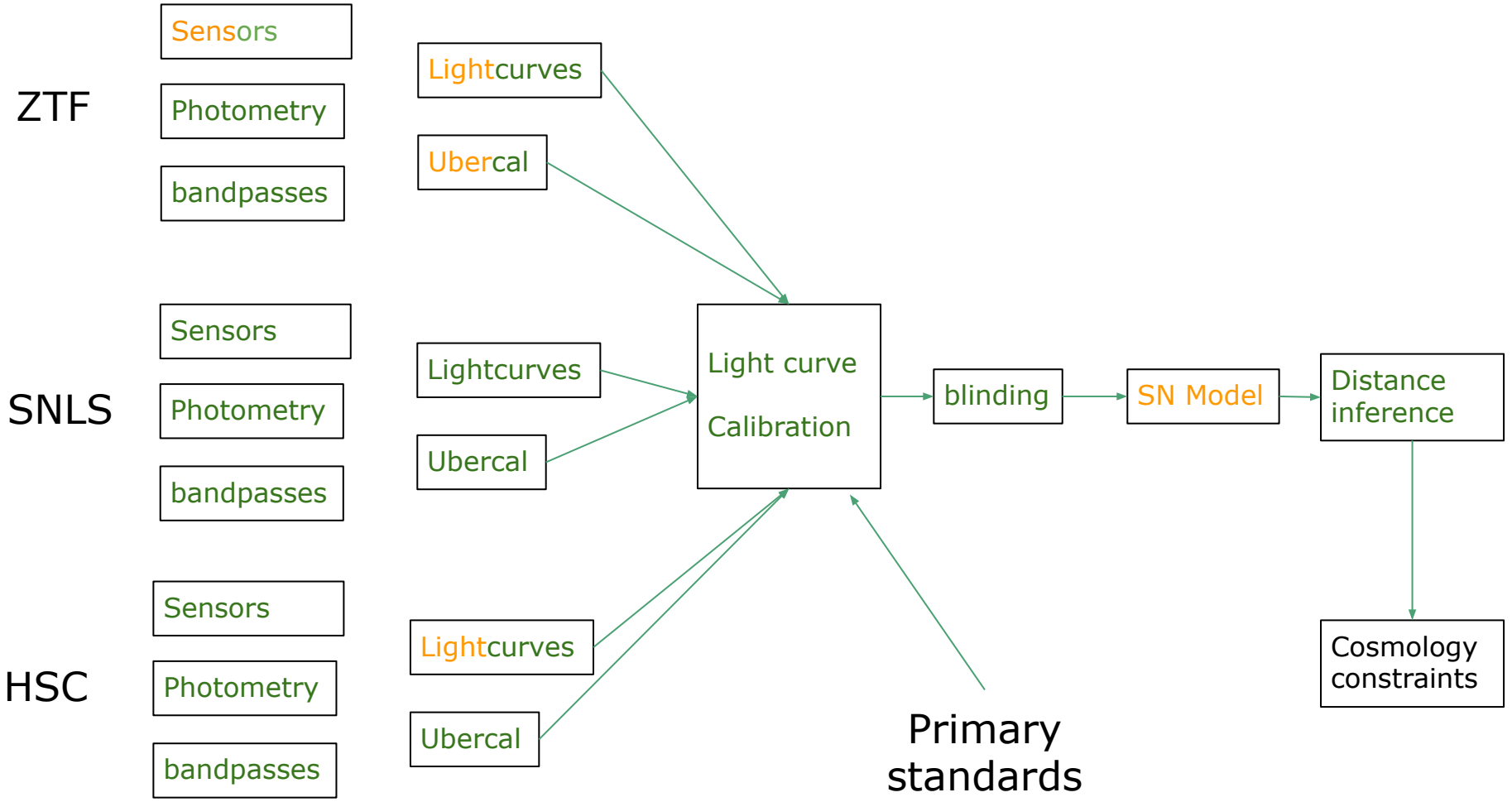
HSC SN Ia · z = 1.33

Two seasons, COSMOS and SXDS

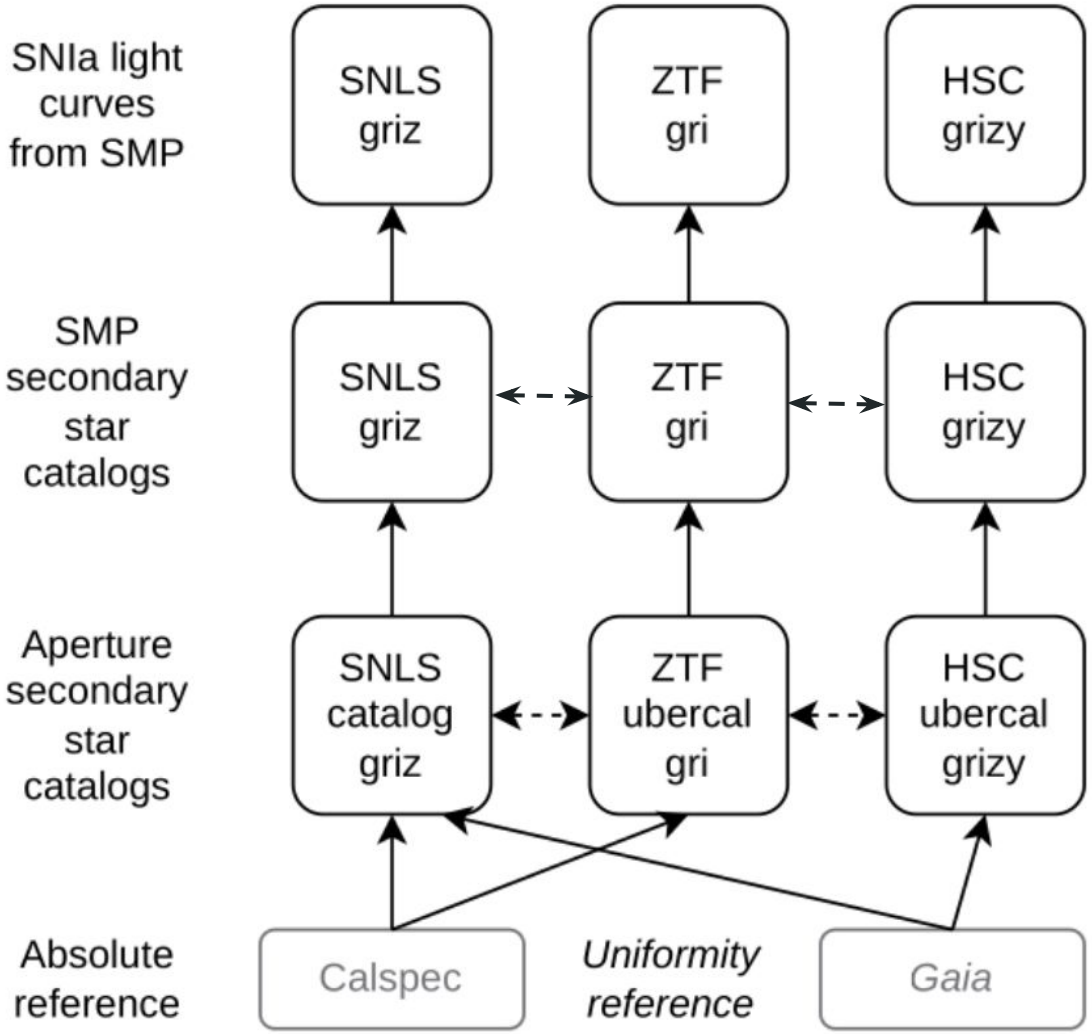
Median z ≈ 0.8; g r i z Y

Spectroscopic redshifts from several facilities

Analysis of the LEMAÎTRE dataset



Calibration

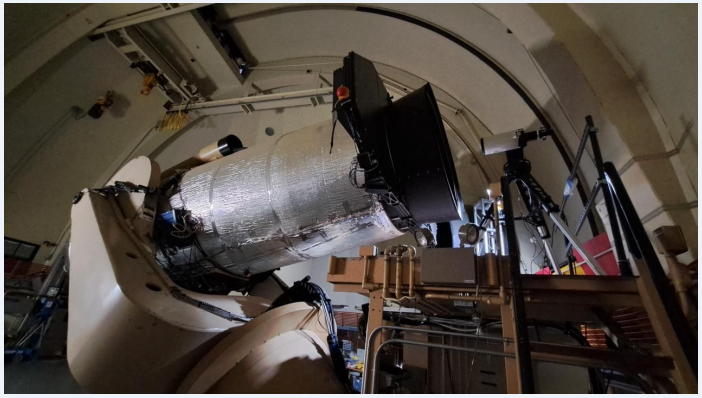


Principles

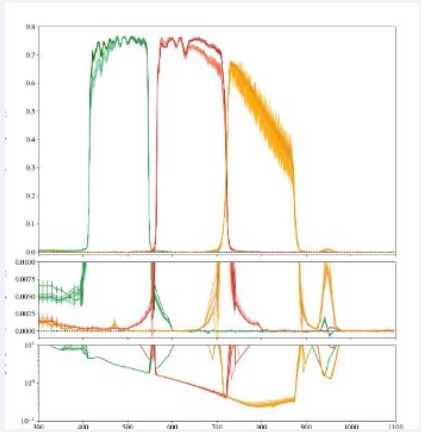
- 3 step transfer to the Supernovae
- Redundancy between surveys up to the secondary star catalog
- Aperture/SMP consistency is a check of SMP

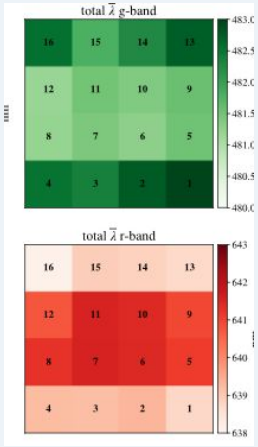
Bandpass metrology — ZTF & SNLS

Direct measurements of instrumental transmission functions



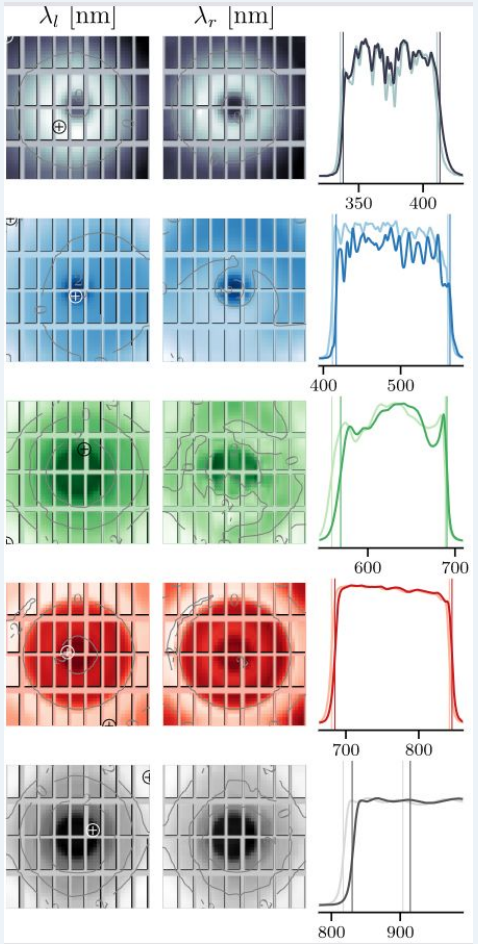
ZTF · in-situ tCBP at Palomar





Aubert et al, Van den Abeele et al.

ZTF gr(i) · measured transmissions & Filter uniformity

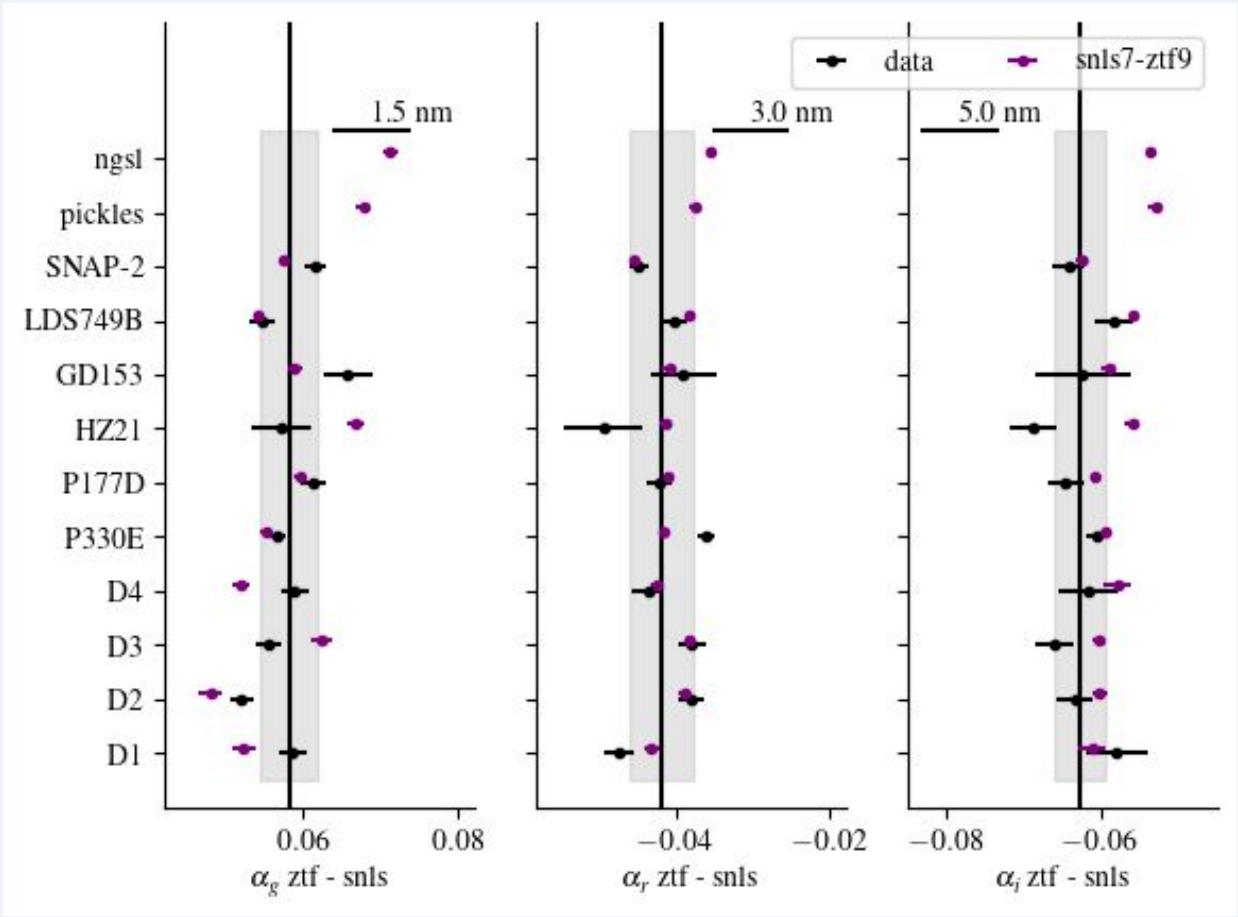


Betoule, Lejeune et al

SNLS · Measured transmissions and filter uniformity

Independent bandpass cross-checks

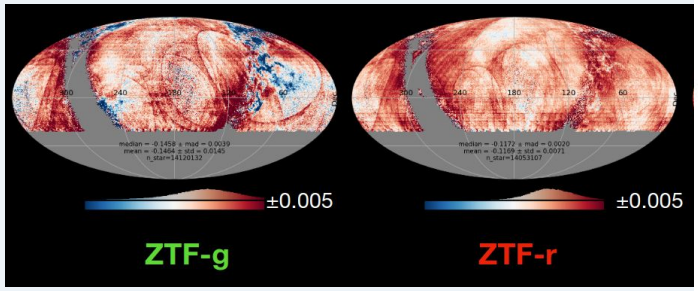
Consistency of filter shifts inferred from multiple stellar data sets



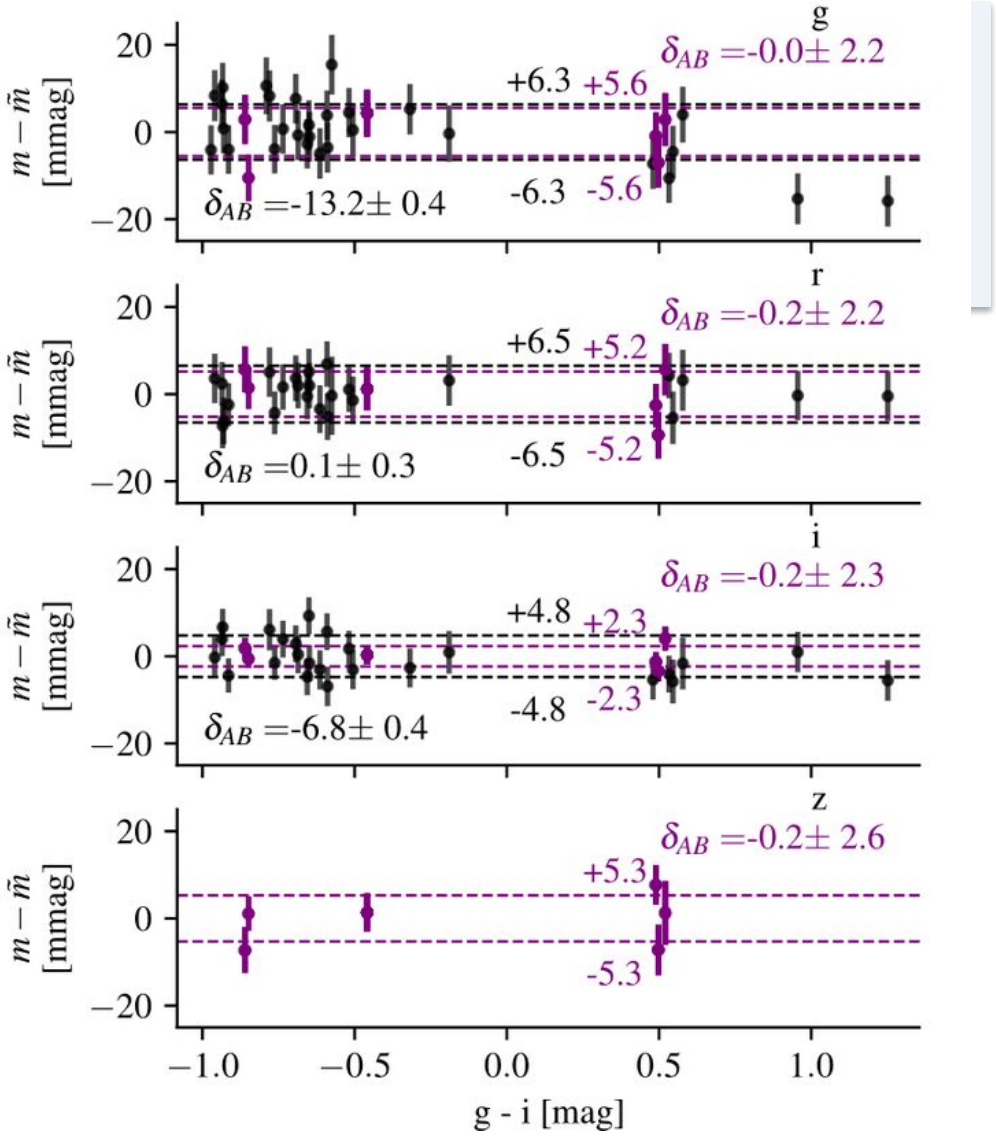
SNLS / ZTF: compare measured transmissions with stellar color constraints
Star are used as independent x-check only

Flux calibration — from survey catalogs to CALSPEC

Sky uniformity and direct observations of primary standards



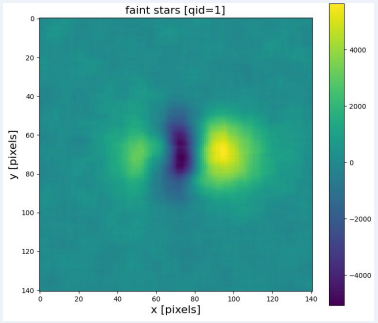
- ZTF full-sky ubercal · large-area uniformity checks
- Primary standards · direct CALSPEC observations with ZTF & SNLS
-

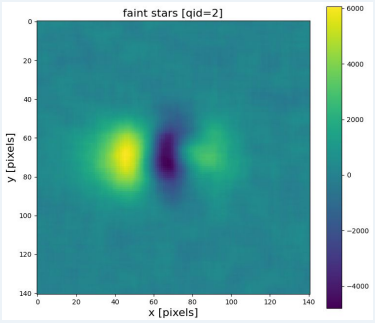


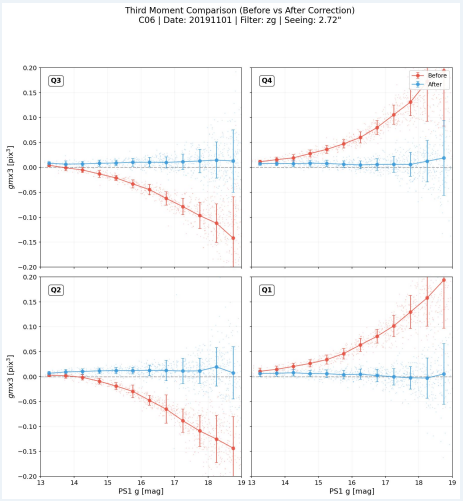
Sensor effects — pixel-level corrections

Sensor effects : must be characterized and corrected at pixel level

Pocket effect





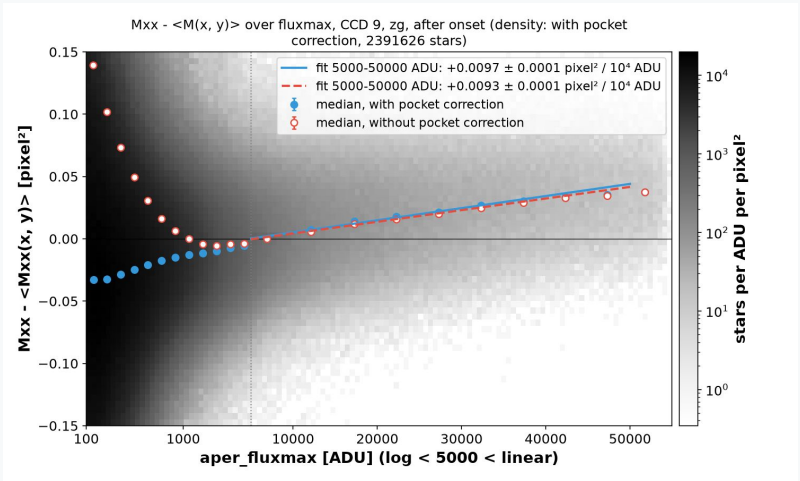


Charge trap

- Near end of serial register
- Affect skewness & astrometry
- Induced ~15% non-linearit
- Corrected @ pixel level

Pocket effect · morphology, skewness and astrometry

Brighter-fatter



Affects CCD drift field as pixels fill up

- PSF homotheticity
- 2% residual non-linearities after pocket effect correction
- Hope to reduce to <1% after correction

Combined pocket + BF pixel correction

What will it take to test evolving dark energy?

Calibration accuracy, independent data and end-to-end control

01 CALIBRATION IS THE LIMITING SYSTEMATIC

Current calibration precision can mimic a w_0–w_a tension.

Required: ≈ 1 mmag in flux • < 0.5 Å in passband position — extremely demanding

02 CURRENT COMPILATIONS ARE NOT INDEPENDENT

Many surveys, but overlapping low-z samples and shared calibration / analysis choices.

03 LEMAÎTRE: AN INDEPENDENT TEST

ZTF DR2 + SNLS-5 + HSC, with a common, traceable metrology chain.

ZTF: < 0.3 nm filters; ~ 1 mmag flux | SNLS: < 0.3 nm filters; ~ 3 mmag flux

Standing issue: combined brighter-fatter + pocket corrections at pixel level.

Independent observations are necessary; robust, validated calibration is essential.