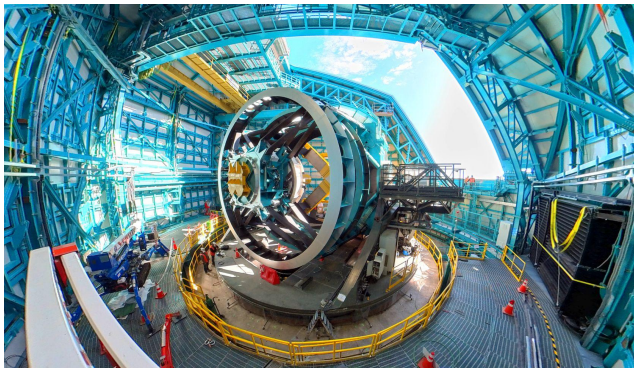
IJCLab : Groupe Rubin-LSST

M. Moniez, S. Dagoret-Campagne, J-E. Dagoret-Campagne, J. Chevalier,
J. Peloton, **J. Neveu, E. Van den Abeele**



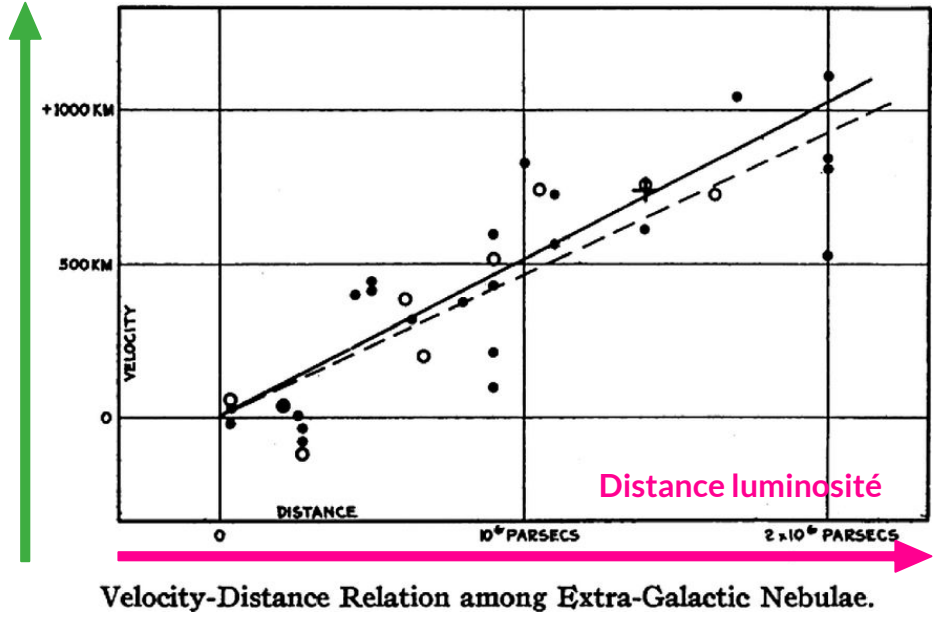
Expansion de l'Univers

Georges Lemaître

Edwin Hubble

→ **1927, 1929** : Expansion de l'Univers

Vitesse



Velocity-Distance Relation among Extra-Galactic Nebulae.

$$cz = H_0 d$$

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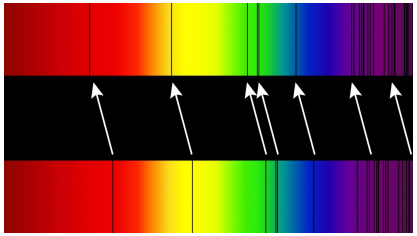

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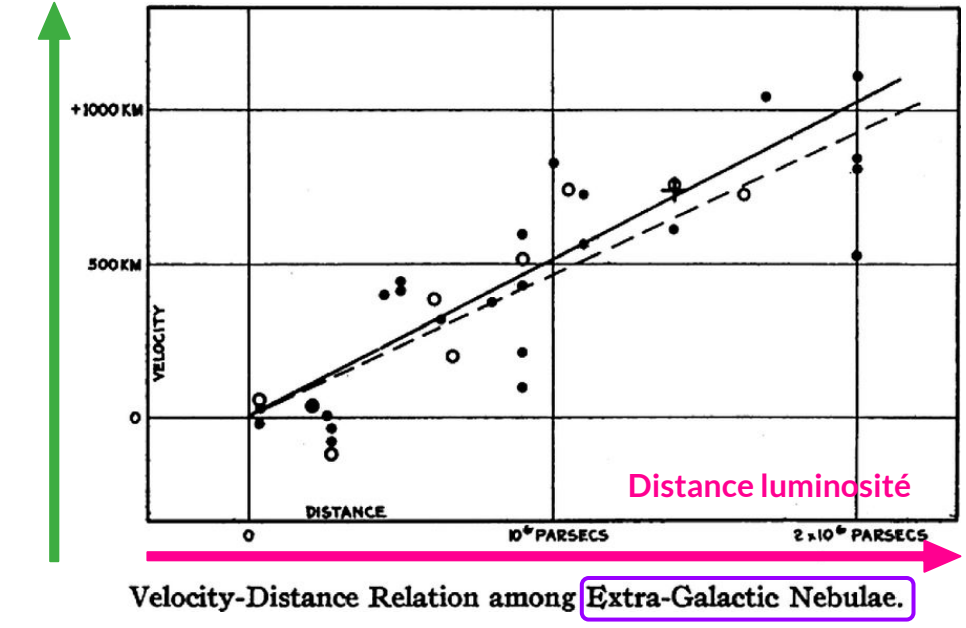

Velocity-Distance Relation among Extra-Galactic Nebulae.

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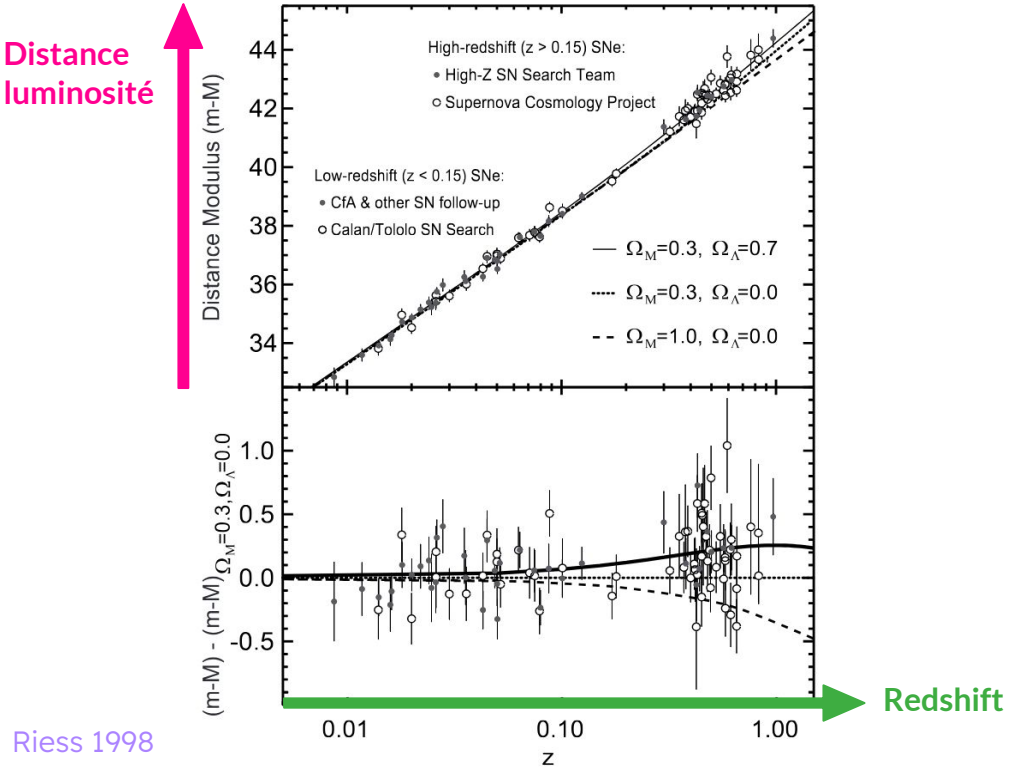
$$cz = H_0 d$$

Redshift : décalage des raies spectrales vers les hautes longueurs d'onde

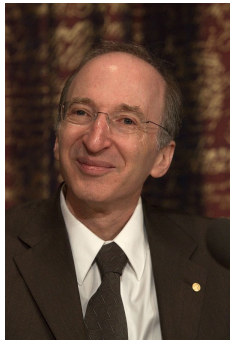
Chandelles standard : source de luminosité connue

L’énergie noire

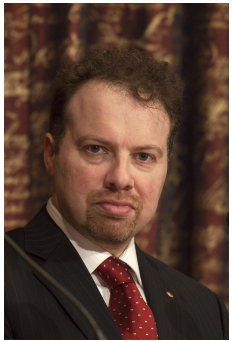
→ **1998** : Expansion **accélérée** de l’Univers



Riess 1998



Saul Perlmutter



Adam Riess

Brian Schmidt

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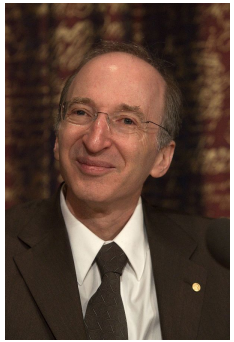

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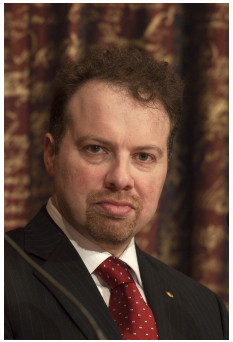

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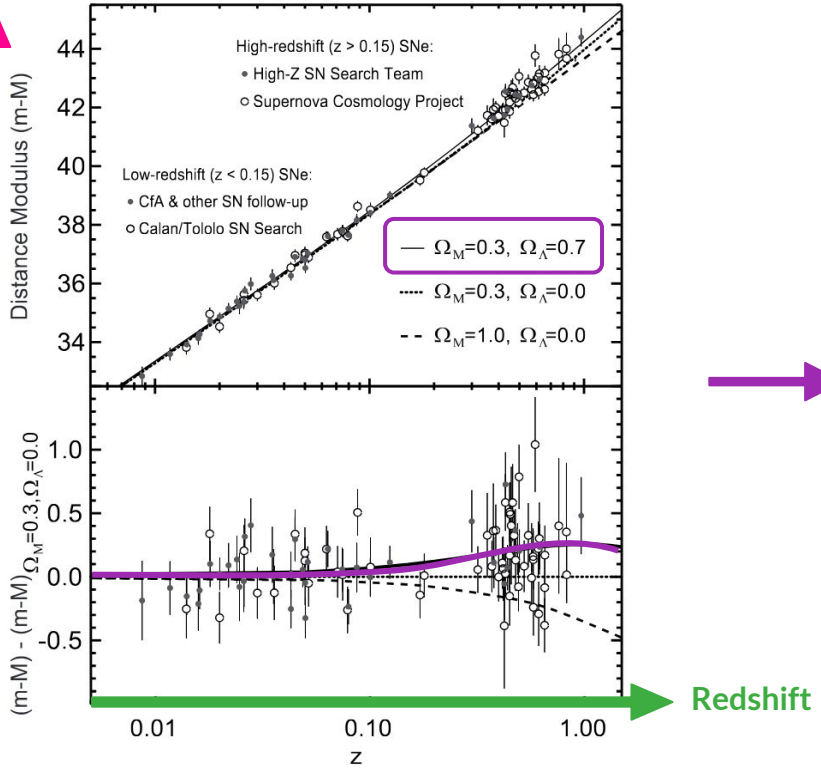
Distance luminosité



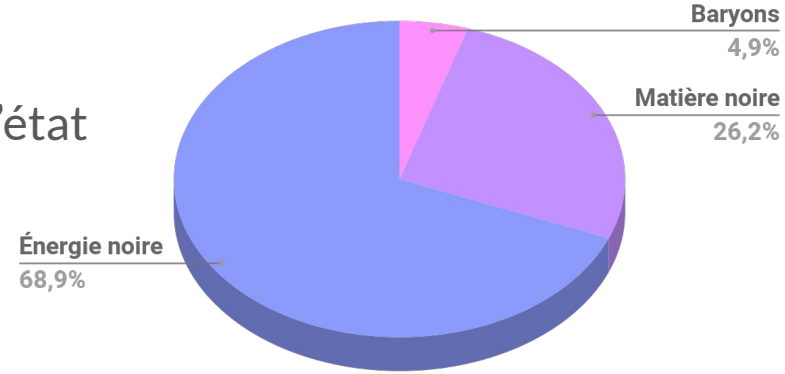
→ **Énergie noire**

Riess 1998

L’énergie noire

Énergie noire → fluide décrit par une équation d’état de paramètre w :

$$\rho_{\mathrm{de}} \propto a^{-3(1+w)}$$



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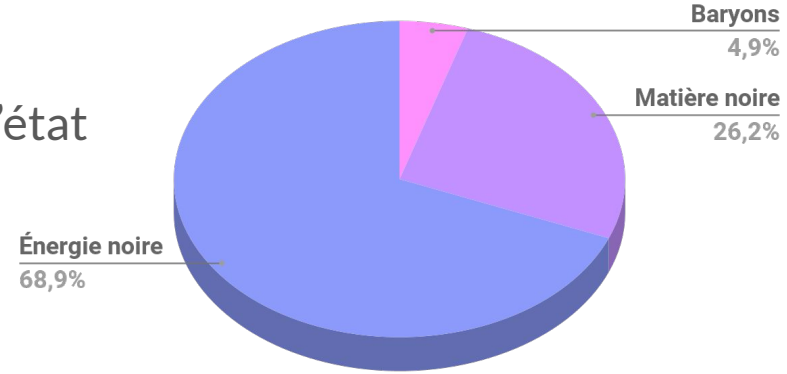

- **ΛCDM, le modèle standard :**
  - **Λ** pour la **constante cosmologique**, **CDM** pour **Cold Dark Matter**, w = -1

- **Autres modèles :**
  - $w \neq -1$, constant (w**CDM**), ou dynamique (w_0w_a**CDM**)

↳ $w(a) = w_0 + w_a(1 - a)$

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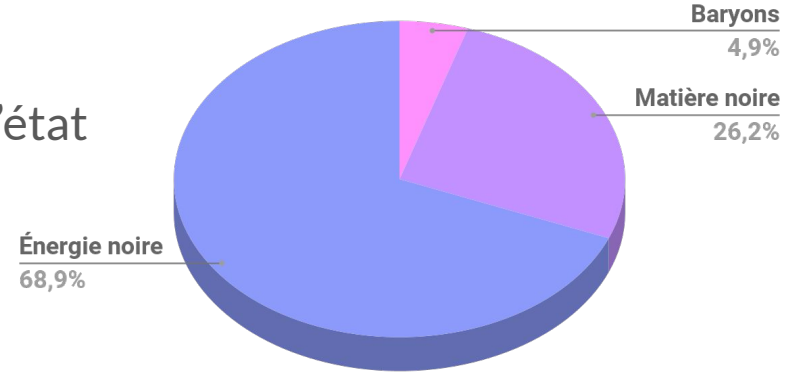

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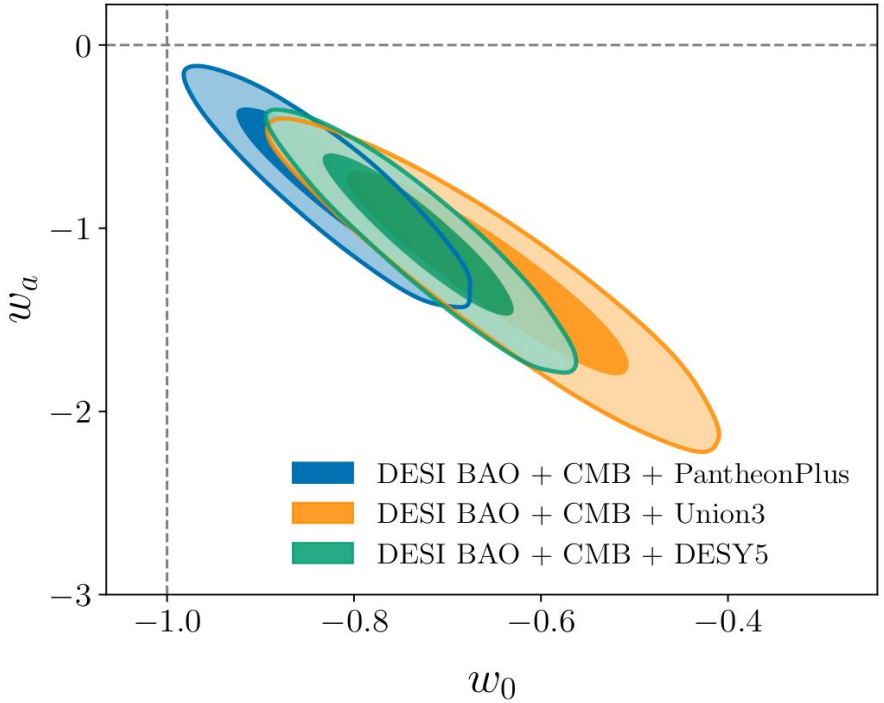
⇒ Quel modèle décrit le mieux les observations ?

L’énergie noire

Combinaison de sondes :

- Supernovae de type Ia
- Fond diffus cosmologique (CMB)
- Oscillations acoustiques de baryons



Constraints in the w_0-w_a plane parameters
(DESI Collaboration et al., 2024)

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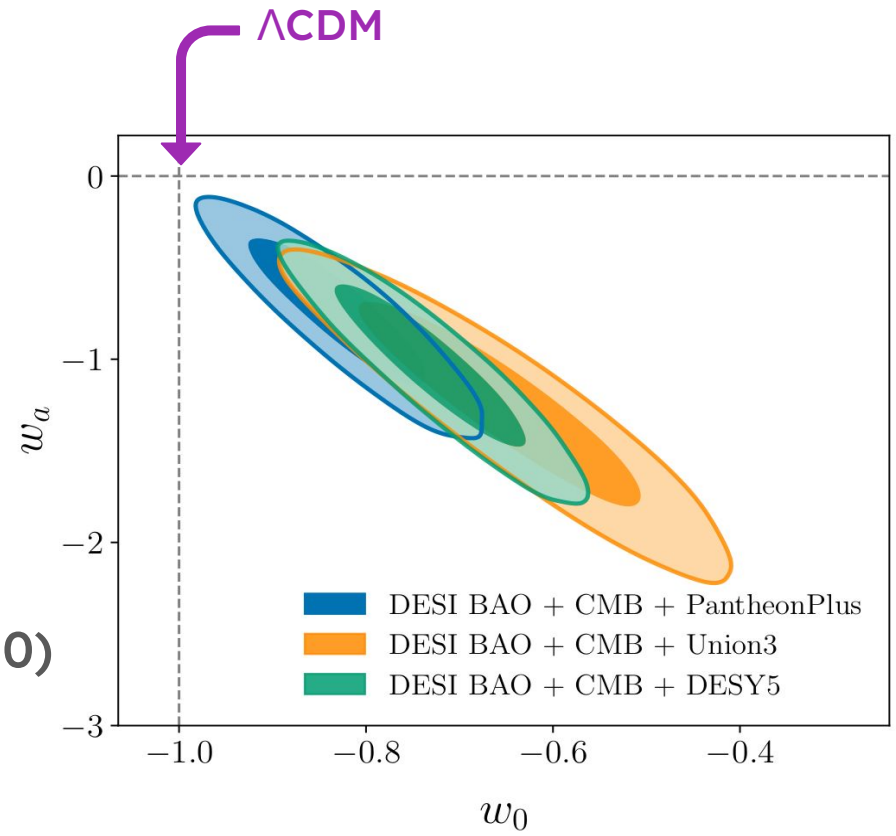

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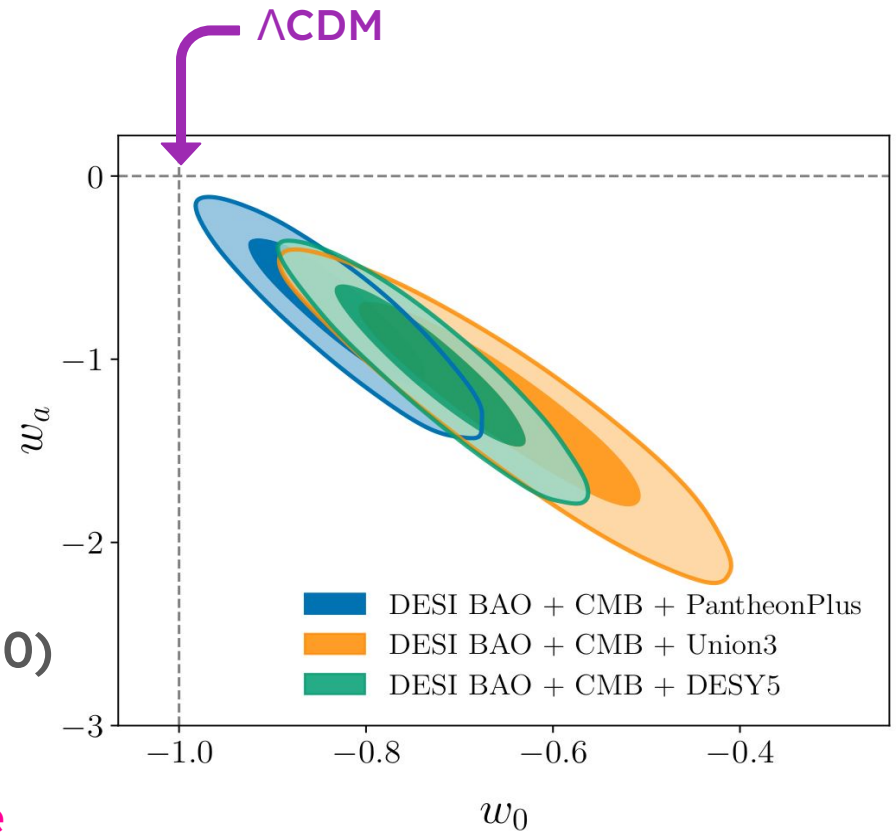
⇒ Mesures précises ? Ou y a-t-il une source de biais, notamment pour les SNe Ia ?



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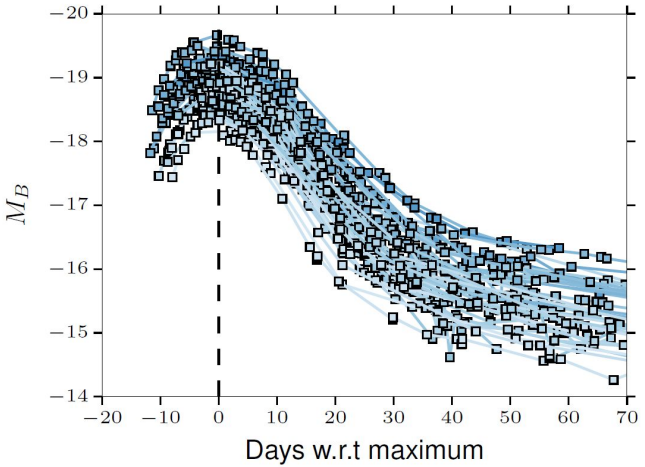

Courbes de luminosité absolue de SNe Ia proches dans la bande B (François Hazenberg)

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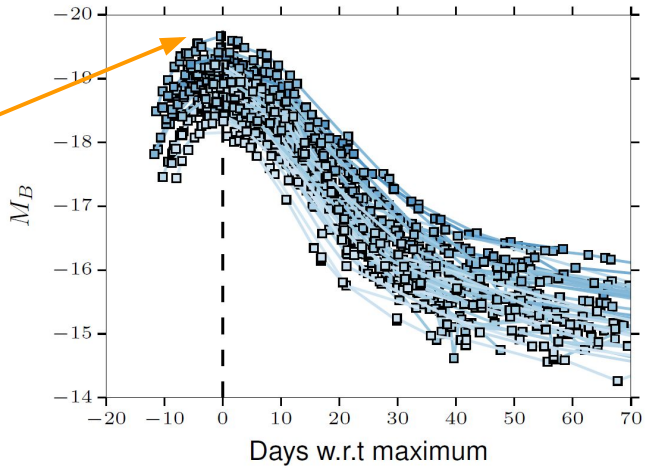
Mesure des distances :

$$F_{\max} = \frac{L_{\max}}{4\pi D_L^2}$$



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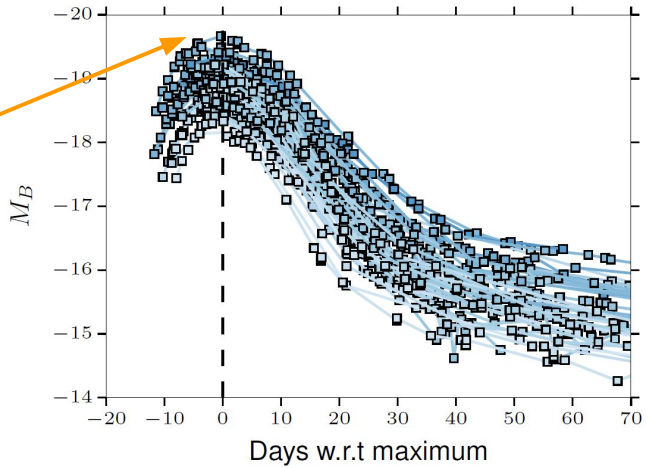
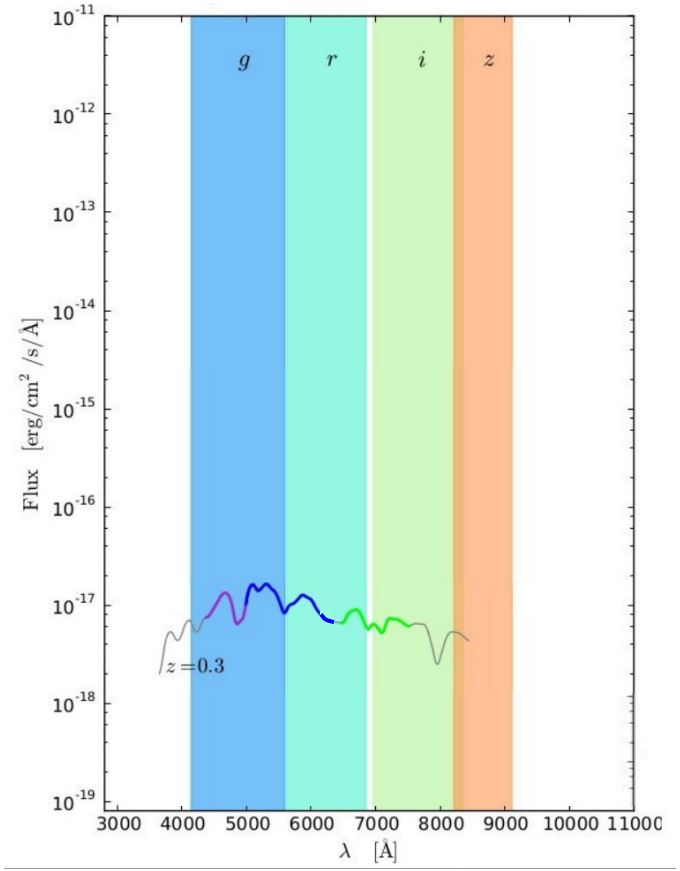


Courbes de luminosité absolue de SNe Ia proches dans la bande B (François Hazenberg)

Mesure de flux des SNIa

Spectre de SN Ia observé à travers les filtres d'un télescope



Spectre de la SN

Transmission filtre X

Transmission atmosphérique

$$F_X = \int \lambda d\lambda \times S_\star(\lambda) T_X(\lambda) T_{\rm atm}(\lambda)$$

Slide : Thierry Souverin

Mesure de flux des SNIa

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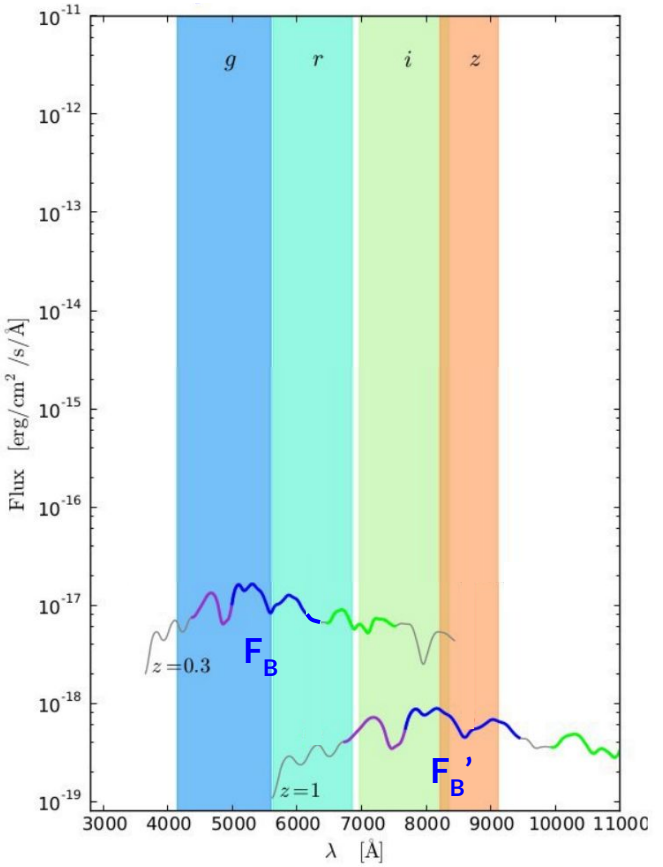

Spectre de la SN — Transmission filtre X — Transmission atmosphérique

$$F_X = \int \lambda d\lambda \times S_\star(\lambda) T_X(\lambda) T_{\rm atm}(\lambda)$$

Objectif : Mesurer relativement F_B issus de spectres de SN à différents redshift **z**

Mais :

- Spectres étendus sur plusieurs filtres
- F_B pour différents **z** mesuré dans différentes bandes

Slide : Thierry Souverin

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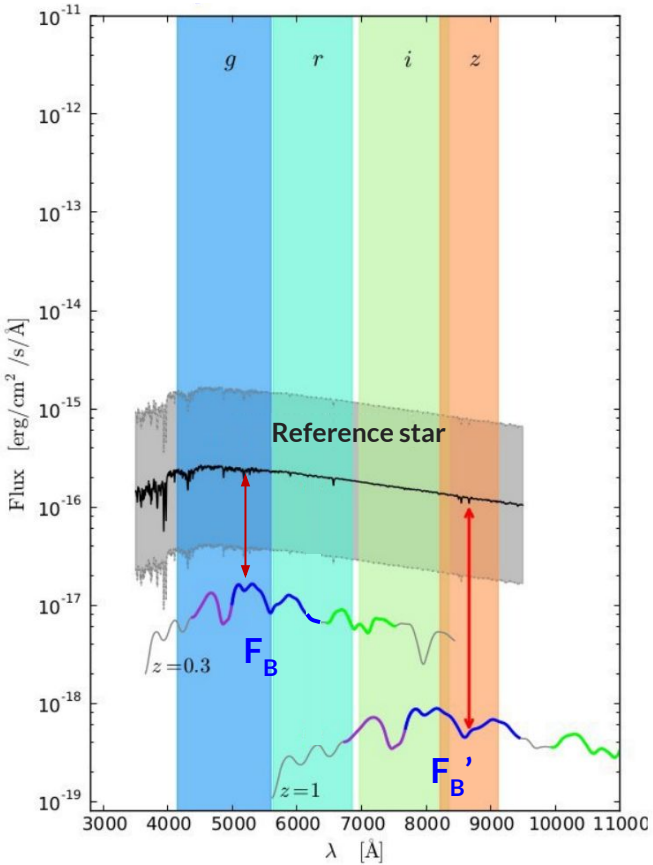

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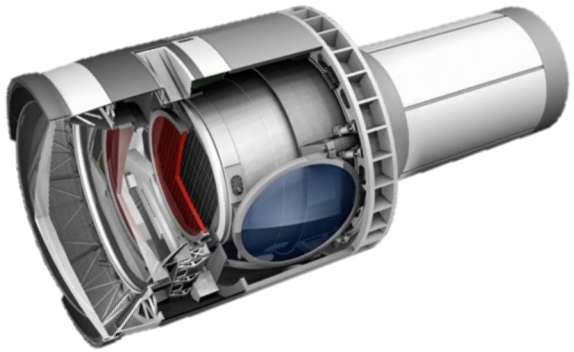
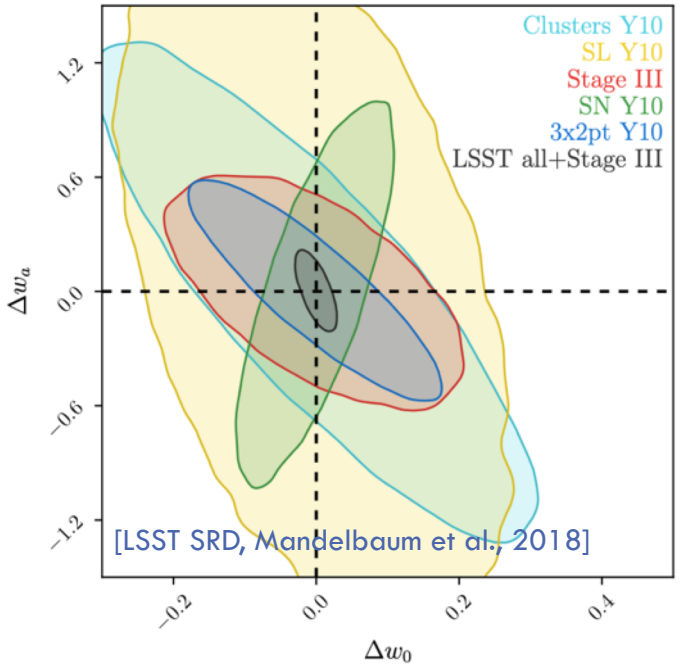
Étoile de référence : Calibrer la transmission du flux pour chaque filtre → **Calibration CALSPEC**

Slide : Thierry Souverin

Vera Rubin Observatory – LSST survey

- Multiprobe photometric survey for cosmology and astrophysics
  - **Wide:** all the austral sky, field of view of 9.6 square degrees with 3.2Gpix (=400 4K UHD TV)
  - **Fast:** every 3 days on average after 10 years of survey
  - **Deep:** 6 bands ugrizy, with magnitude limit
    - r < 24.03 in 1 15" exposure (~DES DR1)
    - 26.9 after 10 years (5σ)





- Number of objects (full survey, DR11):
  - 20B galaxies
  - 17B resolved stars
  - 6M orbits of solar system bodies
  - Average number of alerts per night: about 10 million

[https://www.lsst.org/scientists/keynumbers]

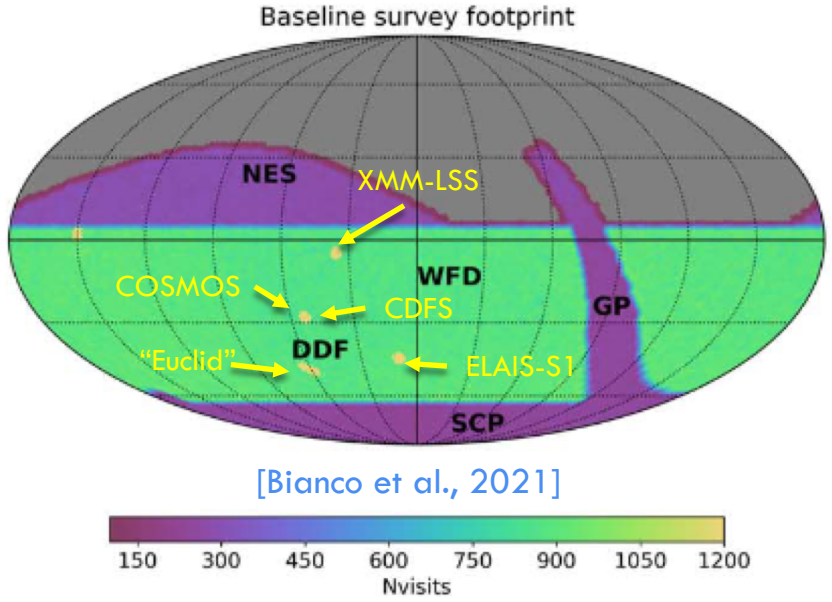
Vera Rubin Observatory – LSST survey

- On-sky commissioning starts July 2024, science survey starts mid-2025
- Data Release 1 scheduled between mid-2026 early 2027 (6 months of LSST data)
  - Then 1 public data release per year

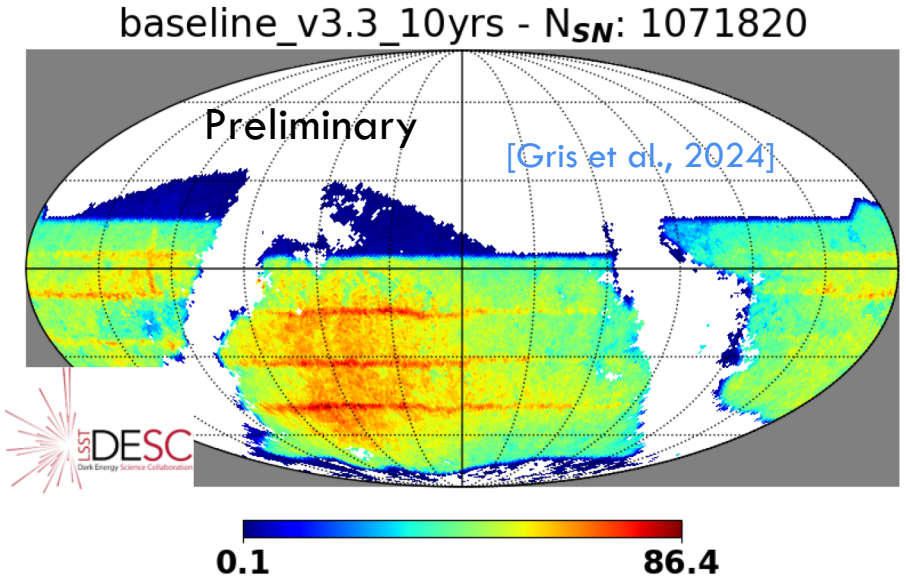
Camera ready for shipment in Chile in May 2024

Type Ia supernova cosmology with LSST

- Wide survey (WFD) + 5 Deep Drilling Fields (DDF: COSMOS, Euclid fields, …)
- Cadence is not decided yet but… with current baseline scenario the LSST/DESC Cadence Working Group get (preliminary):
  - 1 000 000 SNIa in 10 years with "good quality cuts", 35 000 may get spectra
  - 20 000 good SNIa in DDF, with ~700 SN at z>0.8



[Bianco et al., 2021]

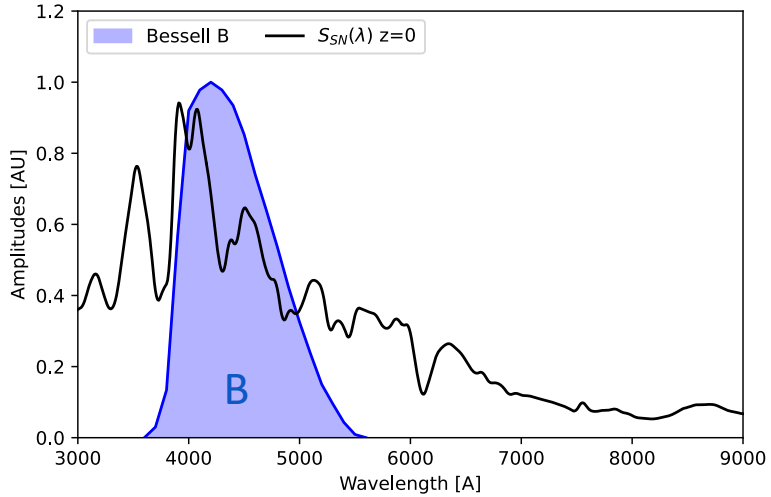


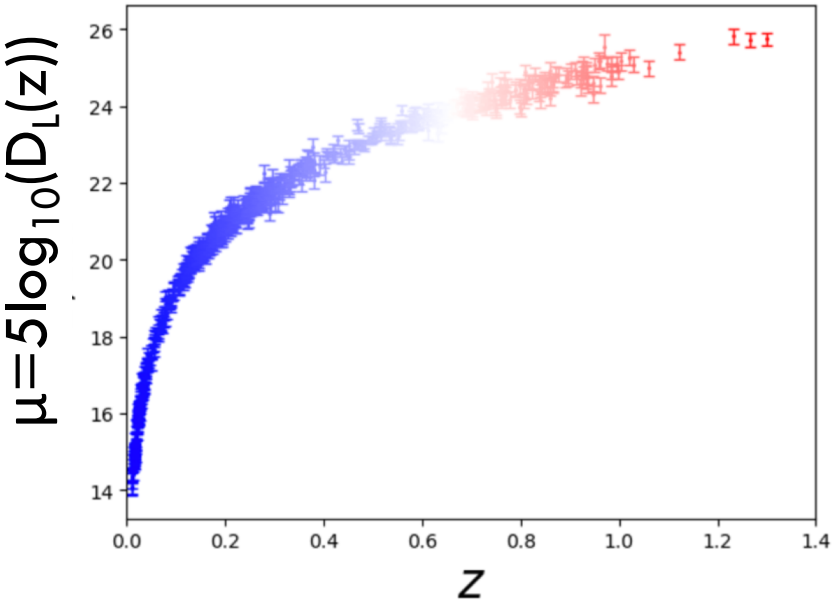
Type Ia supernova cosmology with LSST

- SNIa Hubble diagram is built using standardized B band rest-frame magnitudes of supernovae with:

$$\mu = 5\log_{10}(D_L(z)) \sim B - 3(B\text{-}V)$$

- It depends strongly on our capacity to convert observer frame magnitudes (ugrizy) to rest-frame B magnitudes ➔ photometric calibration
- Back-of-the-envelope computations:
  - SNIa intrinsic dispersion: σ_{int}=0.15mag
  - with 35000 SNIa: $\sigma_\mu = \sigma_{int}/\mathrm{sqrt}(35000) \sim 1$mmag
  - **Photometric calibration systematics must be at most of 1mmag also to benefit from the full statistical power of the LSST survey**



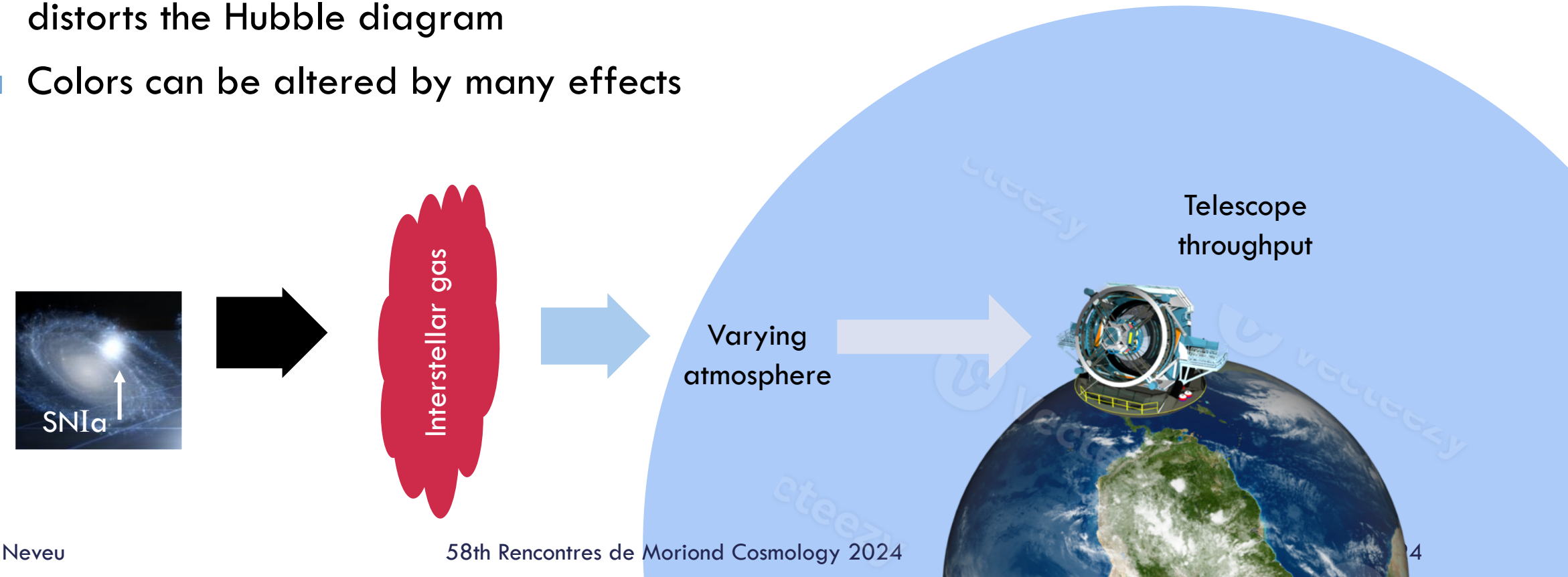


Photometric surveys for cosmology

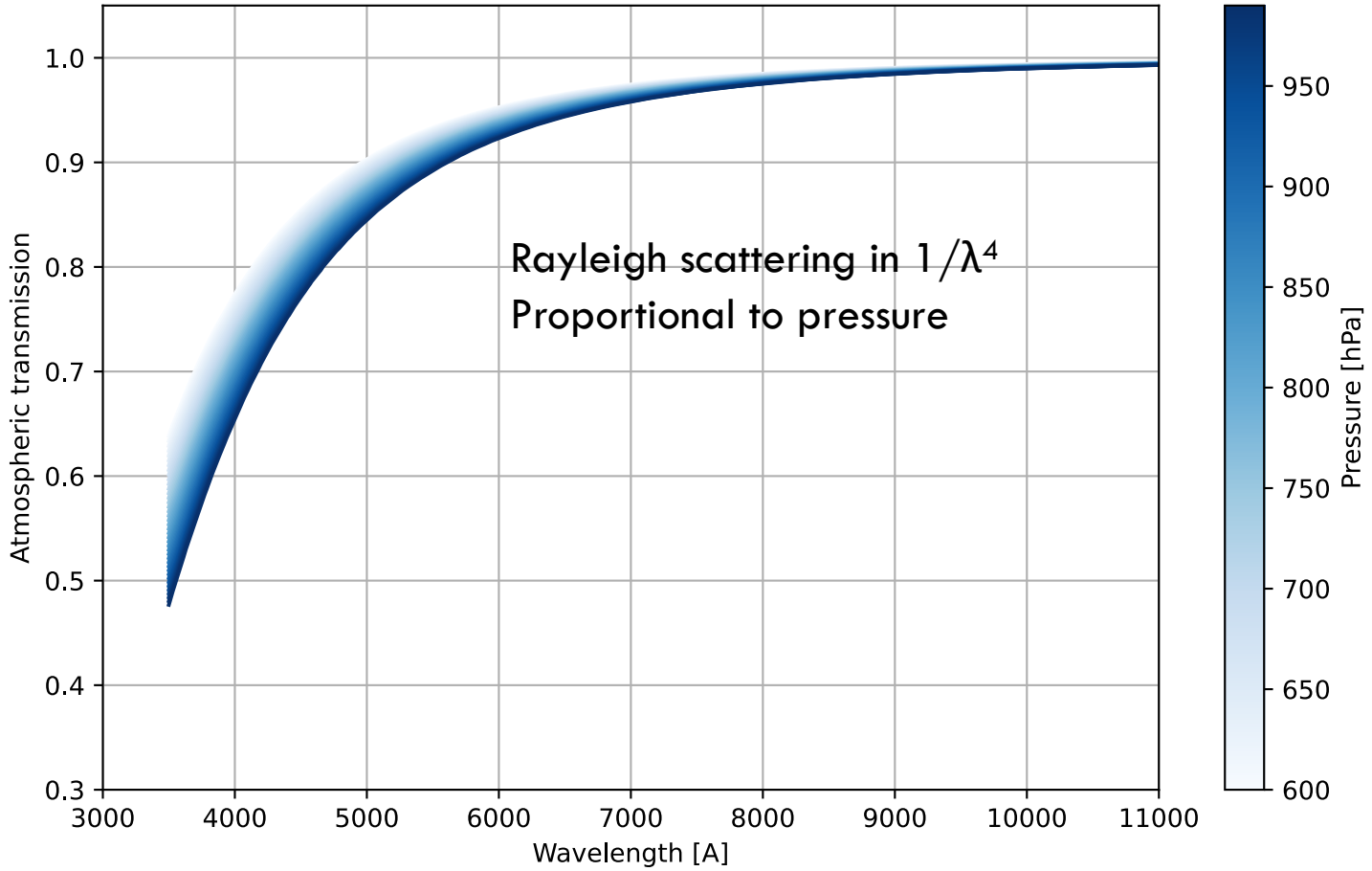
- In cosmology the farther, the redder!

➔ colors contain information on cosmological distances

- Any unwanted colored effect on your measurements distorts the Hubble diagram
- Colors can be altered by many effects



Atmosphere transmission



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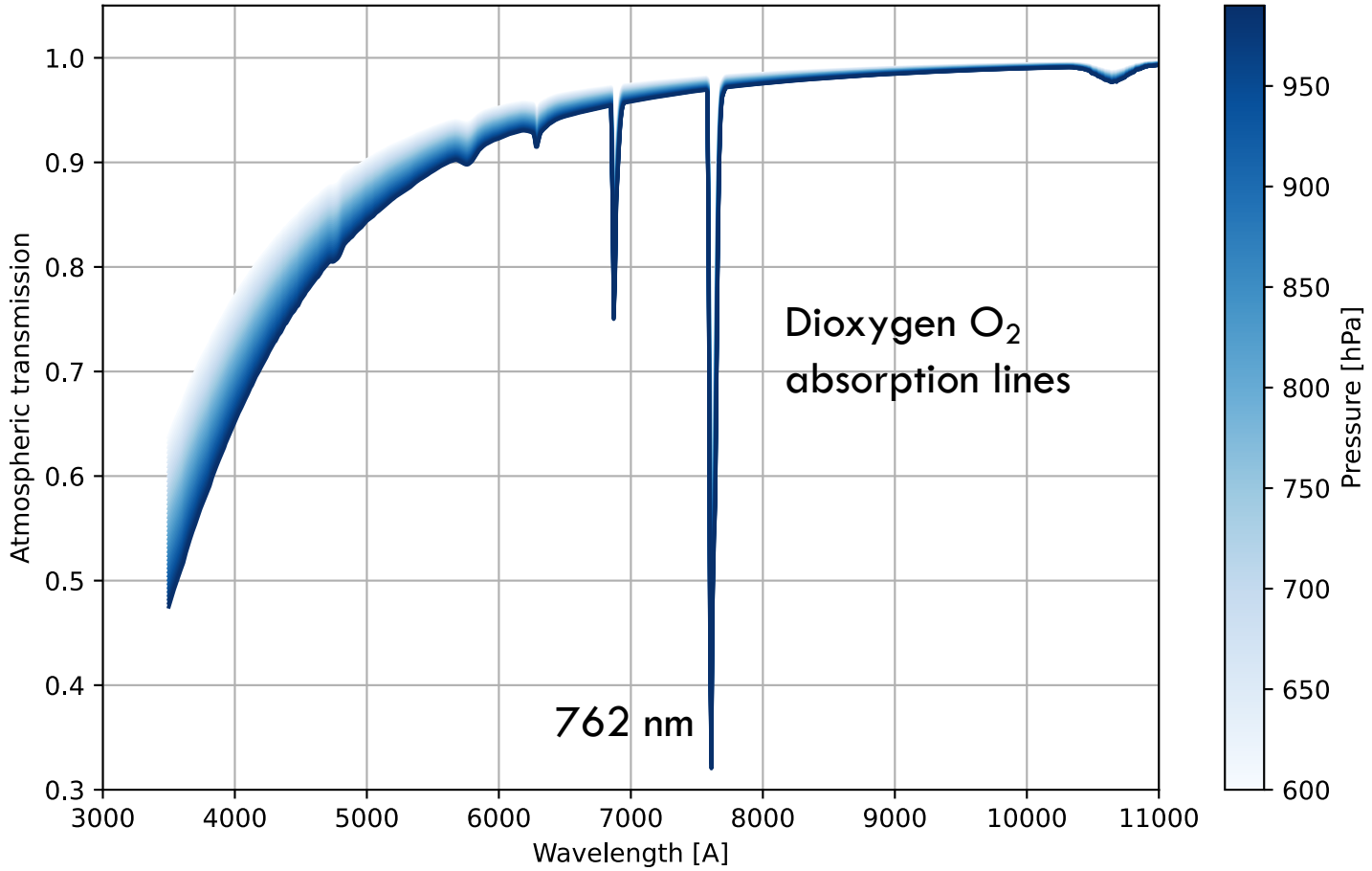

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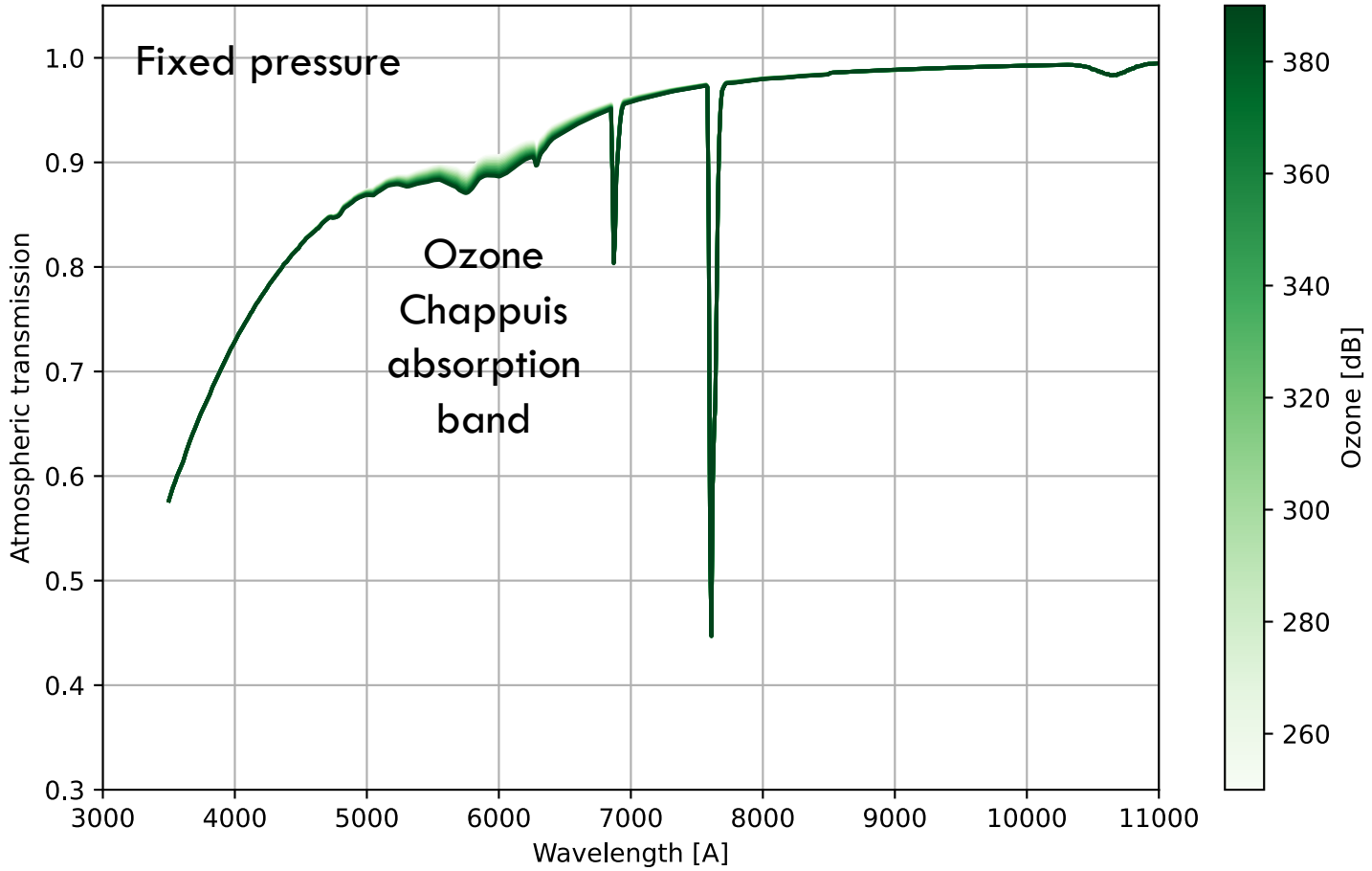

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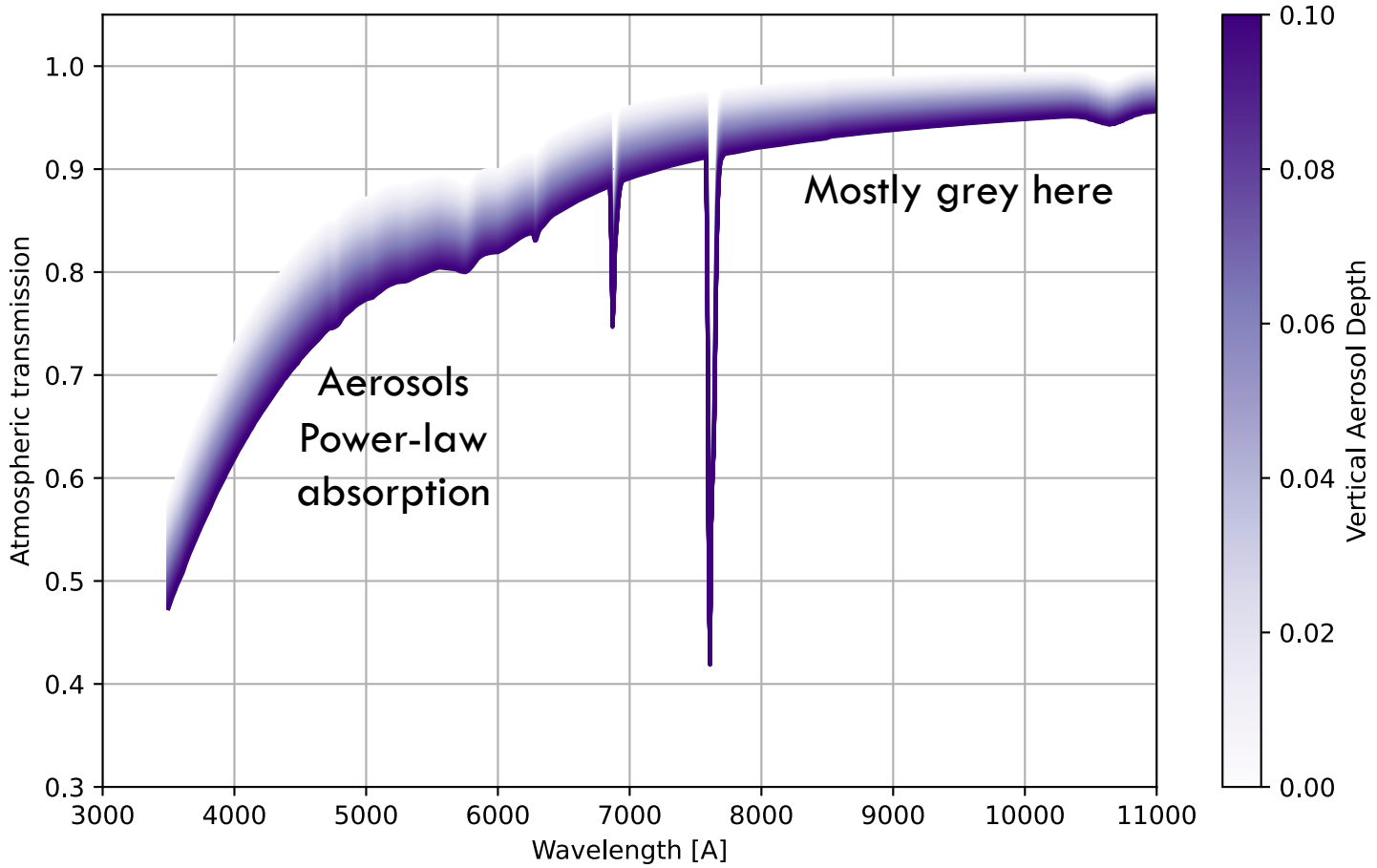

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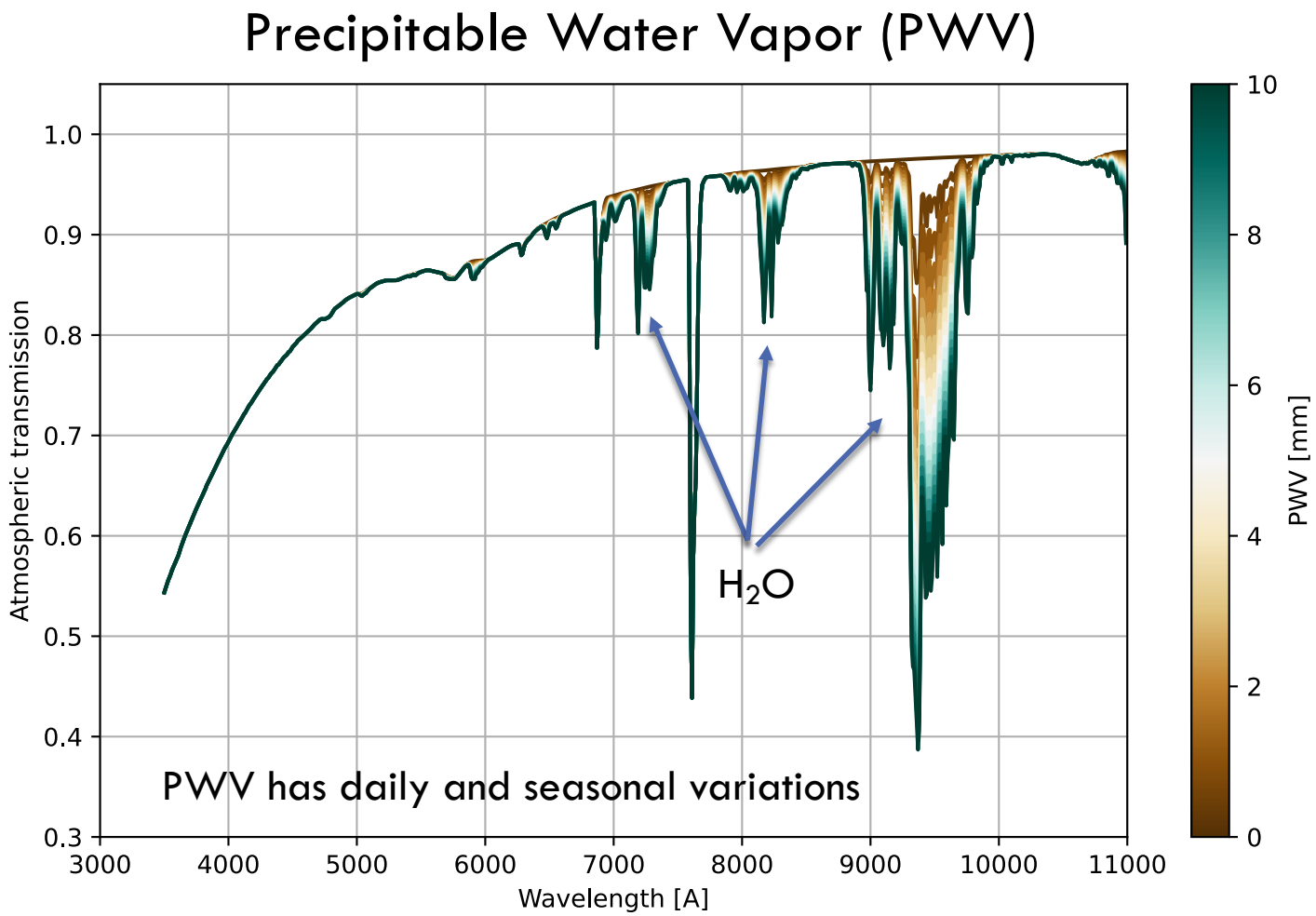
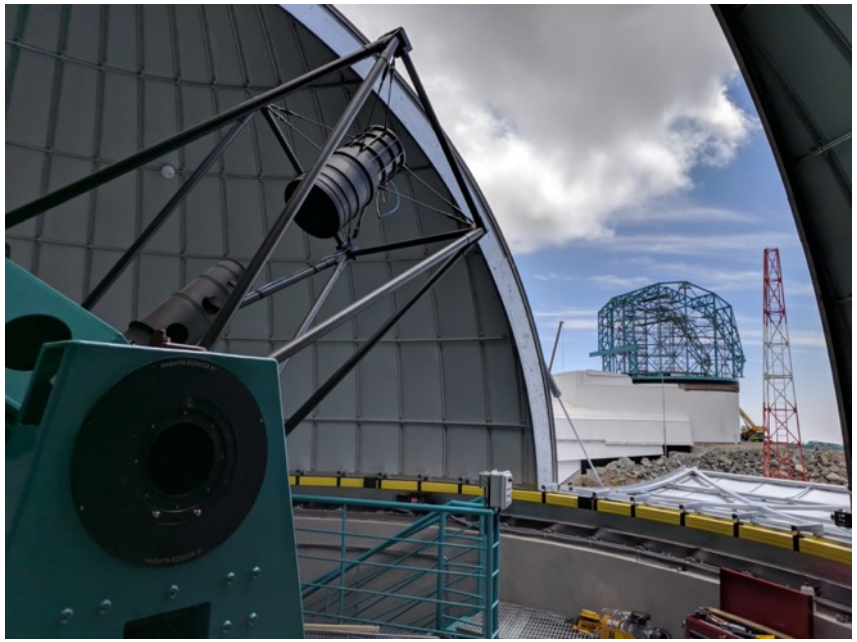


Rubin Auxiliary Telescope (Auxtel)

- Rubin Auxiliary Telescope mission is to measure atmospheric transmission on-site parallel to main telescope
- 1.2m telescope on Rubin site with slitless spectrograph



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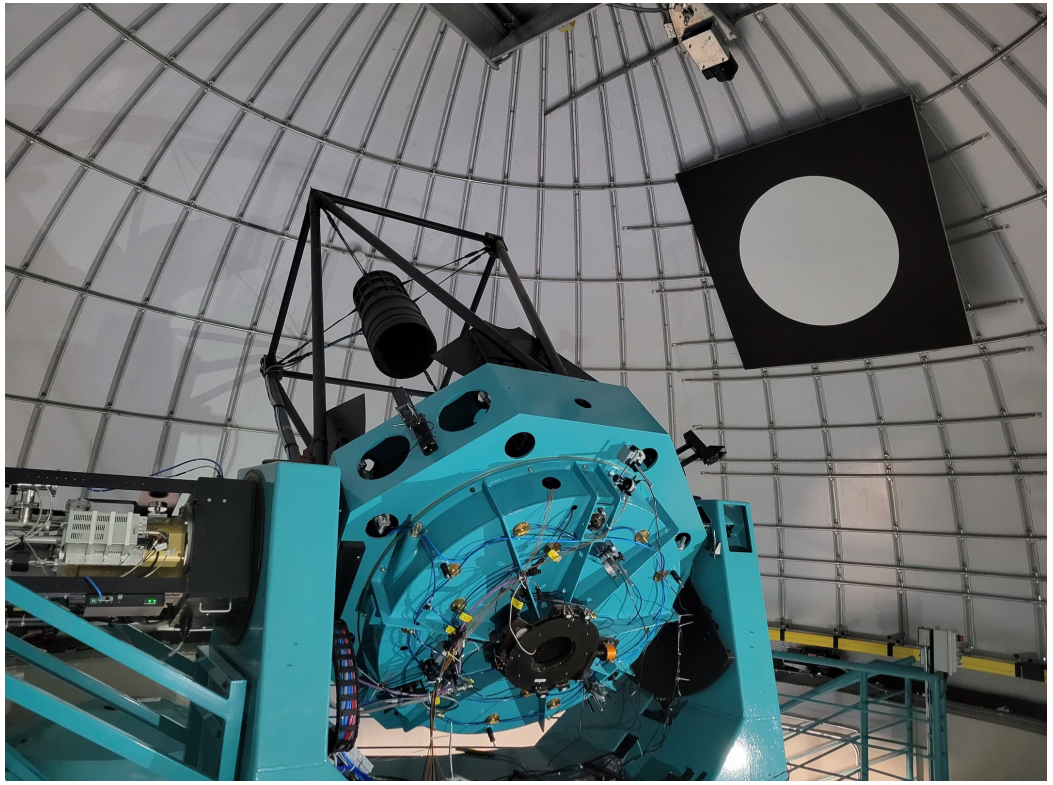
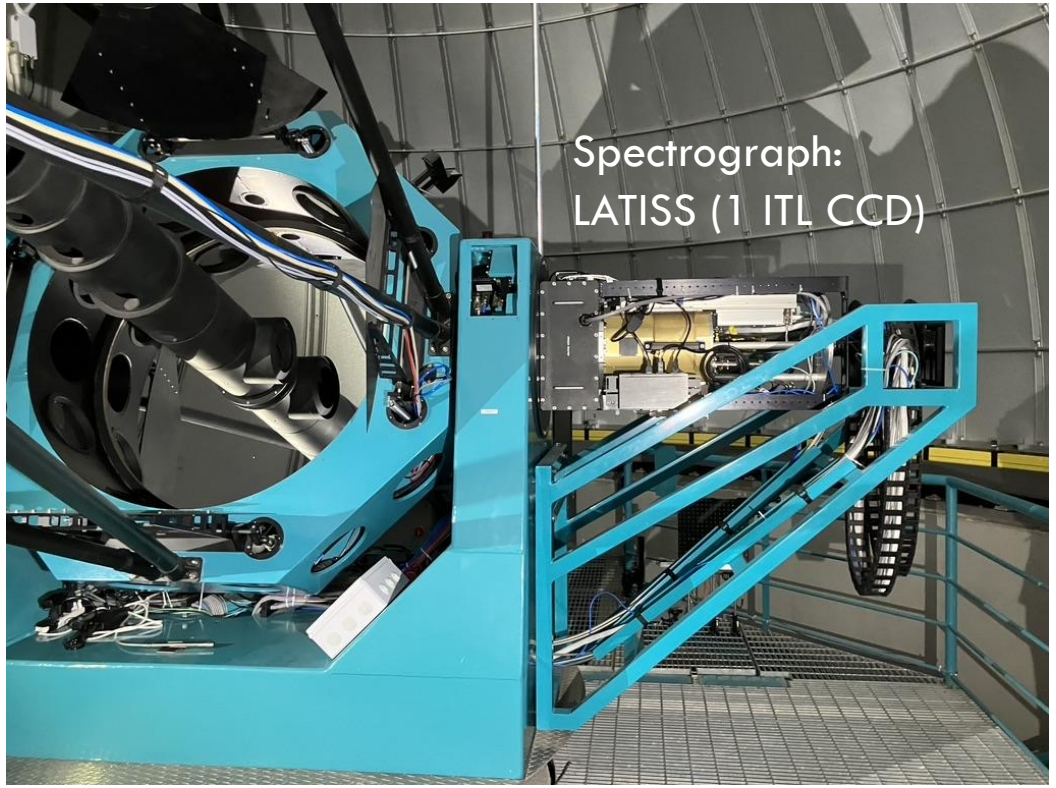
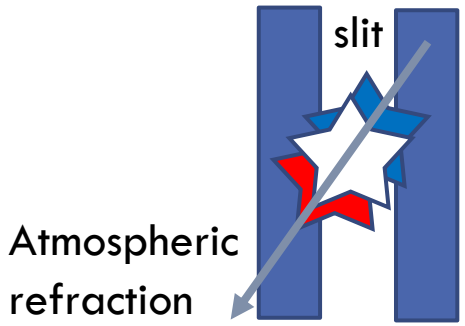
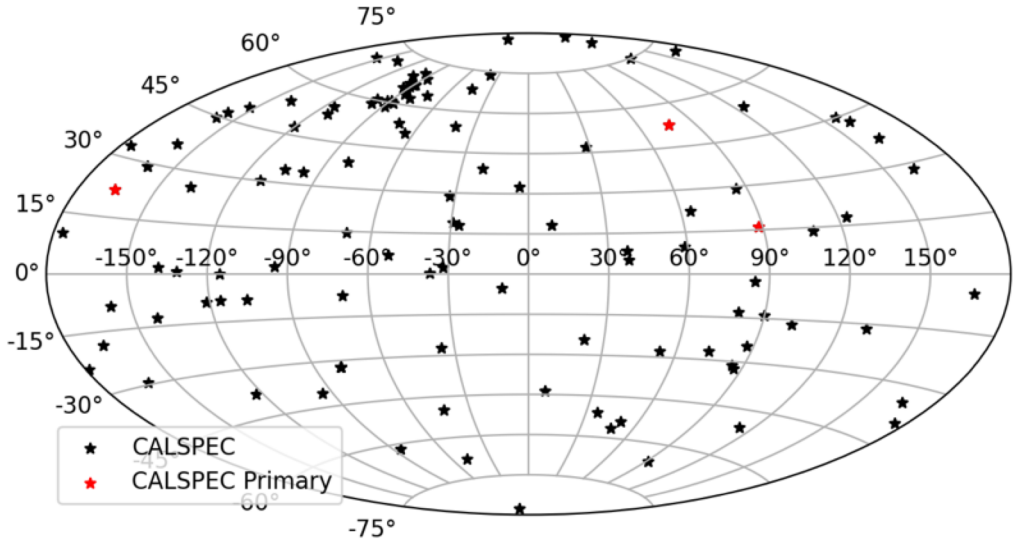


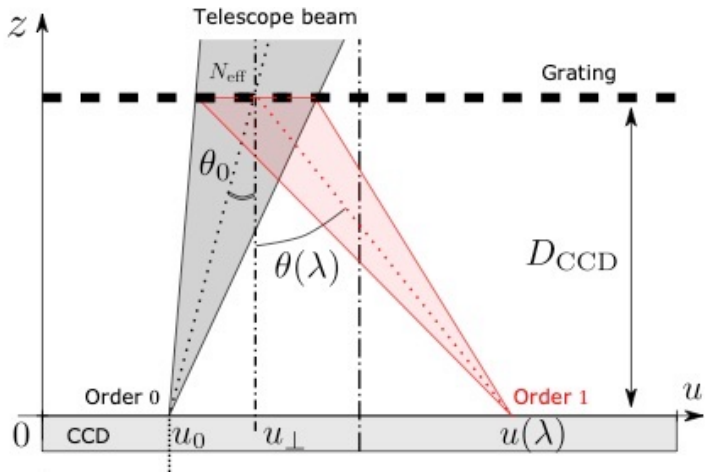


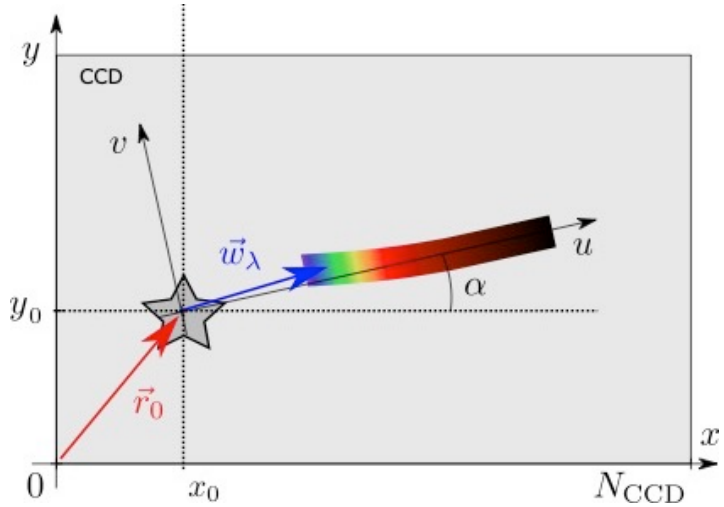
Atmosphere with slitless spectrophotometry

- **Baseline method:** measurement of Earth's atmosphere looking at reference stars with known out-of-atmosphere spectra with a slitless spectrograph

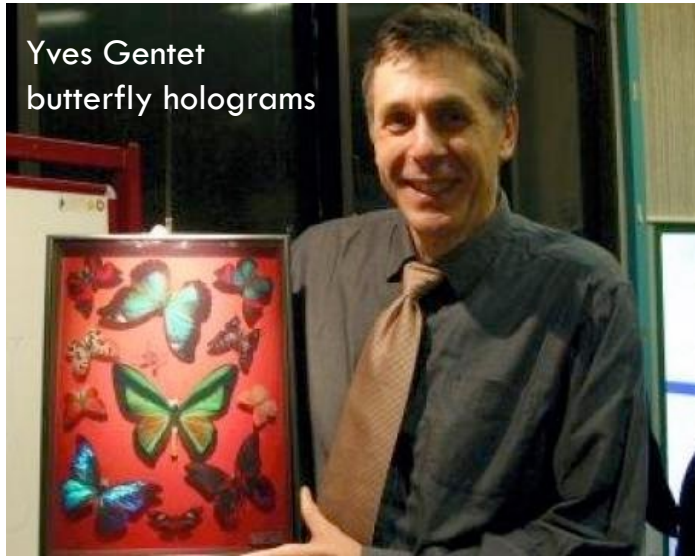


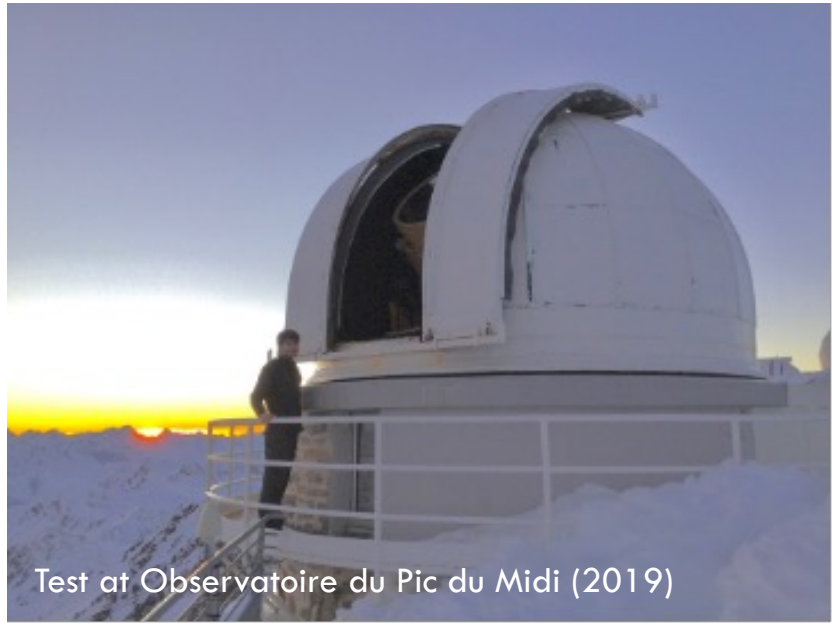


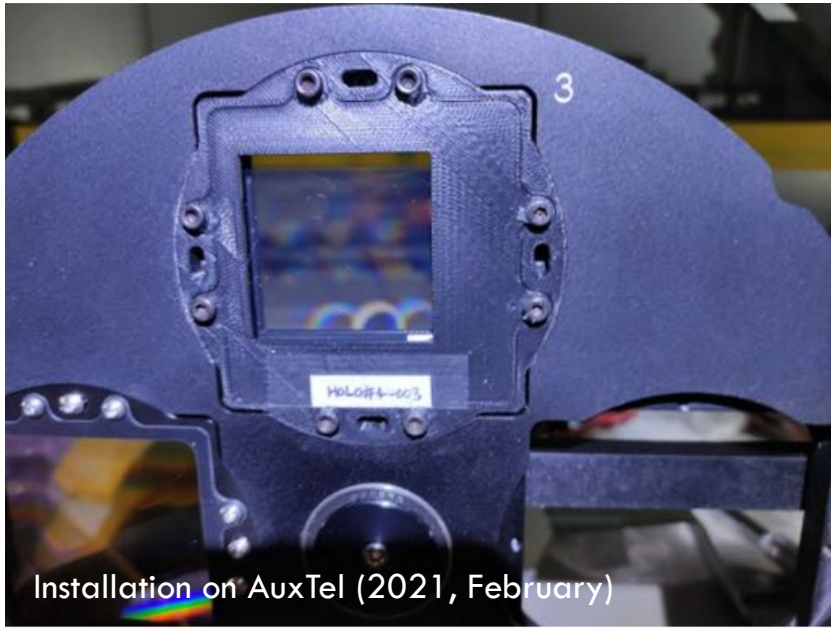




Hologram story

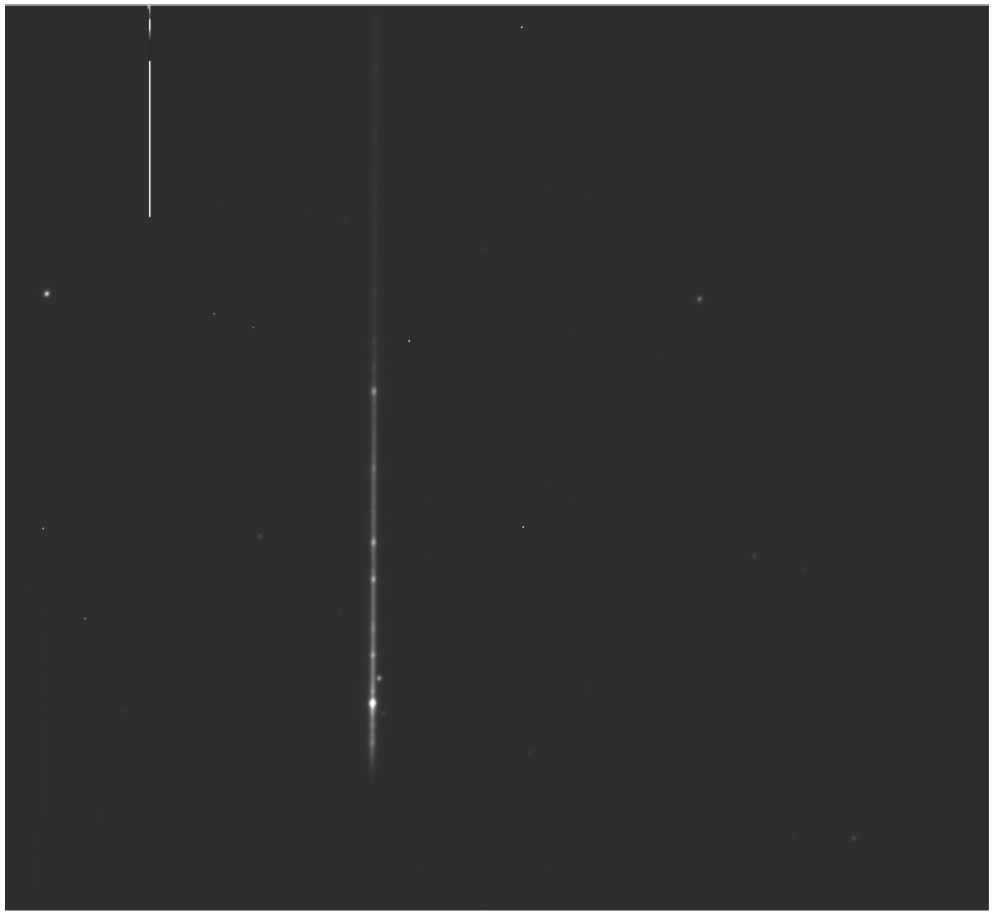


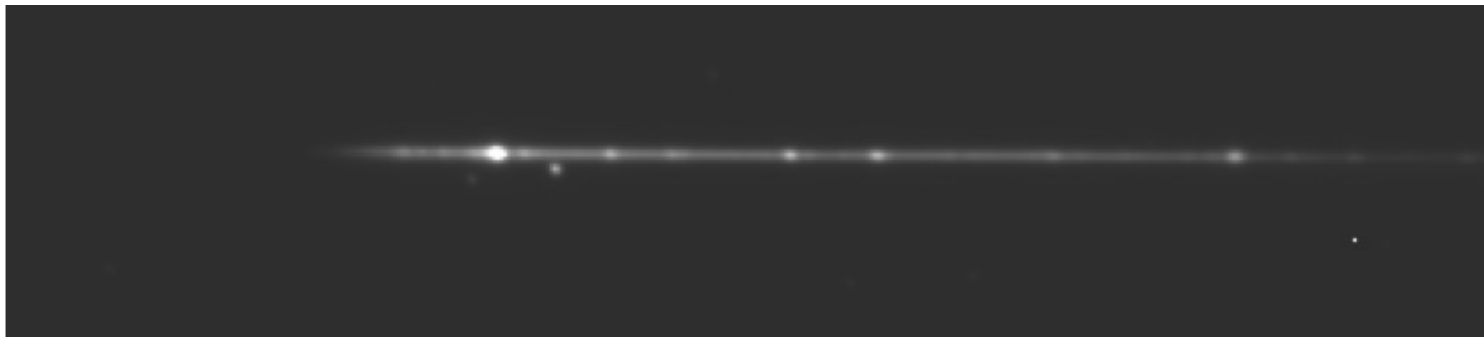




The very first spectrum

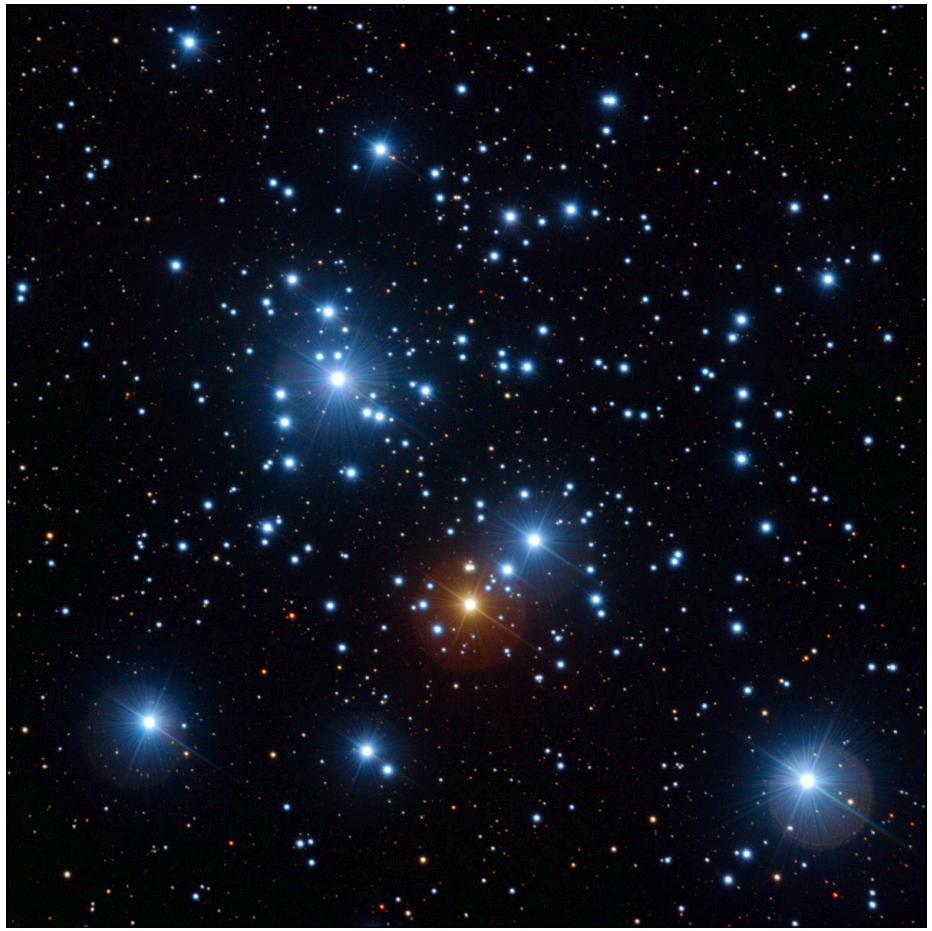
- Wolf-Rayet 6 star, HD50896, exposure 20210216002O9, T=90s

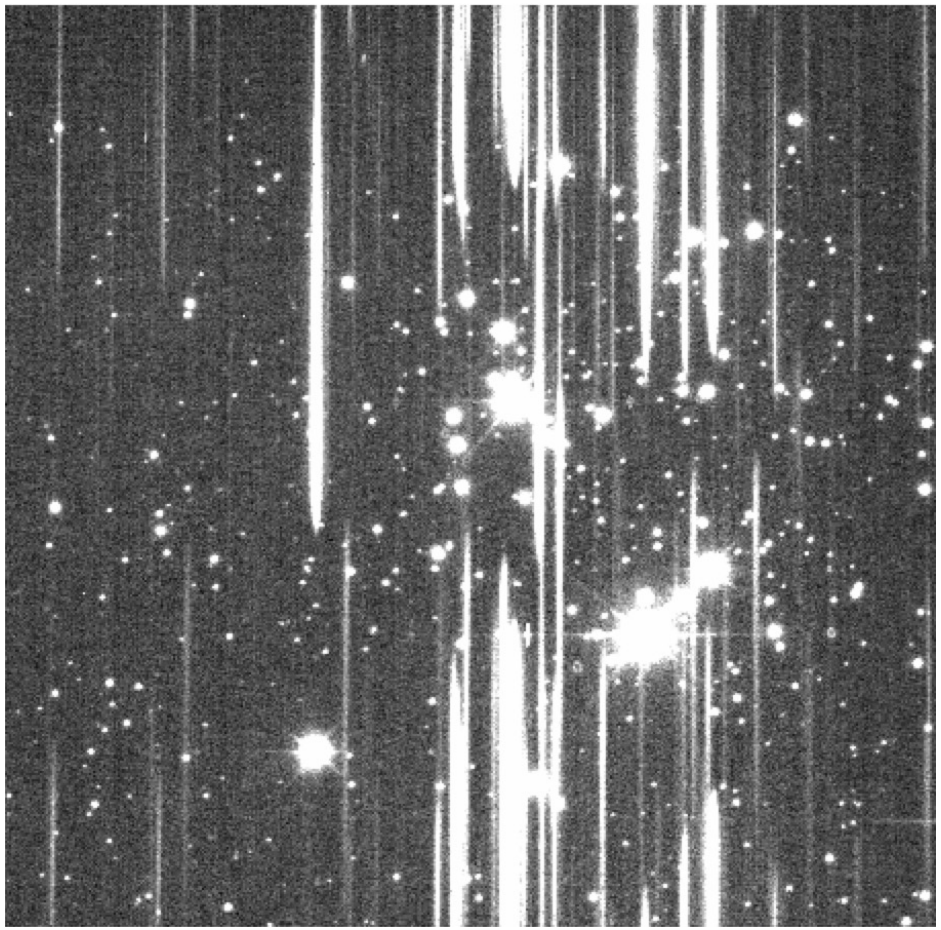




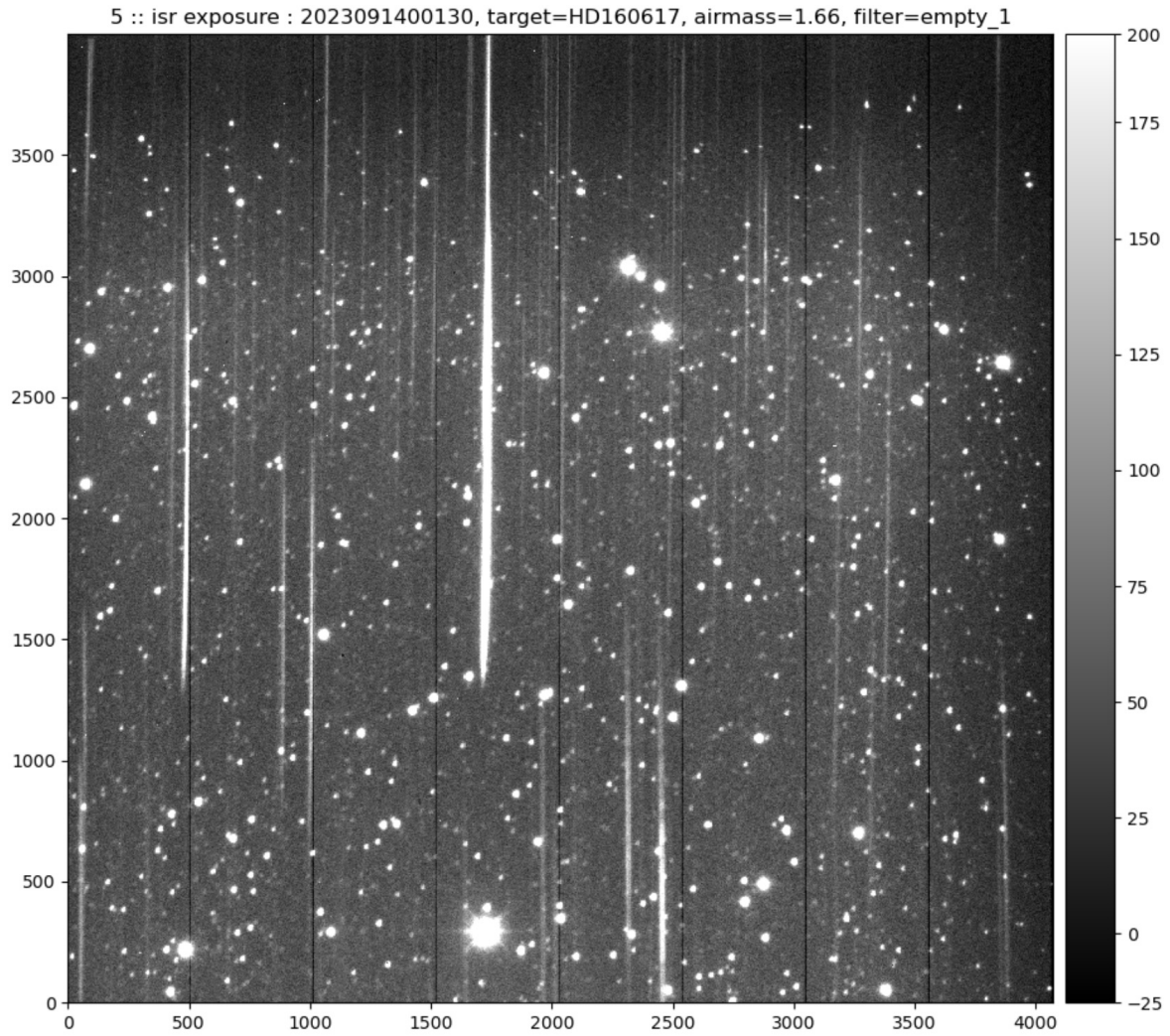
The Jewel Box (open cluster)

- NGC4755, exposure 201021700352, T=6s



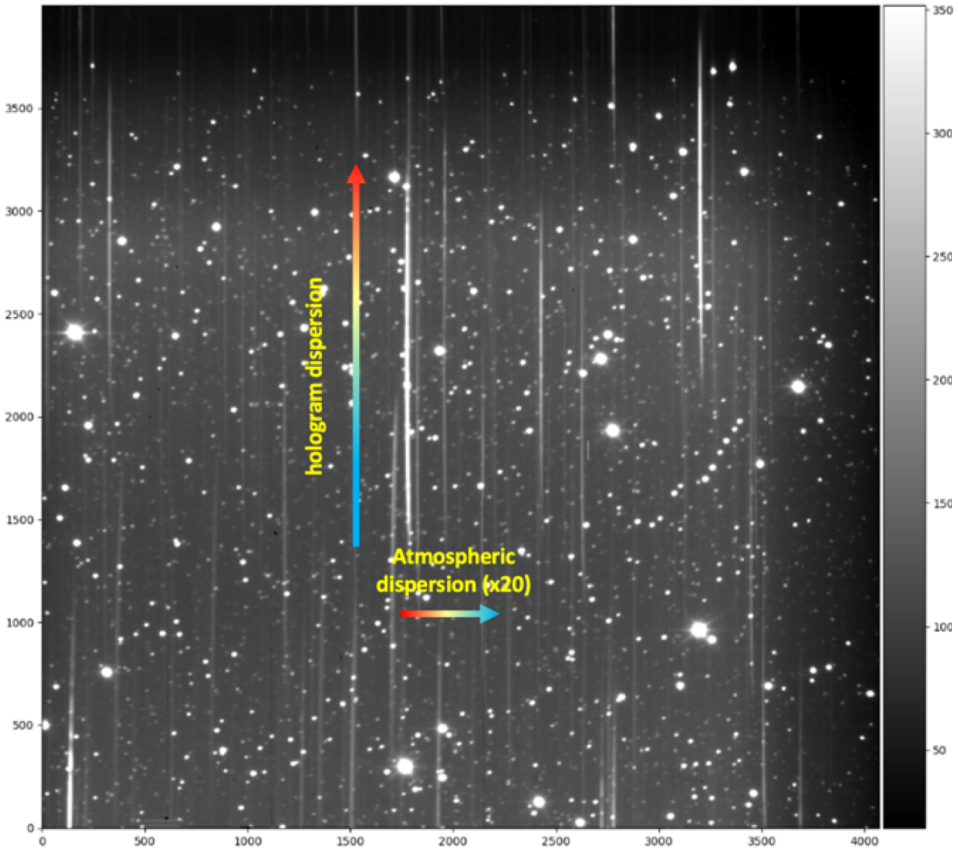


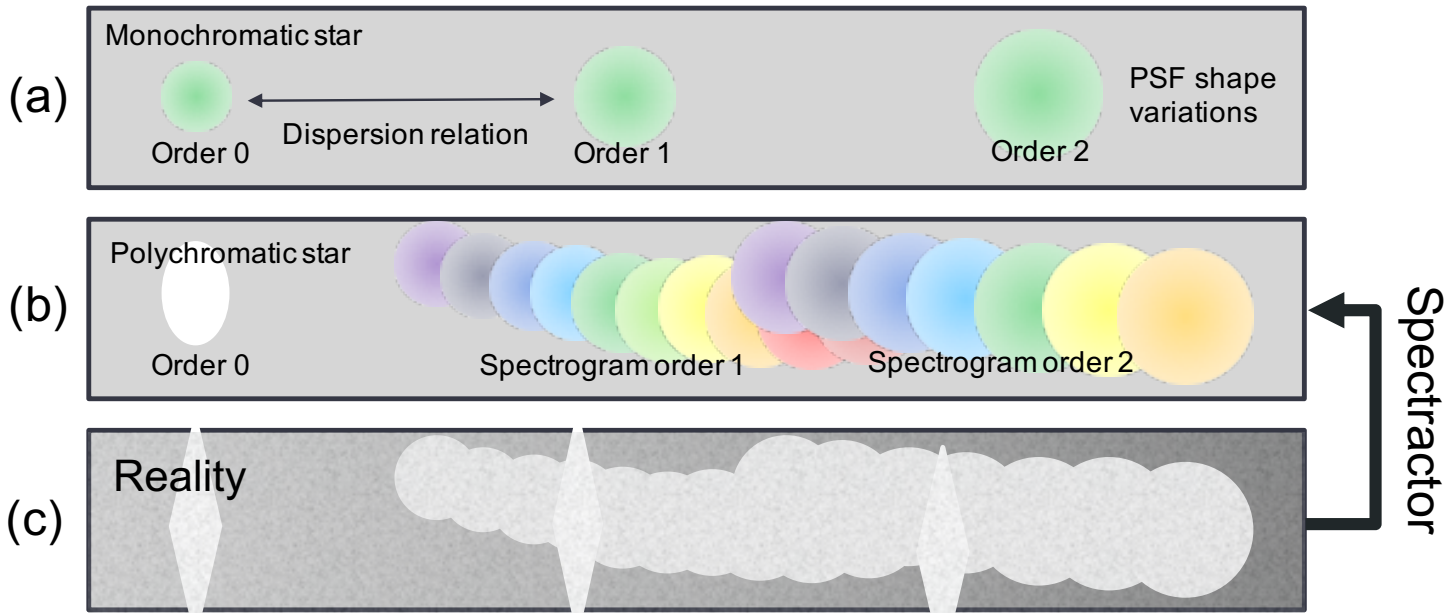
A common hologram spectra



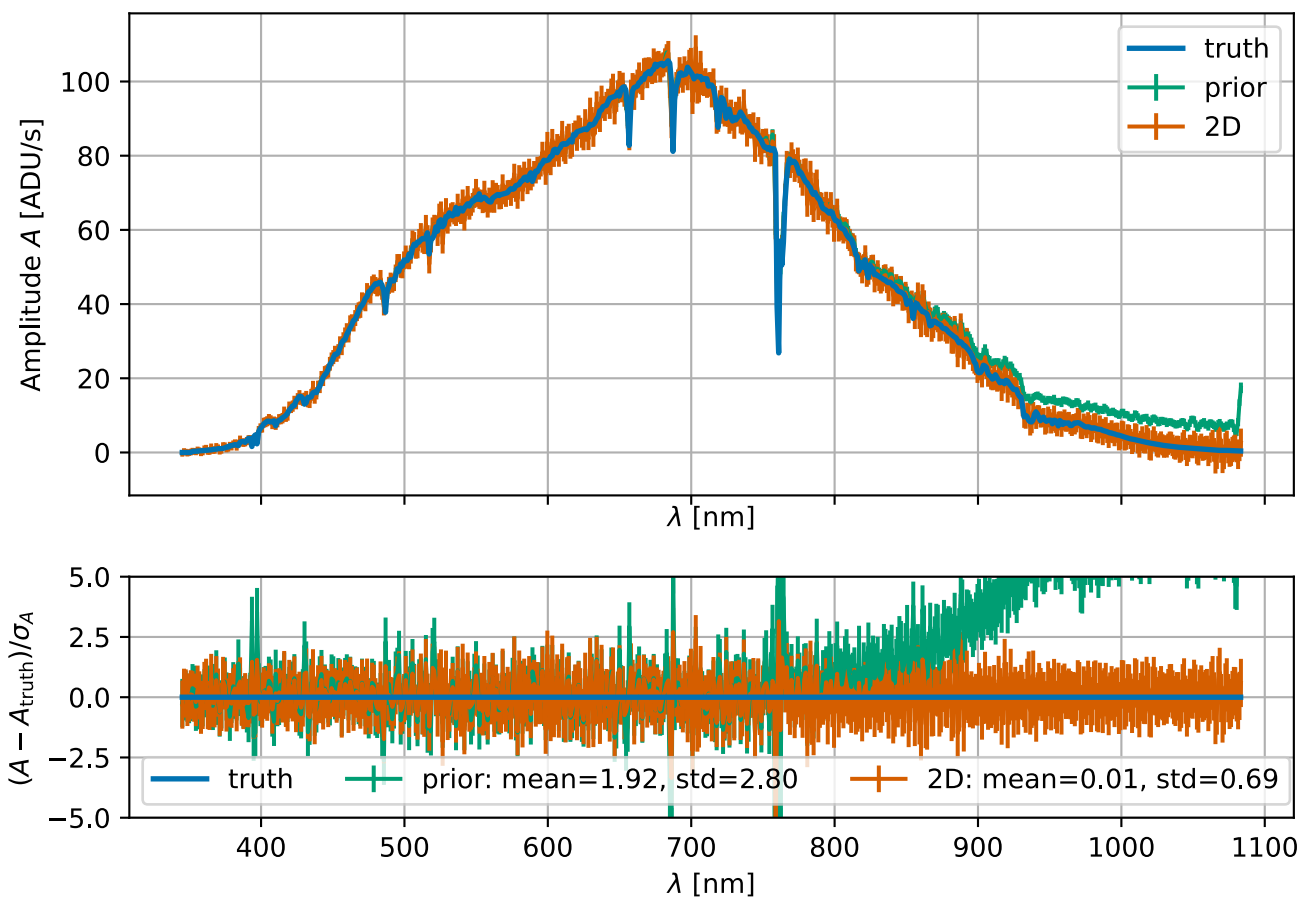
Rubin Auxiliary Telescope (Auxtel)

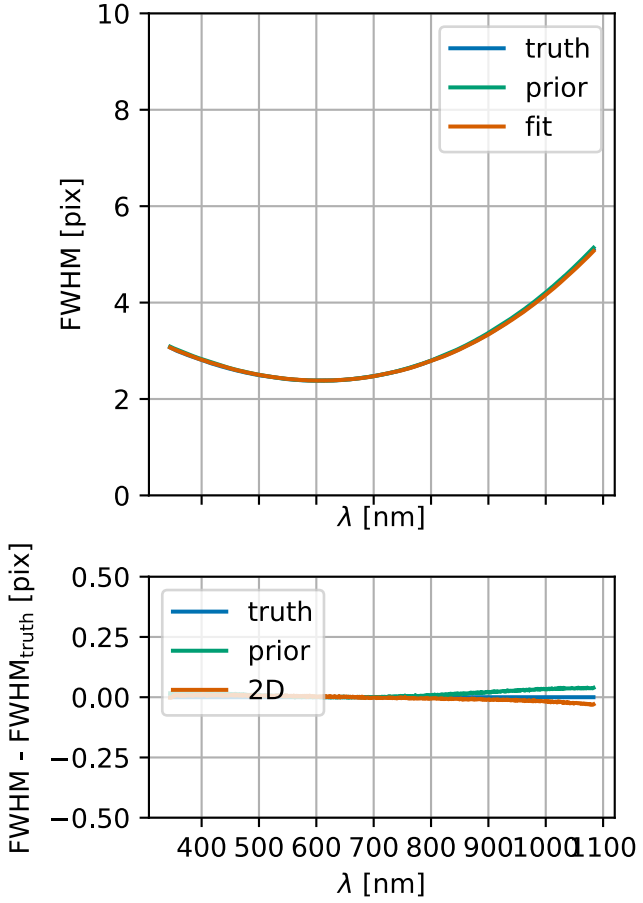
- Spectrophotometric extraction by forward modelling [Neveu et al., 2023]





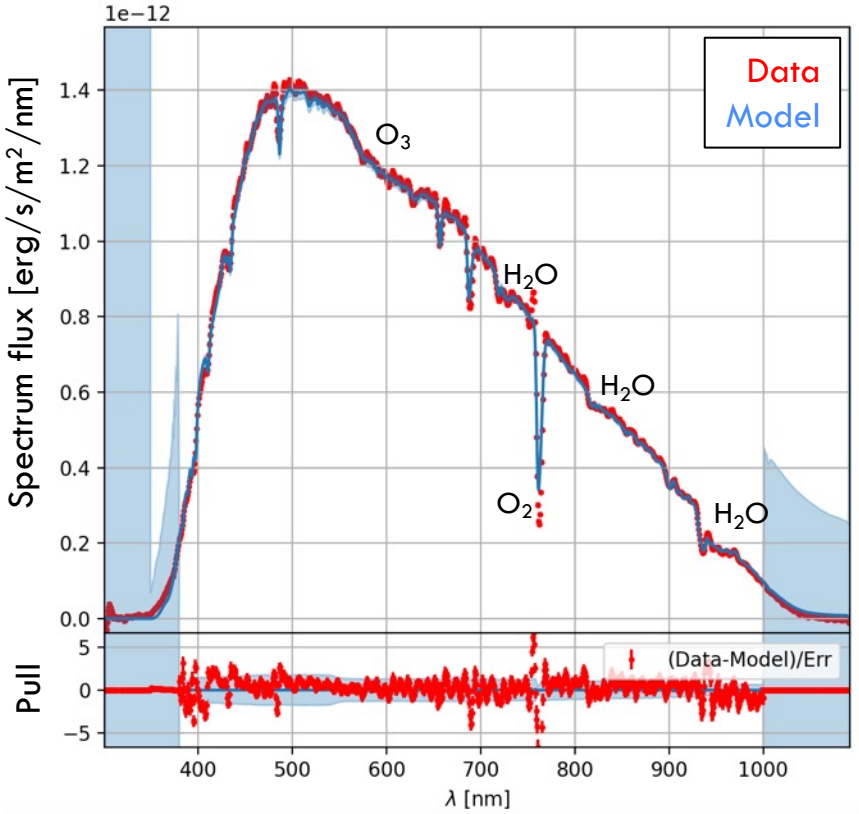
Forward model tested on simulations





Rubin Auxiliary Telescope (Auxtel)

- Fit of atmospheric parameters on ~4000 spectra since 2023/01 via Libradtran library [Emde et al., 2016]



Rubin Auxiliary Telescope (Auxtel)

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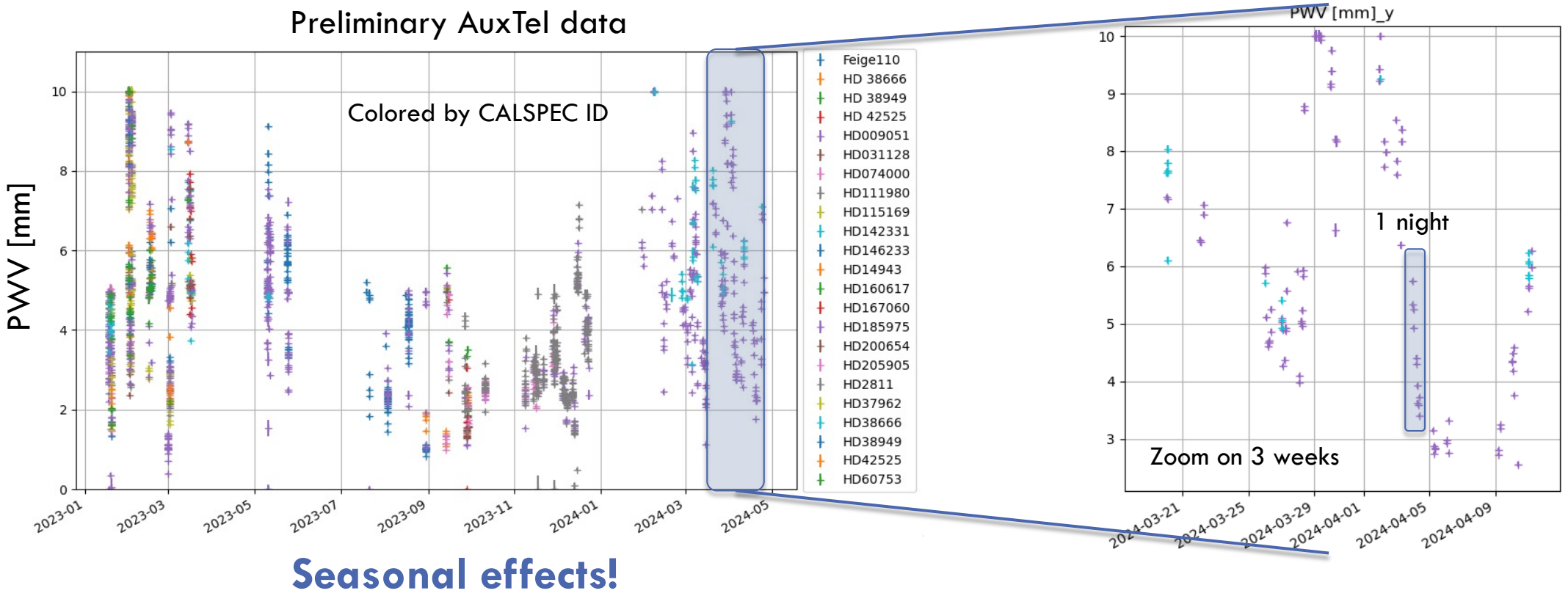


Seasonal effects!

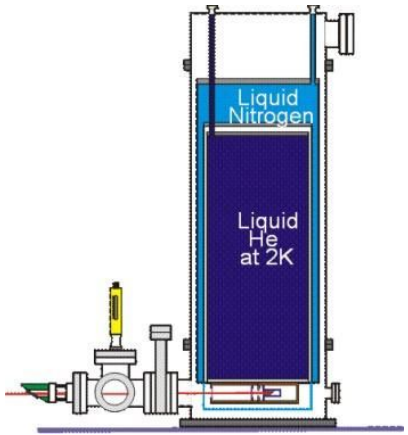
Photometric calibration transfer

Standard watt (NIST)

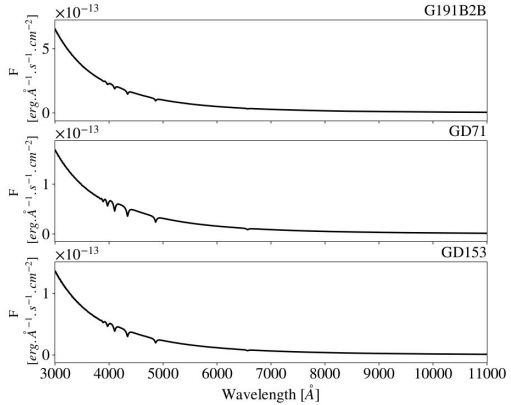
???

CALSPEC standard stars

1 W



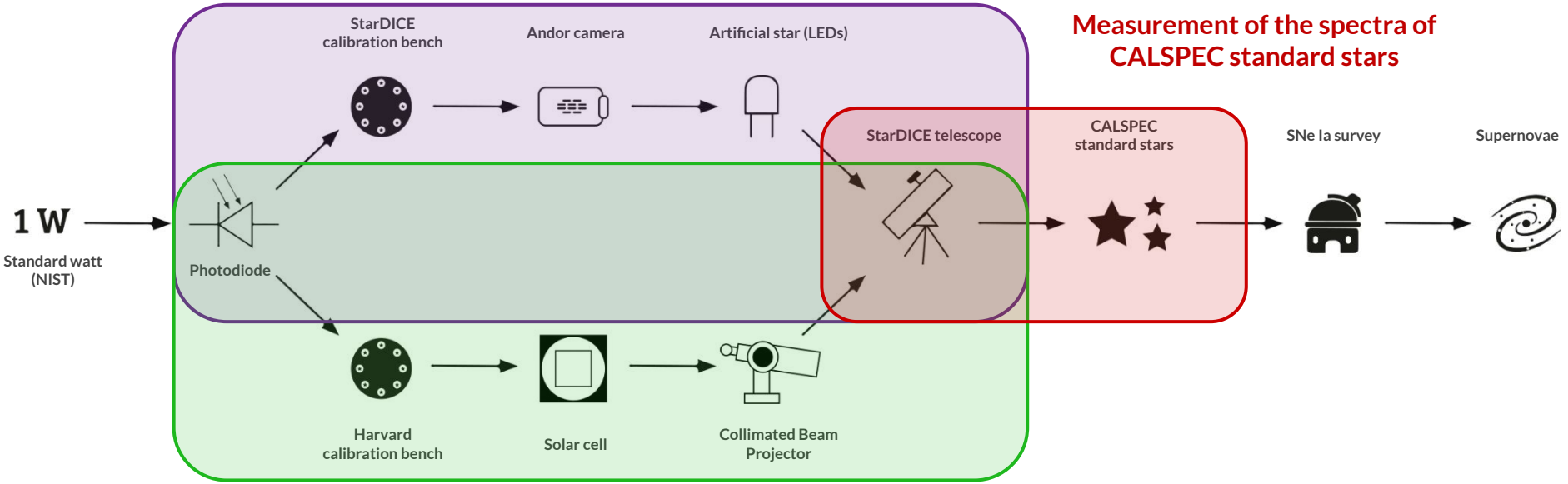
POWR facility
Houston et al. 2006



CALSPEC primary standard stars

Photometric calibration transfer

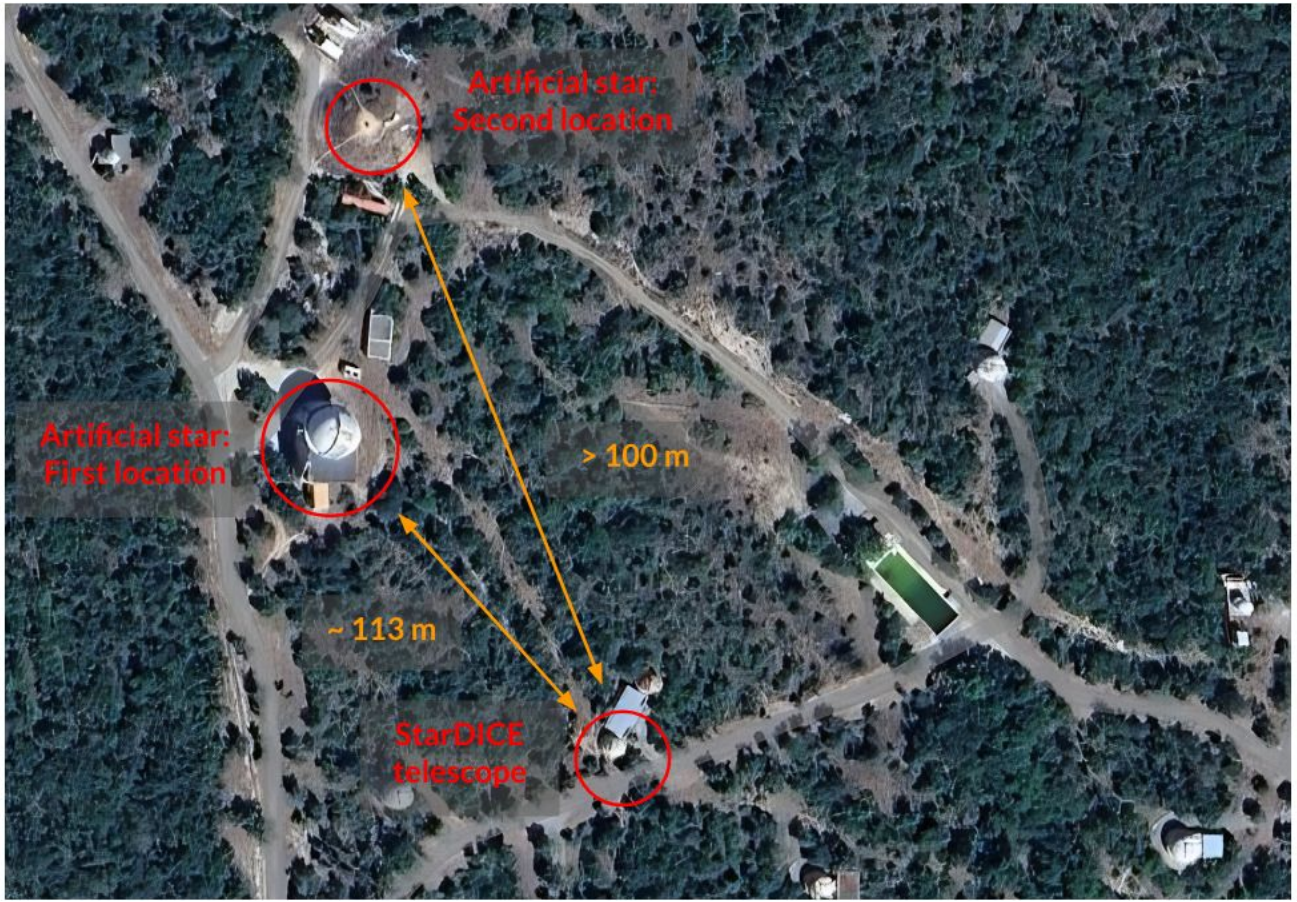
Pros: In situ conditions, full pupil illumination
Cons: Broadband fluxes



Pros: High wavelength resolution
Cons: Laboratory conditions, partial mirror illumination

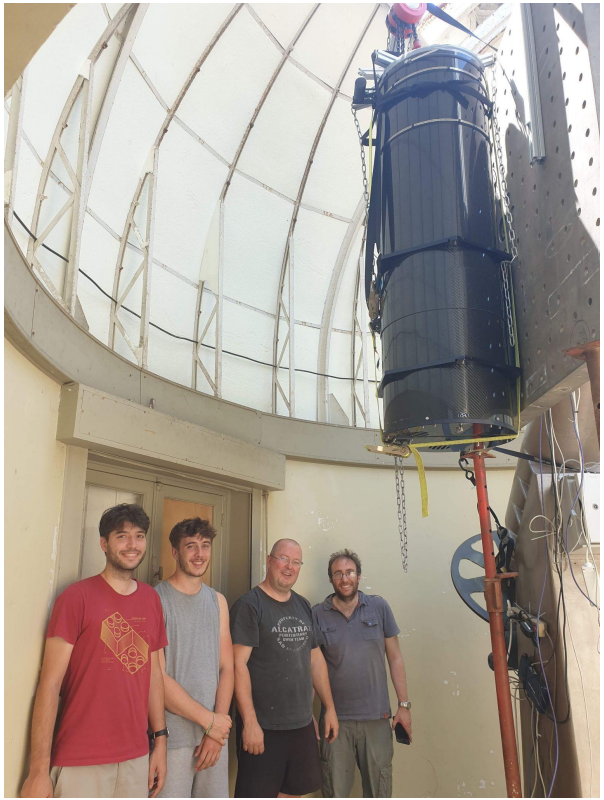
More sensitive detectors

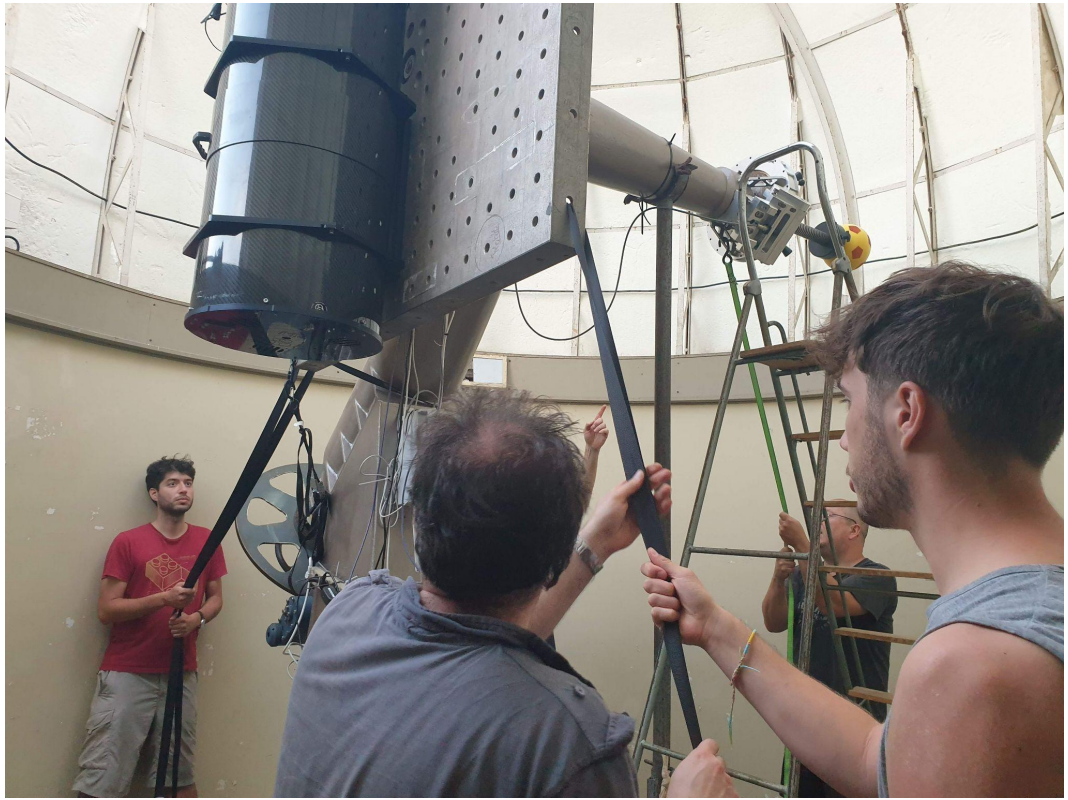
Observatory of Haute-Provence



Observatoire de Haute-Provence satellite view

Installation of the telescope





A happy StarDICE team (not pipe smoking) balancing the telescope they have installed

StarDICE telescope

Newton telescope:

- D=40cm
- f=1.6m
- 1.68'' resolution
- 28.6' x 28.6' field of view

Filterwheel:

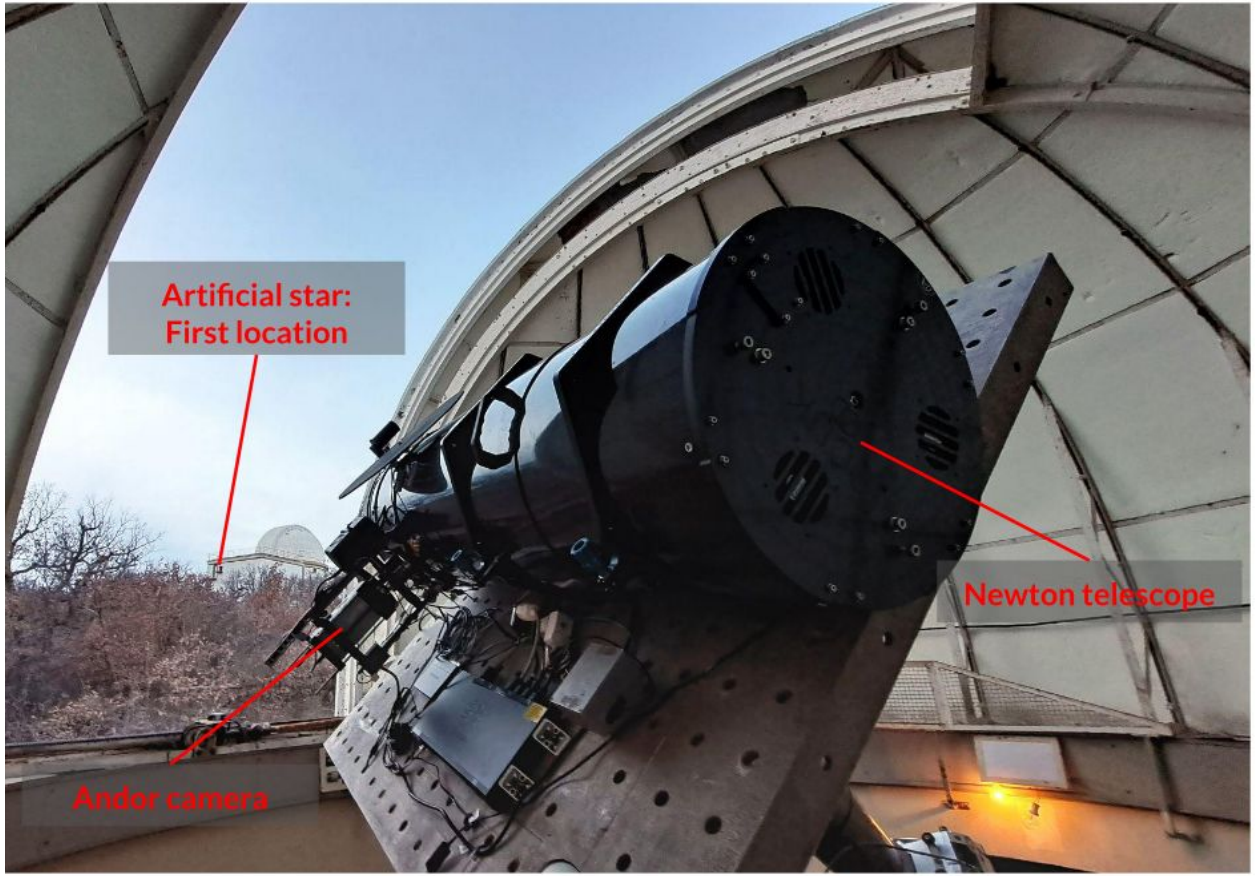
- "ugrizy" photometric filters
- Diffraction grating

Monitoring instruments:

- Hygrometer
- Thermometers
- Barometer
- Rain detector

Fully robotic

StarDICE telescope on its mount

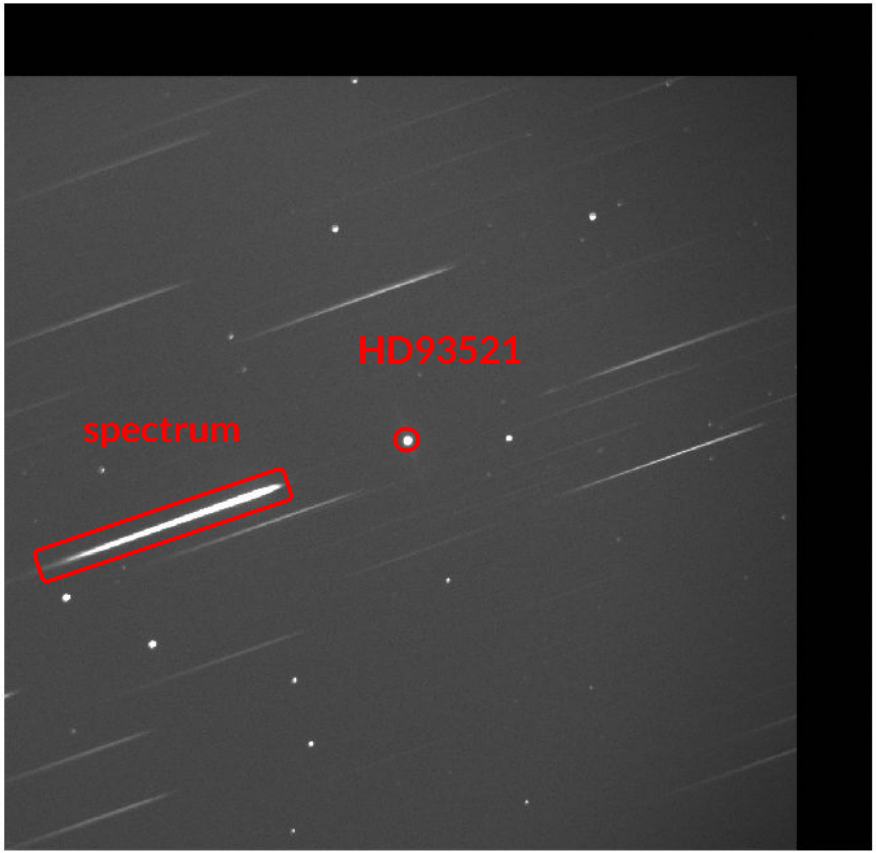


HD93521 spectrum

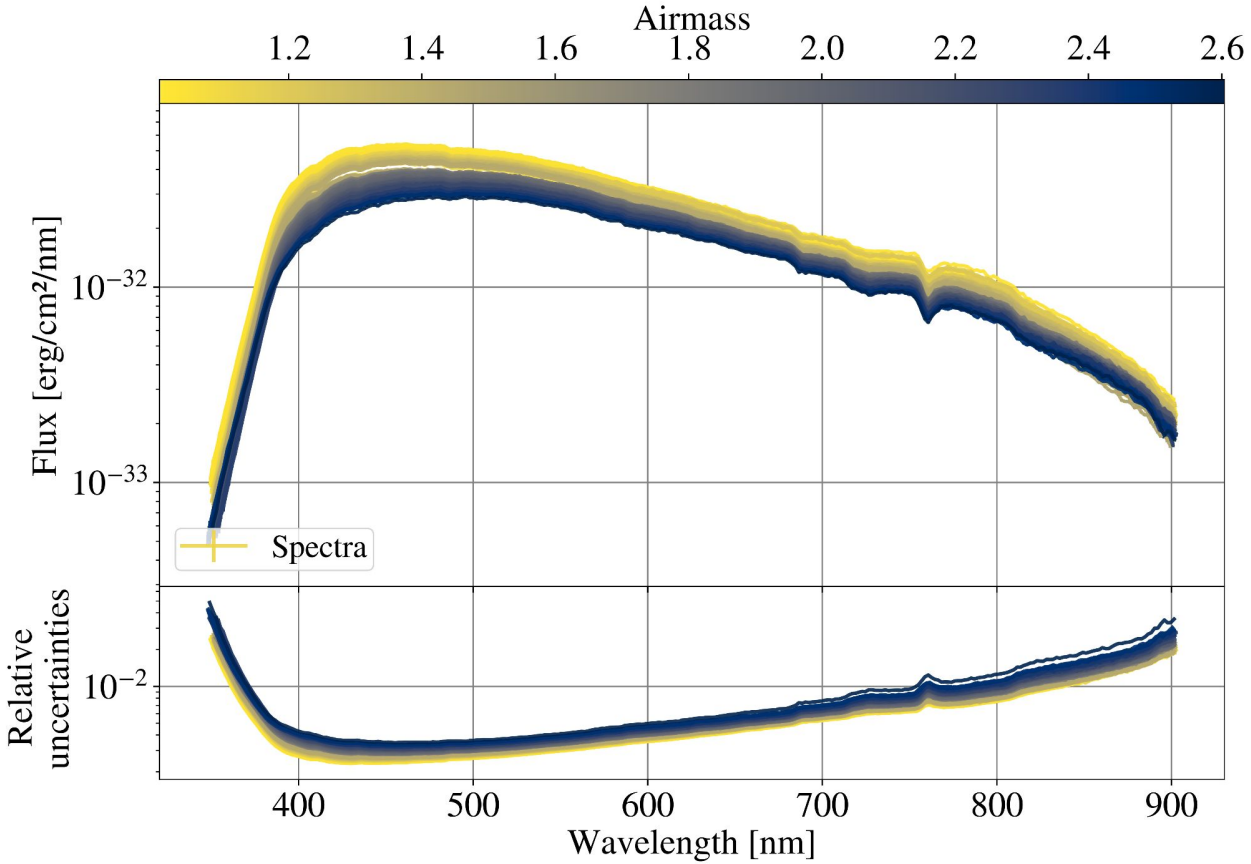
Spectrum extraction of HD93521

- Part of CALSPEC calibration
- Bright: $m_{HD93521} = 6.99$
- Isolated field

Image of HD93521 observed by StarDICE with the grating in the filterwheel



HD93521 spectra extraction



- ~300 images at different airmasses
- Spectra extracted with <0.1% uncertainties in [360-750]nm

⇒ Validated method for a bright and isolated star

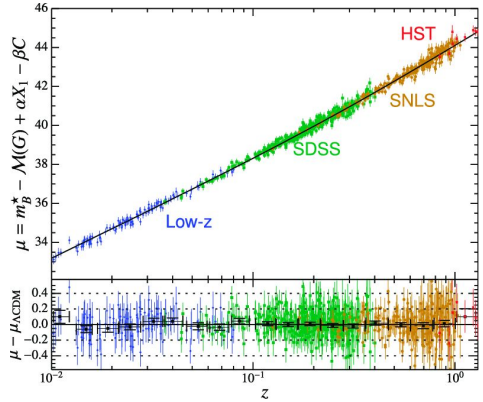
Stage + thèse 2025 !

Sujet de thèse :

- Mesure de la transmission atmosphérique sur StarDICE et Auxtel (LSST)
- Premier diagramme de Hubble calibré au pour mille !

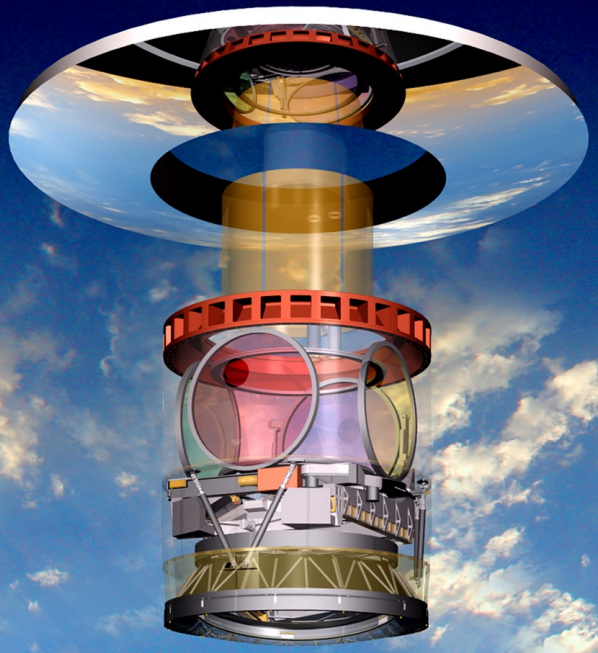
Voyages tous frais payés à l'OHP et au Chili !

StarDICE - Observatoire de Haute Provence



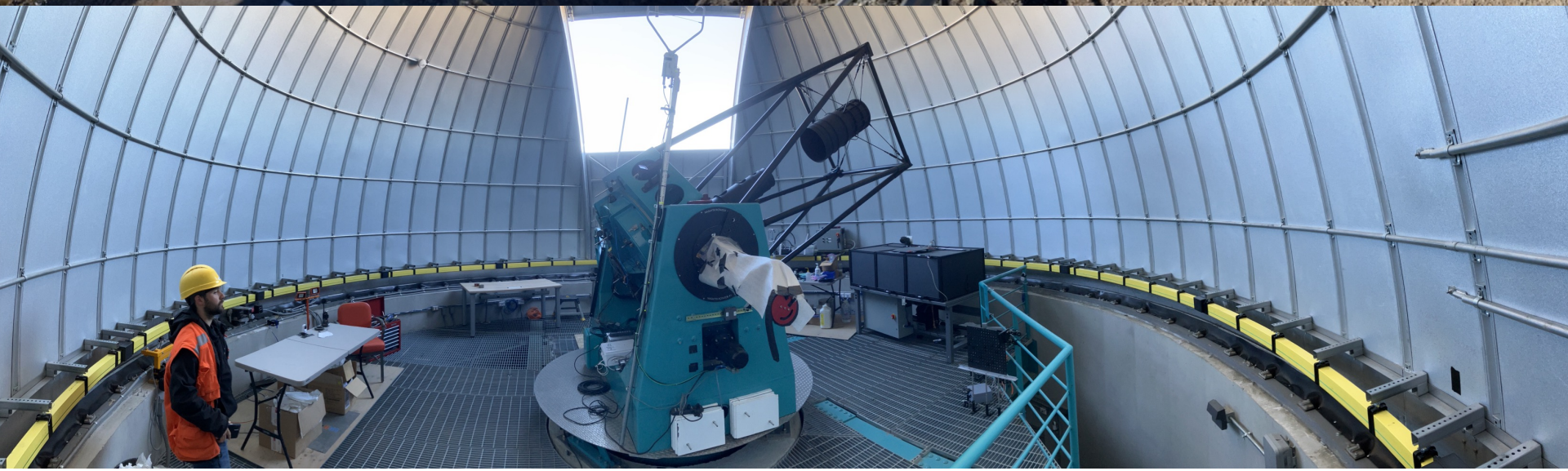
LSST - Vera Rubin Observatory (Chili)

Campagne
evalier
agoret-Campagne
Moniez
eveu
loton
an Den Abeele

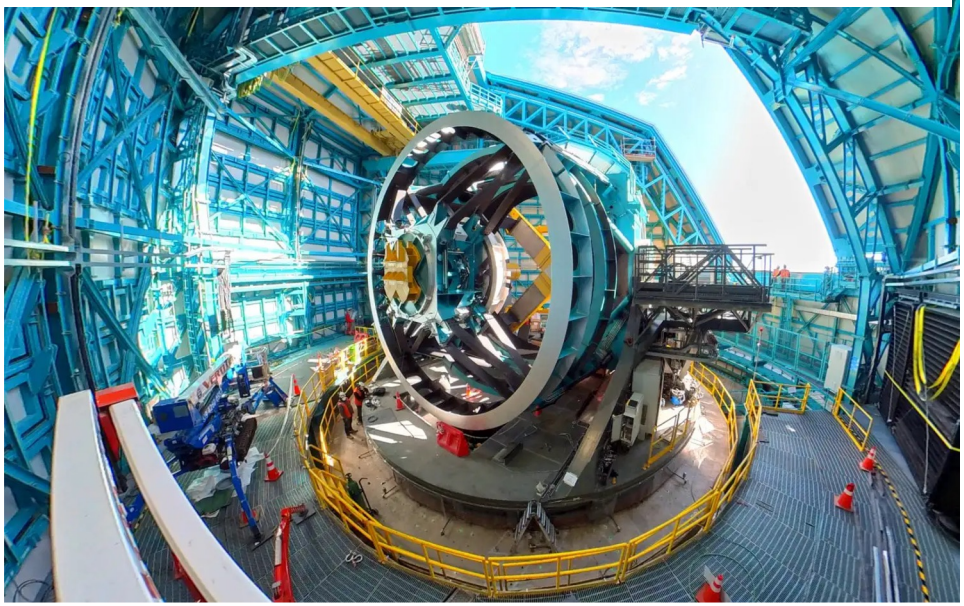


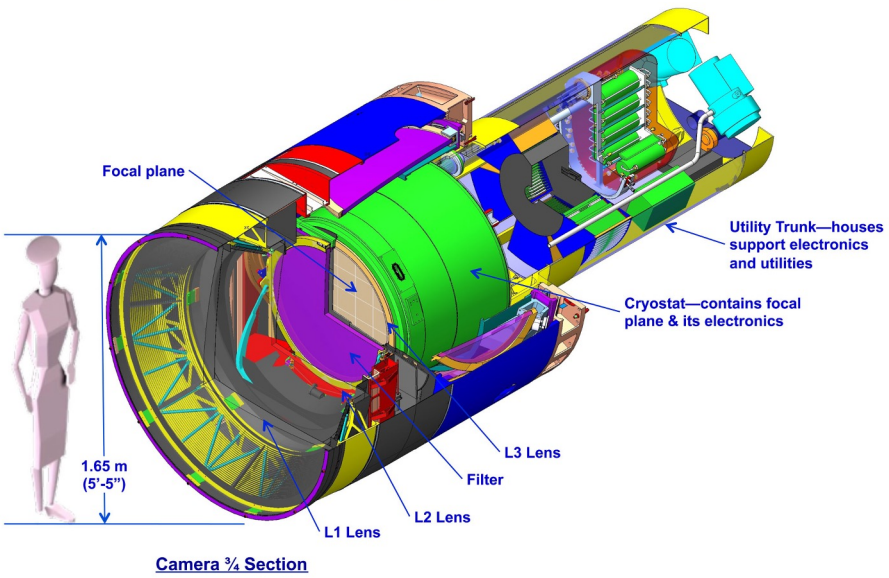
Rubin-LSST à IJCLab

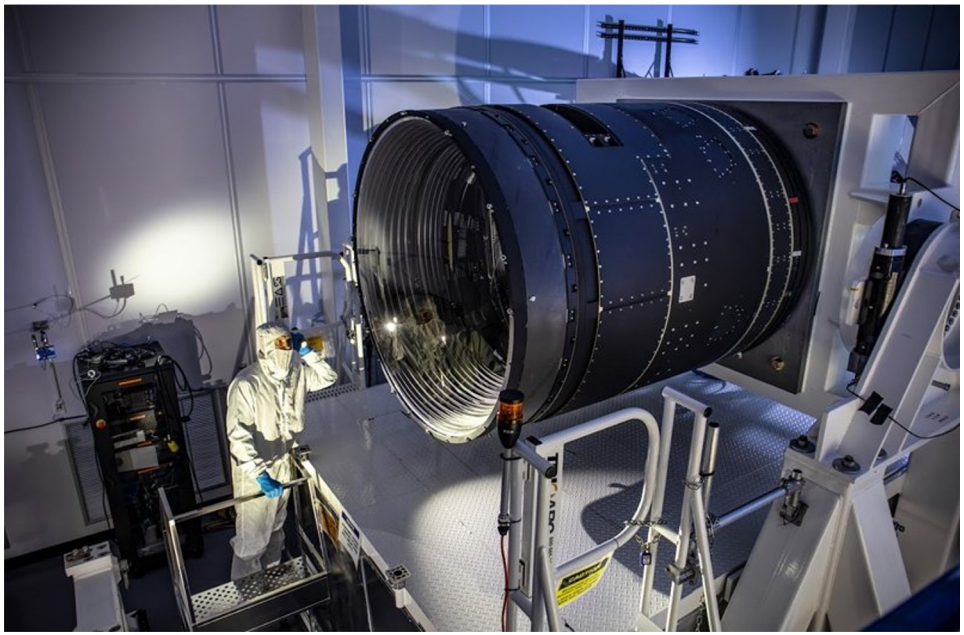
Les télescopes (sept. 2023)



LSST le dessin, et enfin en vrai…

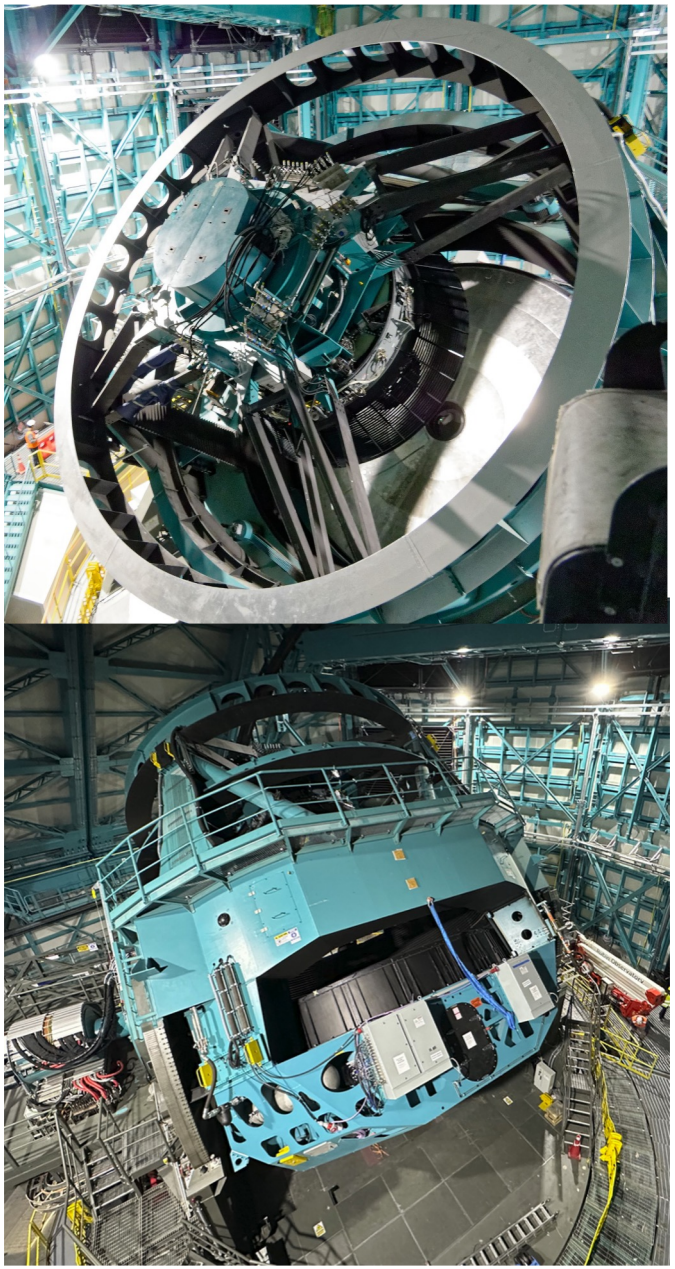






LSST in a few figures

- Optical telescope 8.4 m diameter
- Wide-field camera : 3.5°, 3.2 Gpixels
- 6 wide-band filters u g r i z y
- Galaxies: r_{lim}=27.5 after 10 year coadd.
- Final catalogue: 10^{10} galaxies, 10^{10} stars
- Final database 15 PetaBytes
- Weak lensing up to z ~ 3
- 1,000,000 SNIa up to z ~ 1
- Transients with alerts (10^7/night)
- ~ 1000 scientists in the world (50% US)
- Only Chile & France-IN2P3 (builder since 2005) have privileged access to all data



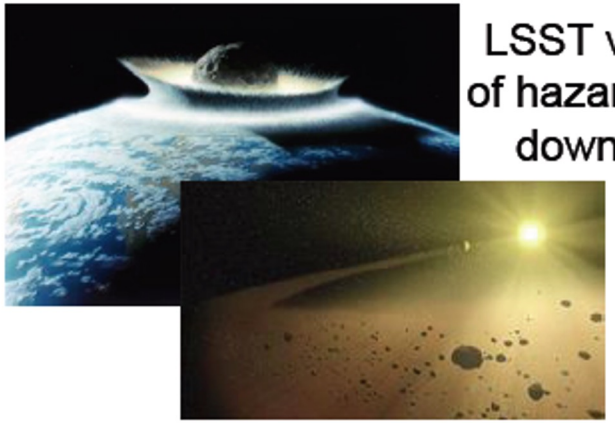
See LSST science-book http://www.lsst.org

Science with LSST catalogs: All astrophysics

Dark Energy-Dark Matter

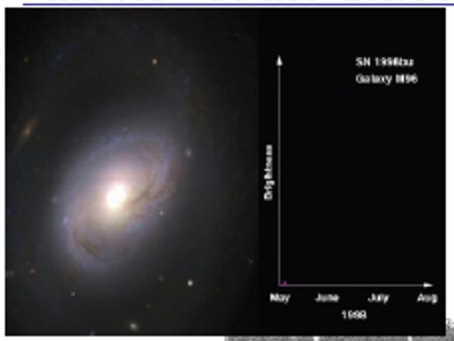
LSST enables multiple investigations into our understanding of the universe

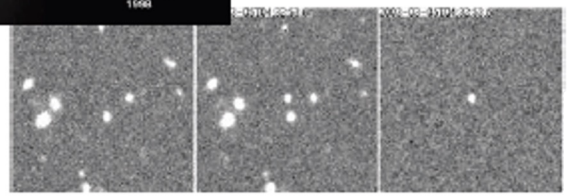
Exploring our Solar System



LSST will find 90% of hazardous NEOs down to 140 m in 10 yrs

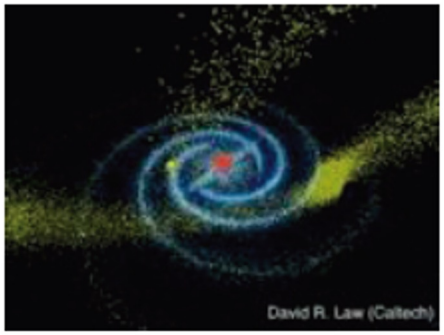
"Movie" of the Universe: time domain





Discovering the transient and unknown on multiple time scales

Mapping the Milky Way

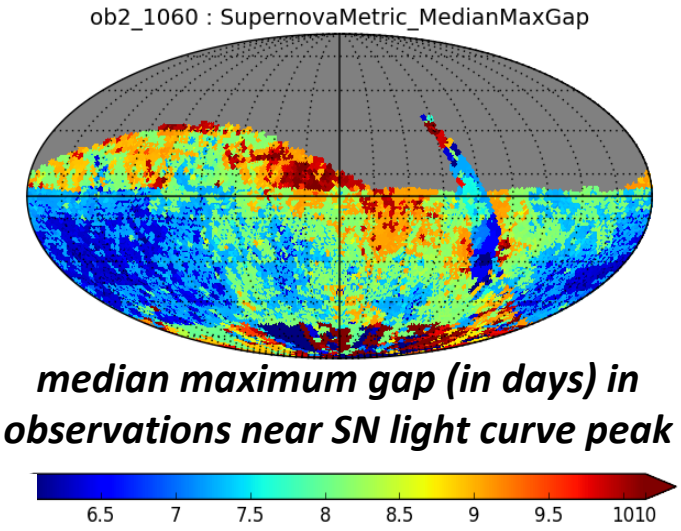


LSST will map the rich and complex structure of our Galaxy.

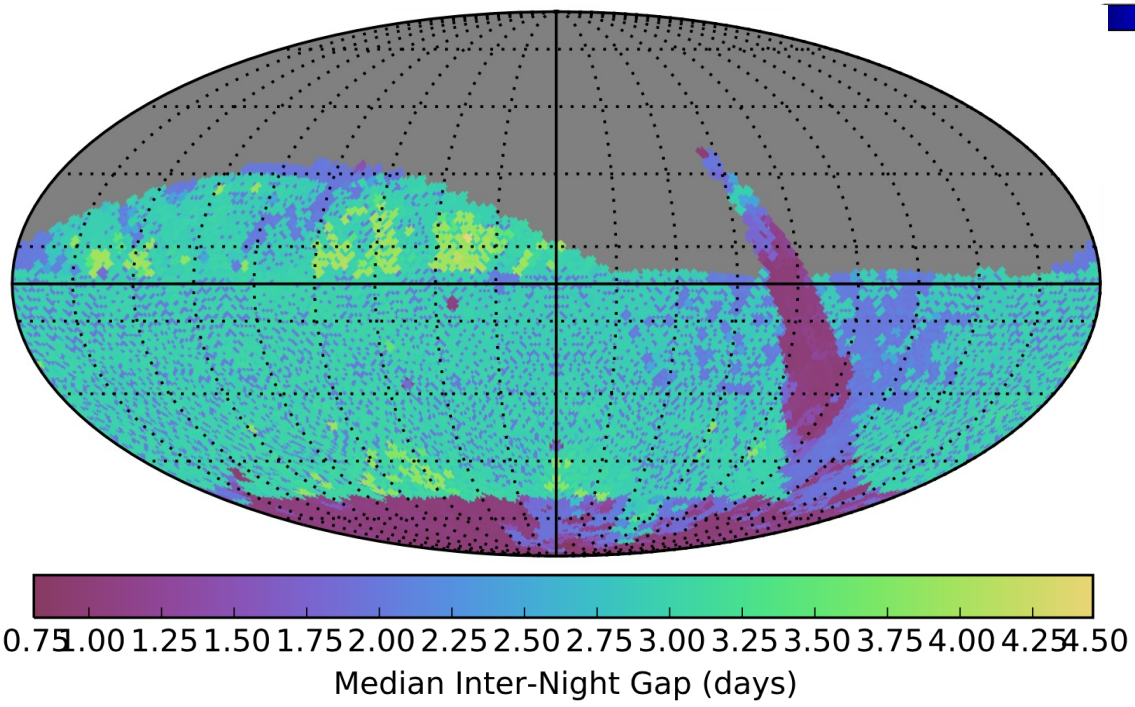
LSST main survey deliverable

« 4D » object mapping (stars, galaxies...) of 18,000 sq. deg. to an uniform depth

- (α,δ) positions on the sky
- Photometric redshifts z
- Time variations
  - -> SN, lensing, AGN…



median maximum gap (in days) in observations near SN light curve peak

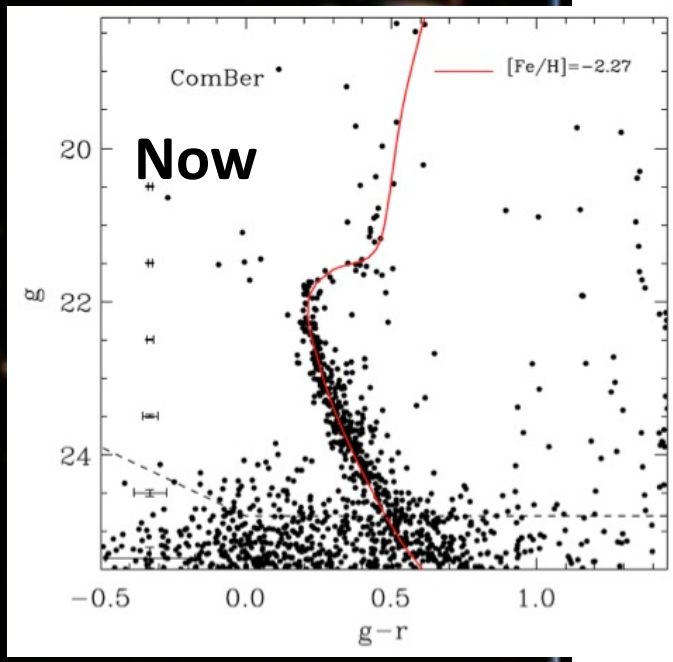


Other survey modes

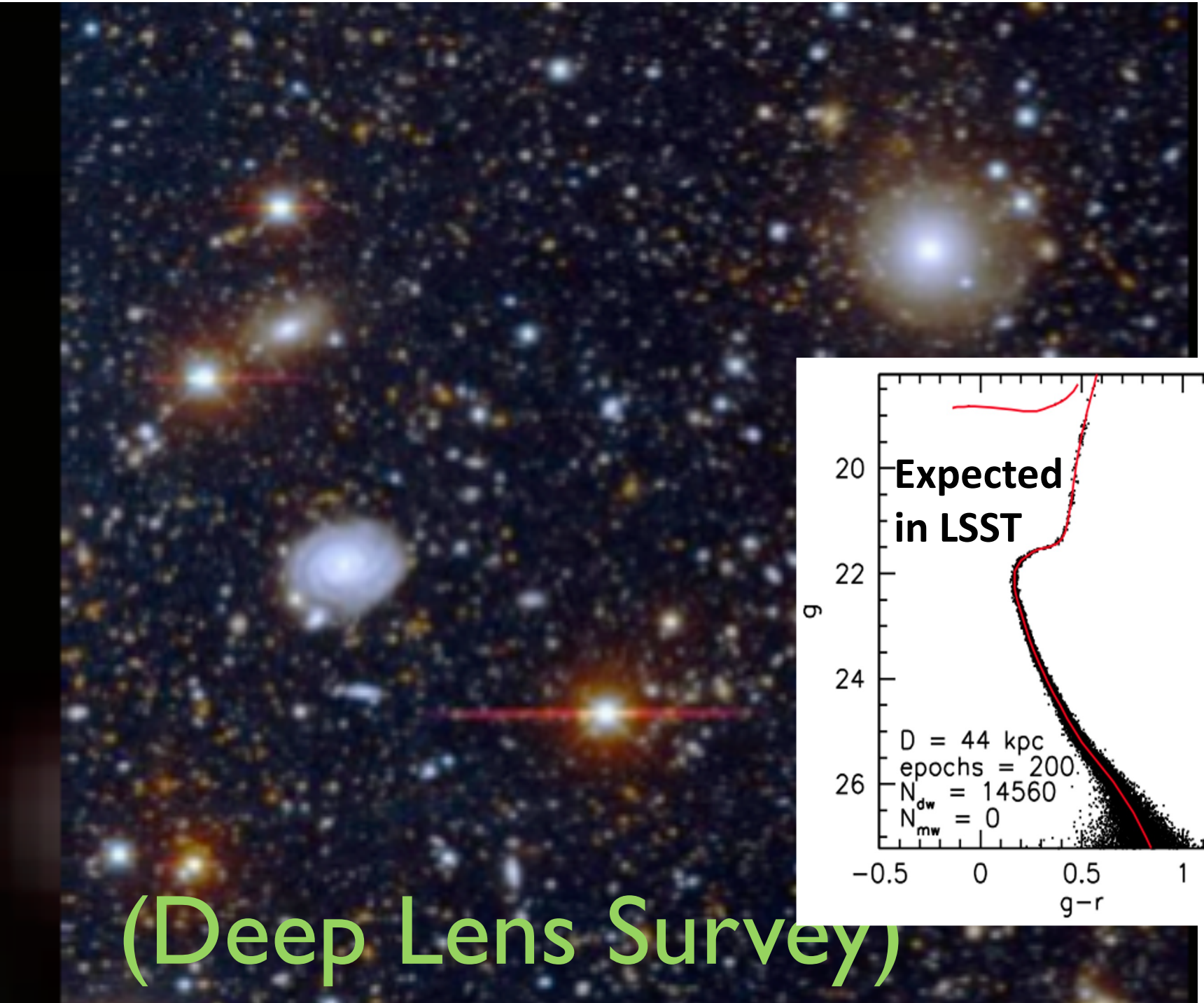
~10% of time ~1h/night

Very Deep + fast time domain + special zones (ecliptic, galactic plane, Magellanic clouds)

3x3 arcmin, gri



SDSS

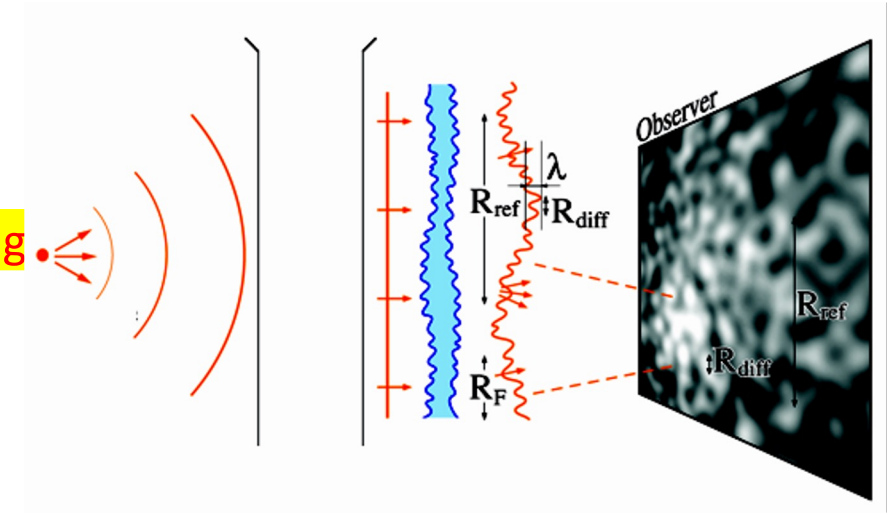


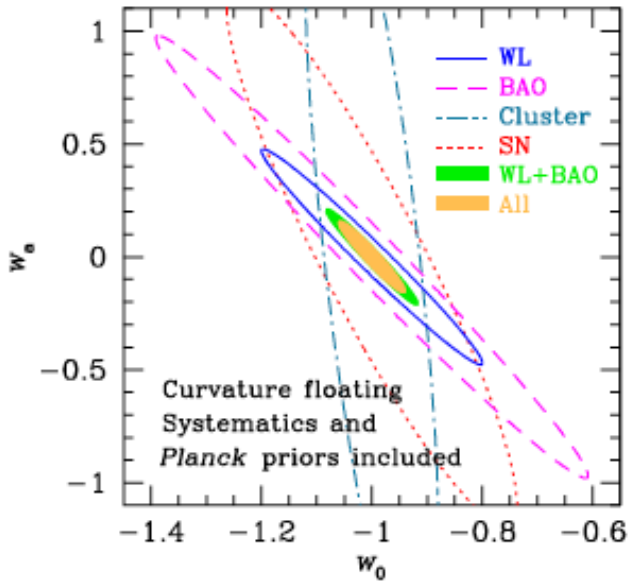
(Deep Lens Survey)

The Science Enabled by LSST
(see science book: arXiv:0912.0201)

- **Time domain science (broker Fink)**
  - Novae, supernovae, GRBs
  - Source characterization
  - GW optical counterparts
  - Gravitational micro/strong lensing
  - Interstellar scintillation
- **Finding moving sources**
  - Asteroids and comets
  - Proper motions of stars
- **Mapping the Milky Way**
  - Tidal streams
  - Galactic structure
- **Dark energy and dark matter**
  - Gravitational lensing
  - Supernovae studies
  - Large scale structures (incl. BAO)
  - Slight distortion in shape

  -> Trace the nature of dark energy





Pratique de la cosmologie

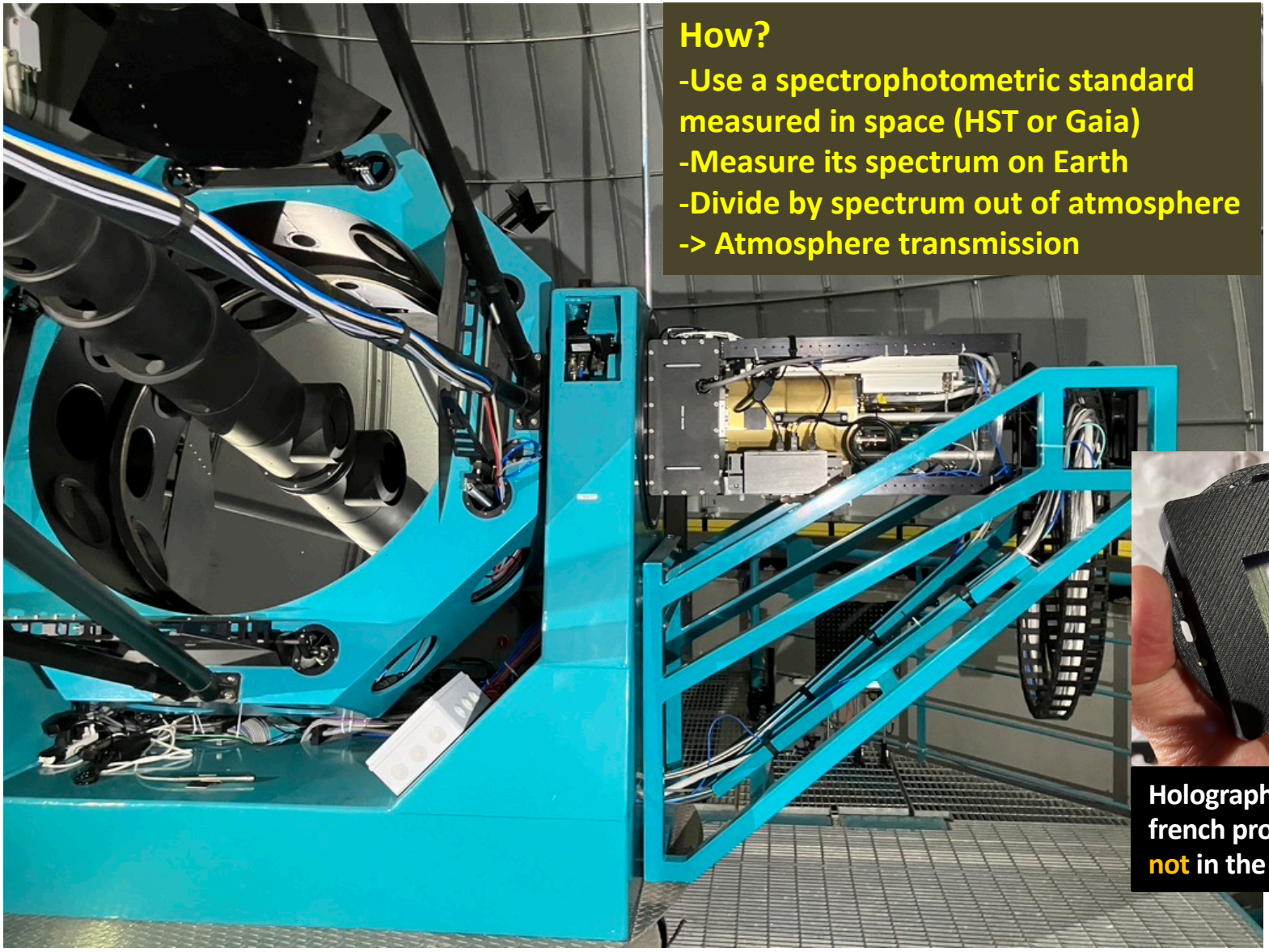
- Passe par l'analyse de la lumière d'objets très lointains (galaxies, SN, quasars…)
- Sur son trajet, cette lumière
  - Est décalée vers le rouge

    -> **redshift**, qu'on cherche à mesurer par photométrie
  - Traverse le milieu intergalactique (stable)
  - Et les derniers 10km

    -> **atmosphère changeante**, qu'on cherche à compenser

AuxTel spectrograph mission

measure the atmospheric transmission as a function of λ to derive the expected fluxes for each object under standard atmospheric conditions



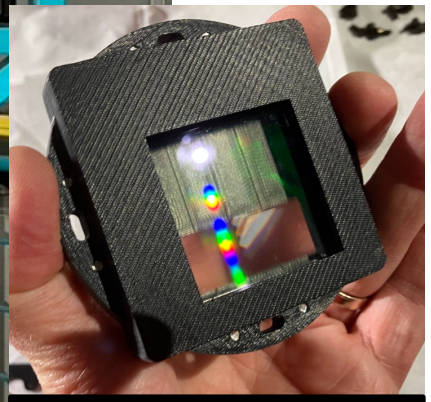
How?

-Use a spectrophotometric standard measured in space (HST or Gaia)

-Measure its spectrum on Earth

-Divide by spectrum out of atmosphere

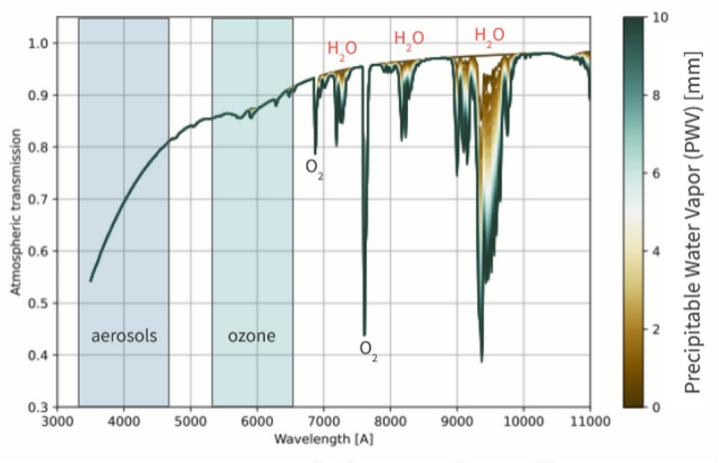
-> Atmosphere transmission

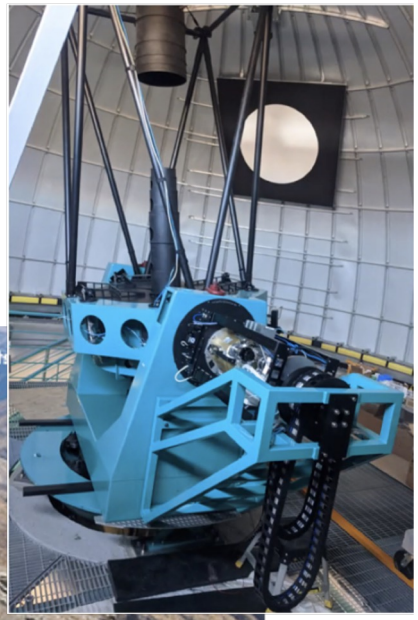


Holographic disperser, a french proposal that was not in the initial project

Rubin's Calibration Telescope - AuxTel

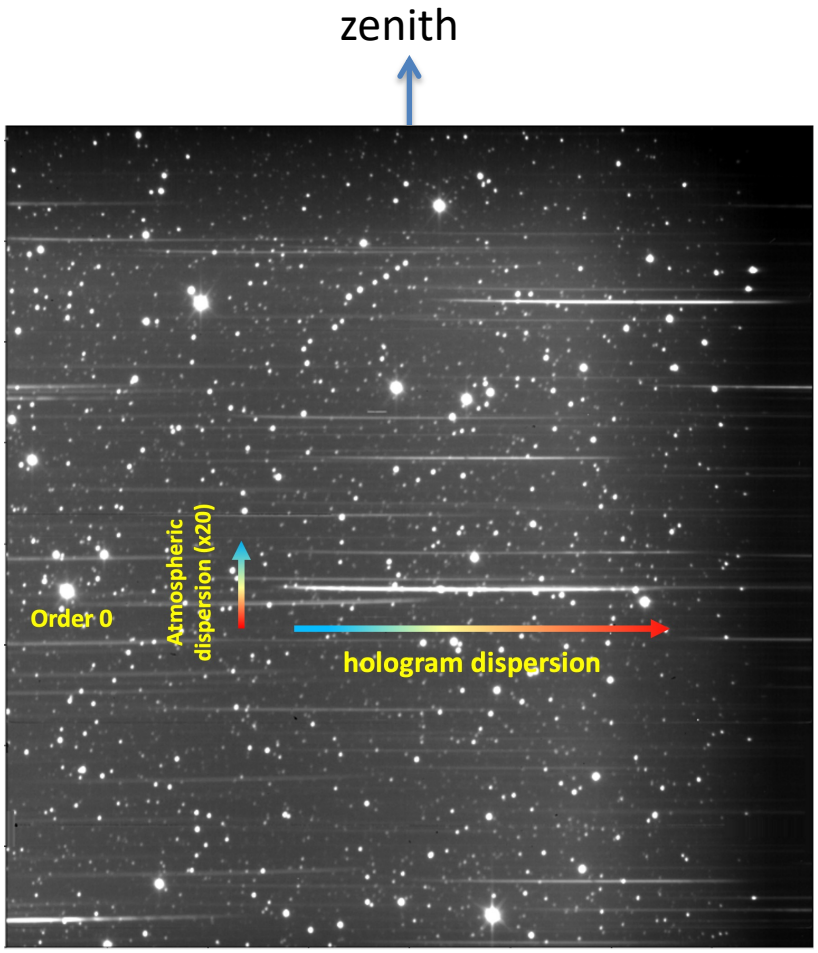
- Team continues to operate and do significant early commissioning
- 1.2 m telescope with a slitless spectrograph (LATISS)
- Primary objective is to characterize and monitor the local atmospheric transmission in parallel with the main Simonyi telescope:





From Z. Ivezic presentation in LSST@europe6 (La Palma, sept. 24)

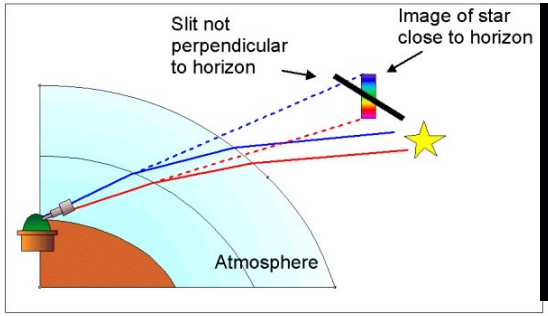
How does it look like?

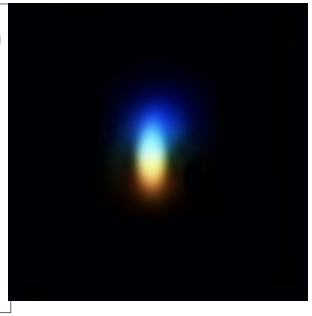


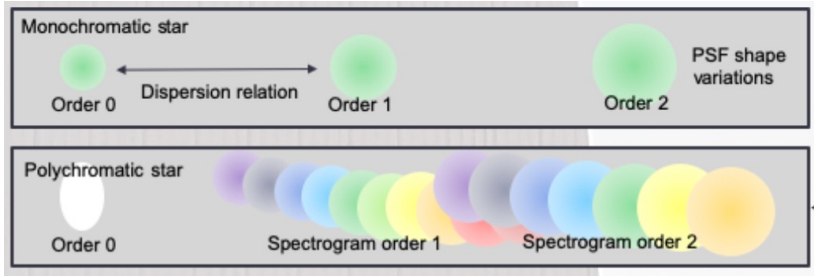
Atmospheric differential refraction

-> along the vertical

-> Turn hologram for horizontal dispersion

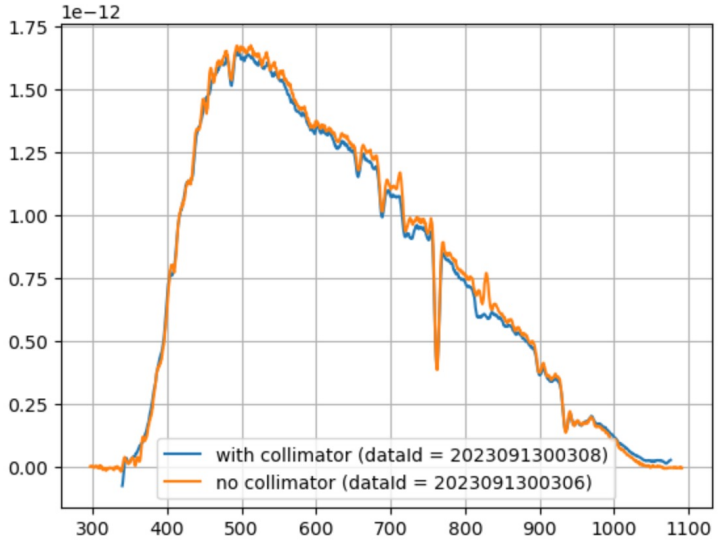


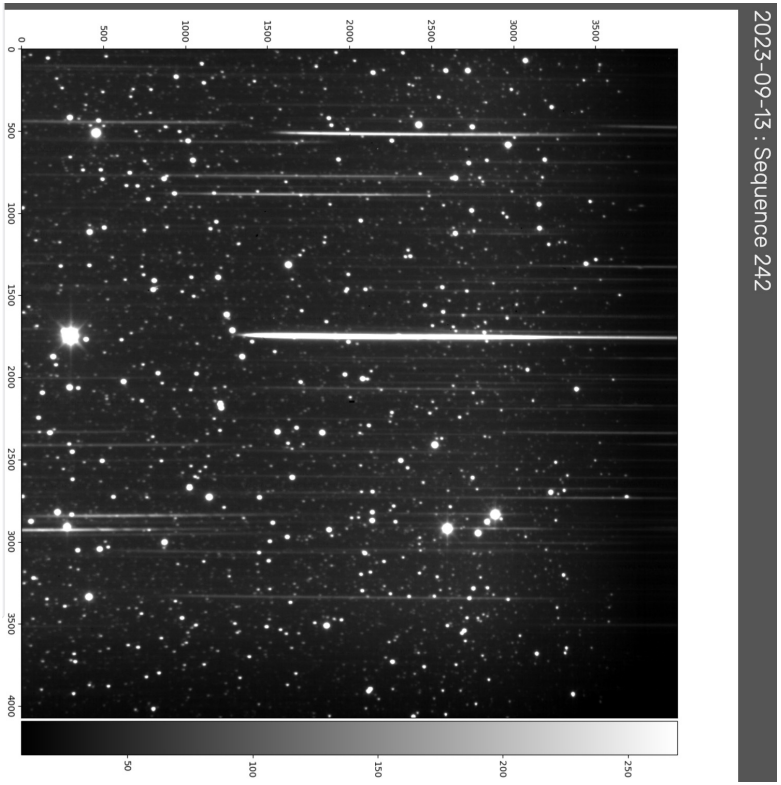


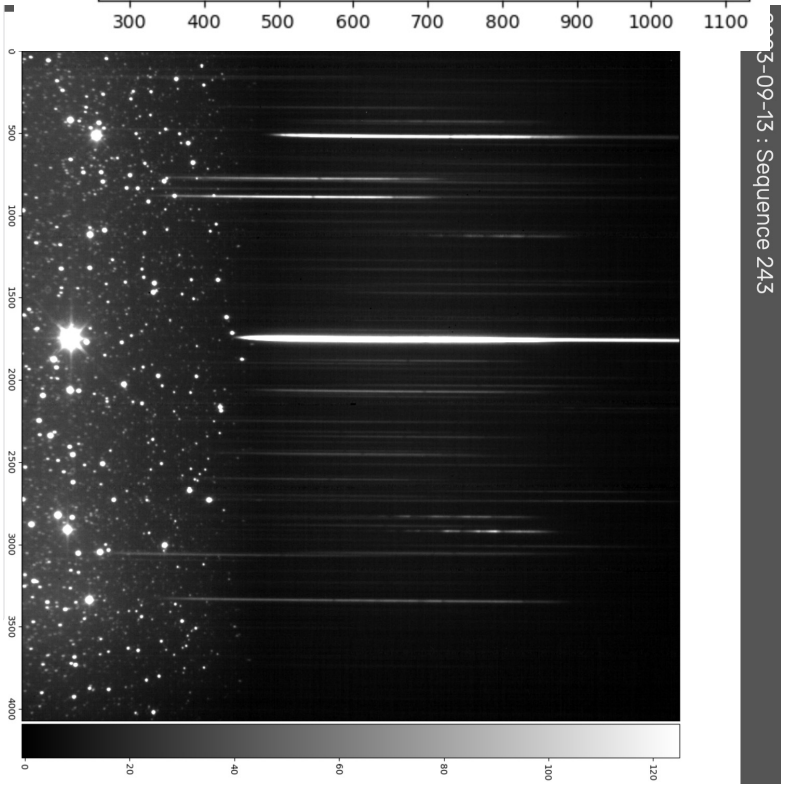


Recent improvement: collimator

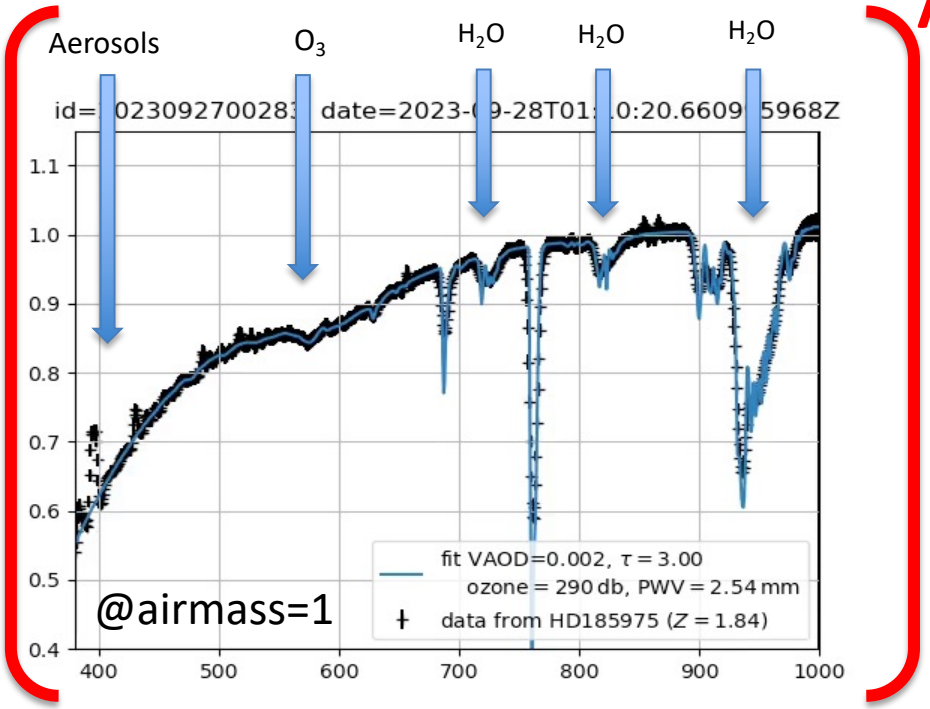
- To mitigate the impact of field stars and of sky background (implemented since sept 2023)





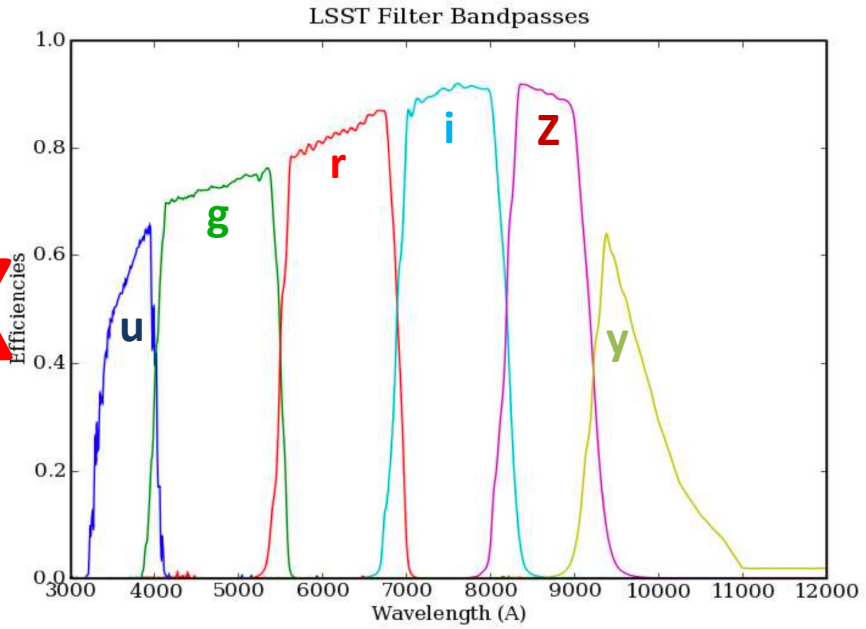


3 years of transmission measurements



Airmass

X



Atmospheric transmision (variable)

Instrument throughput (stable)

= **effective (instantaneous) passbands**

Objectifs scientifiques de AuxTel

- Ramener les mesures de flux lumineux mesurées sur les images de LSST (6 bandes passantes) à des conditions d'atmosphère normales -> Précision de qqs pour mille
  - Essentiel pour la cosmologie (notamment SN)
  - Mais aussi pour tous les domaines de l'astronomie
- Sous produits
  - Utilisation de la technique holographique pour convertir d'autres télescopes en spectrographes
  - Etude de la variation de transmission atmosphérique sur du long terme (>10 ans)

Implications IJCLab dans LSST

- Procédures de compensation atmosphérique
- D'ici un an: calibrer AuxTel avec le Collimated Beam Projector -> **missions à l'OHP**
- Redshifts photométriques
- Détection du ciel variable (broker Fink)
- Cosmologie avec SN1a, ondes gravitationnelles, effets de lentille
- Noter: **LSST démarre en 2025 -> missions au Chili et premières analyses de données**

SUPPLEMENTS

Some facts about AuxTel

- **D = 1.20m**, **f/D = 18**, **f = 21.6m**
- Depth of focus 1 arcsec (10 pixels) for **1.8mm** change in distance (small aperture).

- Secondary mirror (M2) Obturation: **0.3m**
- Total collection area : **S= 0.99 m^2** (taking into account M2-baffle obturation)

- Plate scale: **105µm/arcsec** -> about **10 pixels/arcsec**.
- Field of view : **6.3 Arcmin**.

- Distance entrance window-CCD : 63.85mm. Light beam diameter at this distance : 3.55mm
- Distance disperser-CCD: about 191.4mm (tilted). beam diameter at this distance : 10.6mm
- Distance filter-CCD : 229mm (tilted).

- Saturation (no filter, no disperser, assuming seeing of 1''): **M_{sat}=13.35+2.5Log_{10}(Texp/30s)**

Atmospheric studies

Objective of the AuxTel calibration:

Estimate colour corrections to vector $(\mathbf{UGRIZY})_{LSST}$ for each object, as a function of

- the atmospheric parameters **(airmass, PWV, τ_{VAOD})** -> the baseline
- or the directly measured atmospheric transmission function **$T_{atm}(\lambda, RA, Dec)$** synchroneously within the LSST field

What are the orders of magnitude of the corrections ?

From simulation: atmospheric fluctuations induce typically less than **10mmag** (max. ~30mmag @ airmass=2 for cold stars) residual colour variations per airmass after removing grey common absorption

-> Correction precision **δC** needs to be such that:

0.010 x δC < wanted resolution

i.e. **δC=50%** for 5mmag / **10%** for 1mmag

Spectroscopie avec AuxTel

essentiellement une activité française

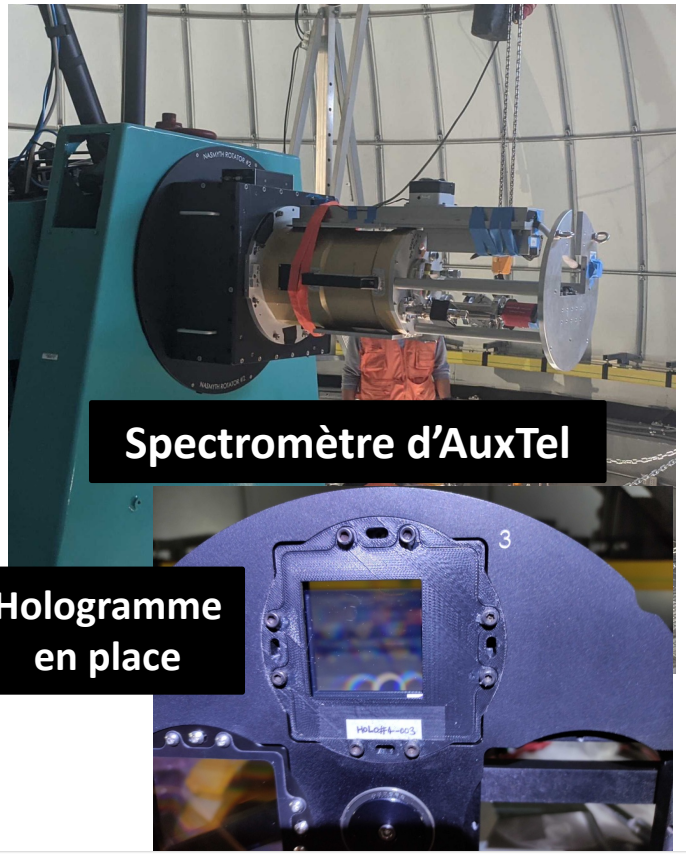
IJCLab + LPNHE

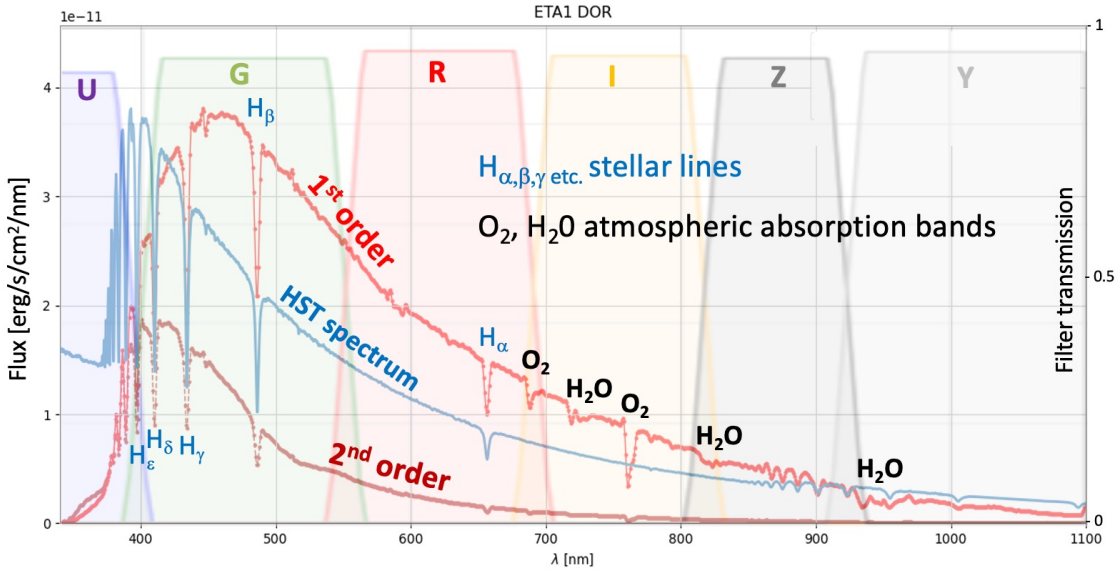
Pourquoi la spectroscopie?

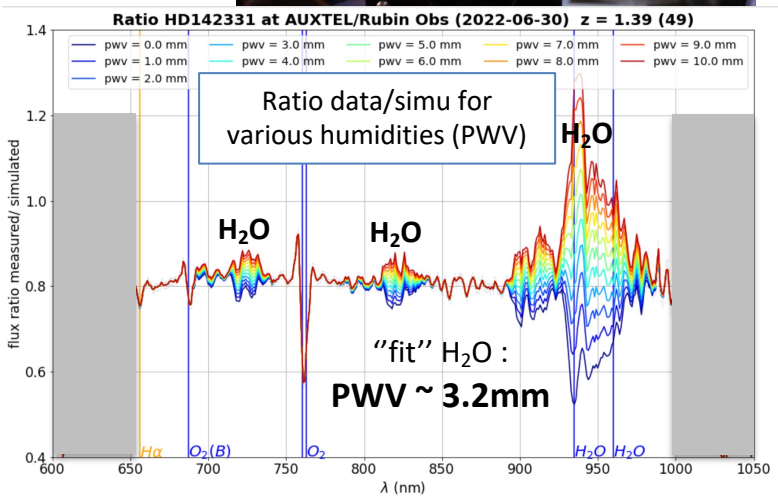
- Mesure de la transparence de l'atmosphère -> **calibration** en fonction de λ
- A partir du rapport : *flux hors atmosphère (HST) / flux mesuré au sol*
- en temps réel (peut varier de 20% dans la nuit)

Données avec hologramme depuis février 2021: plusieurs milliers de spectres

- Extraction de spectres entre **350** et **1050**nm opérationnelle avec *séparation des 2 ordres* de diffraction (Spectractor dans DM).
- Caractérisation fine délicate, mais à peu près terminée.
- On commence à mesurer des paramètres de l'atmosphère (O_2, H_2O et bientôt aérosols), par comparaison avec la simulation LibRadTran.
- Egalement en cours: procédure de déflatage (non standard).







Rubin-LSST : contexte

Communité de ~ **1000 scientifiques** dans le monde (50% **US**) :

- **Chili** (site) & **France-IN2P3** (contributions à la camera, la calibration, le computing et data management) sont membres de plein droit de LSST / **droits privilégiés** d'accès aux données.
- La France et en particulier le LAL/IJCLab sont dans le projet depuis le tout début (2005)
  - Le LAL-IJCLab a produit le processeur de lecture du CCD (bas bruit)
  - L'IJCLab leader pour la calibration atmosphérique avec le télescope auxiliaire.
- Hors USA, Chili et France, les chercheurs devront passer par d'autres canaux pour accéder aux données de LSST.

Sujet de thèse:

Mesure du taux d'expansion de l'Univers avec les premières données du relevé LSST

Science

-> Deux estimations distinctes de H_0

- Mesure des délais de propagation entre images lentillées de quasars: strong lensing time-delay
- Contreparties optiques des ondes gravitationnelles

  Principe

  – distance mesurée avec l'onde gravitationnelle
  – Redshift mesuré en optique

Outils spécifiques IJCLab

- Corrections atmosphériques mesure/mesure grâce au télescope auxiliaire
  - Enjeu: la précision photométrique pour mesurer les décalage en temps des courbes de lumière
- Broker Fink: détecteur de changements dans le ciel -> pour trouver des quasars variables
  - Enjeu: accroître la statistique des quasars multiples et variables

Transient science with LSST

<--Time critical-->

LSST alerts -> broker Fink -> trigger follow-up for specific events

- Microlensing (with caustic crossing) -> ***Dark matter / planets*** ***[hours]***
- SNs -> ***Cosmology*** ***[days]***
- Asteroids -> ***Save the Earth!*** ***[minutes-days]***
- …

Search for optical counterparts AND trigger follow-up ***[minutes-hours]***

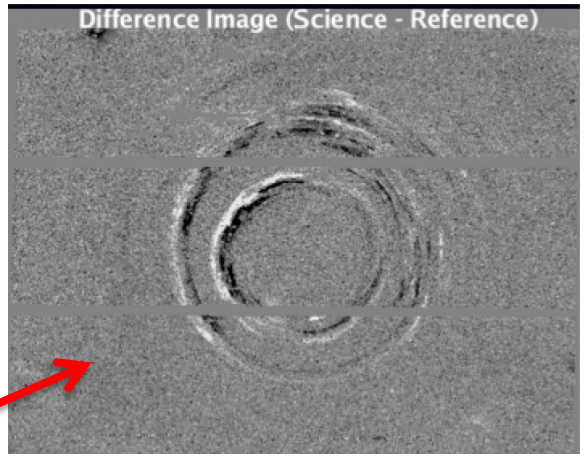
- GW -> ***Hubble constant*** (with spectro-*z*) ***[minutes]***
- GRB afterglows
- Neutrino sources
- High Energy cosmic ray sources

<- Offline ->

« Offline » science ***[minutes AND years]***

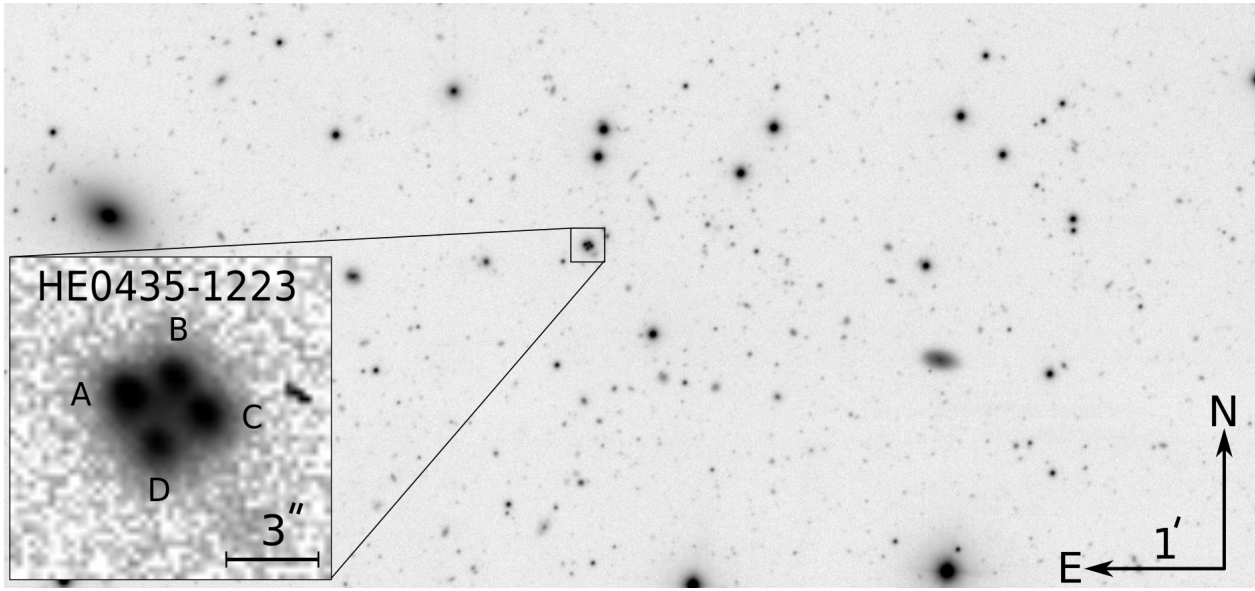
Search for signals through the broker files

- Retroactive targetted search for GW in the interferometer records
  - -> Potential factor 2 for GW searches
  - -> Also GRB afterglows ?
- Microlensing ***[months-years]***
- Interstellar scintillation: search for turbulent molecular (hidden) gas in the MW ***[minutes]***
- SN echoes… Varying large structures ***[years]***

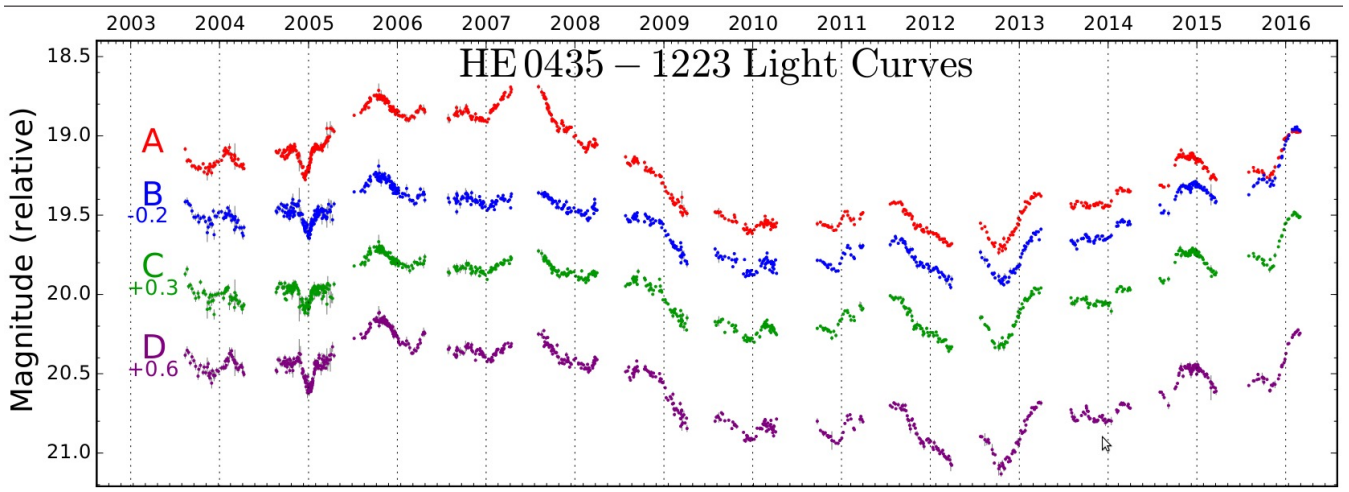


Strong lensing time-delay

time delays of HE0435−1223: H_0 to 3.8% precision from strong lensing



Estimate H_0 from the measured delays and lens model



Le broker Fink

Un dispositif destiné à trier les millions d'alertes attendues chaque nuit dans les données de LSST

Fonctionne déjà avec les données de ZTF

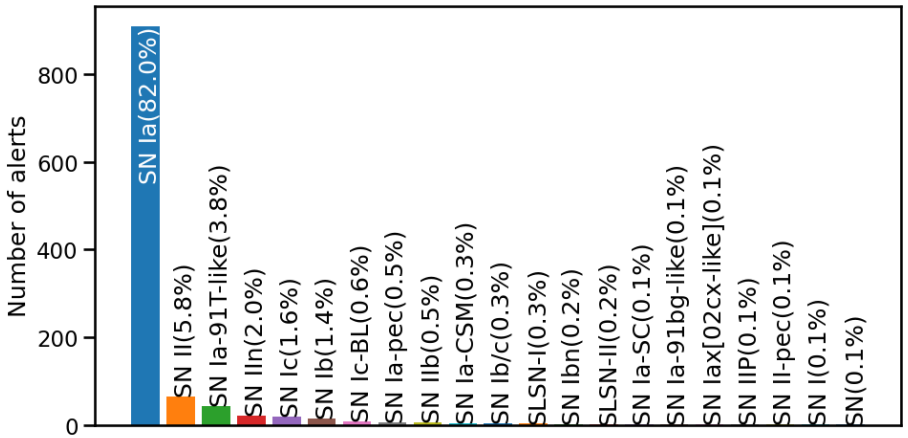
Web portal & API : 140 millions d'alertes disponibles (~10 To), 100+ utilisateurs uniques/jour, 3000 requêtes/jour

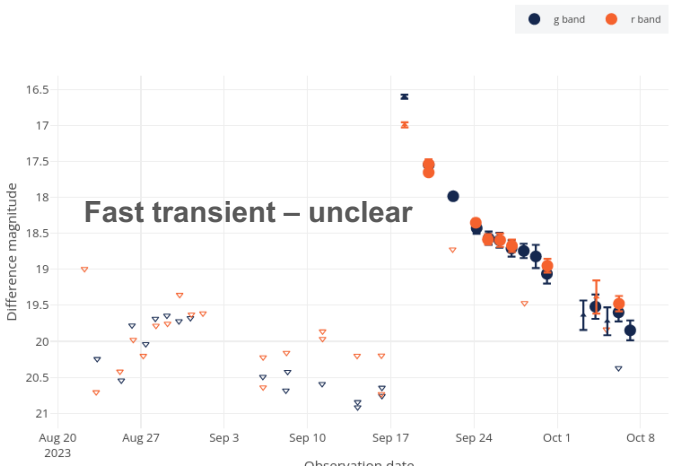
Livestream : 10 utilisateurs pour le suivi temps réel : YSO, AGN, supernovae, kilonovae.

Data download : +1 milliard d'alertes téléchargées/mois… :-)

Suivis déjà opérés par :

- South African Large Telescope, South Africa
- Caucasus Mountain Observatory, Russia
- Australian National University, Australia
- Observatoire de Haute-Provence, France
- ESO-NTT / EFOSC2-NTT, Chile



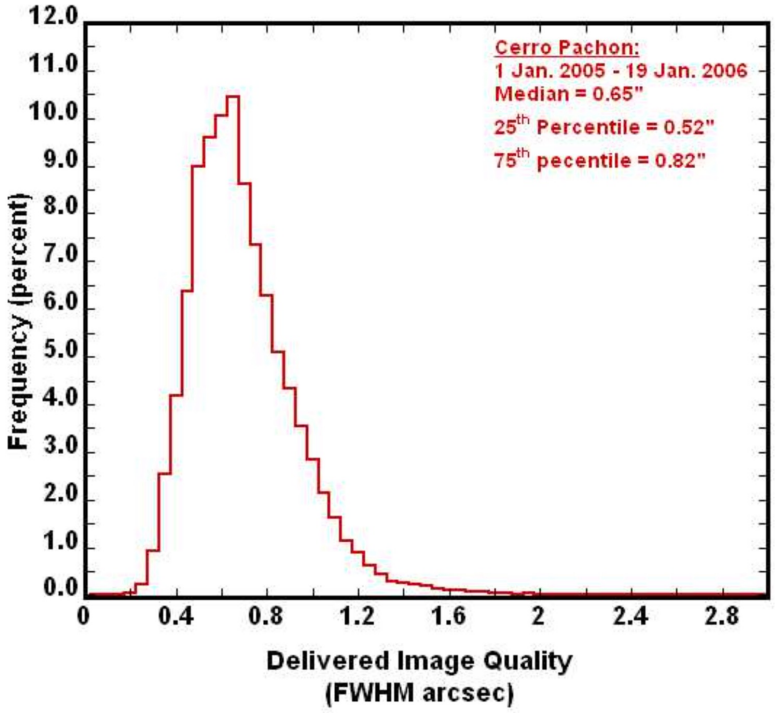


Summary of High Level Science Requirements

Survey Property	Performance
Main Survey Area / duration	18000 sq. deg. / 10 years
Total visits per sky patch	825 (1 visit per ~3-4 nights)
Filter set	6 filters (ugrizy) from 320-1050nm
Single visit	2 x (15 second exposures + 1s shutter + 2s readout)
Single Visit Limiting Magnitude (AB 5σ)	**u = 23.9; g = 25.0; r = 24.7; I = 24.0; z = 23.3; y = 22.1**
10 year coadd. Limiting Magnitude	u = 26.1; g = 27.4; r = 27.5; I = 26.8; z = 26.1; y = 24.9
Photometric calibration	< 5mmag repeatability & colors, <10mmag absolute
Median delivered image quality	~ 0.7 arcsec. FWHM
Transient processing latency	**60 sec after last visit exposure**
Data release	Full reprocessing of survey data annually

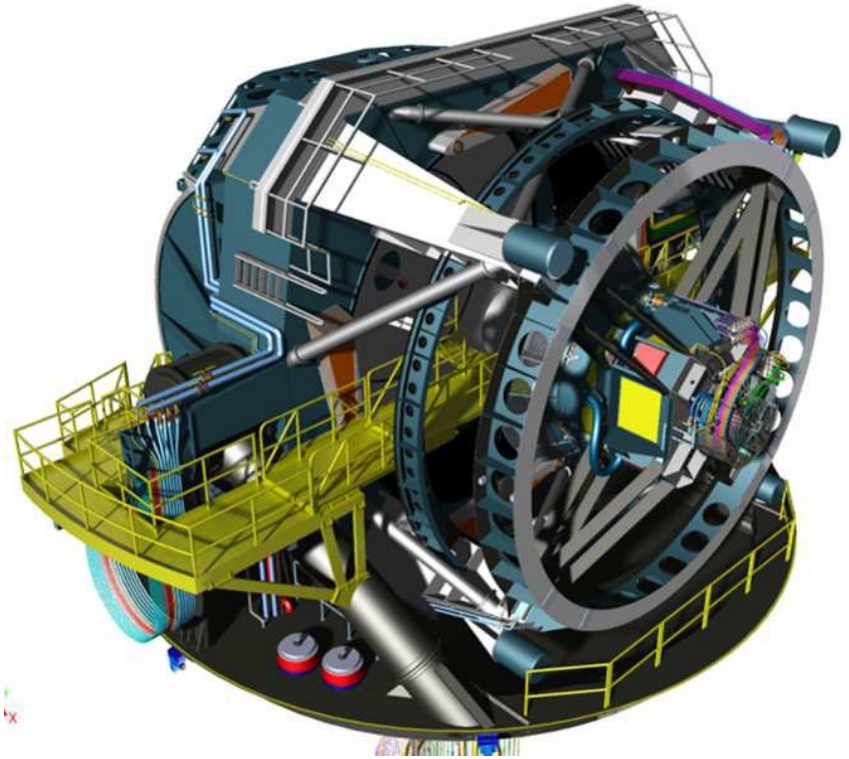
Site quality

- 1 year study
- Median seeing @500nm : 0.65 ”



Telescope Mount Enables Fast Slew and Settle

- Points to new positions in the sky every 39 seconds (average)
- Tracks during exposures and slews 3.5° to adjacent fields in ~ 4 s



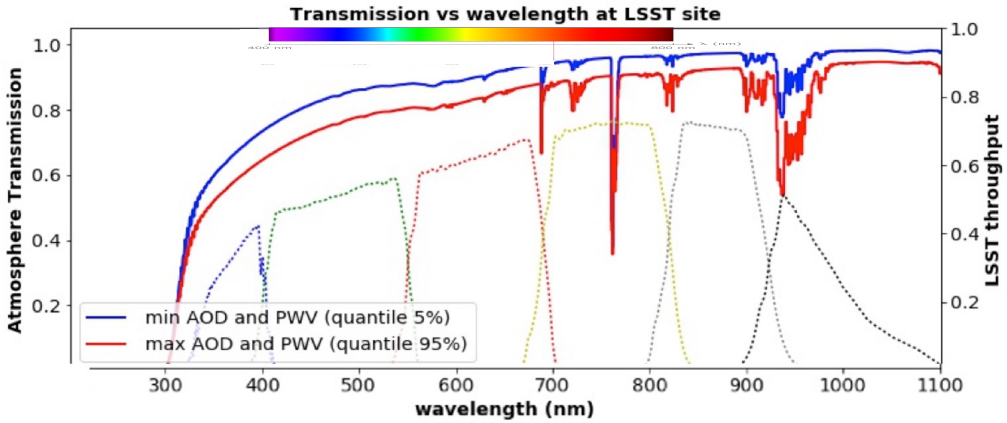
AuxTel spectrograph mission:

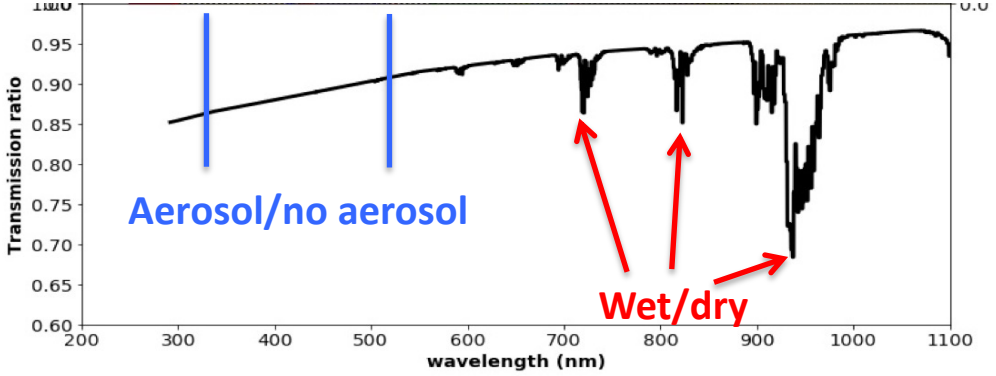
measure the atmospheric transmission to derive the expected fluxes for each object under standard atmospheric conditions

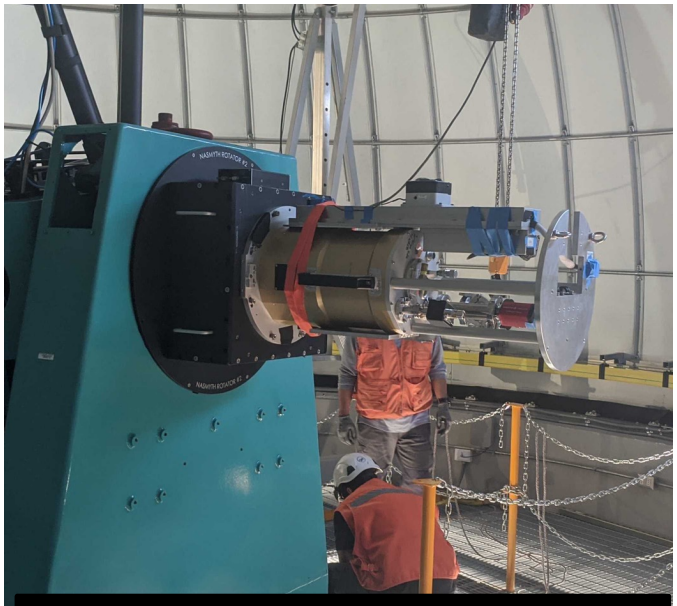
Estimate colour corrections, as functions of the atmospheric conditions and of the object UGRIZY in every LSST field

Example below

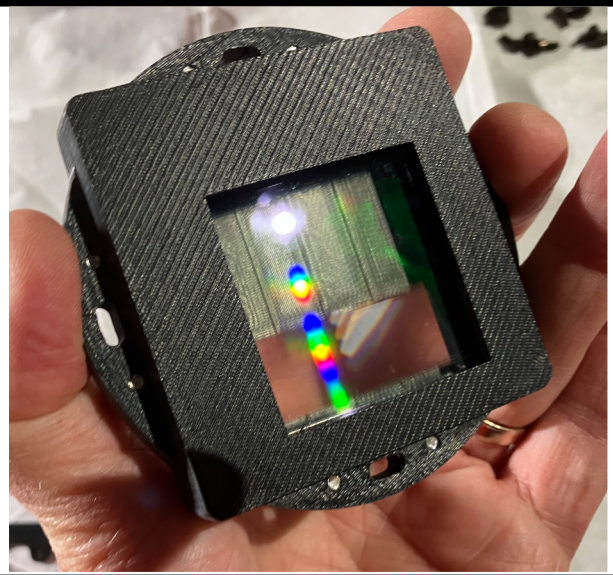
- Constant airmass, constant O_2 and O_3. No cloud
- Change only : **H_2O (PWV),** **Aerosols**







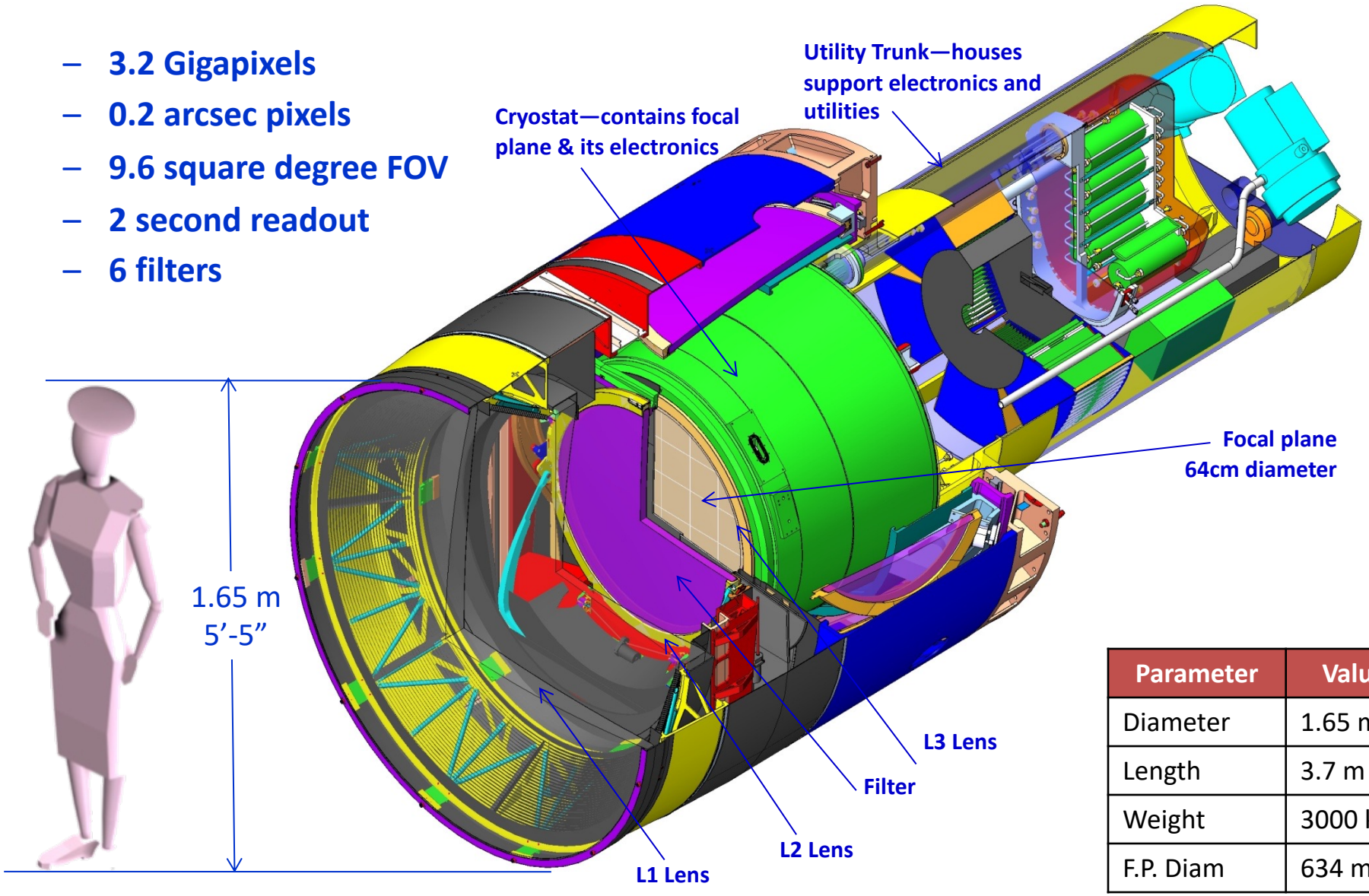
AuxTel slitless spectrometer



Holographic disperser, a french proposal that was not in the initial project

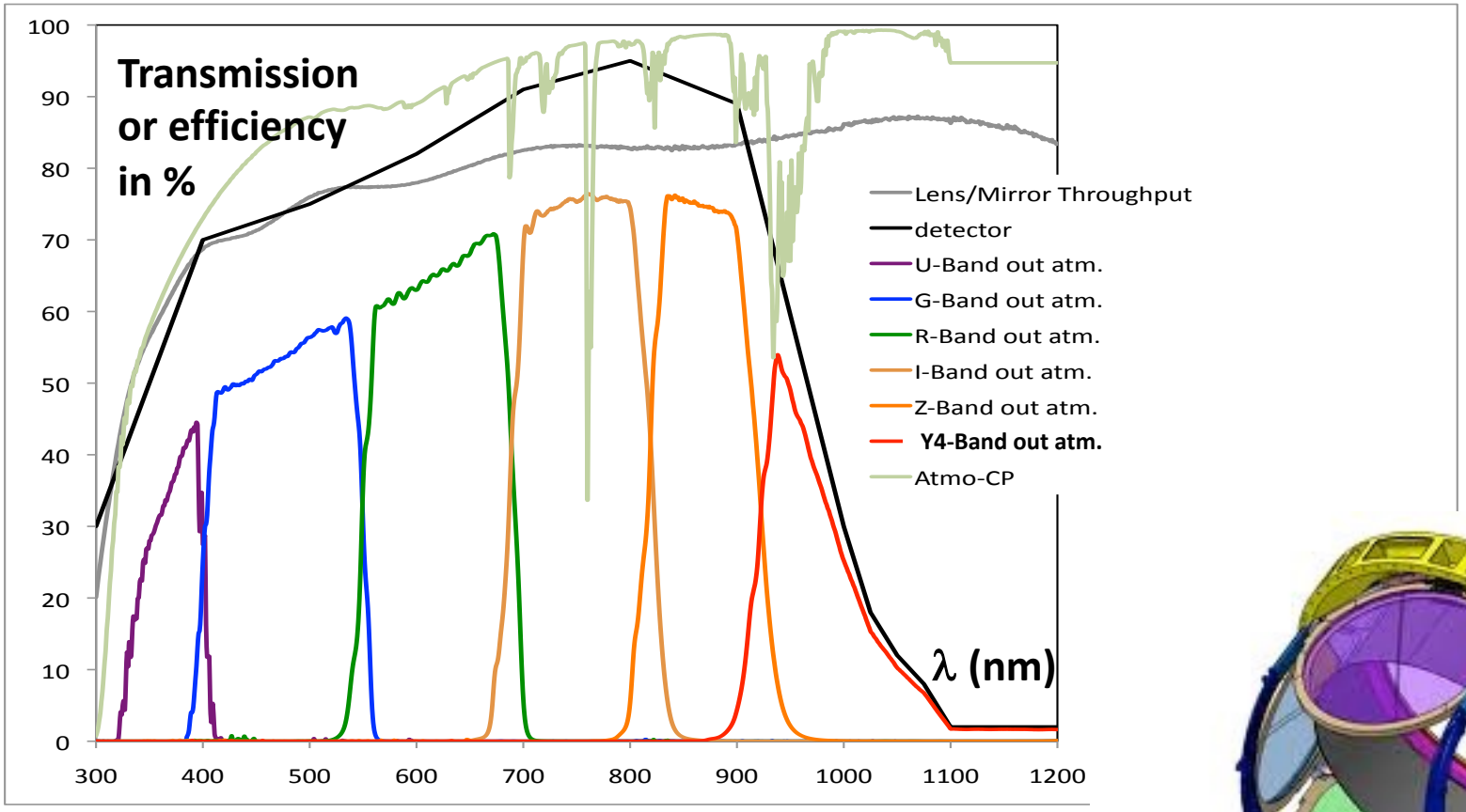
Camera Overview

- 3.2 Gigapixels
- 0.2 arcsec pixels
- 9.6 square degree FOV
- 2 second readout
- 6 filters



Parameter	Value
Diameter	1.65 m
Length	3.7 m
Weight	3000 kg
F.P. Diam	634 mm

System throughput



Includes - Atmospheric transmission
- Optics
- Detector QE
- Filters