Accurate measurement of telescope filter bandpasses with a Collimated Beam Projector and impact on cosmological parameters

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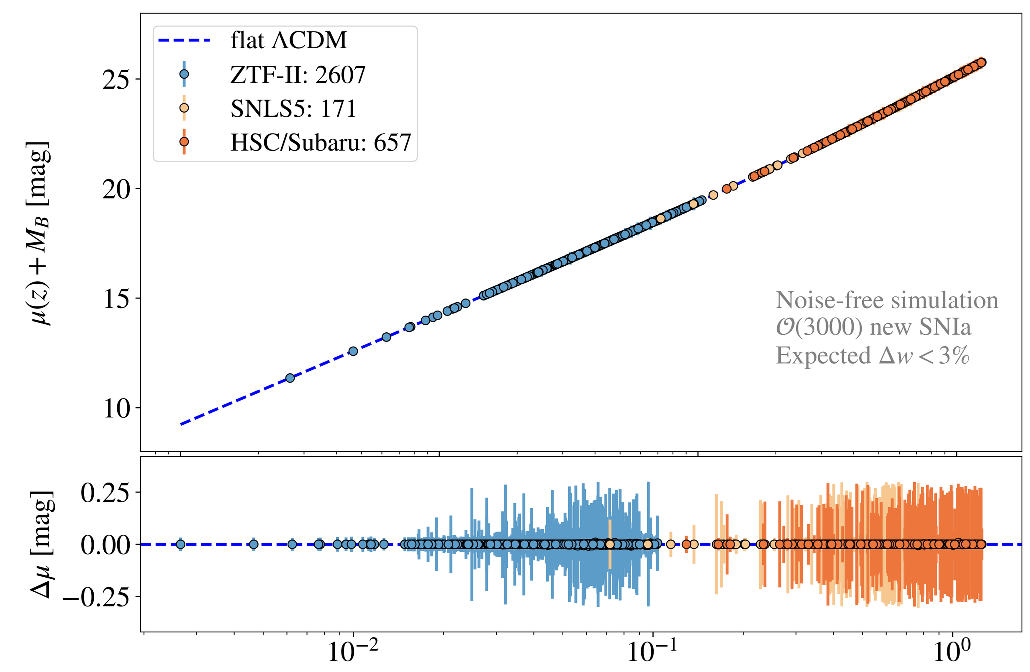
Abstract

The measurement of magnitudes with different filters in photometric surveys gives access to cosmological distances and parameters. However, for current and future large surveys like the ZTF, DES, HSC or LSST, the photometric calibration uncertainties are almost comparable to statistical uncertainties in the error budget of type Ia cosmology analysis, which limits our ability to use type Ia supernovae for precision cosmology. The knowledge of the bandpasses of the survey filters at the per-mill level can help reach the sub-percent precision for magnitudes. We will show how a misknowledge of the bandpasses central wavelengths or of the presence of out-of-band leakages leads to biased cosmological measurements. Then, we will present how to measure the filter throughputs at the required precision with a Collimated Beam Projector (CBP). We built a CBP with a tunable laser source and a reversed telescope to make a parallel monochromatic light beam monitored in flux and wavelength. We tested its performance on the measurement of the StarDICE telescope filters. After carefully analysing the systematic uncertainties, we will show that we reached the sub-nanometer accuracy on the filter central wavelengths and detected out-of-band leakages at the sub-per mill level.

The LEMAÎTRE type Ia supernova Hubble diagram

LEMAÎTRE: *Latest Extended Mapping of Acceleration with an Independent Trove of Redshifted Explosions.*



LEMAÎTRE project is the combination of 3 new and independent surveys of $\approx$ 3000 spectroscopically confirmed SNe Ia, anchored on an instrumental photometric calibration.

Hubble-Lemaître diagram modelling from observed magnitude m_X in band X to cosmological parameters involves colour transformations, cosmology and astrophysics:

$$m_B^* = \underbrace{m_X - K_{XB}}_{\text{observations}} = \underbrace{\mu(z)}_{\text{cosmology}} + \underbrace{M_B + \alpha x_1 + \beta c + \Delta M_{\text{host}}}_{\text{astrophysics}}$$

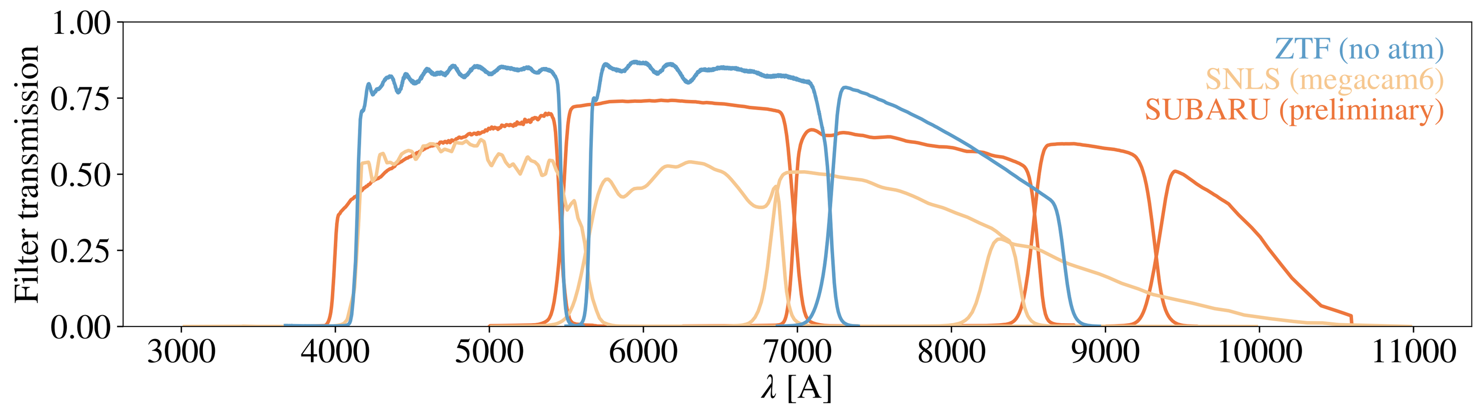
- $\mu(z)$, the distance modulus that contains the cosmological model;
- $M_B + \alpha x_1 + \beta c + \Delta M_{\text{host}}$, the SNIa absolute magnitude in band B;
- $K_{XB}(z)$, the K-correction represents the correction in magnitude that would have to be made if the star were observed in its reference frame at rest; it depends on the **redshift z and of the knowledge of transmissions**.

$$K_{XB} = -2.5\log_{10}\left[\frac{1}{(1+z)}\frac{\int \lambda d\lambda F_{\text{ref}}(\lambda)B(\lambda)\int \lambda d\lambda L_\lambda(\lambda/(1+z))T_X(\lambda)T_{\text{atm}}(\lambda)}{\int \lambda d\lambda F_{\text{ref}}(\lambda)T_X(\lambda)T_{\text{atm}}(\lambda)\int \lambda d\lambda L_\lambda(\lambda)B(\lambda)}\right]$$

Every factor must be well-known in order to measure w at the sub-percent level.

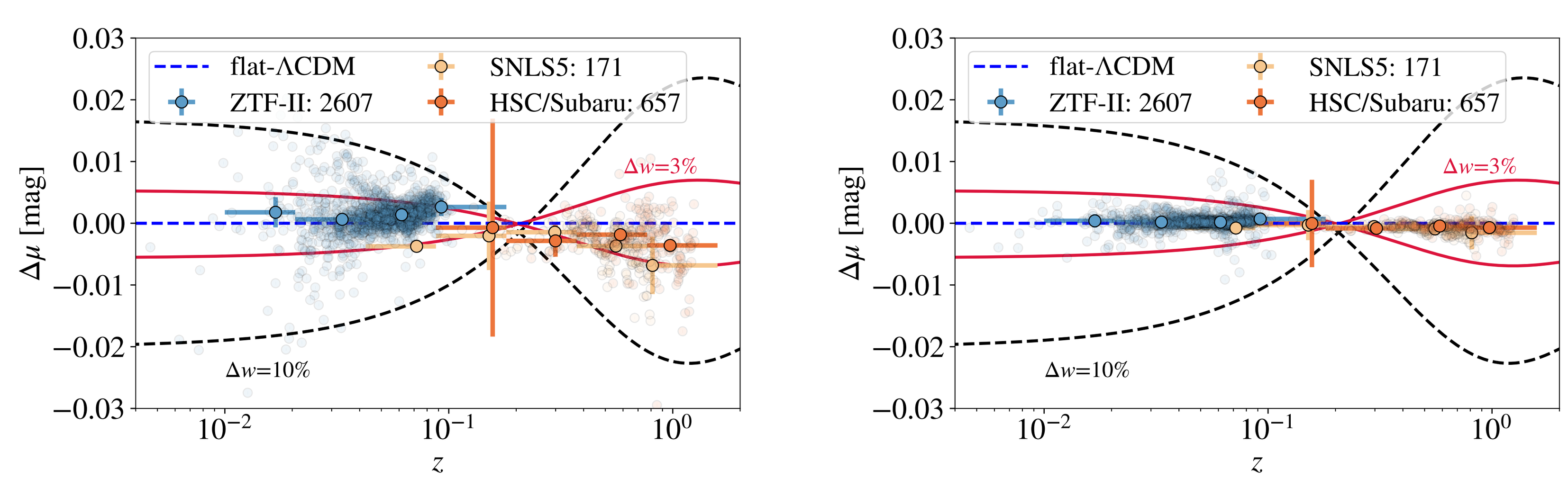
From filter transmissions to cosmology

We investigate the impact on w, the dark energy equation of state parameter, of errors on the filter passband estimates.



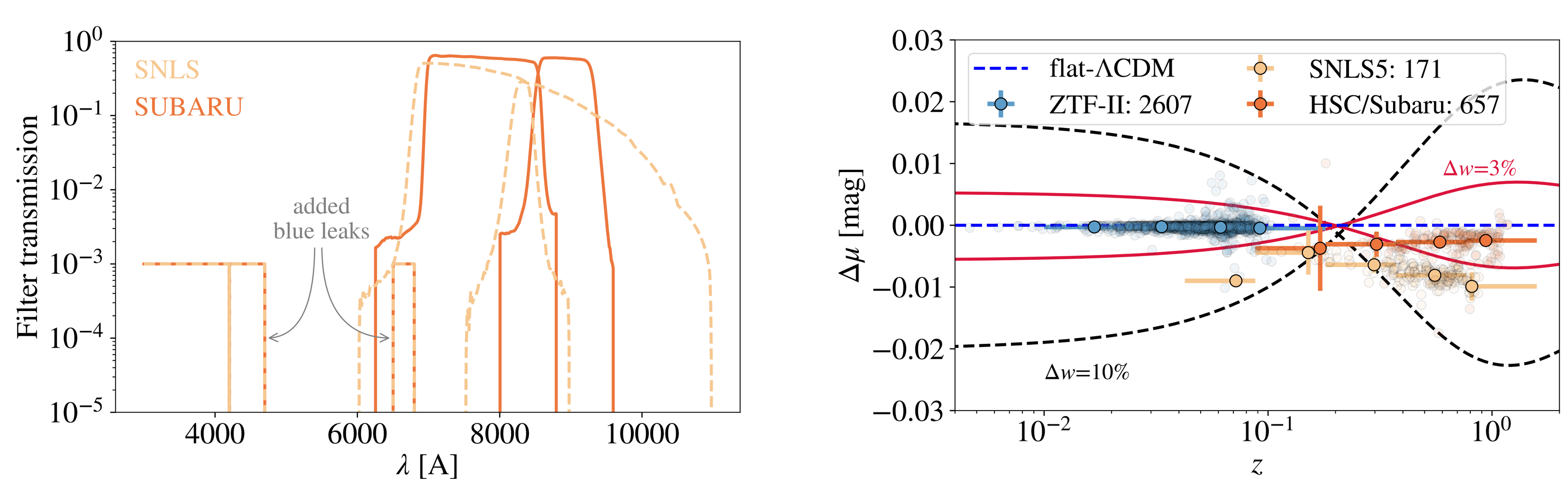
LEMAÎTRE filter transmissions used for simulation (preliminary).

First scenario: the ZTF filters are shifted by -5 A and the others by 5 A. We observe a distortion of the Hubble diagram, which can lead to a deviation on w of about 2%. The future goal to get $\Delta w \lesssim 1\%$ is to measure the filter positions at the 1 A level.



Left: $\Delta\mu$ distortion with ZTF filters shifted by -5 A, others by 5 A. Right: same for 1 A.

Second scenario: the *iz* filters of all surveys have un-noticed blue leakages of peak amplitude 10^{-3}. w can be bias by $\approx 2\%$.

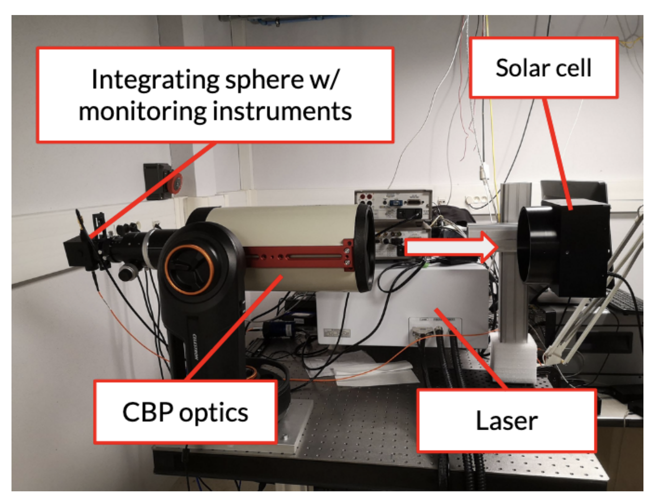


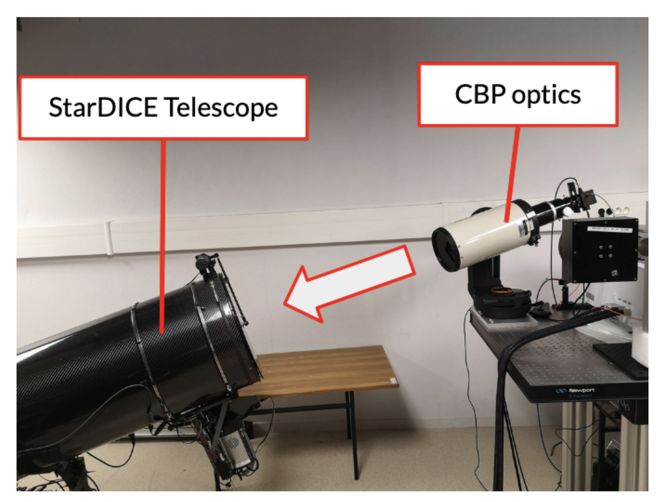
$\Delta\mu$ distortion with added blue leaks in i and z filters of 10^{-3} peak amplitude.

Caveat: no re-training of SALT2 in this toy model; effects of filter miscalibration may be worse with training!

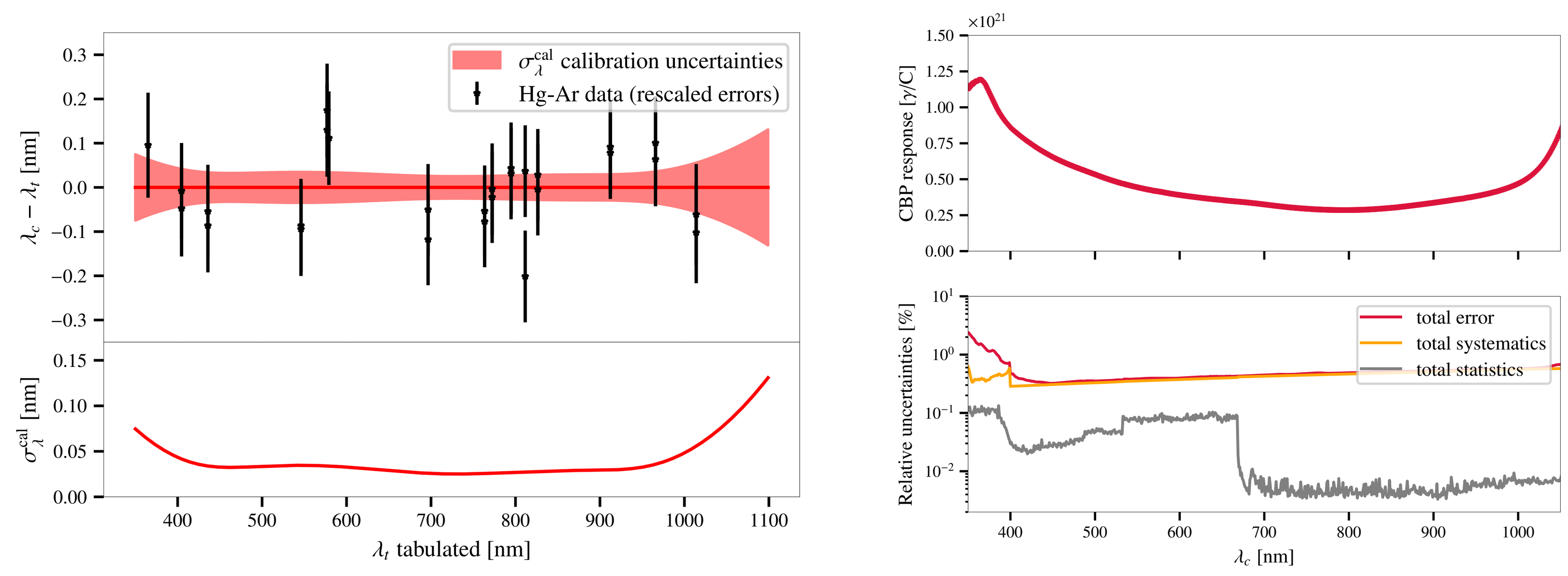
Measurement of $T_b(\lambda)$ with a Collimated Beam Projector

CBP: a parallel beam of monochromatic light monitored in flux and wavelength to measure $T_X(\lambda)$ at **0.1% in flux and at the Angström level in wavelength**.

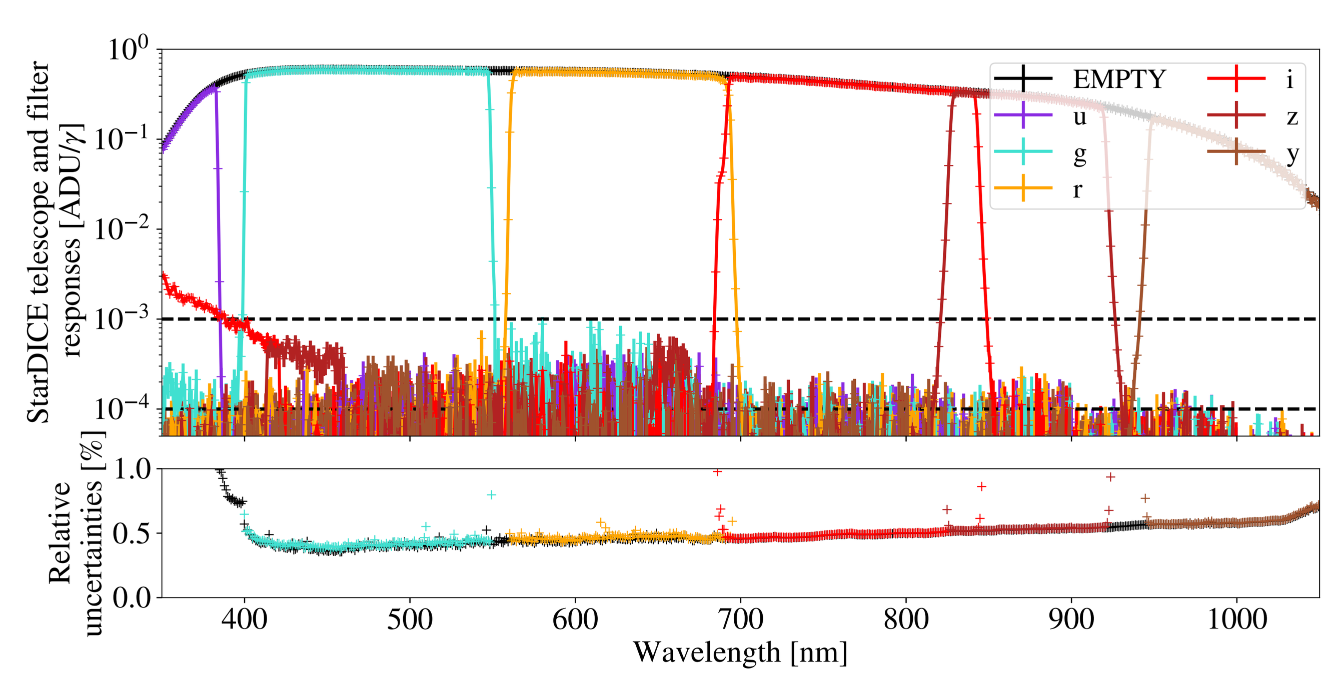




In the lab, we succeeded in calibrating the CBP throughput at 0.5% systematics included (due to scattered light) and in wavelength at $\approx$ 0.2 A using a Hg-Ar lamp.



Left: spectrograph wavelength calibration using a Hg-Ar lamp and uncertainties. Right: CBP throughput calibration and error budget.



Measurement of the StarDICE ugrizy filters. Blue leaks at the 10^{-4} level are clearly detected in the StarDICE red filters.