From λ to Λ

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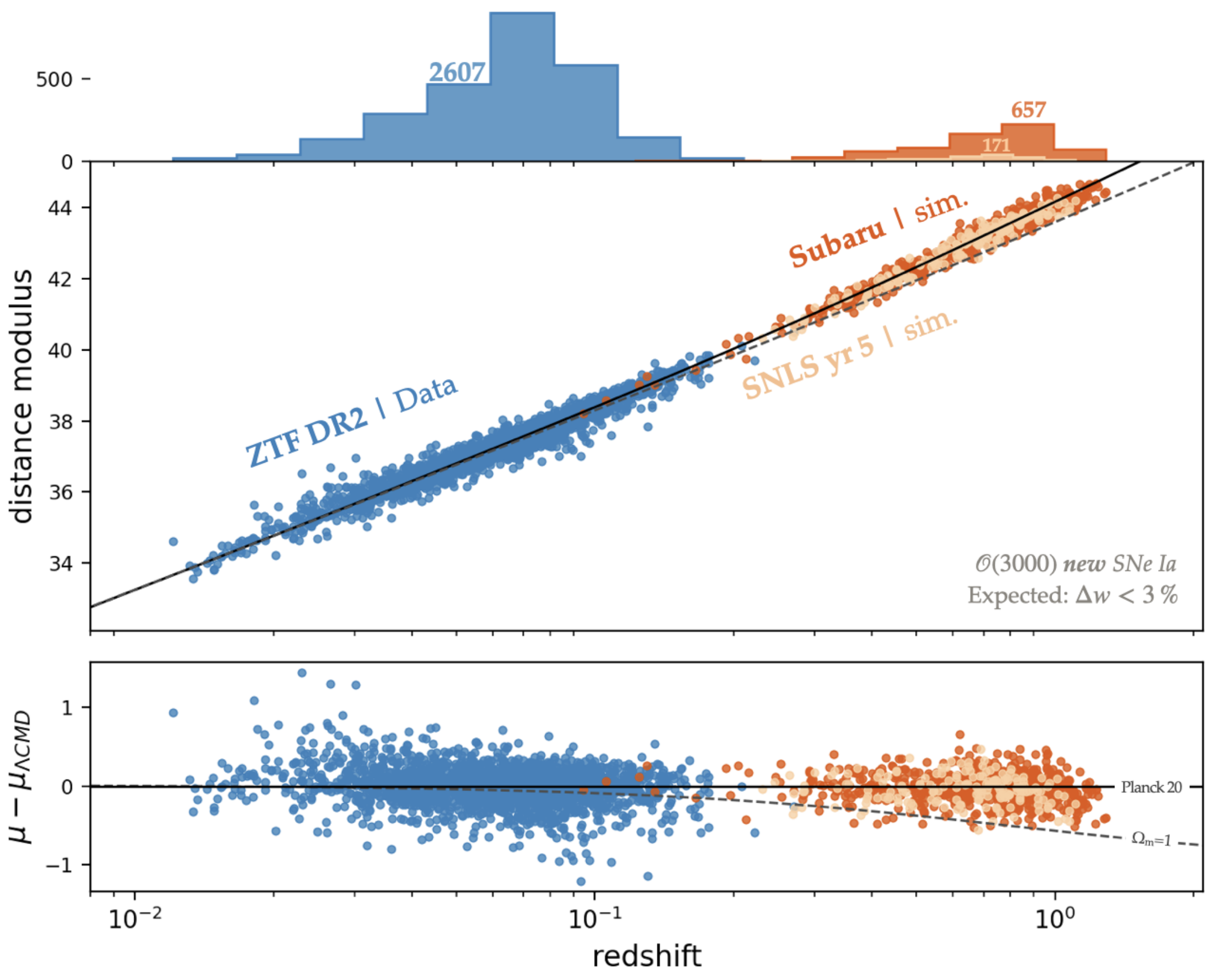
The 2030's Legacy Hubble diagram: LEMAÎTRE project

Type Ia supernovae made it possible to discover the accelerated expansion of the Universe in 1998 with the help of around forty events. In the 2010s, with a batch of $\lesssim$ 1000 SNe Ia, the measurement of w_{DE} has reached an accuracy of 4% but is dominated by systematic uncertainties in photometric calibration. In 2030, the objective of the LEMAÎTRE project is to publish a Hubble-Lemaître diagram of about 6000 exquisitely measured SNIa, with a precision on the w_{DE} measurement at the percent level, along with first constraints on its potential variations with redshift.

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



A preview of the LEMAÎTRE *Hubble diagram.*

Ingredients:

1. 5000 spectroscopically confirmed SNe Ia from the ZTF-I and ZTF-II surveys, with an exquisite photometric follow-up;
2. the largest possible set of very-high-z SNe Ia obtained using the largest possible wide field camera mounted on an 8-m class telescope (Subaru/HSC)
3. a flux metrology chain as simple and robust as possible in order to ensure the control of the calibration uncertainties at the level of 0.1%.

In a band b of transmission $T_b(\lambda)$, the apparent magnitude is related to the luminosity distance by :

$$\begin{aligned} m_b &= -2.5\log_{10}\left[\frac{\int \lambda \mathrm{d}\lambda F_\lambda(\lambda) T_b(\lambda) T_{\mathrm{atm}}(\lambda)}{\int \lambda \mathrm{d}\lambda F_{\mathrm{ref}}(\lambda) T_b(\lambda) T_{\mathrm{atm}}(\lambda)}\right] \\ &= -2.5\log_{10}\left[\frac{1}{4\pi(1+z)D_L^2(z)} \frac{\int \lambda \mathrm{d}\lambda L_\lambda(\lambda/(1+z)) T_b(\lambda) T_{\mathrm{atm}}(\lambda)}{\int \lambda \mathrm{d}\lambda F_{\mathrm{ref}}(\lambda) T_b(\lambda) T_{\mathrm{atm}}(\lambda)}\right] \\ &= M_B + \mu(z) + K_{bB}(z) \end{aligned}$$

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

- M_B, the absolute magnitude in band B, is an additive constant
- $\mu(z)$, the luminosity distance, contains the cosmological model via the luminosity distance $D_L(z)$.
- $K_{bB}(z)$, 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.

We write $m_B^* = m_b - K_{bB}$ the rest-frame B-band apparent magnitude, *as if there was no expansion but only a distance effect*. After applying the K-correction, the Hubble diagram is simply modelled by:

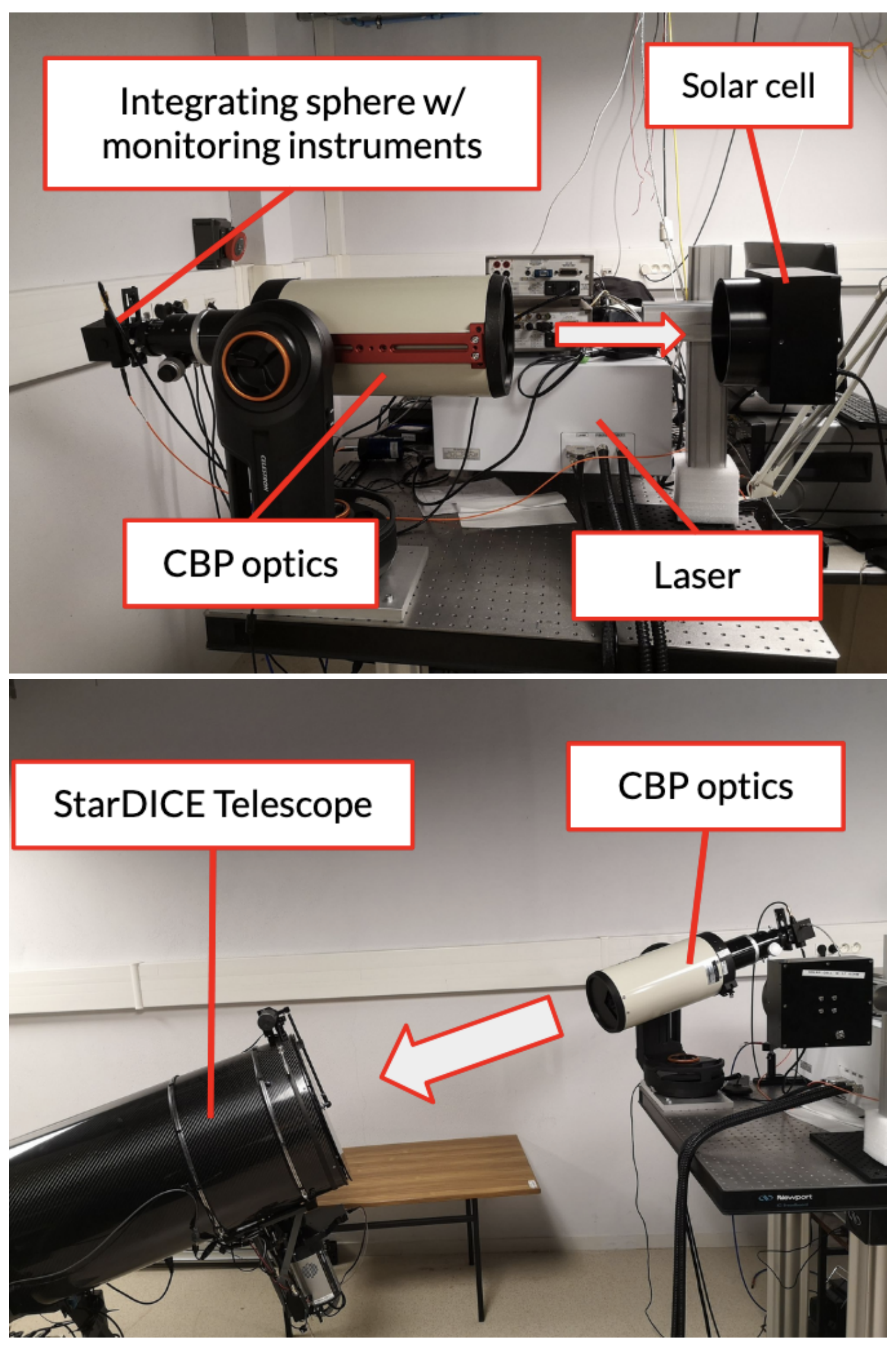
$$\boxed{m_B^* = m_b - K_{bB} = M_B + \mu(z)}$$

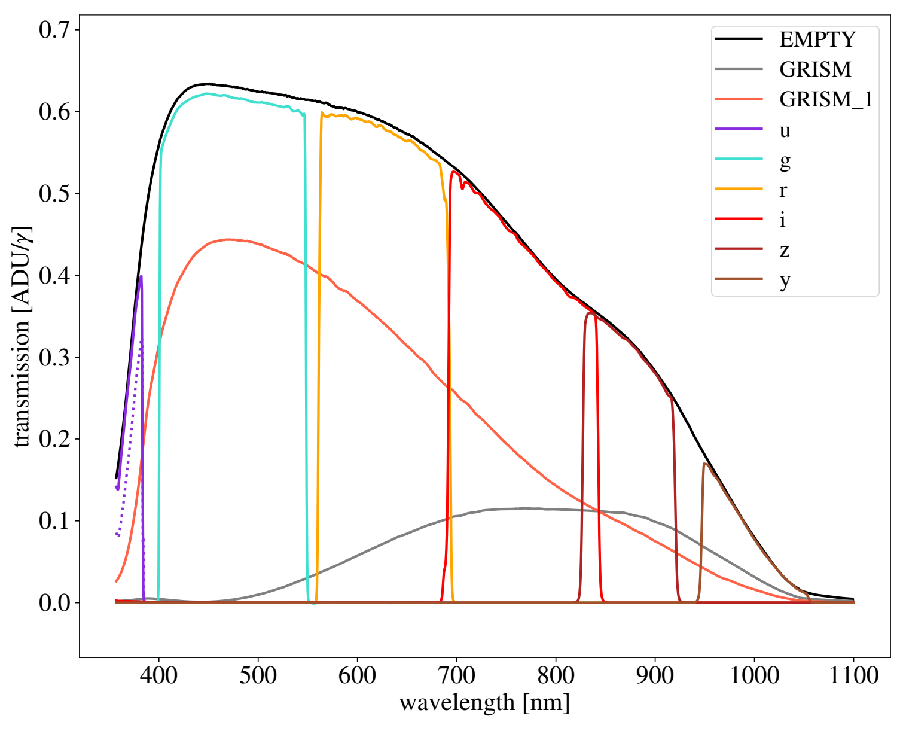
Unfortunately, the K-correction depends on a number of ingredients, which you need to know in order to calculate it to an accuracy of 0.1% :

- the reference spectral density $F_{\mathrm{ref}}(\lambda)$, to be established by measurements or stellar atmosphere modelling;
- the transmission of the telescope filters T_b;
- the atmospheric transmission of the observation site $T_{\mathrm{atm}}(\lambda)$.

$T_b(\lambda)$: Collimated Beam Projector

CBP: parallel beam of monochromatic light monitored in flux and wavelength to measure $T_b(\lambda)$.

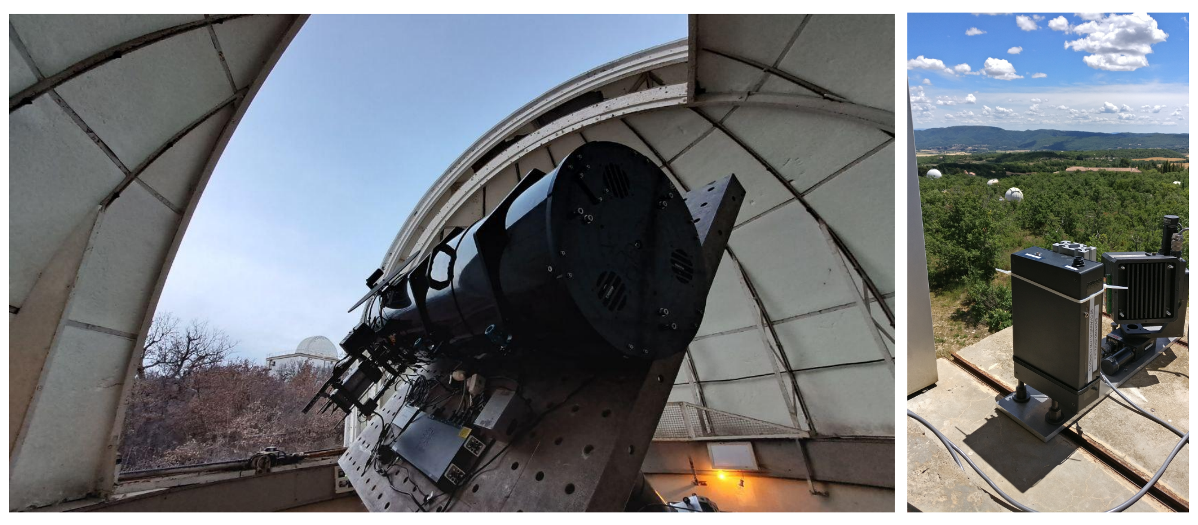




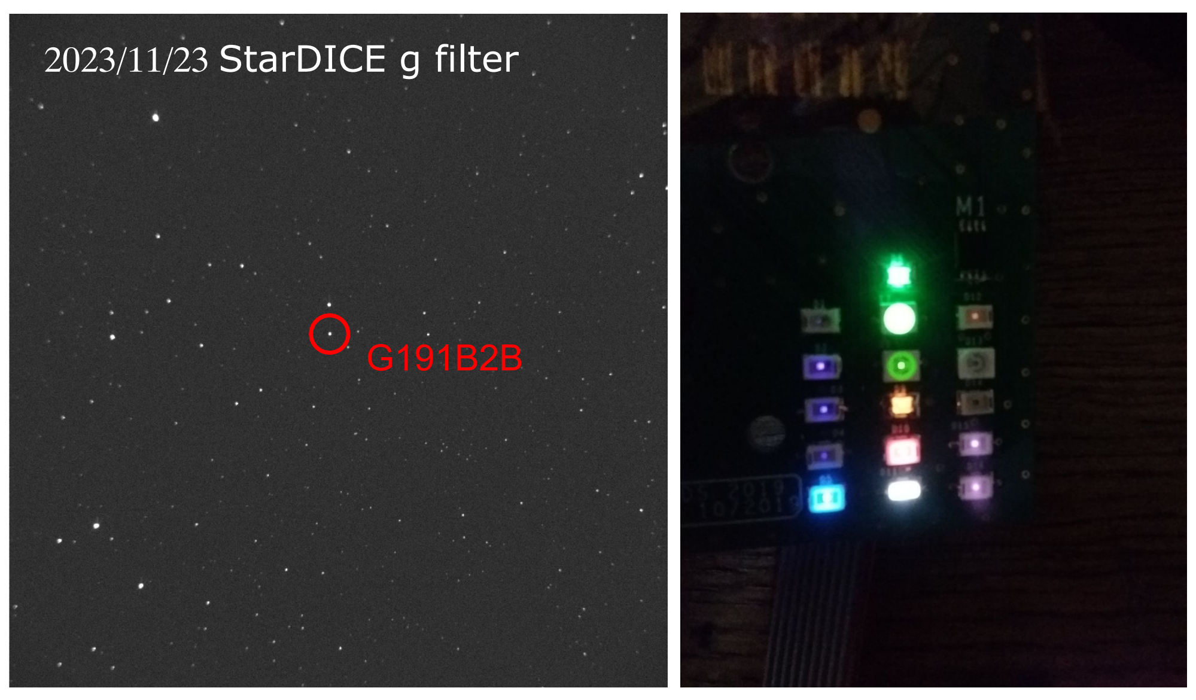
Measurement of the StarDICE bandpasses at Angström and permil precision.

$F_{\mathrm{ref}}(\lambda)$: StarDICE

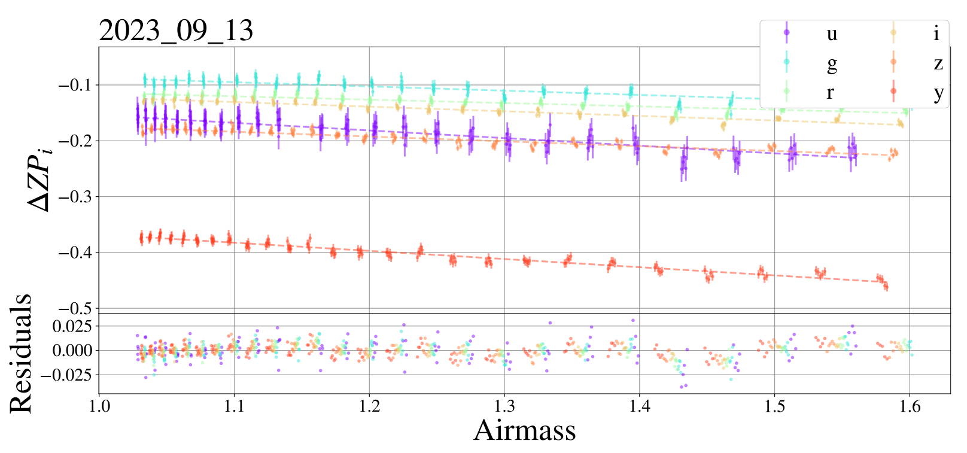
StarDICE: anchoring the reference star fluxes $F_{\mathrm{ref}}(\lambda)$ on the NIST optical power standard by comparing flux-calibrated LEDs with stellar magnitudes.



Robotized StarDICE telescope at Observatoire de Haute Provence observing LED sources.



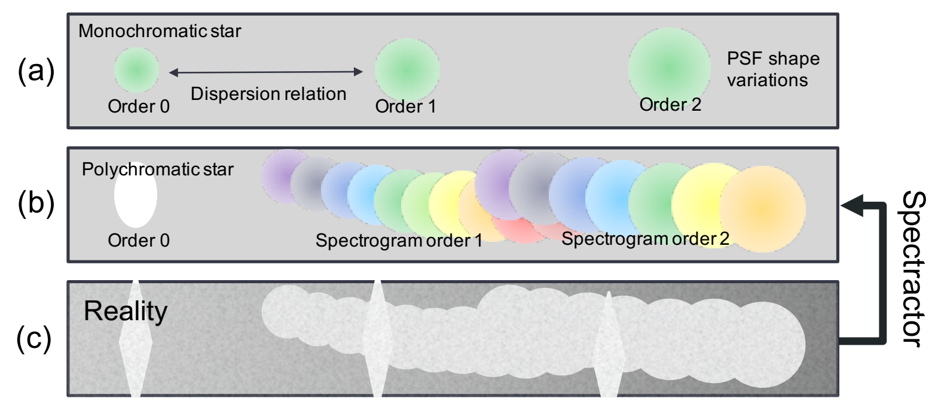
Observation of reference star G191B2B (CO white dwarf) with StarDICE g filter and picture of LEDs.



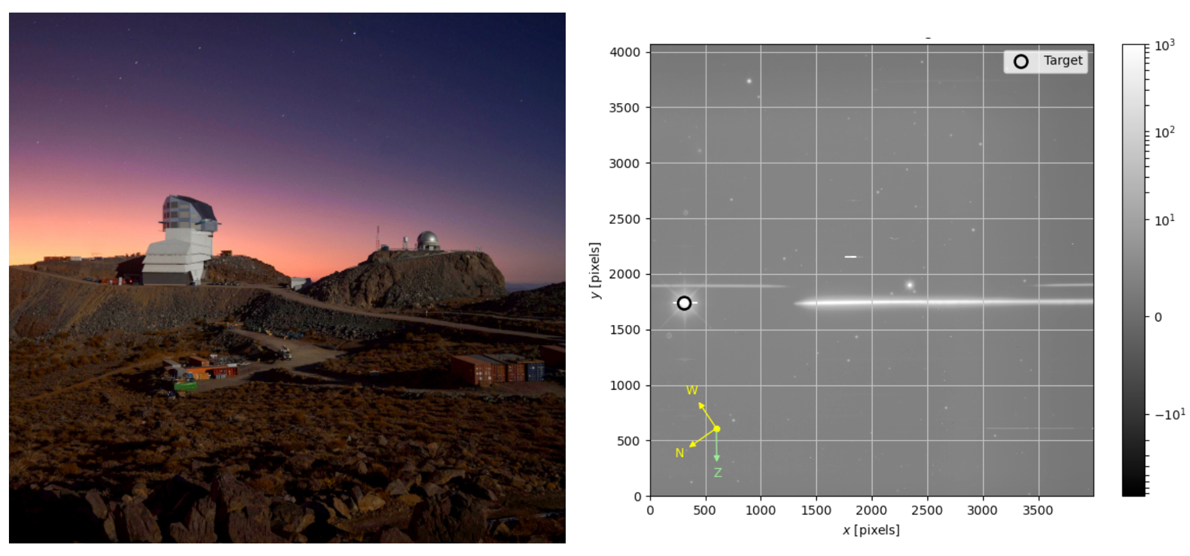
Airmass regression of a photometric night to get out-of-atmosphere star zero points.

$T_{\mathrm{atm}}(\lambda)$: slitless spectrophotometry

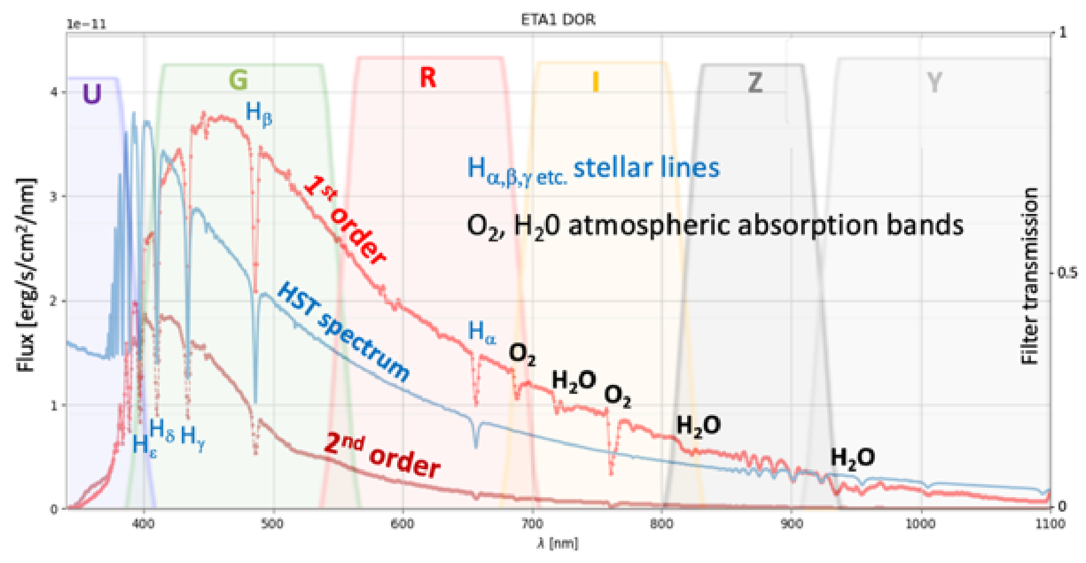
Slitless spectroscopy is a technique that transforms any imaging telescope into a spectrophotometer by simply inserting a disperser in a filter wheel before the sensor. This allows us to measure $T_{\mathrm{atm}}(\lambda)$ thanks to forward modelling with the `Spectractor` code.



`Spectractor` pipeline extraction is based on the forward modelling of the dispersed image.



Processed exposure of star HD111980 observed by Rubin-LSST AuxTel with a holographic grating made at IJCLab.



Auxtel spectrum of ηDor compared with its HST SED with identified atmospheric absorption lines.