Color corrections for LSST with AuxTel

LSST-France Meeting
Lyon, 15-12-2023

Martín Rodríguez Monroy - IJCLab, Orsay, France
on behalf of LSST-IJCLab group
Marc Moniez, Sylvie Dagoret-Campagne, Jérémy Neveu, Joseph Chevalier, Laurent Le Guillou

Outline

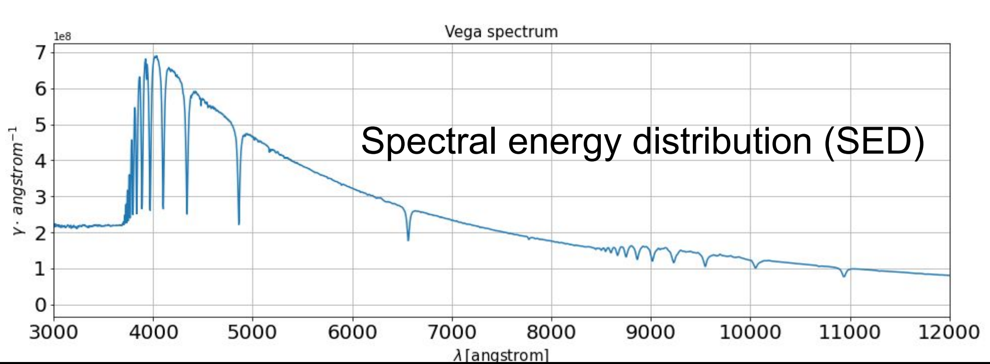
- Impact of the atmosphere on the measured magnitudes
- LSST’s Auxiliary Telescope: AuxTel
- From the instruments to the measurements
- From the measurements to the atmospheric parameters
- From the atmospheric parameters to the color corrections
- Role of AuxTel on LSST
- Color correction method
- Summary

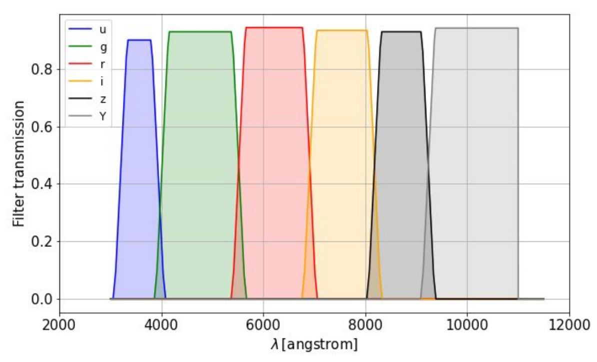
Impact of atmosphere

We wish to **recover the information** (magnitudes, colours, etc) of the objects (stars, galaxies, etc) **as seen from top of atmosphere**

- LSST measures **broadband** fluxes over a range of frequencies **filters:** *u, g, r, i, z, Y*
- From magnitudes we define **colours:** *u-g*, *g-r*, *r-i*, etc….

Flux in # of photons: $F^{obs}_{filter} \propto \int F_\nu(\lambda) S_{filter}(\lambda) \frac{d\lambda}{h\,\lambda} \rightarrow m^{obs}_{filter}$



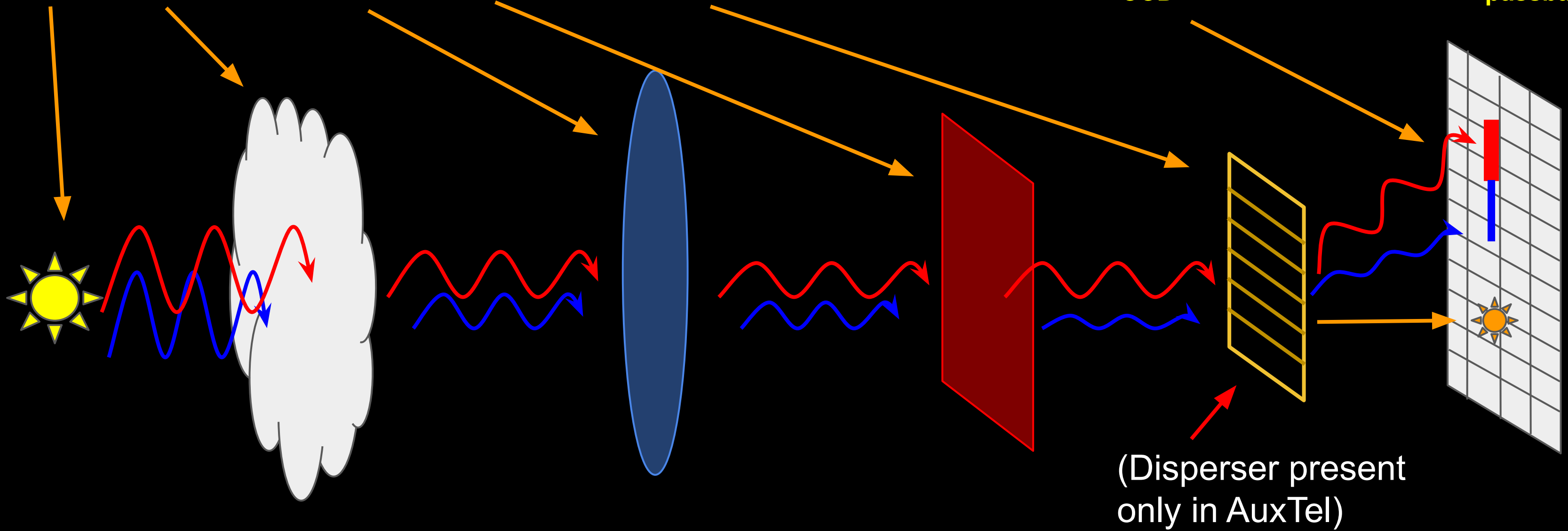


Impact of atmosphere

The amount of signal at each pixel (ADUs) depends on the different “obstacles” on optical path:

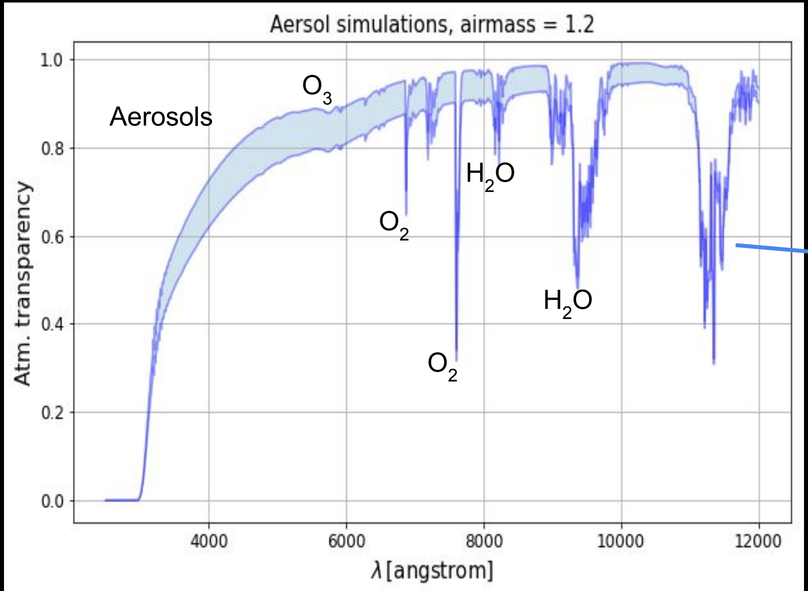
Telescope’s throughput

SED x atm. x mirrors x filter x disperser x entrance window x ε_{CCD} x analysis = $ADU_{passband}$



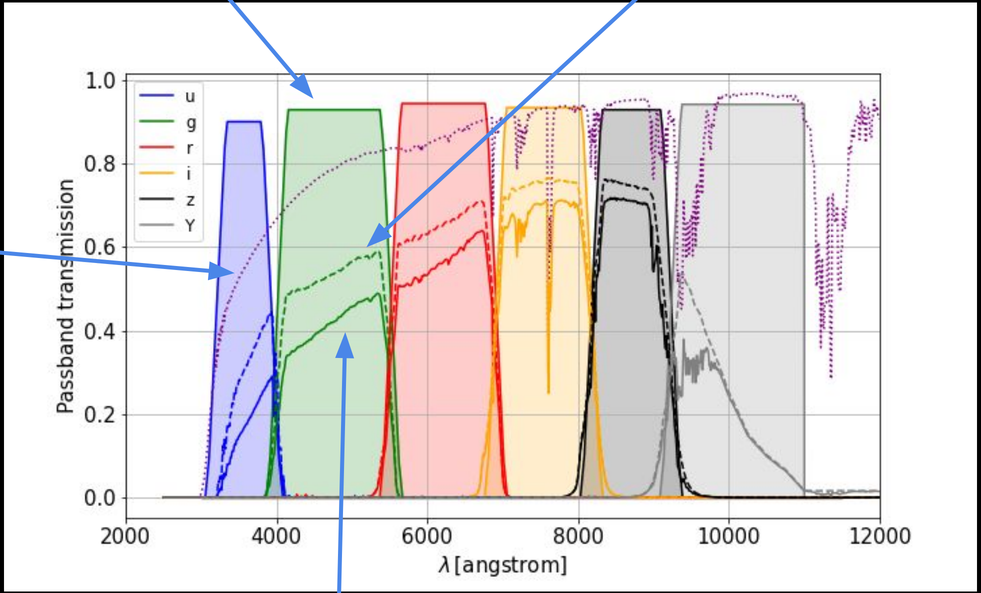
Impact of atmosphere

Simulated **atmospheric transparency** for two extreme aerosol values



LSST's **filter transmission** curves

LSST telescope's **throughput**



Effective passbands

Impact of atmosphere

How does it look like?

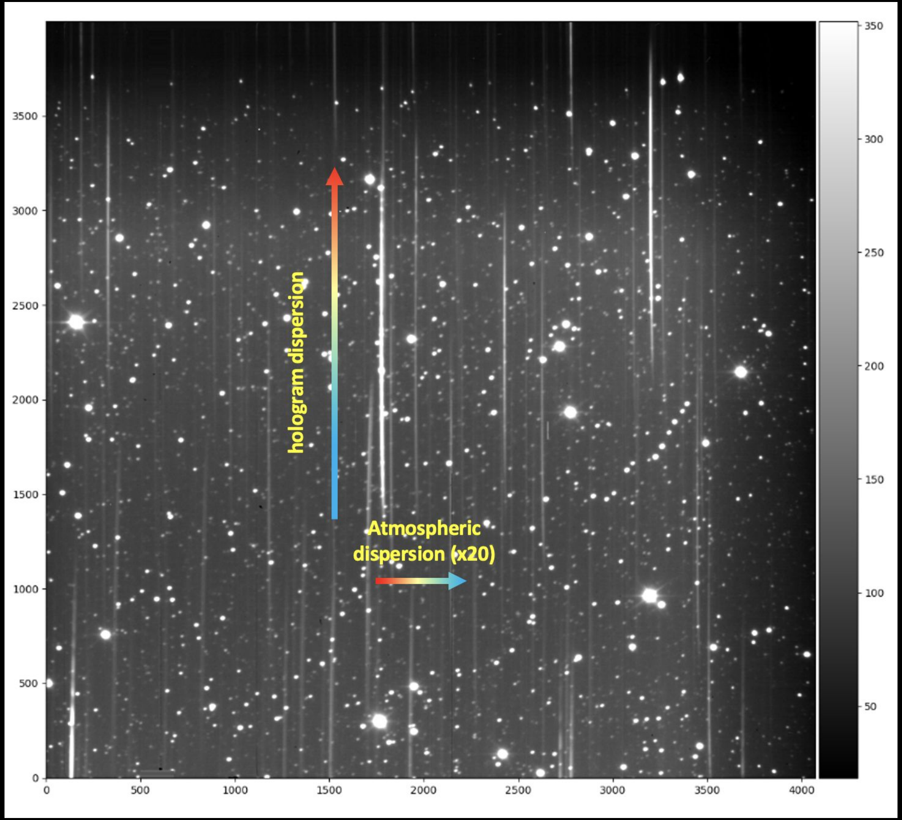
- **Clouds** = grey absorption
- **Rayleigh** scattering
- **Aerosols** scattering

→ Continuous features

- **Telluric lines** = absorption lines

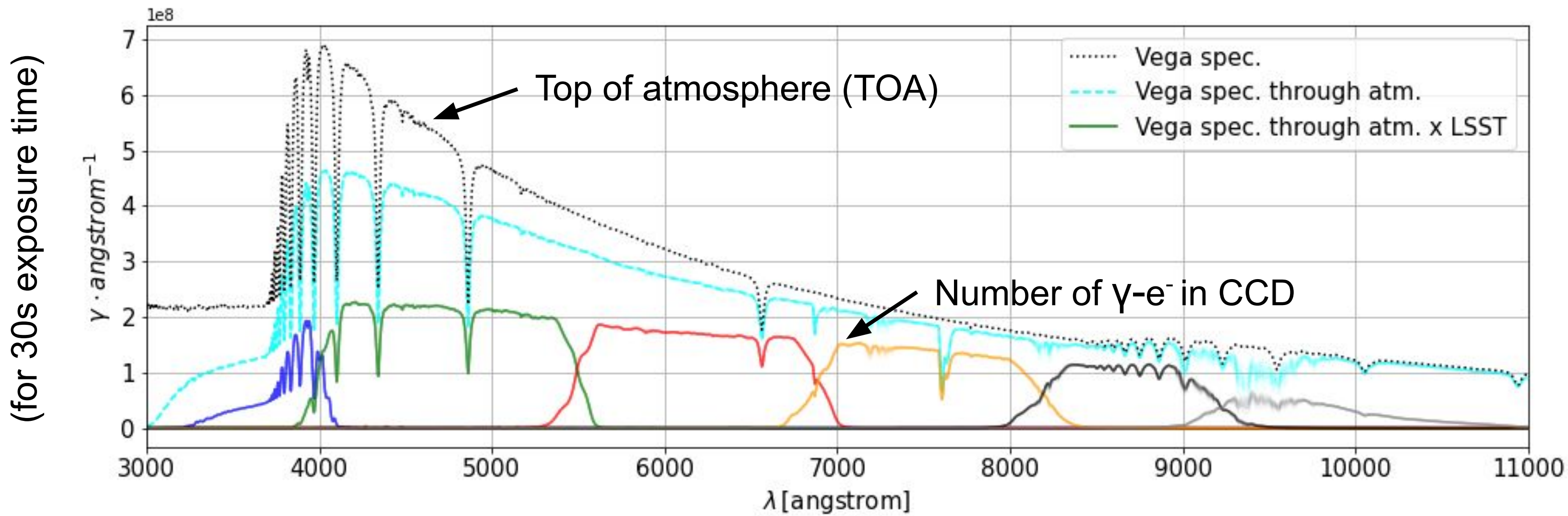
→ Discrete features

- **Bending of spectrum ∝ airmass**

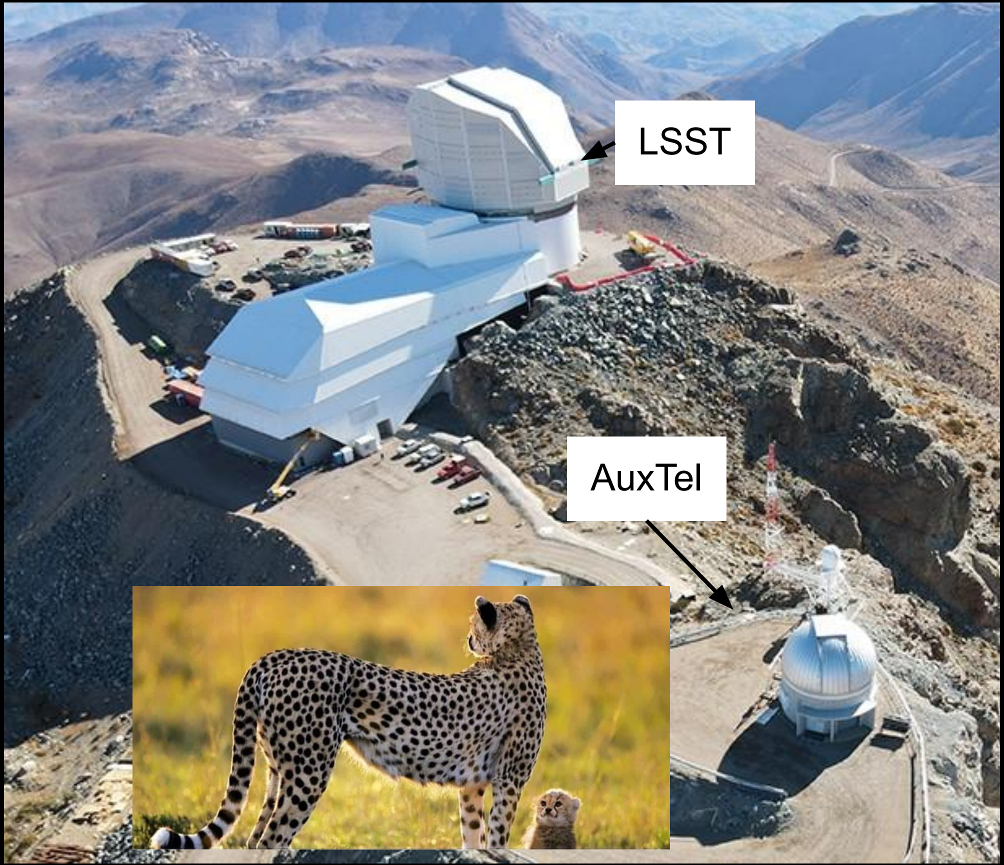


Effective passband: from SEDs to ADUs

of photons / Å: $F_{pb}^{obs} \propto \int F_\nu(\lambda) S_{pb}(\lambda) \frac{d\lambda}{h\lambda} \to m_{pb}^{obs}$



LSST's Auxiliary Telescope: AuxTel



LSST's Auxiliary Telescope: AuxTel

LATISS camera

- Auxiliary telescope: **1.2m, f/18**
- Equipped with a **spectrograph**
- Provides **spectra in real time** to compare them with space observations (calibration objects)
- **Hologram** installed in February 2021 to provide improved spectral resolution
- **Currently providing the only real data from LSST!** More than 3000 reconstructed spectra since september 2022 (and reprocessed according to analysis progress)

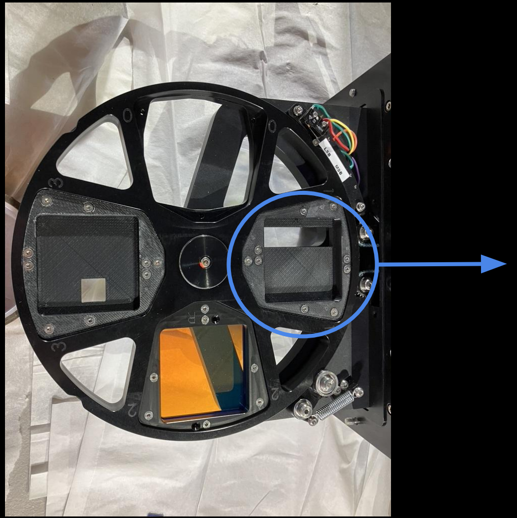
We use AuxTel to measure the atmosphere and compensate its impact:

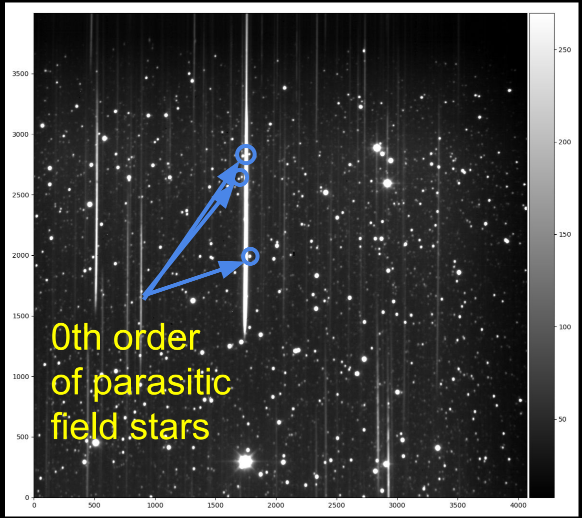
- **Measure atmospheric components,** e.g. PWV, O_3, aerosols, that impact the colors that LSST will measure
- **Real time atmosphere transmission x LSST throughput** ⟶ Derive color compensations for each object observed by LSST

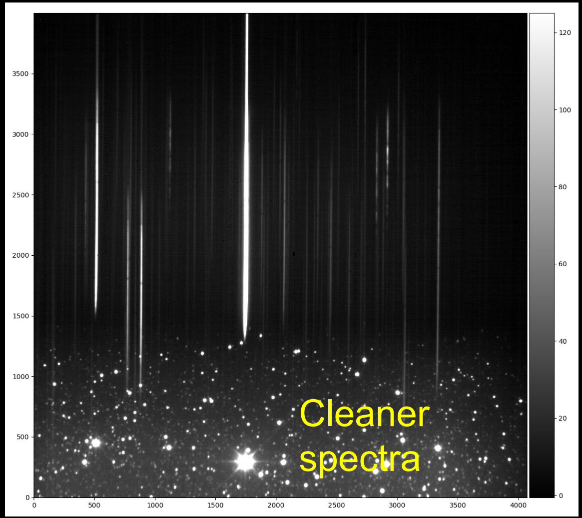
From the instruments to the measurements

Latest technical updates: recent work on Cerro Pachón to install, validate and characterize several new devices:

- Characterization of **spare hologram**
- Installation and characterization of **mask to reduce sky / stellar contaminations**



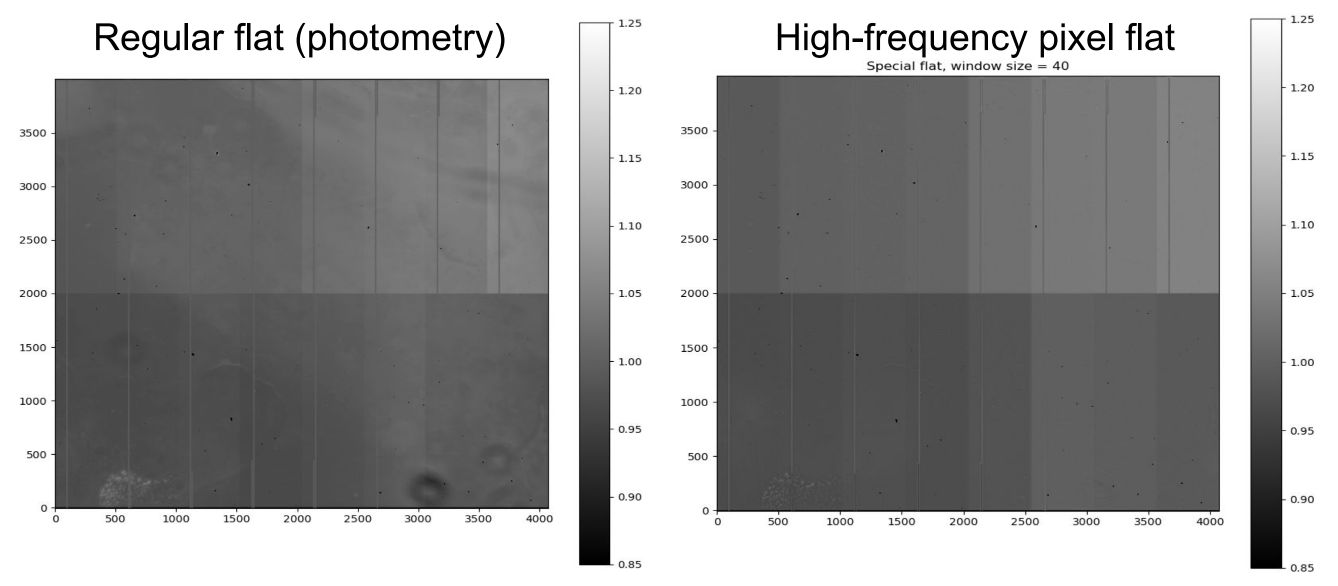


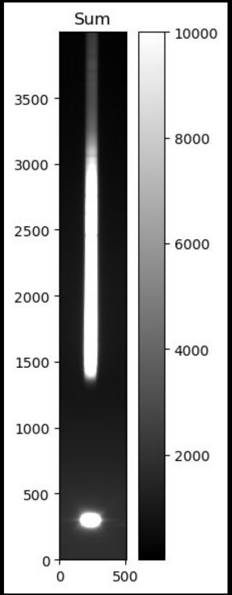


From the instruments to the measurements

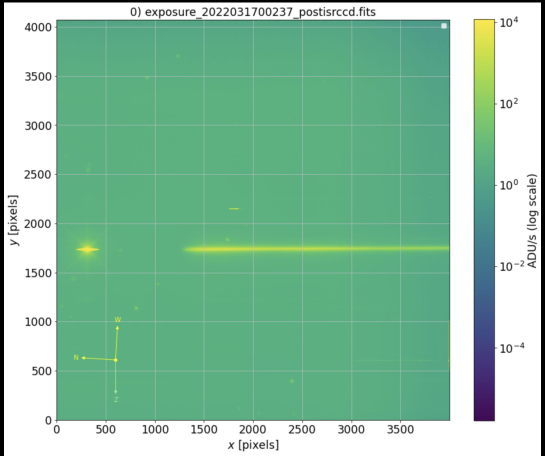
Studying different methods to produce **"flat-fields" for spectroscopy:**

- Low frequency component removal → **Pixel flats**
- Spectral exposures with horizontal shifting star → **Spectral flats**

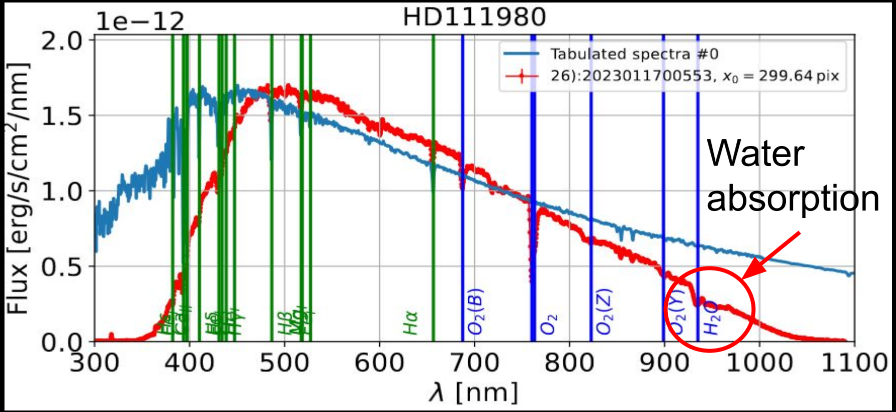




From the measurements to the atmospheric parameters



Spectrum extraction



We characterize the atmosphere by **taking spectra:**

- CALSPEC **standard stars**
- Different **airmasses** and **atm. conditions**

The spectra are extracted with the **Spectractor** software. It provides: Neveu et al. (arXiv:2307.04898)

- Data = **spectrum**
- Covariance

The **modeling** is given by:

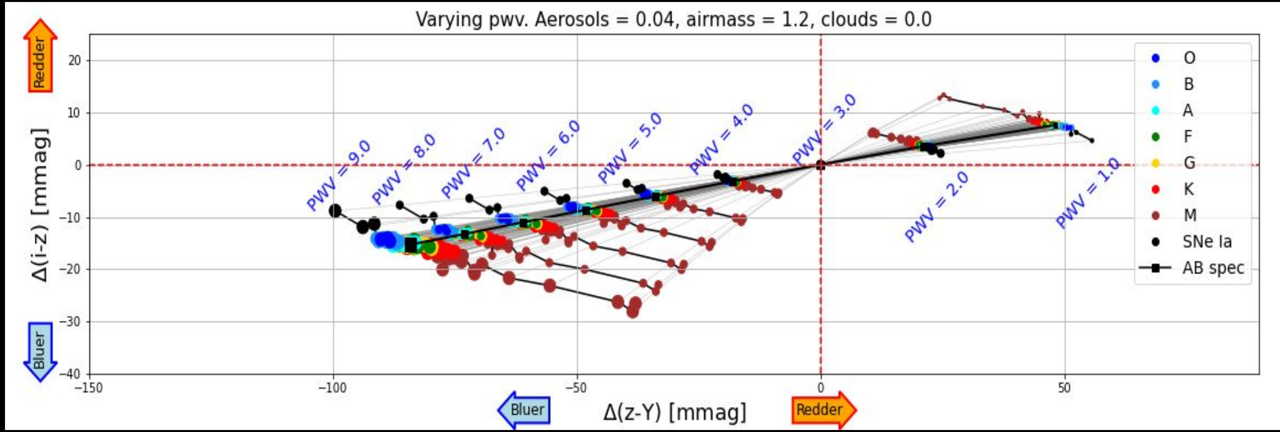
- **CALSPEC** spectrum
- **Throughput**
- ~~LibRadtran~~ model of atm
  Atm. emulator

Fit atmospheric parameters

From atmospheric parameters to color corrections

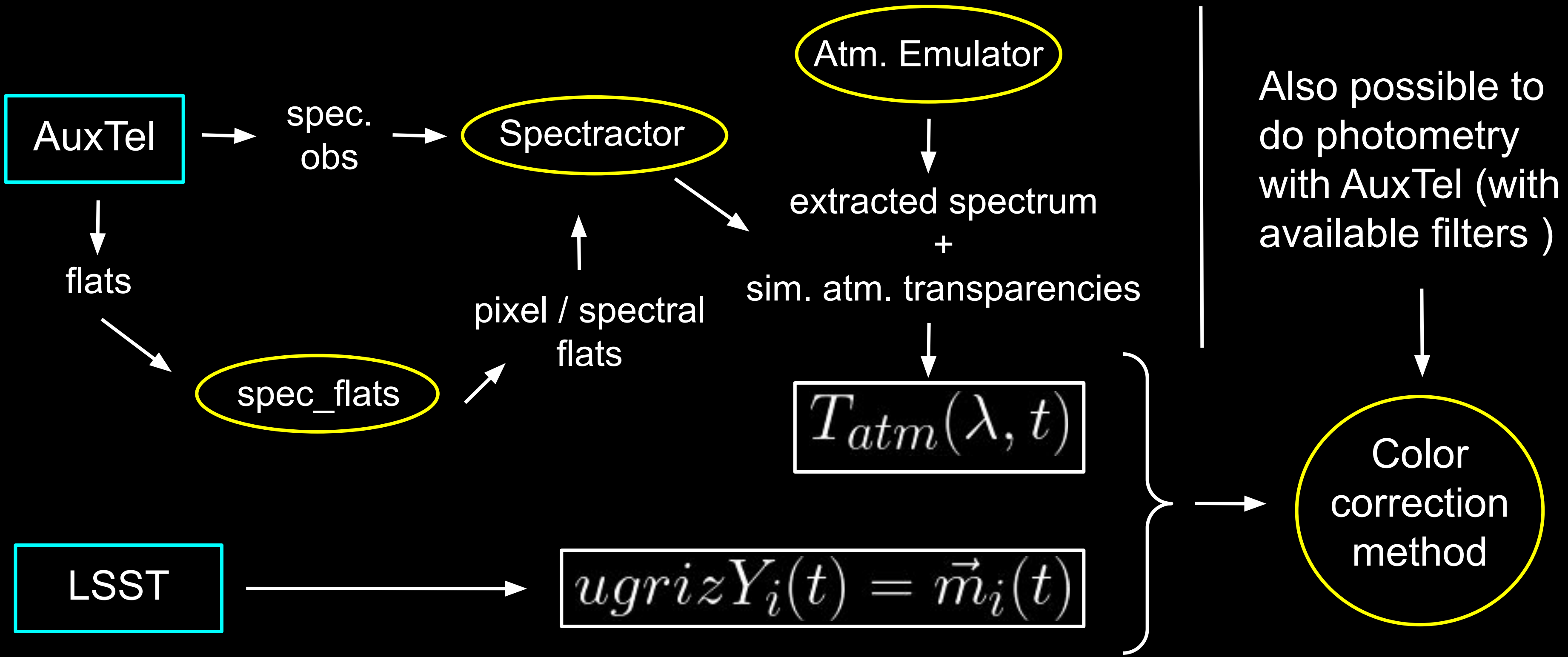
Derive **photometric corrections for LSST** for varying **atmospheric conditions.**
Different options:

- Baseline: measure atmospheric parameters (clouds, PWV, τ_{VAOD}, O_3) and derive model of the atmosphere (if AuxTel points far away from LSST during the night)
- Directly measure atmospheric transparency if AuxTel points to the same field as LSST
- Also, possible prior to other methods (FGCM)



Role of AuxTel on LSST

Sylvie Dagoret-Campagne:
https://github.com/LSSTDESC/getObsAtmo



Color correction method

LSST = photometric survey ⇒ we will have access only to broad-band magnitudes (photometric bands ~ very low resolution spectra)

$$m_{i,b}(t) = -2.5 \log_{10} \frac{\int F_i(\lambda)\, T_b(\lambda, t)\, S_{eff}\, t_{exp} \frac{d\lambda}{h\lambda}}{\int F_{AB}\, T_{tel,b}(\lambda)\, S_{eff}\, t_{exp} \frac{d\lambda}{h\lambda}} = -2.5 \log_{10} \frac{\varphi_{i,b}(t)}{\Phi_{AB}}$$

i = observed object

$$T_b(\lambda, t) = T_{tel,b}(\lambda) \cdot T_{atm}(\lambda, t)$$

← Depends on local atm. at moment of observation

How do we go “back” to a standard atmosphere? →

$$T_b^{std}(\lambda) = T_{tel,b}(\lambda) \cdot T_{atm}^{std}(\lambda)$$

Color correction method

LSST = photometric survey ⇒ we will have access only to broad-band magnitudes (photometric bands ~ very low resolution spectra)

$$m_{i,b}(t) = -2.5 \log_{10} \frac{\int F_i(\lambda)\, T_b(\lambda,t)\, S_{eff}\, t_{exp} \frac{d\lambda}{h\lambda}}{\int F_{AB}\, T_{tel,b}(\lambda)\, S_{eff}\, t_{exp} \frac{d\lambda}{h\lambda}} = -2.5 \log_{10} \frac{\varphi_{i,b}(t)}{\Phi_{AB}}$$

Color / magnitude correction:

LSST ⟷ $\vec{\varphi}_i^{\,corr} = \vec{\varphi}_i(t) \cdot \frac{\vec{\Phi}_i^{std}}{\vec{\Phi}_i(t)}$ ← AuxTel ⇕ **real time atm. transparency**

Color correction method

$$\vec{\varphi}_i^{corr} = \vec{\varphi}_i(t) \cdot \frac{\vec{\Phi}_i^{std}}{\vec{\Phi}_i(t)}$$

We need to go back to top of atmosphere (TOA)

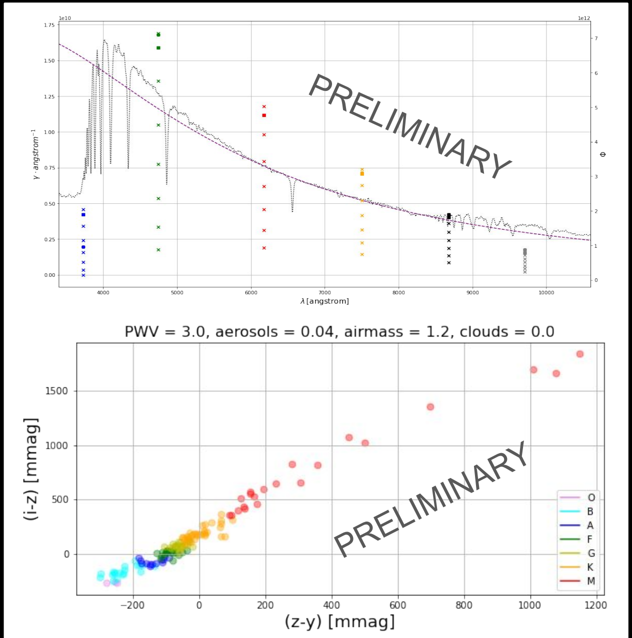
Model of SED for object *i*, $\hat{F}_i(\lambda)$, provided by "LSST archive"

$$\Phi_{i,b}^{std} = \int \hat{F}_i(\lambda) T_b^{std}(\lambda) S_{eff}\, t_{\exp} \frac{d\lambda}{h\lambda}$$

$$\Phi_{i,b}(t) = \int \hat{F}_i(\lambda) T_b(\lambda, t) S_{eff}\, t_{\exp} \frac{d\lambda}{h\lambda}$$

Color correction method

$$\vec{\varphi}_i^{\,corr} = \vec{\varphi}_i(t)\cdot\frac{\vec{\Phi}_i^{std}}{\vec{\Phi}_i(t)} \longleftarrow \times \; T_{atm}(\lambda, t) \text{ and } T_{atm}^{std}(\lambda)$$



"LSST archive":

- **Known** SED$_{i,TOA}$ / $\vec{m}_{i,\mathrm{toa}}$ $\Rightarrow \hat{F}_i(\lambda) = F_i(\lambda)$
- Partially known or unknown $\vec{m}_{i,\mathrm{toa}}$ ⇒ **modeling:**

$\hat{F}_i(\lambda) \longrightarrow$

- ❑ Black body fitting
- ❑ Interpolation
- ❑ 5D color clusters
- ❑ ....

$$\longrightarrow \vec{\varphi}_{i,\mu+1}^{\,corr} = \vec{\varphi}_{i,\mu}(t)\cdot\frac{\vec{\Phi}_{i,\mu}^{std}}{\vec{\Phi}_{i,\mu}(t)}$$

Color correction method

$$\vec{\varphi}_i^{corr} = \vec{\varphi}_i(t) \cdot \frac{\vec{\Phi}_i^{std}}{\vec{\Phi}_i(t)} \leftarrow \times \; T_{atm}(\lambda, t) \text{ and } T_{atm}^{std}(\lambda)$$

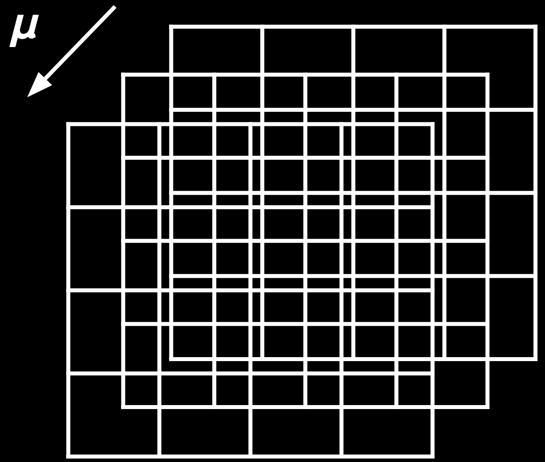
"LSST archive":

- **Known** SED$_{i,\mathrm{TOA}}$ / $\vec{m}_{i,\mathrm{toa}}$ $\Rightarrow \hat{F}_i(\lambda) = F_i(\lambda)$
- Partially known or unknown $\vec{m}_{i,\mathrm{toa}}$ $\Rightarrow$ **modeling:**

$\hat{F}_i(\lambda) \rightarrow$

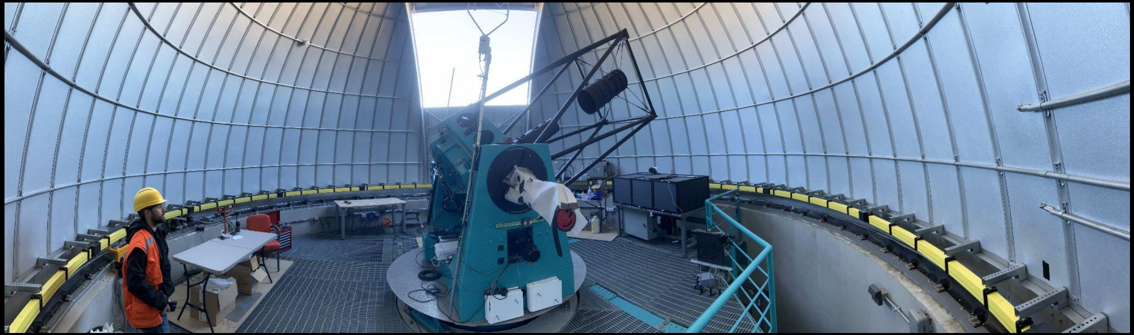
- ❑ Black body fitting
- ❑ Interpolation
- ❑ 5D color clusters
- ❑ ….

Update archive



Summary

- **Great technical improvements** carried out on AuxTel during the two September observing runs
- **Improved data quality thanks to the mask installed**
- Working on **new methods to flat-field spectroscopic exposures**
- Working on the **measurement of atmospheric parameters**
- Developing **color compensation method for LSST with AuxTel** observations
    - Conceptual changes to simplify analysis
    - Iterative process to incorporate known information
    - Studying options to model SEDs
- **AuxTel is an essential asset for the quality of LSST's data**



Merci beaucoup!