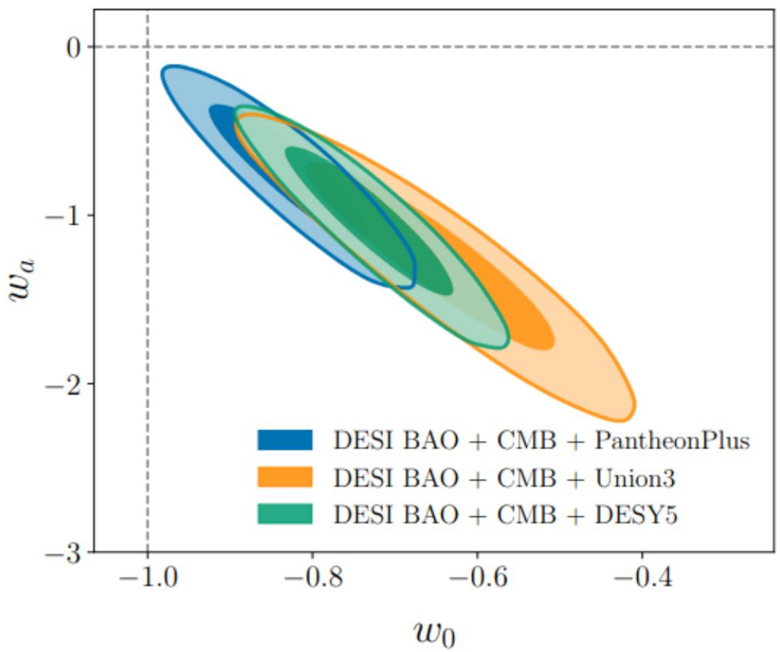
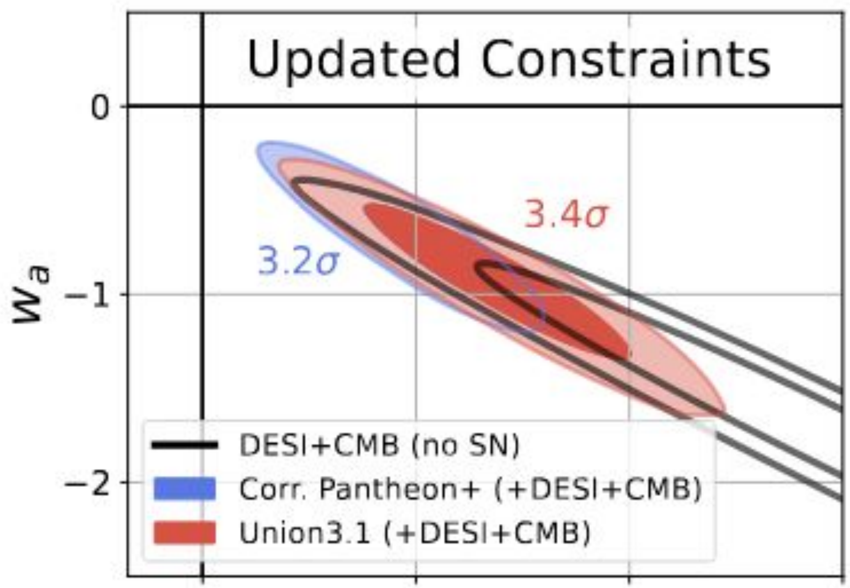
The Lemaître project:

An independent Probe of the w-wa Tension

N. Regnault, for the Lemaitre collaboration

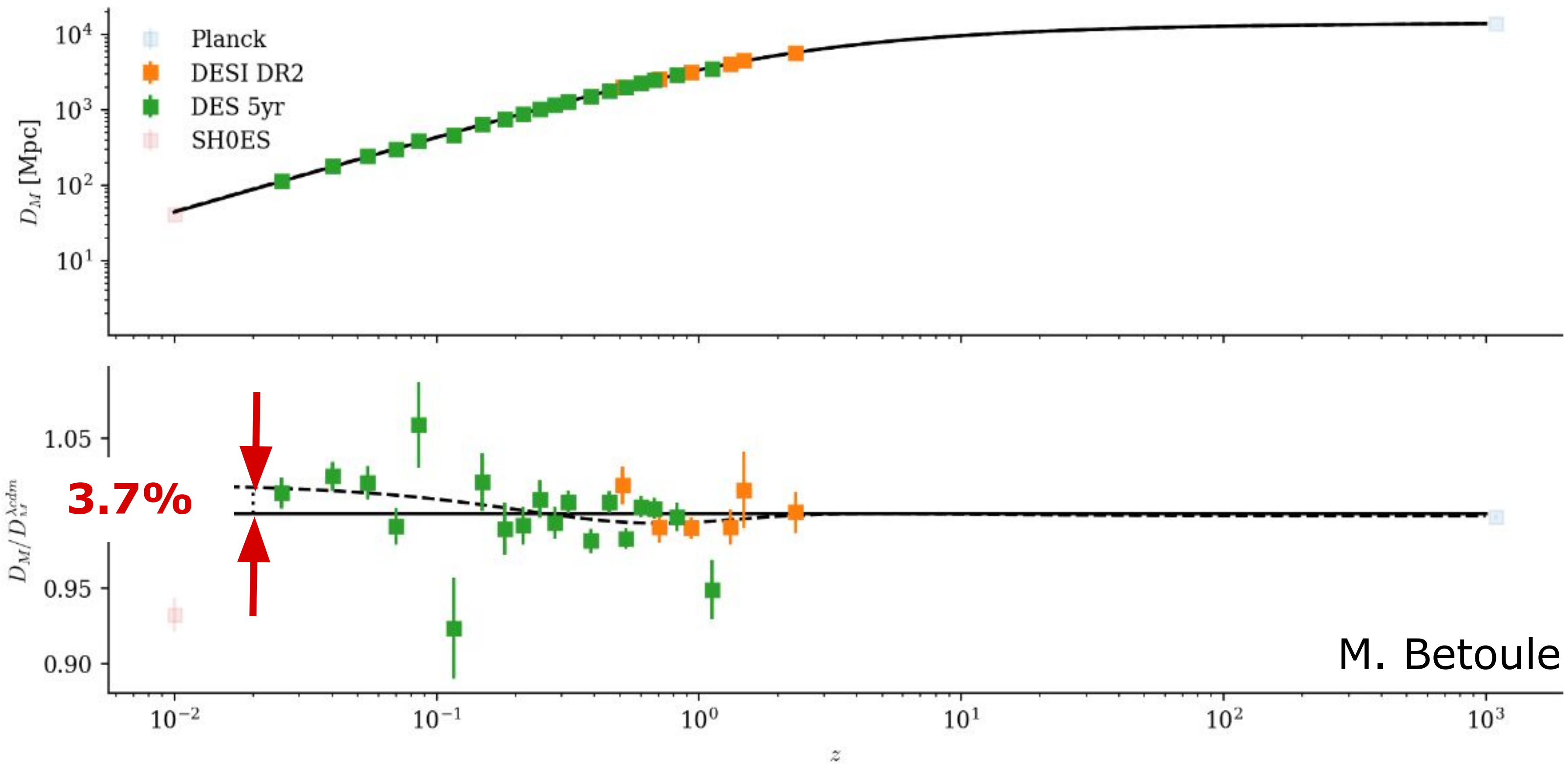
Context





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

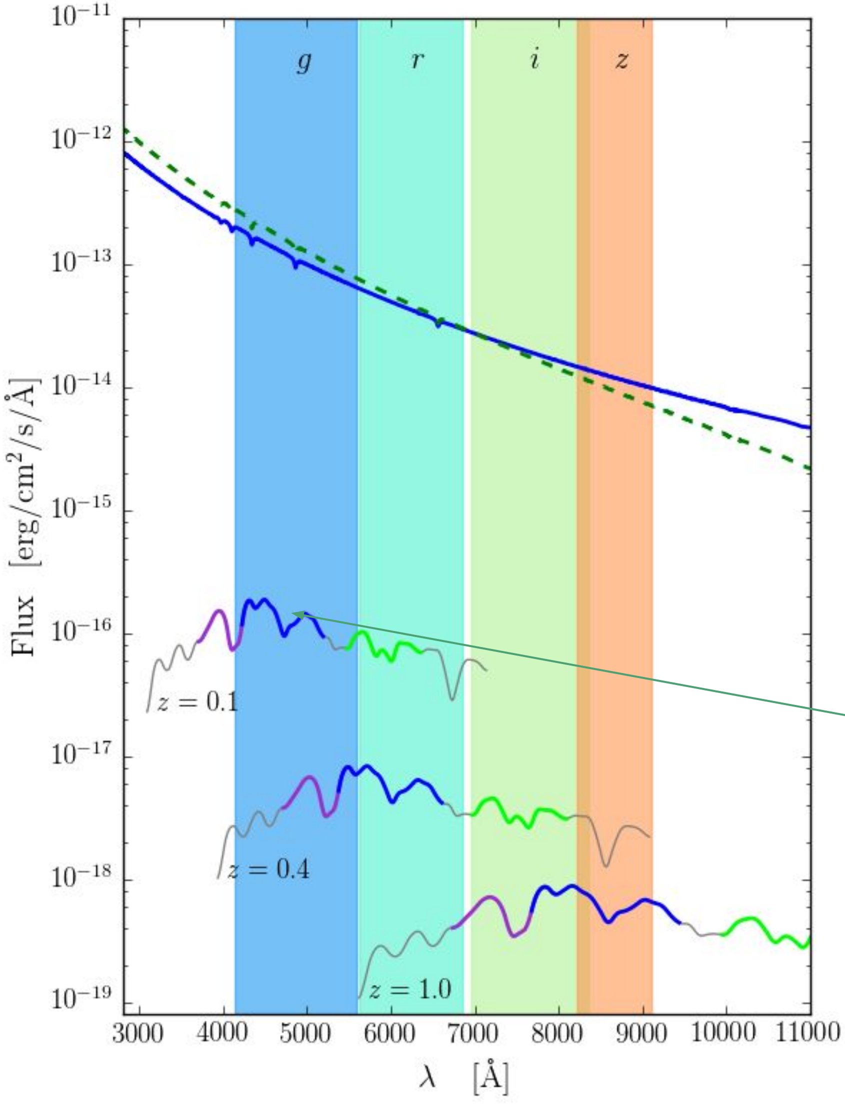
The w-wa tension in the Hubble diagram



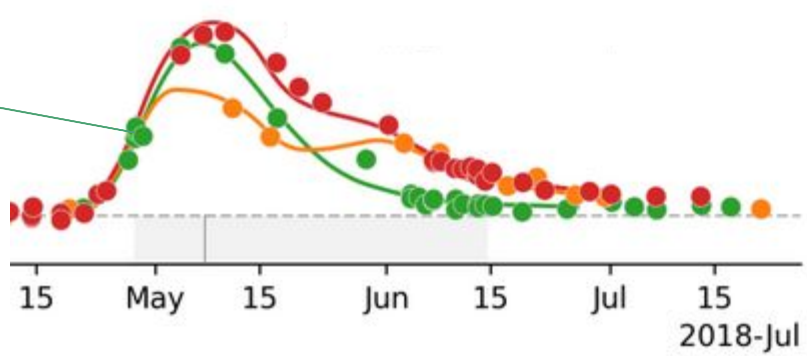
... a differential 3.7% effect between low and high-z

→ target accuracy: 0.5%

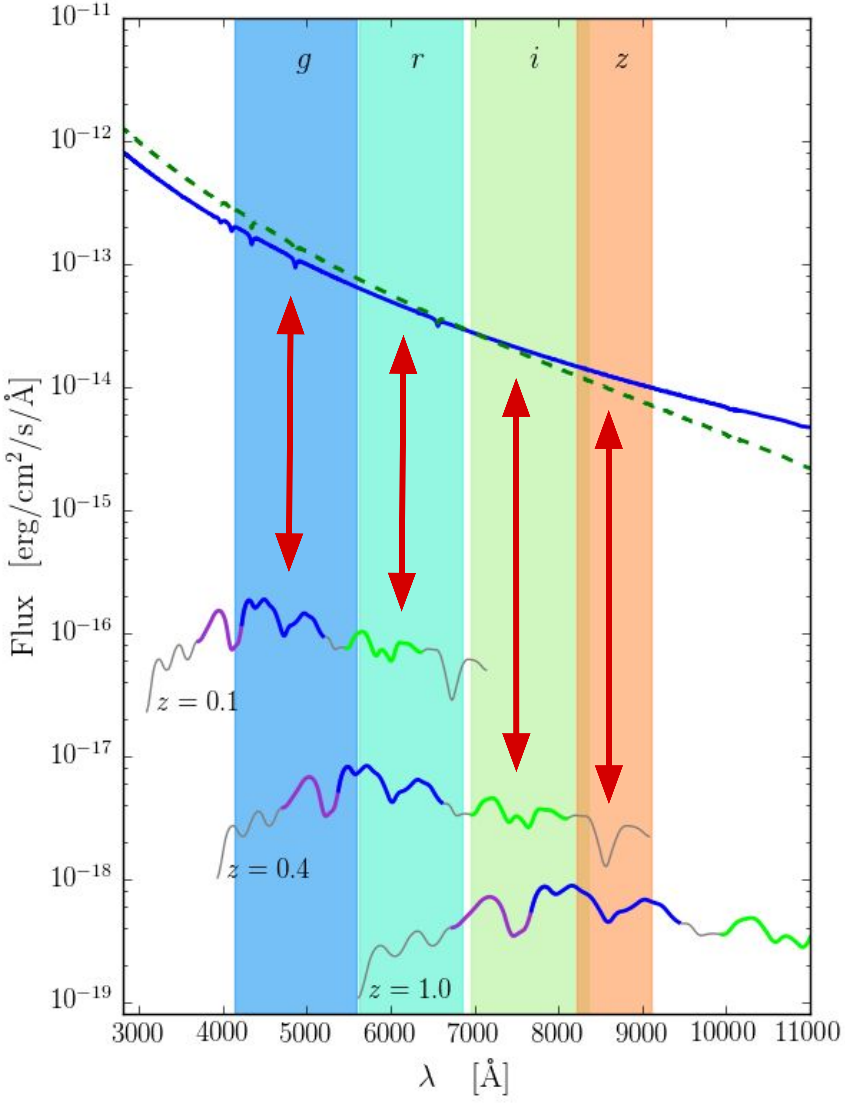
The essence of the measurement



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

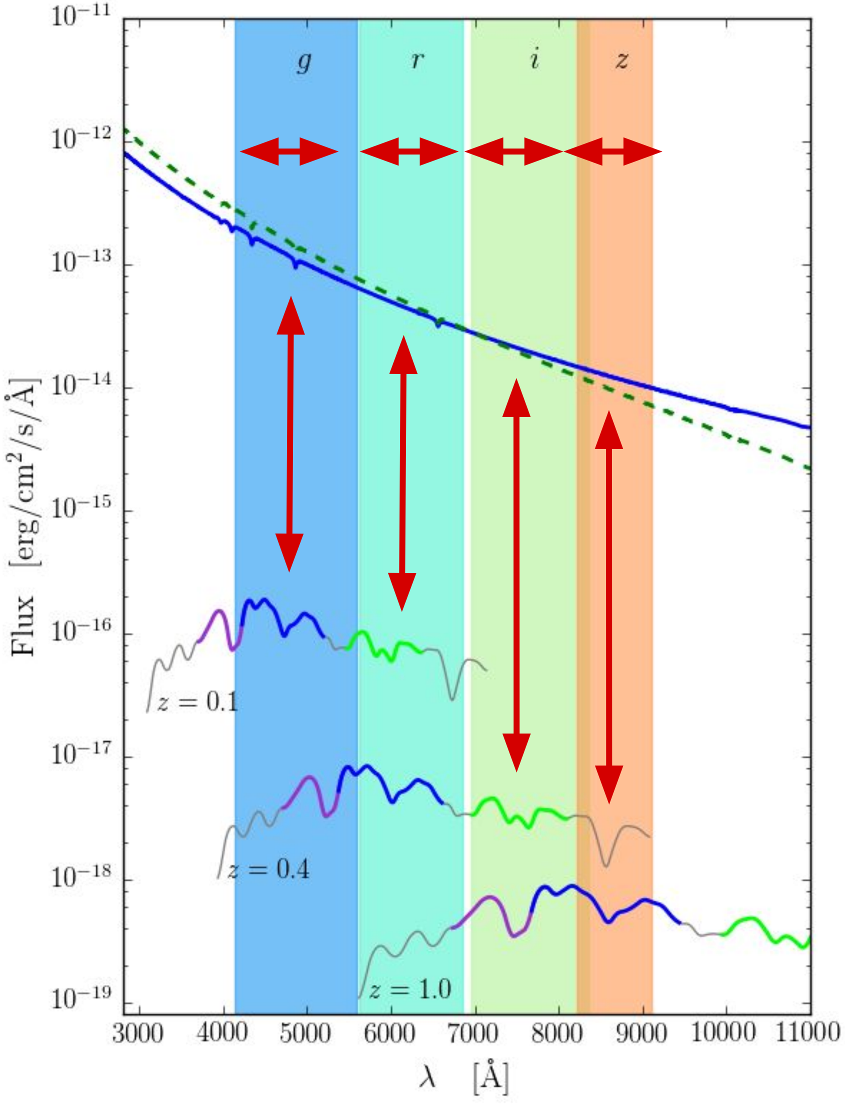


The essence of the measurement



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

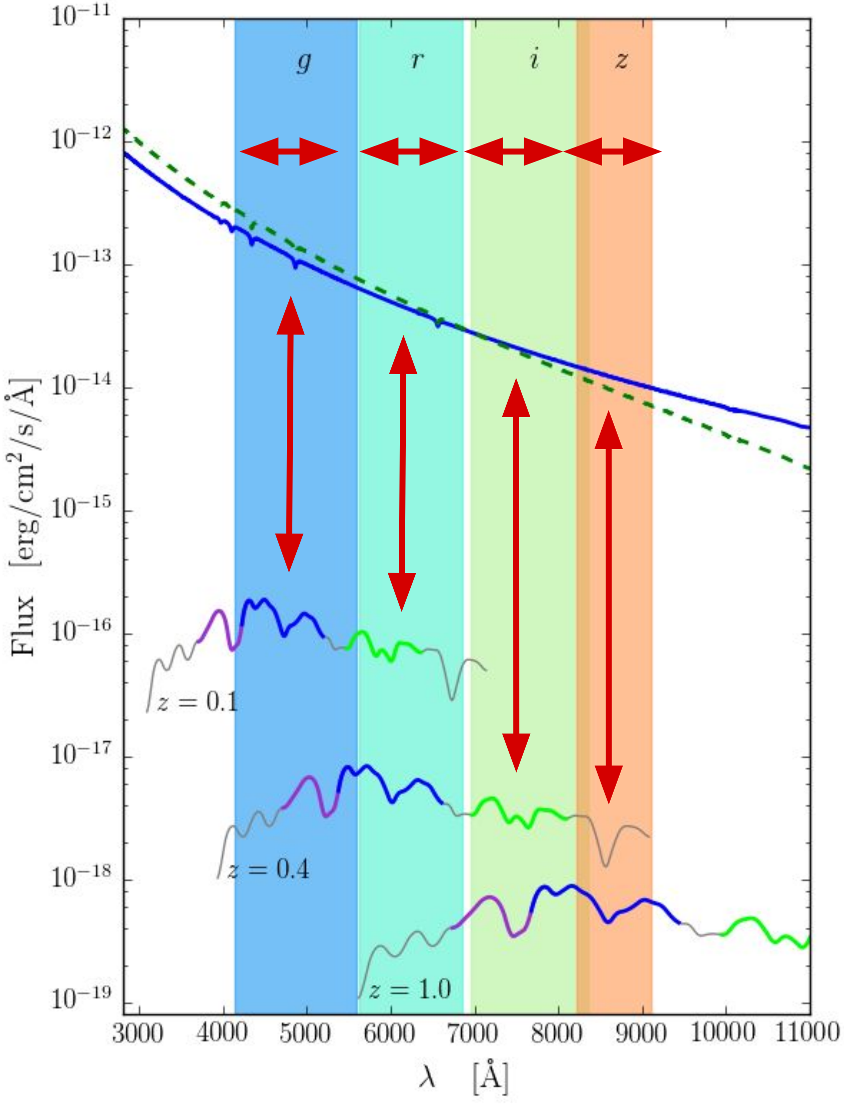
The essence of the measurement



- 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

Minimal requirements for 0.5% accuracy

- Statistical uncertainties
  - At least O(1000) SNe in the low (resp high) redshift bins

$$\frac{\sigma_{SN}}{\sqrt{N_{sn}}} = \frac{0.15}{\sqrt{1500}} \approx 0.004$$

- Calibration systematics

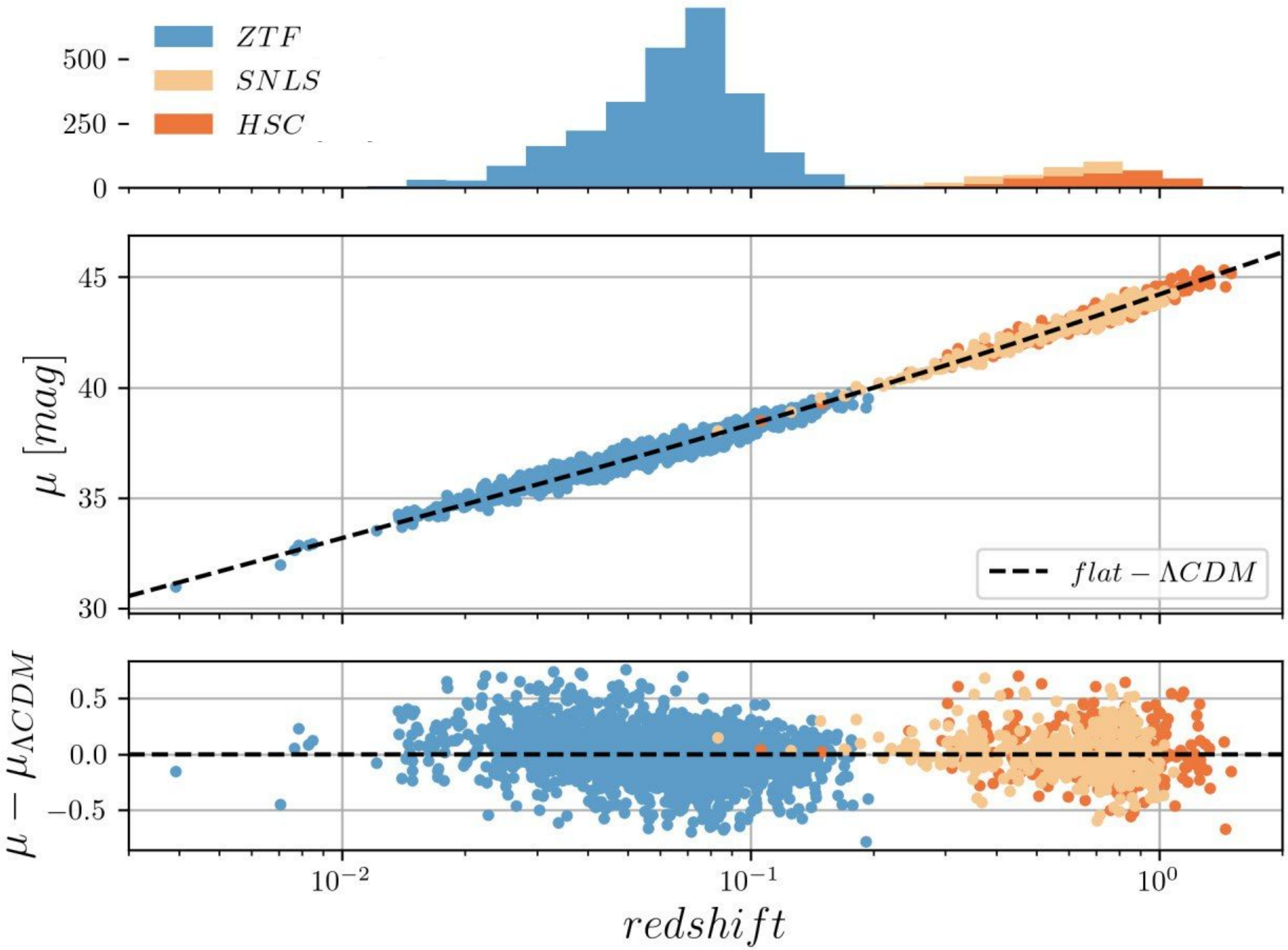
$$\mu \approx B_{\mathrm{restframe}} - 3(B-V)_{\mathrm{restframe}}$$

Source of uncertainty	Scaling of σ_μ	Requirement
Zero-point calib [a]	$\sigma_\mu \approx 3.6\,\sigma_{\mathrm{zp}}$	$\sigma_{\mathrm{zp}} < 0.001$
Bandpass $\bar{\lambda}$ [b]	$\sigma_\mu \approx 11\,\mathrm{mmag\,nm^{-1}}\,\sigma_\lambda$	$\sigma_\lambda < 2\,\mathrm{\AA}$

Requirements (cont'd)

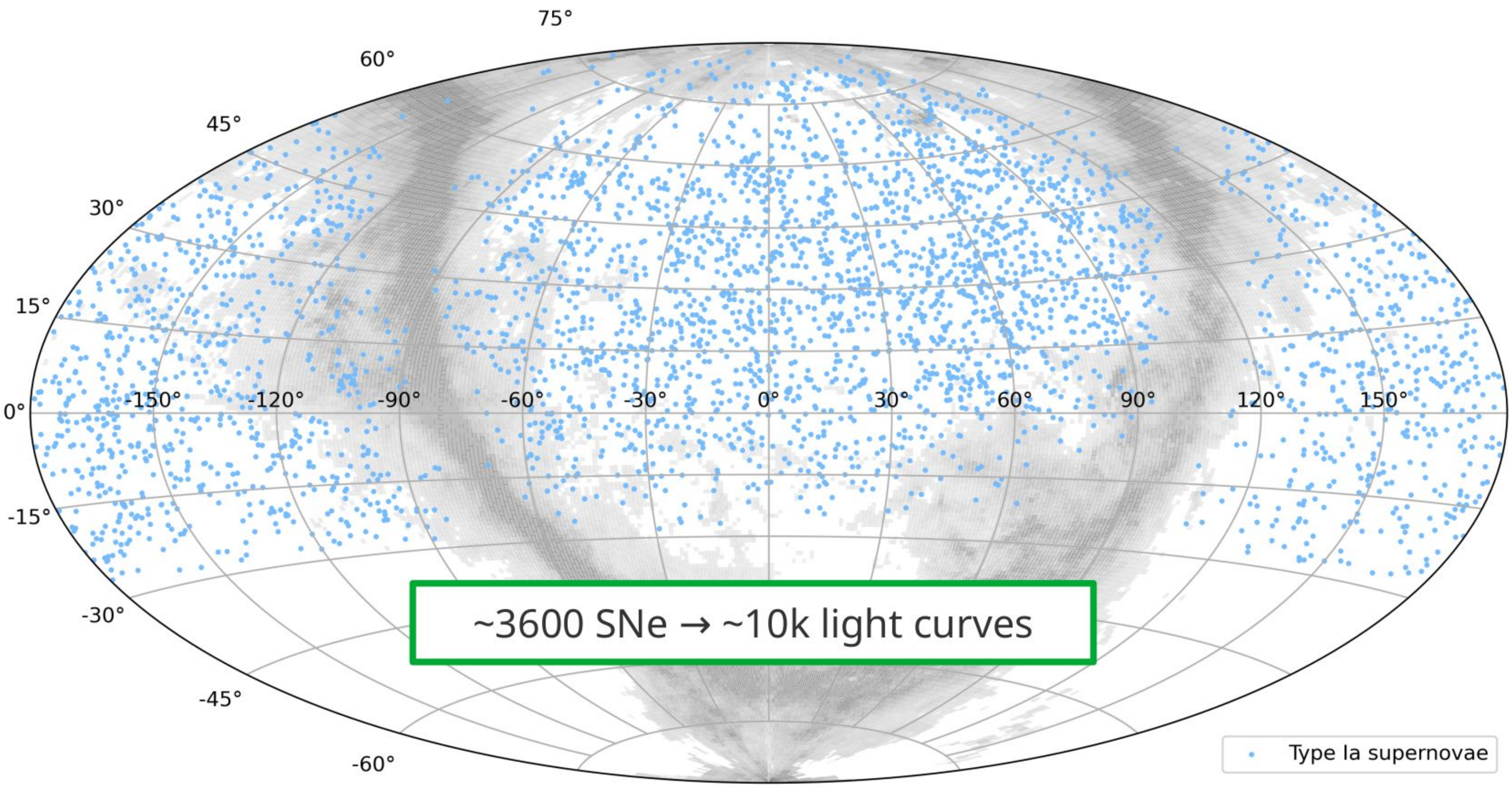
- Redundant flux metrology chain
  - Not only one link from supernova fluxes to primary standards
- Uniform analysis
  - *same* photometry & calibration code
  - for all sne at all redshifts
- ***Blind*** analysis
- Inference pipeline (from calibrated fluxes to cosmology)
  - Kept as simple as possible
  - Testable with O(100) mocks

The LEMAÎTRE Hubble diagram



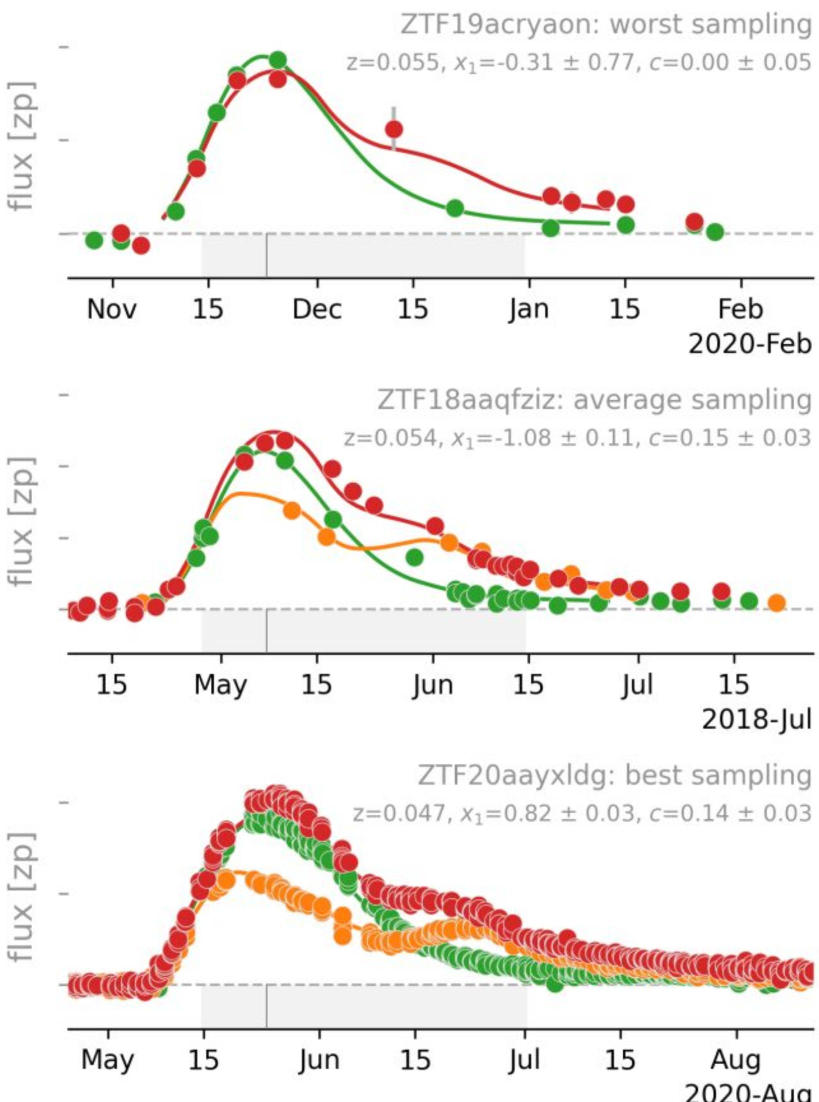
Zwicky Transient Facility

ZTF DR2: 2.5yr, northern sky, high cadence



L. Lacroix

DR2: photometric & spectral coverage

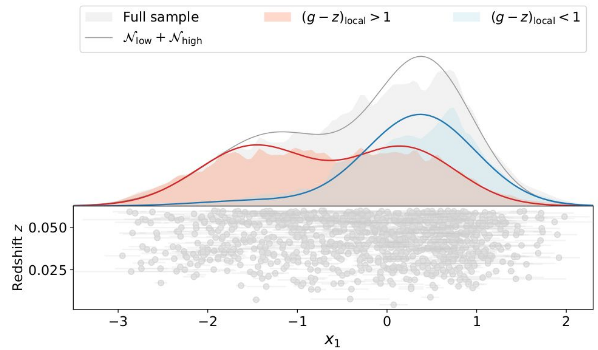


Rigault et al, DR2

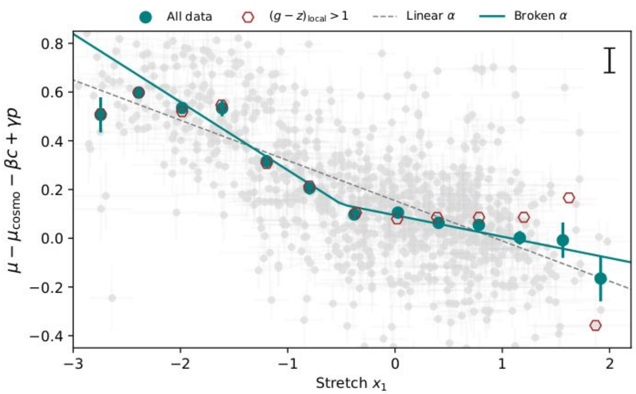
- 3628 SNe, 2668 after light curve quality cuts (sampling)
- Exquisite light curves
- All candidates up to g < 18.5 spectroscopically identified with SEDm. O(5000) spectra.
- Redshifts from (1) public catalogs (60%, incl DESI 40%), SEDm spectra of host or SN (40%)
- Simple selection function: sample is volume-limited up to z<0.06

Era of very large, homogeneous SN samples has begun

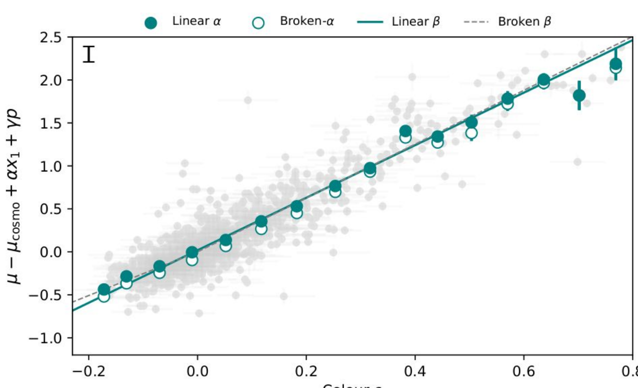
ZTF DR2: population & standardization studies



Bimodal stretch distribution

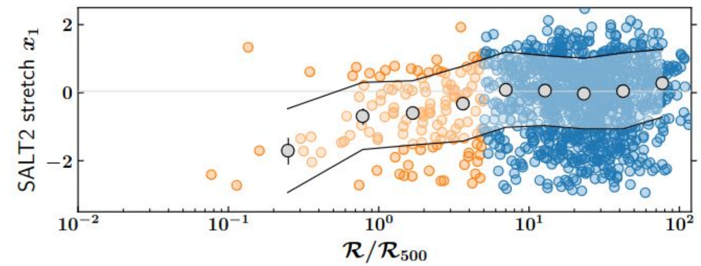


Non-linear stretch-magnitude relation



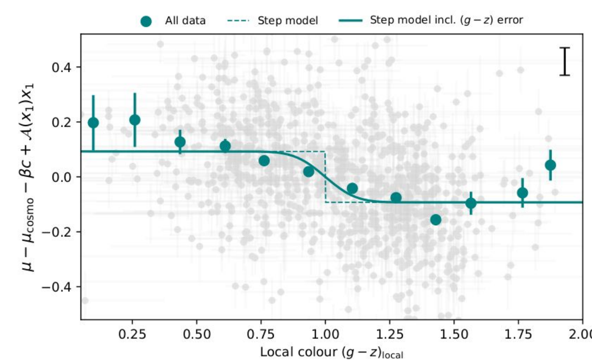
Fully linear color-magnitude relation

Ginolin et al, DR2



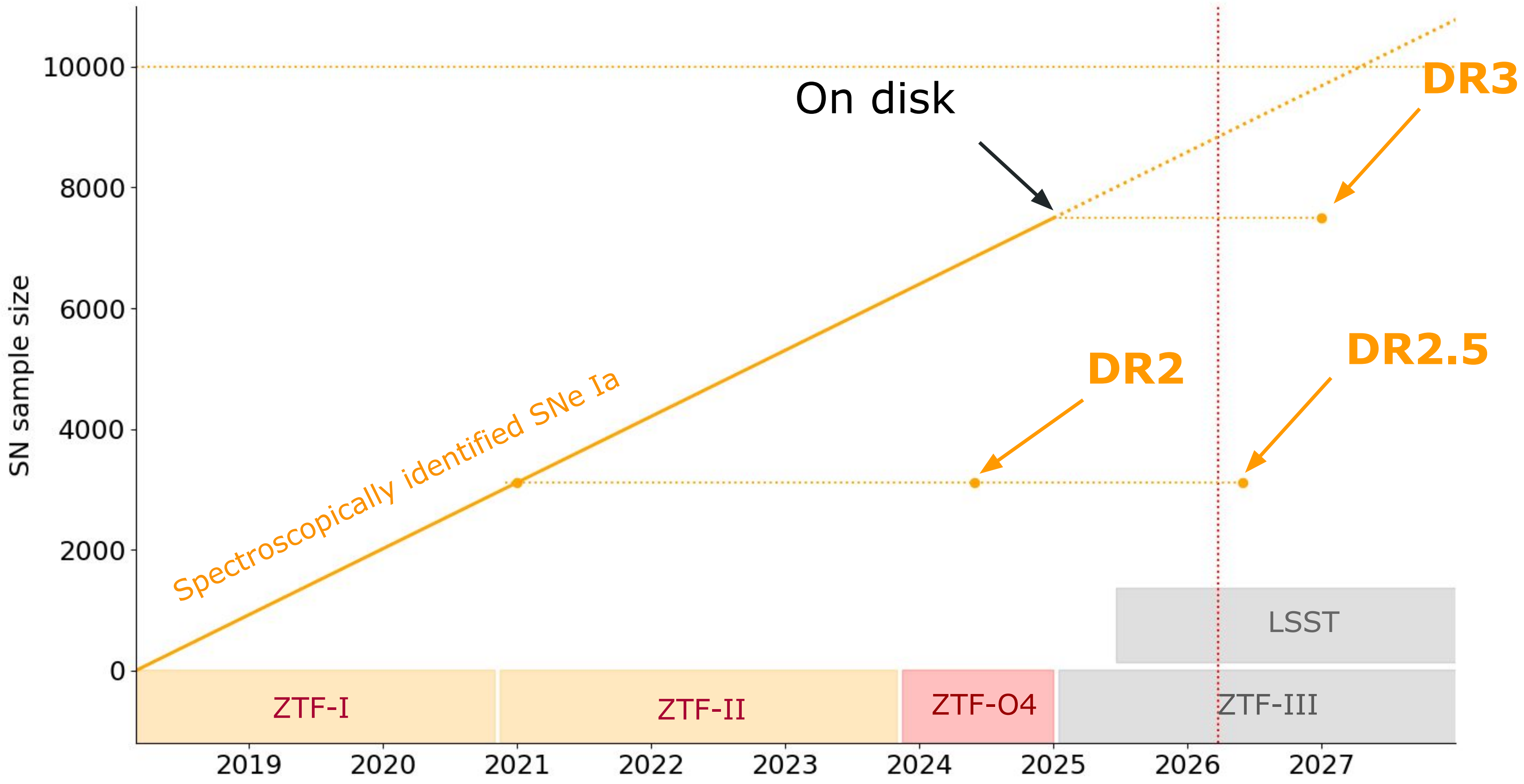
Ruppin et al, DR2

SNe inside clusters have lower stretch (older, non star-forming environments)



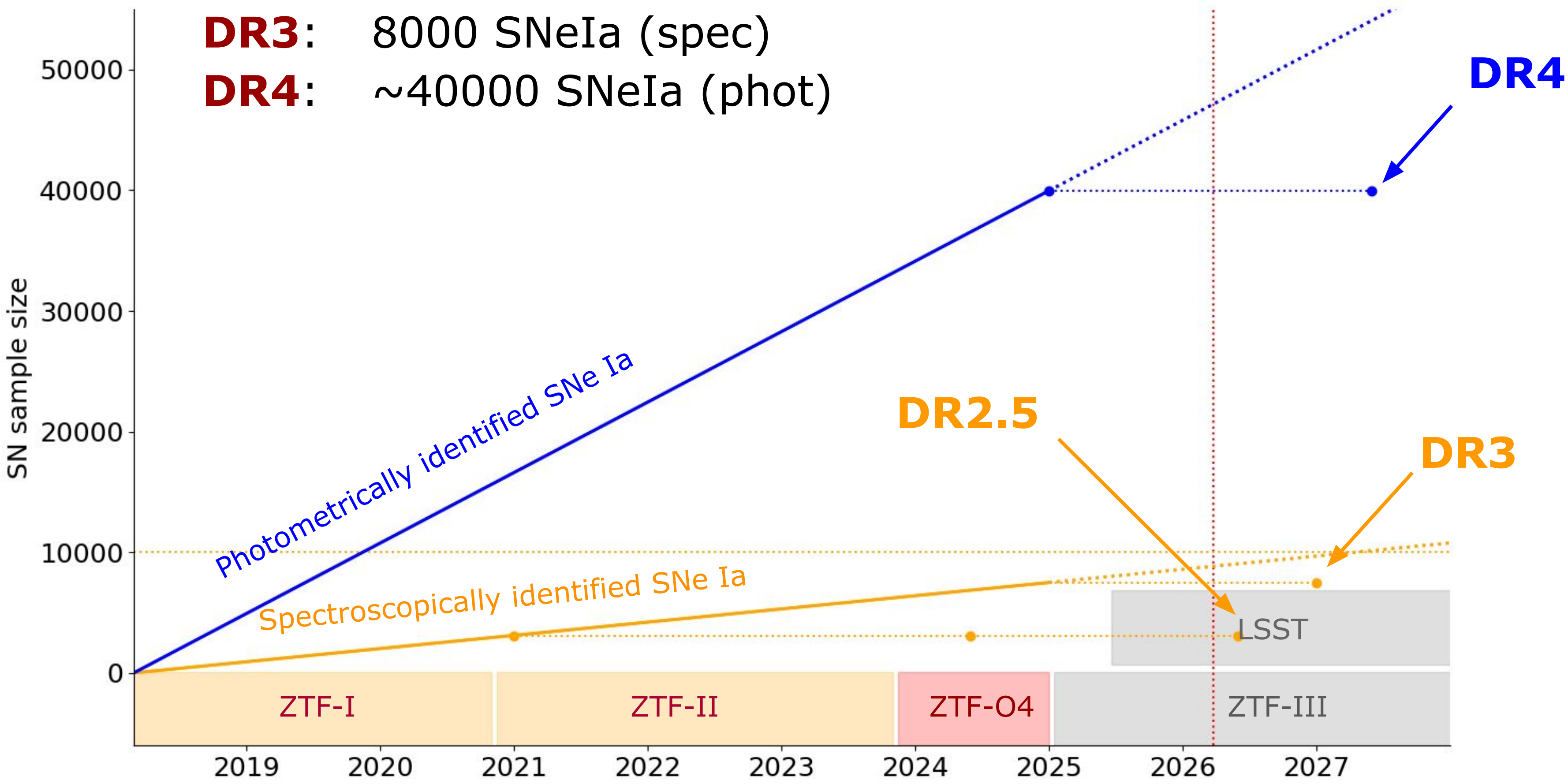
Environmental biases larger than expected ~ 0.18 mag

ZTF data releases

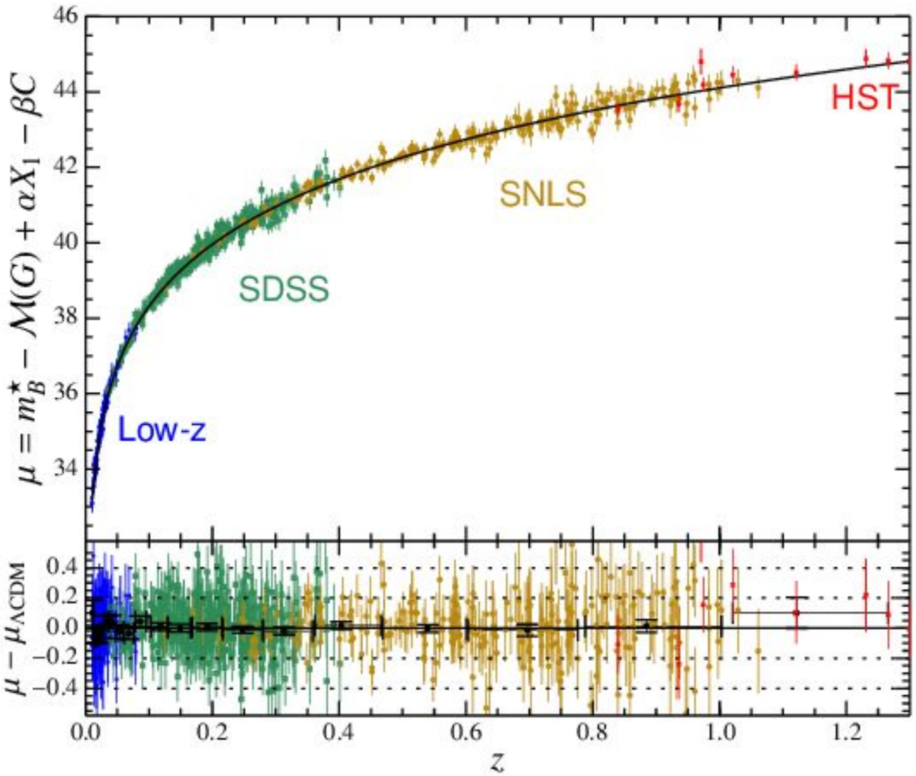


ZTF data releases

DR2.5: 3500 SNeIa (spec)
DR3: 8000 SNeIa (spec)
DR4: ~40000 SNeIa (phot)

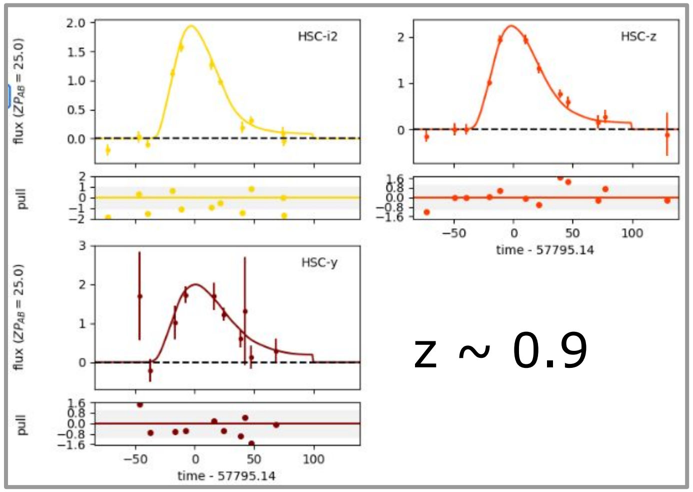


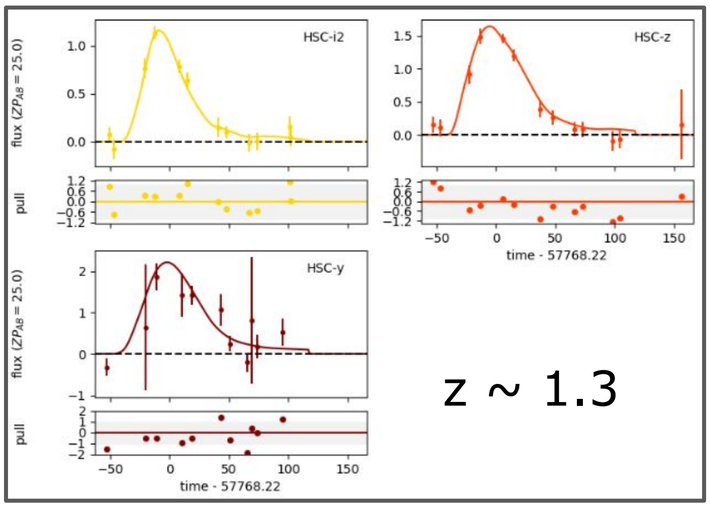
Dataset: (2) SNLS



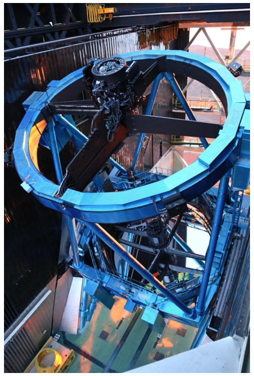
- 171 ***unpublished*** SNe discovered during the last 2 years of ***SNLS***
  - High quality light curves
  - Junction between low-z and high-z dataset
- ***Direct calibration on Calspec***
  - Dedicated program (*MAPC*)
- ***Filter metrology***
  - Decommissioned MegaCam filters remeasured at LAM (Lyon) (Sassolas, Betoule et al)

Dataset (3): Subaru/HSC





C. Saunders



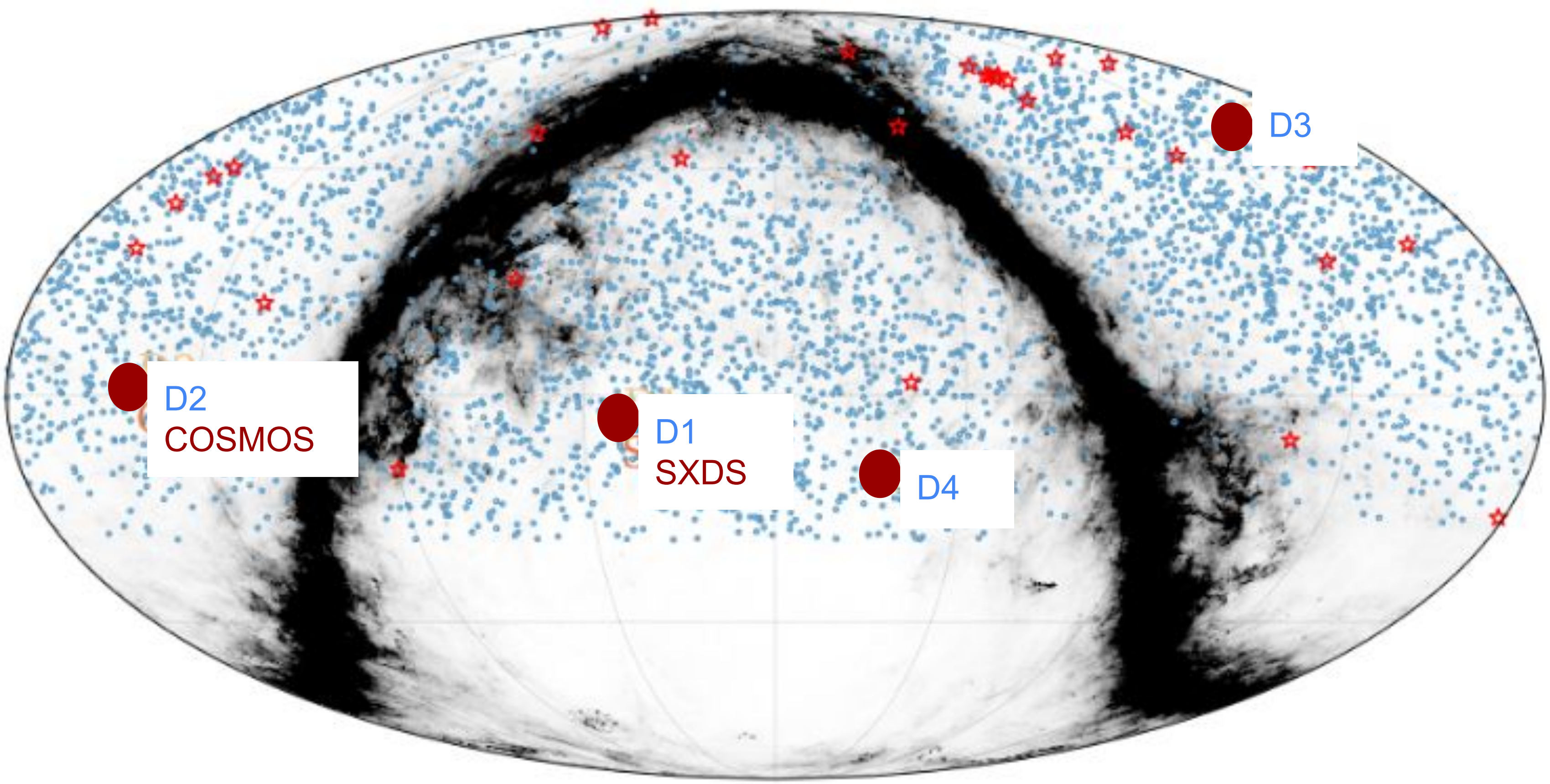
- O(300) very high-z supernovae
- Collected with HyperSuprimeCam
  - 2 seasons / 2 fields
  - g,r,i,z,Y follow-up
- Redshifts collected with
  - Subaru-FOCAS / AAT / DESI
  - Median redshift: ~ 0.8
- No direct calibration to CALSPEC
  - Same sky as SNLS & ZTF

Project led by N. Suzuki (FSU), N. Yasuda (IPMU), D. Rubin (Hawaii)

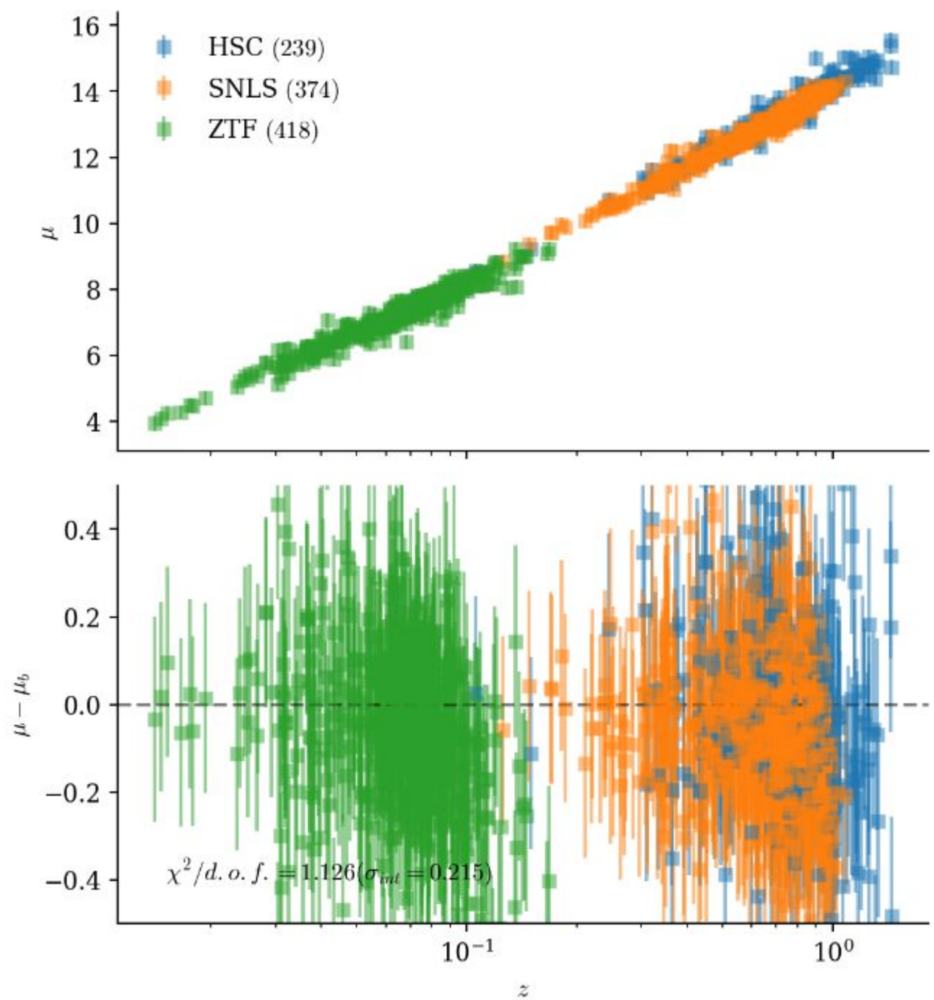
The Lemaitre Project

- Independant analysis, of the w-wa tension
    - Fully **independant** dataset
    - With approximately the same constraining power
    - Same processing pipeline / calibration chain for all
- Dataset
    - Low-z: 3 first years of ZTF ~ 3000 SNe
    - Medium-z: 2 last years of SNLS ~ O(200) SNe
    - High-z: HyperSuprimeCam survey ~ O(300) SNe
- **Direct**, **explicit** and **redundant** calibration chain
    - From the SNe to the Primary flux standards
- **Fully rewritten analysis chain**

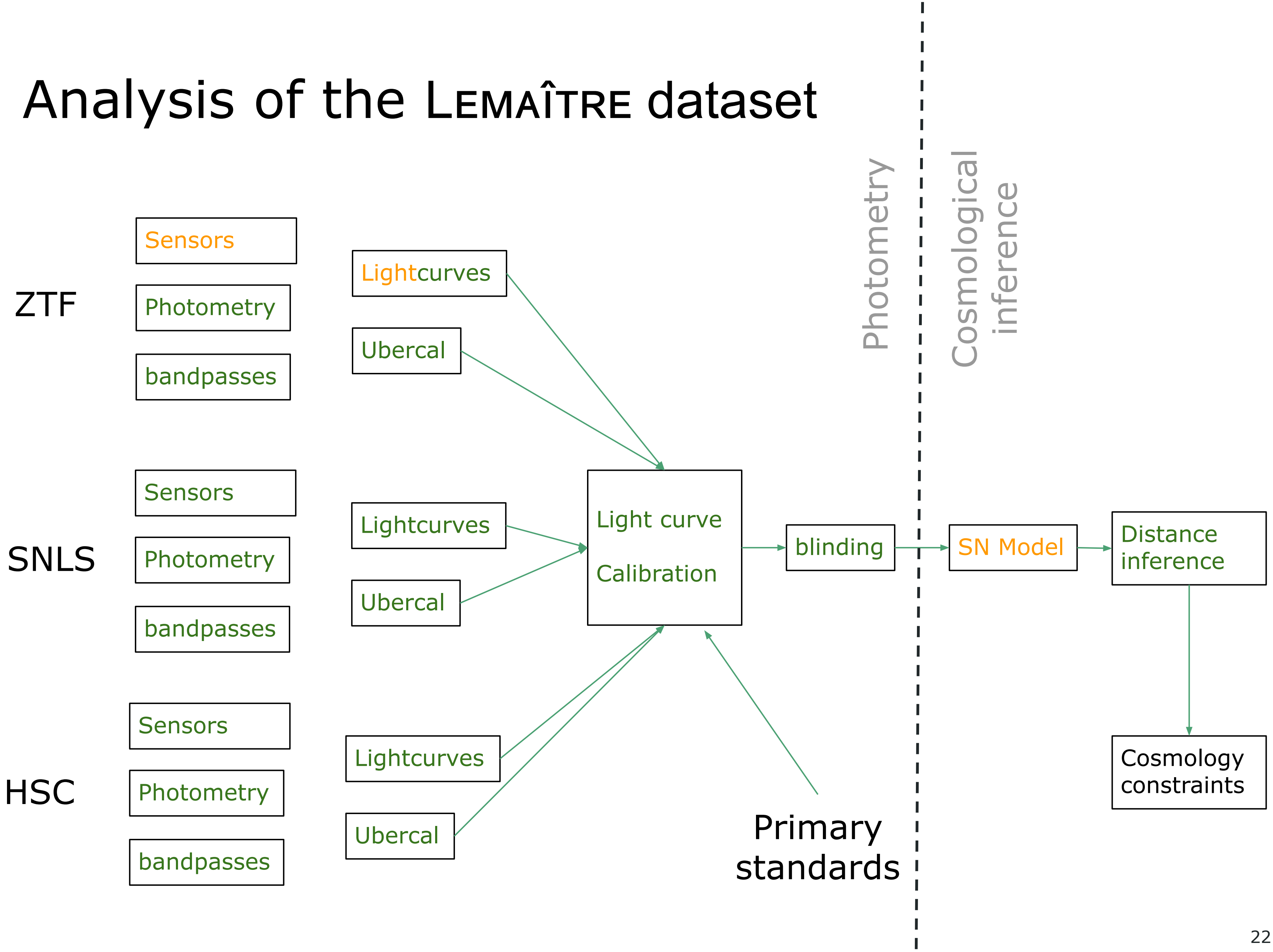
The Lemaître Dataset



The LEMAÎTRE Hubble Diagram

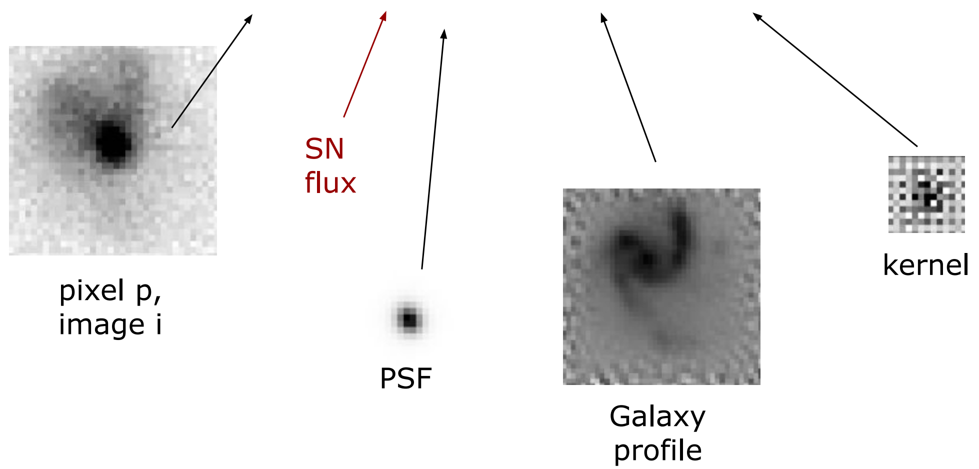


Analysis of the Lemaître dataset



Scene modeling photometry

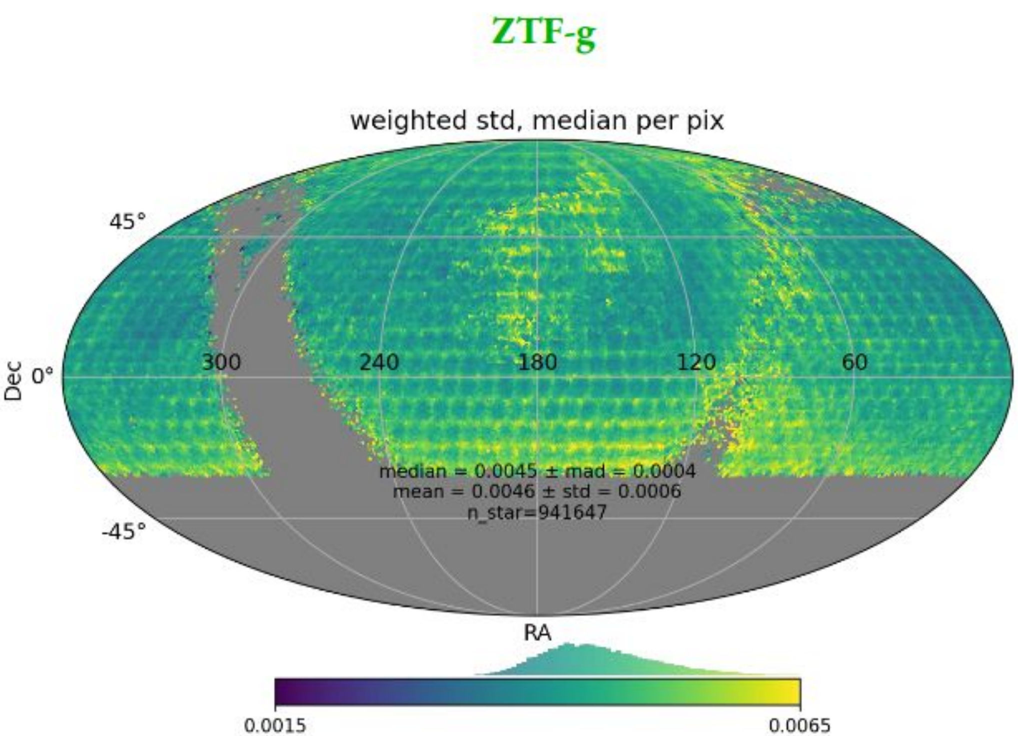
$$I_{ip} = f_i \, \phi_i + \mathrm{Gal} \otimes K_i + \ldots$$



- Forward model of image sequence
- Simultaneous fit of
  - Galaxy profile
  - SN fluxes
- Same estimator applied to
  - supernova
  - Field stars
- Autocancellation of photometry biases (except linearity)

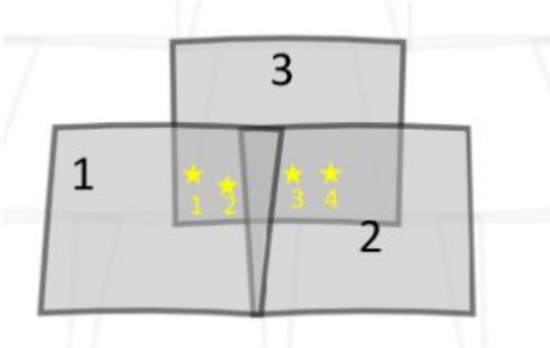
- In LEMAÎTRE, all 3 surveys are reduced with the *same* SMP code
- Demonstrated to be accurate at the 0.1% (Astier et al, 2013)
- For ZTF: 0.02 - 0.05 mag shifts w.r.t forced photometry (Lacroix et al, 2025)

Calibration catalog(s)



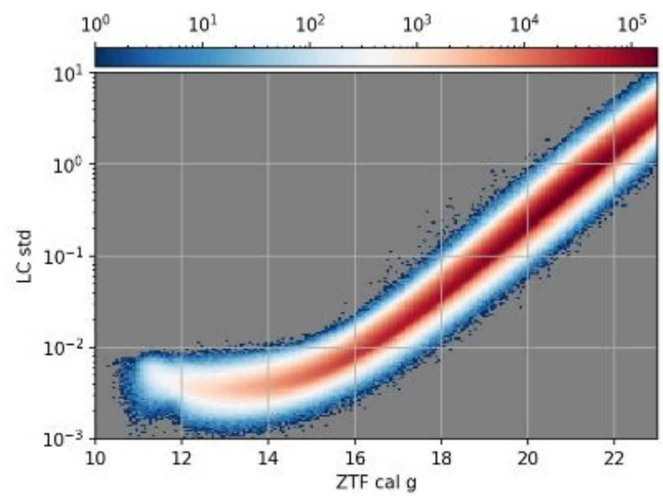
Precision on bright stars = 4.5 ‰

Plot : Benjamin Racine



Method :

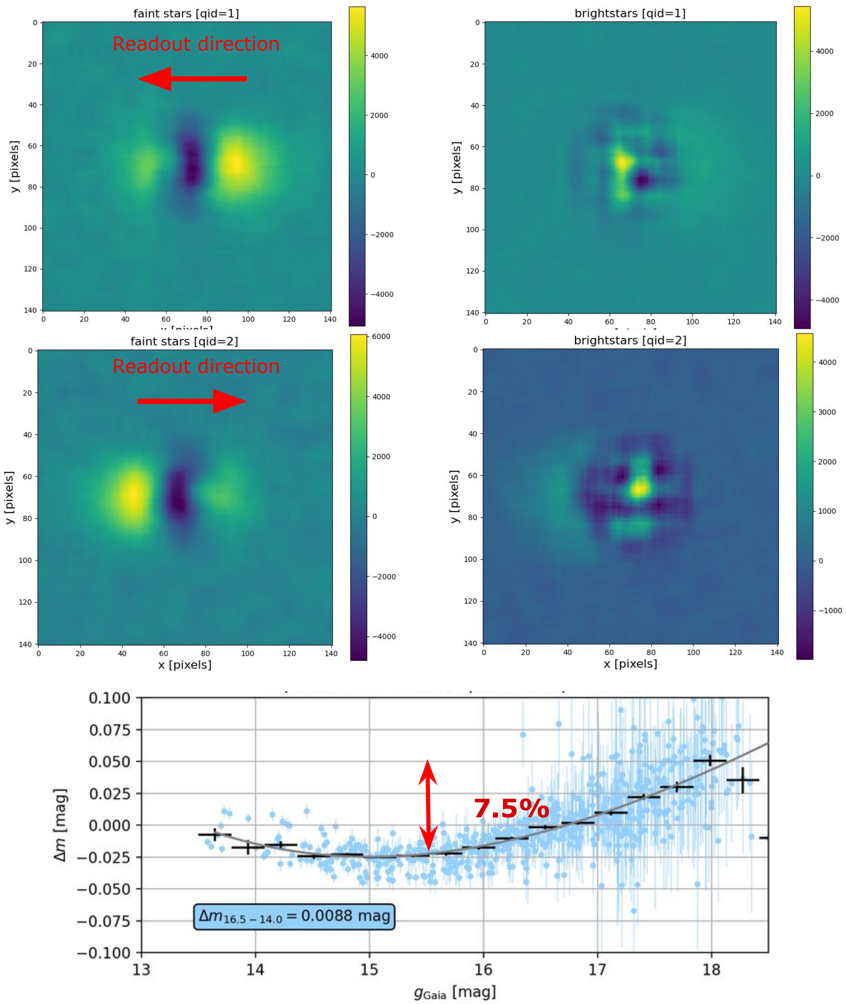
$$m_{i_{star}} + ZP_{j_{field}} = m^{obs}_{i_{star}, j_{field}}$$



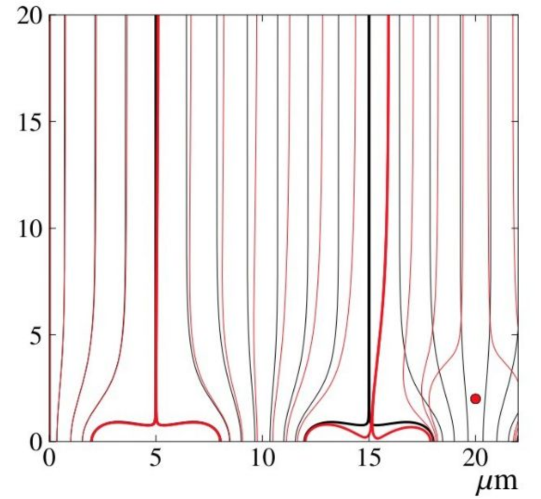
Linearity / sensor effects

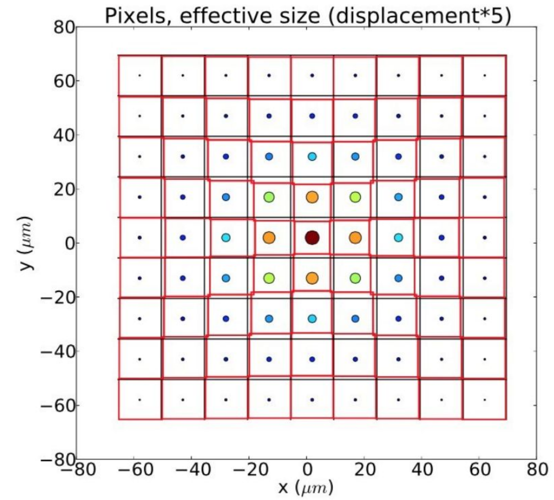
Sensor effects affect the PSF shape in a flux-dependent way

ZTF: pocket effect

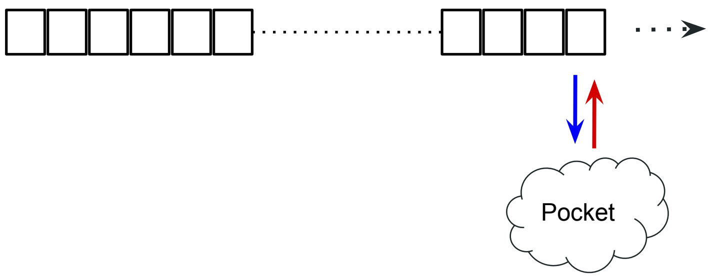


All surveys : brighter-fatter

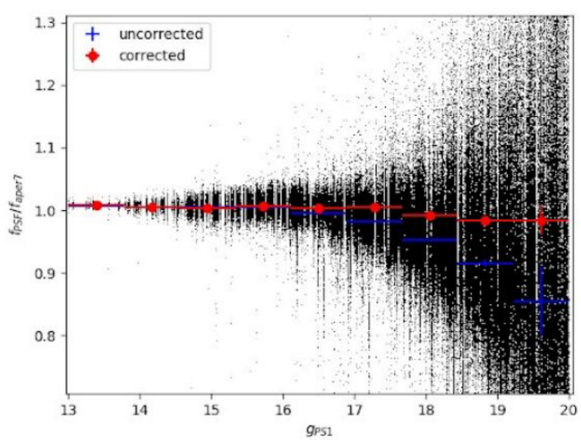


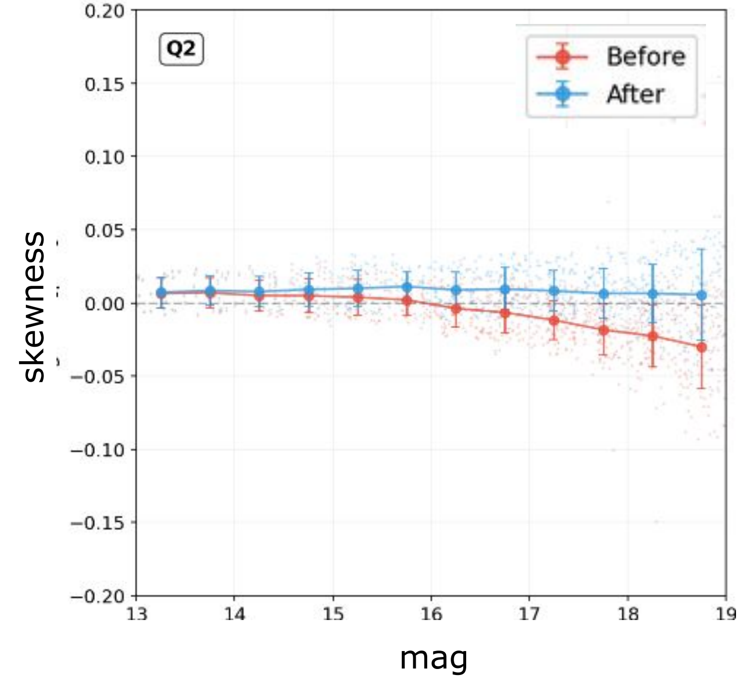


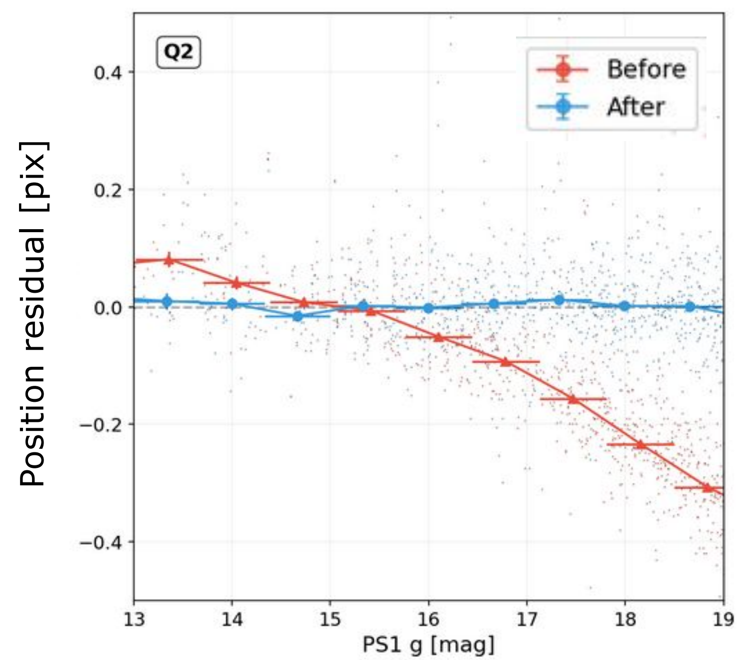
ZTF “pocket” effect



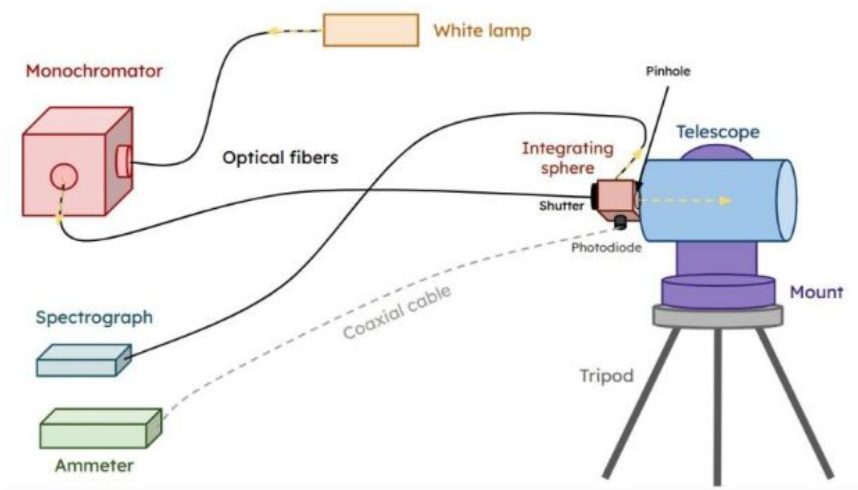
- Large trap (pocket) near end of CCD serial register
- Capture/release of electrons during readout
- Depends on: CCD / channel, Time , sky-level, CCD-temperature, …
- Ruled by a pocket - pixel equilibrium function
- Correction at pixel-level

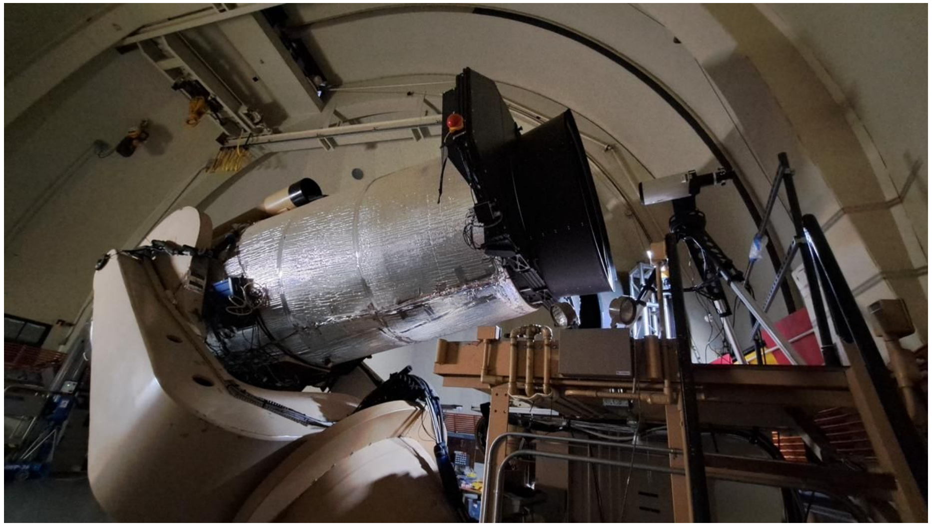






Bandpass metrology & calibration

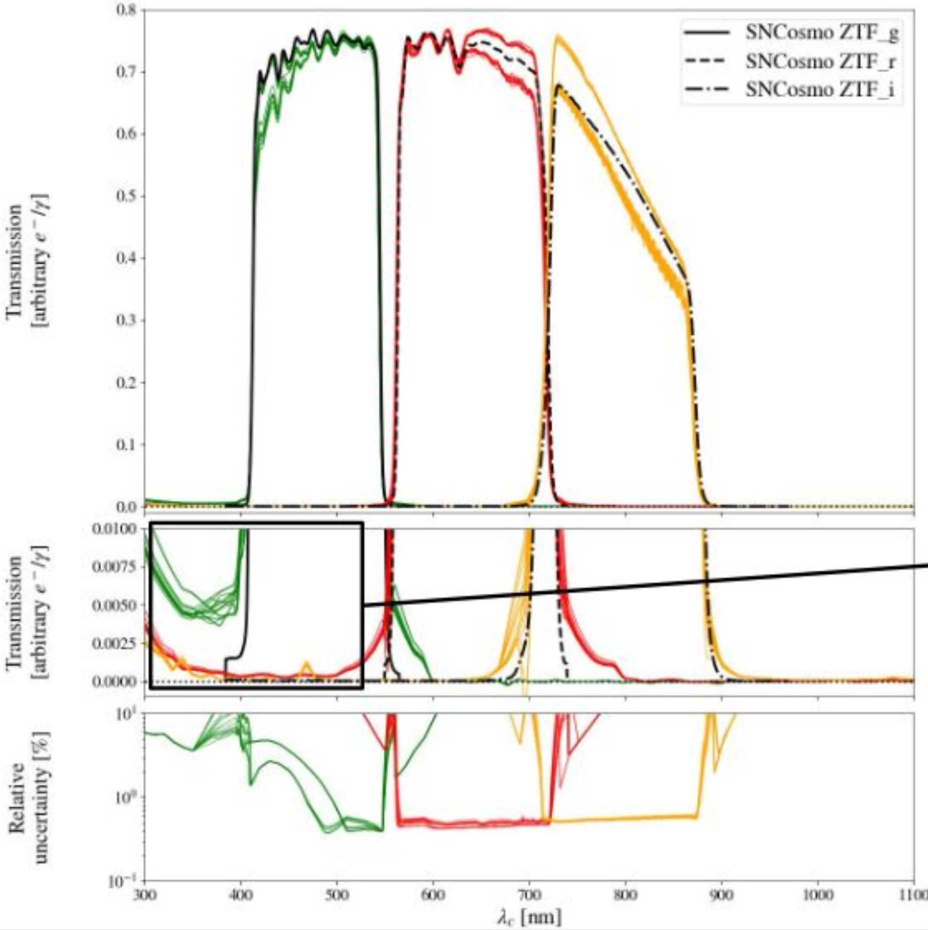




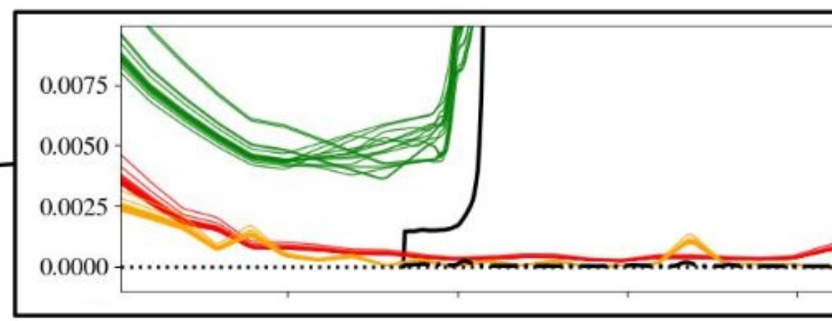
- Team sent to Palomar to measure ZTF bandpasses
- **TCBP**: Traveling Collimated Beam Projector
    - Injects monochromatic pencil beam in telescope optics
    - With controlled flux and wavelength

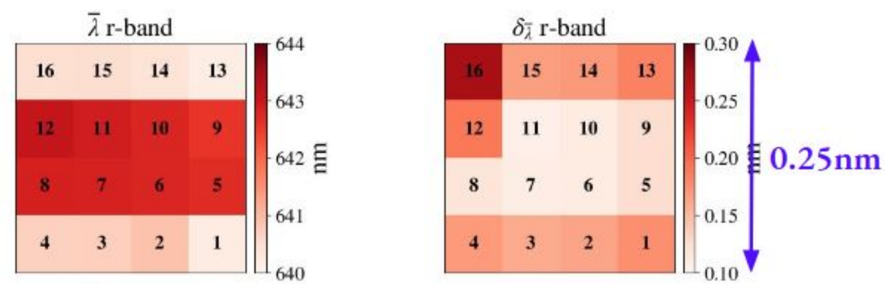
Van den Abeele, Barjoux, Aubert, Neveu, Rosnet, Sepulveda

Passband metrology & calibration



- One transmission curve per CCD, measured with uncertainties < % level in the passband
- Strong differences with public models (black curves)

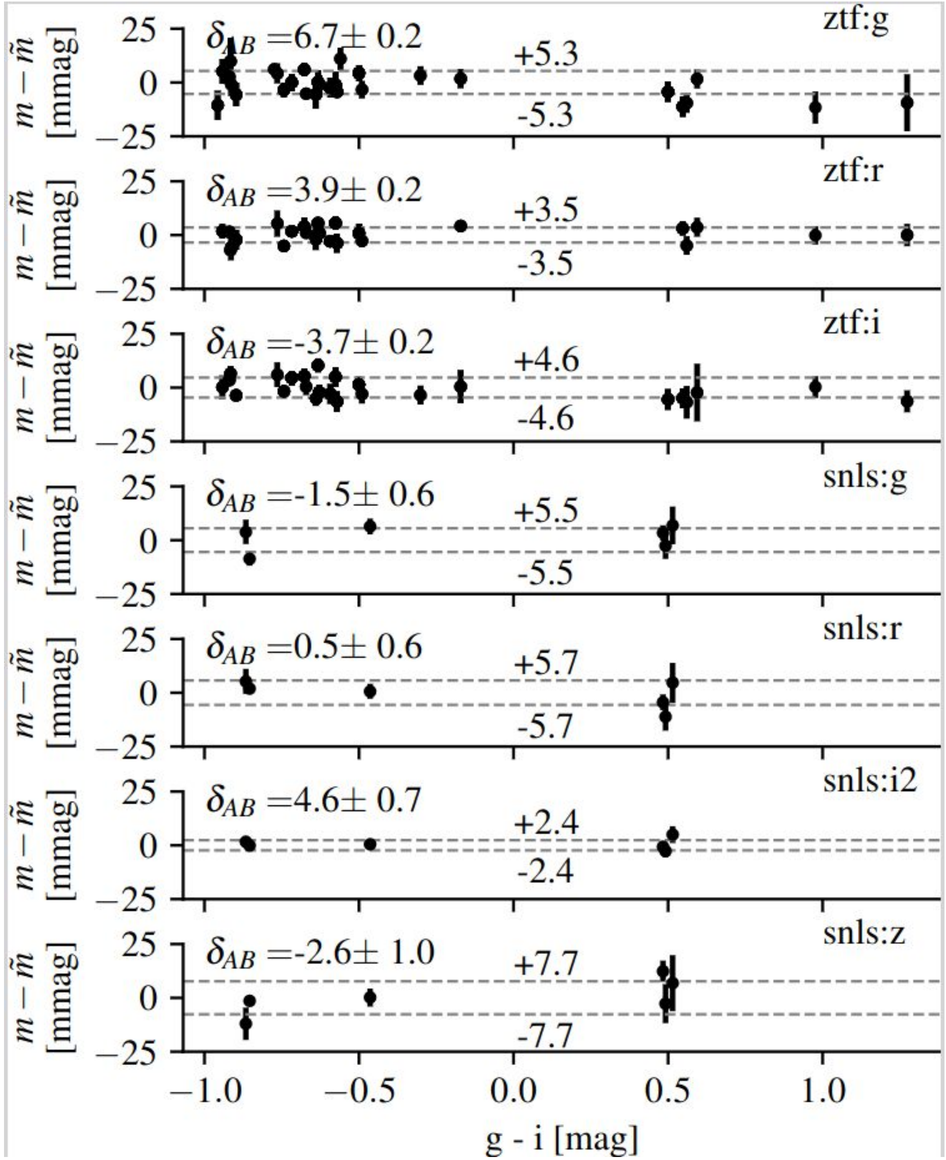


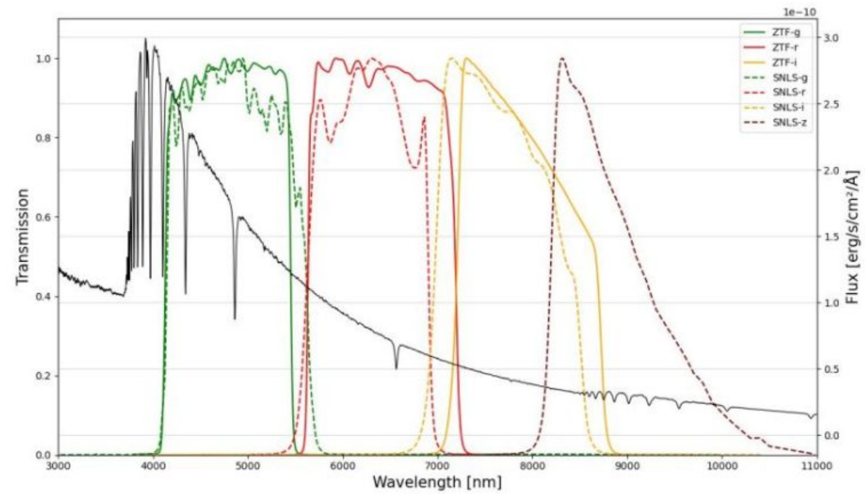


Uncertainties: 2-7A

Van den Abeele et al

Absolute calibration

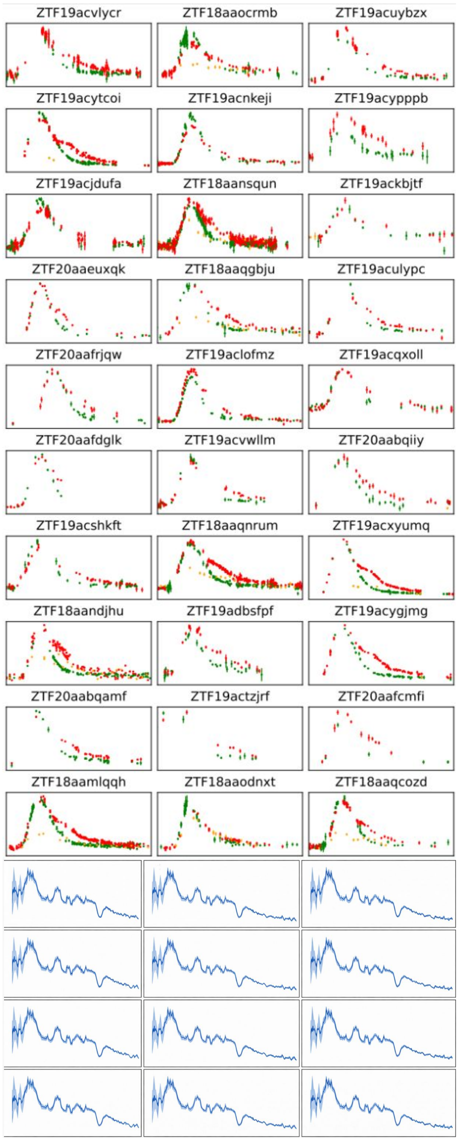




- Primary flux standards give absolute flux scale
- Per-mil precision reached:
  - ZTF: < 0.1%
  - SNLS ~ 0.2%

Lejeune et al, in prep.

NaCl



Osman, Regnault et al in prep.

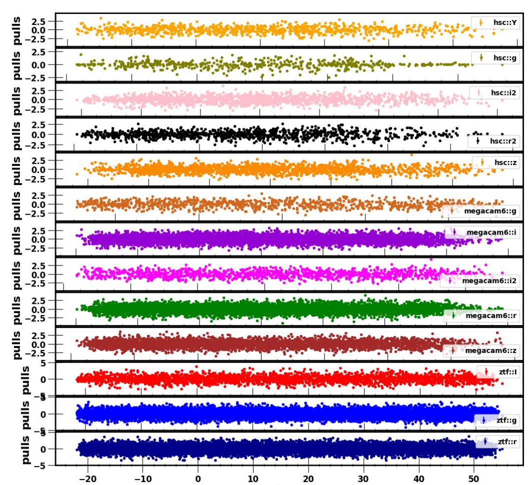
Calibration covmat

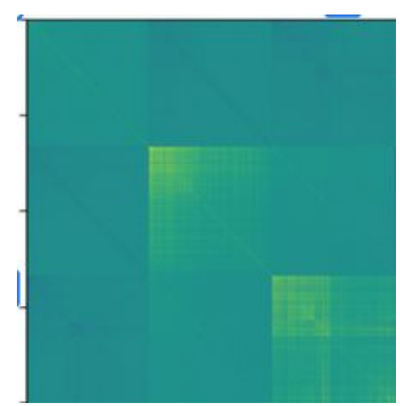
Bandpass models

Model training

light curve fitting

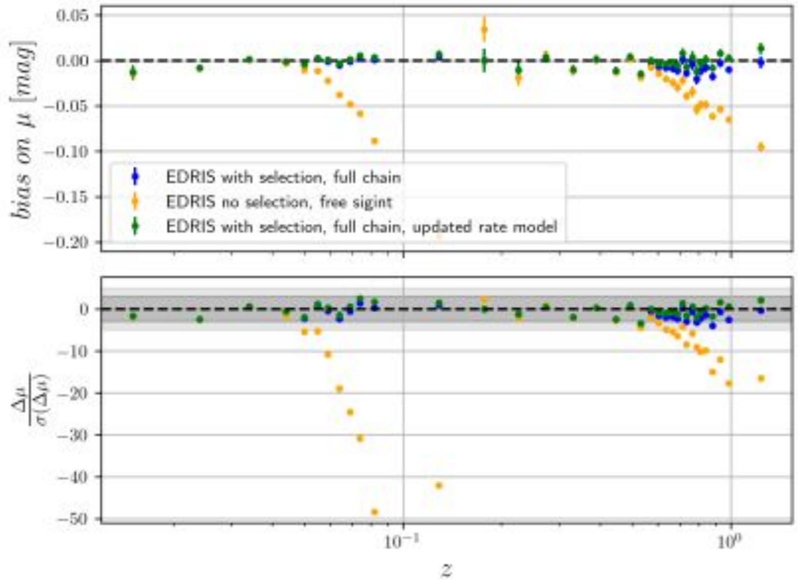
$$\begin{pmatrix} \begin{pmatrix} x_{0,1} \\ \vdots \\ x_{0,N} \end{pmatrix} \\ \begin{pmatrix} x_{1,1} \\ \vdots \\ x_{1,N} \end{pmatrix} \\ \begin{pmatrix} c_1 \\ \vdots \\ c_N \end{pmatrix} \end{pmatrix}$$

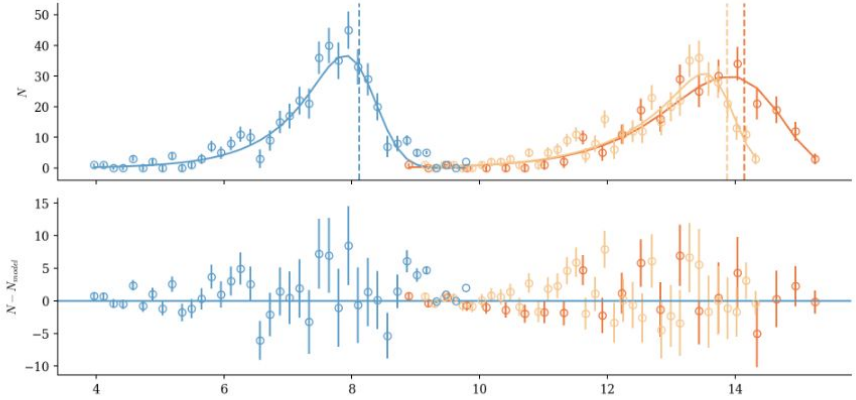




EDRIS

- Direct, unbiased MLE of
  - standardized distances
  - selection functions
  - (frequentist analog to Unity)
- Advantages
  - fast
  - No simulation in the inference
  - Testable on O(100) mocks at no cost
- Selection functions
  - 3 rolling search surveys
  - Uncertainties on selection funct can be neglected





Kuhn, Betoule et al, in prep

EDRIS

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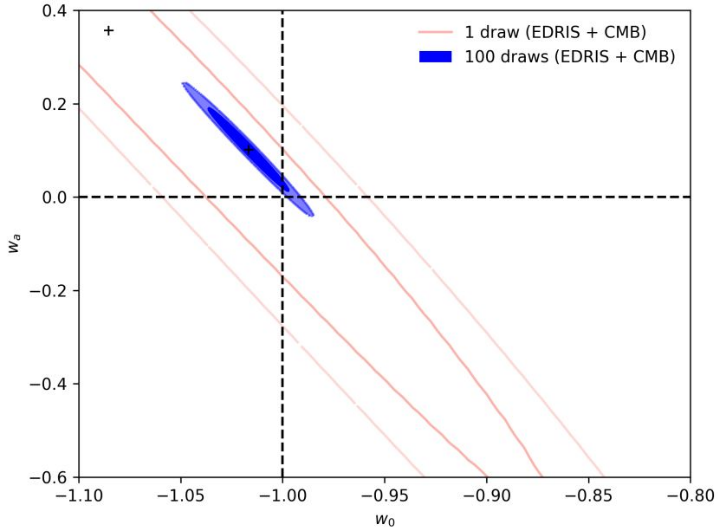
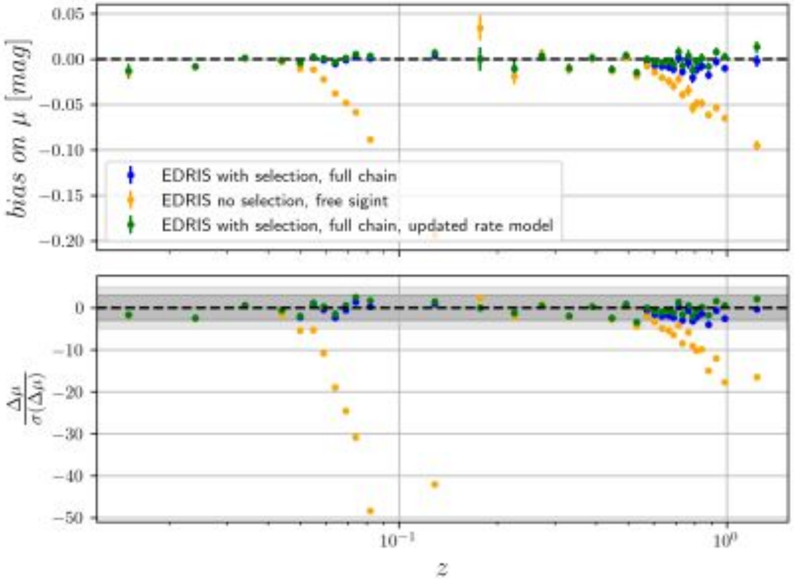
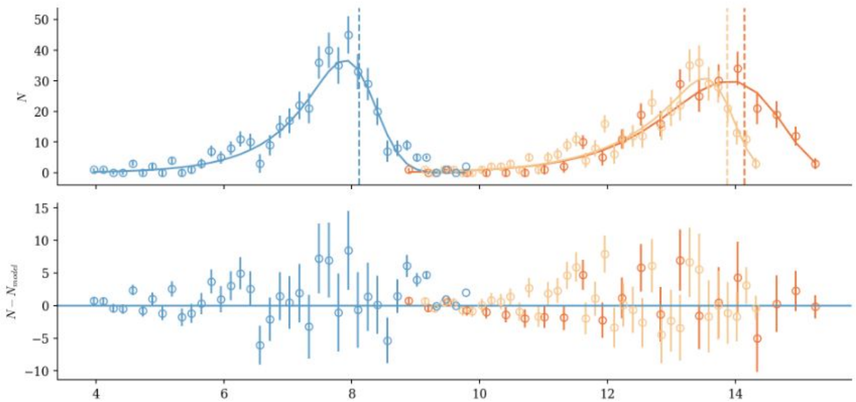
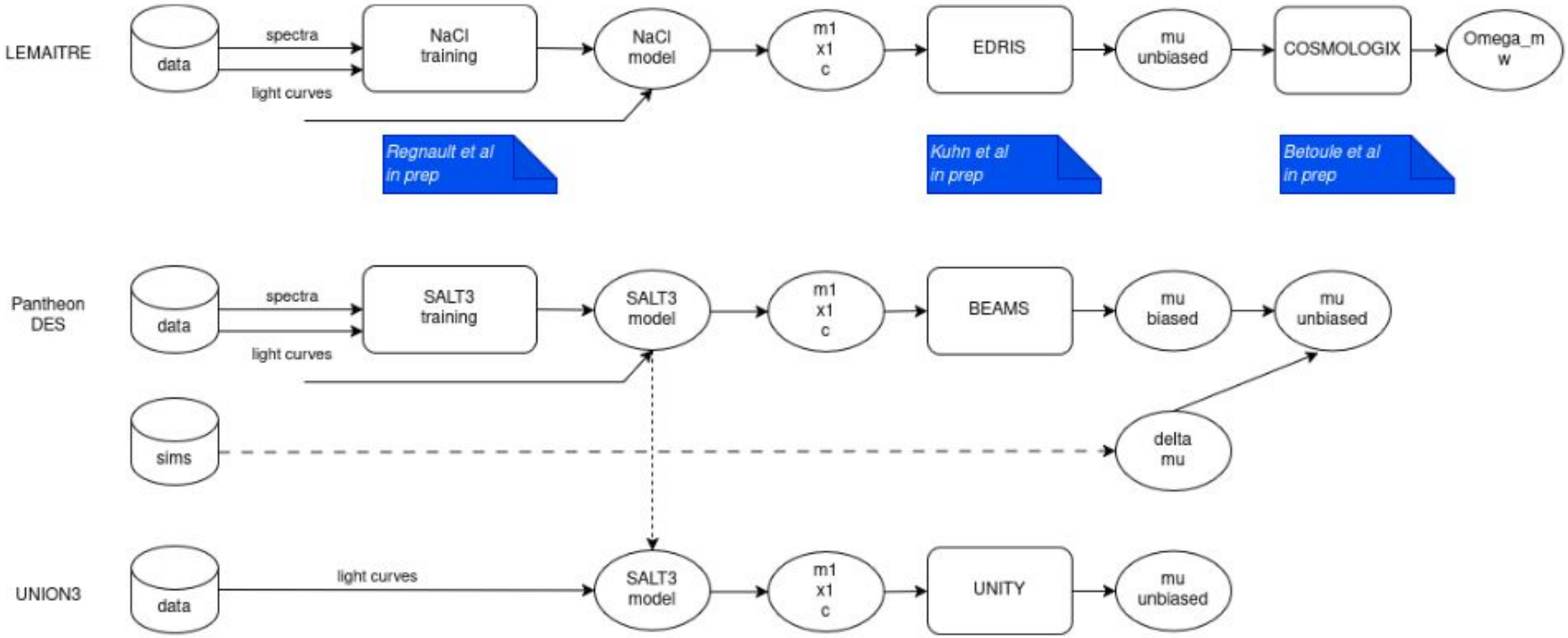




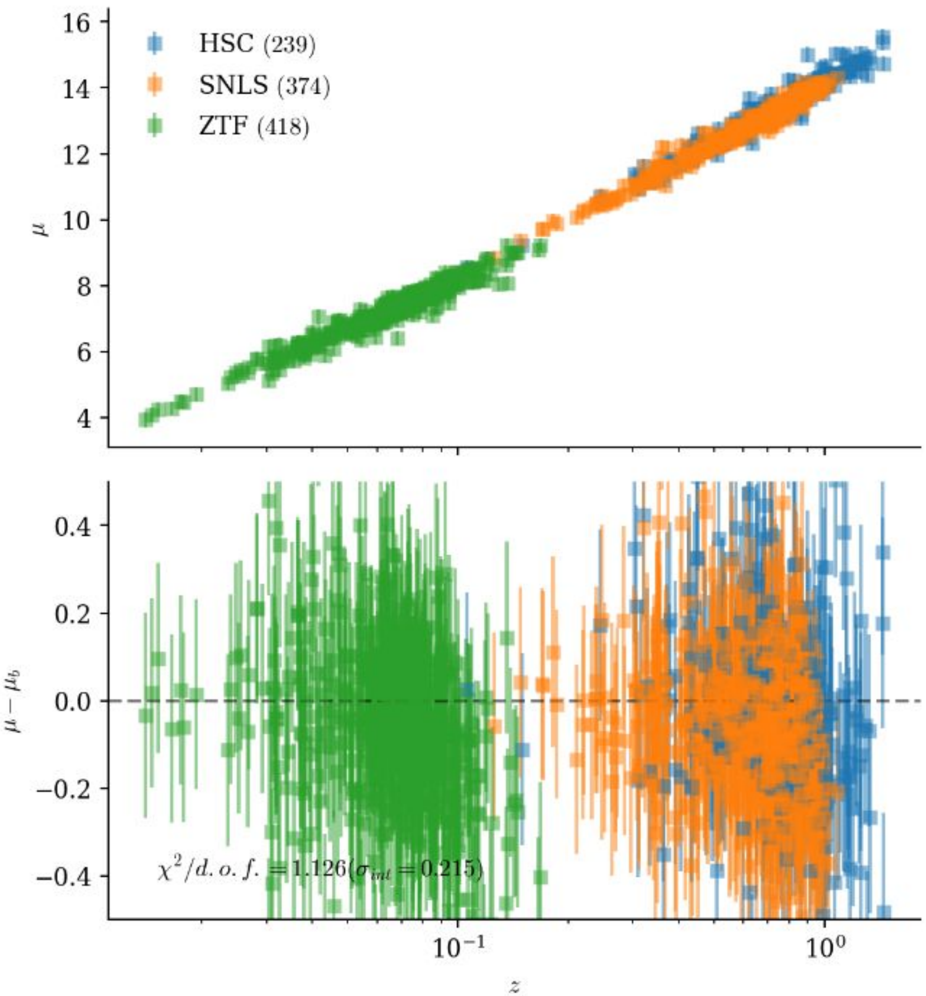


Kuhn, Betoule et al, in prep

Inference chain : *Georges*



Conclusion



- The LEMAÎTRE data sample
  - Statistically independent of all previous compilations
  - Solves most potential issues in the current low-z samples
- Blind analysis
  - Unblinding when inference chain validated in data challenges.