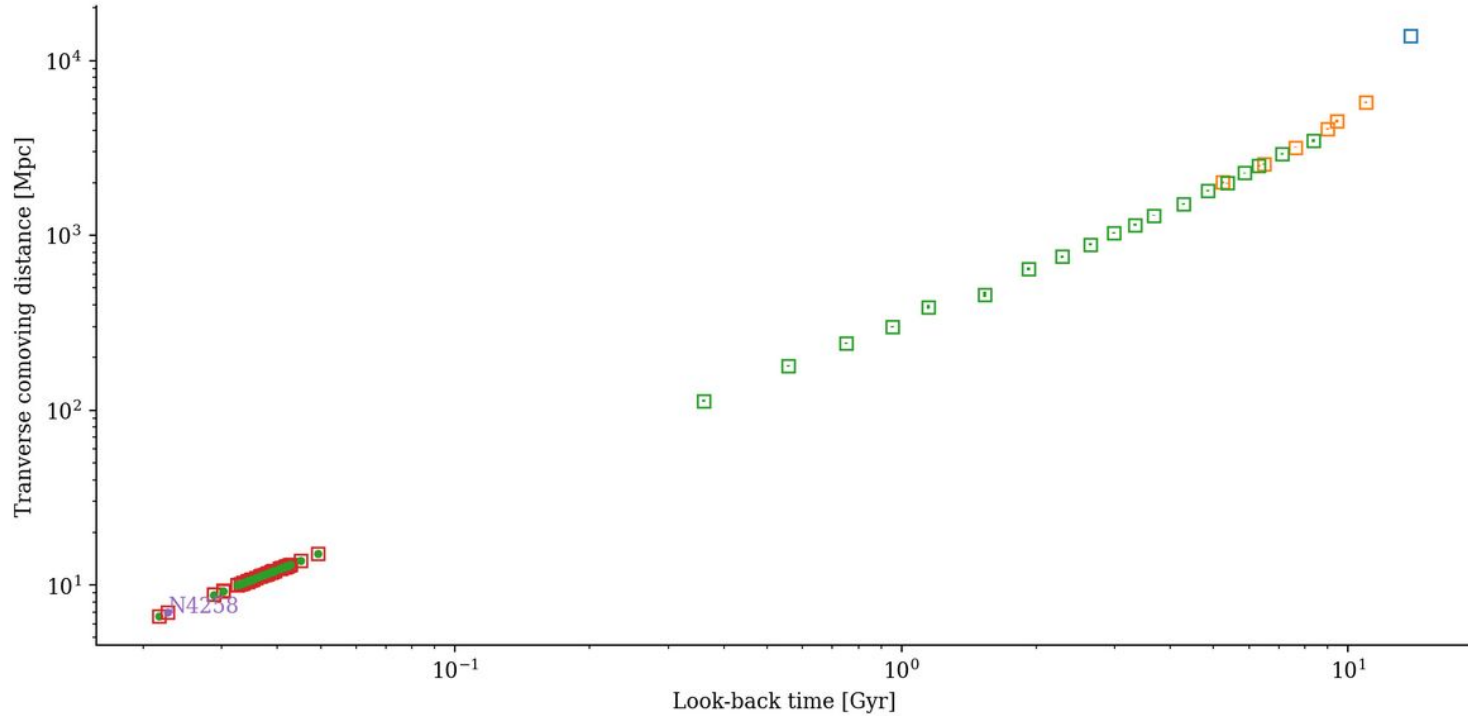


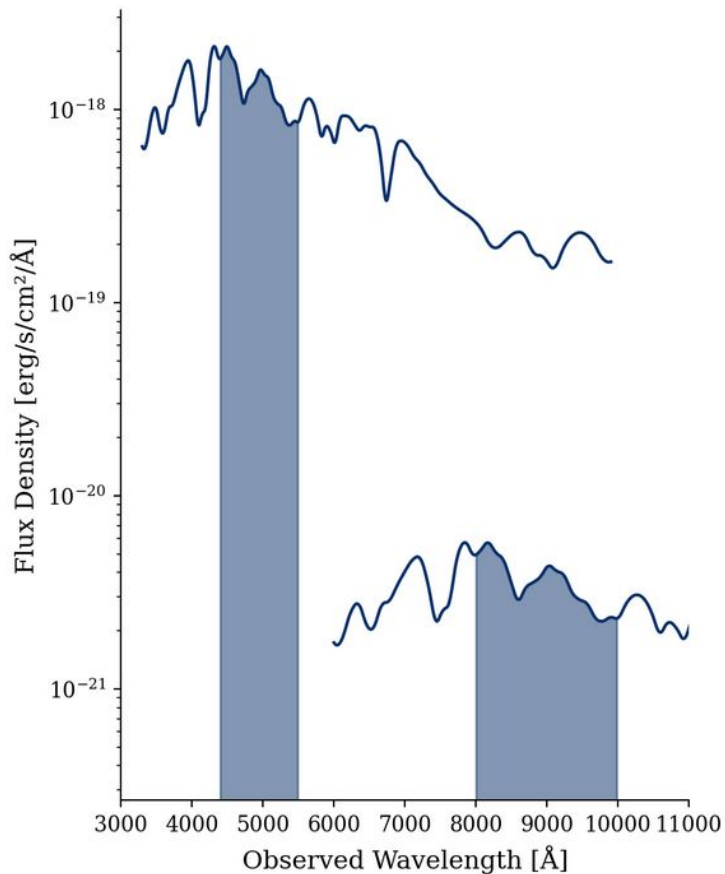
The measurement of apparent fluxes of type Ia SNe in the Lemaître compilation

Marc Betoule

The Cosmic Distance Ladder



Potential issues with supernovae



Basics: B band luminosity comparison between nearby and distant events

Measurement issues

Linearity - Calibration - Interpolation - Truncation

Astrophysical issues

Dust - Galactic evolution - Structures

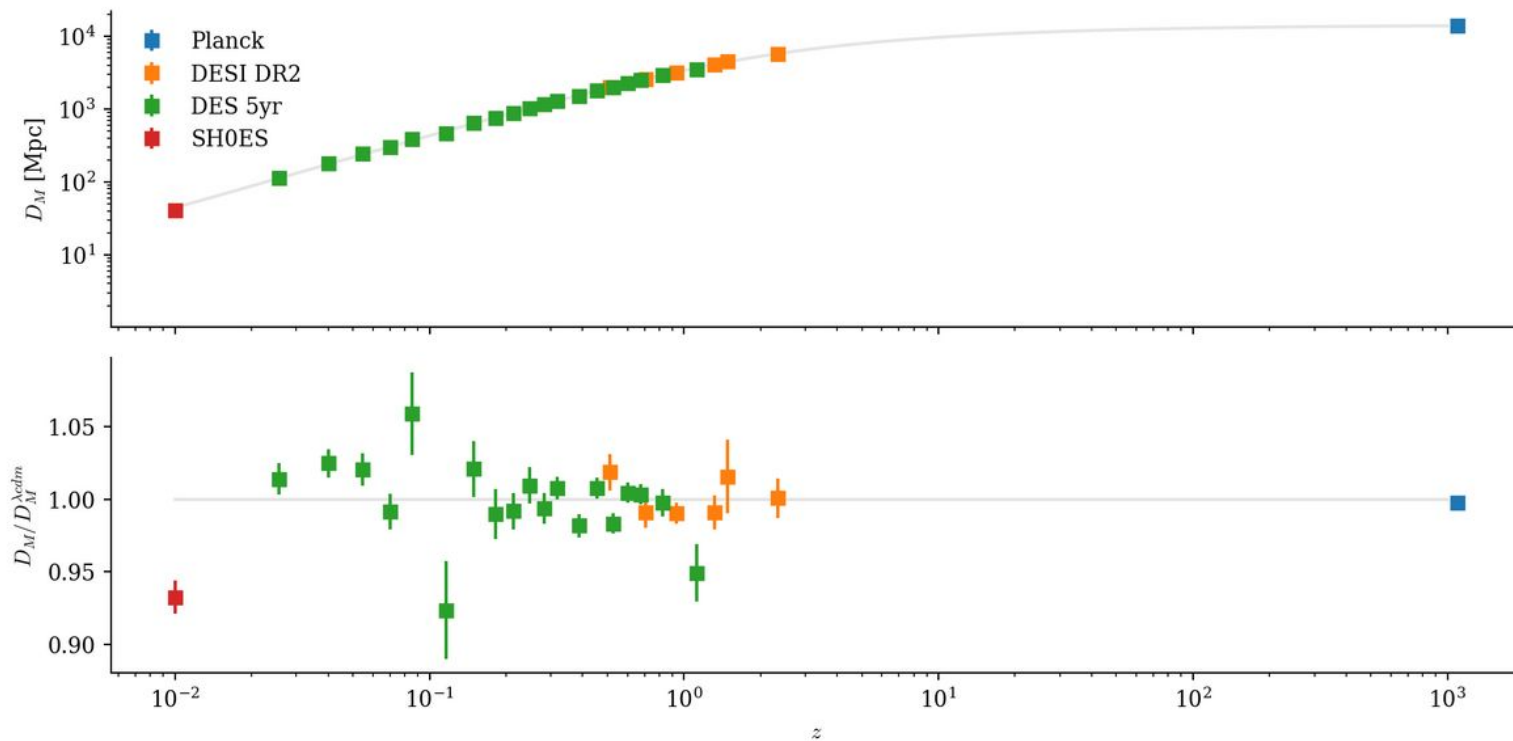
Probe issues

Empirical models - Population evolution

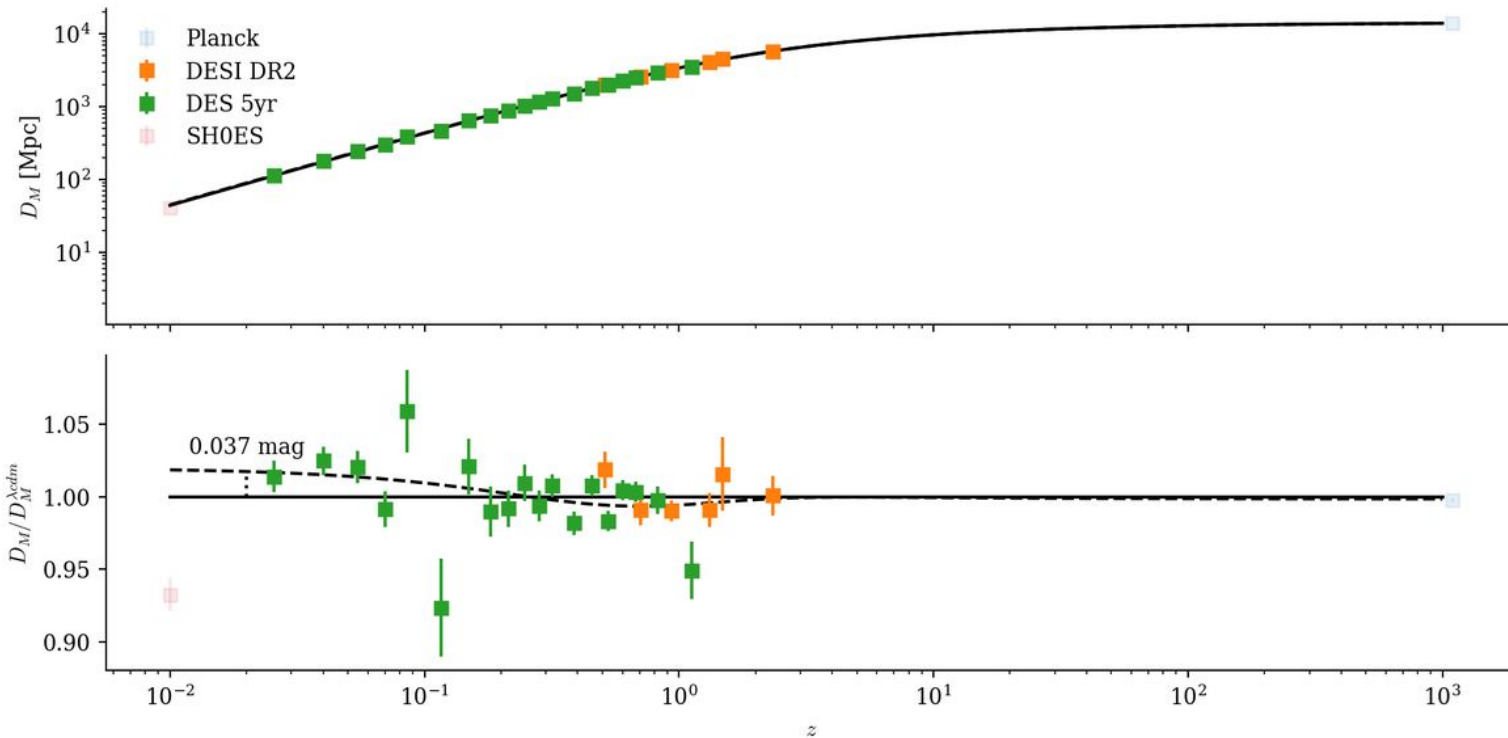
Analysis issues

Compilations - bias corrections

The Hubble tension: Direct comparison of two distance scales

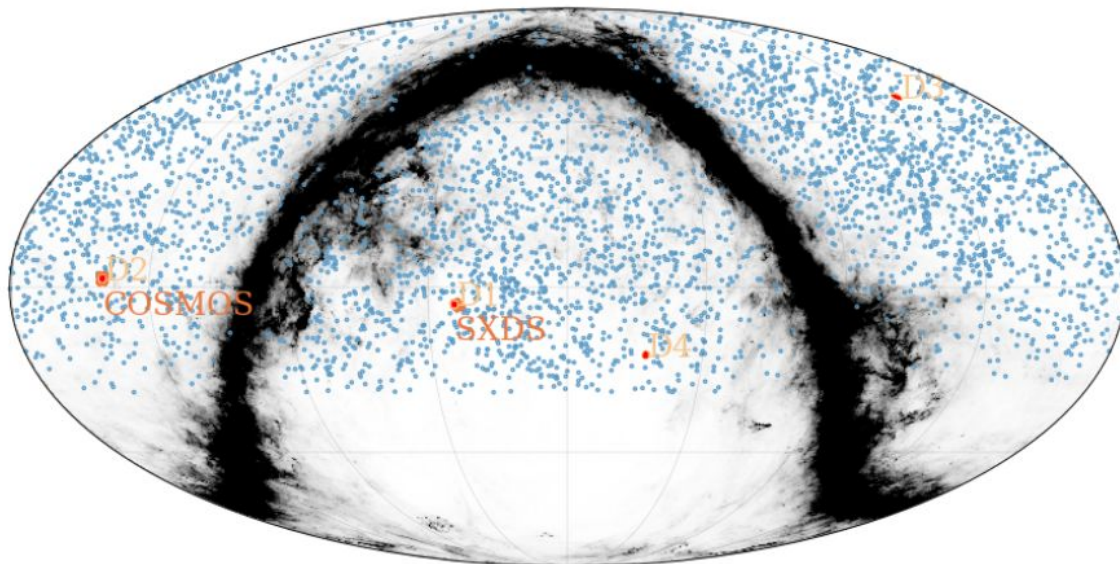


Probing the Background dynamics



The LEMAITRE Project

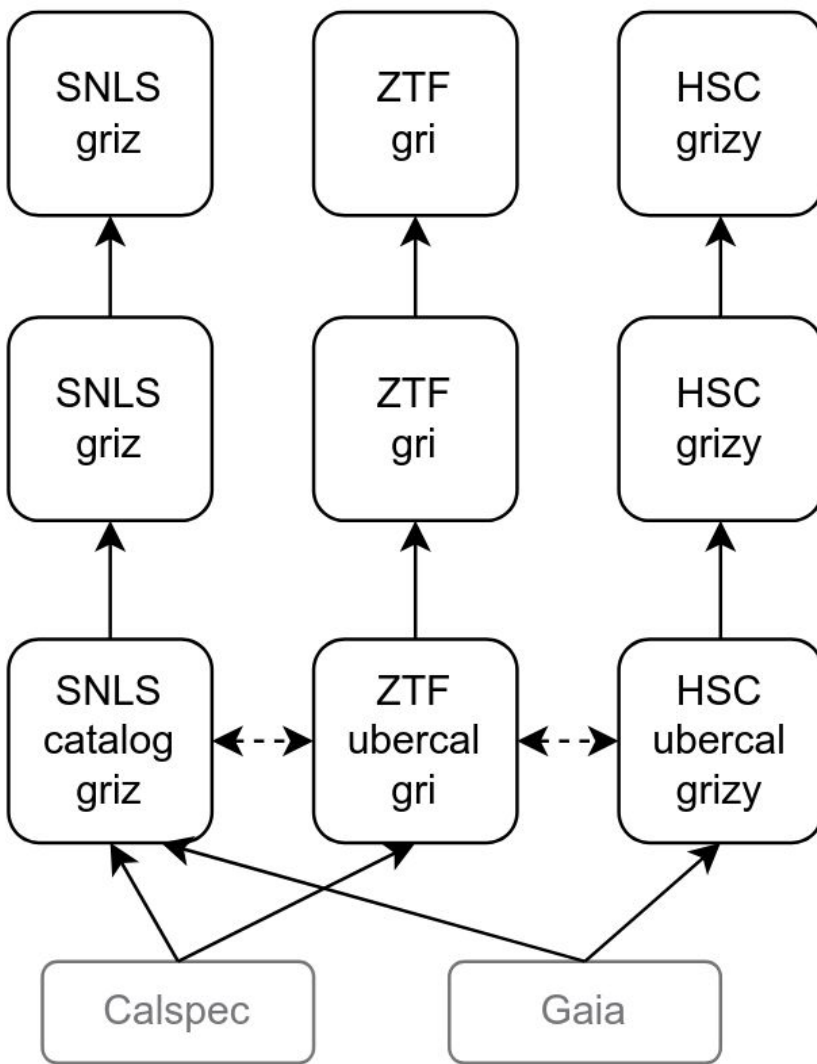
A compilation from only 3 collaborations:



- ZTF: 2π , 2yr,
 $m_{lim} \sim 18.5$
- SNLS: $4deg^2$,
2yr
 $m_{lim} \sim 24$
- HSC: $3deg^2$,
1yr,
 $m_{lim} \sim 25$

3 overlapping surveys: large collaborative effort to deliver the most careful measurement

SN Ia light
curves
from SMP



A 3 step process

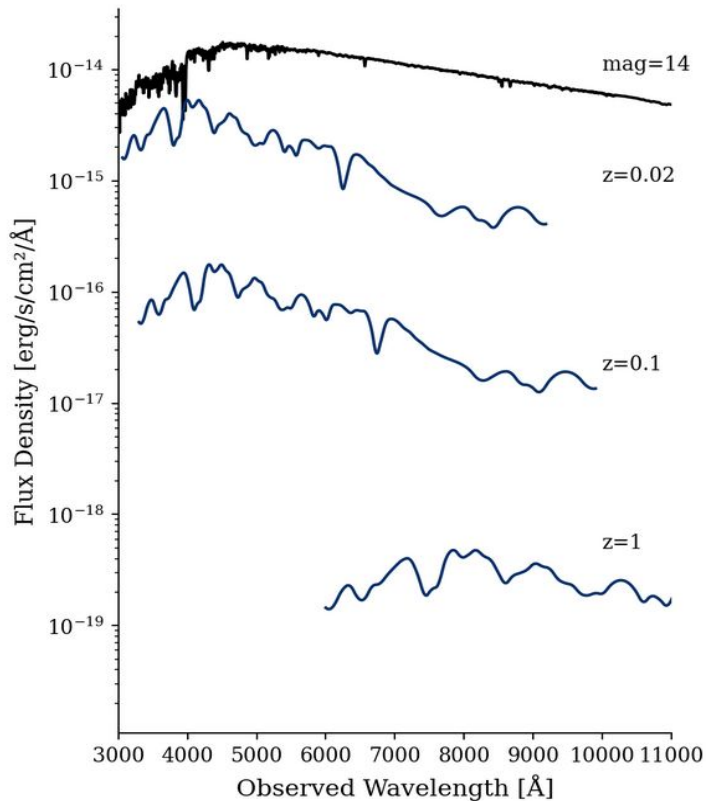
- Ratio SN/field stars
- Ratio PSF/Aperture
- Ratio Field stars/Primary standards

SMP
secondary
star
catalogs

Aperture
secondary
star
catalogs

Absolute
reference

Linearity of the SN photometry



Difficulties:

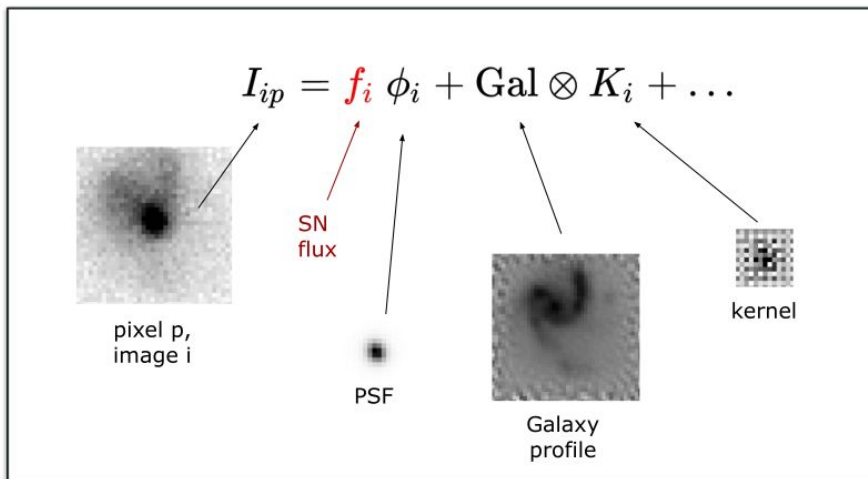
- Subtraction of host galaxy flux
- Variation of observing conditions

Many low-z survey: photometry on resampled images differences

- Suboptimal

Loose the ability to check flux conservation

Scene modeling photometry

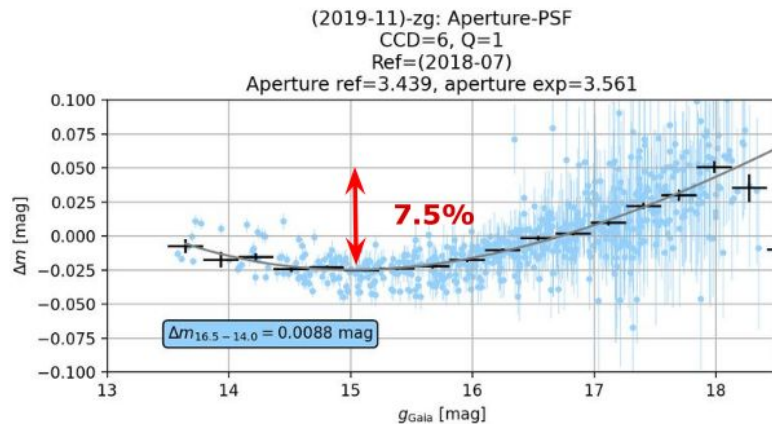
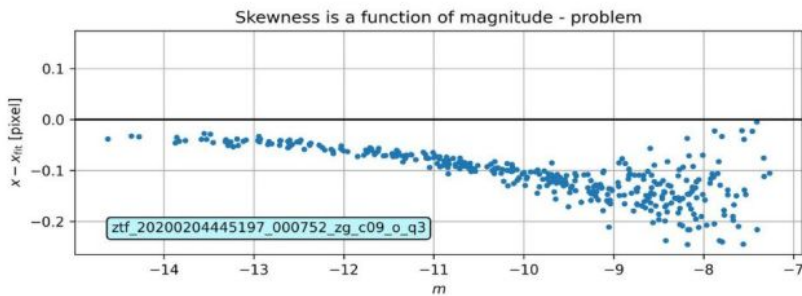
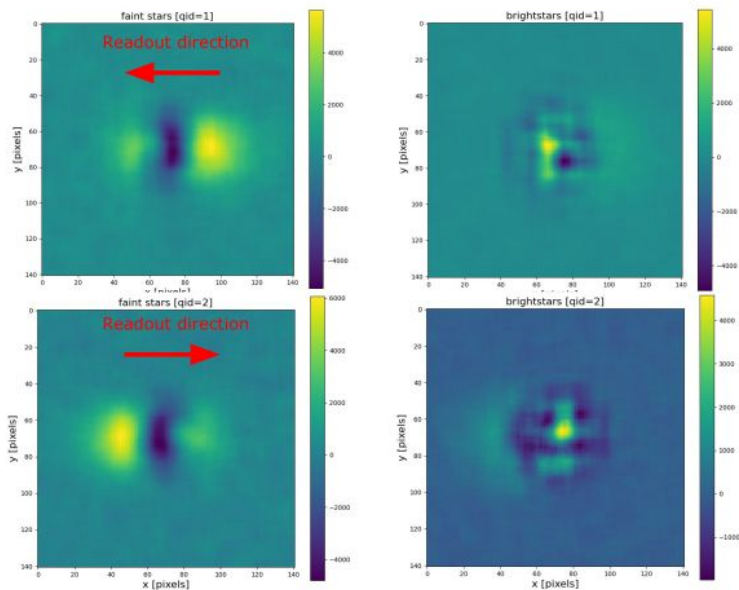


- Forward model of image sequence
 - Simultaneous fit of
 - Galaxy profile
 - SN fluxes
 - Same estimator applied to
 - supernova
 - Field stars
 - Autocancellation of photometry biases (except linearity)
- In LEMAÎTRE, all 3 surveys are reduced with the same SMP code
 - Demonstrated to be accurate at the 0.1% (Astier et al, 2013)
 - For ZTF: 0.02 - 0.05 mag shifts w.r.t forced photometry (Lacroix et al, 2025)

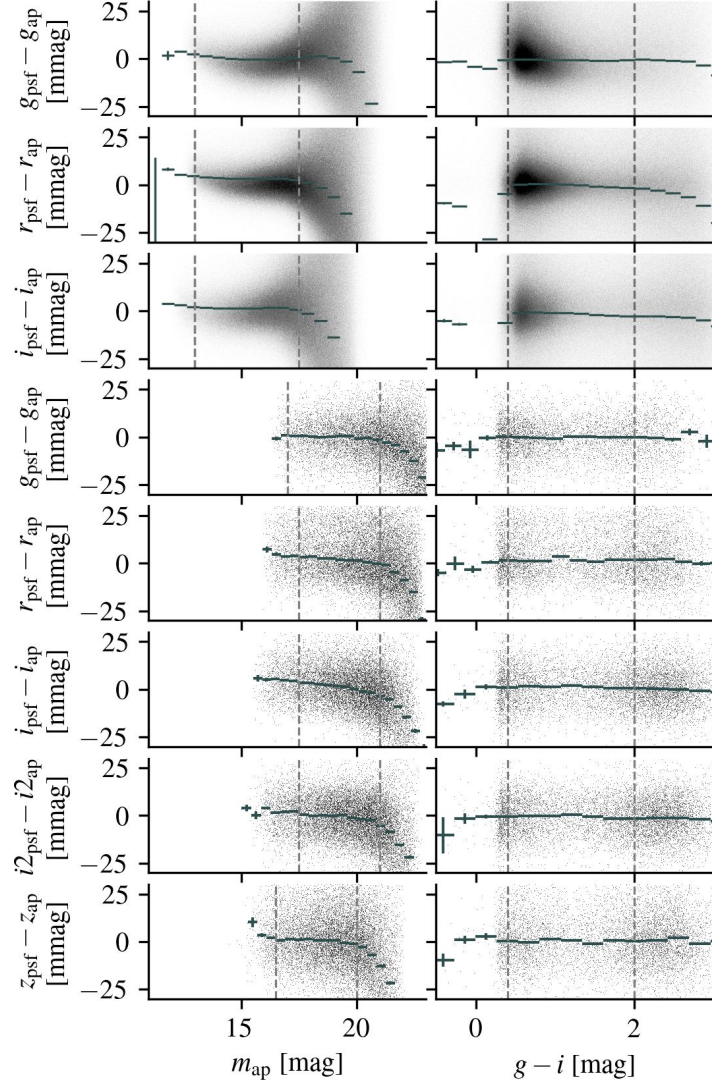
Linearity / sensor effects

Nicolas, Mathieu Mickael

- **Sensor effects** affect the PSF shape in a flux-dependent way
 - **Brighter fatter** (all surveys)
 - **ZTF**: pocket effect



2nd step: light-curves calibration



- The PSF is slightly chromatic
- PSF photometry is affected
- More generally it is safer to measure bright stars with aperture photometry
- But aperture photometry is affected by aperture contamination

Mixed approach:

- Fit PSF/aperture color terms -> Filter model
- Model the contamination of apertures
- limit the comparison to the range of color and magnitudes where the two models hold

Maude Le Jeune

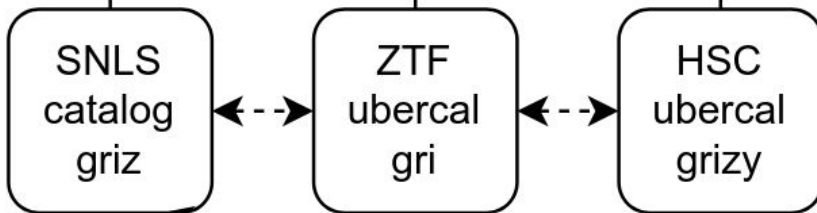
SN Ia light
curves
from SMP



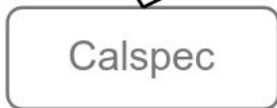
SMP
secondary
star
catalogs



Aperture
secondary
star
catalogs



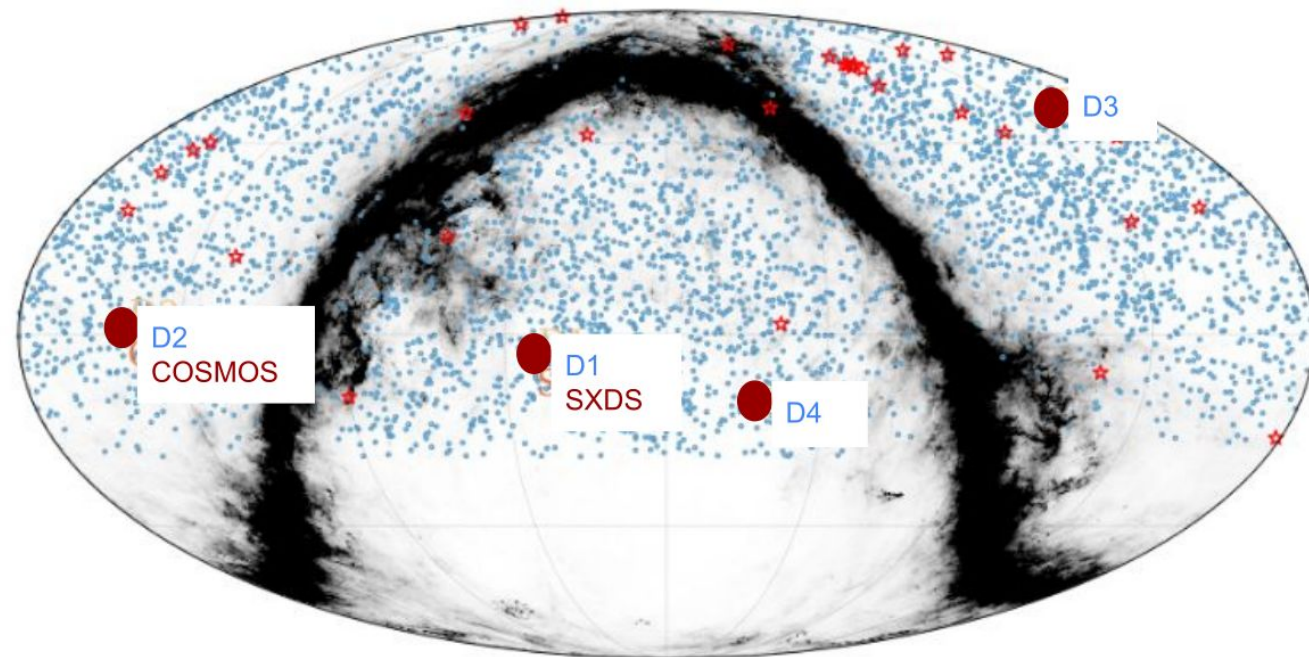
Absolute
reference



The backbone is the
uniformity of the secondary
star aperture photometry
catalog:

- Link all supernovae of a survey to the same scale
- Link all survey
- and primary standards

Strong specific points

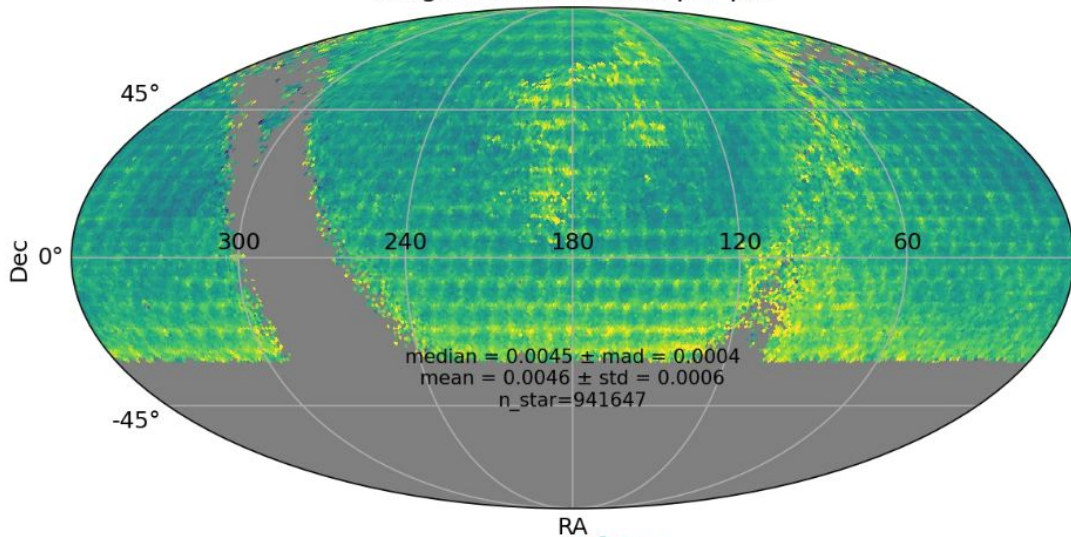


- All 3 survey overlap
- Many primary standards in the ZTF footprint
- Part of the **normal** ZTF observations
- Specific observations of 6 Calspecs with SNLS brings redundancy

Ubercal

ZTF-g

weighted std, median per pix

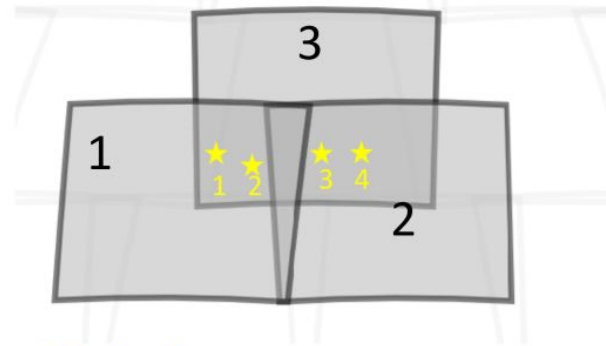


median = $0.0045 \pm \text{mad} = 0.0004$
mean = $0.0046 \pm \text{std} = 0.0006$
 $n_{\text{star}}=941647$

0.0015 0.0065

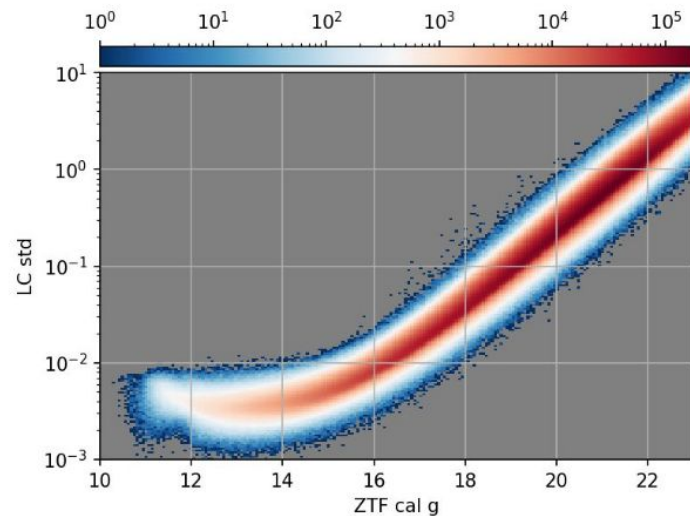
Precision on bright stars = 4.5 %

Benjamin Racine, Fabrice Feinstein

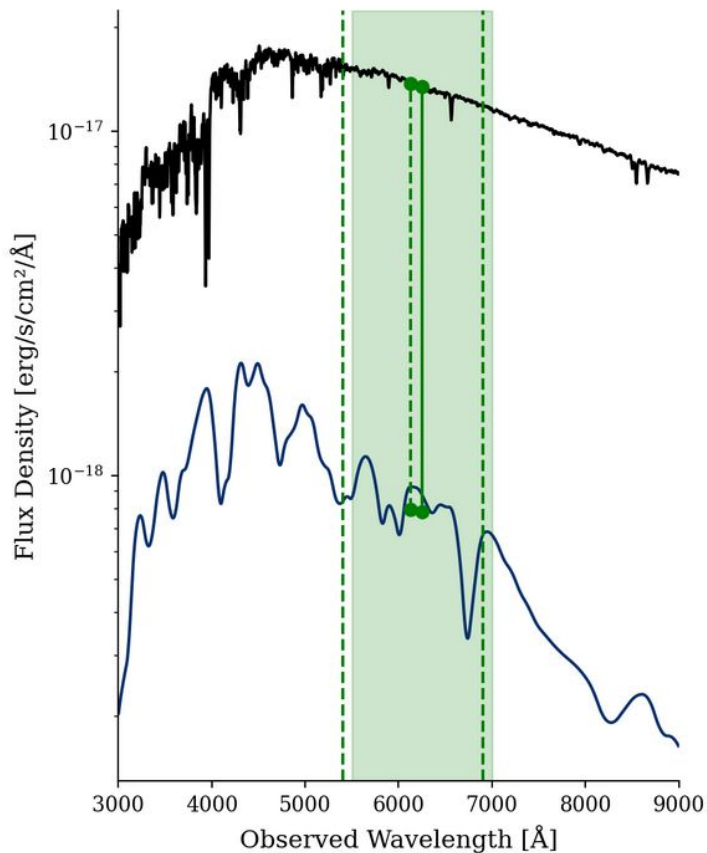


Method :

$$m_{i_{\text{star}}} + ZP_{j_{\text{field}}} = m_{i_{\text{star}}, j_{\text{field}}}^{\text{obs}}$$



Instrument passband knowledge

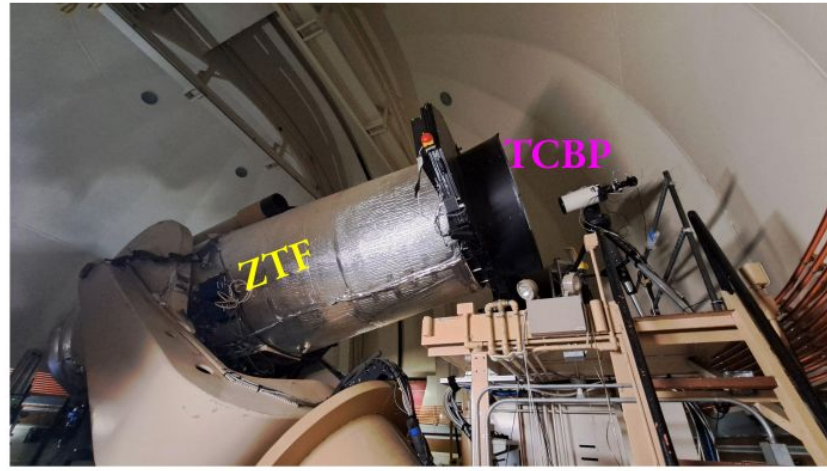
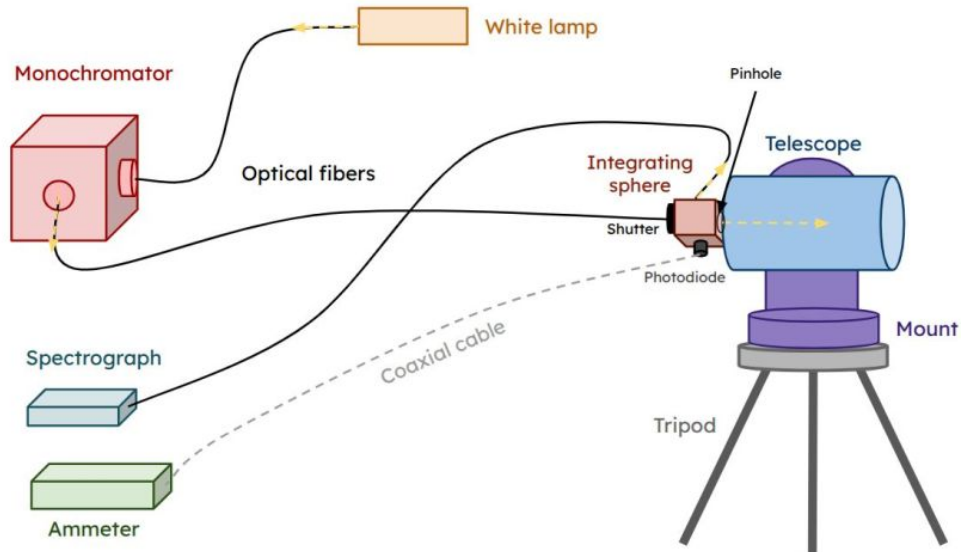


- Reference stars and SNe have very different spectra.
- Errors in instrument passbands translate into z-dependant errors in photometry.
- Rule of thumb: 1nm shift translates to 5mmag per mag in color
- Most historical low-z passbands are reverse engineered to PS1 in current analyses

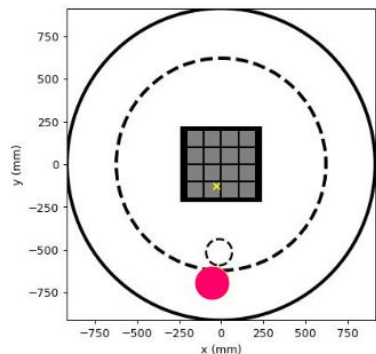
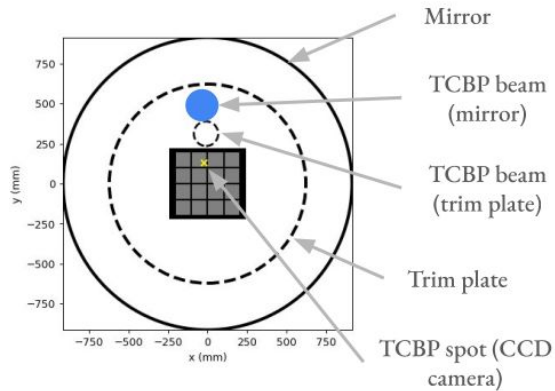
In Lemaître, we made the effort to measure 2 of the **integrated** instruments (ZTF and SNLS). The last has good measurement of the filter transmission.

Passbands : ZTF

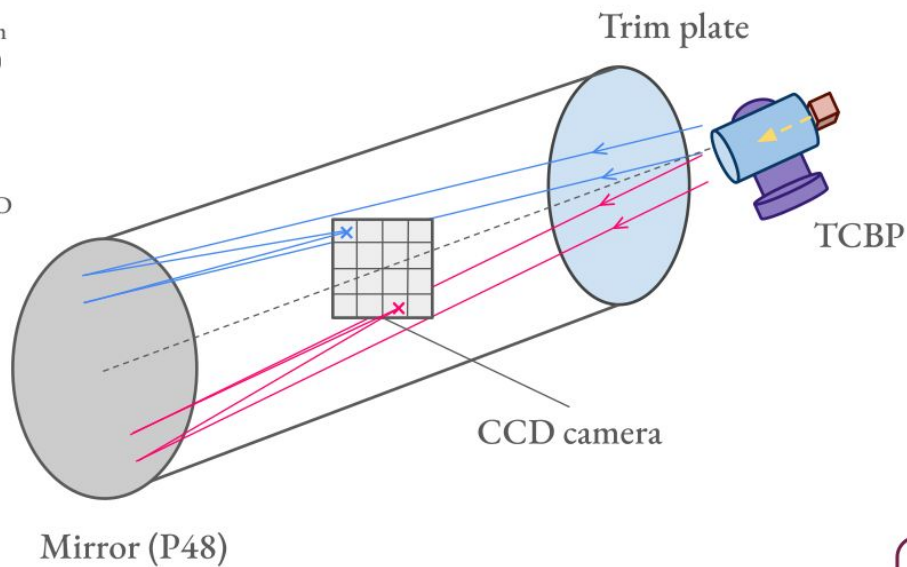
Traveling collimated beam projector (TCBP) : instrument that sends monochromatic parallel light beam with controlled flux & wavelength



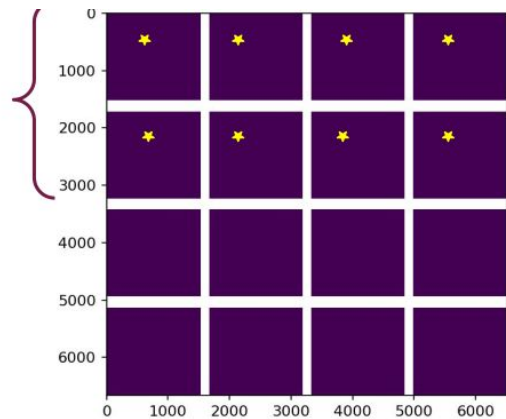
Passbands : ZTF



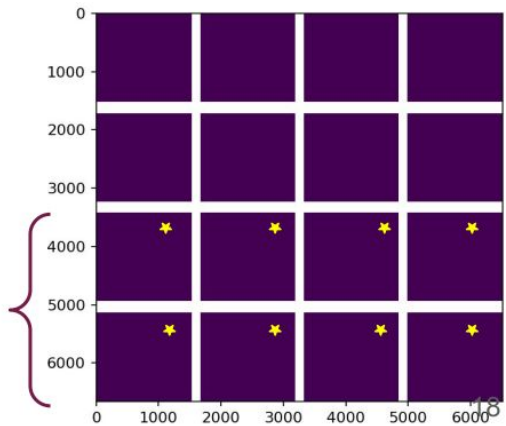
One spot per CCD at 4 different incident angles for the 3 bands + no filter



CCD 01-08

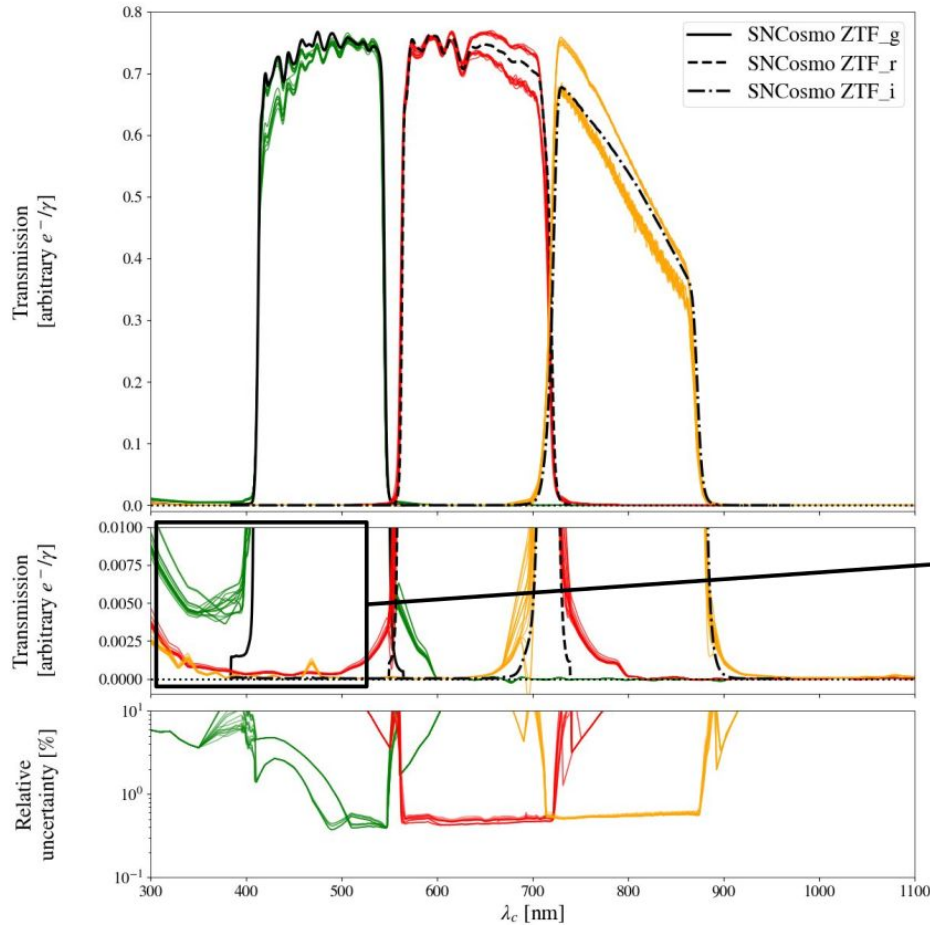


CCD 09-16

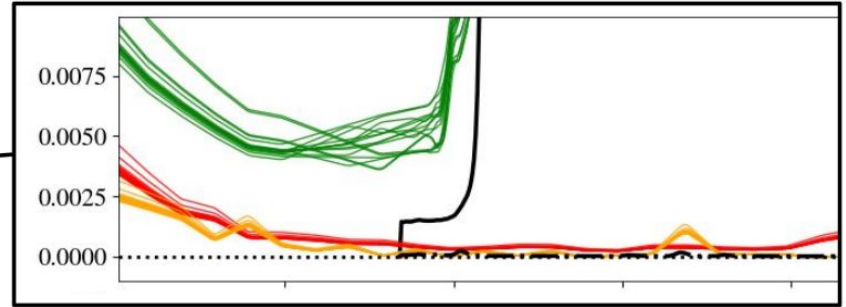


Jérémy, Enya, Philippe, Chloé, Marie, Édo

Passbands : ZTF



- One transmission curve per CCD, measured with uncertainties $< 1\%$ level in the passband
- Strong differences with public models (black curves)

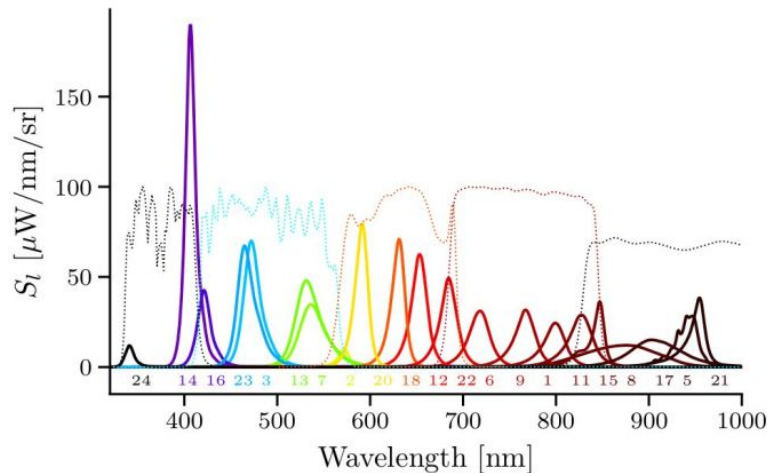


Passbands : SNLS

Two measurements :

- **SnDICE** : In-situ measurement with 23 NIST-calibrated LEDs
- **LMA** : Bench measurement (monochromatic + white lamp) at several incident angles

Datasets both used to constrain a filter transmission model (position + angle dependence) → **uncertainties on mean wavelength well below the nm level**

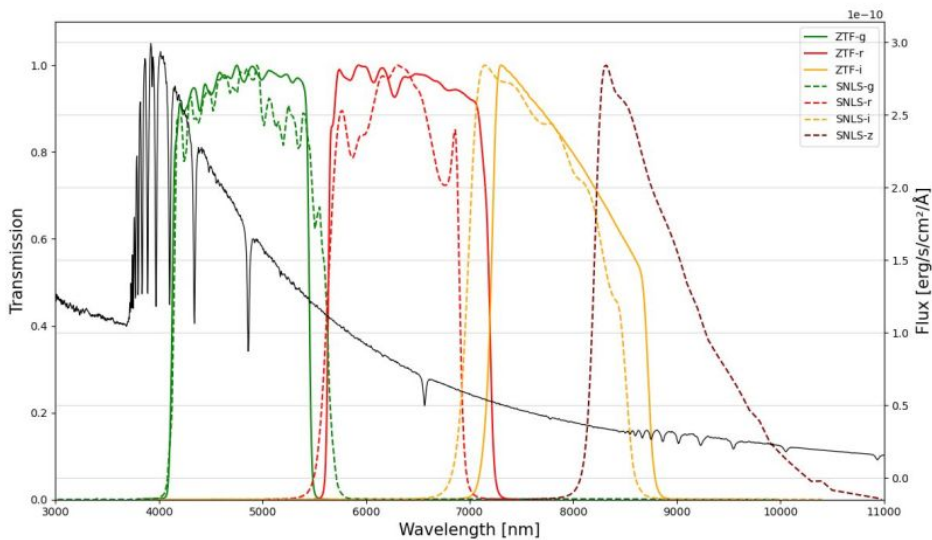
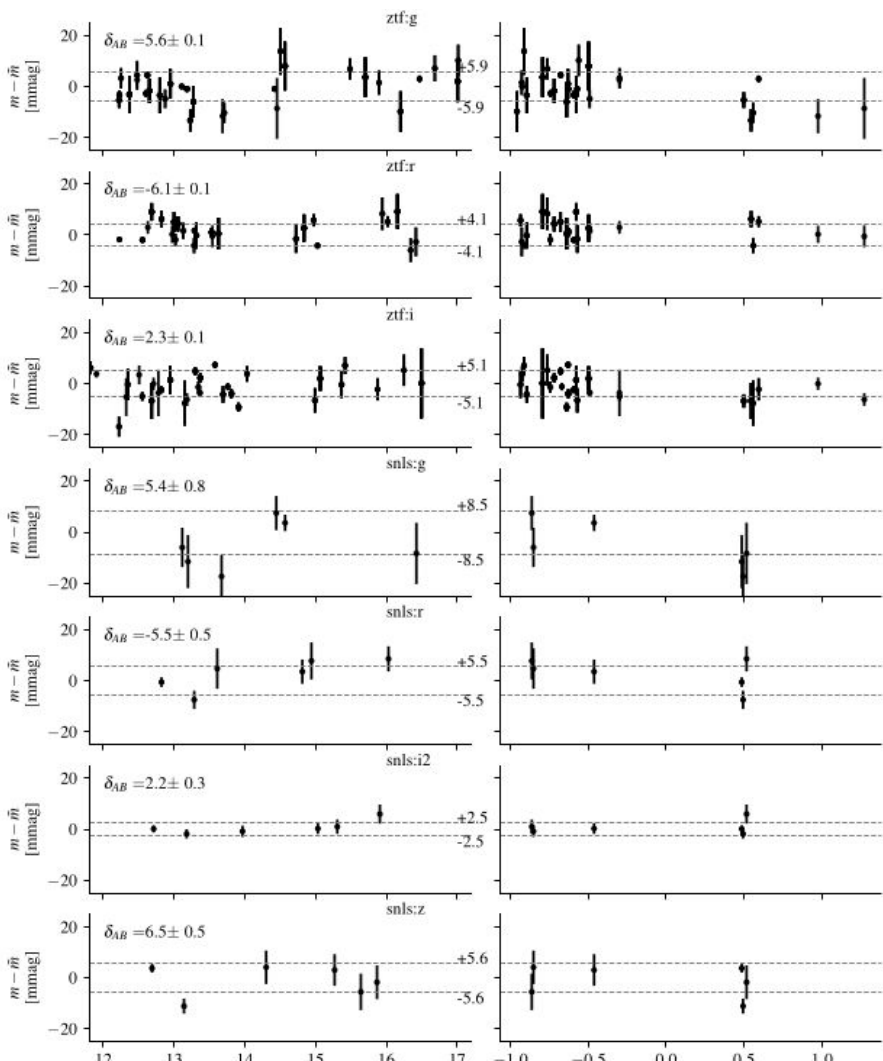


Marc Betoule

| <i>Band</i> | <i>u</i> | <i>g</i> | <i>r</i> | <i>i2</i> | <i>z</i> |
|-------------------------------|----------|----------|----------|-----------|----------|
| λ_0 | 500.000 | 550.000 | 625.000 | 750.000 | 800.000 |
| n | 1.506 | 1.756 | 1.742 | 1.766 | 1.786 |
| k_n | -0.002 | -0.001 | -0.001 | -0.000 | 0.000 |
| δ_λ | 1.775 | 1.314 | 1.448 | 1.635 | 1.592 |
| R_A | 0.005 | 0.114 | 0.201 | 0.130 | 0.065 |
| R_B | 0.103 | 0.091 | 0.138 | 0.140 | 0.099 |
| σ | 0.006 | 0.001 | 0.001 | 0.001 | 0.015 |
| $\sigma(\Delta\bar{\lambda})$ | 0.170 | 0.135 | 0.100 | 0.100 | 0.107 |
| $max(\Delta\bar{\lambda})$ | 0.636 | 0.561 | 0.444 | 0.657 | 0.422 |

6.4 Å 5.6 Å 4.4 Å 6.6 Å 4.2 Å

Setting the absolute scale



Difference between the expected synthetic flux and the aperture catalog flux sets the scale of the catalog.

We can do that independently for all the standard we observed

A pretty consistent picture so far

Maude Le Jeune

Conclusion

- LEMAITRE calibration has some specific strong point
 - 3 overlapping surveys.
 - Well characterized passbands in all 3 cases. Actual measurements of the integrated instrument for 2 of them.
 - Many primary standards in the routine observation of ZTF
 - Some redundancy thanks to SNLS
 - Work on sensor systematics affecting the photometric linearity
- We aim at releasing a collection of supernovae fluxes with state of the art accuracy
- Groundwork for LSST
 - CBP technique in particular