StarDICE: Calibration at the per mil level of a new generation of telescopes for dark energy measurement

Advised by J. Neveu and P. Antilogus

Presented by Thierry Souverin

25/09/2024

Presentation summary

I. **General introduction**
   1. A brief introduction to cosmology
   2. Type Ia supernovae
   3. Photometric calibration

II. **The StarDICE experiment**
   4. Description of the experiment
   5. Collimated Beam Projector
   6. On-sky measurements analysis with StarDICE

I. General introduction

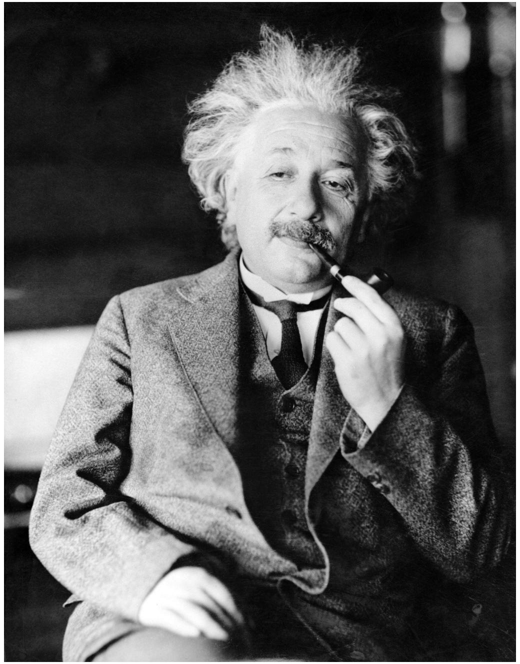
1. A brief introduction to cosmology

What is cosmology ?

What is cosmology ?

It is the field of physics describing the nature of the **Universe**, its **structure** and its **evolution**

General relativity



Albert Einstein, pipe smoking

General relativity

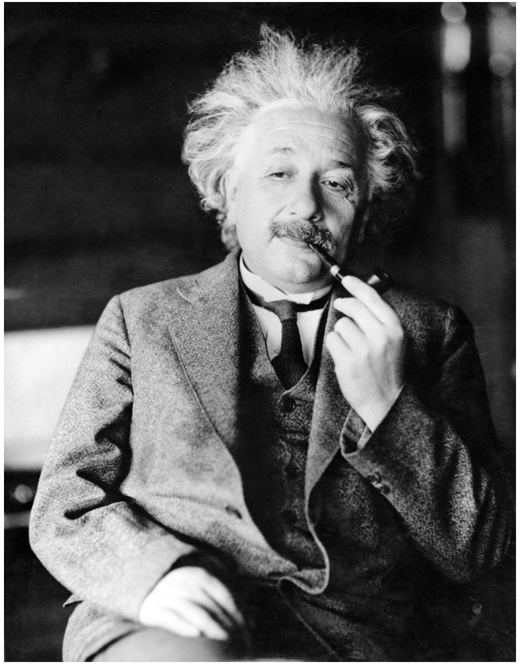
Einstein equation:

Newtonian gravitational constant

$$G_{\mu\nu} = \frac{8\,\pi\,G_N}{c^4}\,T_{\mu\nu}$$

4D spacetime curvature

Energy content of the Universe (baryonic matter, photons, neutrinos…)



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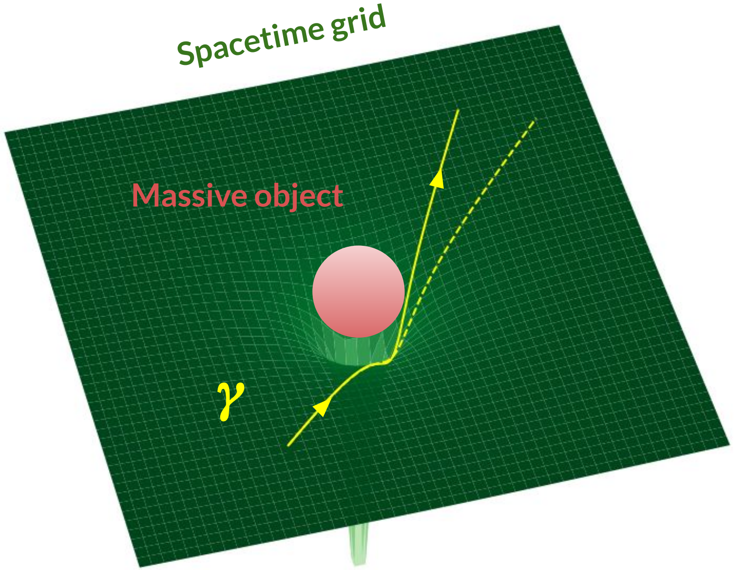

2D representation of spacetime deformed by a massive object

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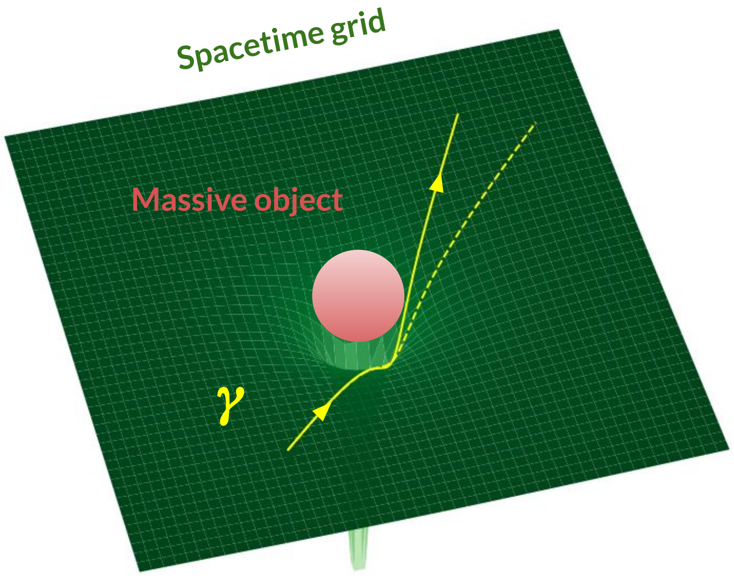

2D representation of spacetime deformed by a massive object

⇒ **But the Universe is complex and full of materials, so how can we study it ?**

Cosmological principle

Cosmological principle: at cosmological scales, the Universe is **homogeneous** and **isotropic**

⇒ implies symmetry considerations for both $T_{\mu\nu}$ and $G_{\mu\nu}$

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Friedmann's equations (solution to Einstein equation)

Scale factor

$$\frac{\ddot{a}}{a} = \frac{4\pi G_N}{3}\left(\rho + \frac{3p}{c^2}\right)$$

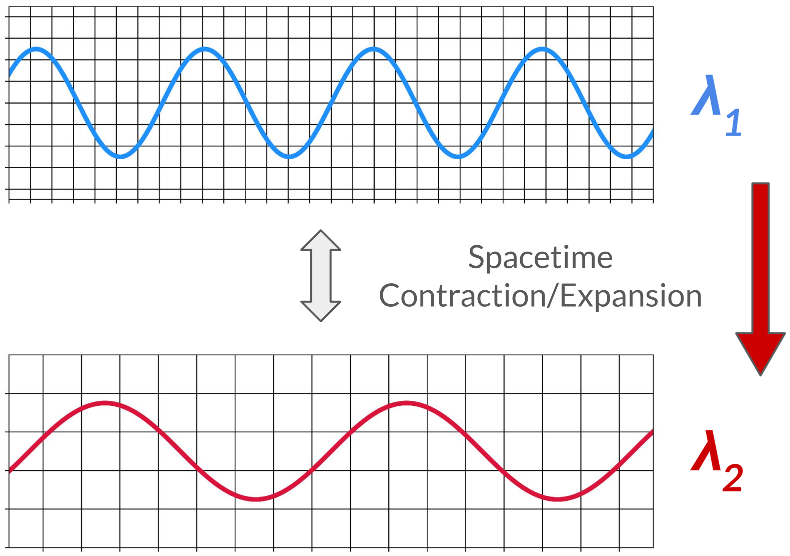
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N}{3}\rho - \frac{kc^2}{a^2}$$

Aleksandr Friedmann, not pipe smoking

⇒ links the **dynamic behavior** of the Universe with its **energy content**

Redshift definition

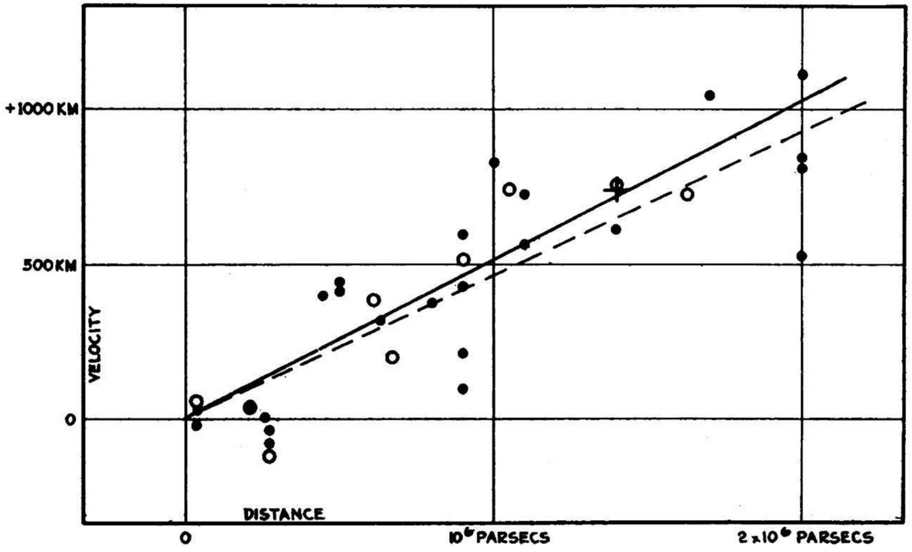
$\lambda_1 < \lambda_2$



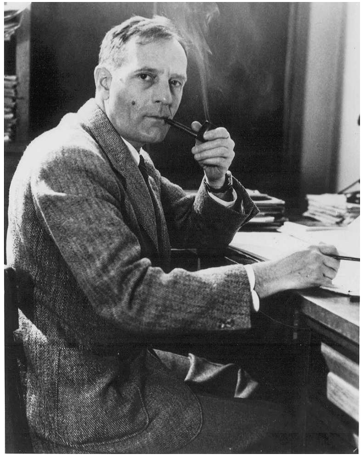
Redshift: $z = \dfrac{\lambda_2 - \lambda_1}{\lambda_1}$

Spacetime expansion affects light **wavelength**
⇒ The redshift *z* is a tracer for studying spacetime evolution

Expansion of the Universe, 1929



Galaxy velocities against their distances
(Hubble, 1929)



Edwin Hubble, pipe smoking

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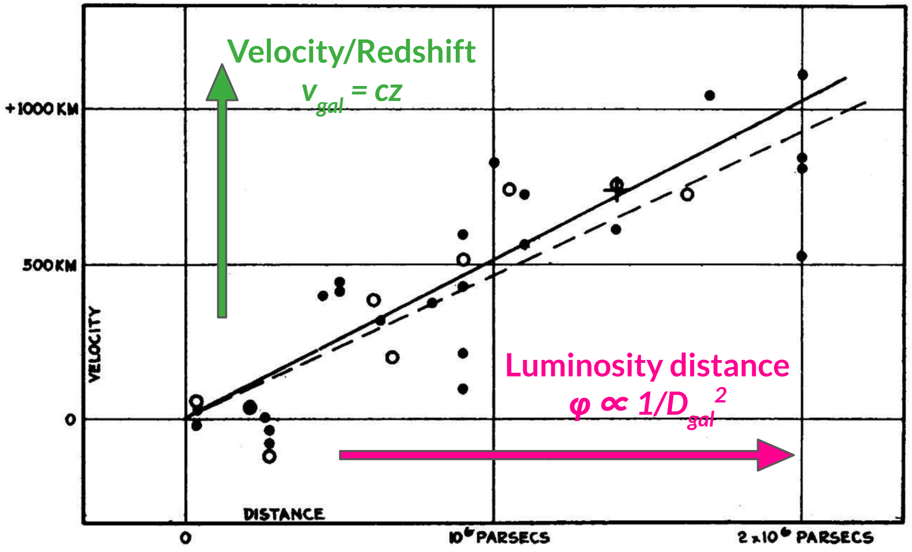

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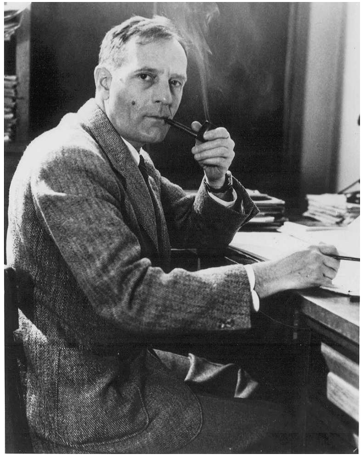

Edwin Hubble, pipe smoking

$$v_{\mathrm{gal}} \propto D_{\mathrm{gal}}$$

$$\Longleftrightarrow$$

$$cz \propto D_{\mathrm{gal}}$$

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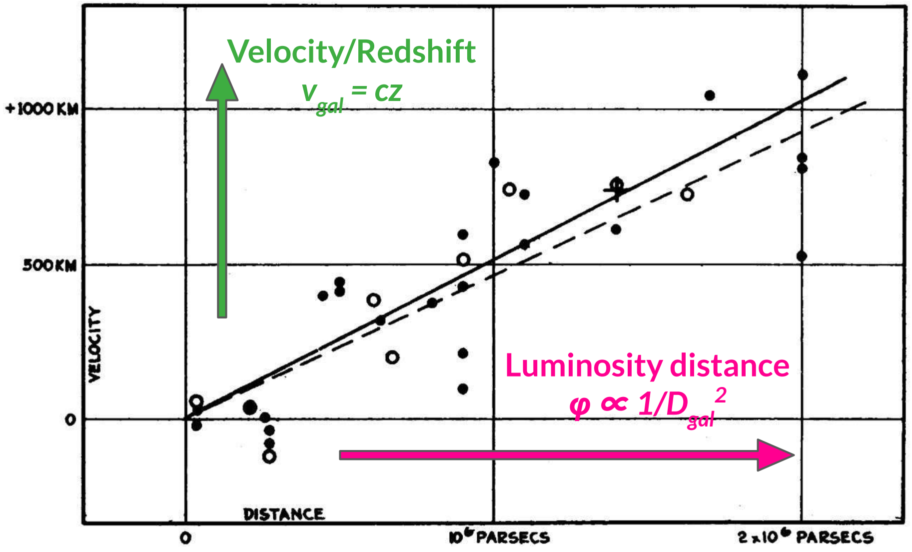

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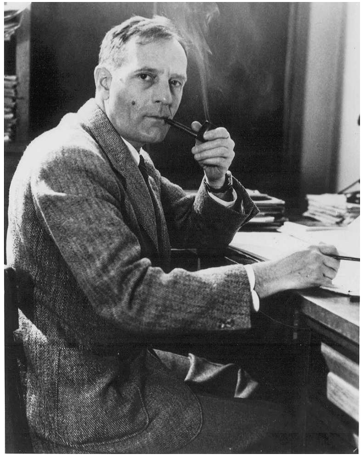

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$$v_{\text{gal}} \propto D_{\text{gal}}$$

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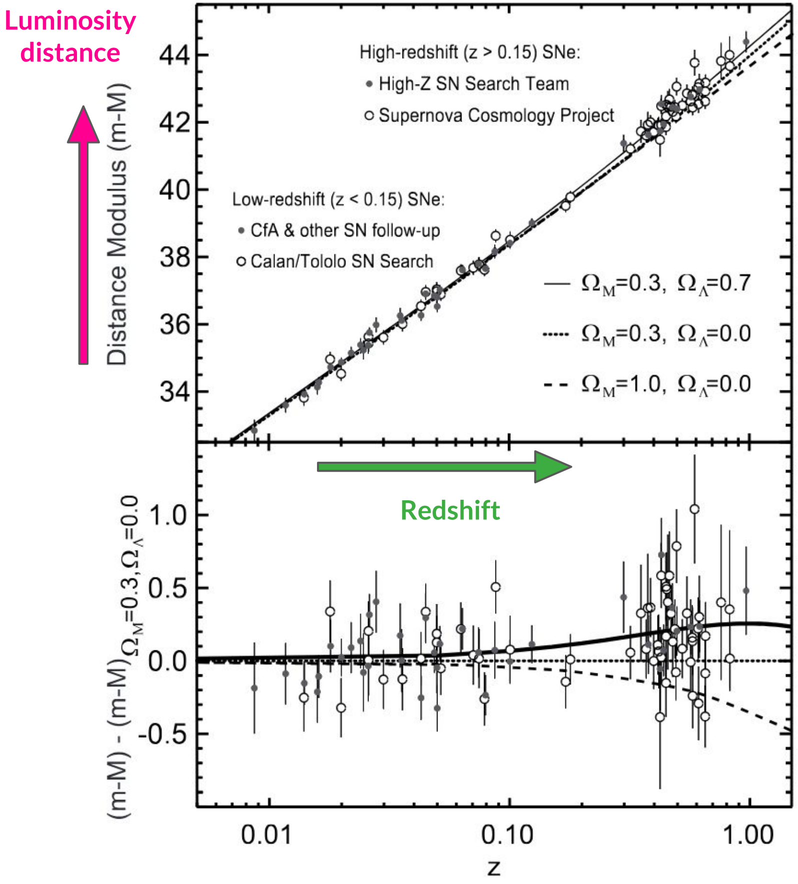
The redshift z increases with the galaxy distance D_{gal}

⇒ First evidence of the Universe's expansion

Expansion's acceleration, 1998/1999



High-Z Supernova Search Team and **Supernovæ Cosmology Project (SCP)**
→ First evidence of the acceleration of the Universe's expansion

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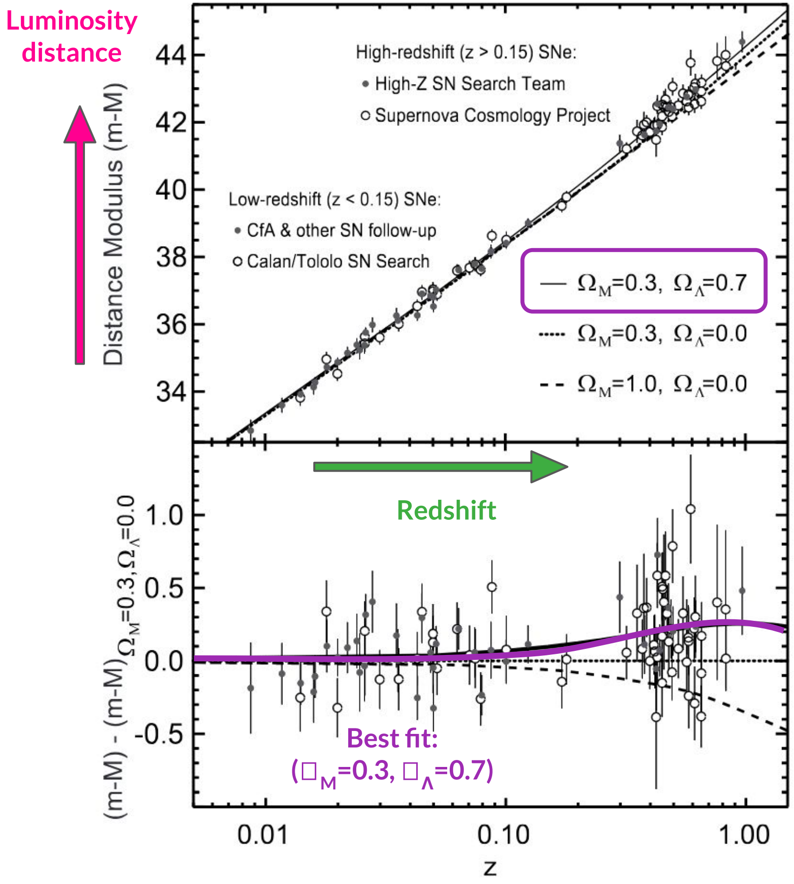

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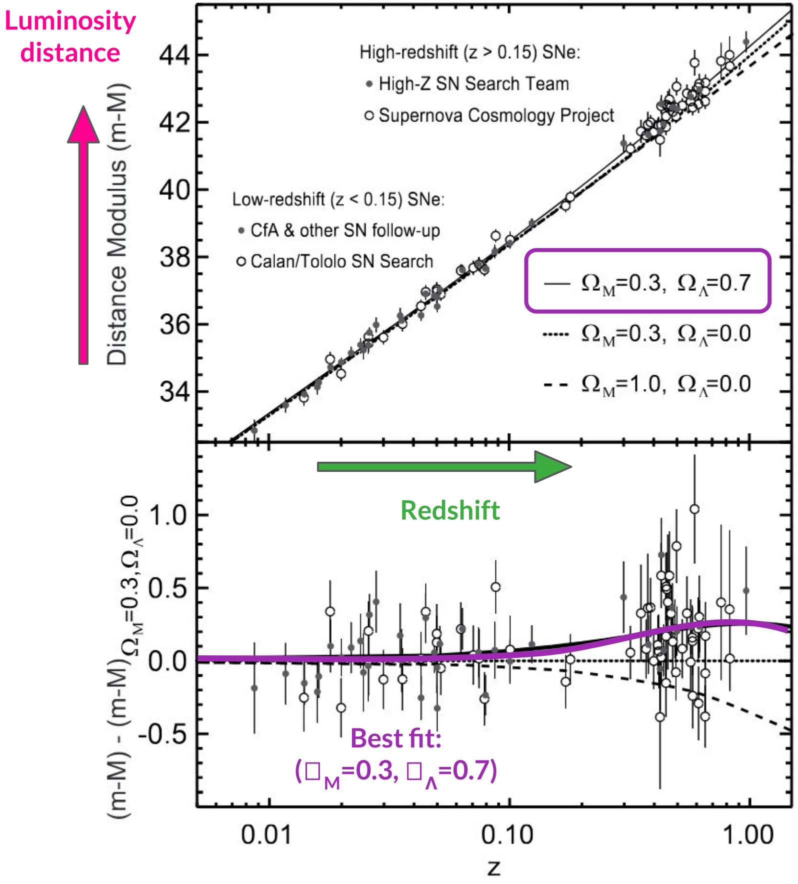

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$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G_N}{c^4} T_{\mu\nu}$$

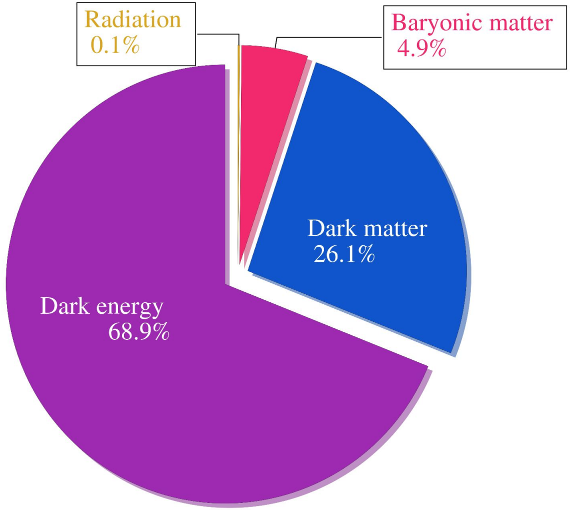
Cosmological constant

The cosmological constant can be seen as an additional component of the energy content
⇒ **dark energy**

Dark energy models

Dark energy → fluid described by an equation of state with the parameter $\boldsymbol{w}$:

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



Pie chart of the energy contents distribution in the Universe today

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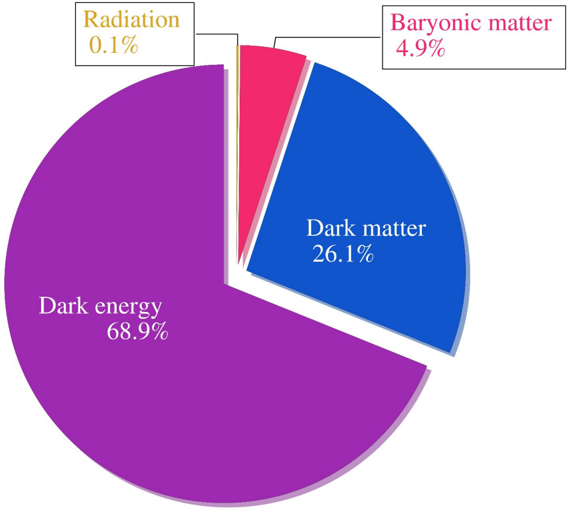
- **ΛCDM, the standard model**
  - **Λ** for **the cosmological constant**, **CDM** for **Cold Dark Matter**, w = -1, and a flat Universe



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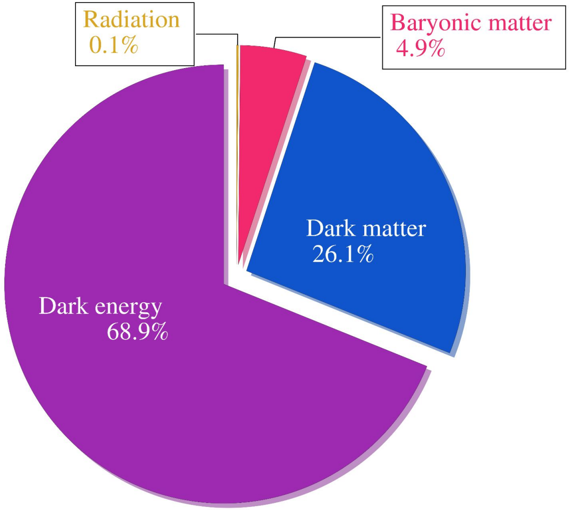
  - $w \neq$ -1, where it can be constant (**wCDM**), or dynamic (**$w_0 w_a$CDM**)



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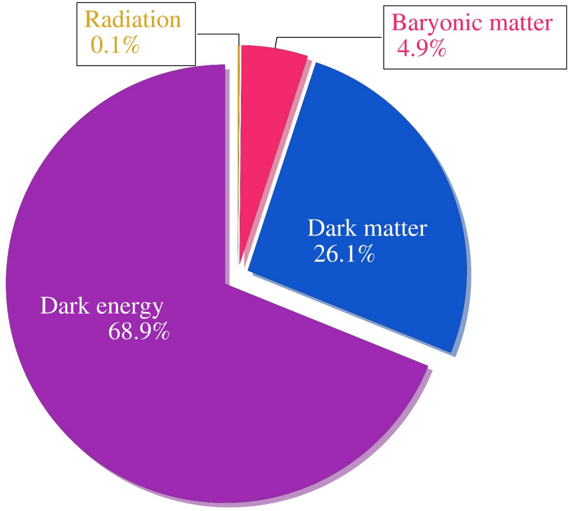
⇒ **Which model describes better the observations ?**



Pie chart of the energy contents distribution in the Universe today

Cosmological probes

Several astrophysical probes can be observed to infer cosmological parameter constraints:

- Cosmic Microwave Background (CMB)
- Baryon Acoustic Oscillations (BAO)
- Weak gravitational lensing
- **Type Ia supernovae (SNe Ia)**

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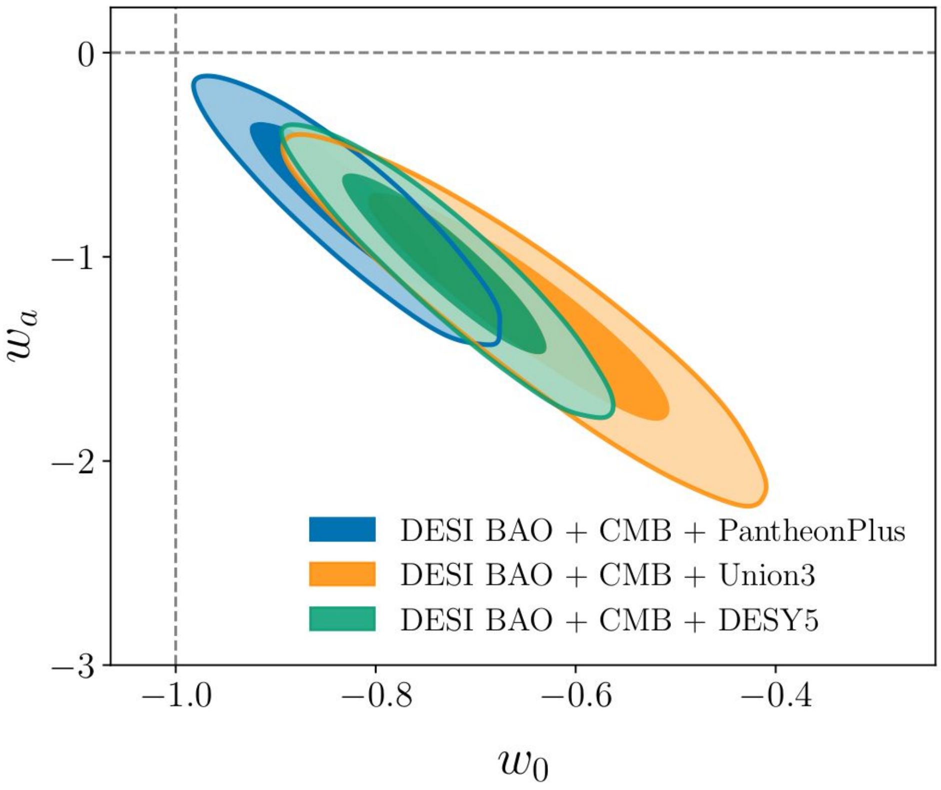
Probe combinations



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

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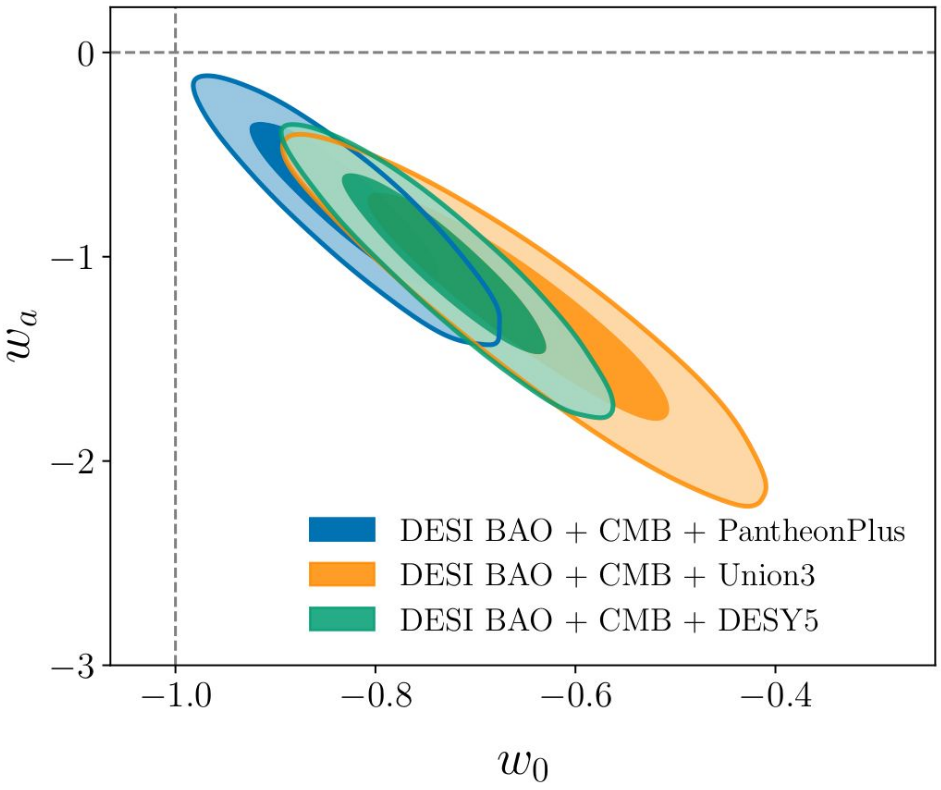
(w_0=-1, w_a=0)



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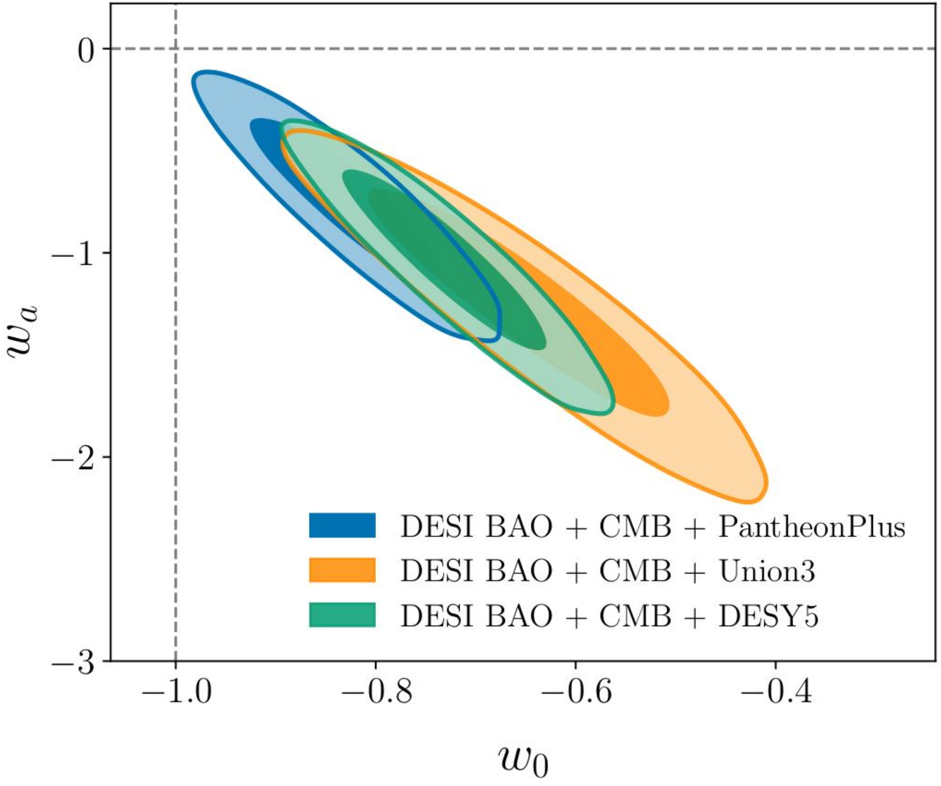
⇒ Accurate measurements, or is there any source of bias, notably for SNe Ia ?

Probe combinations



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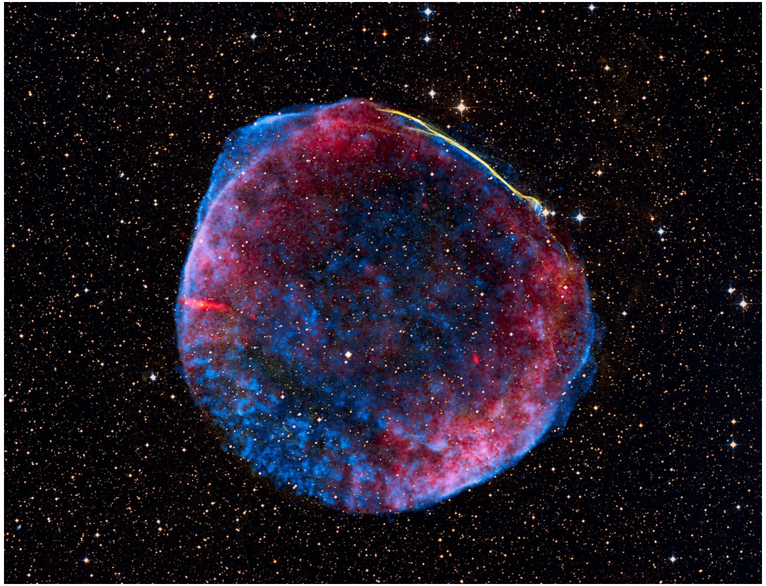
2. Type Ia supernovae

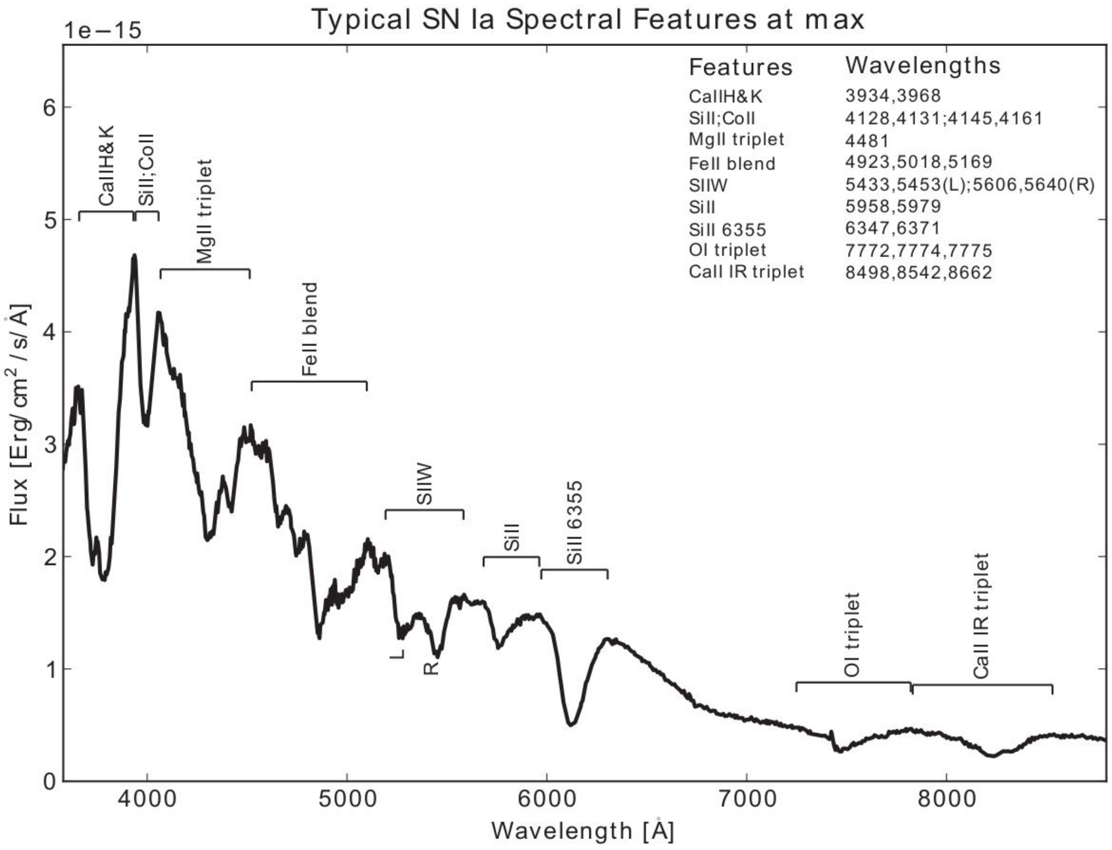
Explosion mechanism

- Explosion of a carbon-oxygen white dwarf (WD) with a mass > 1.4 $M_\odot$



Remnant of SN 1006
observed with the Chandra X-ray Observatory

Type Ia supernovae spectrum



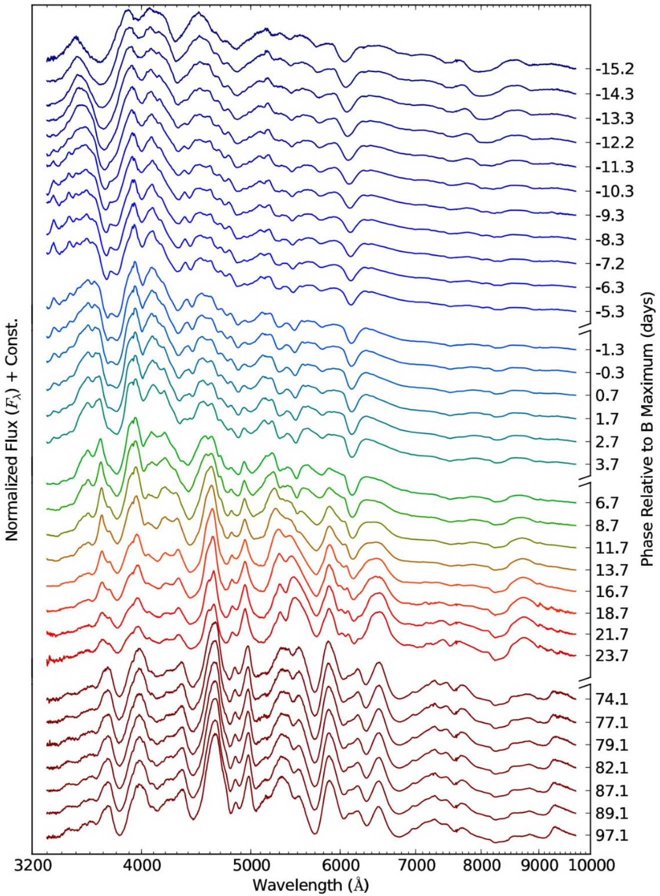
SN Ia spectrum (Chotard, 2011)

<u>Characteristics:</u>

- Absence of hydrogen line
- Strong Si line (6355 Å)
- Intermediate-mass elements from oxygen to calcium

SNe Ia light curve

Spectrum temporal evolution of SN2011fe
(Pereira et al., 2013)



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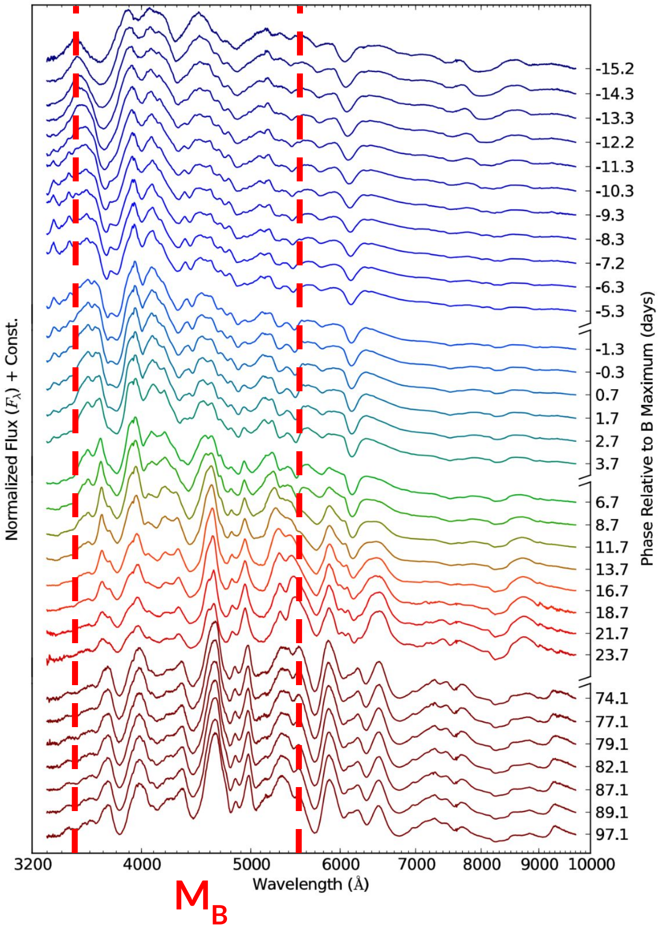
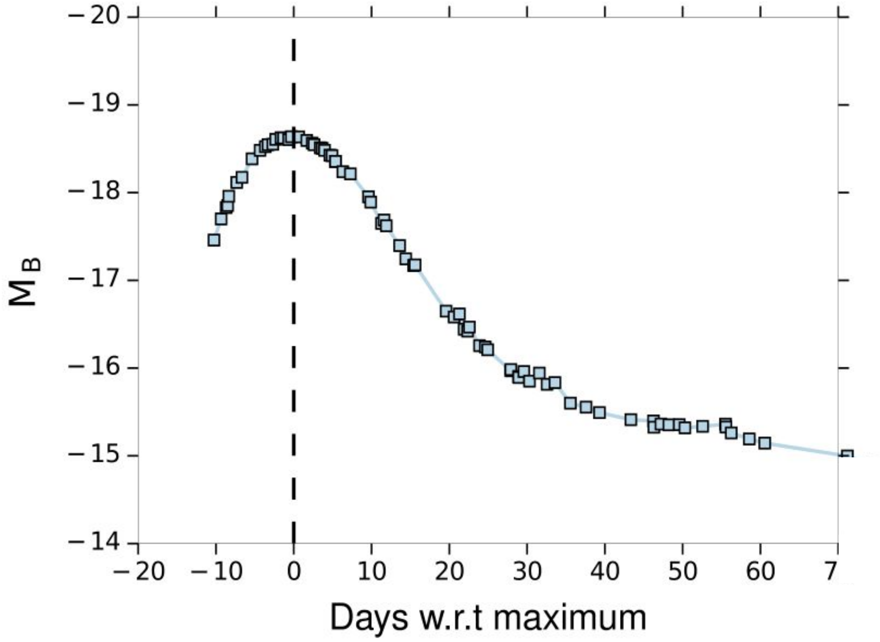


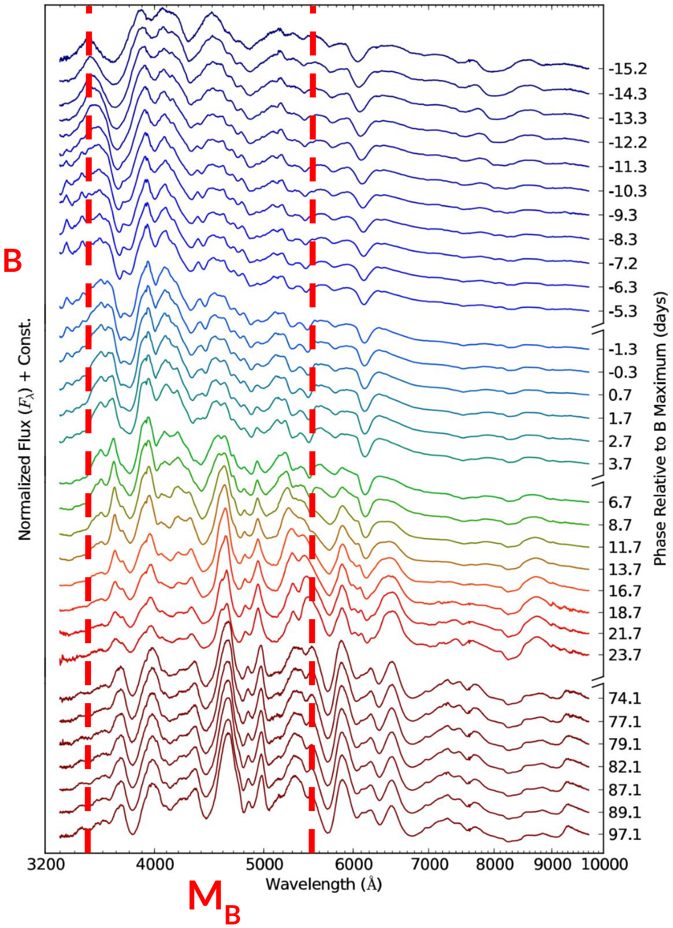
SNe Ia light curve

SN Ia light curves in B band (Hazenberg, 2019)



Restframe B band

Spectrum temporal evolution of SN2011fe (Pereira et al., 2013)



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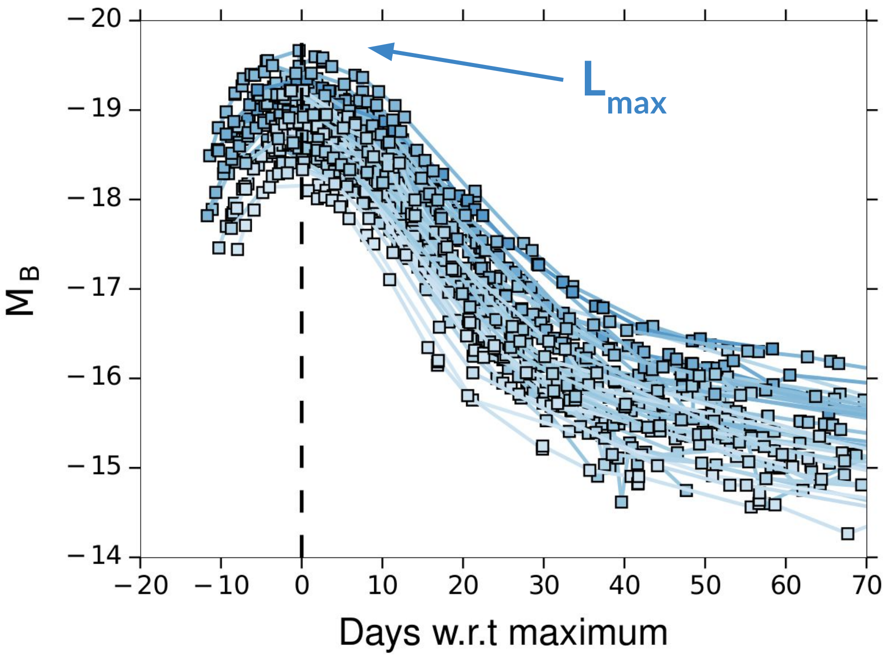

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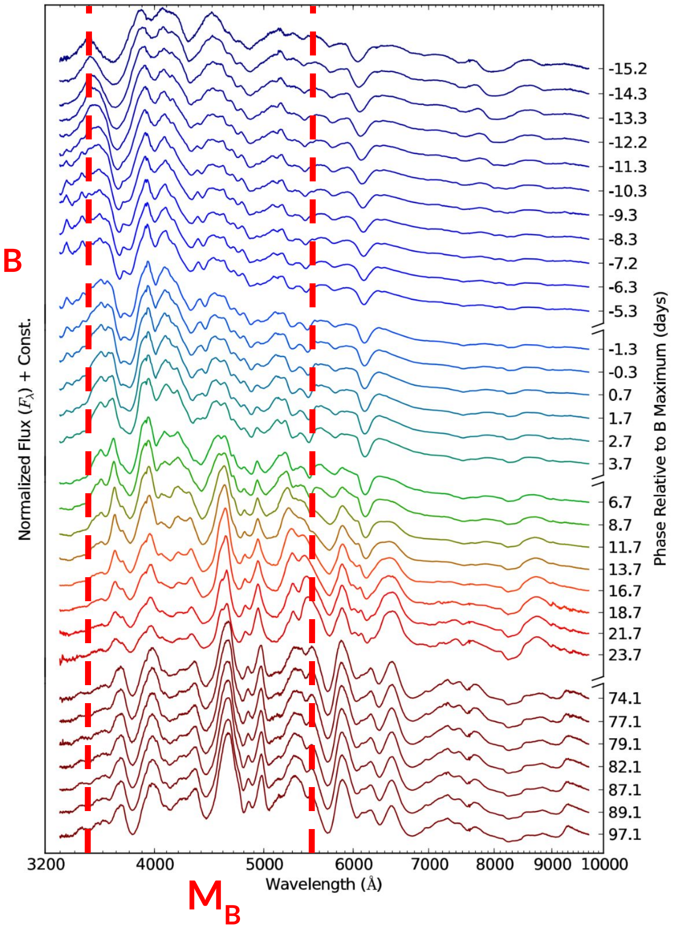

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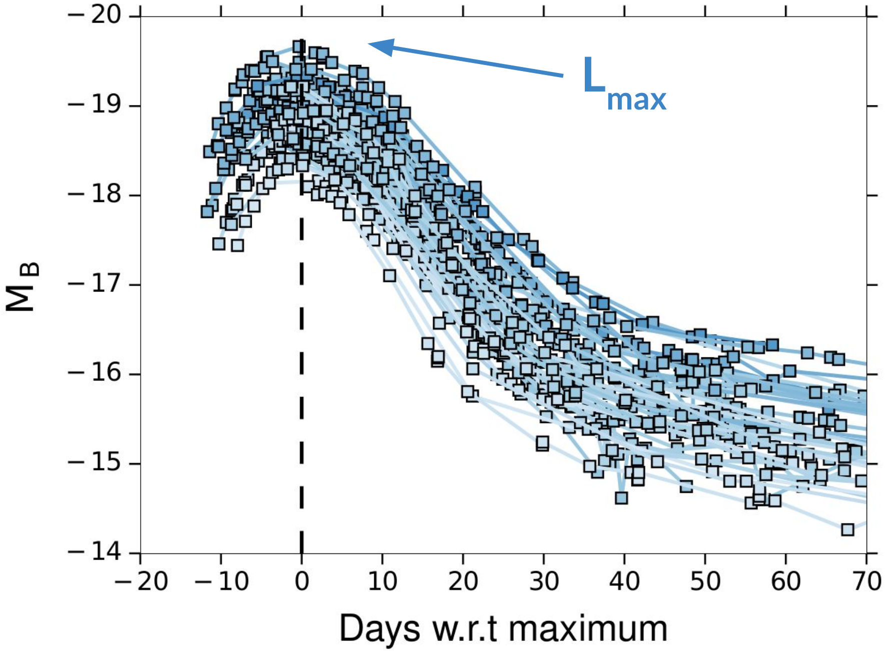

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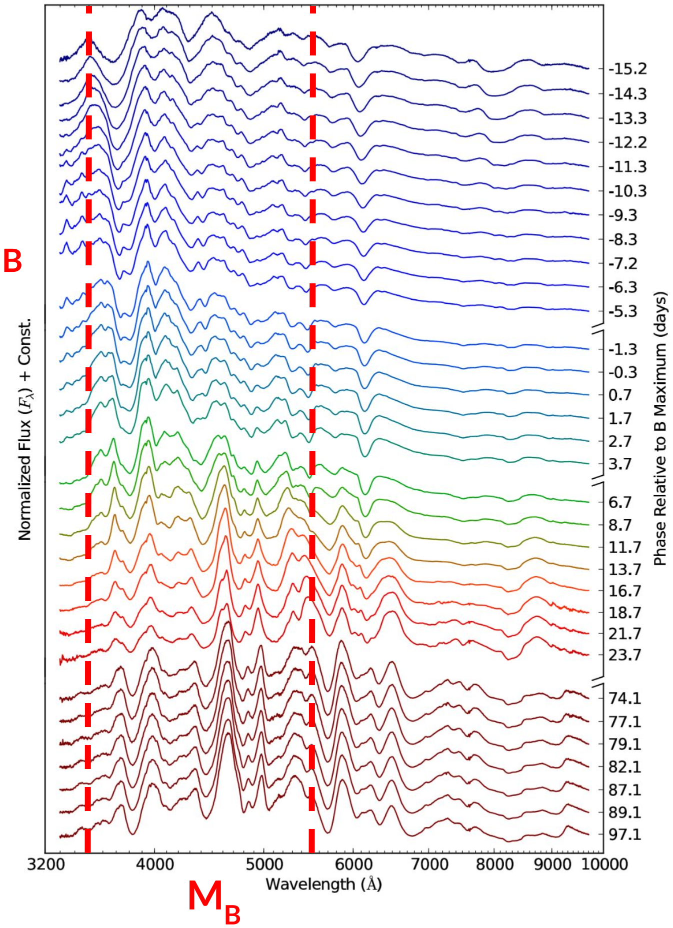


Luminosity distance:

$$F_{\max} = \frac{L_{\max}}{4\pi D_L^2} \quad ; \quad M_B = m_B^\star - 5\log_{10}\frac{D_L}{10\mathrm{pc}}$$

Hubble diagram

Plot μ against z → Hubble Diagram

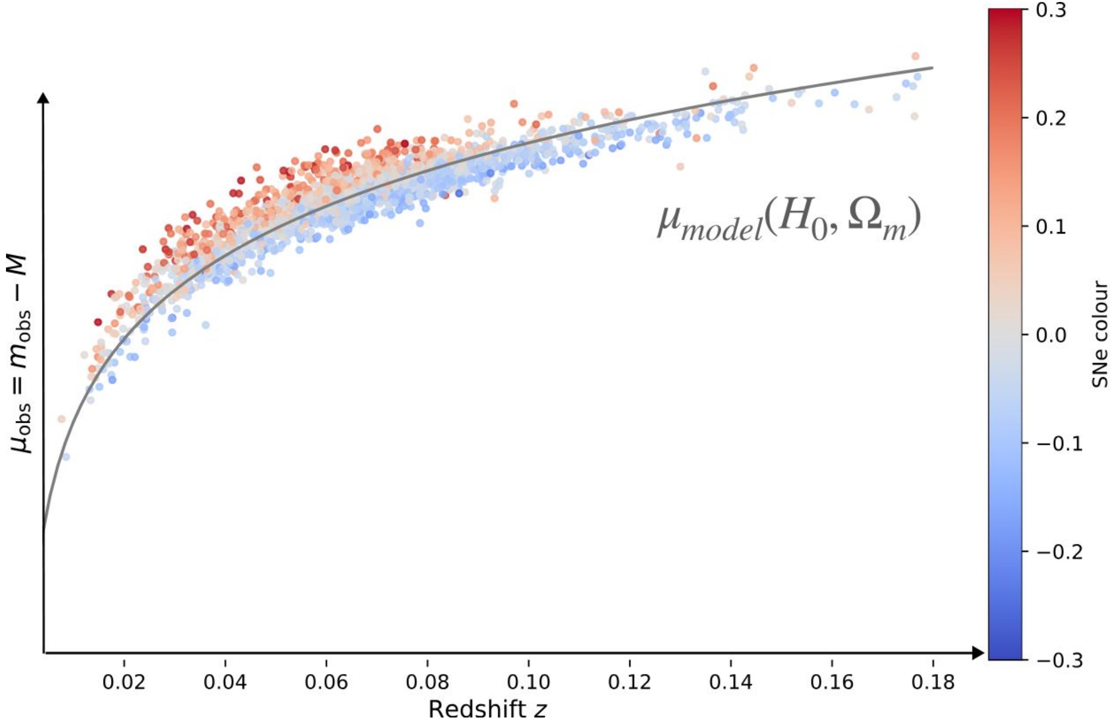
Distance modulus:

$$\mu = m_B^\star - M_B$$

Restframe magnitude

Absolute magnitude

⇒ dispersion in μ of **~40%**



Hubble diagram
(https://moriond.in2p3.fr/2024/Cosmology/transparencies/2_tuesday/1_morning/05_Ginolin.pdf)

Standardization parameters

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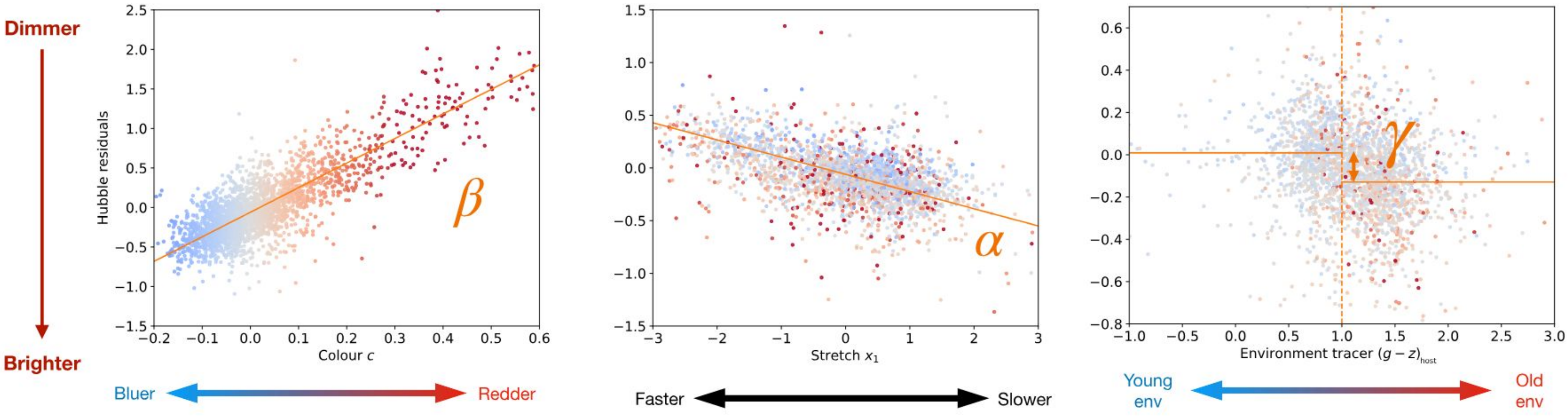

$$\mu = m_B^\star - M_B - \beta c + \alpha x_1 - \gamma p$$

Standardized Hubble diagram

Distance modulus:

$$\mu = m_B^{\star} - M_B - \beta c + \alpha x_1 - \gamma p$$

⇒ μ dispersion reduced to ~14%

Hubble diagram

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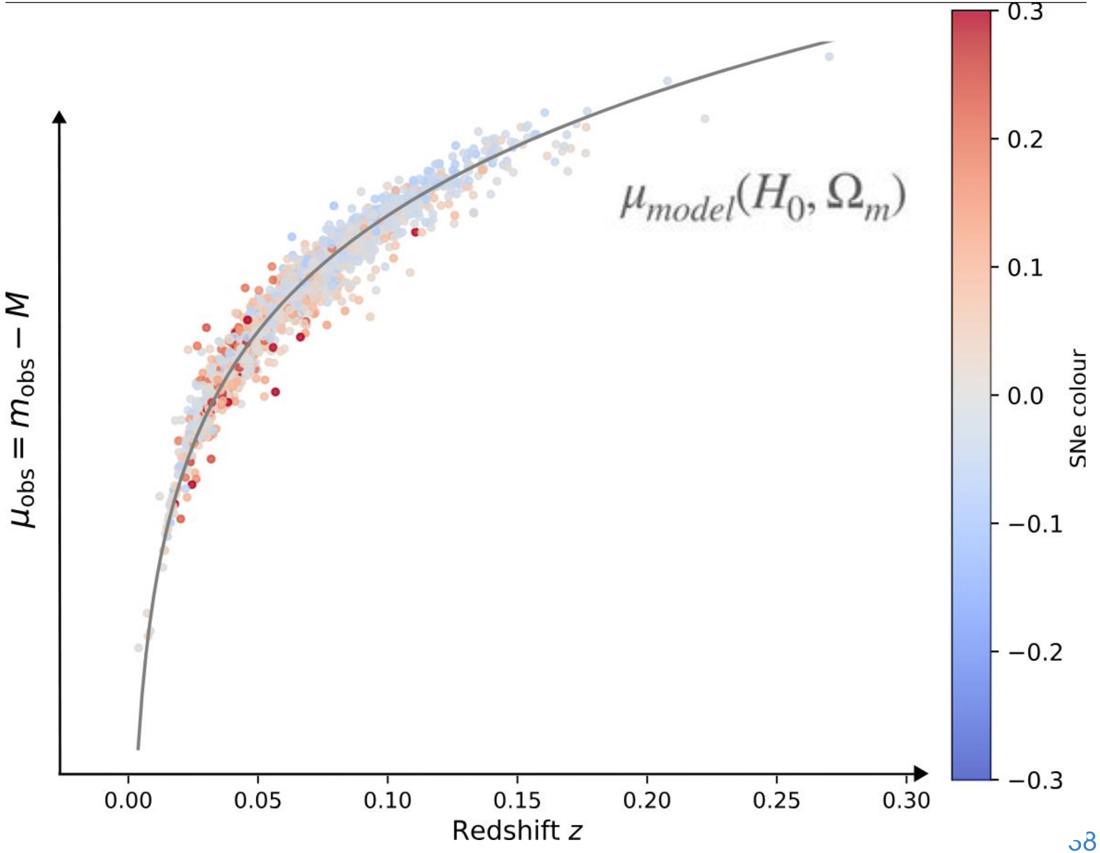

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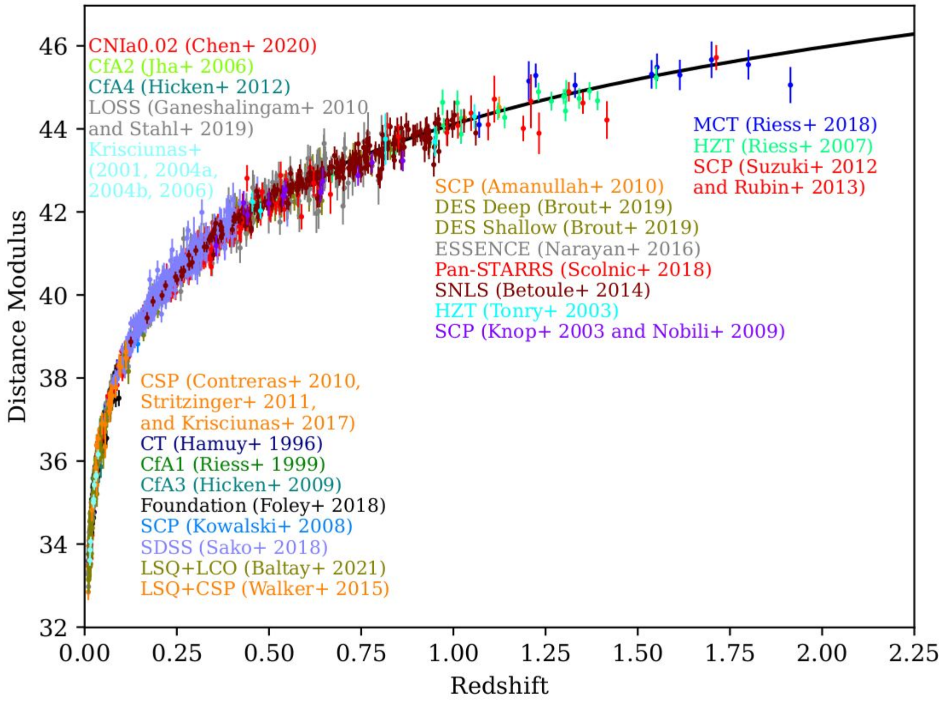
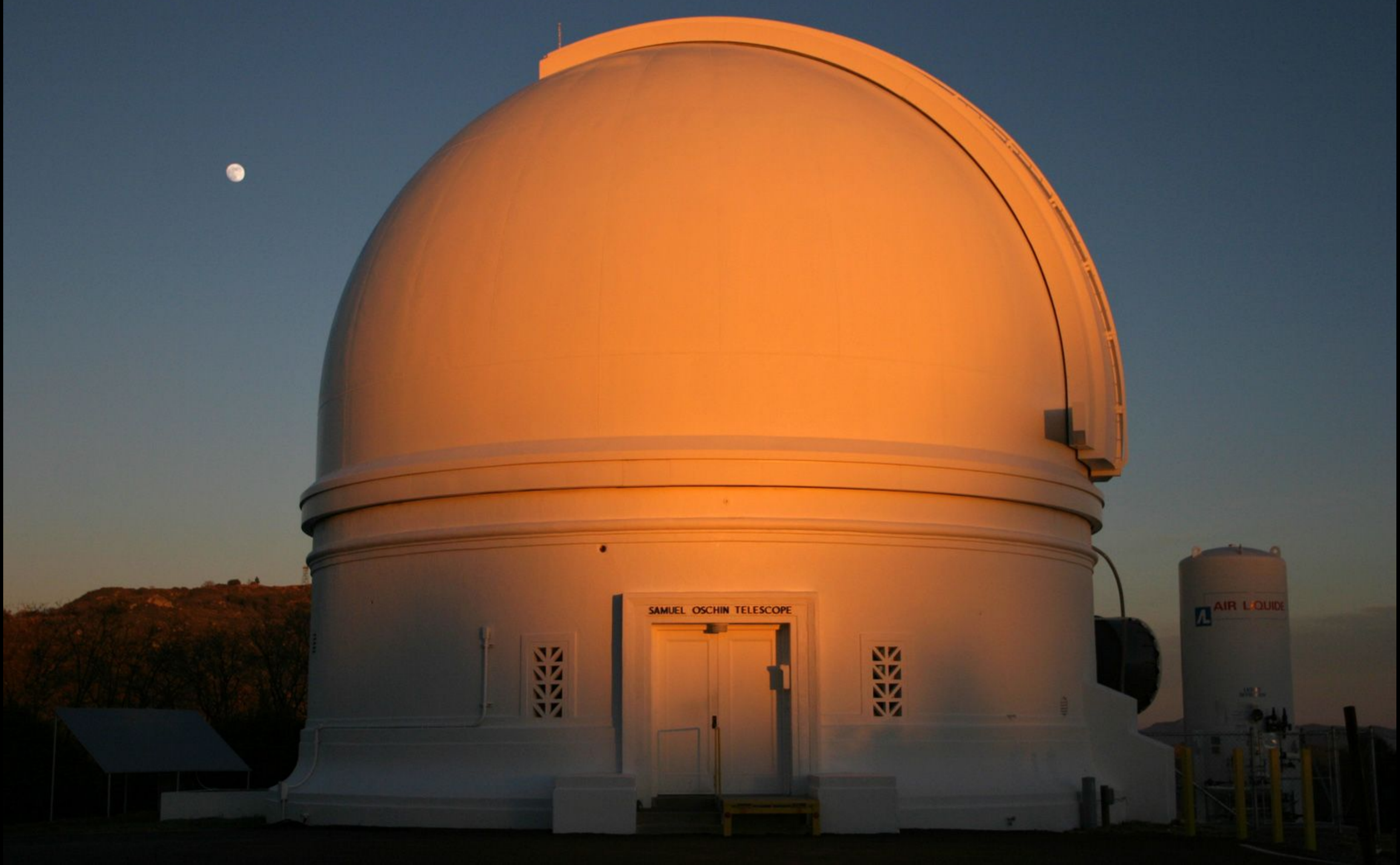
⇒ Infer constraints on cosmological parameters such as w

Hubble diagram (Rubin et al., 2023)

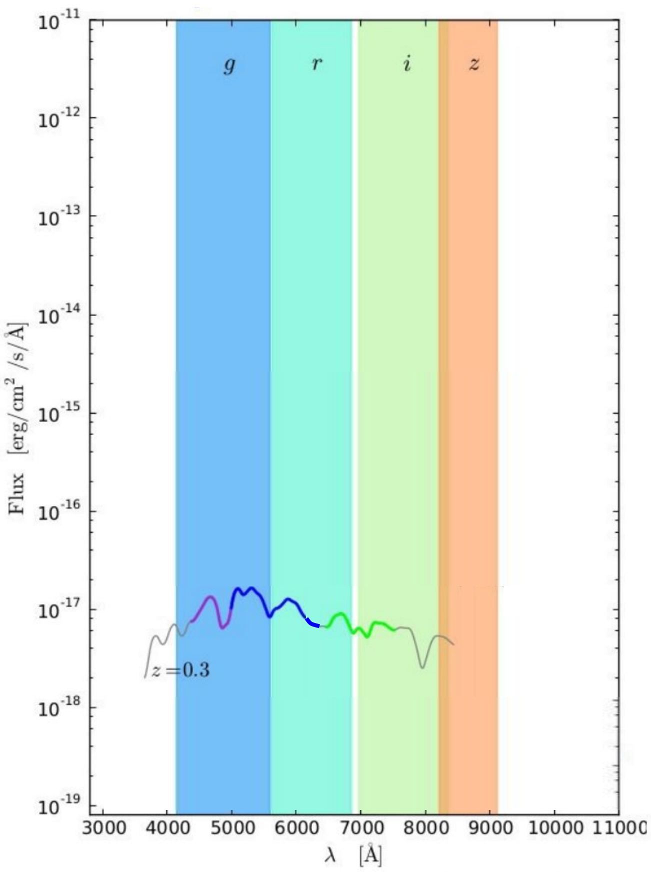


3. Photometric calibration


SAMUEL OSCHIN TELESCOPE
AIR LIQUIDE

SNe Ia flux measurement

SN Ia spectrum observed through telescope filter



SN spectrum

X filter transmission

Atmosphere transmission

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

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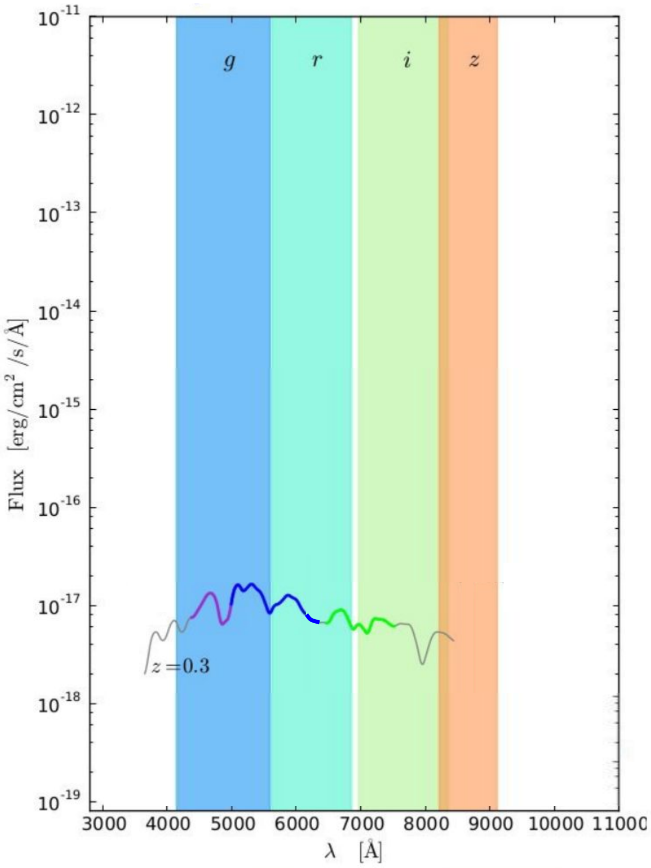

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Section 5

Section 6

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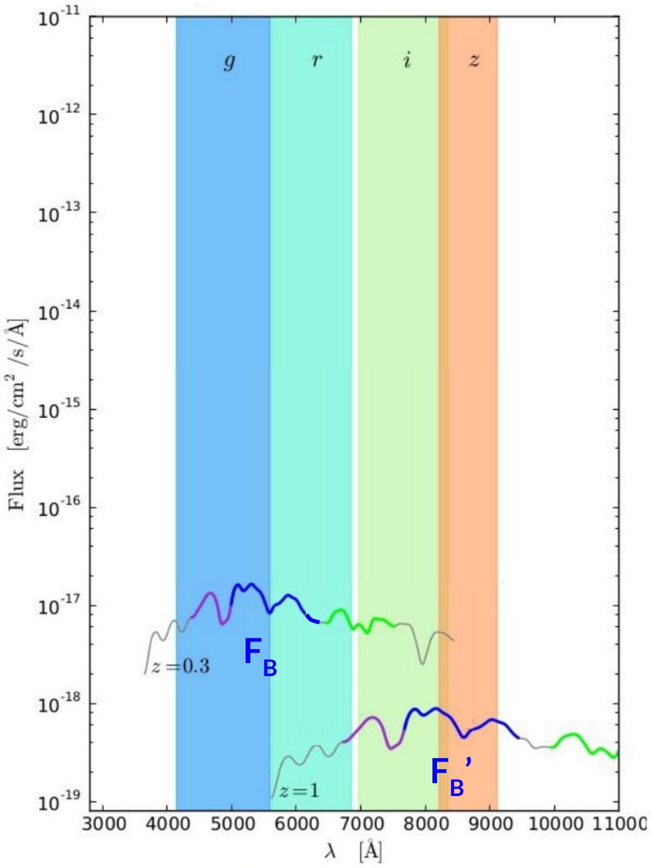

$$F_X = \int \lambda d\lambda \times S_\star(\lambda) T_X(\lambda) T_{\mathrm{atm}}(\lambda)$$

Goal : Measure relatively $\mathbf{F_B}$ of SNe spectra at different redshift **z**

But :

- spectra extend on several filters
- $\mathbf{F_B}$ for different redshift **z** is measured in different bands

SNe Ia flux measurement

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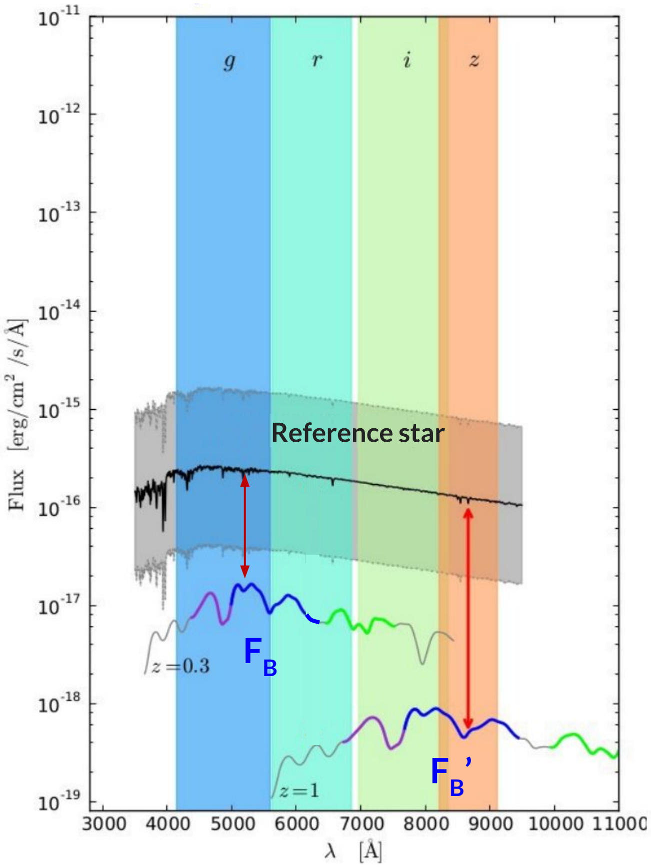

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Reference star ⇒ calibrate the flux transmission for each filter

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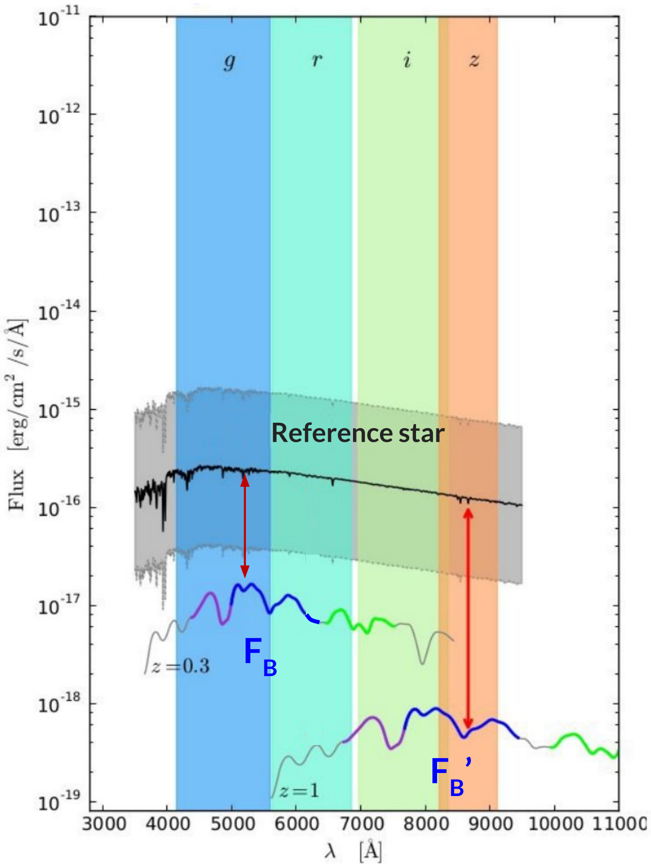

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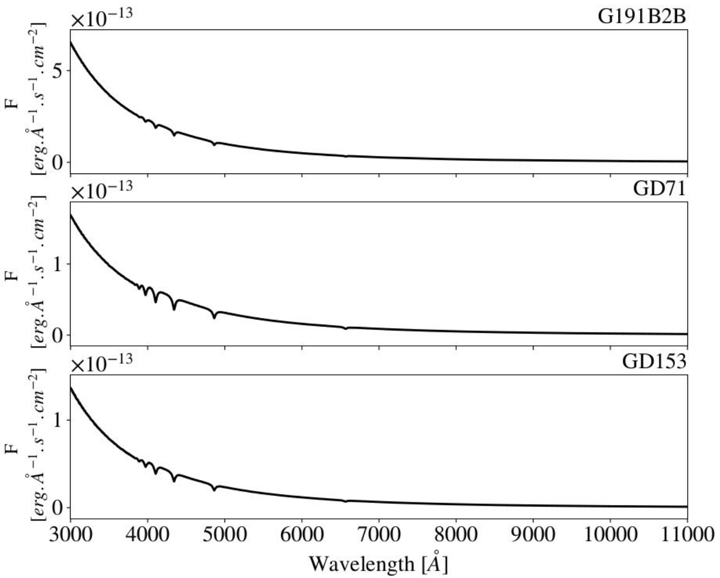
⇒ CALSPEC calibration

CALSPEC calibration

WD atmosphere model coupled with **observations** with the **Hubble Space Telescope**

CALSPEC primary standard stars
(https://archive.stsci.edu/hlsps/reference-atlases/cdbs/current_calspec/)



⇒ **~0.5%** uncertainties in the optical wavelengths

CALSPEC calibration

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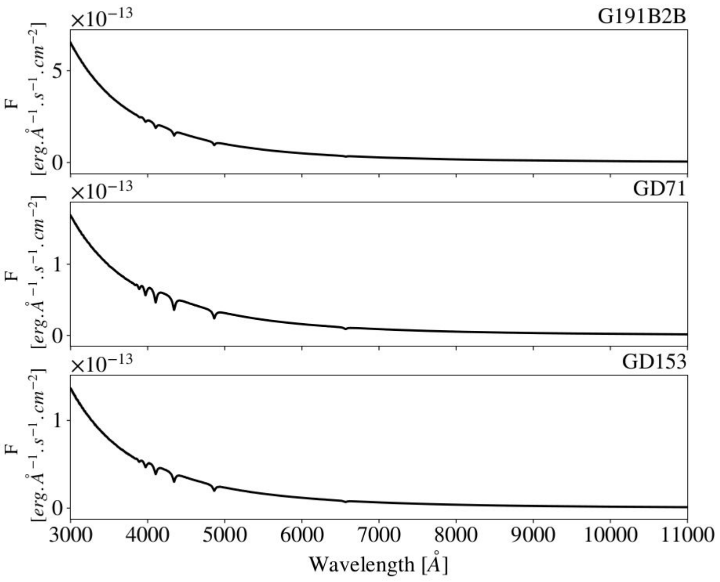
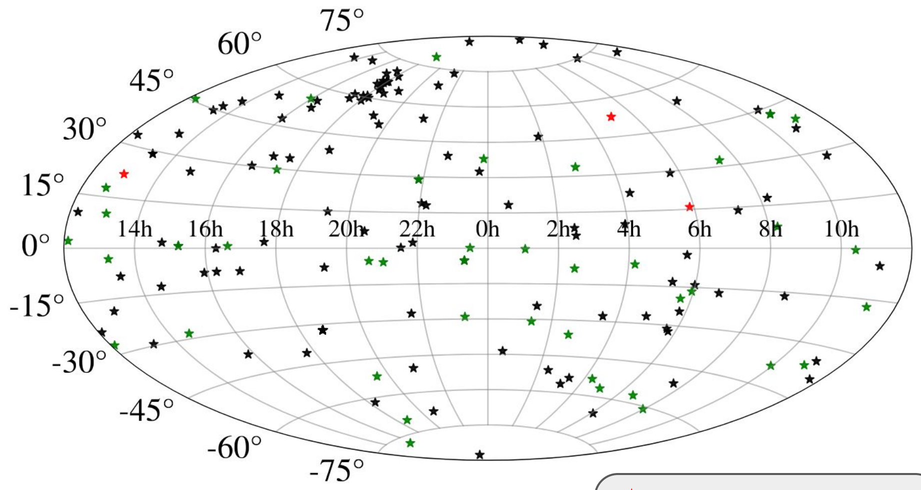


Sky map of the CALSPEC network



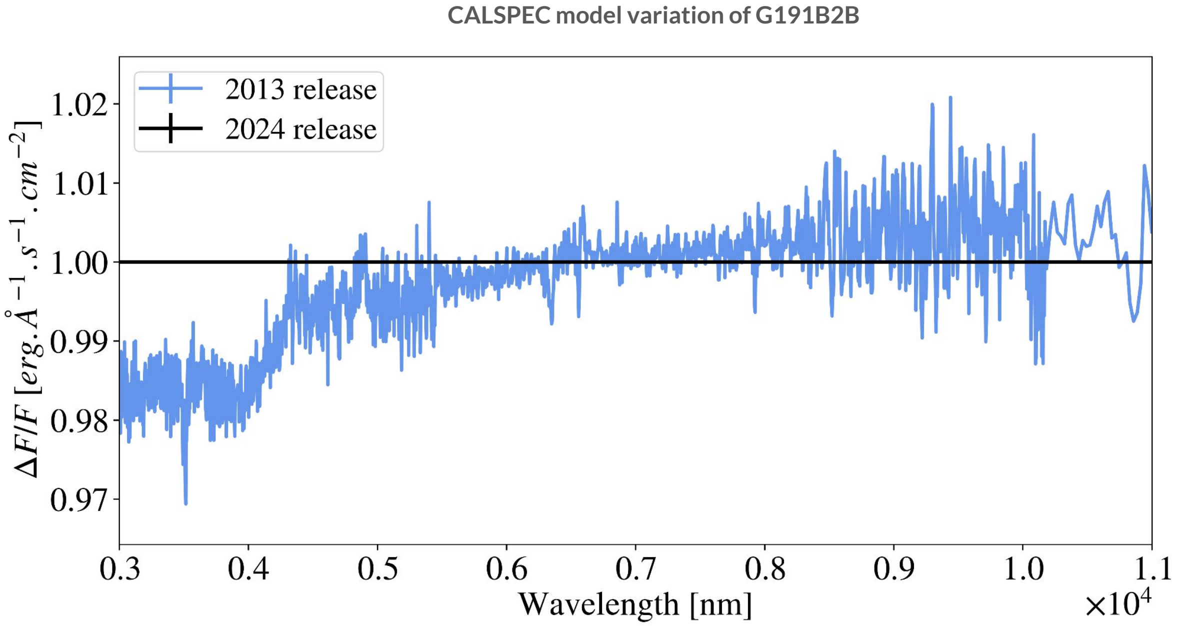
★ Primary standards
★ Secondary standards
★ Faint star extension (Narayan et al. 2019)

⇒ Network of calibrated sources covering the full sky

⇒ **~0.5%** uncertainties in the optical wavelengths

Variations of CALSPEC model

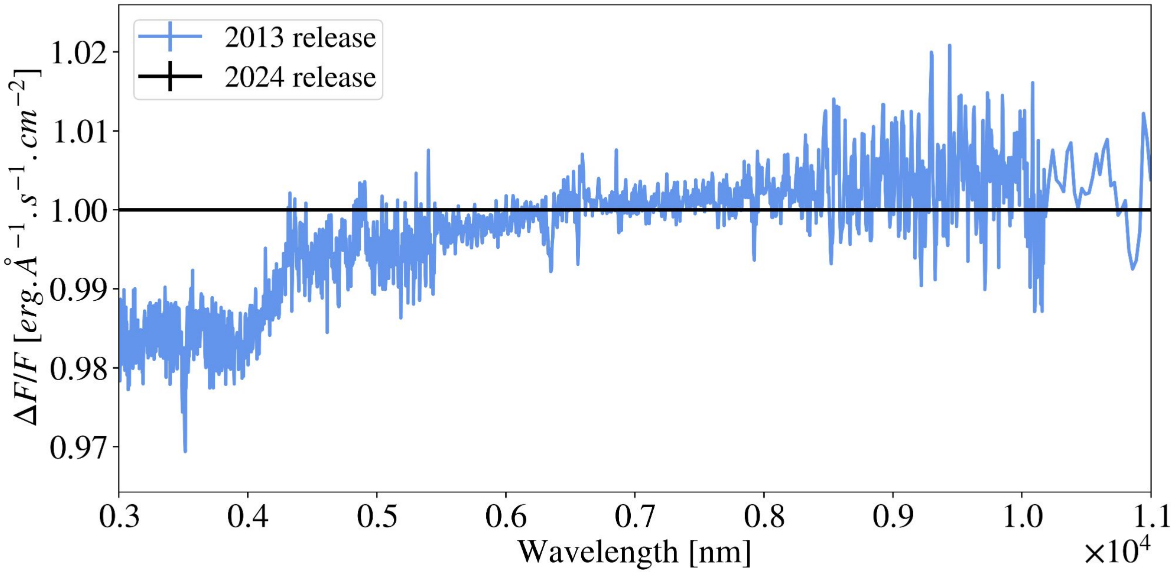
- The white dwarf atmosphere model has evolved in the past 10 years
- **Chromatic variations of ~2%** between the first and last model



Variations of CALSPEC model

- The white dwarf atmosphere model has evolved in the past 10 years
- **Chromatic variations of ~2%** between the first and last model

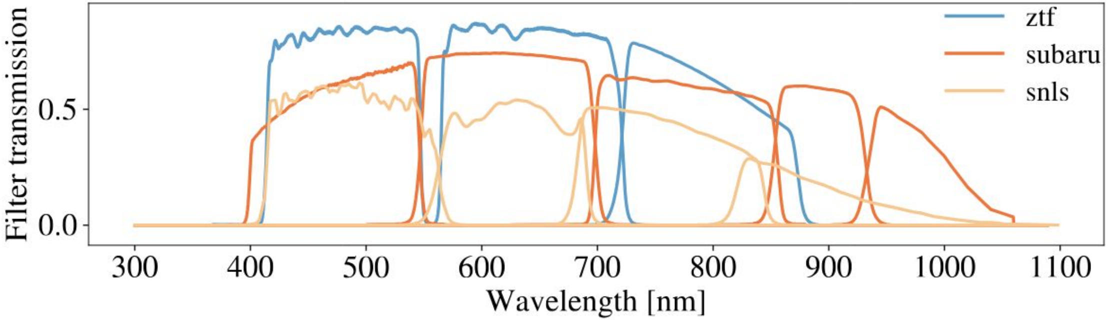
CALSPEC model variation of G191B2B



Impact cosmological parameters inference? ⇒ Hubble diagram with simulated SNe Ia

Variations of CALSPEC model

CALSPEC calibration differences simulated
(LEMAÎTRE joint analysis)



<u>Simulation of 3 SNe Ia surveys:</u>

- Low-z: **ZTF DR2**
- Intermediate-z: **SNLS yr5**
- High-z: **Subaru**

- Calibration of the bandpass with each CALSPEC release

Variations of CALSPEC model

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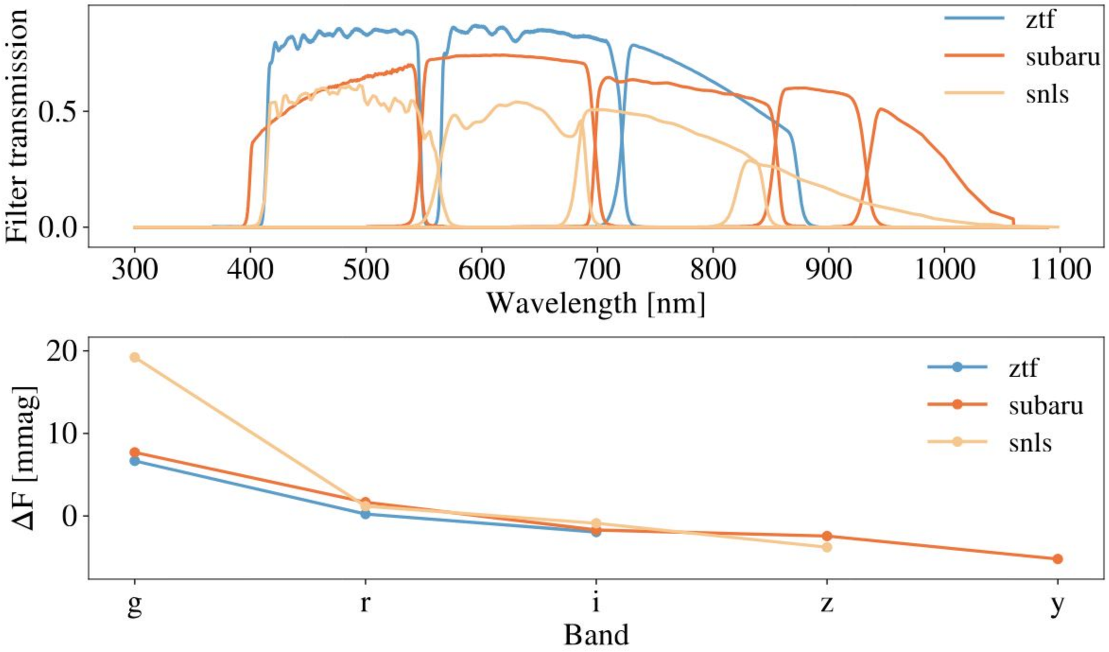

Simulation of 3 SNe Ia surveys:

- Low-z: **ZTF DR2**
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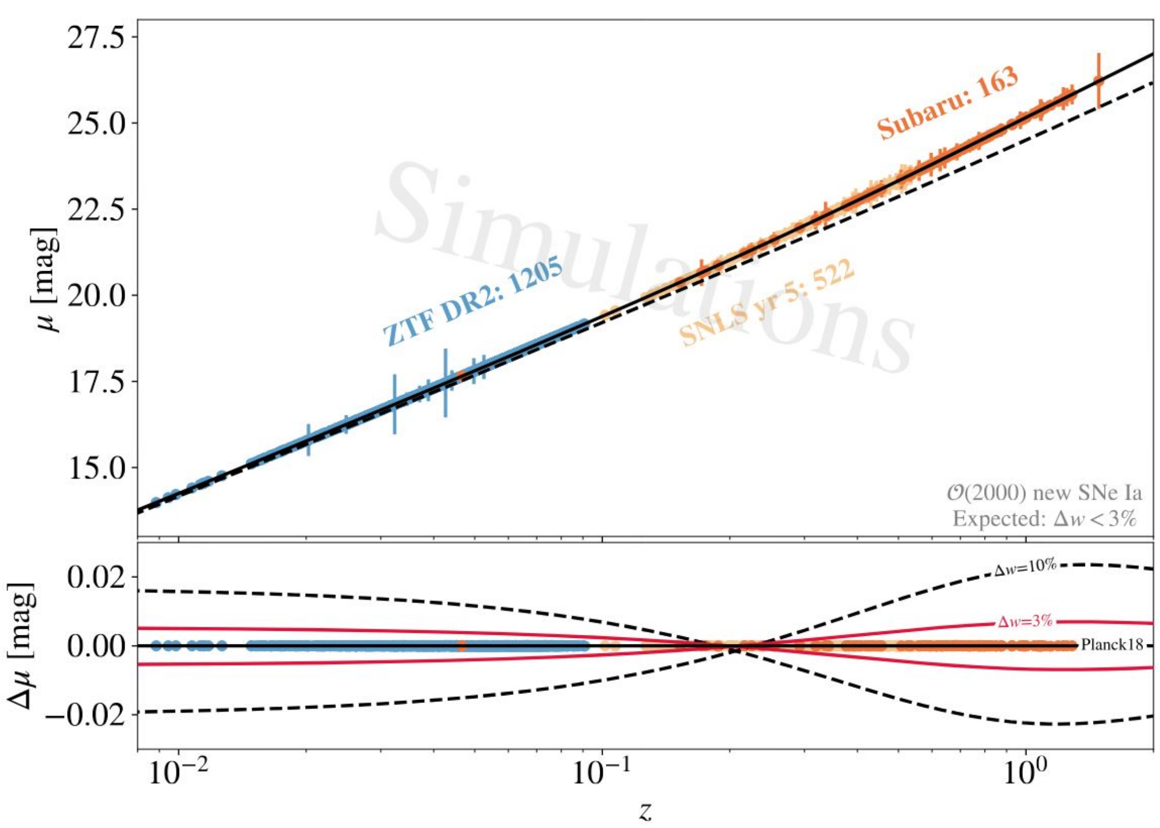
⇒ up to **20 milli-mag** difference

Variations of CALSPEC model

Hubble diagram obtained with LEMAÎTRE simulations

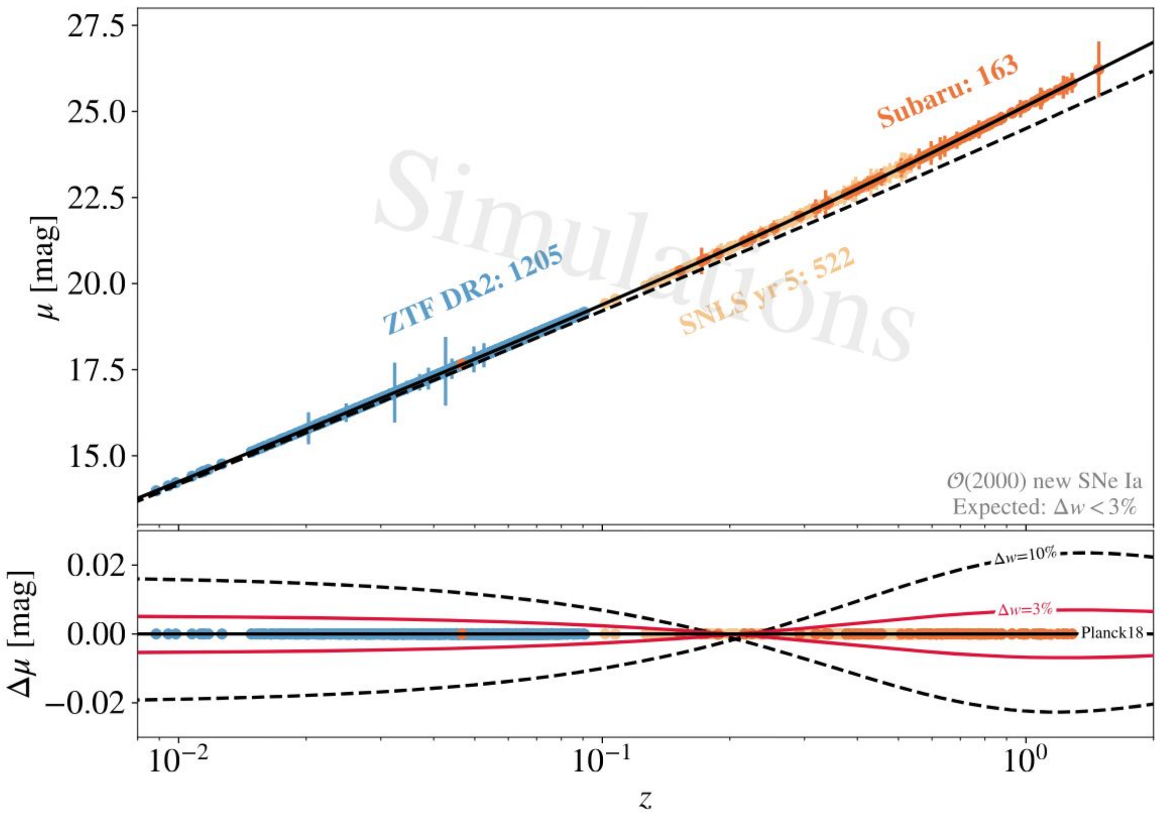


- Fitting distance moduli μ of simulated SNe Ia

⇒ Hubble diagram

Variations of CALSPEC model

Hubble diagram obtained with LEMAÎTRE simulations



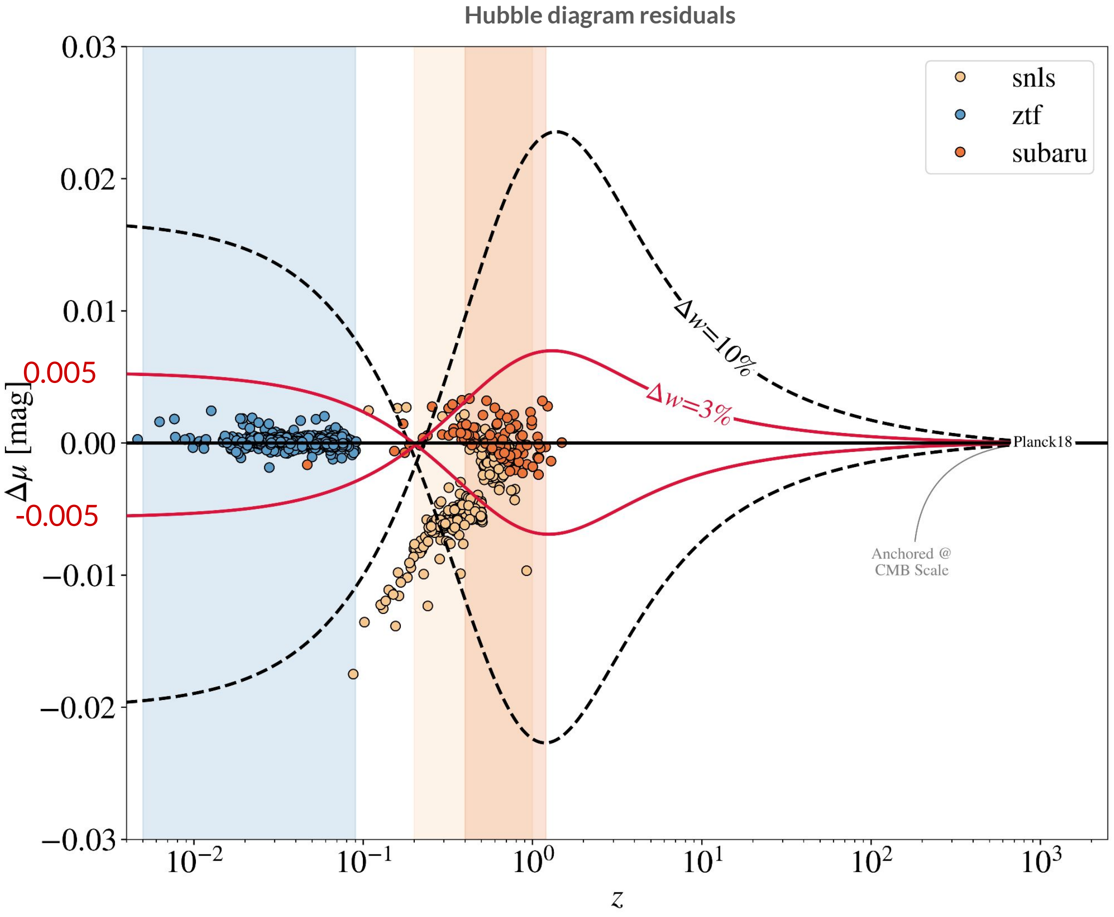
- Fitting distance moduli μ of simulated SNe Ia

⇒ Hubble diagram

- Adding flux calibration bias estimated with CALSPEC releases

⇒ focus on the residuals to the ΛCDM model

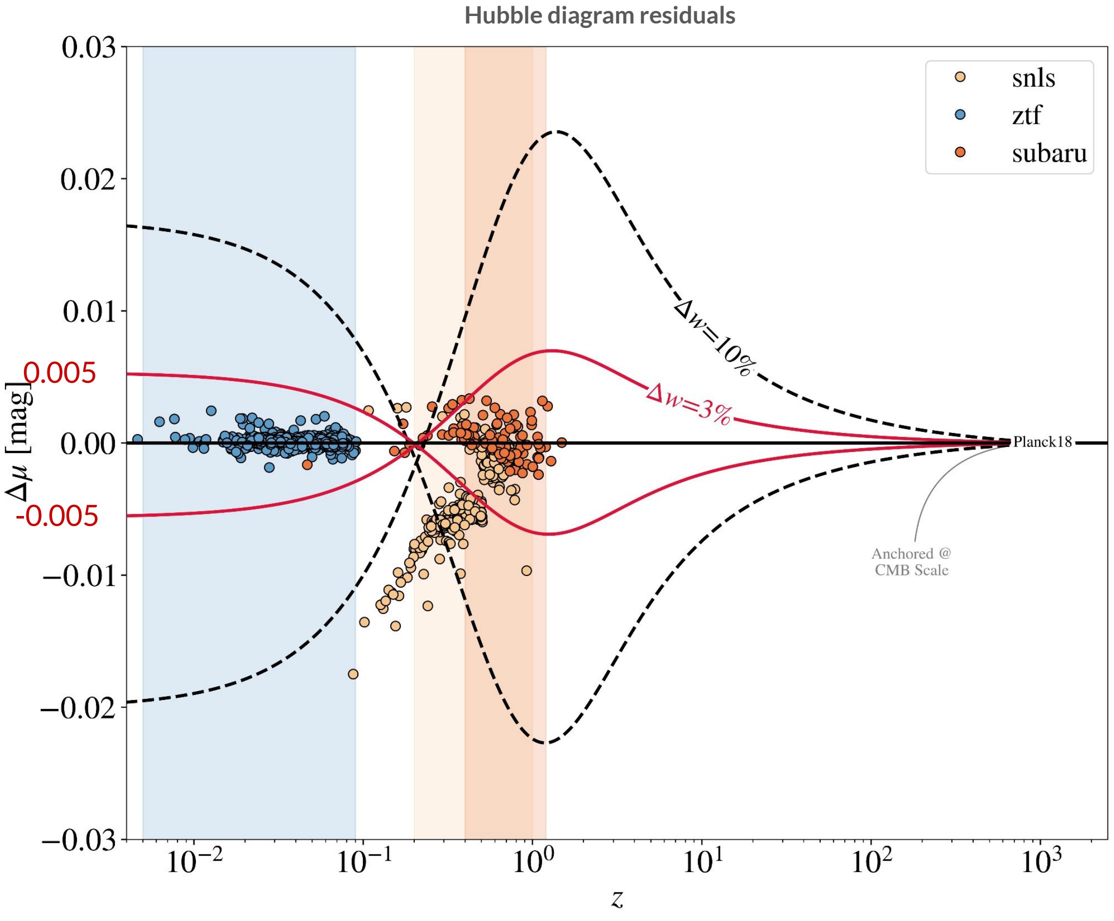
Variations of CALSPEC calibration



- 3% deviation of w from ΛCDM

⇔ ~ 0.005 mag deviation in μ (0.01<z<1)

Variations of CALSPEC calibration



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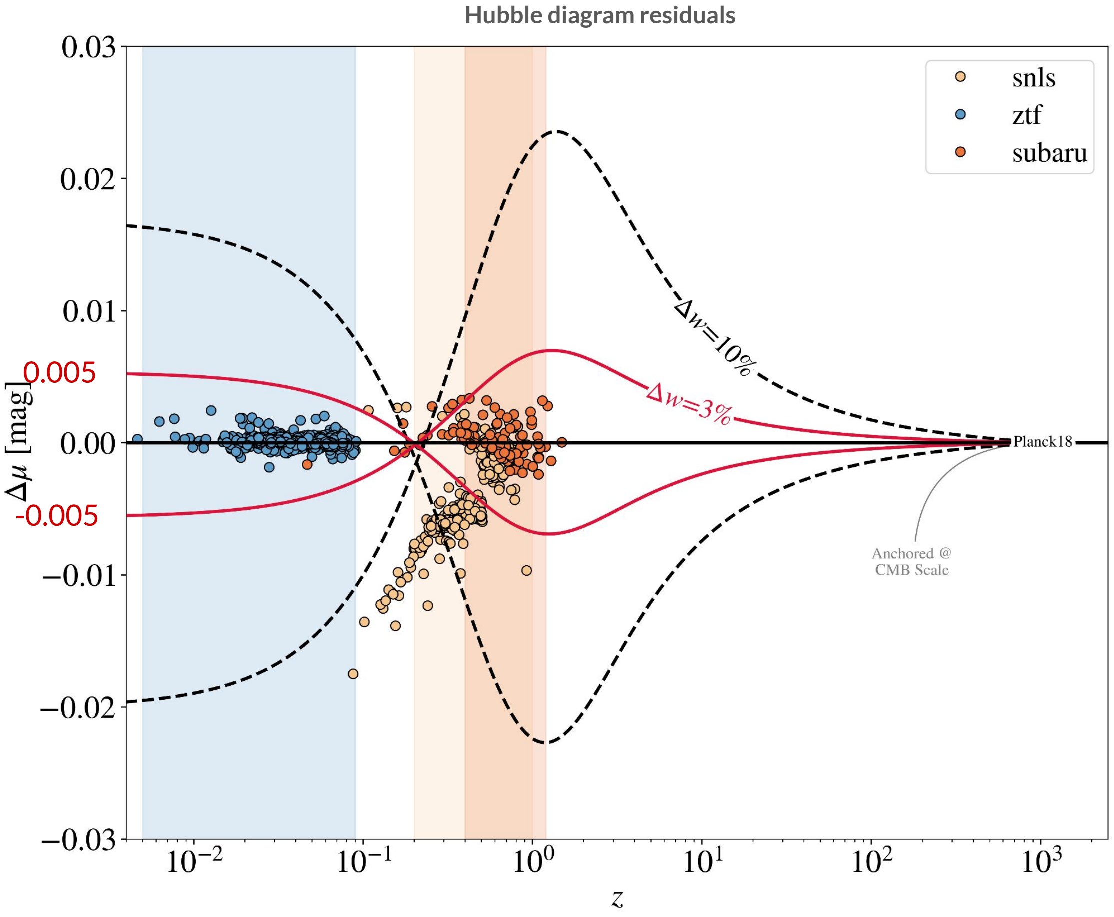
2% chromatic bias ⇒ Δμ > 0.005 mag

⇒ deviation similar than Δw > 3%

Variations of CALSPEC calibration



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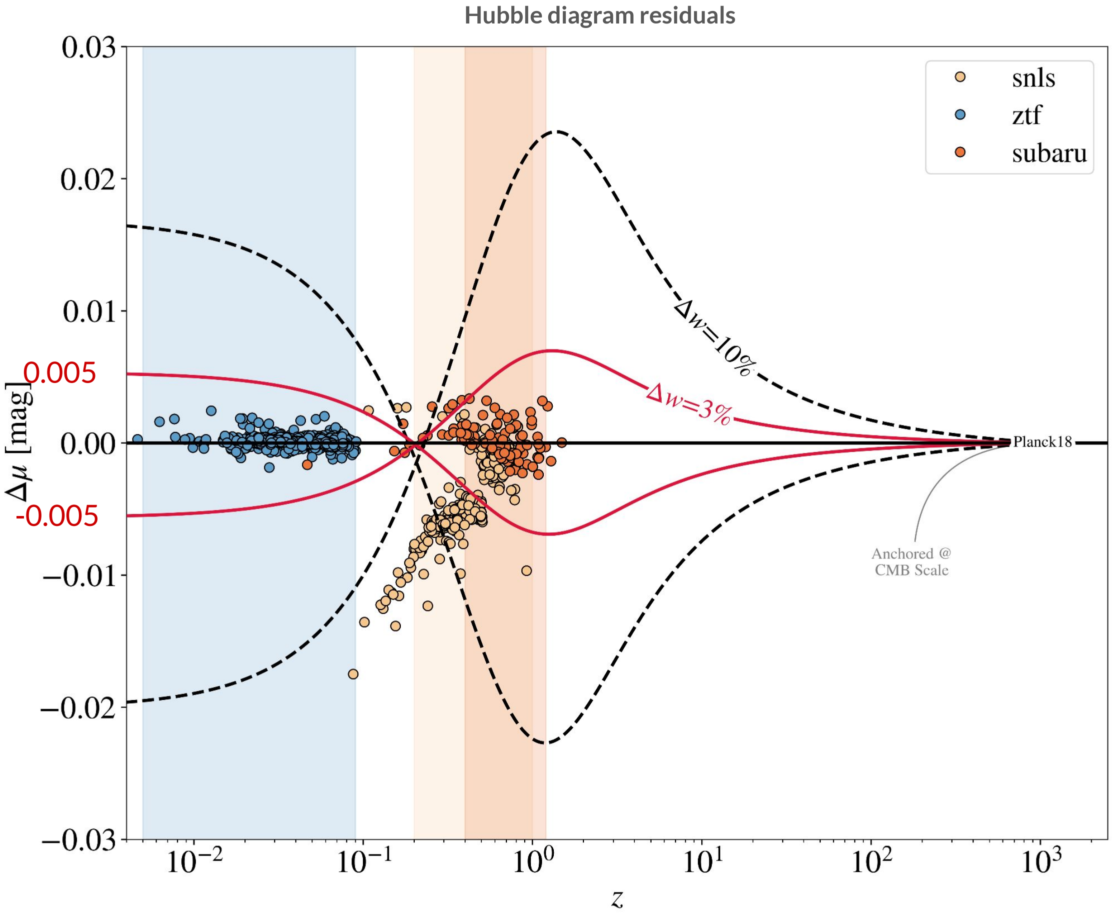
How much confident are we about WD atmosphere models ?

Variations of CALSPEC calibration



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2% chromatic bias ⇒ Δμ > 0.005 mag

⇒ **deviation similar than Δw > 3%**

How much confident are we about WD atmosphere models ?

⇒ Better not rely on model-dependant **reference stars**

II. The StarDICE experiment

4. Description of the experiment

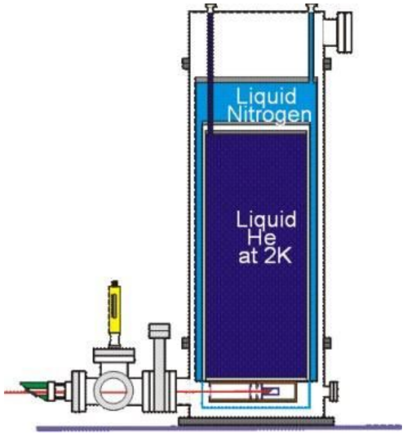
Photometric calibration transfer

Standard watt (NIST)

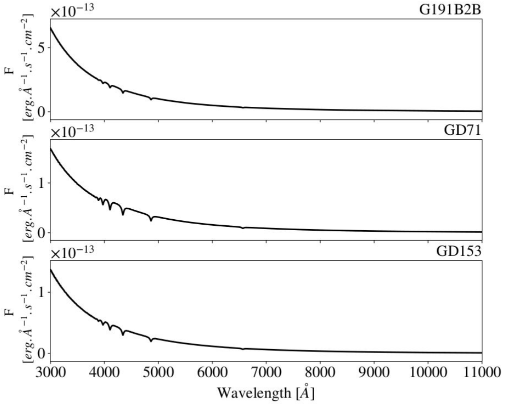
???

CALSPEC standard stars

1 W

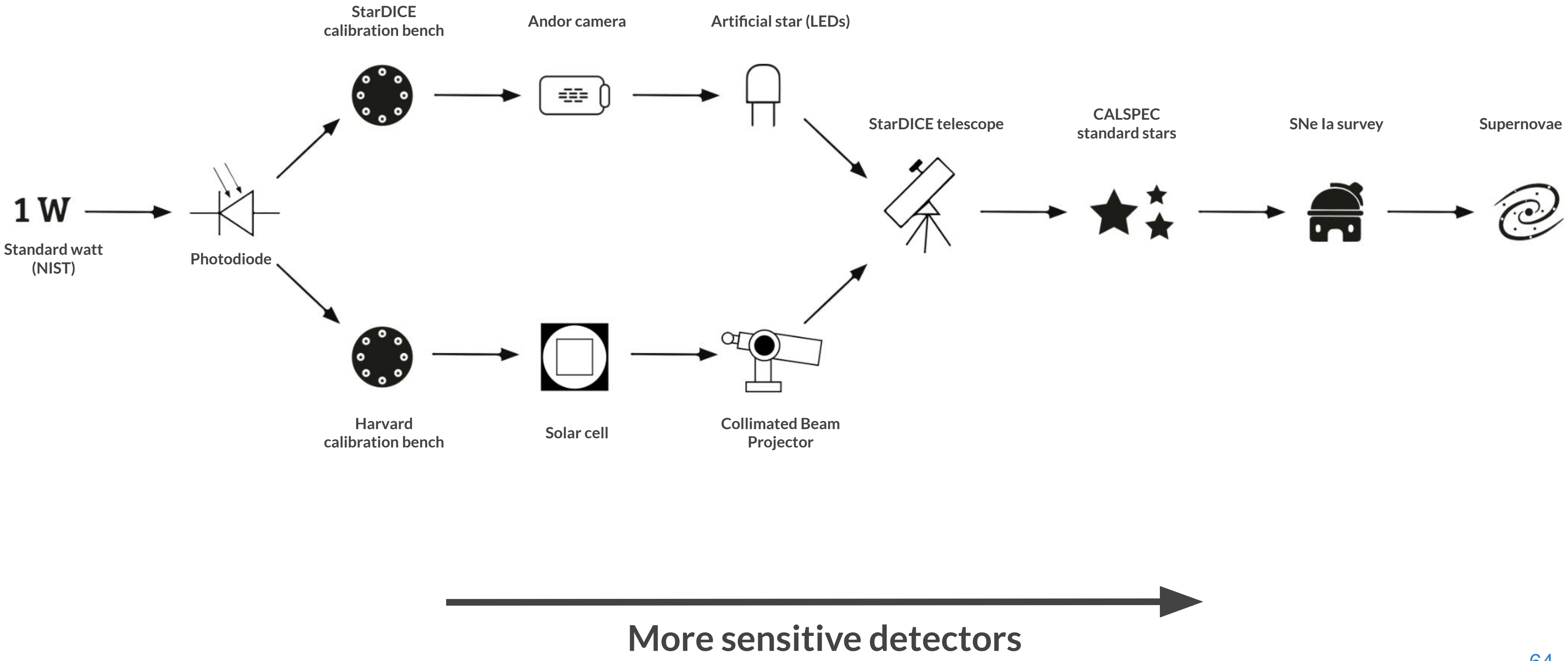


POWR facility
Houston et al. 2006



CALSPEC primary standard stars

Photometric calibration transfer



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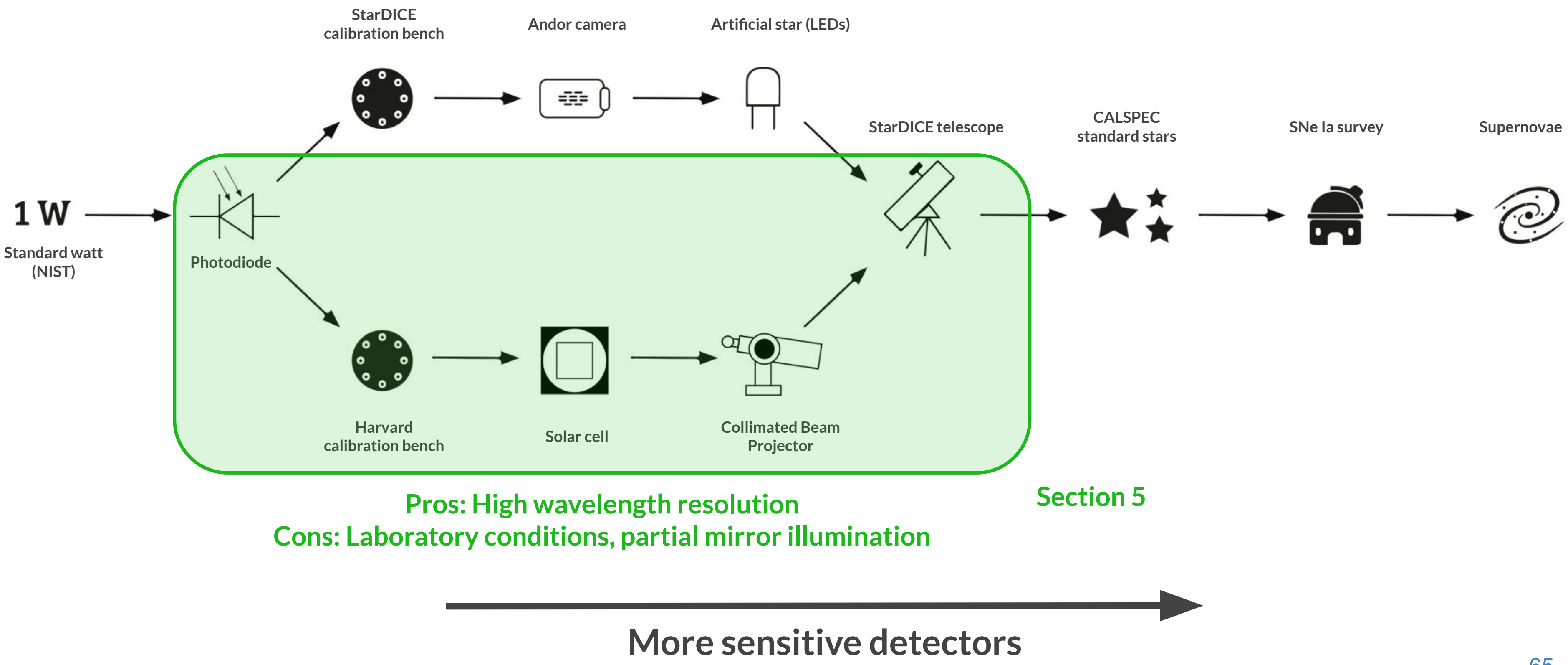

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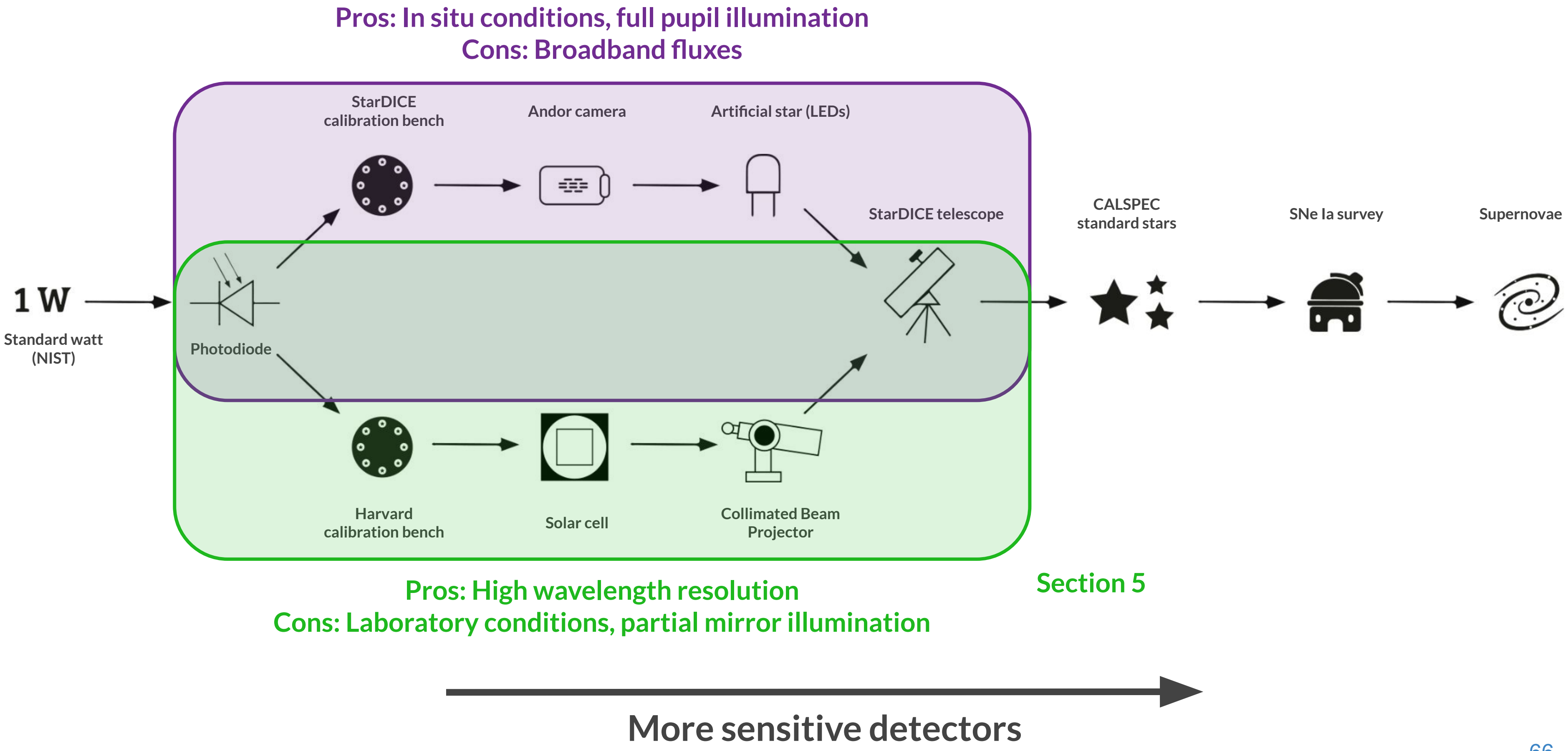

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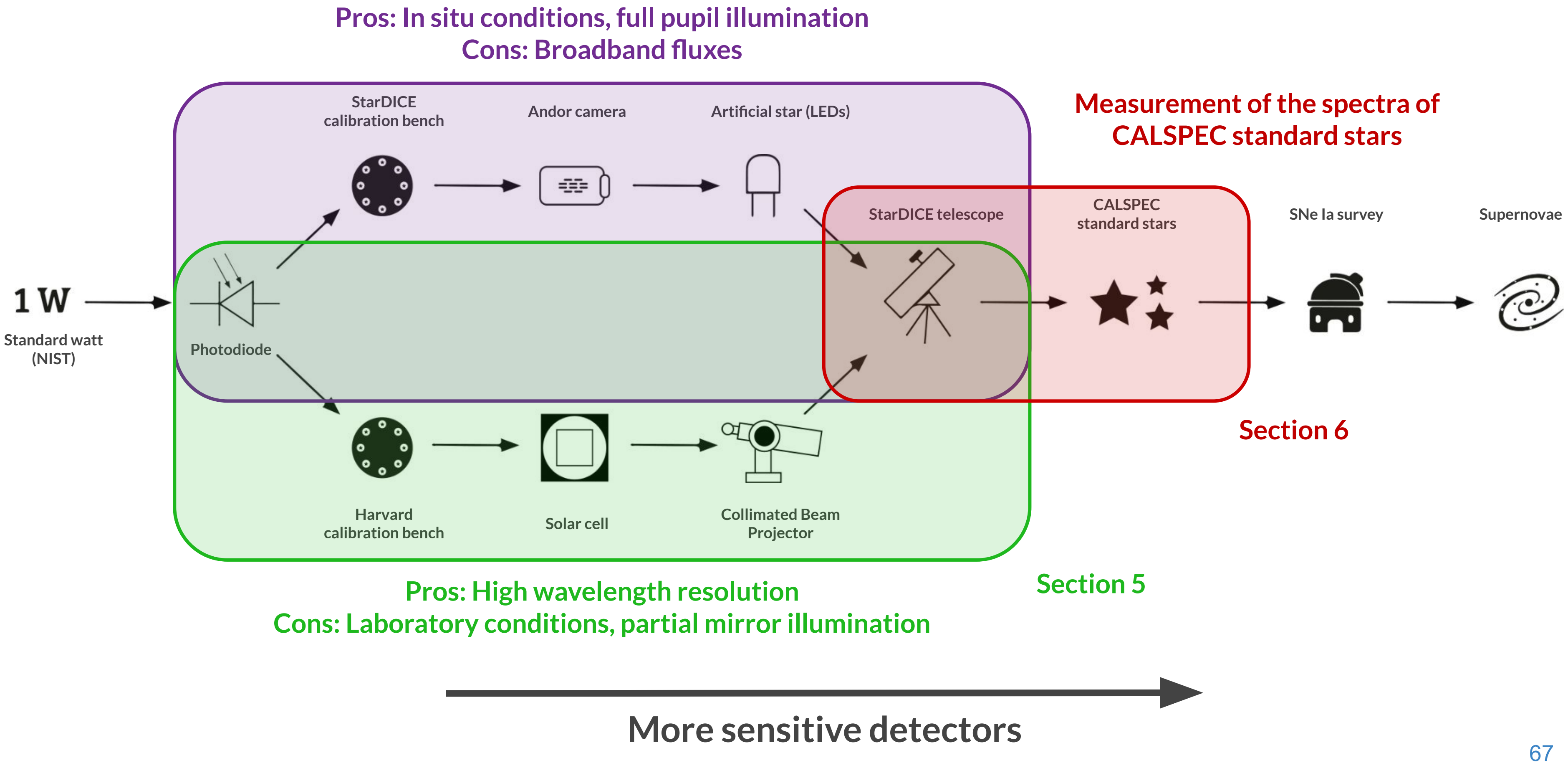
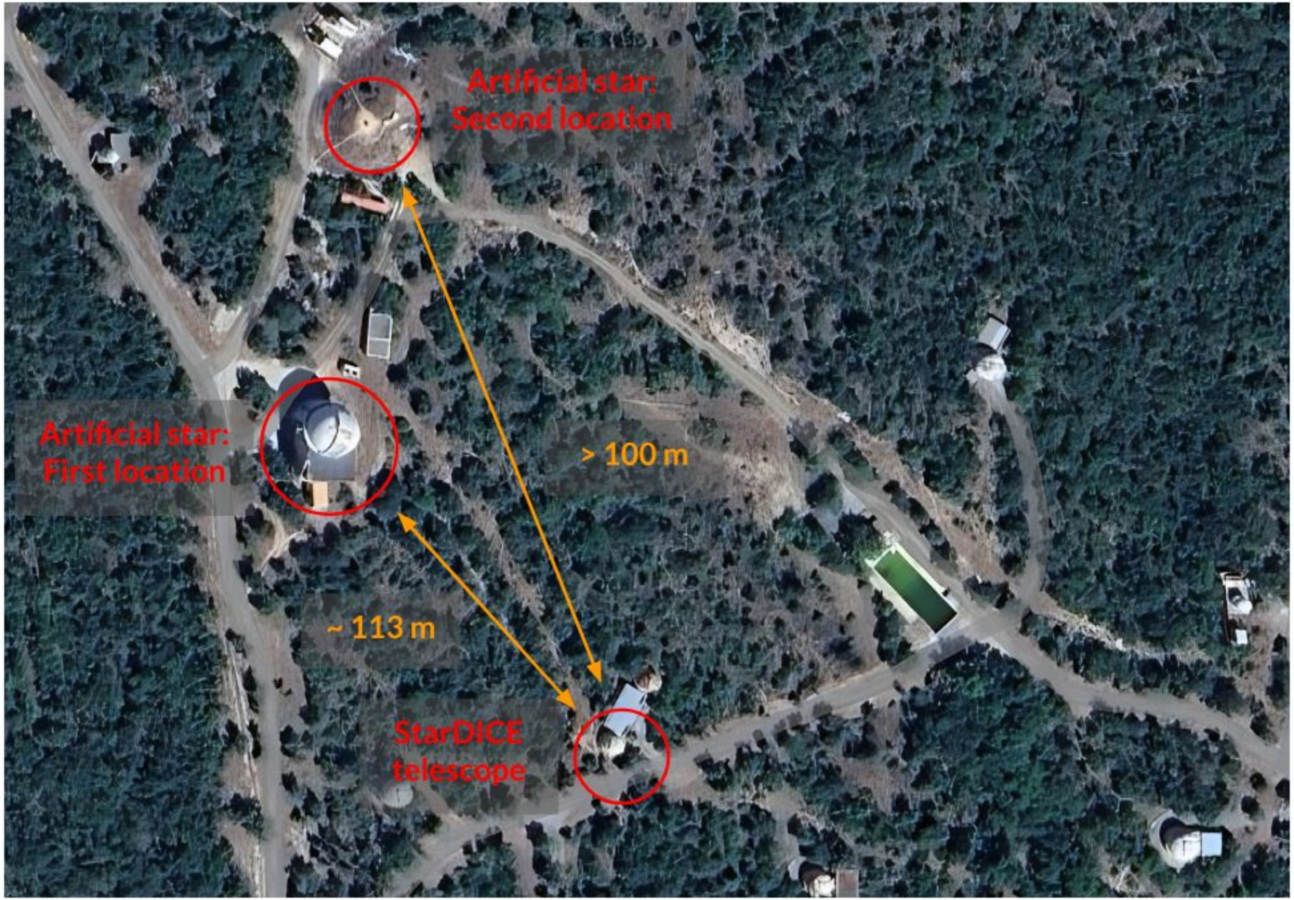
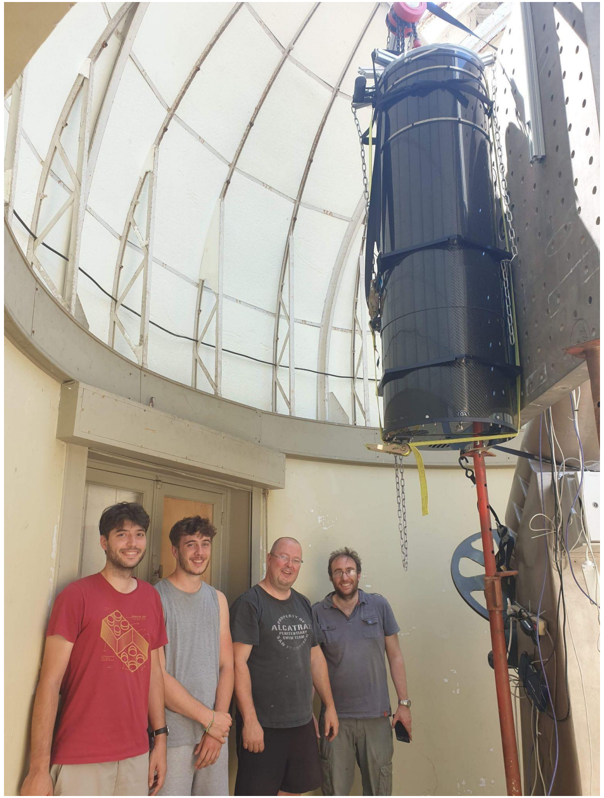


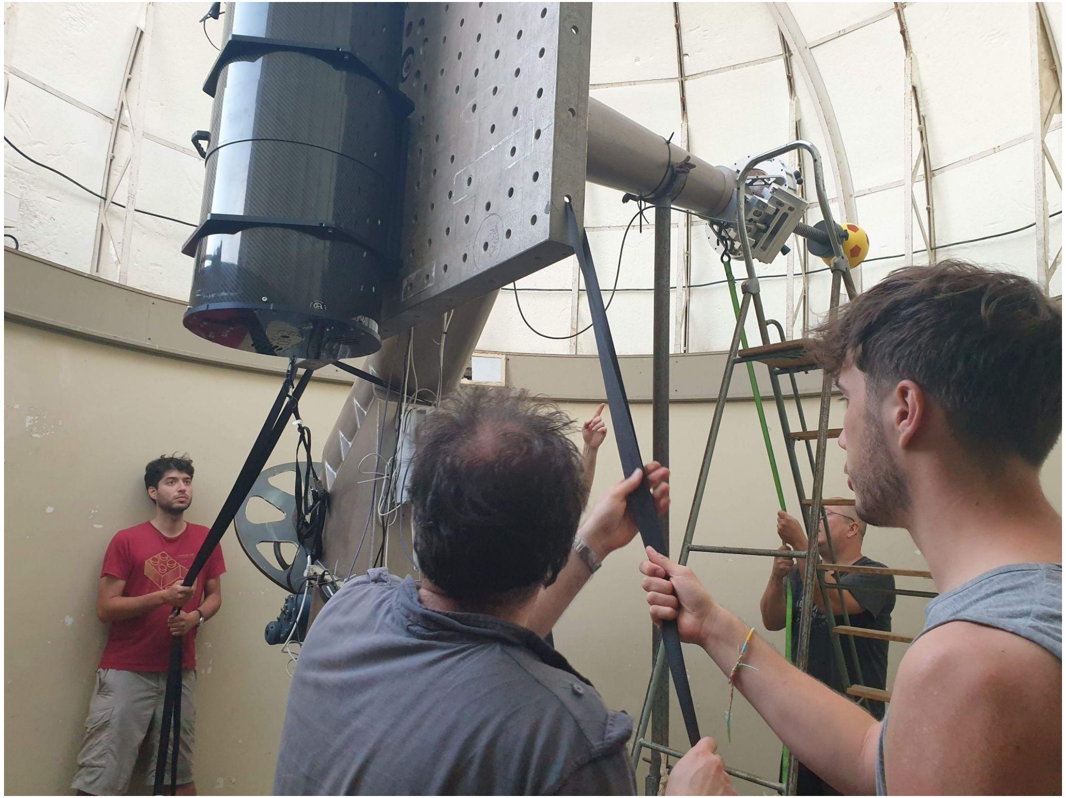
Observatory of Haute-Provence



Observatoire de Haute-Provence satellite view

Installation of the telescope





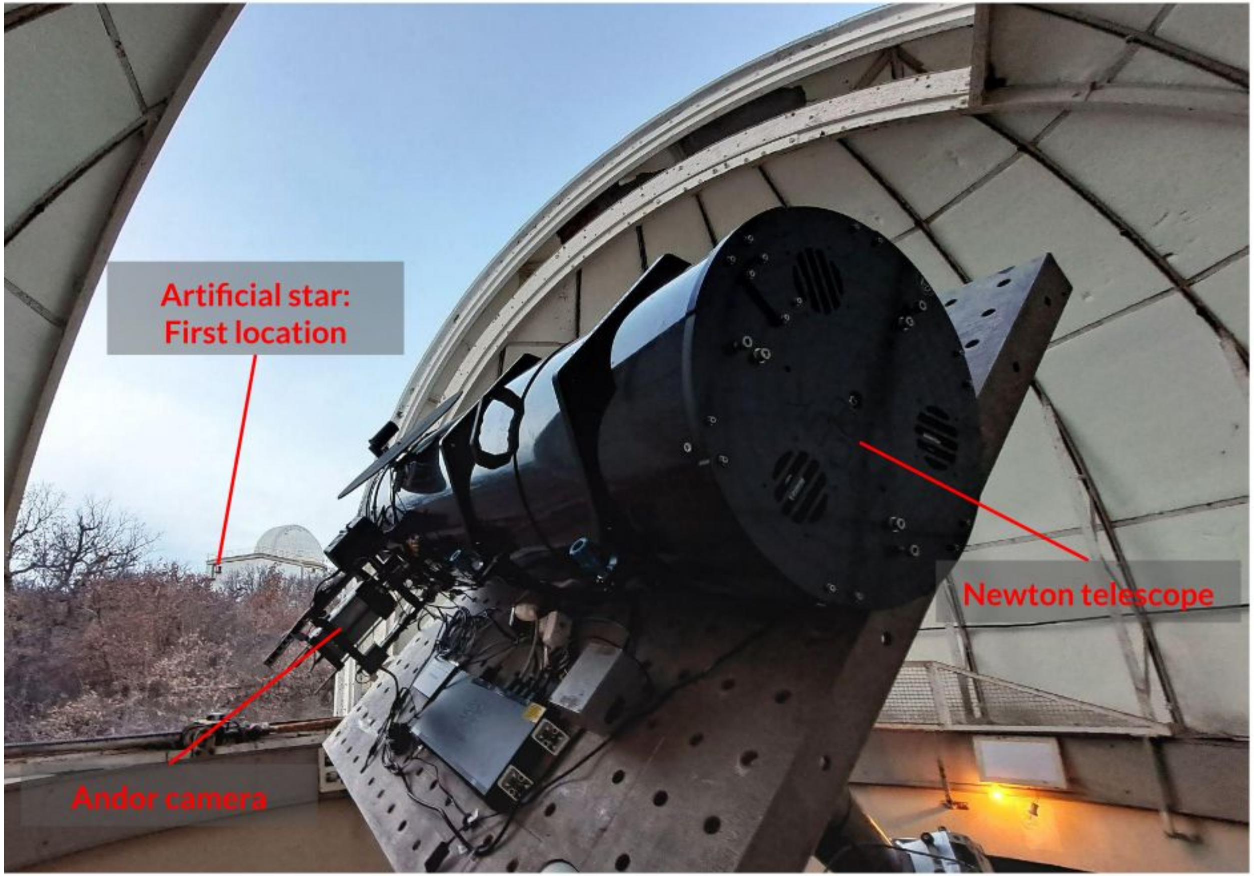
A happy StarDICE team (not pipe smoking) balancing the telescope they have installed

StarDICE telescope

Newton telescope:

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

StarDICE telescope on its mount



StarDICE telescope

Newton telescope:
- D=40cm
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Filterwheel:
- "ugrizy" photometric filters
- Diffraction grating

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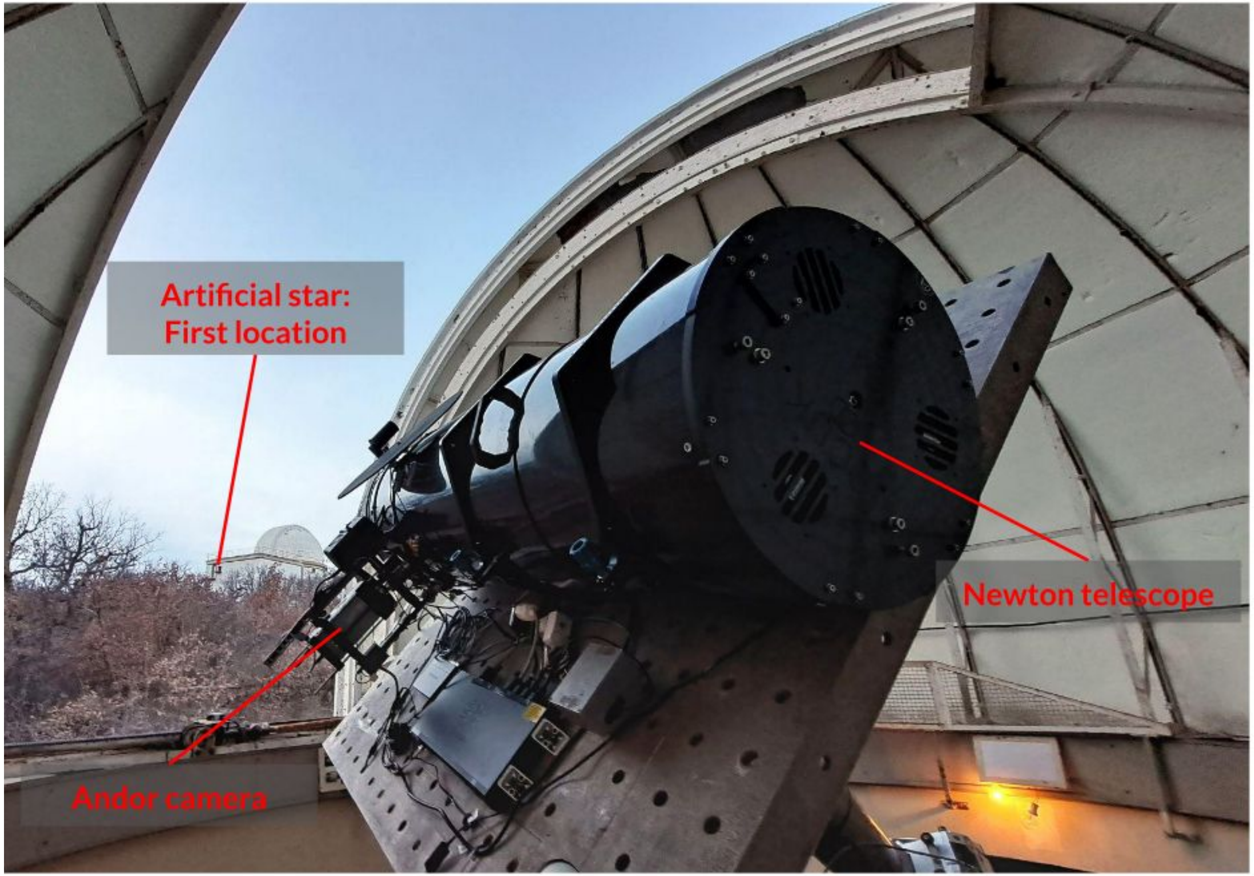

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Monitoring instruments:
- Hygrometer
- Thermometers
- Barometer
- Rain detector

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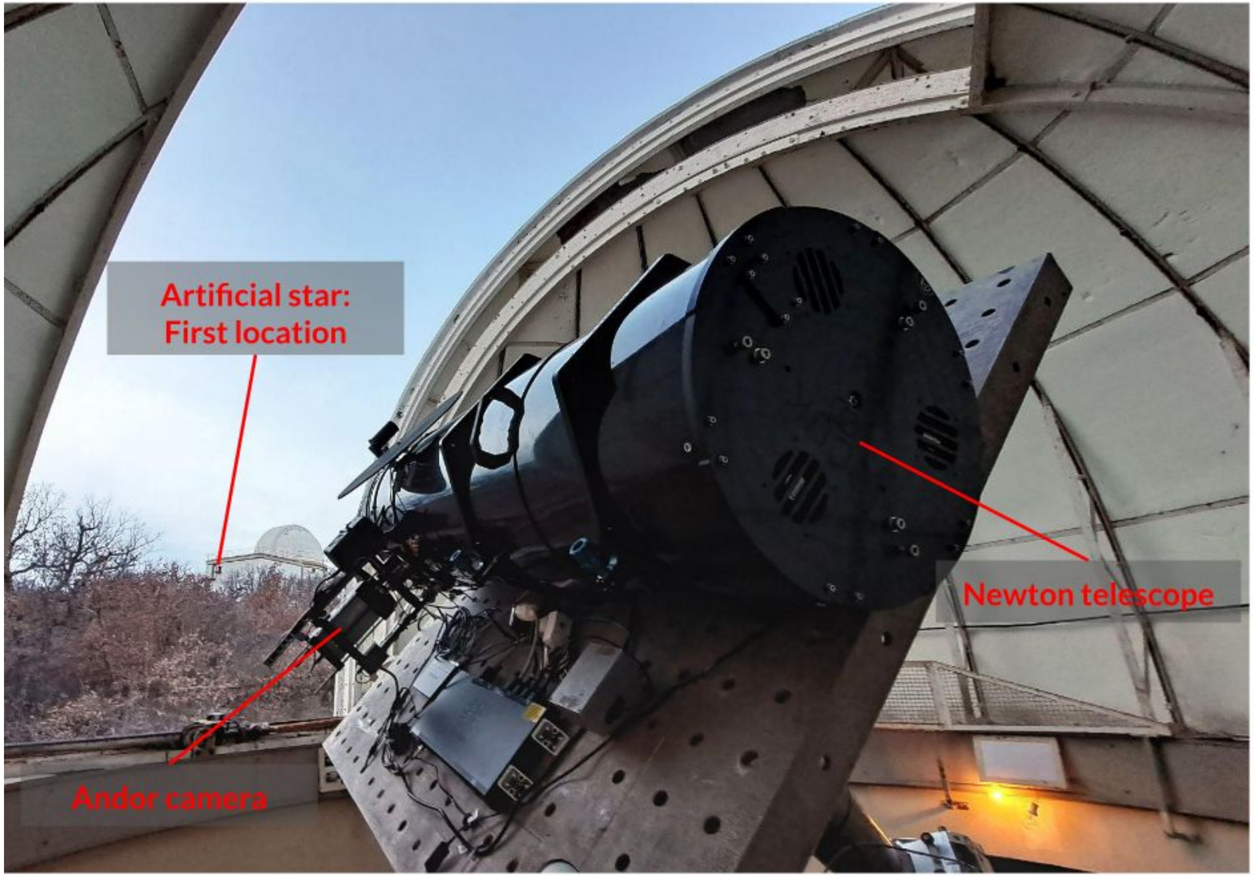

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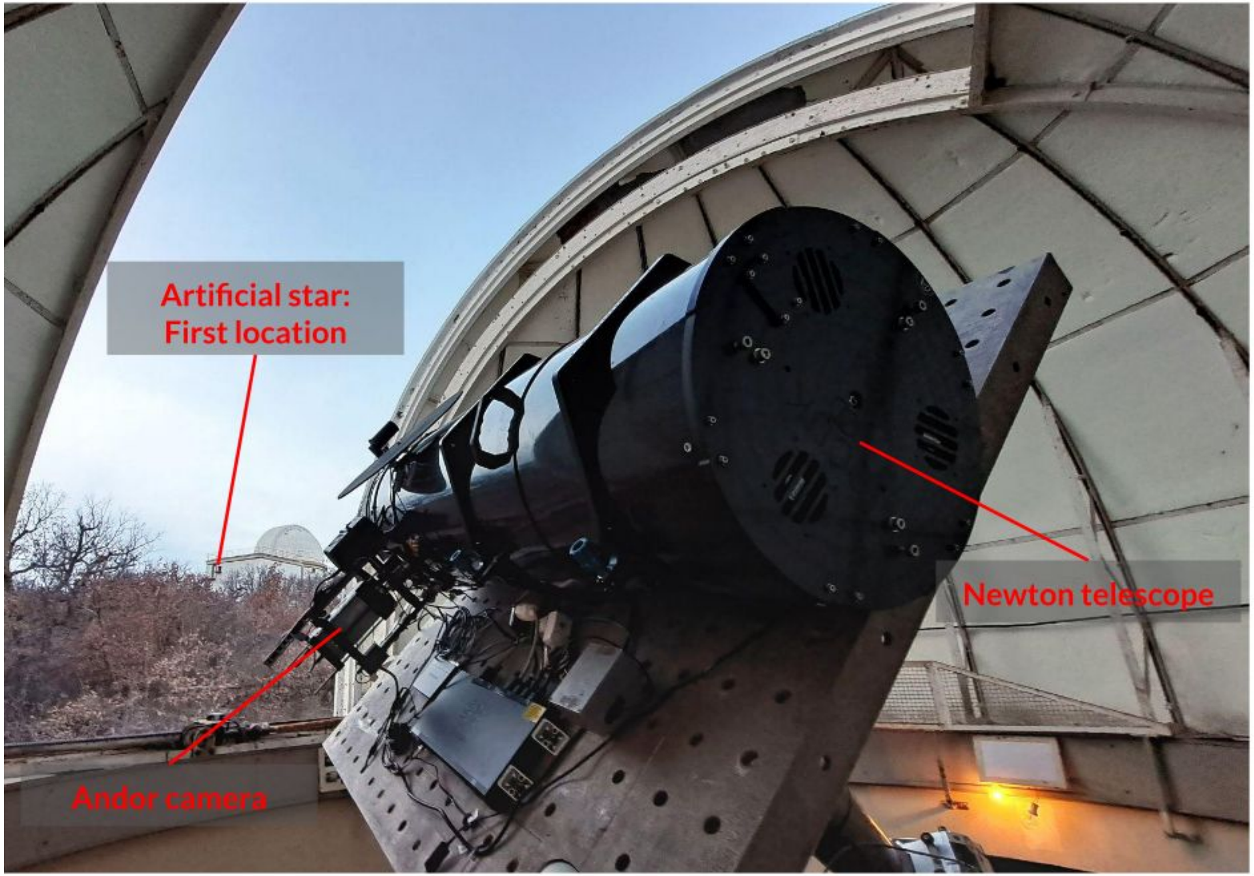
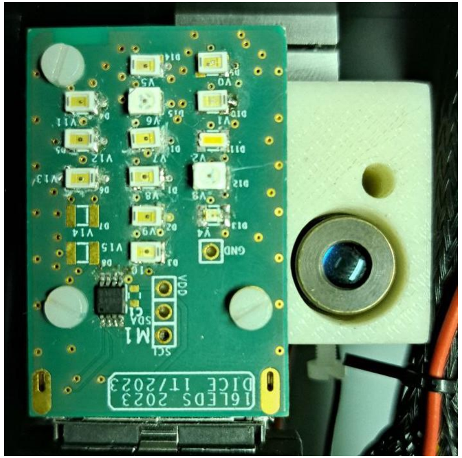
Fully robotic

StarDICE telescope on its mount



Artificial star

- 16 LEDs covering visible and near-IR range
- Flux calibrated in laboratory
- Mounted in July 2024 (after all the analyses I will present)



Artificial stars LEDs off

Artificial stars LEDs on

Helmet enclosing the artificial star

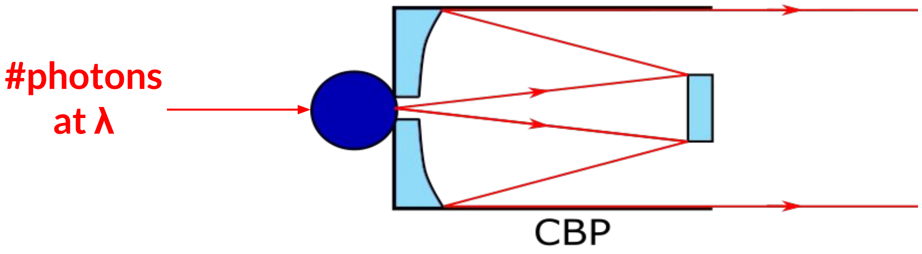
5. Collimated Beam Projector

a. Setup description

What is a CBP ?

CBP, for **Collimated Beam Projector**, is a **calibration device** emitting a **monochromatic light** of **known flux**, in a **parallel beam**

⇒ **calibrate** the **response** of a photometric instrument and its filters.



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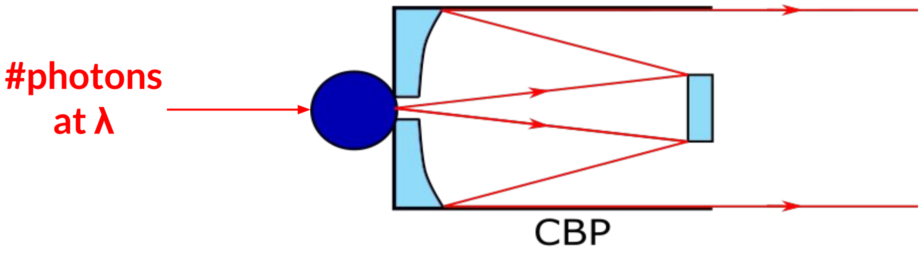

Two purposes:

- **Calibrate the StarDICE telescope response**
- **Proof of concept for the CBP at Rubin Observatory for the LSST**

How to use a CBP ?

Ingredients:

- A tunable laser
- A mounted-backward telescope to recreate a parallel beam from a point source
- A PhD student locked in the basement to make it work

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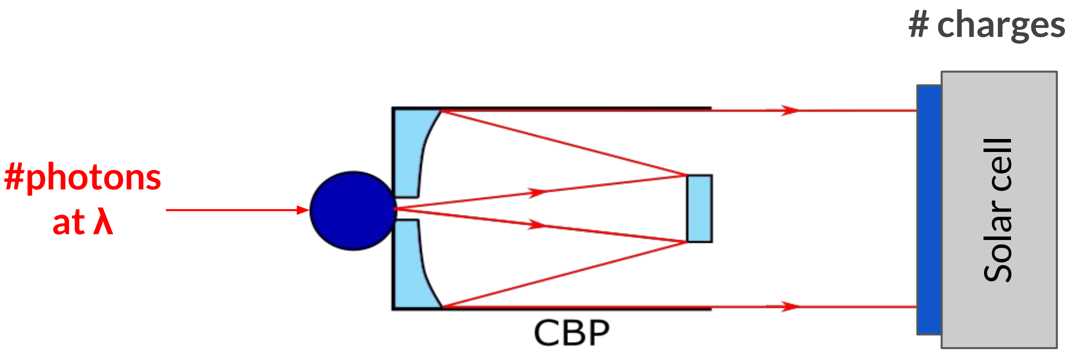
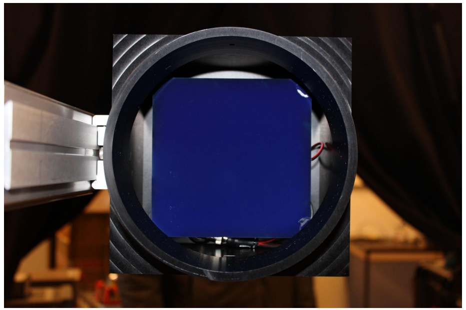
Recipe:

(1) Shoot light inside a calibrated sensor to measure CBP optics throughput R_{CBP}





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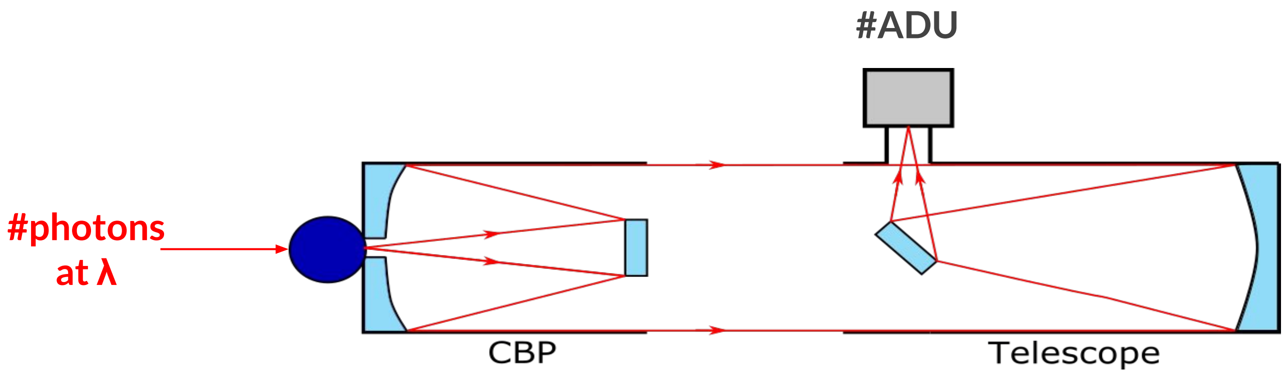
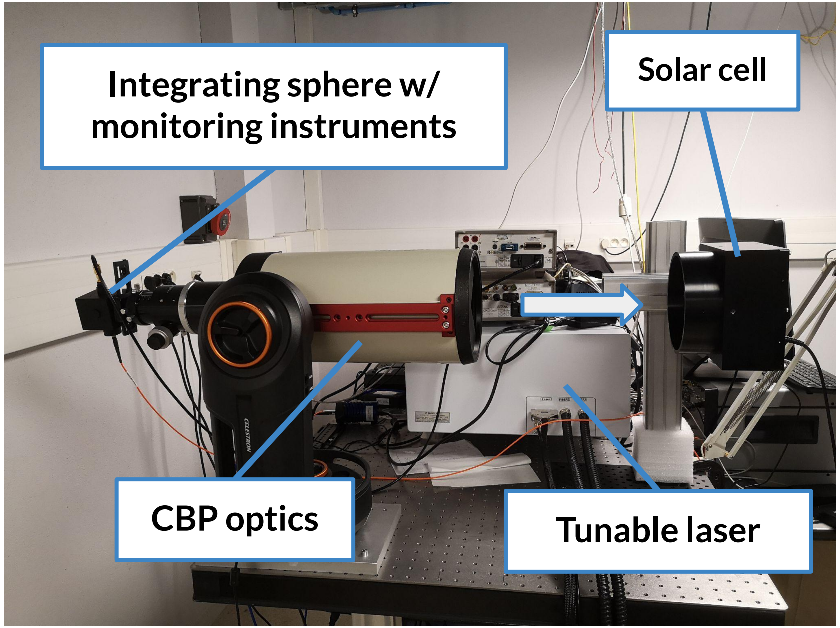
Recipe:

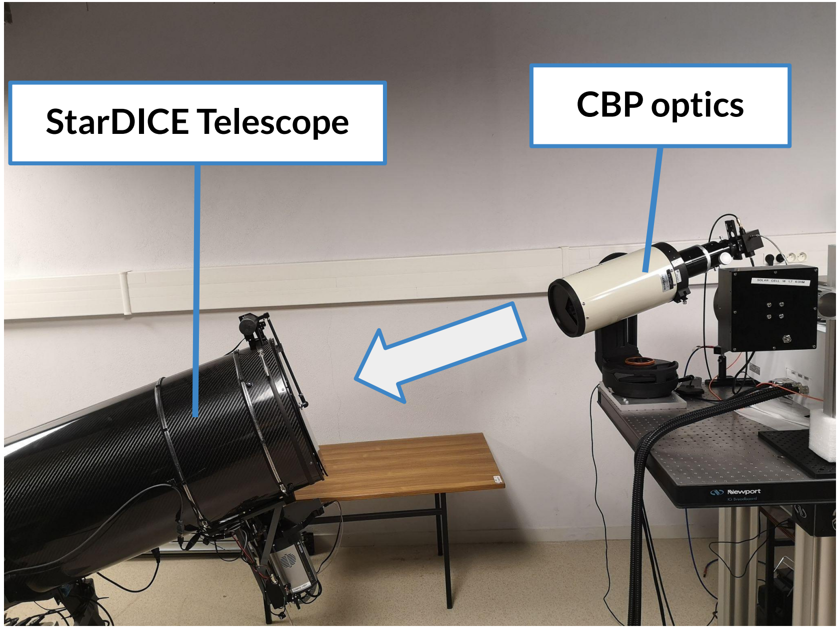
(1) Shoot light inside a calibrated sensor to measure CBP optics throughput R_{CBP}
(2) Shoot light inside the instrument to calibrate, using R_{CBP}



Setup device

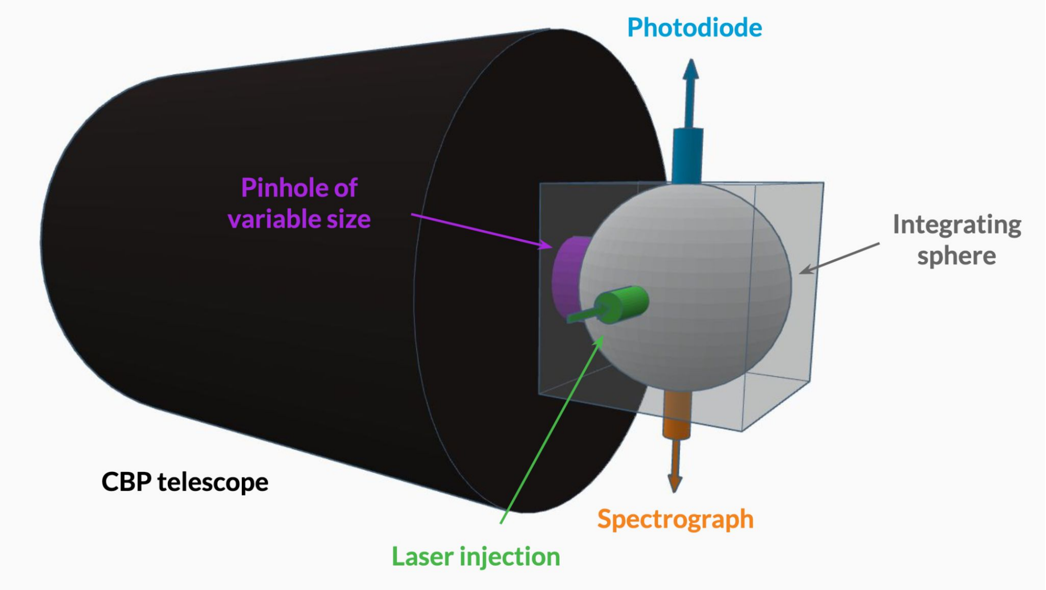


(1) CBP response measurement



(2) StarDICE response measurement

Integrating sphere



Two instruments in the integrating sphere, to monitor the input light:

a. a spectrograph to monitor the laser wavelength
b. a photodiode to monitor the flux quantity

How do we measure our responses ?

(1) **CBP response R_{CBP} [γ.C^{-1}]**

$$R_{\mathrm{CBP}} = \frac{Q_{\mathrm{solar}}}{Q_{\mathrm{phot}} \times \epsilon_{\mathrm{solar}} \times e}$$

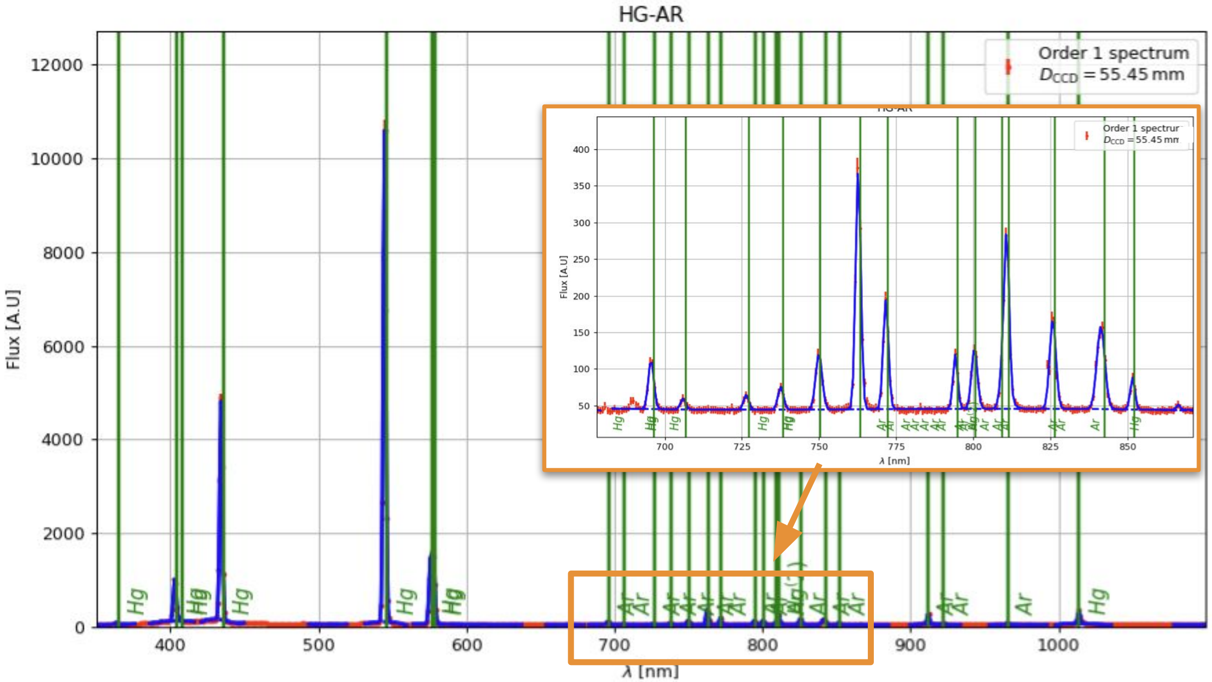
(2) **StarDICE response R_{SD} [ADU.γ^{-1}]**

$$R_{\mathrm{tel}} = \frac{Q_{\mathrm{ccd}}}{Q_{\mathrm{phot}} \times R_{\mathrm{CBP}}}$$

- Q_{solar}: solar cell charges [C]
- Q_{phot}: photodiode charges [C]
- Q_{ccd}: stardice charges [ADU]
- ϵ_{solar}: solar cell quantum efficiency [γ^{-1}]
- e = 1.6x10^{-19} [C]

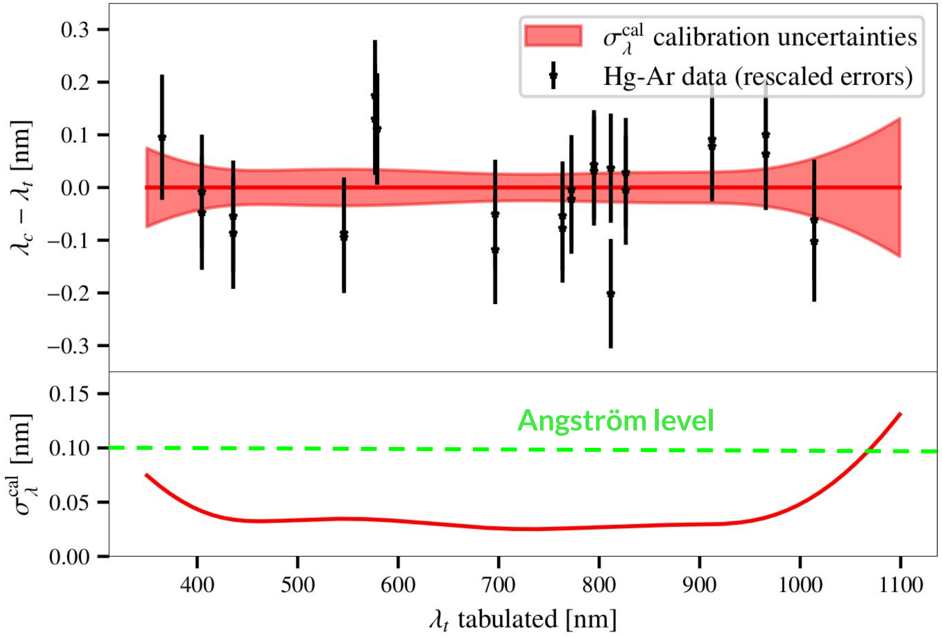
5.b. Data presentation and reduction

Spectrograph wavelength calibration



- Acquisition of Hg-Ar spectrum before and after measurements campaign
- Line detection with gaussian fit
- Compute the difference between tabulated and measured wavelengths

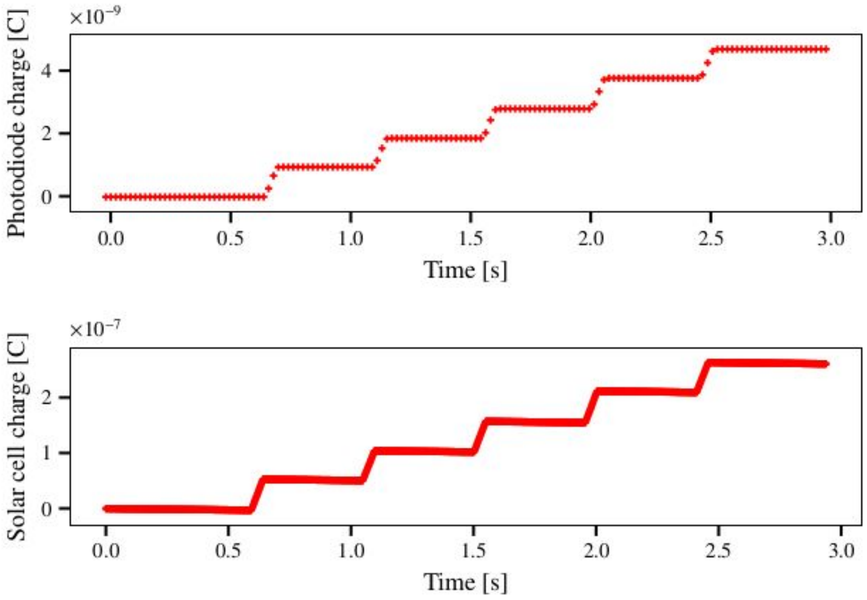
Spectrograph wavelength calibration



- Acquisition of Hg-Ar spectrum before and after measurements campaign
- Line detection with gaussian fit
- Compute the difference between tabulated and measured wavelengths

⇒ Total uncertainties below the Angström level: **σ_λ < 0.1nm for [350 - 1080] nm**

Photodiode and solar cell dataset

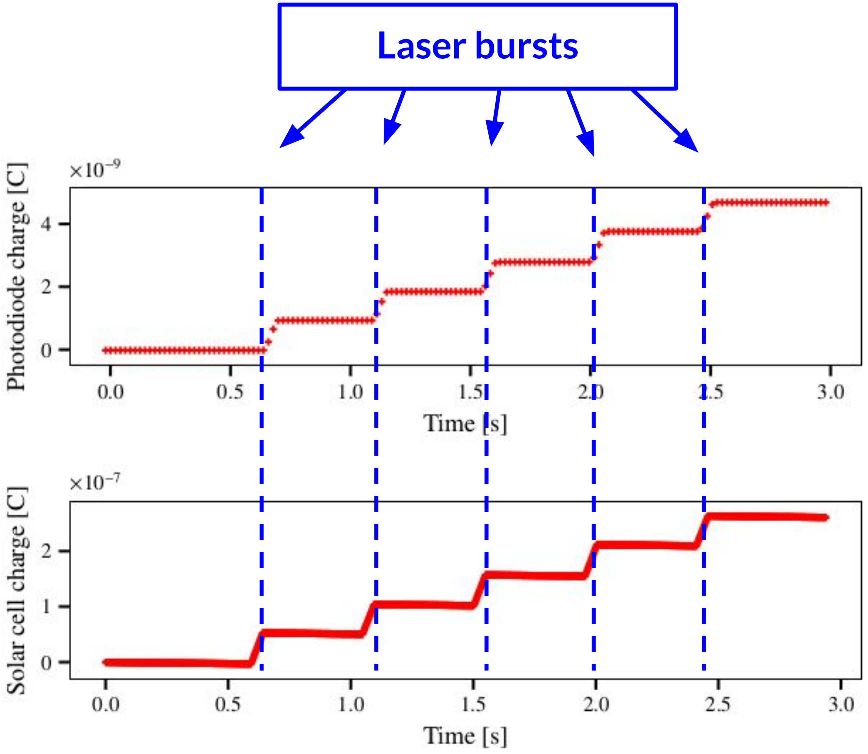


Two **electrometers** measuring **charges [C]**:

- **monitoring photodiode (Q_{phot})**
- **solar cell (Q_{solar})**

$$R_{\mathrm{CBP}} = \frac{Q_{\mathrm{solar}}}{Q_{\mathrm{phot}} \times \epsilon_{\mathrm{solar}} \times e}$$

Photodiode and solar cell dataset



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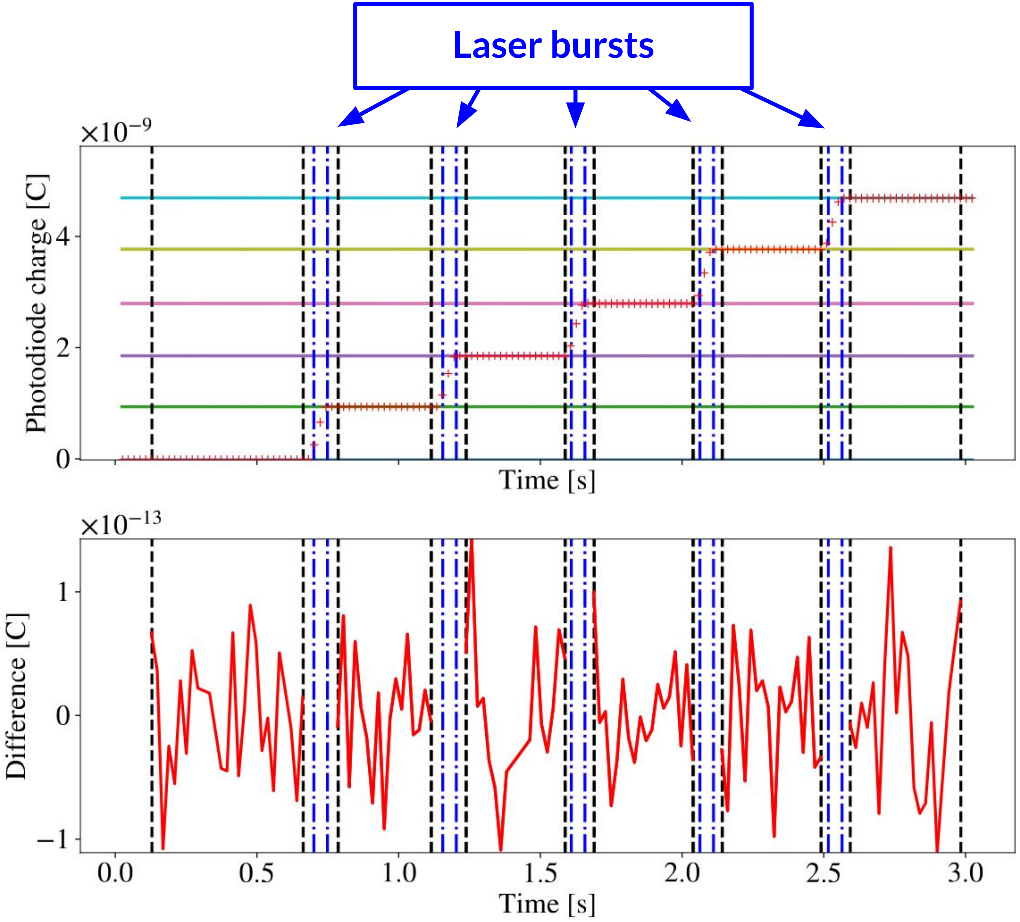
Photodiode reduction



- Compute the differences between dark sequences
- Residuals 4 orders of magnitude smaller

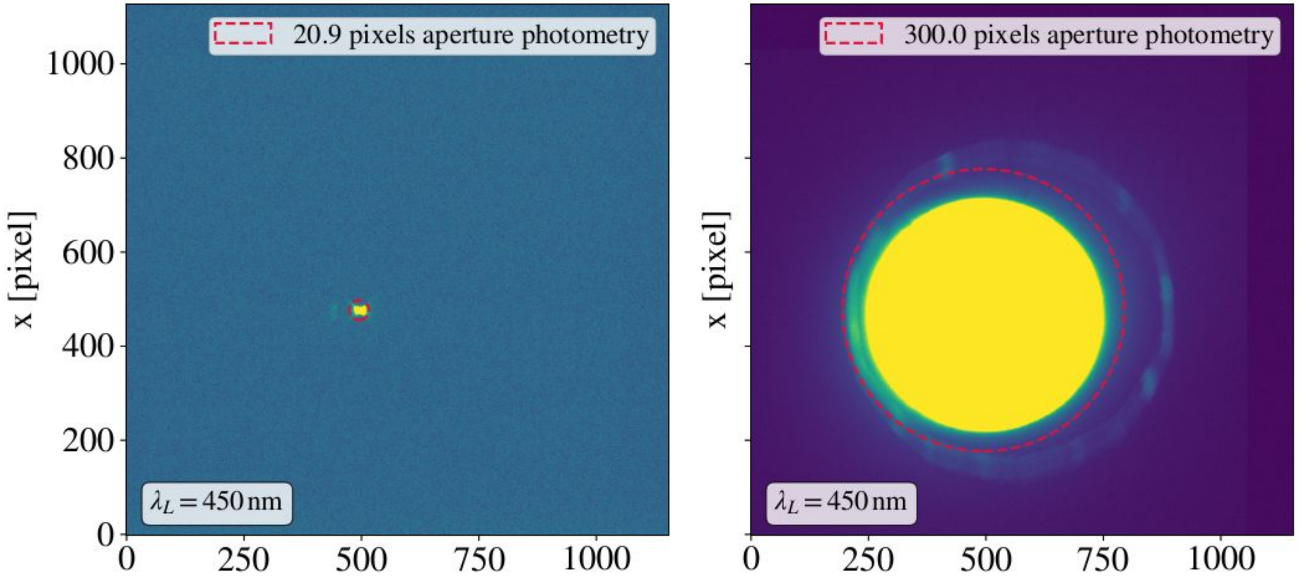
⇒ Monitor total charges Q_{phot} and Q_{solar}

$$R_{\mathrm{CBP}} = \frac{Q_{\mathrm{solar}}}{Q_{\mathrm{phot}} \times \epsilon_{\mathrm{solar}} \times e}$$

StarDICE telescope

75µm pinhole
→ mimic punctual source

5mm pinhole
→ enough signal in solar cell



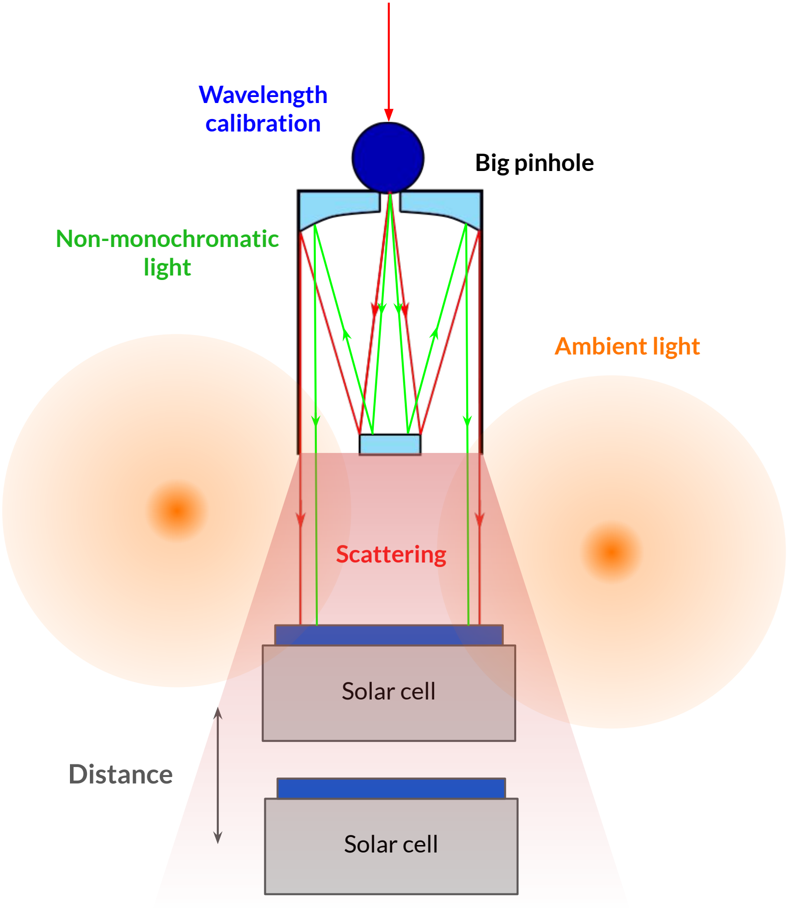
- Background subtraction + aperture photometry at optimized radius

$$R_{\mathrm{tel}} = \frac{Q_{\mathrm{ccd}}}{Q_{\mathrm{phot}} \times R_{\mathrm{CBP}}}$$

⇒ Measure Q_{CCD} the photons collected in ADU

5.c. Systematics

CBP in real life



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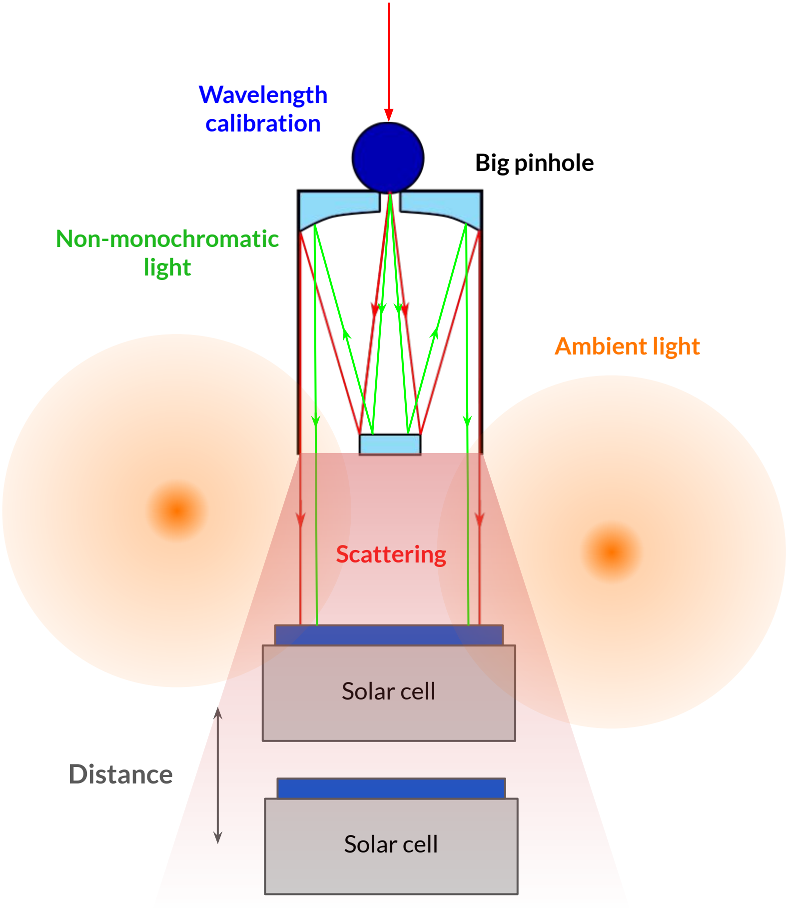
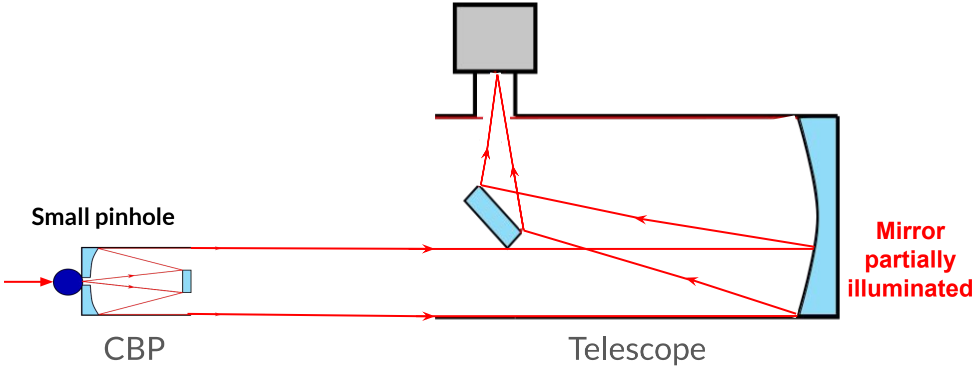
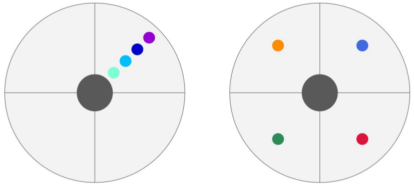
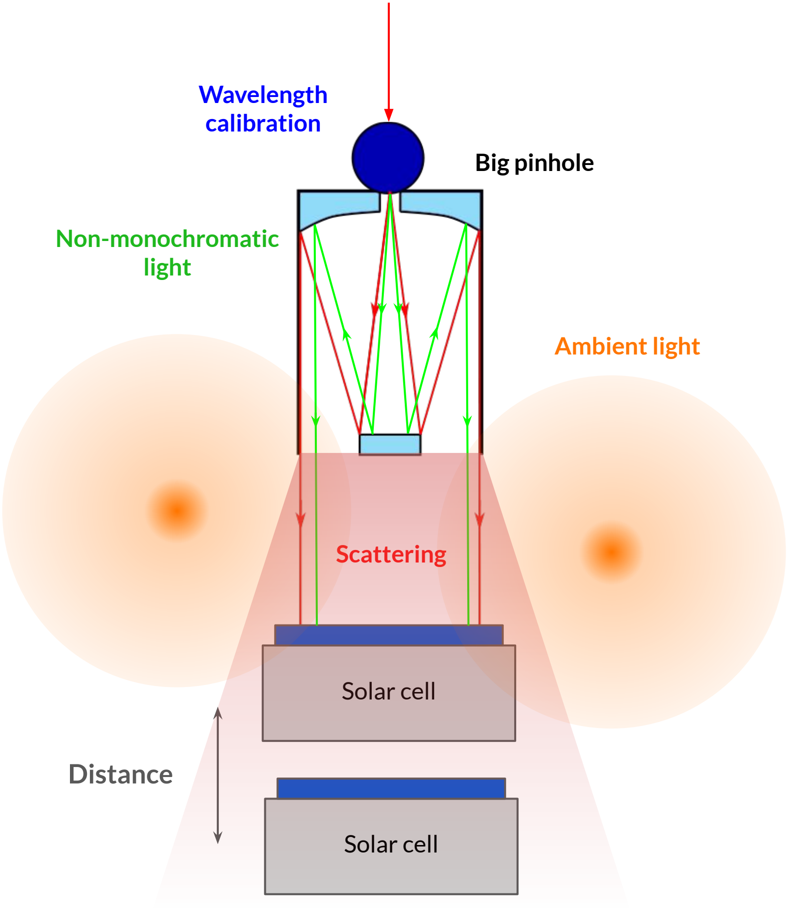


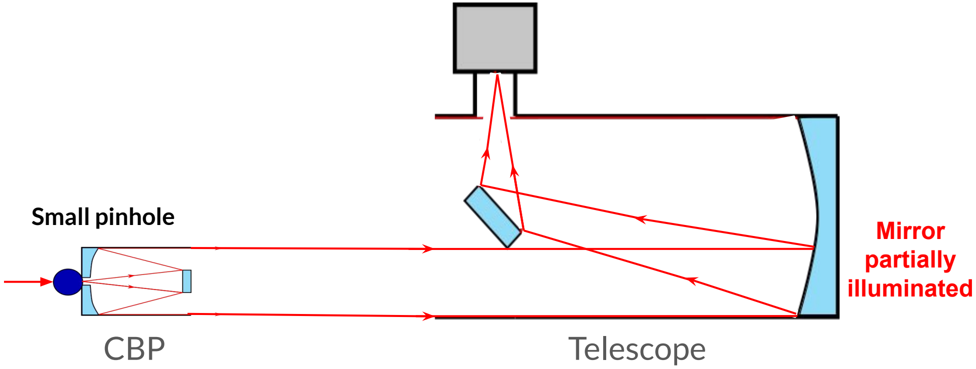


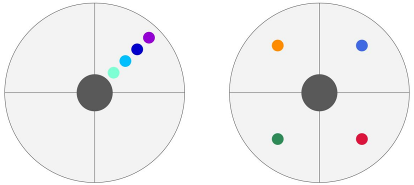


Combination of CBP measurements at every mirror position = **"Pupil stitching"**

CBP in real life







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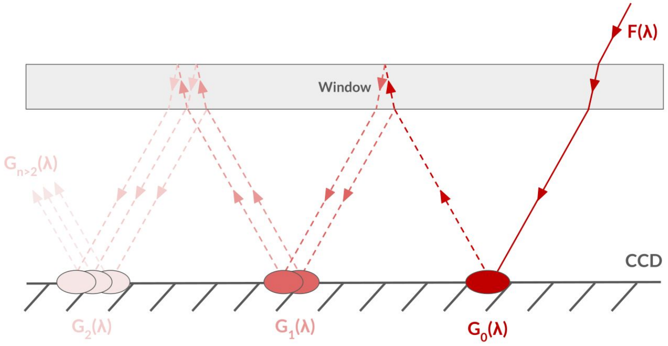
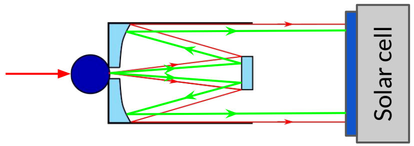
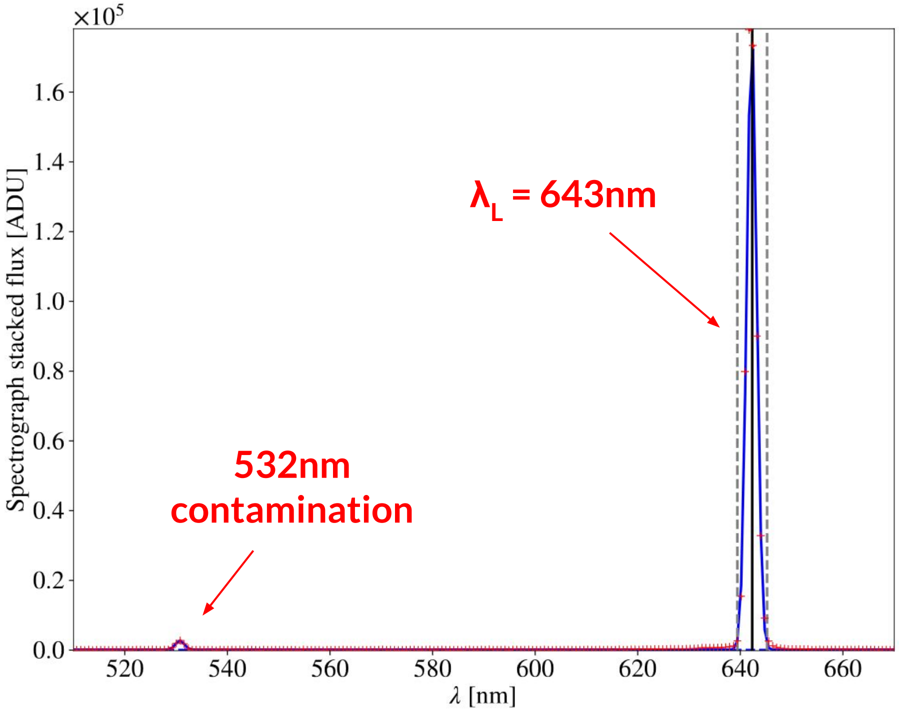
Ghosts



Laser light contamination

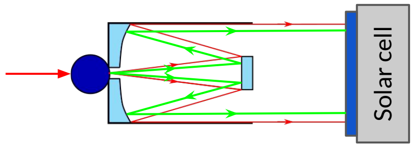




<u>Signal</u>: λ_L + 532nm contamination

Charges $Q_{spectro}(\lambda)$ measured with a gaussian fit
⇒ Estimate the ratio of contamination light over main wavelength

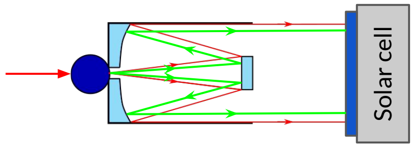
Laser light contamination



Similar ratio contamination/main wavelength in **spectrograph** and **photodiode**:

$$\alpha(\lambda_L) = \frac{Q^{532}_{\text{phot}}(\lambda_L)}{Q_{\text{phot}}(\lambda_L)} = \frac{Q^{532}_{\text{spectro}}(\lambda_L)}{Q_{\text{spectro}}(\lambda_L)} \times \frac{\epsilon_{\text{spectro}}(\lambda_L)}{\epsilon_{\text{spectro}}(532)} \times \frac{\epsilon_{\text{phot}}(532)}{\epsilon_{\text{phot}}(\lambda_L)}.$$

Laser light contamination



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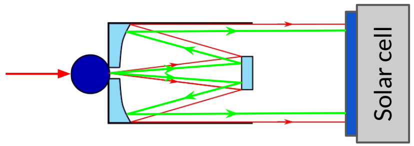
Calibrate the charges measure with α:

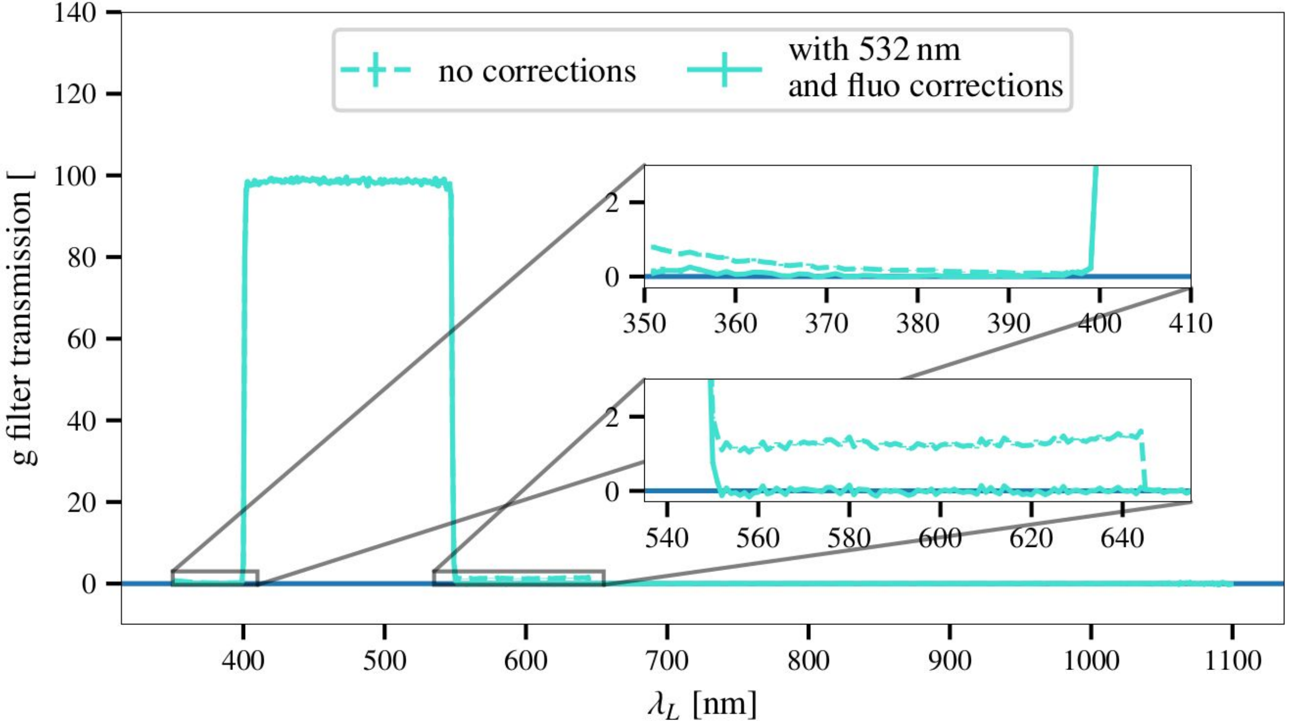
$$Q^{\lambda_L}_{\text{phot}} = \frac{Q^{\text{mes}}_{\text{phot}}}{1 + \alpha(\lambda_L)}$$

$$Q^{\lambda_L}_{\text{solar}} = Q^{\text{mes}}_{\text{solar}} - R_{\text{CBP}}(532)\, \alpha(\lambda_L)\, Q^{\text{mes}}_{\text{phot}}$$

$$Q^{\lambda_L}_{\text{ccd}} = Q^{\text{mes}}_{\text{ccd}} - R_{\text{CBP}}(532)\, R_{\text{tel}}(532)\, \alpha(\lambda_L)\, Q^{\text{mes}}_{\text{phot}}$$

Laser light contamination

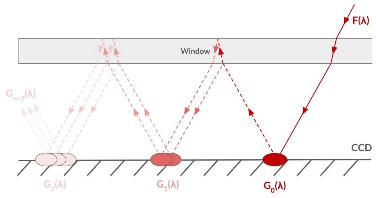


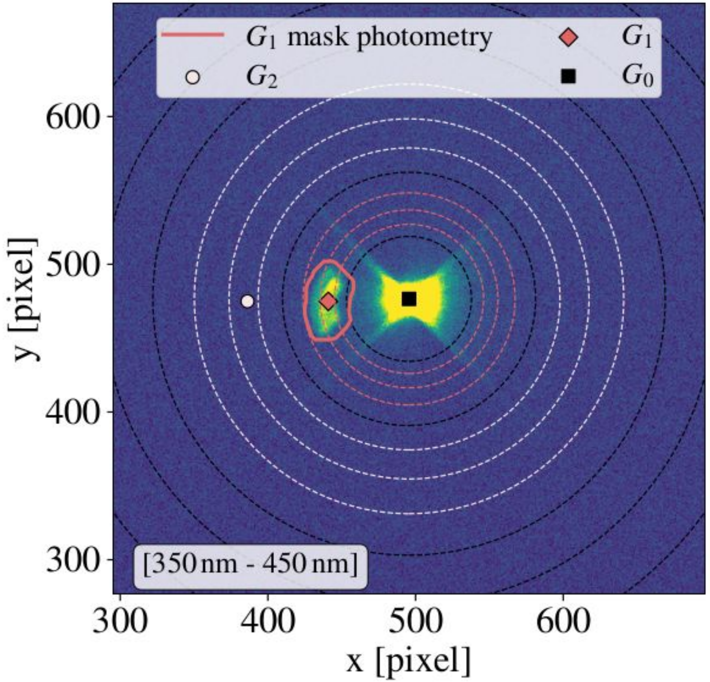


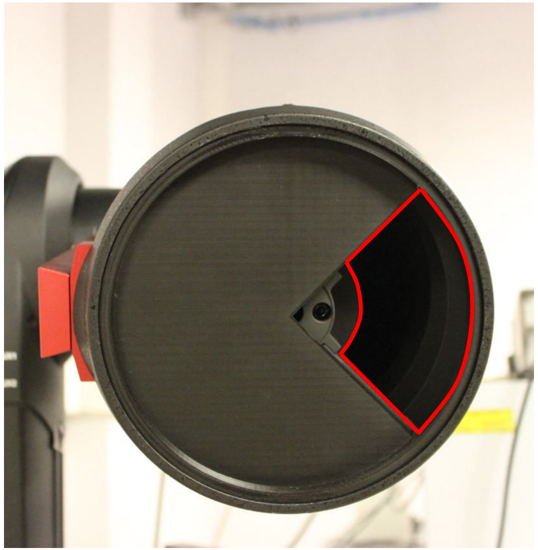
$$Q_{\text{phot}}^{\text{cal}}(\lambda_L) \equiv \frac{Q_{\text{phot}}^{\text{mes}}(\lambda_L)}{1+\alpha(\lambda_L)}$$

Plus: 532nm contamination used to monitor wavelength calibration

Ghost contamination



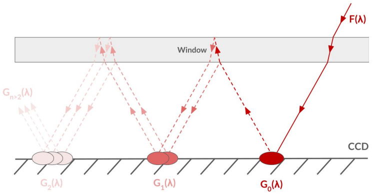




CBP output

⇒ Parasite signal when performing aperture photometry

Ghost contamination



<u>#Method 1:</u> PSF fit with successive aperture photometry with radius *r*

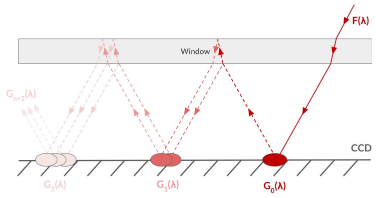
Moffat distribution

Ghost contribution

Background

$$F(r, \lambda) = A(\lambda) \times \frac{M(r, \lambda) + K_{G/A}(r, \lambda)}{1 + K_{G/A}(+\infty, \lambda)} + \mathrm{bkg}(\lambda) \times \pi r^2$$

Ghost contamination



<u>#Method 1:</u> PSF fit with successive aperture photometry with radius *r*

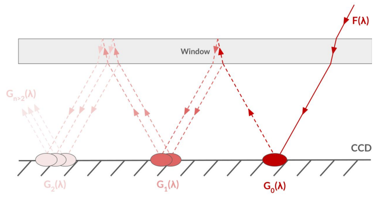
Moffat distribution — Ghost contribution — Background

$$F(r,\lambda) = A(\lambda) \times \frac{M(r,\lambda) + K_{G/A}(r,\lambda)}{1 + K_{G/A}(+\infty,\lambda)} + \mathrm{bkg}(\lambda) \times \pi r^2$$

<u>#Method 2:</u> Ghost photometry with a custom mask:

$$K_{G_1/G_0}(\lambda) = \frac{G_1(\lambda)}{G_0(\lambda)}$$

Ghost contamination



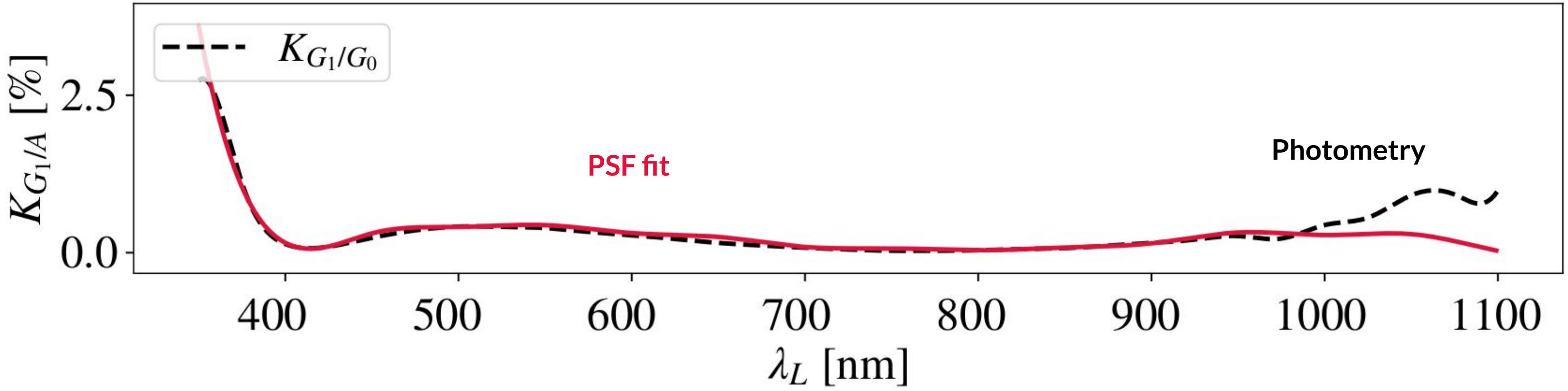
#Method 1: PSF fit with successive aperture photometry with radius *r*

Moffat distribution — Ghost contribution — Background

$$F(r,\lambda) = A(\lambda) \times \frac{M(r,\lambda) + K_{G/A}(r,\lambda)}{1 + K_{G/A}(+\infty,\lambda)} + \mathrm{bkg}(\lambda) \times \pi r^2$$

#Method 2: Ghost photometry with a custom mask:

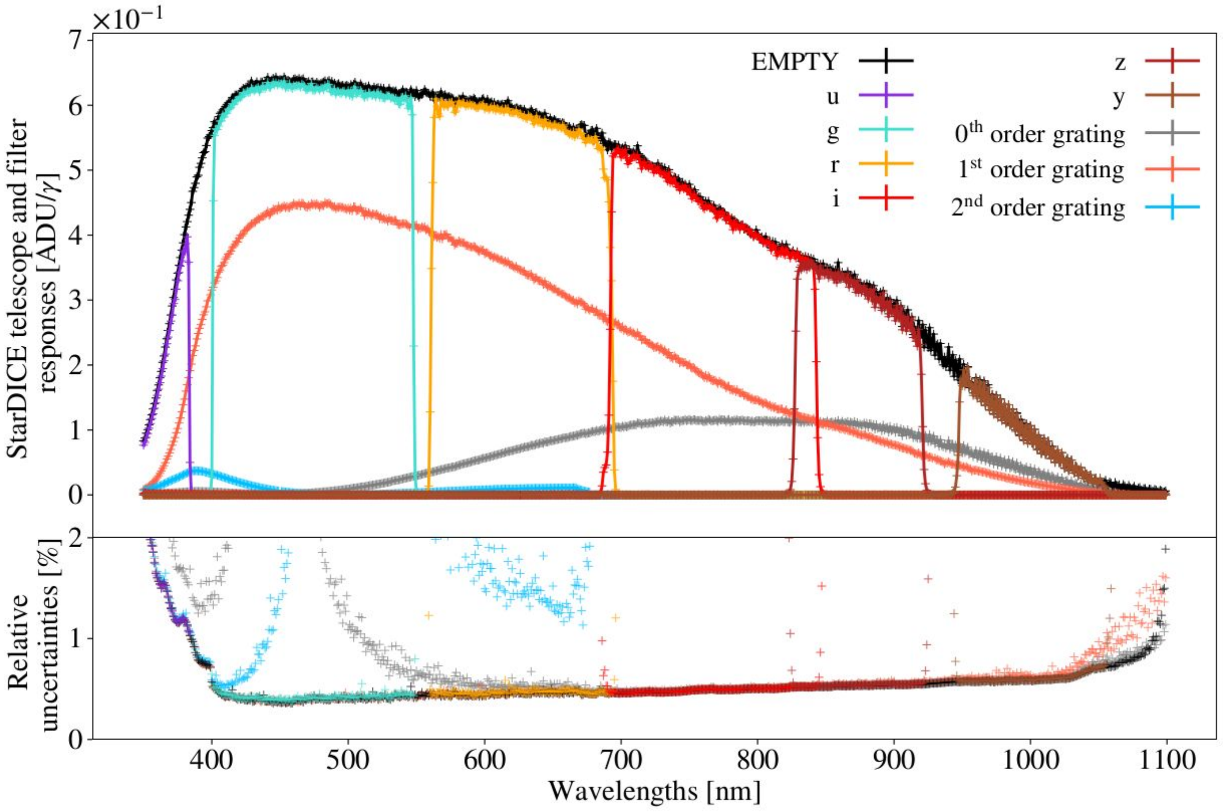
$$K_{G_1/G_0}(\lambda) = \frac{G_1(\lambda)}{G_0(\lambda)}$$



5.d. Results

StarDICE filters transmission

$$R_{\text{tel}} = \frac{Q_{\text{ccd}}}{Q_{\text{phot}} \times R_{\text{CBP}}}$$



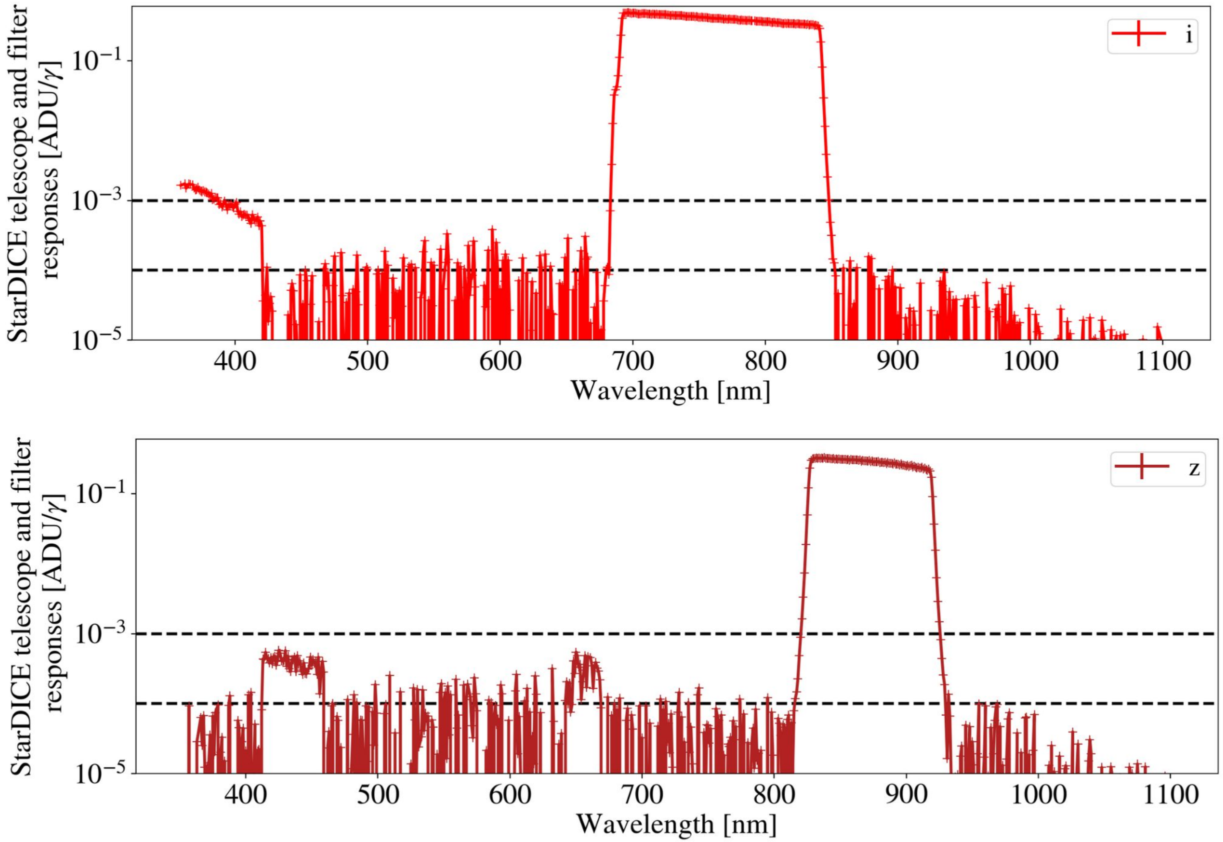
- ~0.5 % per nm uncertainty over [400 - 1000] nm range for every filter
- Wavelength resolution high enough to see the slopes of the filter edges

Filter leakages

Example of i and z filters:

Detection of out-of-band leakages below **0.1%** level

→ **crucial for accurate photometric measurement**



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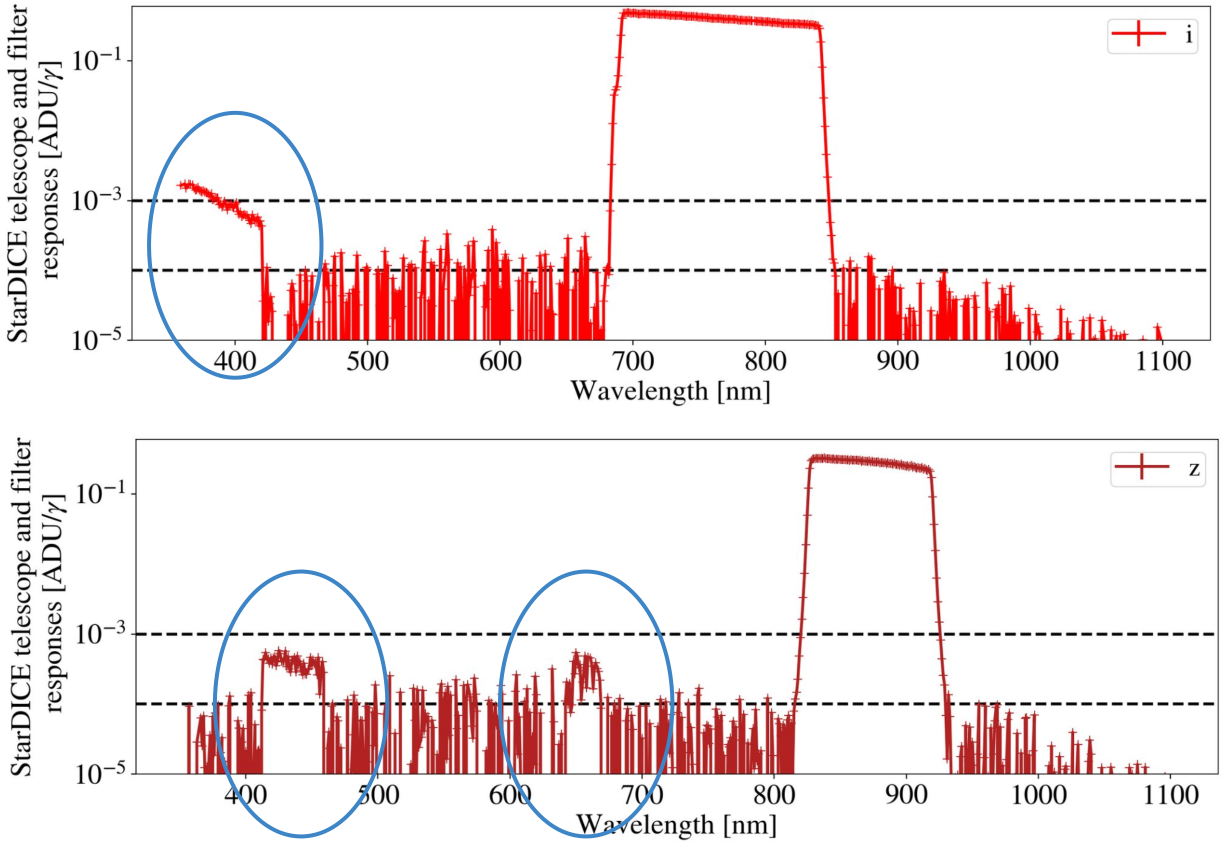
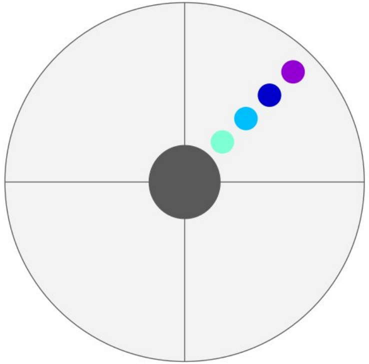
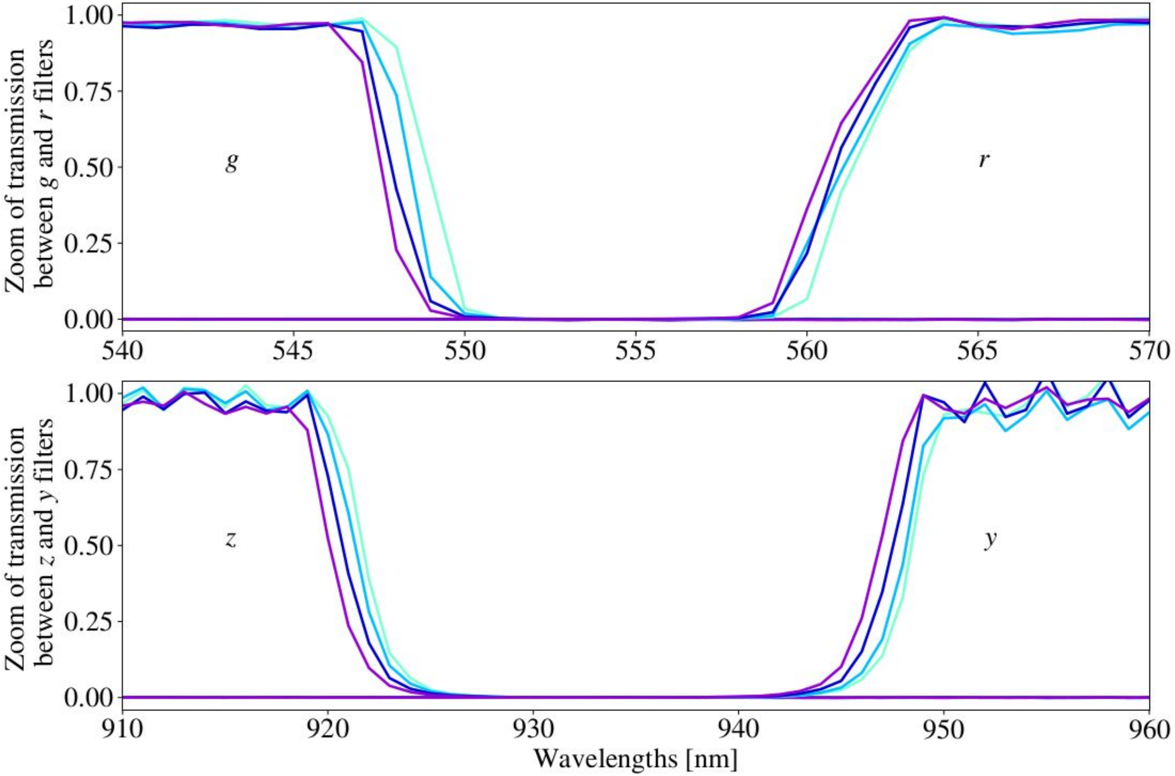


Filter edges : blueshift

$$\lambda_{\text{eff}} = \lambda_0 \sqrt{1 - \frac{\sin^2(\theta)}{n_{\text{eff}}^2}}$$

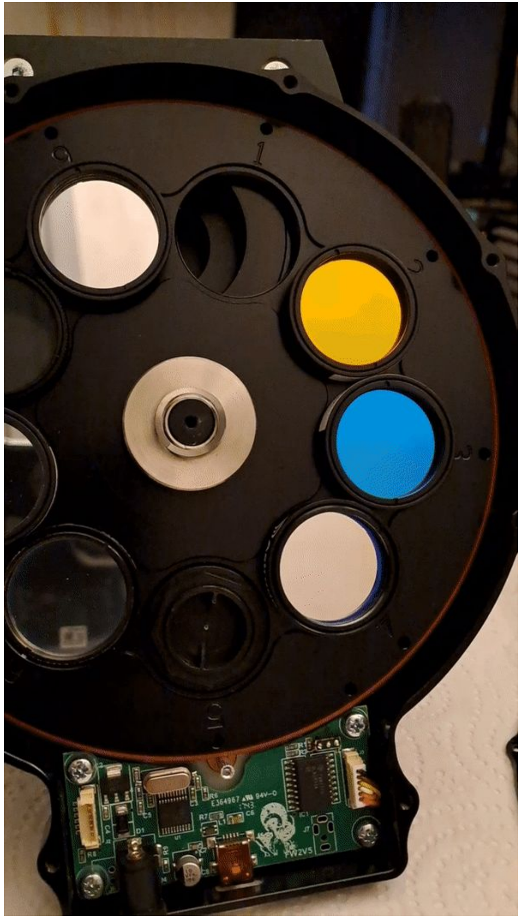
Blue-shift of filter edges when high incident angles

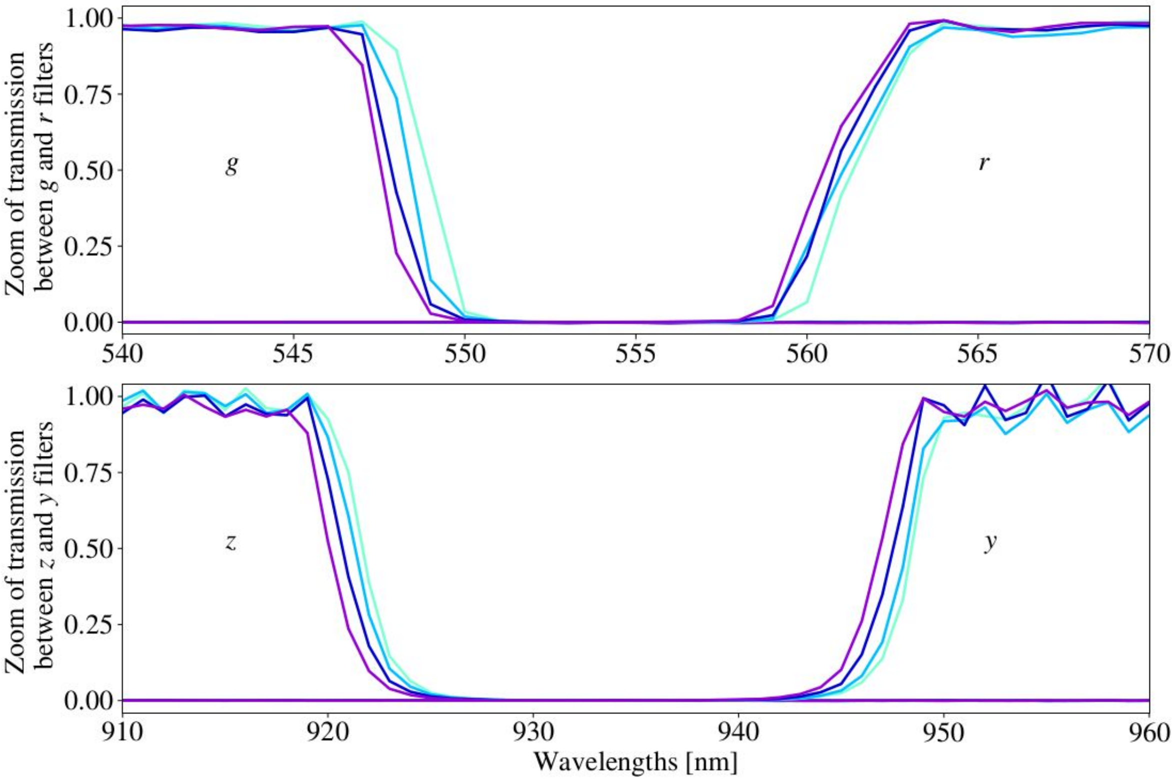




Filter edges : blueshift

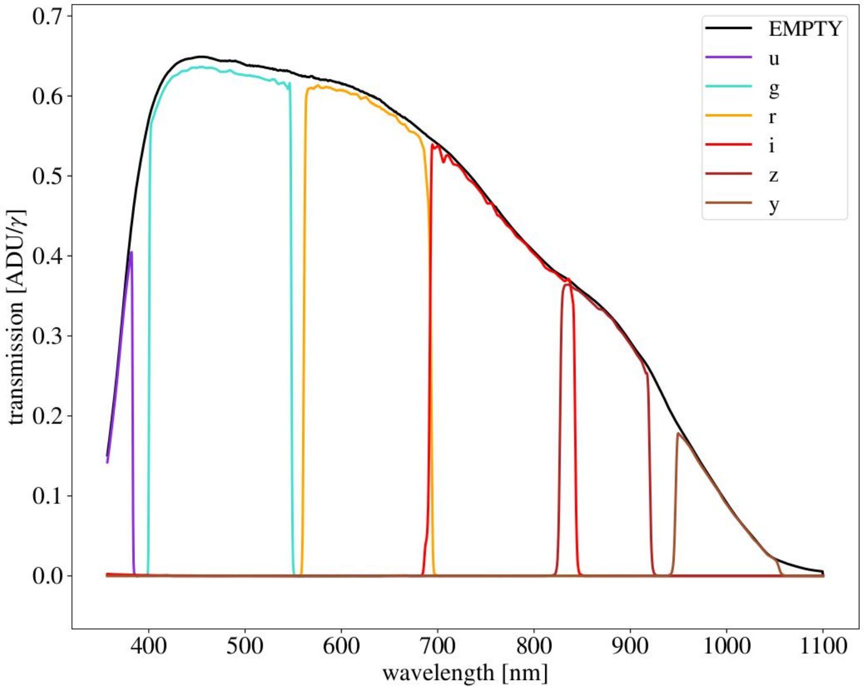
$$\lambda_{\text{eff}} = \lambda_0 \sqrt{1 - \frac{\sin^2(\theta)}{n_{\text{eff}}^2}}$$





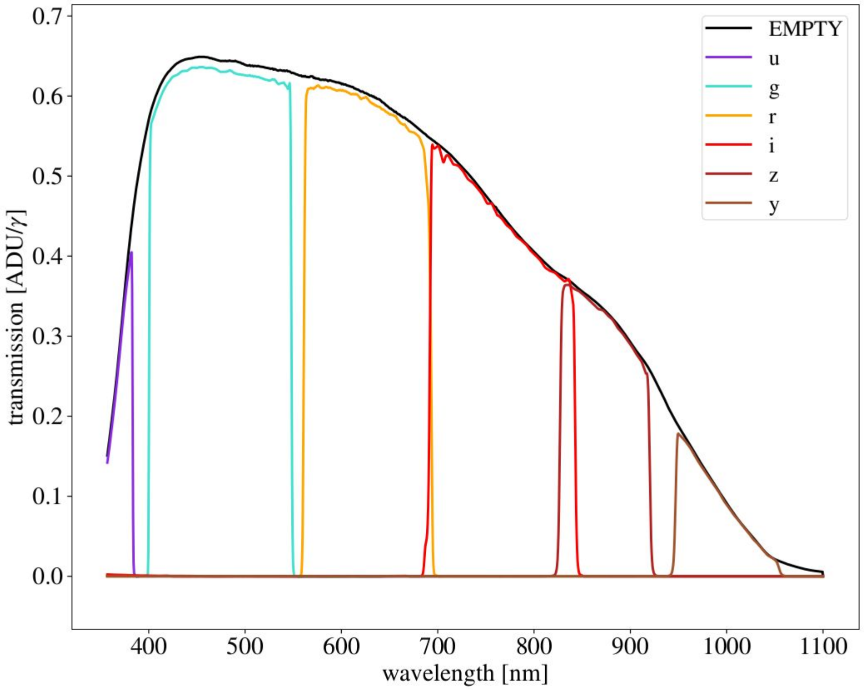
Full illumination synthesis

$$T(\lambda, \theta) = \mathcal{T}\left(\frac{\lambda}{\sqrt{1 - (\sin(\theta)/n_{\text{eff}})^2}}\right)$$



Full illumination synthesis

$$T(\lambda,\theta) = \mathcal{T}\left(\frac{\lambda}{\sqrt{1-(\sin(\theta)/n_{\mathrm{eff}})^2}}\right)$$



Uncertainty propagation for **on-sky** flux measurements, **after** simulating the recalibration with the **artificial star**:

Filter	Uncertainty [%]
u	0.08
g	0.08
r	0.13
i	0.11
z	0.11
y	0.24

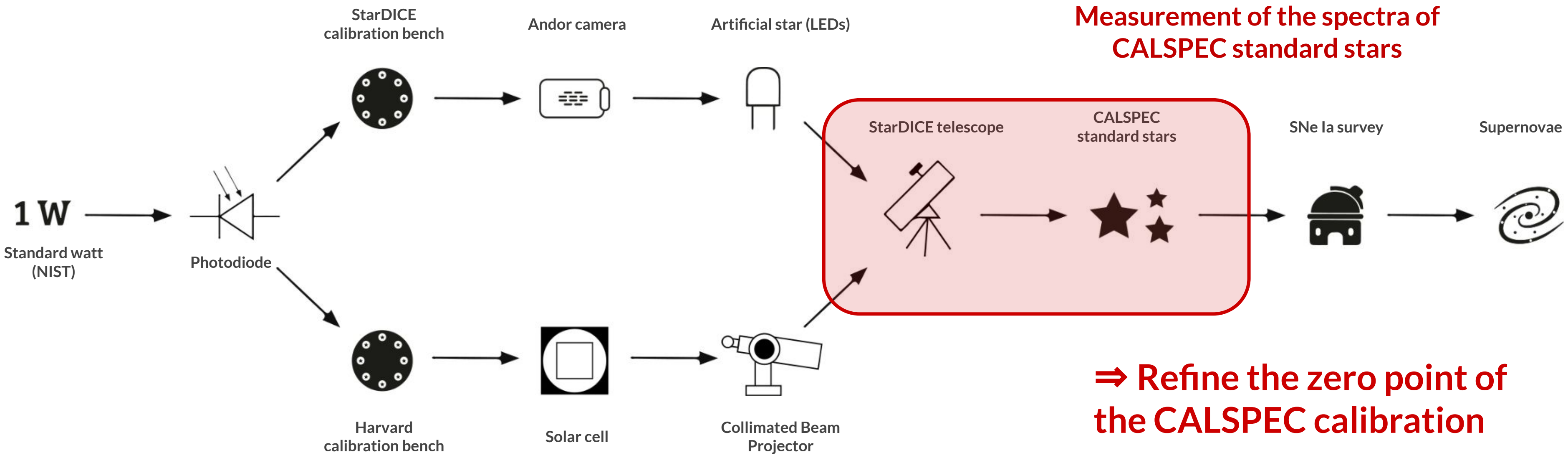
Conclusion

- Filter bandpasses measured with a precision of **~0.2 nm**
- Detected **out-of-band leaks** at relative level 0.01%
- When coupled with **artificial star** ⇒ **flux measurement** at a precision of **~0.1%** for ***ugriz*** with StarDICE

⇒ Proof of concept **validated** for **Rubin-CBP**

6. On-sky measurements analysis with StarDICE

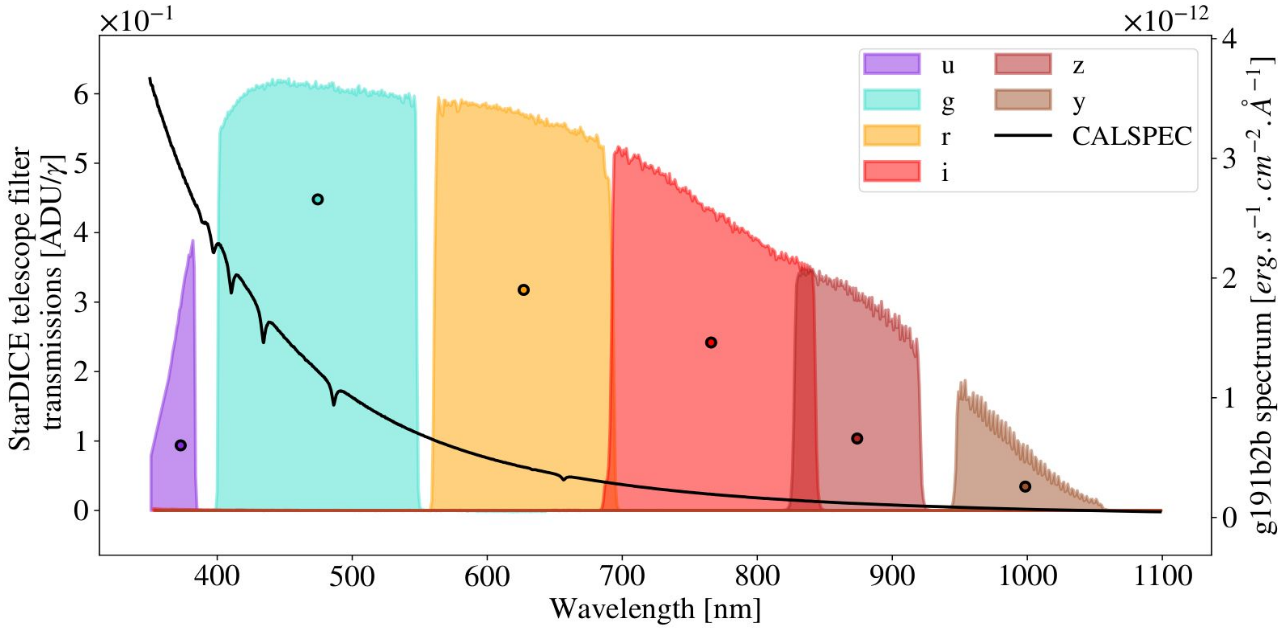
StarDICE goals



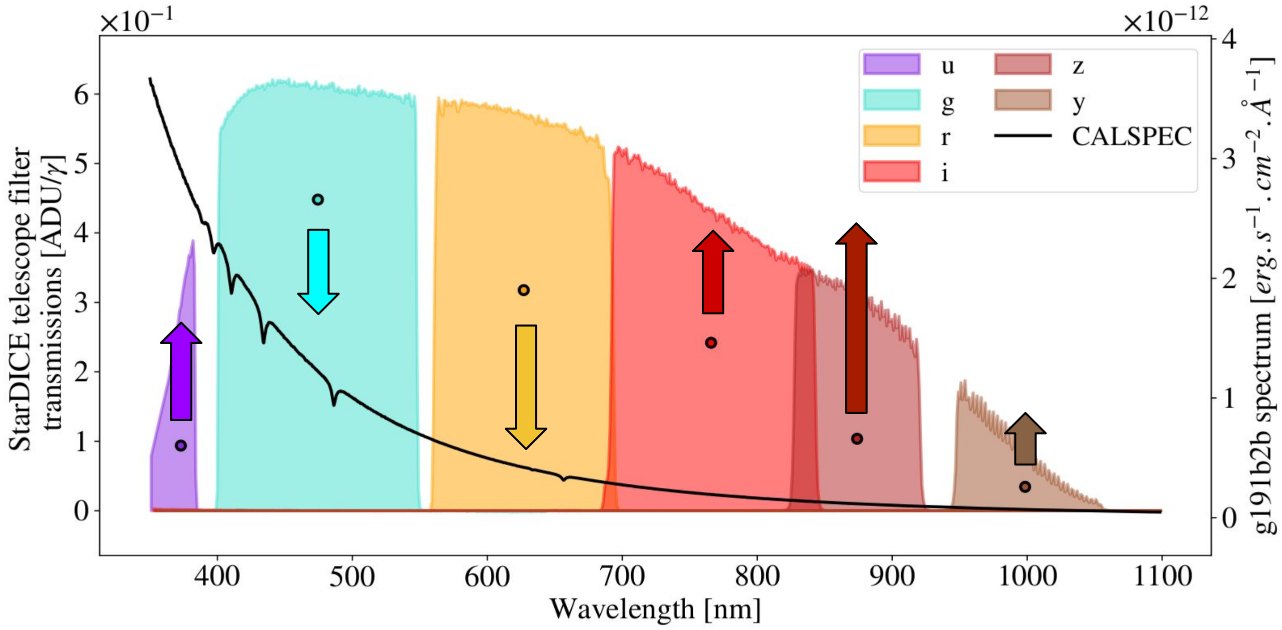
Measurement of the spectra of CALSPEC standard stars

⇒ Refine the zero point of the CALSPEC calibration

Zero point definition



Zero point definition

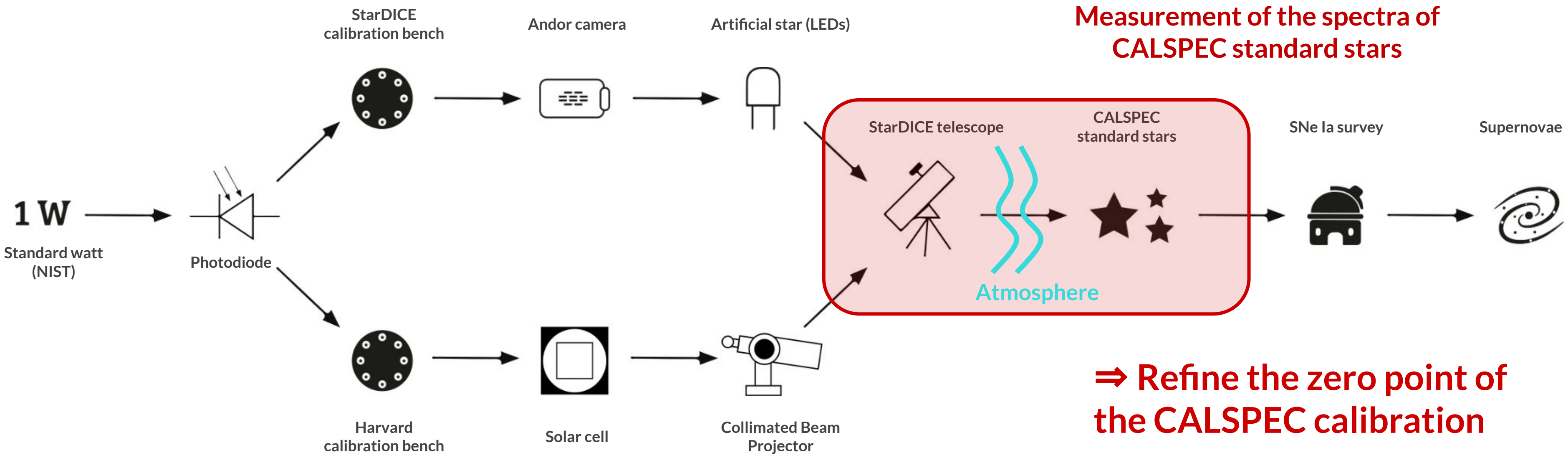


StarDICE is observing photometric standards:

- Prior spectra given by CALSPEC
- Prior knowledge of filter transmissions (CBP + Artificial star)

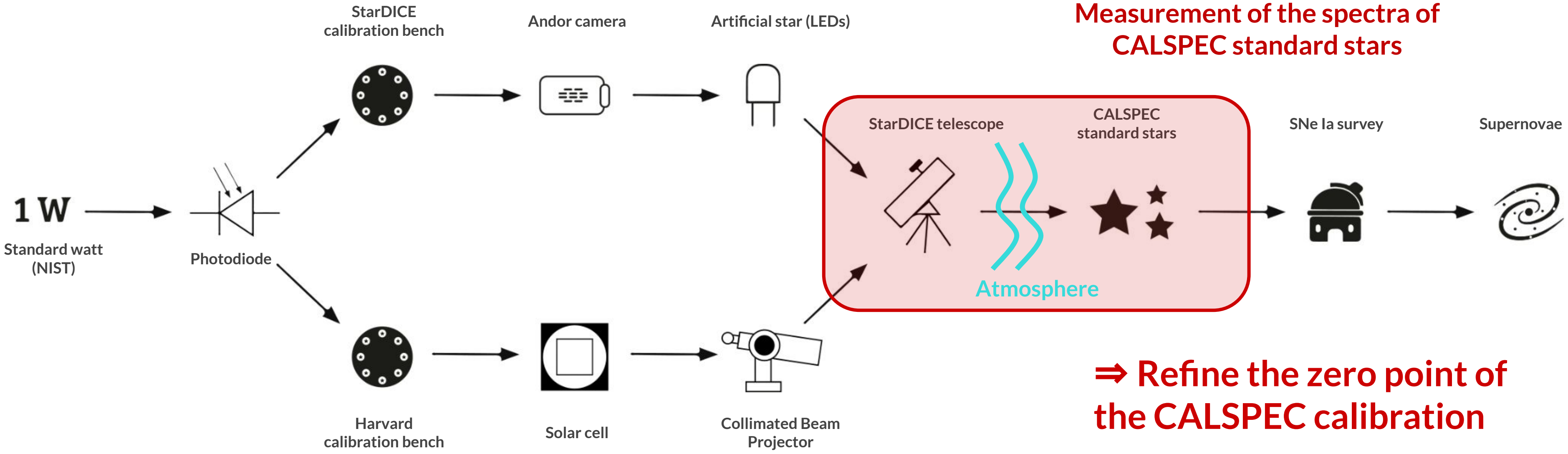
⇒ Theory/Measurements to adjust the zero points

StarDICE goals



⇒ Refine the zero point of the CALSPEC calibration

StarDICE goals



Measurement of the spectra of CALSPEC standard stars

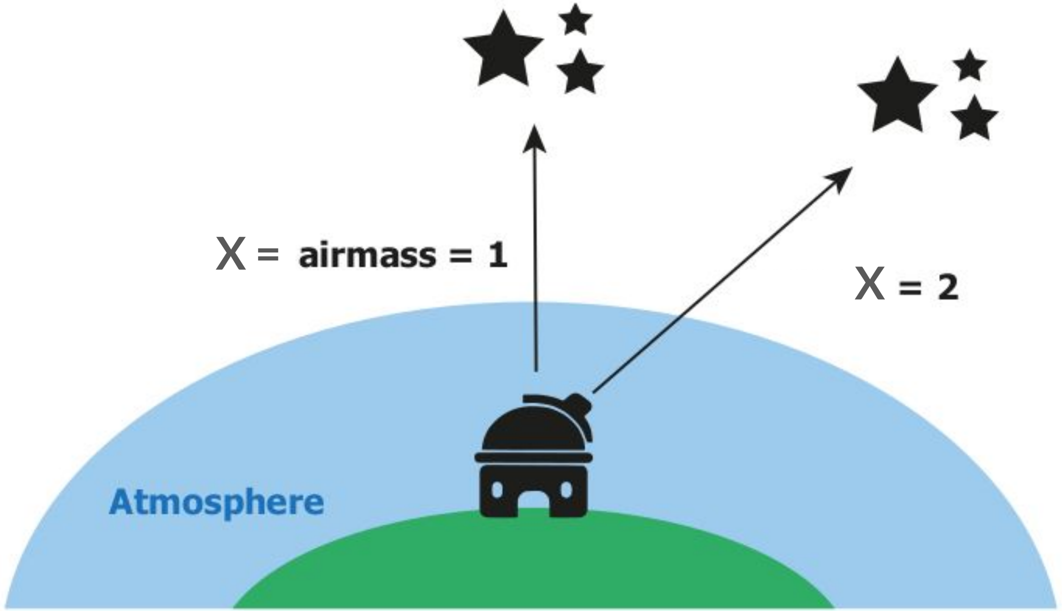
⇒ Refine the zero point of the CALSPEC calibration

Two paths:

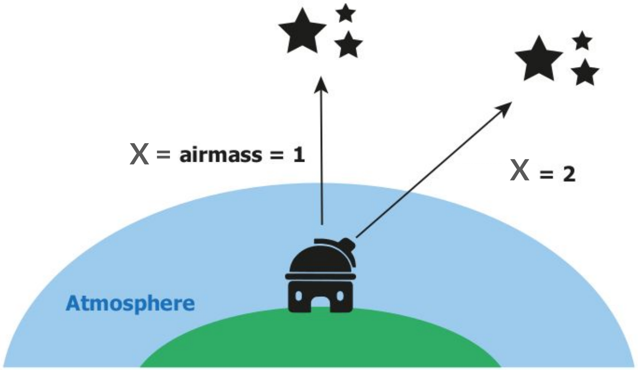
- Photometry at different elevations
- Spectrophotometric measurements

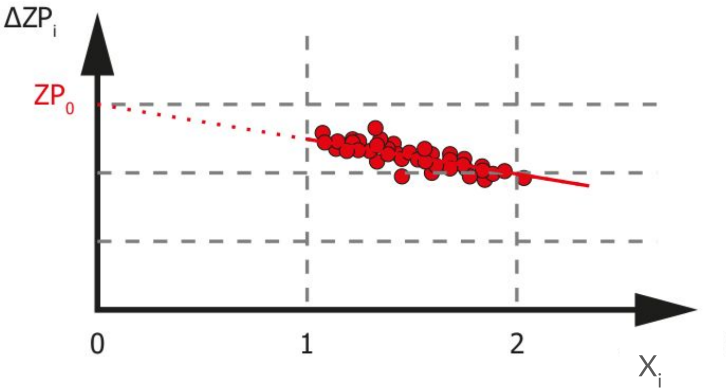
6.a. Photometric analysis

Airmass



Atmospheric considerations

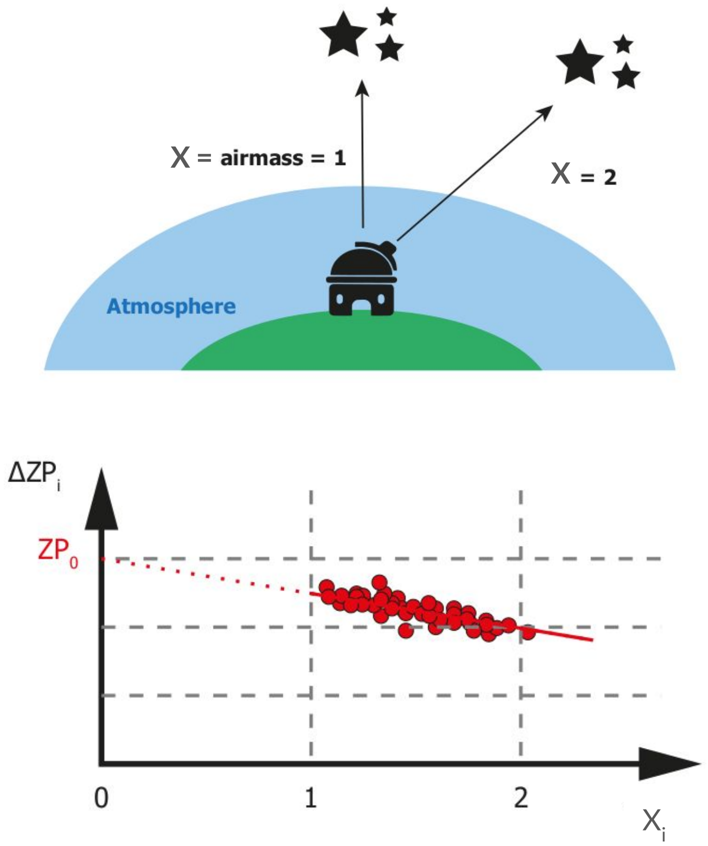




Airmass regression:

- Take images of a reference star at different airmass values $\mathbf{X_i}$
- Compute zero point difference $\mathbf{\Delta ZP_i}$ for each image **i**

Atmospheric considerations



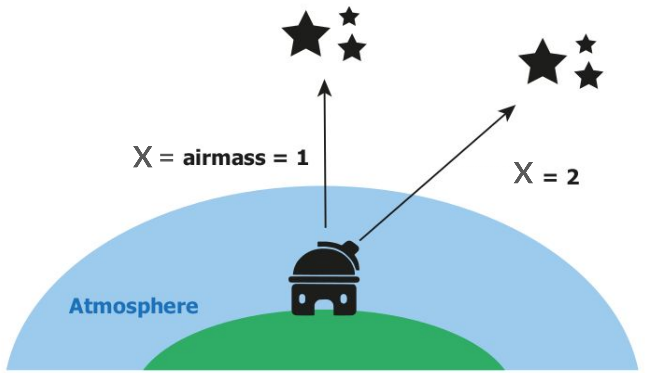
Airmass regression:

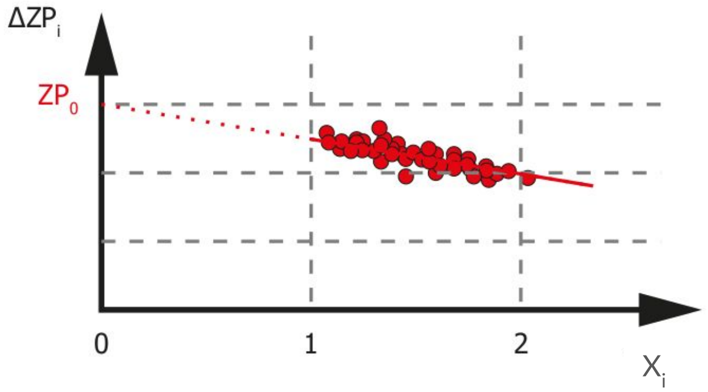
- Take images of a reference star at different airmass values $\mathbf{X_i}$
- Compute zero point difference $\mathbf{\Delta ZP_i}$ for each image **i**

Final goal:

- Estimate the out-of-atmosphere zero point $\mathbf{ZP_0}$ by extrapolating the value at **X=0**

Atmospheric considerations





Airmass regression:

- Take images of a reference star at different airmass values $\mathbf{X_i}$
- Compute zero point difference $\mathbf{\Delta ZP_i}$ for each image **i**

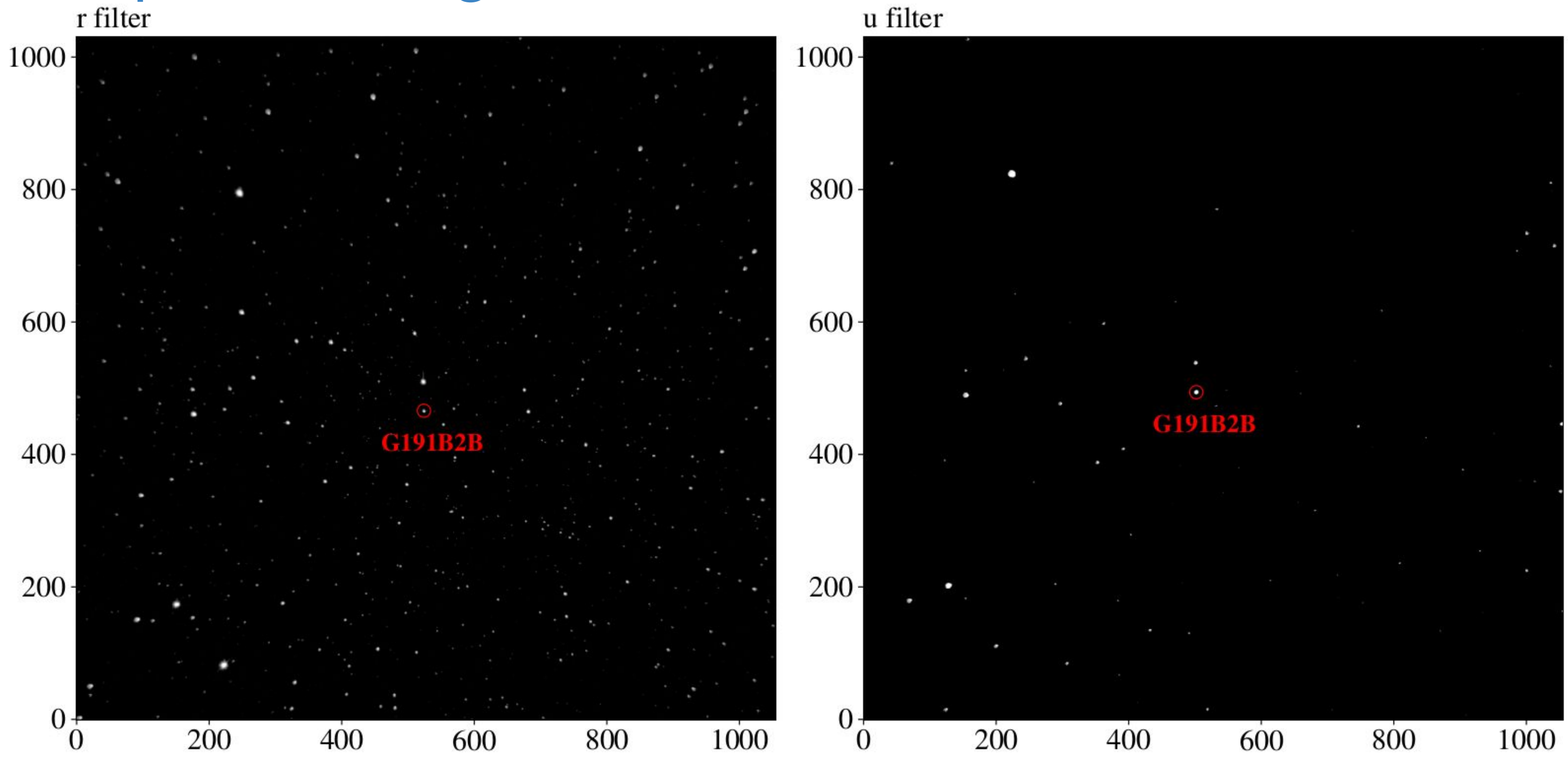
Final goal:

- Estimate the out-of-atmosphere zero point $\mathbf{ZP_0}$ by extrapolating the value at **X=0**

This analysis:

- Estimate the StarDICE performance of refining the $\mathbf{ZP_0}$ with a 2-year survey

Examples of image



Pre-survey: 23 observation nights of the CALSPEC primary standard G191B2B

Synthetic photometry

Star spectral energy density (SED)

Atmosphere transmission

StarDICE collection surface

$$F^{\text{synth}} = \int_\lambda S_\star(\lambda) \times R_{\text{tel}}(\lambda) \times T_{\text{atm}}(\lambda, P_a) \times t_{\text{exp}} \times A_{\text{mirror}} \times \frac{\lambda d\lambda}{hc}$$

StarDICE flux

StarDICE telescope response

Exposition time

Synthetic photometry

$S_\star(\lambda)$ → GAIA catalog low resolution spectra

$R_{\text{tel}}(\lambda)$ → CBP measurements

$T_{\text{atm}}(\lambda)$ → Libradtran simulations with **airmass**, **pressure** and **humidity** (ozone, aerosols and PWV are fixed)

Fitting zero points

Magnitude difference for every star *s* in every image *i*:

$$\Delta\hat{m}_{i,\,s} = m_{i,\,s}^{\mathrm{obs}} - m_{i,\,s}^{\mathrm{synth}}$$

⇒ Estimate the variation $\Delta \mathrm{ZP}_i$ from an image to another, accounting for a star variance model

Fitting zero points

Magnitude difference for every star *s* in every image *i*:

$$\Delta\hat{m}_{i,\,s} = m_{i,\,s}^{\mathrm{obs}} - m_{i,\,s}^{\mathrm{synth}}$$

⇒ Estimate the variation ΔZP_i from an image to another, accounting for a star variance model

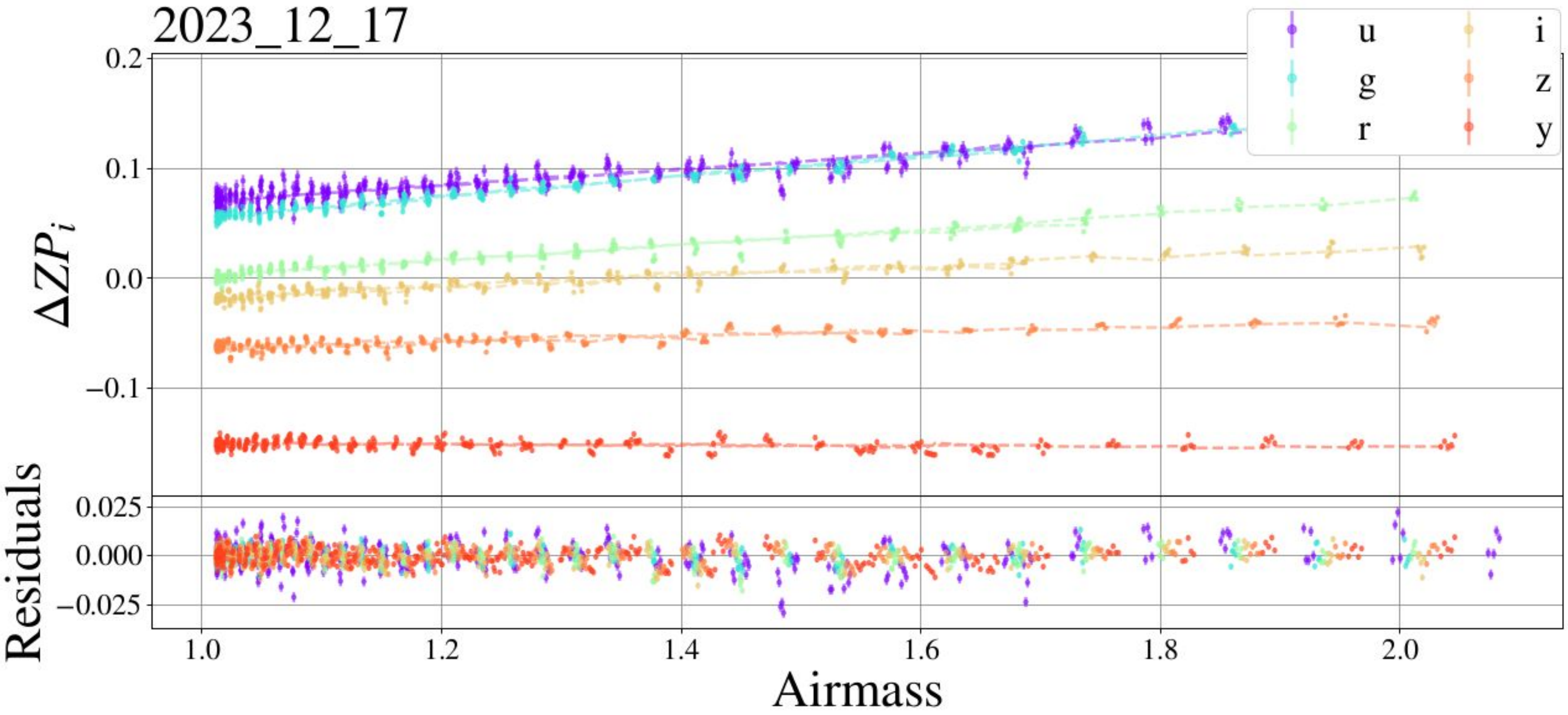
Variation from an image to another for a band *b*:

Atmosphere

Out-of-atmosphere zero point

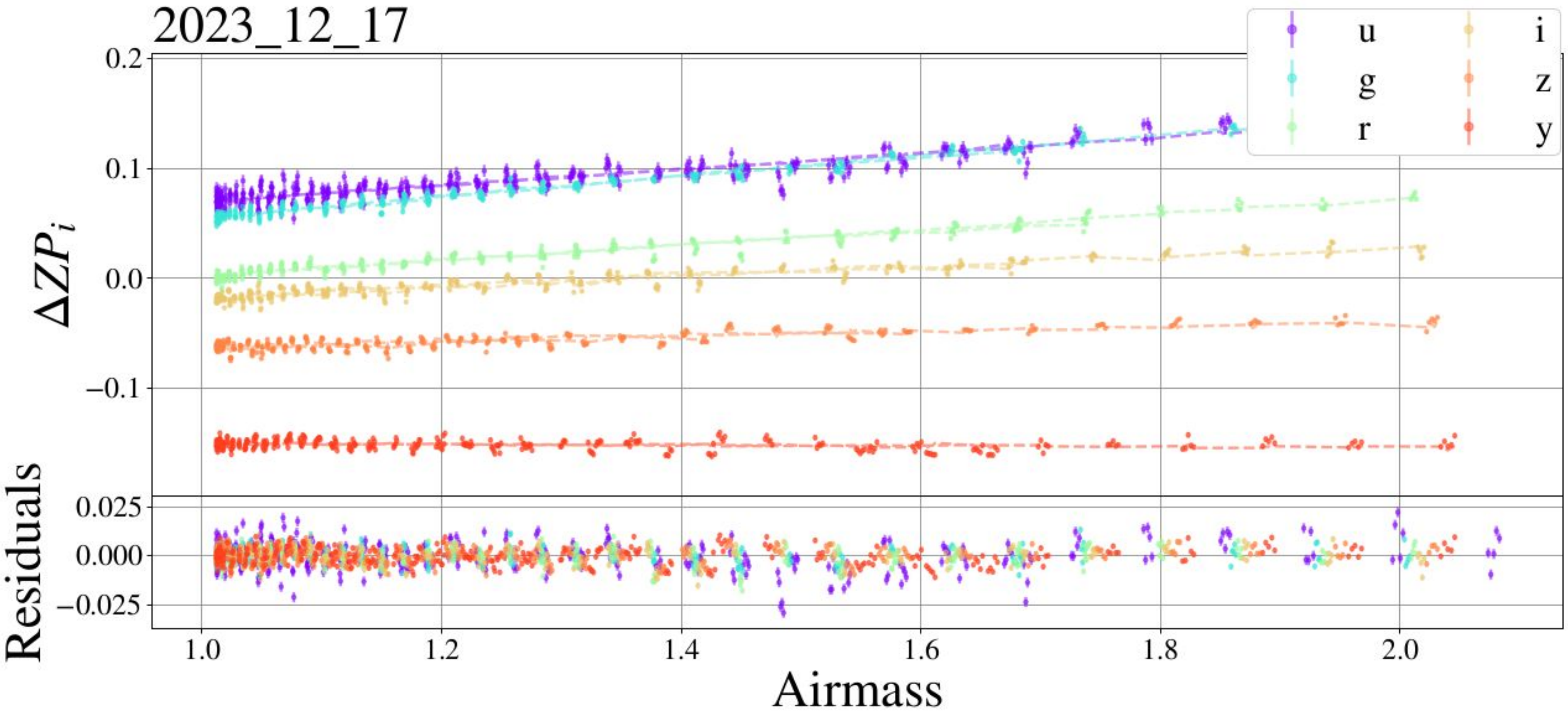
$$\Delta ZP_{\mathrm{b},\,i}(X) = k_{\mathrm{b}} X_i + ZP_{0,\mathrm{b}}$$

ΔZPi vs airmass



$$\Delta ZP_{\mathrm{b},\,i}(X) = k_{\mathrm{b}} X_i + ZP_{0,\mathrm{b}}$$

ΔZPi vs airmass



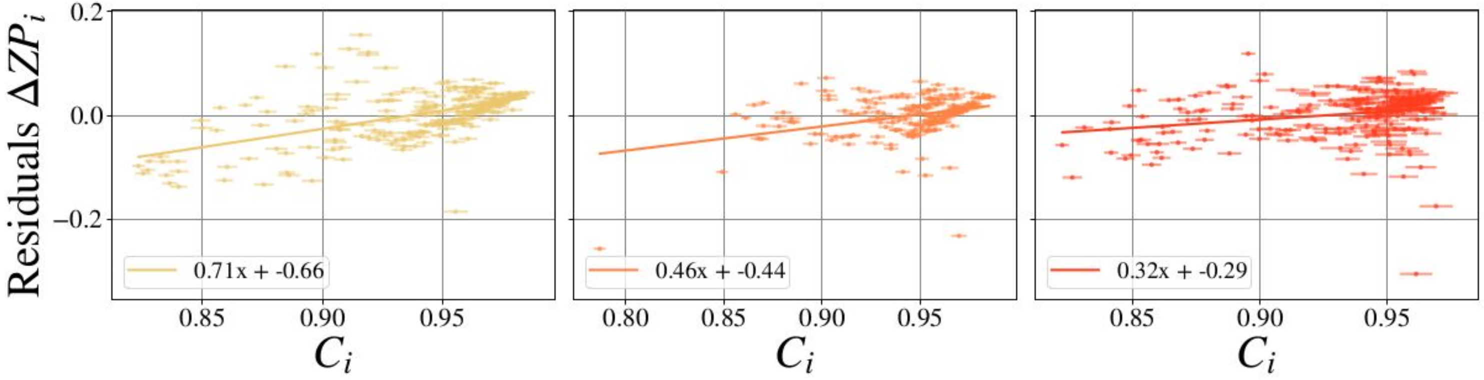
Scintillation, PSF variation...

$$\Delta ZP_{\mathrm{b},\,i}(X) = k_{\mathrm{b}} X_i + ZP_{0,\mathrm{b}}$$

Aperture correction

$$C_i = \frac{1}{20} \sum_{s}^{20} \frac{F_{i,s}^{\mathrm{obs}}\,(5.6\mathrm{px})}{F_{i,s}^{\mathrm{obs}}\,(7.7\mathrm{px})}$$

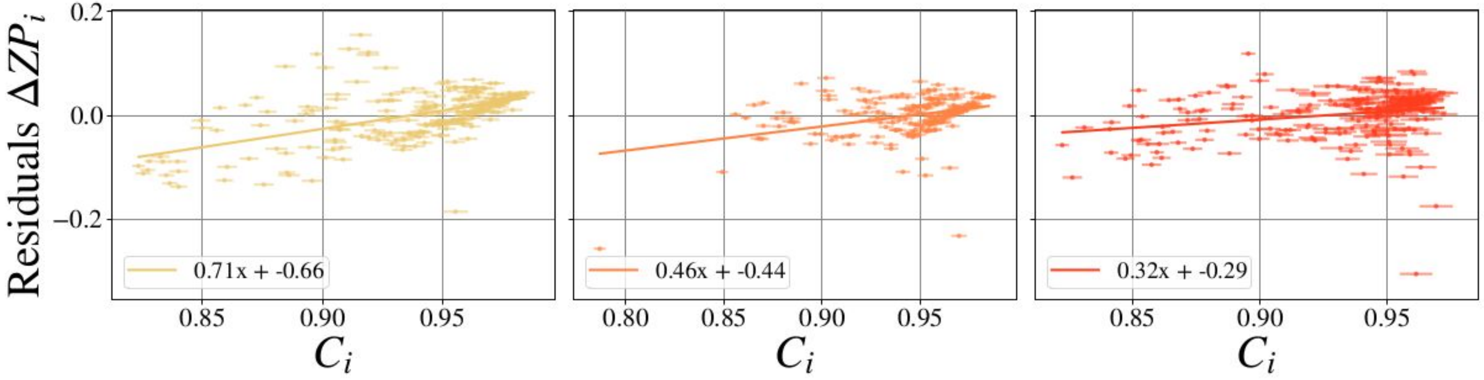
⇒ **Proxy to estimate PSF variations**



Aperture correction

$$C_i = \frac{1}{20} \sum_{s}^{20} \frac{F_{i,s}^{\mathrm{obs}}(5.6\mathrm{px})}{F_{i,s}^{\mathrm{obs}}(7.7\mathrm{px})}$$

⇒ **Proxy to estimate PSF variations**



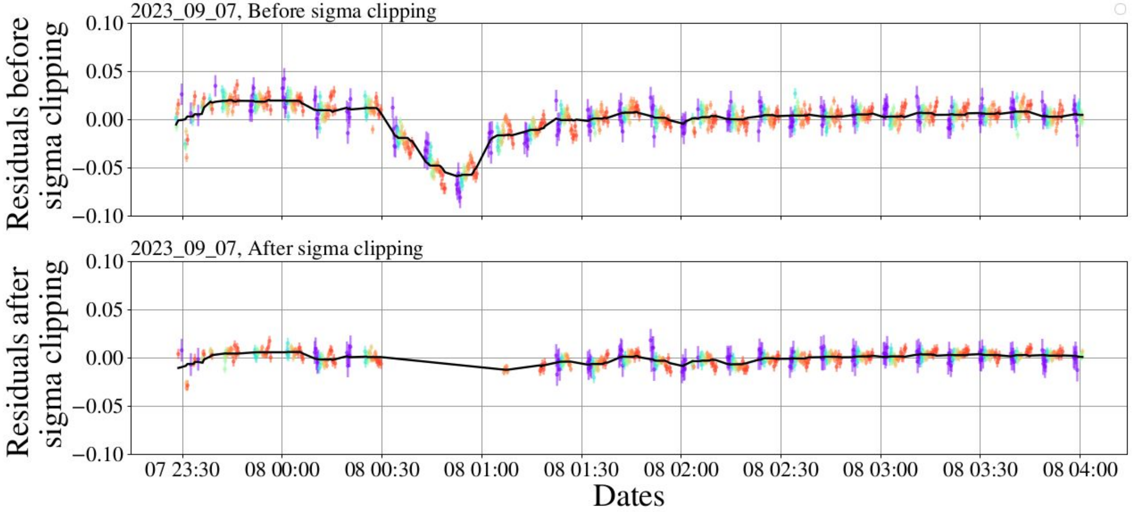
Atmosphere

Out-of-atmosphere zero point

$$\Delta ZP_{\mathrm{b},\,i}(X, C) = k_{\mathrm{b}} X_i + \alpha_{\mathrm{b}} C_i + ZP_{0,\mathrm{b}}$$

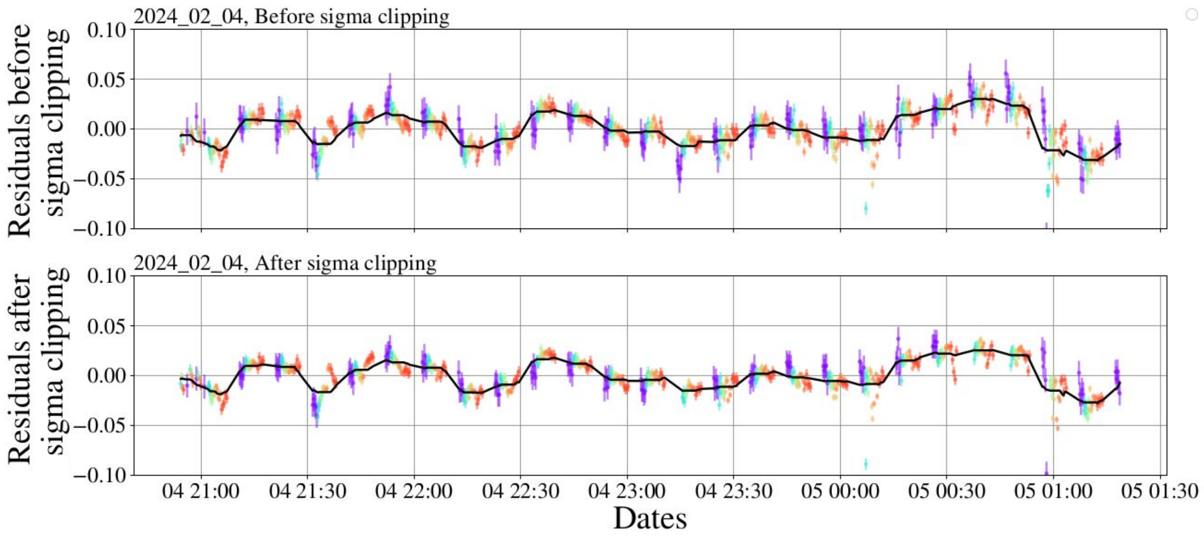
Aperture correction

Rejection of non-photometric nights



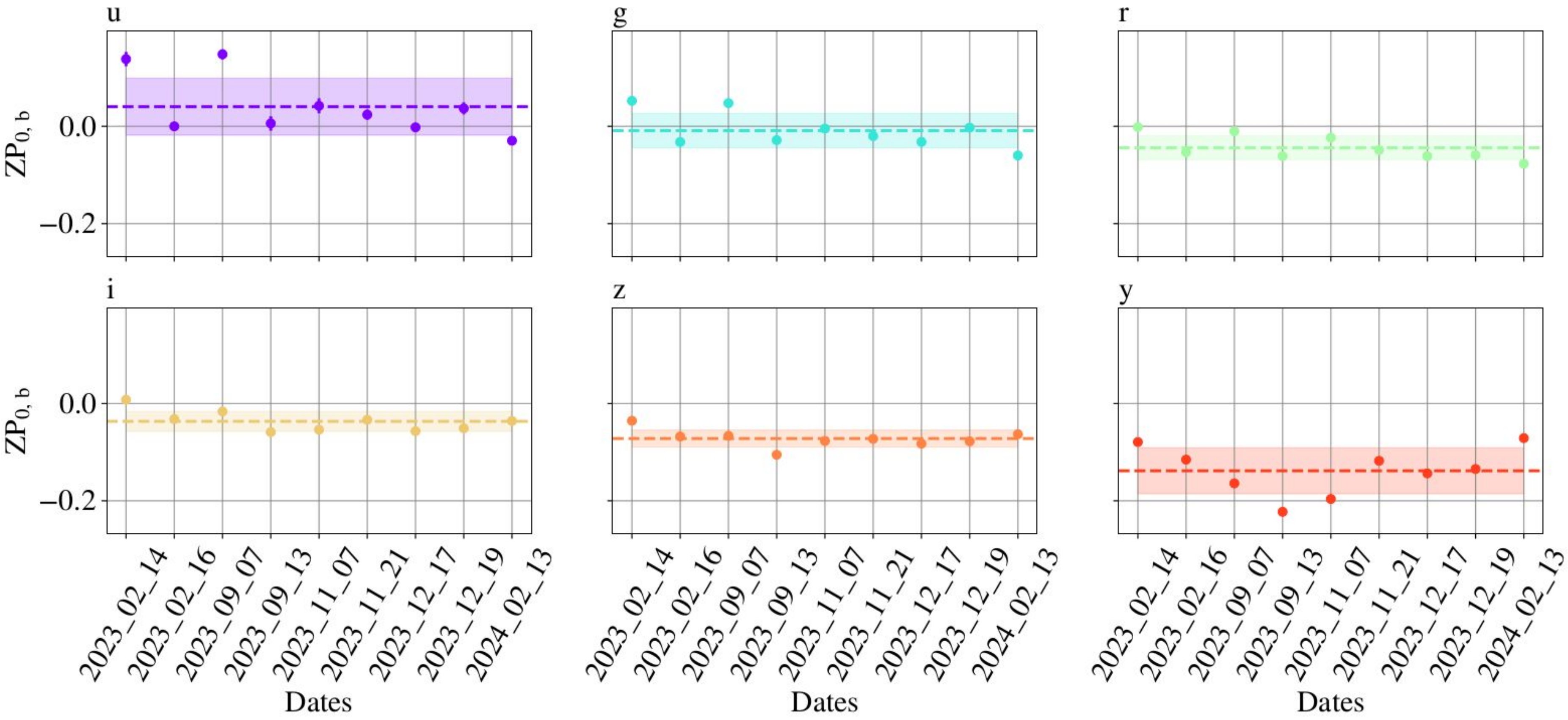
- **Gray extinction** between ~00:30 and ~01:20 ⇒ **cloud extinction**
- Compute **rolling mean $\mu_{rolling}$** in **all bands**
- Cut every points higher than **3$\sigma_{rolling}$**

Rejection of non-photometric nights



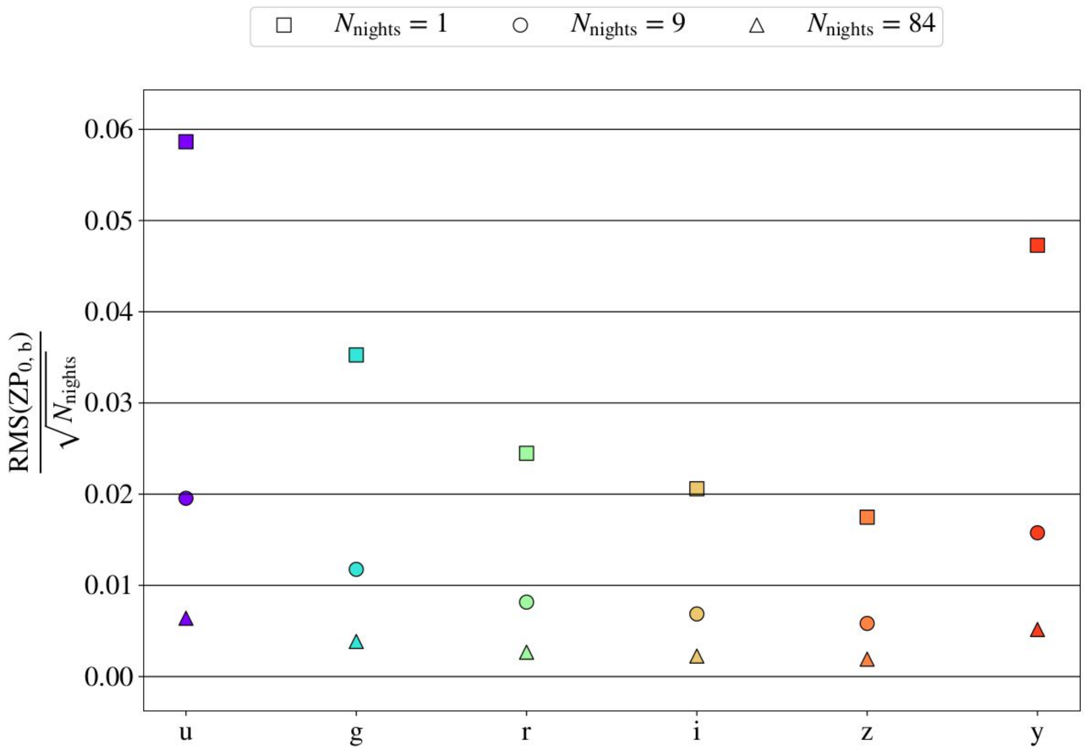
- **Faint oscillations** lower than $\mathbf{3\sigma_{rolling}}$ ⇒ **no cut performed**
- Set the threshold $\boldsymbol{\sigma_{rolling}}$ **> 0.005** to detect non-photometric nights
- Ends up with **9 photometric nights** kept

Results



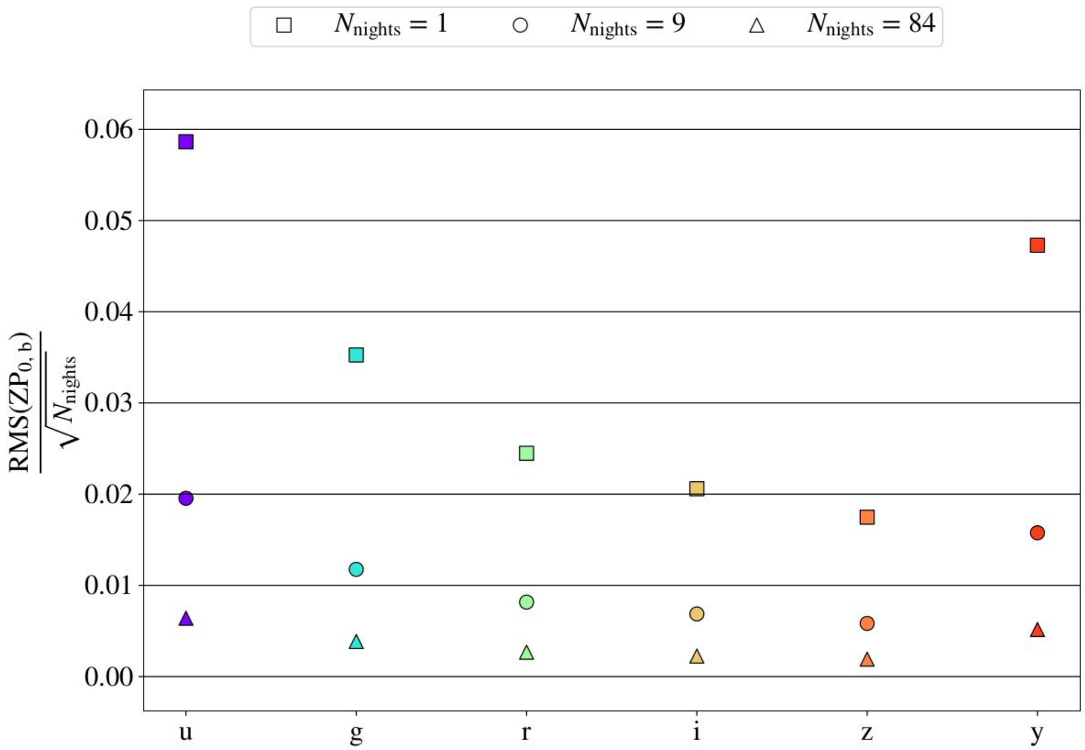
u
g
r
i
z
y
ZP0, b
0.0
−0.2
2023_02_14
2023_02_16
2023_09_07
2023_09_13
2023_11_07
2023_11_21
2023_12_17
2023_12_19
2024_02_13
Dates

StarDICE performances projection



- **9** photometric nights
- StarDICE 2-year survey estimation ⇒ **84 nights**
- **~0.2 to 0.4% uncertainty**

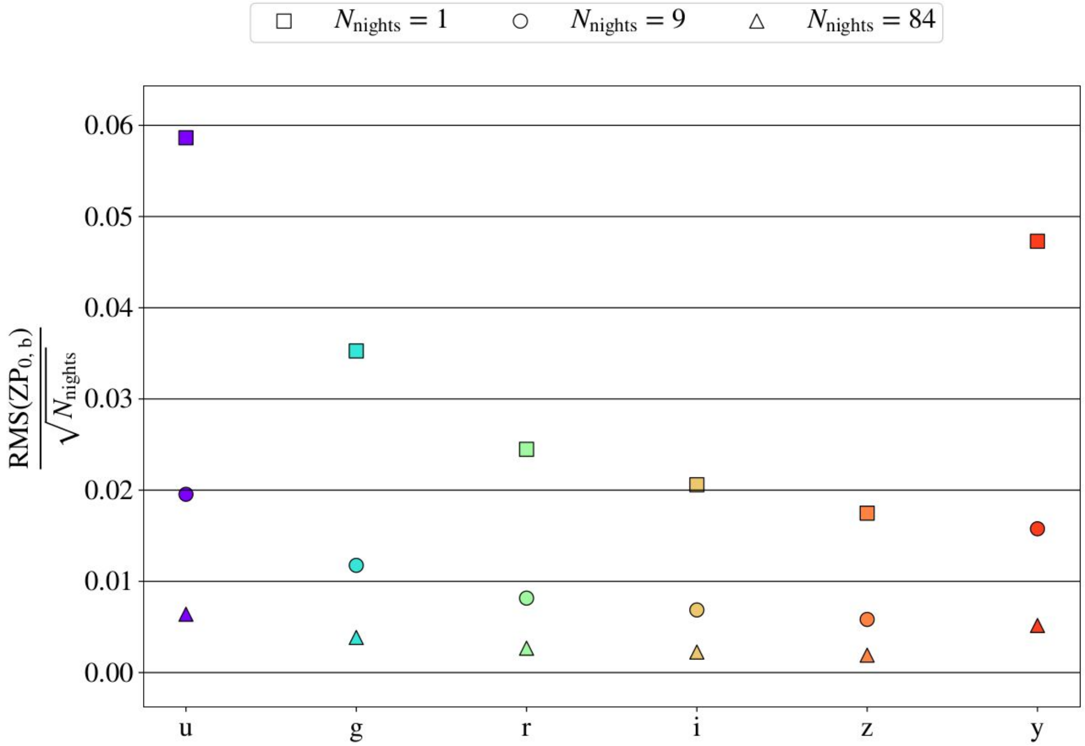
StarDICE performances projection



- **9** photometric nights
- StarDICE 2-year survey estimation ⇒ **84 nights**
- **~0.2 to 0.4% uncertainty**

⇒ 2 to 4 times the suitable value to fully exploit the future LSST SNe Ia dataset

StarDICE performances projection



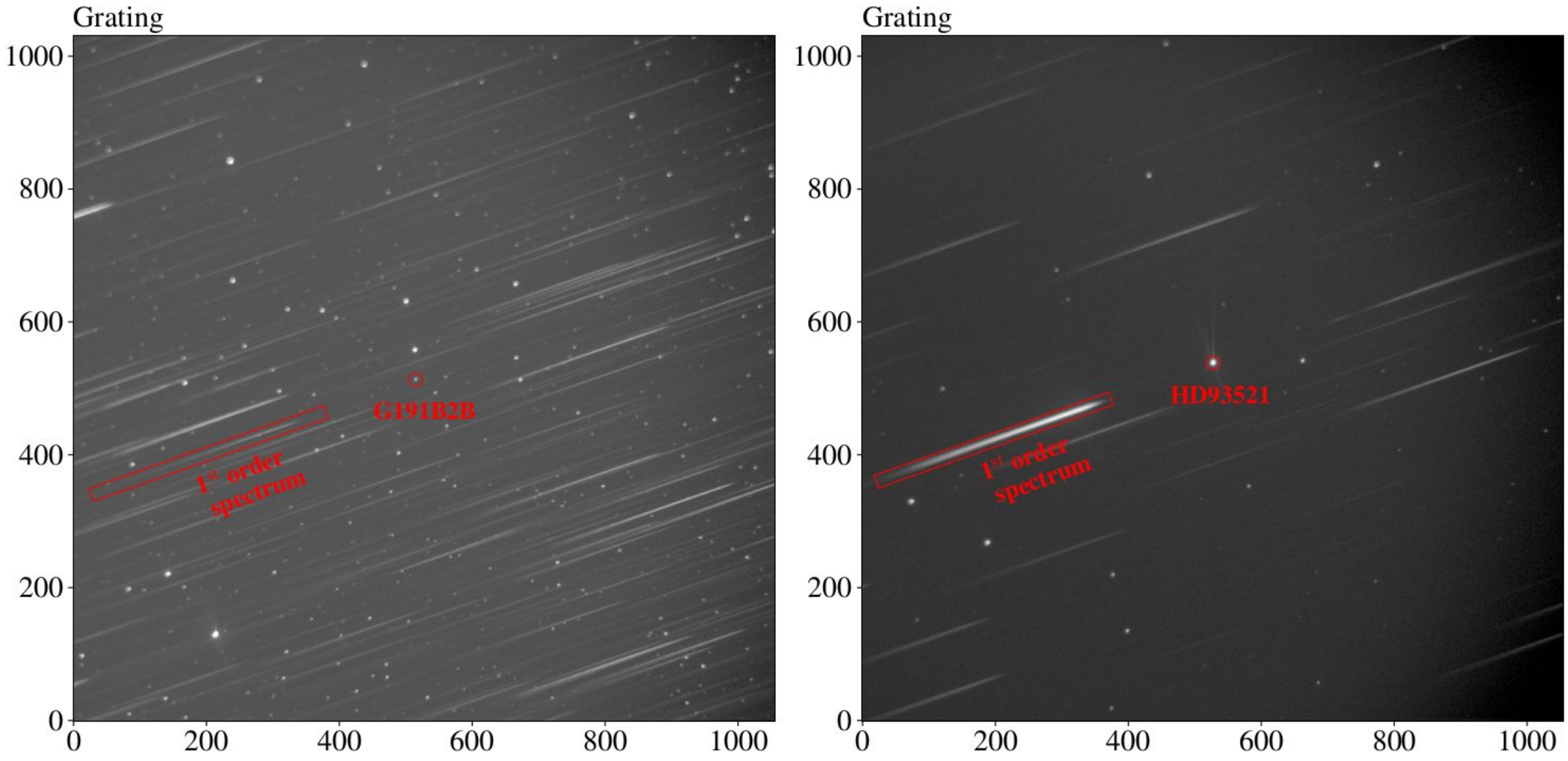
- 9 photometric nights
- StarDICE 2-year survey estimation ⇒ **84 nights**
- **~0.2 to 0.4% uncertainty**

⇒ 2 to 4 times the suitable value to fully exploit the future LSST SNe Ia dataset

⇒ Improve the atmosphere transmission prior by fitting live parameters

6.b. Spectrophotometric analysis

Image examples

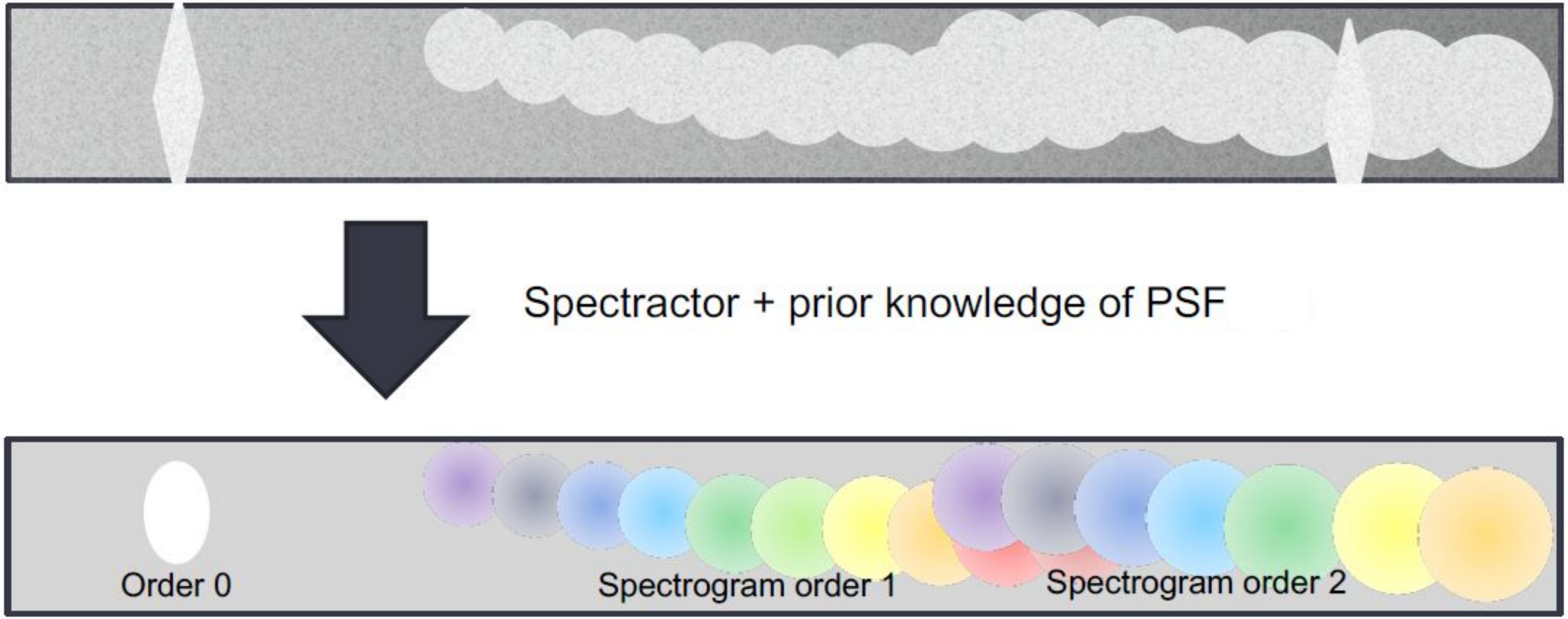


Slitless spectrophotometry

Spectractor software (Neveu et al. 2021)

Slitless spectrophotometry

Spectractor software (Neveu et al. 2021)

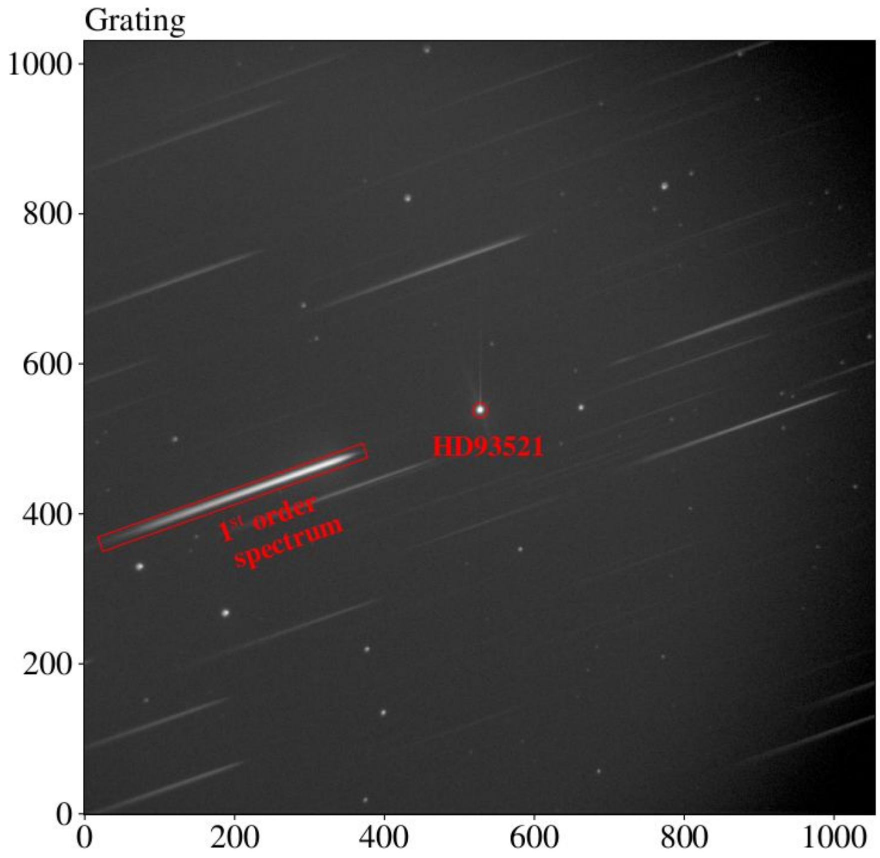


HD93521 spectrum

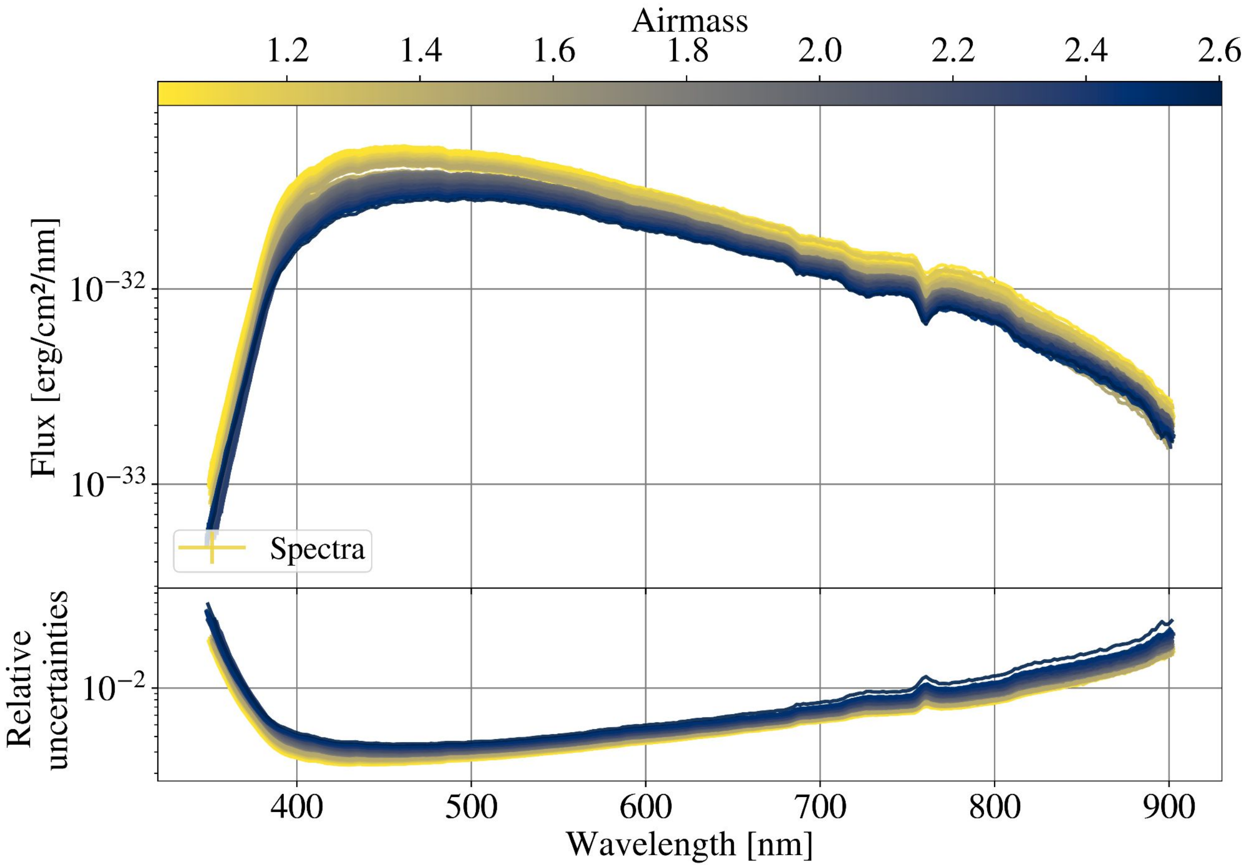
Spectrum extraction of HD93521

- 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

Atmosphere extraction

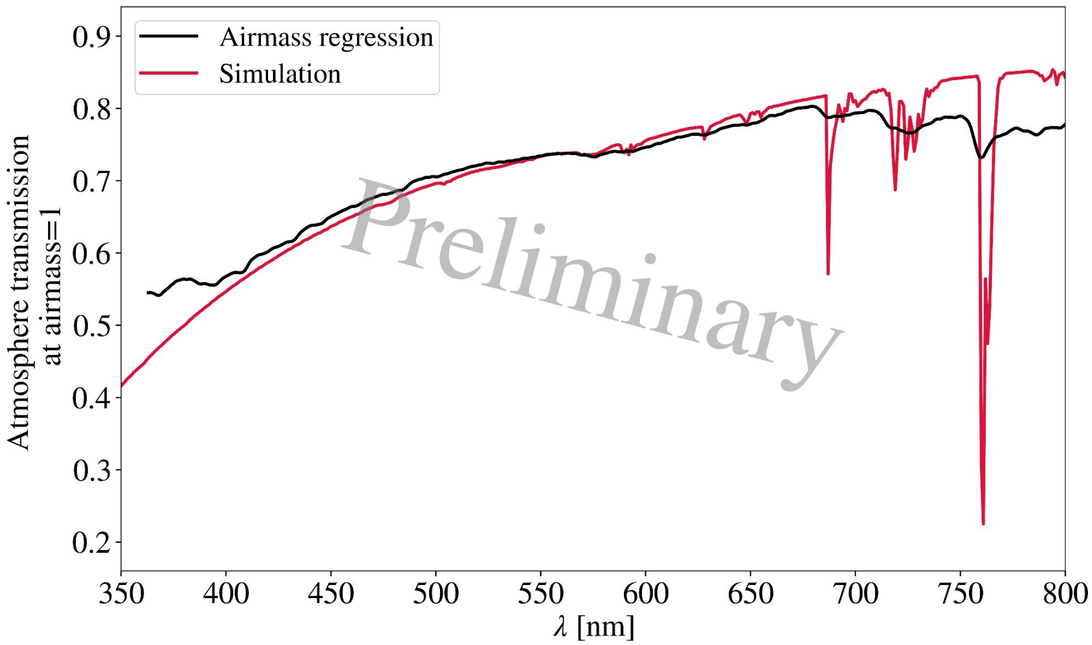
Two methods:

- Fit the atmosphere transmission with prior on the star SED and telescope response

Atmosphere extraction

Two methods:

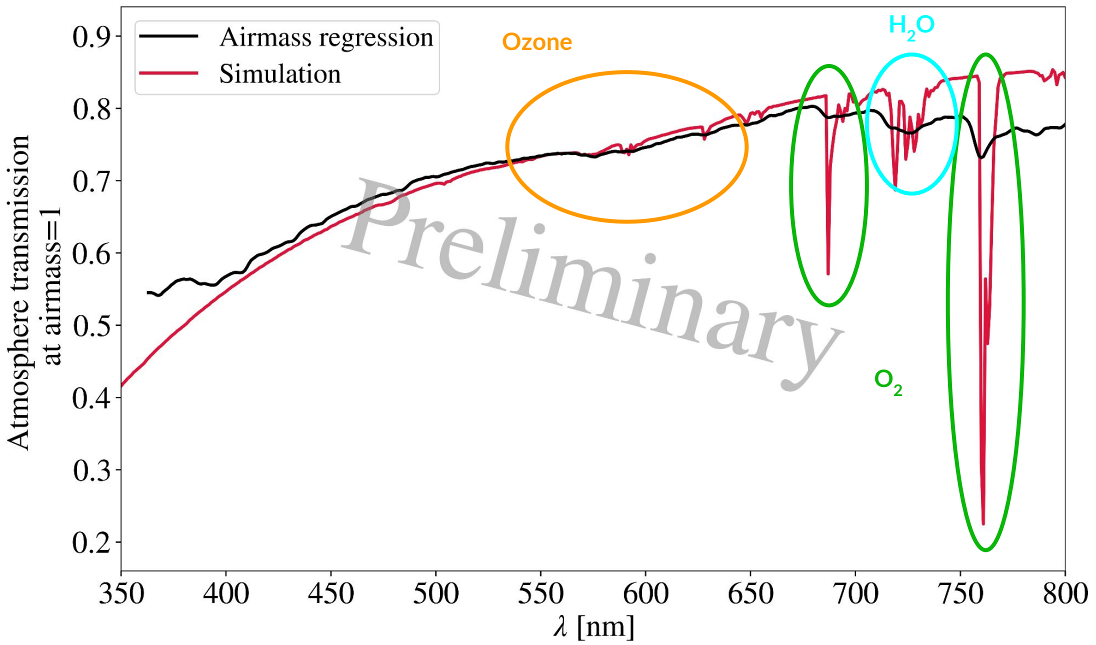
- Fit the atmosphere transmission with prior on the star SED and telescope response
- Perform an airmass regression



Atmosphere extraction

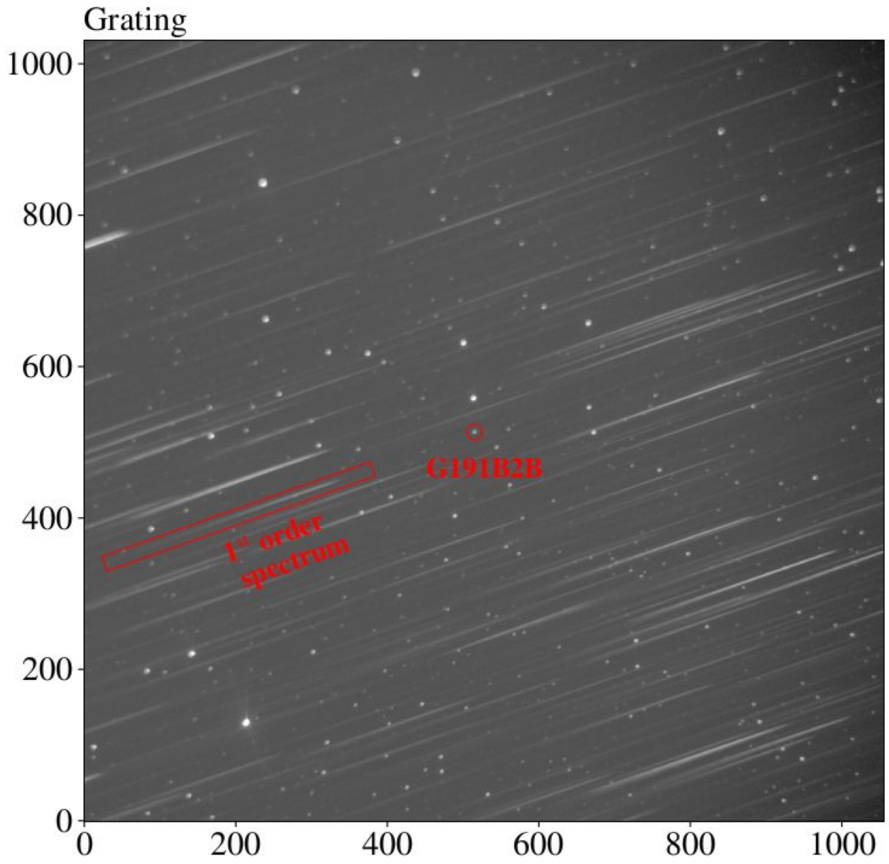
Two methods:

- Fit the atmosphere transmission with prior on the star SED and telescope response
- Perform an airmass regression



G191B2B spectrum

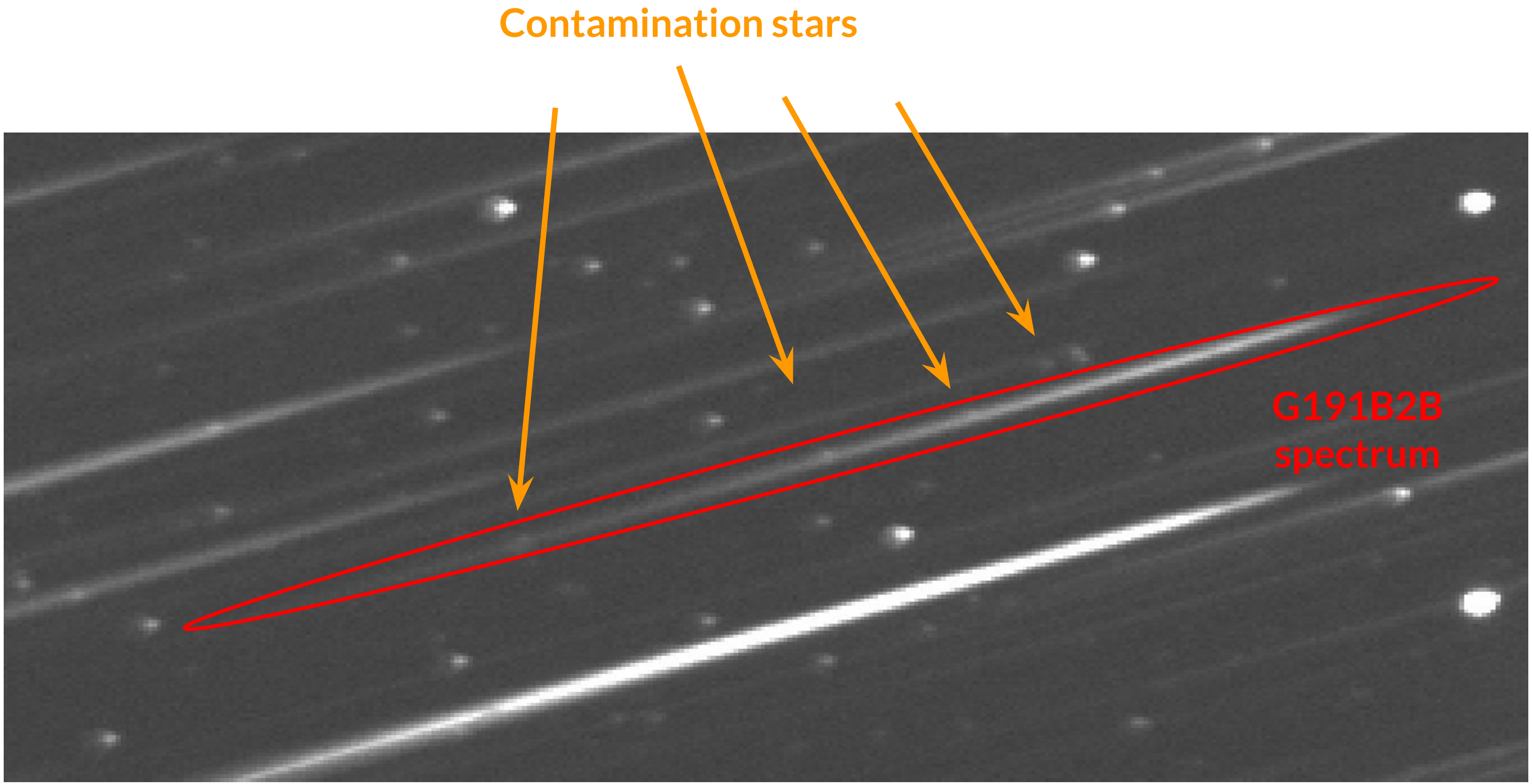
Image of G191B2B observed by StarDICE with the grating in the filterwheel



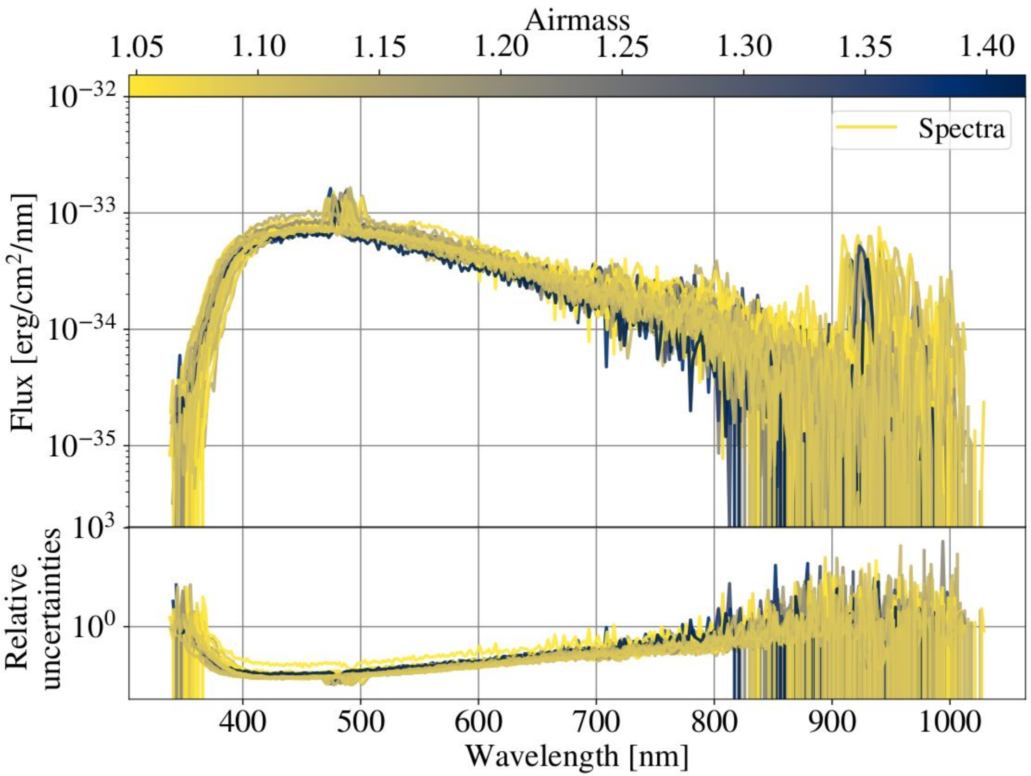
Spectrum extraction of G191B2B

- Primary CALSPEC standard
- Faint: $m_{G191B2B} = 11.69$
- Very crowded field

Zoom on G191B2B spectrum



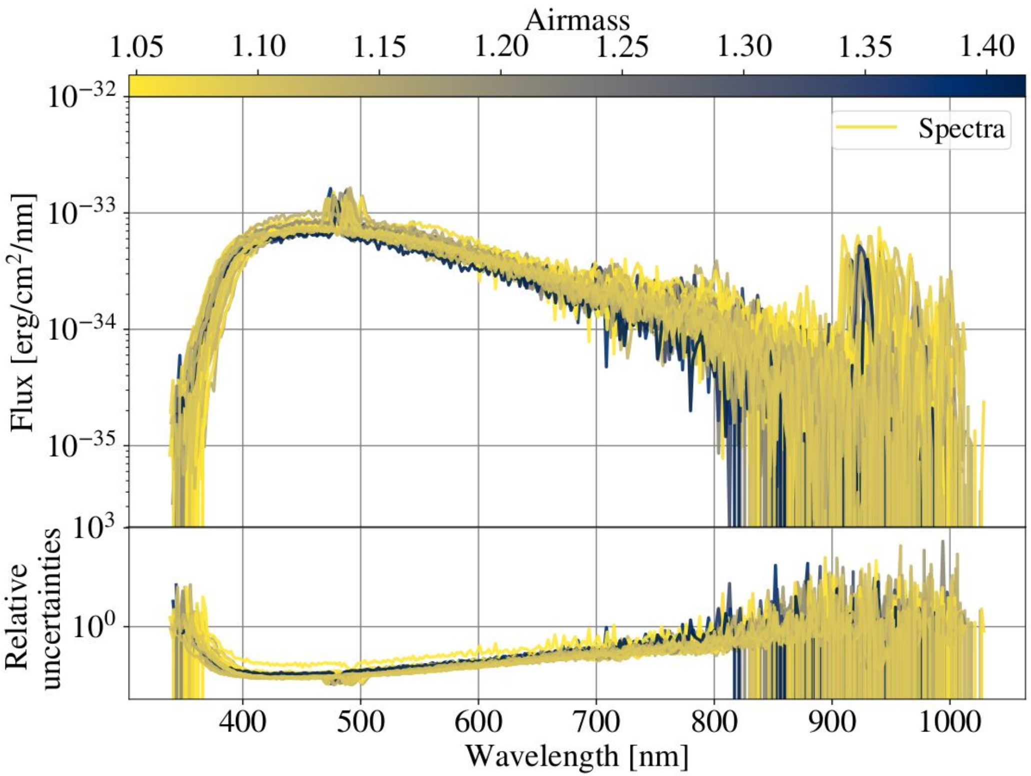
G191B2B spectra extraction



- ~100 images at different airmasses

⇒ The fit crashes because of stars overlapping with the spectrum

G191B2B spectra extraction



- ~100 images at different airmasses

⇒ The fit crashes because of stars overlapping with the spectrum

Solutions:

- Develop full-forward model of the star field (work in progress)
- Extract brighter stars in the field

6.c. Conclusion

Conclusion

Photometry

- Measurements of **ZP_0** for StarDICE filters

Future developments:

- Priors improveable (**artificial star + atmosphere transmission fit**)
- **Forced photometry** to prevent selection bias for faint stars
- Infrared data to measure **smaller gray extinction from clouds**

Spectrophotometry

- **Feasibility** of extracting spectra on **StarDICE images**
- Joint effort with the **Auxiliary Telescope (AuxTel)** at Rubin observatory to measure **atmospheric transmissions**

Future developments:

- Atmosphere fit → **PWV**, **ozone**, **aerosols** ⇒ crucial for photometric analysis
- **Forward model** of the **starfield** for crowded images

7. General conclusion

General conclusion

- SNe Ia cosmology needs to **improve photometric calibration (CBP, StarDICE...)** to be certain of **unbiased dark energy measurements**

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- **CBP:**
    - **Results** will be detailed in a **paper** soon (**Souverin et al., in prep.**)
    - Measured **bandpasses** with **high resolution**, and detected **out-of-band leaks**
    - Proof of concept **validated** for measuring SNe Ia survey telescopes (**Rubin-CBP** for **LSST**, **Traveling-CBP** for **ZTF**…)

General conclusion

- SNe Ia cosmology needs to **improve photometric calibration (CBP, StarDICE…)** to be certain of **unbiased dark energy measurements**
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  - Proof of concept **validated** for measuring SNe Ia survey telescopes (**Rubin-CBP** for **LSST**, **Traveling-CBP** for **ZTF**…)
- **StarDICE:**
  - Pre-survey → Validated the method to **refine zero point** of **CALSPEC calibration**
  - The **2-year survey** will benefit from the **artificial star,** an **infrared camera**, improving the photometric accuracy
  - **Slitless spectrophotometry** is a **powerful tool**, for both **atmospheric considerations**, and measuring the whole spectrum of a target in **one image**

Thank you for your attention

Backup slides

Cosmo

Cosmological principle

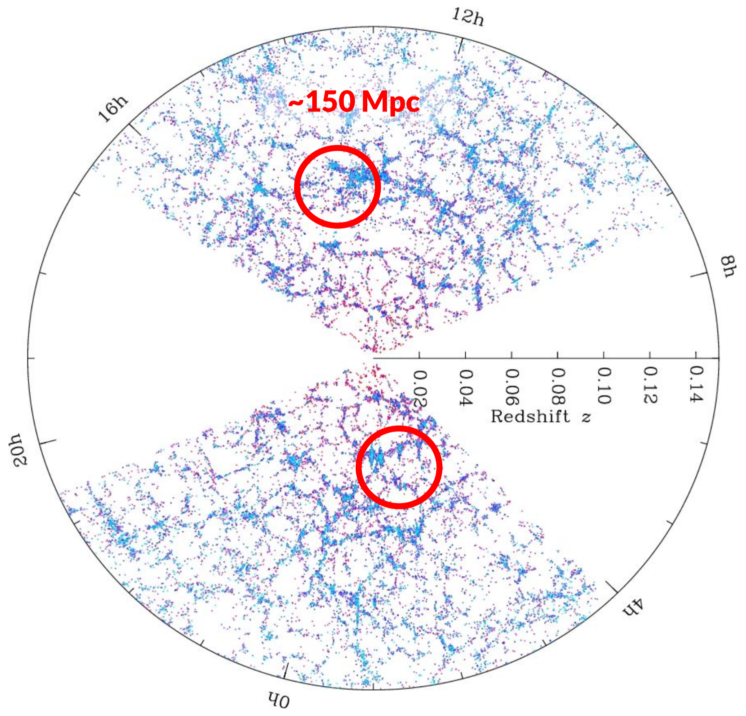
But the Universe is vast and full of stuffs, how can we study it?

Cosmological principle

But the Universe is vast and full of stuffs, how can we study it?

On cosmological scales, the Universe is considered:

- Homogeneous



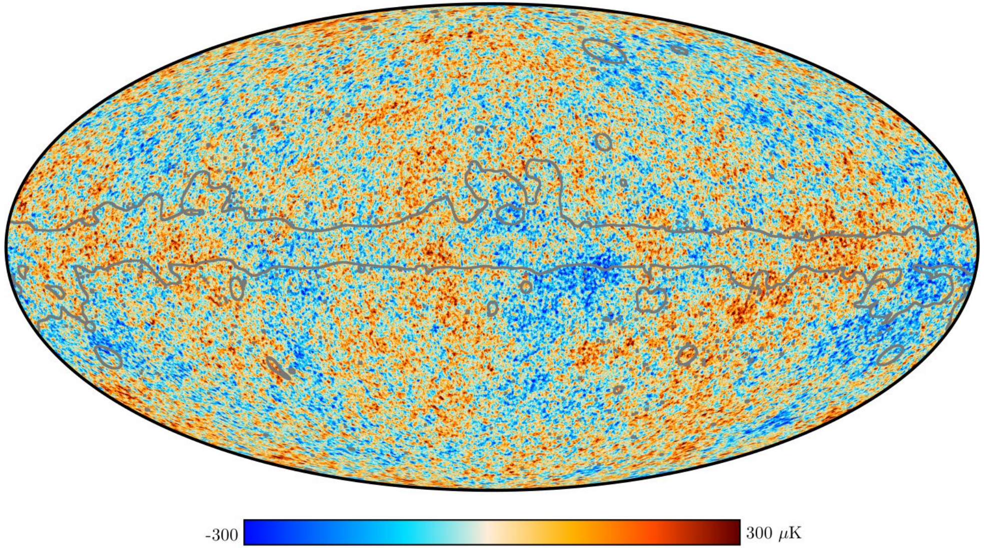
SDSS map of the distribution of galaxies

Cosmological principle

But the Universe is vast and full of stuffs, how can we study it?

On cosmological scales, the Universe is considered:

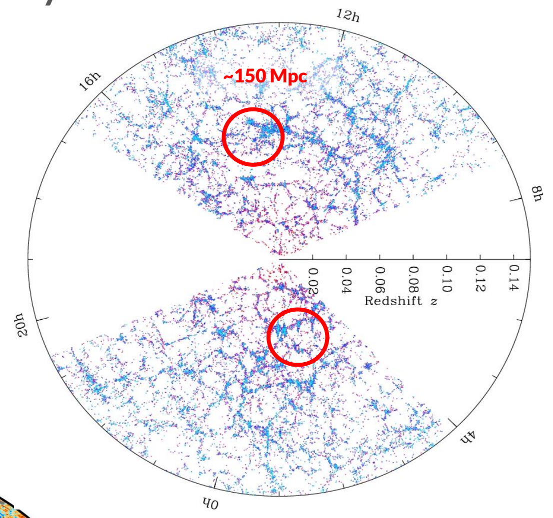
- Homogeneous
- Isotropic



CMB map from Planck Collaboration et al. 2020a

Cosmological principle

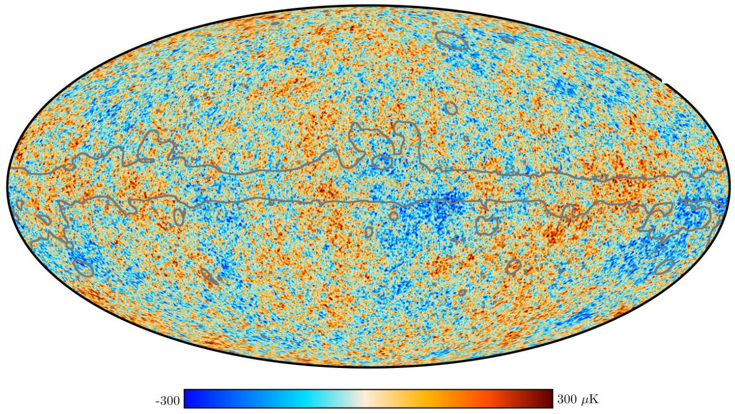
But the Universe is vast and full of stuffs, how can we study it?



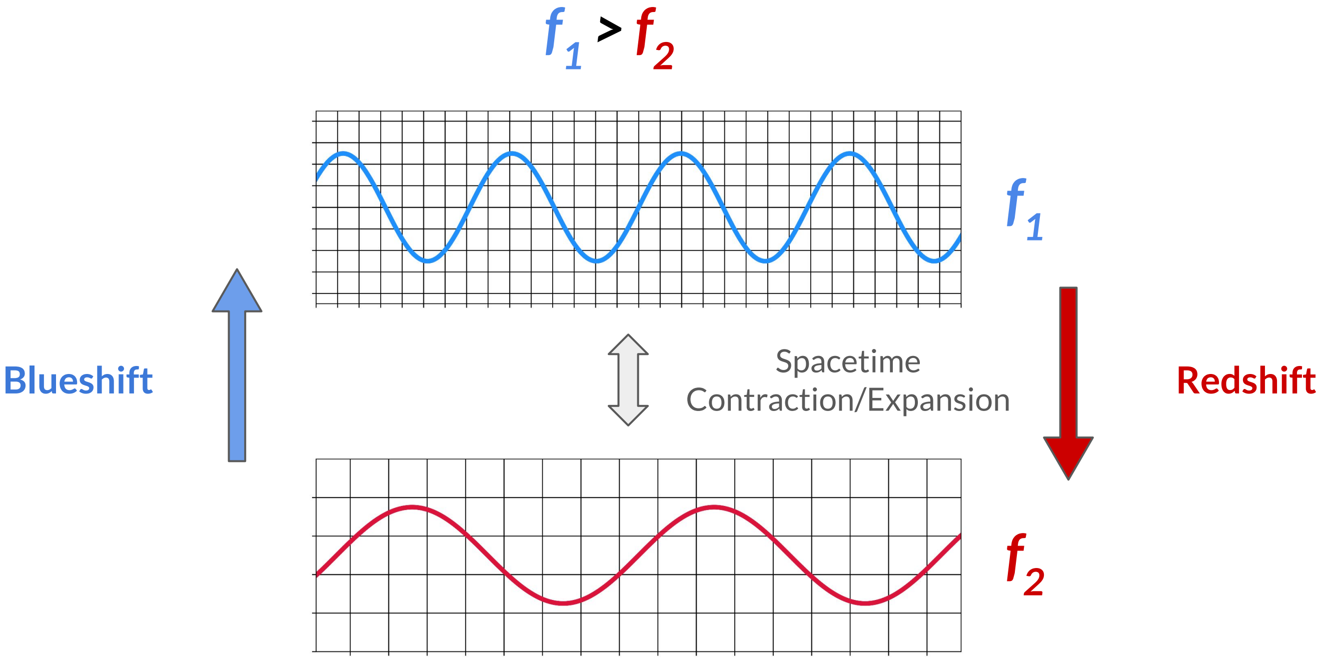
On cosmological scales, the Universe is considered:

- Homogeneous
- Isotropic

⇒ Cosmological principle



Spacetime evolution



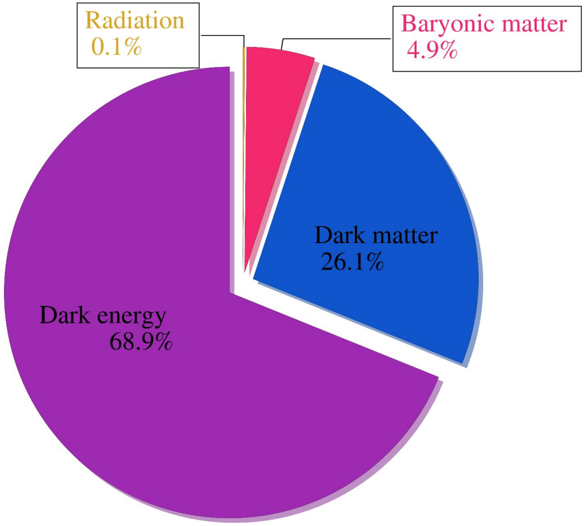
Spacetime deformations affect both light **trajectory** and **wavelength**
⇒ **Light is a tracer for studying spacetime evolution**

Dark energy models

Dark energy → fluid described by an equation of state with the parameter ***w***:

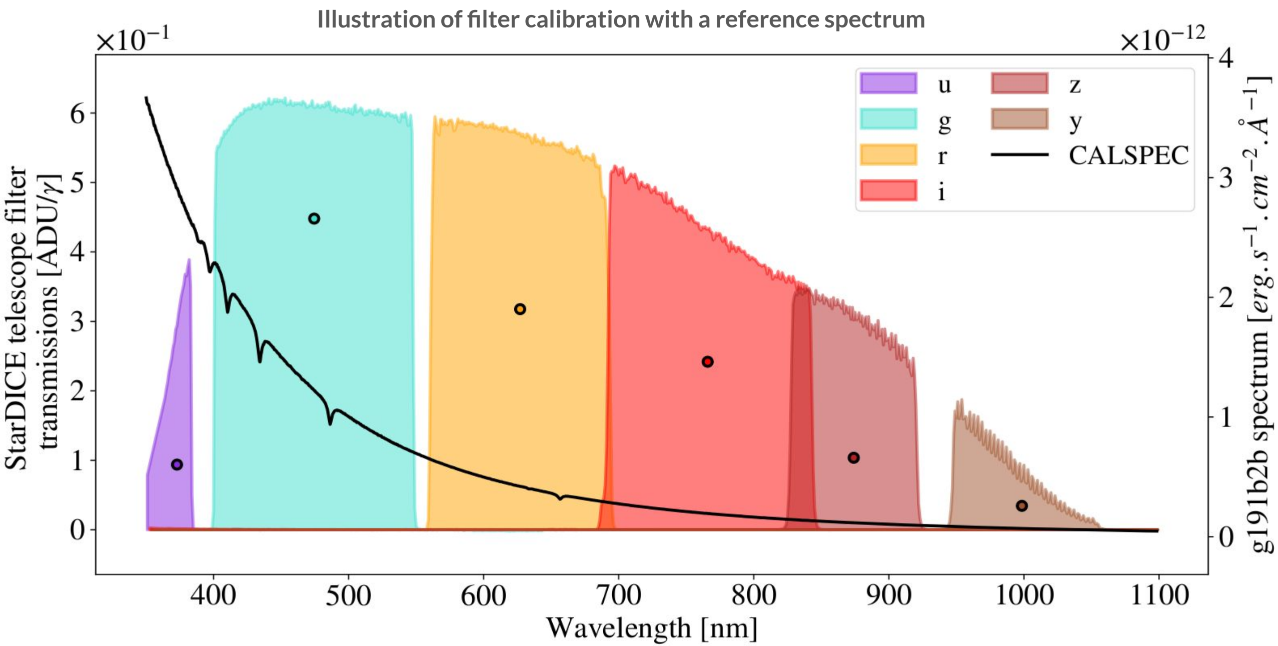
$$\rho_{\mathrm{de}} \propto a^{-3(1+w)}$$

- **ΛCDM, the standard model**
  - w = -1, **Λ** for **the cosmological constant**, **CDM** for **Cold Dark Matter**, and a flat Universe
- ***w*****CDM**
  - constant w but with $w \neq -1$
- **$w_0 w_a$CDM**
  - w is sets dynamic with: $w(a) = w_0 + \left(1 - \frac{a}{a_0}\right) w_a$



Pie chart of the energy contents distribution in the Universe

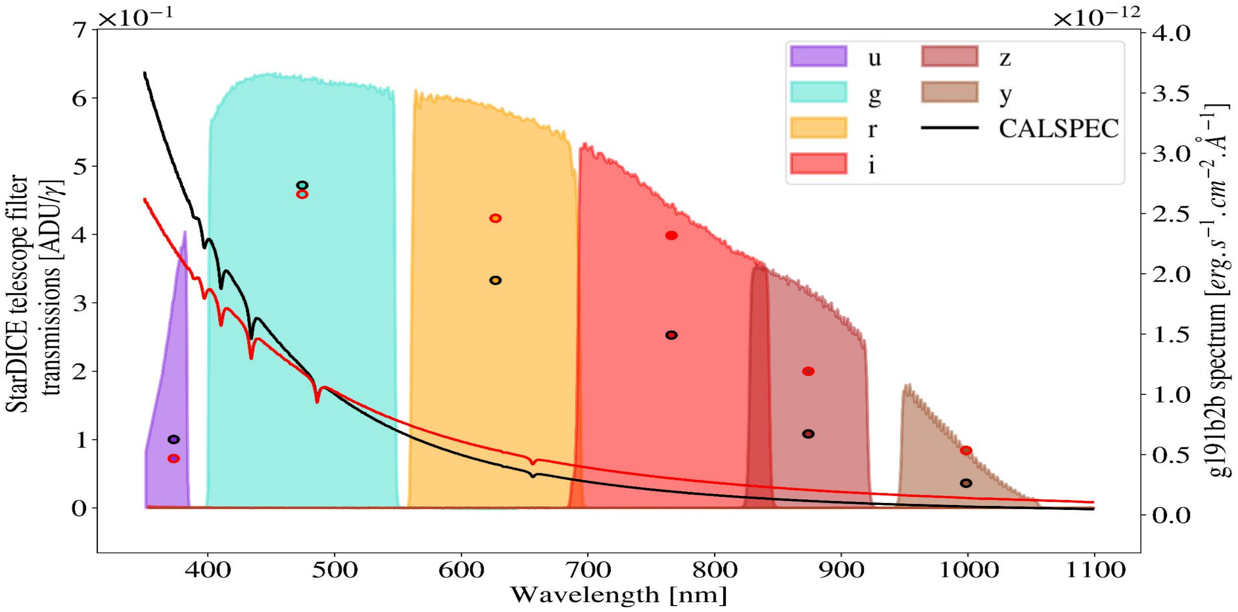
Adjusting bandpasses from CALSPEC



Observations of **CALSPEC photometric standards**
⇒ Calibration of the survey's bands

Adjusting bandpasses from CALSPEC

Illustration of filter calibration with a reference spectrum



Observations of **CALSPEC photometric standards**

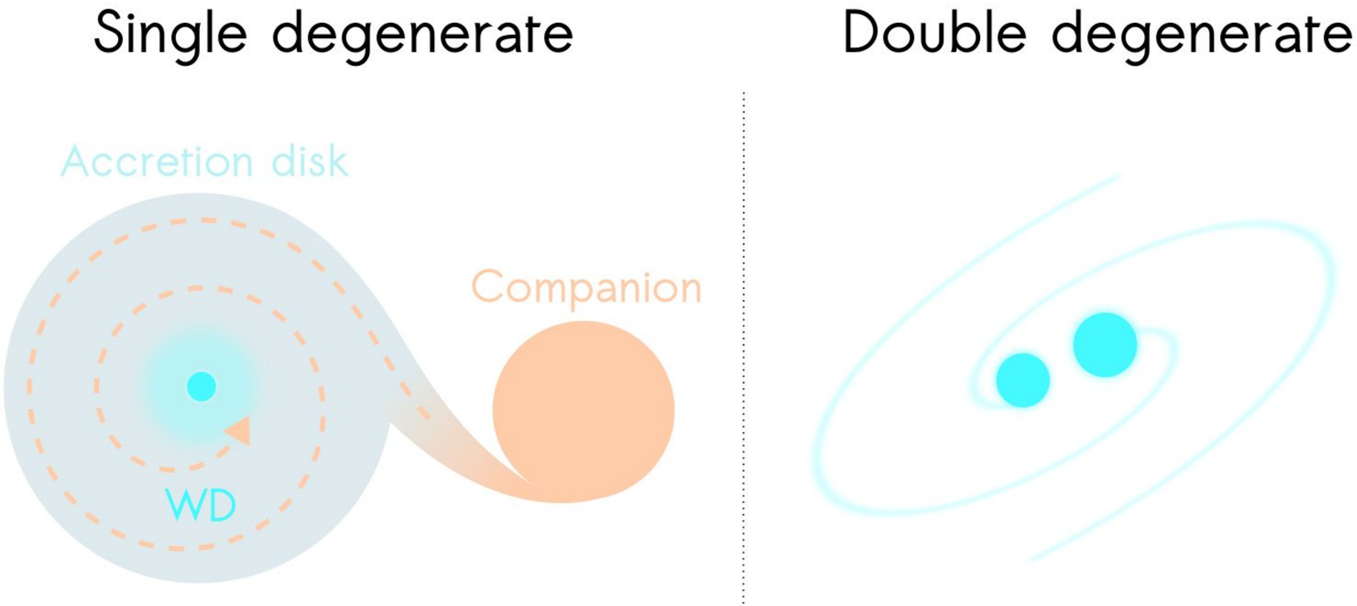
⇒ Calibration of the survey's bands

⇒ A chromatic difference in the model induces a biased calibration

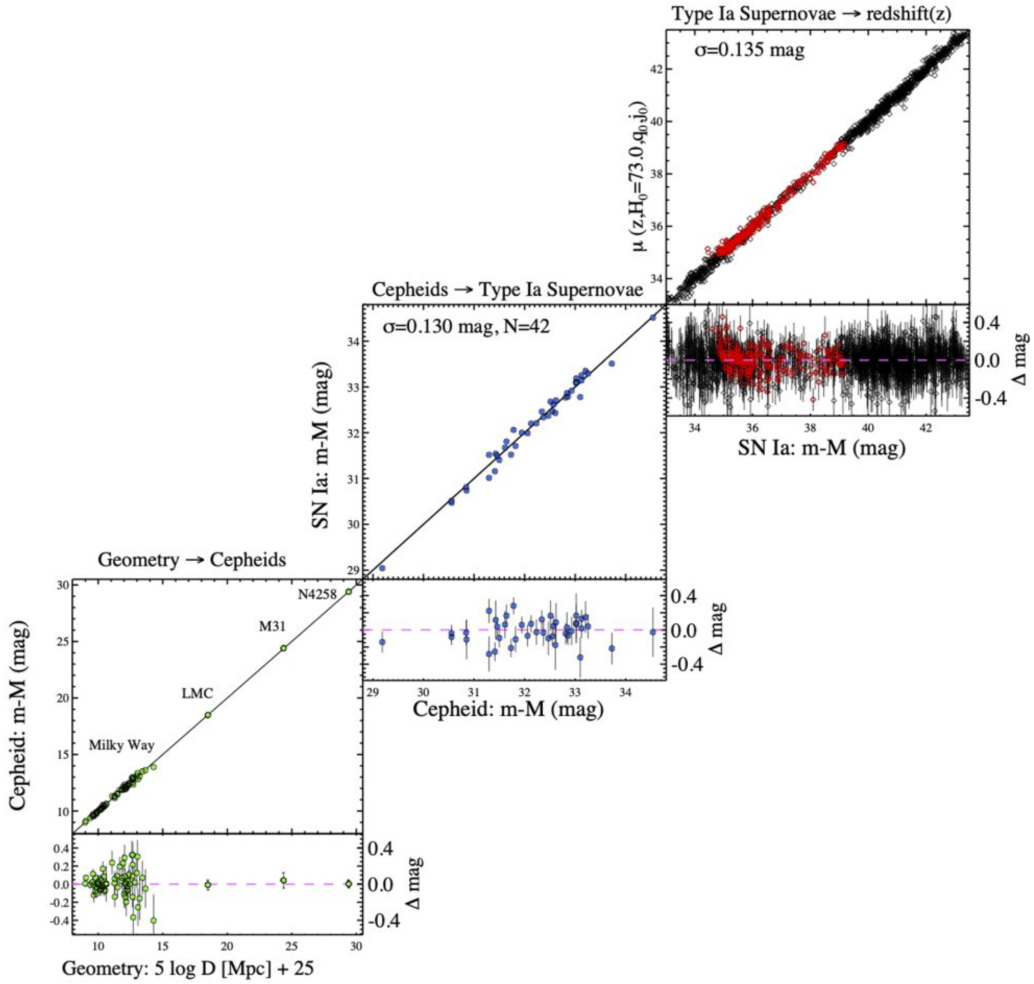
SNe Ia

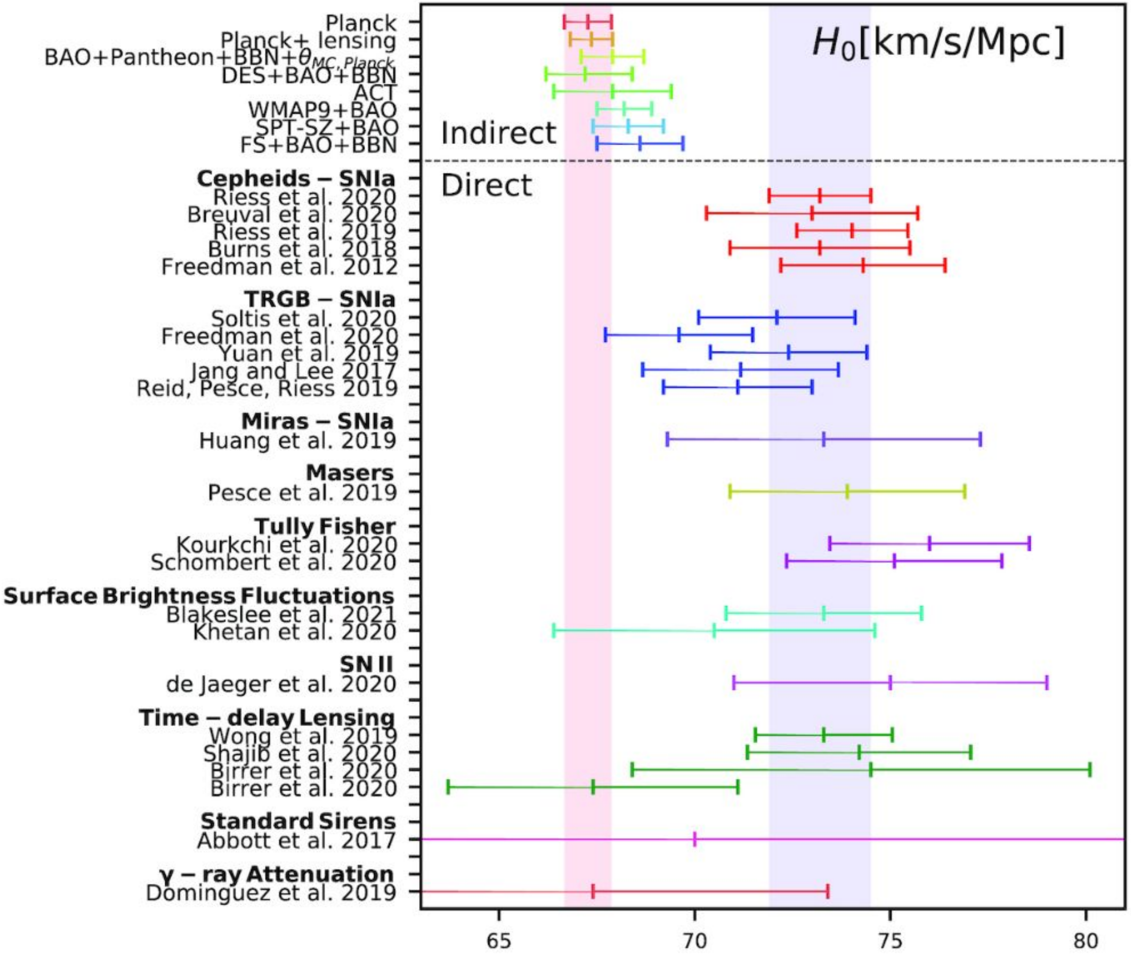
Explosion mechanism

- Explosion of a carbon-oxygen white dwarf (WD) with a mass > 1.4 $M_\odot$
- Two scenarios:

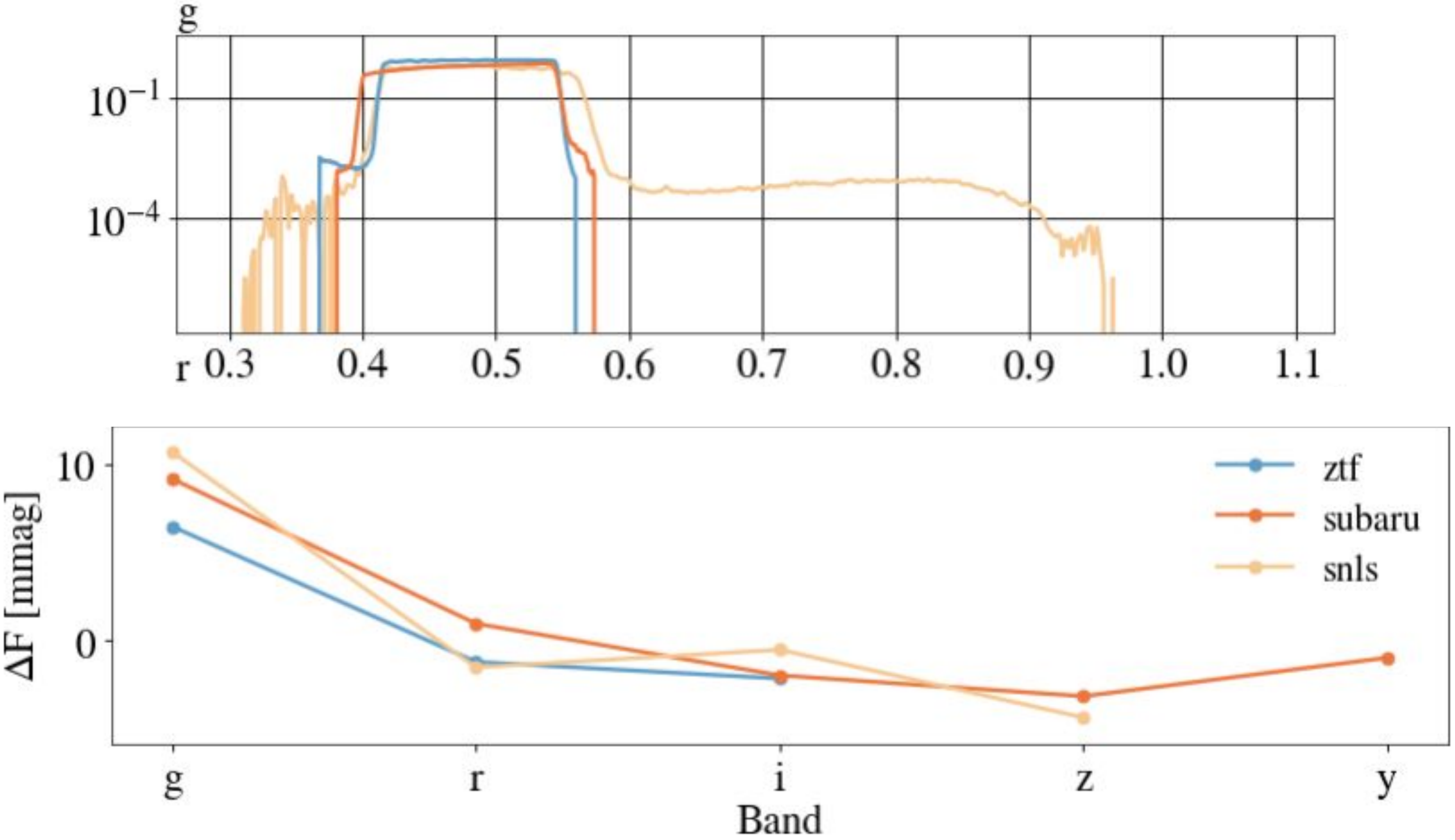


SNe Ia mechanism (https://github.com/HeloiseS/infographics)


Type Ia Supernovae → redshift(z)
σ=0.135 mag
μ (z,H0=73.0,q0,j0)
SN Ia: m-M (mag)
Δ mag
Cepheids → Type Ia Supernovae
σ=0.130 mag, N=42
SN Ia: m-M (mag)
Cepheid: m-M (mag)
Δ mag
Geometry → Cepheids
N4258
M31
LMC
Milky Way
Cepheid: m-M (mag)
Geometry: 5 log D [Mpc] + 25
Δ mag



H_0[km/s/Mpc]
Indirect
Direct
Planck
Planck+ lensing
BAO+Pantheon+BBN+$\theta_{MC, Planck}$
DES+BAO+BBN
ACT
WMAP9+BAO
SPT-SZ+BAO
FS+BAO+BBN
Cepheids – SNIa
Riess et al. 2020
Breuval et al. 2020
Riess et al. 2019
Burns et al. 2018
Freedman et al. 2012
TRGB – SNIa
Soltis et al. 2020
Freedman et al. 2020
Yuan et al. 2019
Jang and Lee 2017
Reid, Pesce, Riess 2019
Miras – SNIa
Huang et al. 2019
Masers
Pesce et al. 2019
Tully Fisher
Kourkchi et al. 2020
Schombert et al. 2020
Surface Brightness Fluctuations
Blakeslee et al. 2021
Khetan et al. 2020
SN II
de Jaeger et al. 2020
Time – delay Lensing
Wong et al. 2019
Shajib et al. 2020
Birrer et al. 2020
Birrer et al. 2020
Standard Sirens
Abbott et al. 2017
γ – ray Attenuation
Dominguez et al. 2019
65
70
75
80

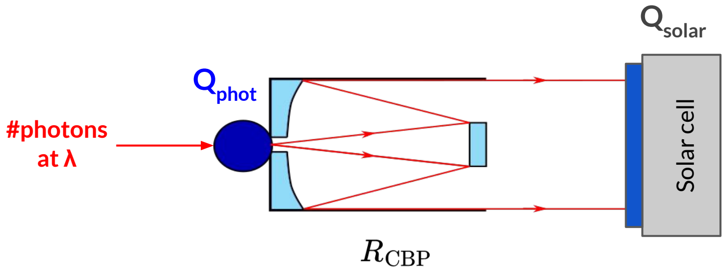


g
10^{-1}
10^{-4}
r 0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
10
0
ΔF [mmag]
ztf
subaru
snls
g
r
i
z
y
Band

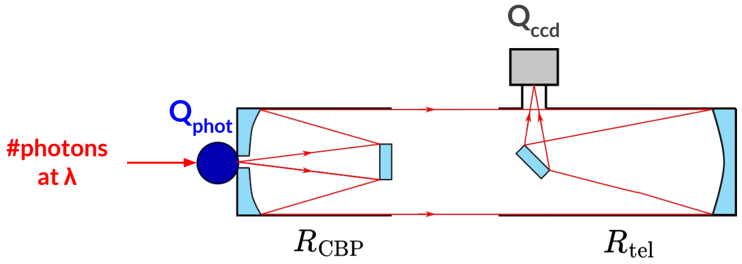
CBP

CBP guideline

Want to calibrate a telescope ? Simple, use another reverse-mounted telescope !



$$R_{CBP} = \frac{Q_{solar}}{Q_{phot} \times \epsilon_{solar} \times e}$$



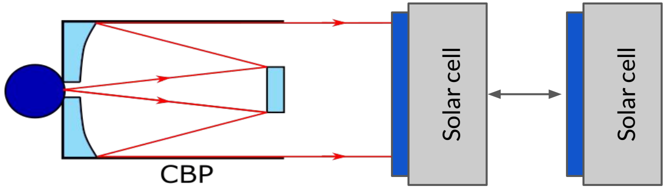
$$R_{tel} = \frac{Q_{ccd}}{Q_{phot} \times R_{CBP}}$$

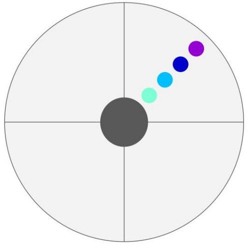
Congratulations, calibration is done !

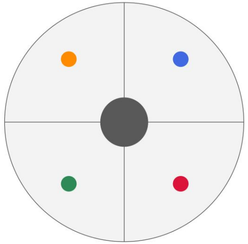
Acquisition plan

Measurements in different conditions to evaluate systematics and make pupil stitching:

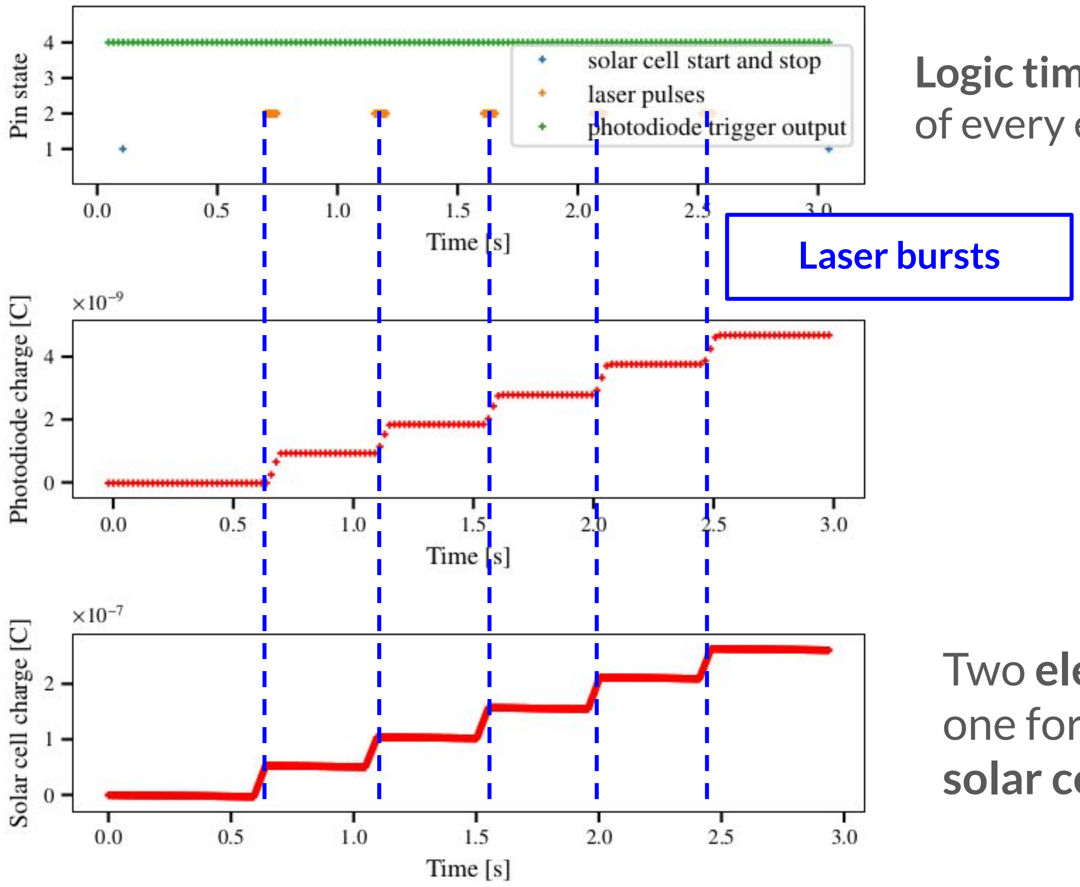
- Spectrograph calibration
- CBP response:
    - Solar Cell measurement; 5mm pinhole
    - Long and short distance (~16cm difference); 5mm pinhole
    - Cap on the CBP to measure ambient light
- StarDICE response:
    - Same position; every camera filter; 75µm & 5mm pinhole
    - 8 positions on the mirror; 75µm pinhole ("pupil stitching")
        - 4 positions on different quadrants but same radius
        - 4 positions at different radius but same quadrant
    - (4x4) positions on the CCD; 75µm pinhole







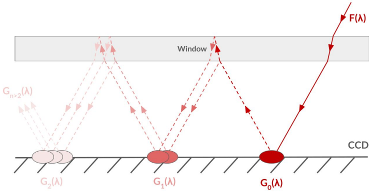
Photodiode and solar cell dataset

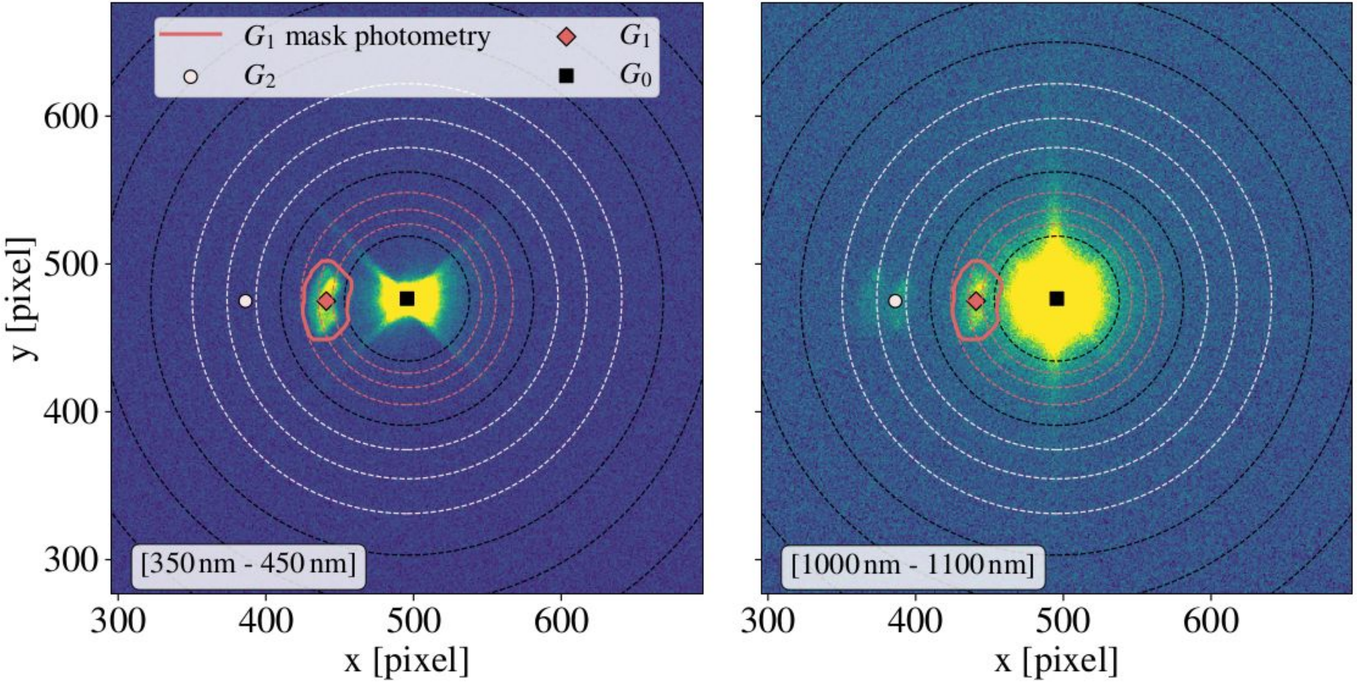


Logic timer device ⇒ synchronizing clocks of every electrometers with the laser

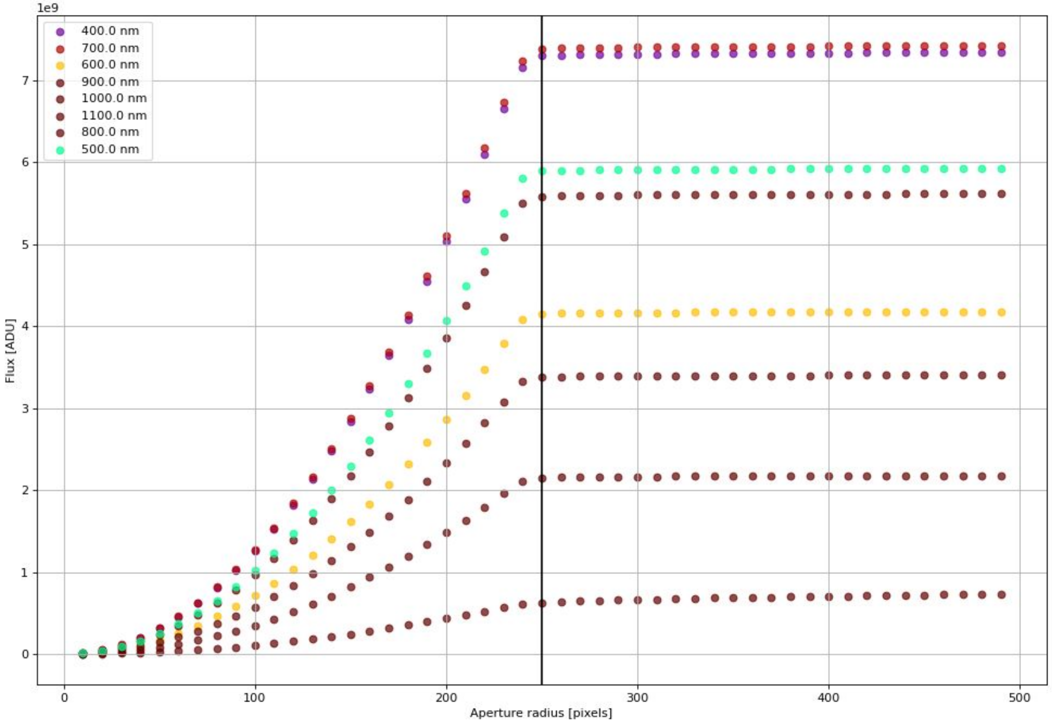
Two **electrometers** measuring **charges [C]**: one for the **photodiode** and one for the **solar cell**

Ghost contamination

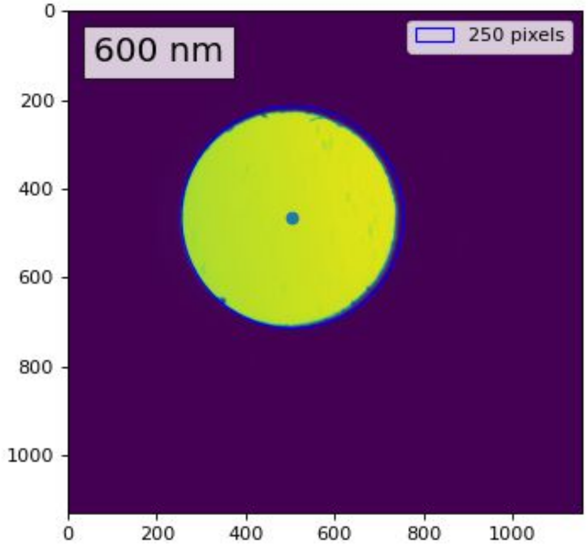




Growth curve



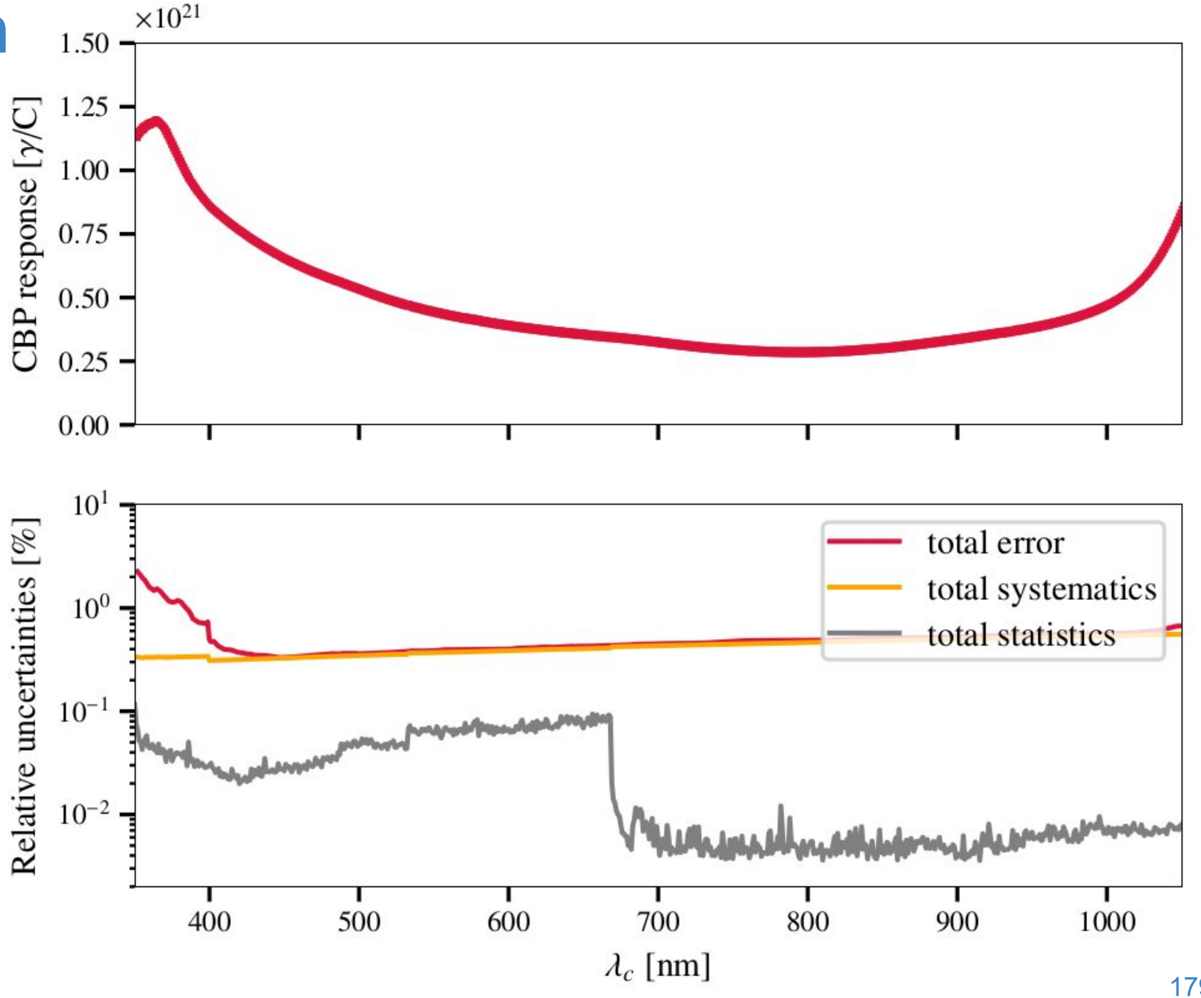
→ Break at 250 pixels



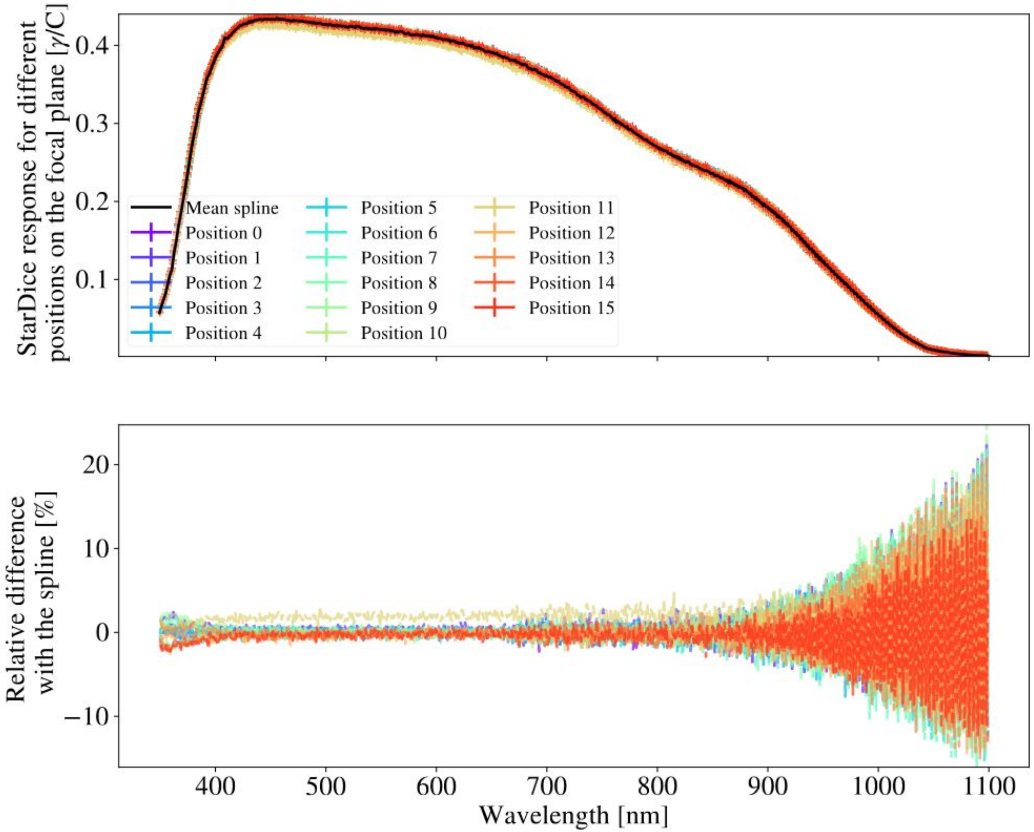
CBP transmission

$$R_{\mathrm{CBP}} = \frac{Q_{\mathrm{solar}}}{Q_{\mathrm{phot}} \times \epsilon_{\mathrm{solar}} \times e}$$

~0.4 % per nm uncertainty over [400 - 1000] nm range

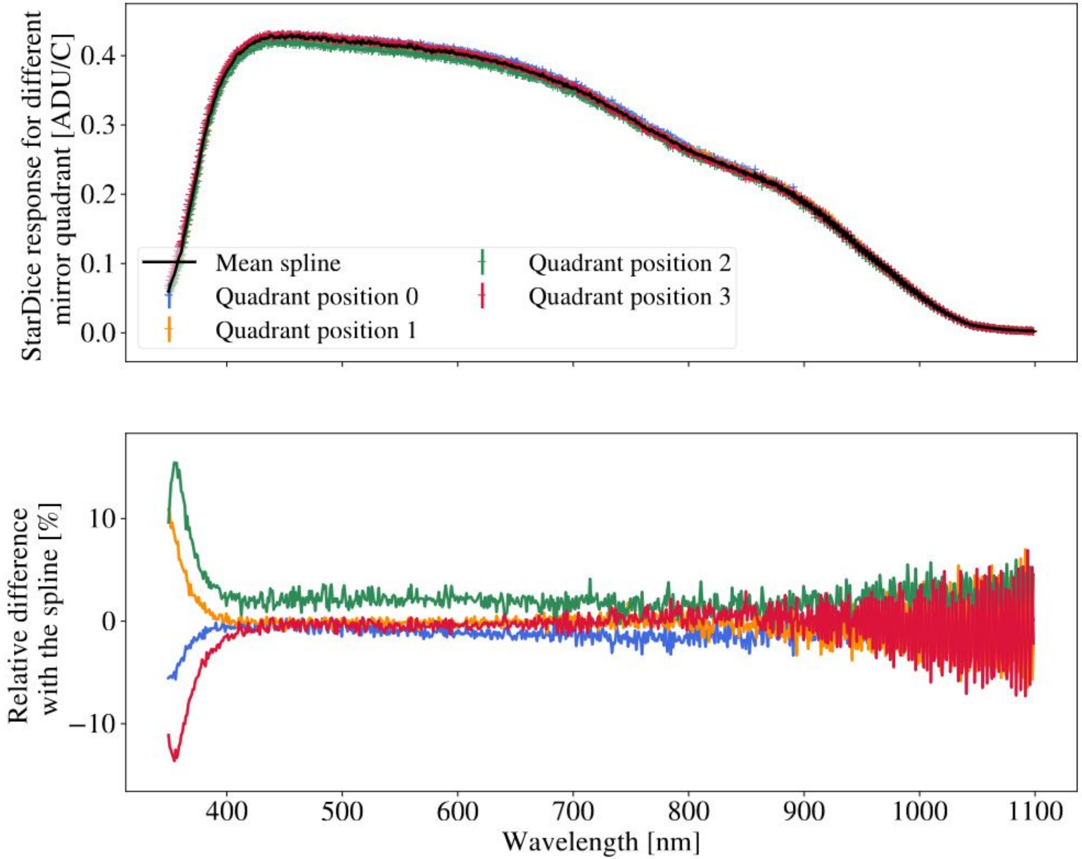


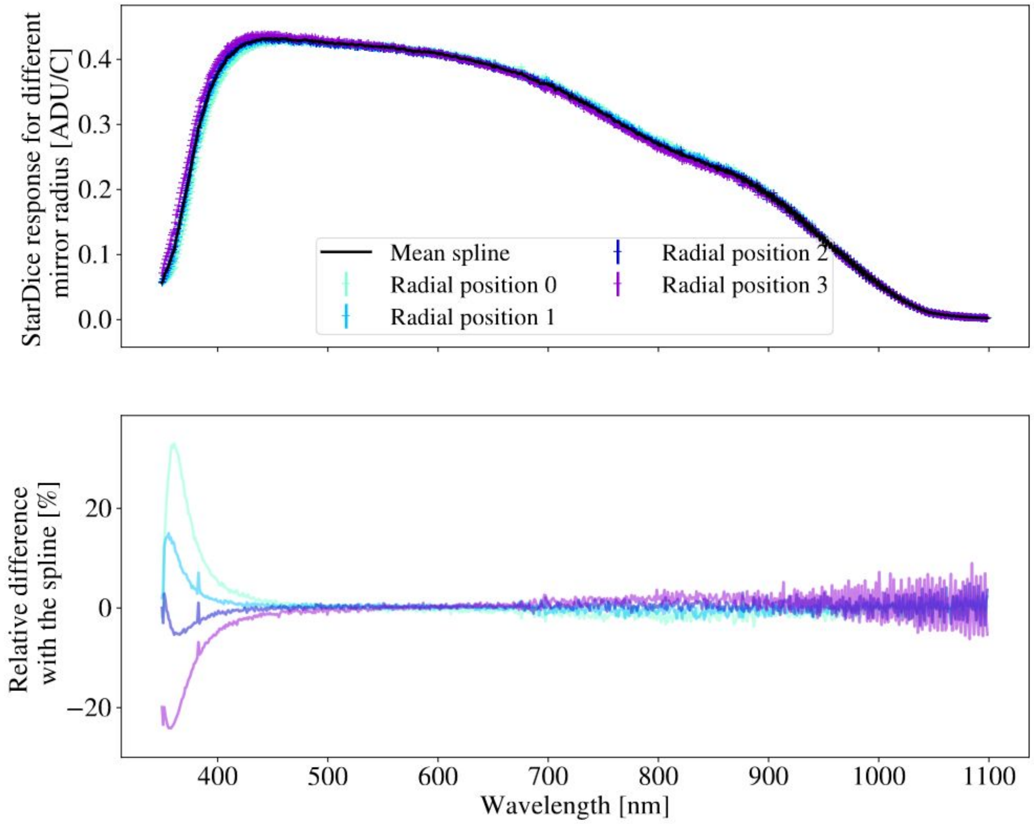
CCD grid



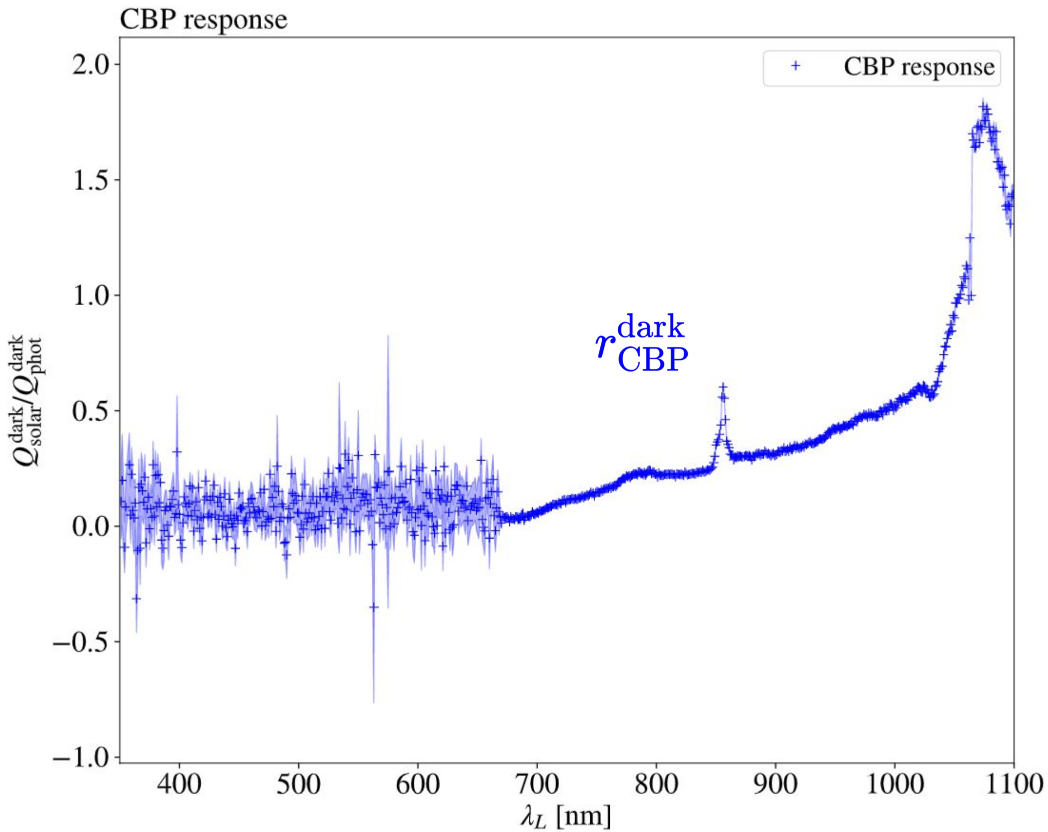
StarDice response for different positions on the focal plane [γ/C]
0.4
0.3
0.2
0.1
Mean spline
Position 0
Position 1
Position 2
Position 3
Position 4
Position 5
Position 6
Position 7
Position 8
Position 9
Position 10
Position 11
Position 12
Position 13
Position 14
Position 15
Relative difference with the spline [%]
20
10
0
−10
400
500
600
700
800
900
1000
1100
Wavelength [nm]

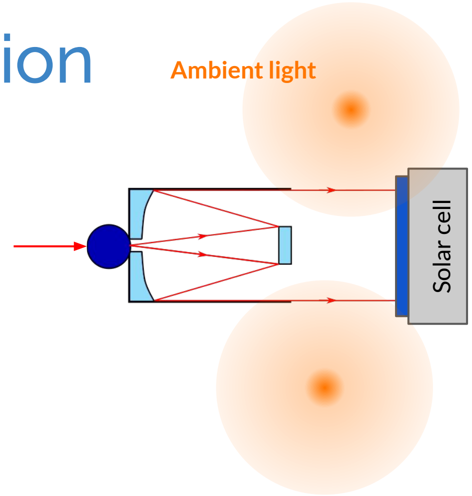
Quadrant positions




StarDice response for different mirror radius [ADU/C]
0.0
0.1
0.2
0.3
0.4
Mean spline
Radial position 0
Radial position 1
Radial position 2
Radial position 3
Relative difference with the spline [%]
−20
0
20
400
500
600
700
800
900
1000
1100
Wavelength [nm]

Ambient light contribution: presentation

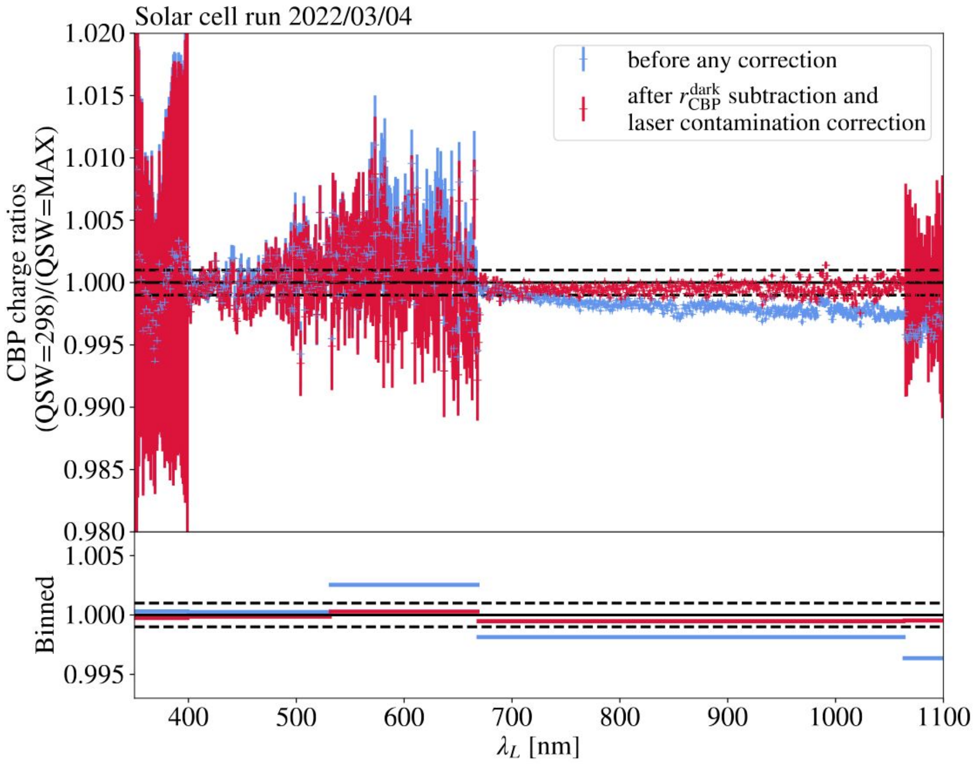


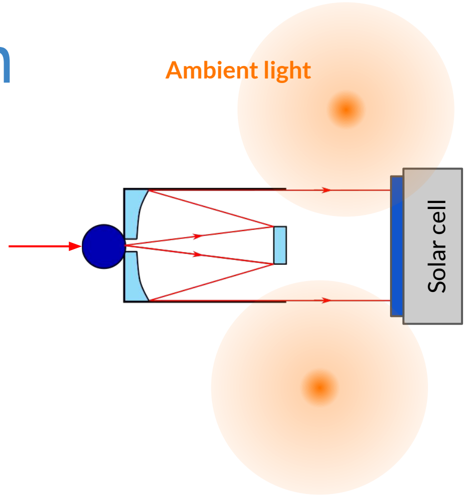


Ambient light contamination depend on wavelength → laser box is not perfectly light tight

$$Q_{\mathrm{solar}}^{\mathrm{cal}} = Q_{\mathrm{solar}}^{\lambda_L} - r_{\mathrm{CBP}}^{\mathrm{dark}} \times Q_{\mathrm{phot}}$$

Ambient light contribution: correction



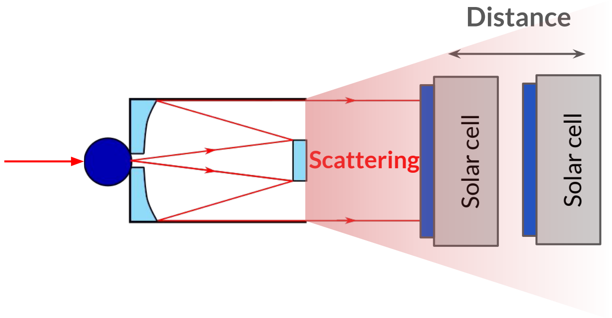


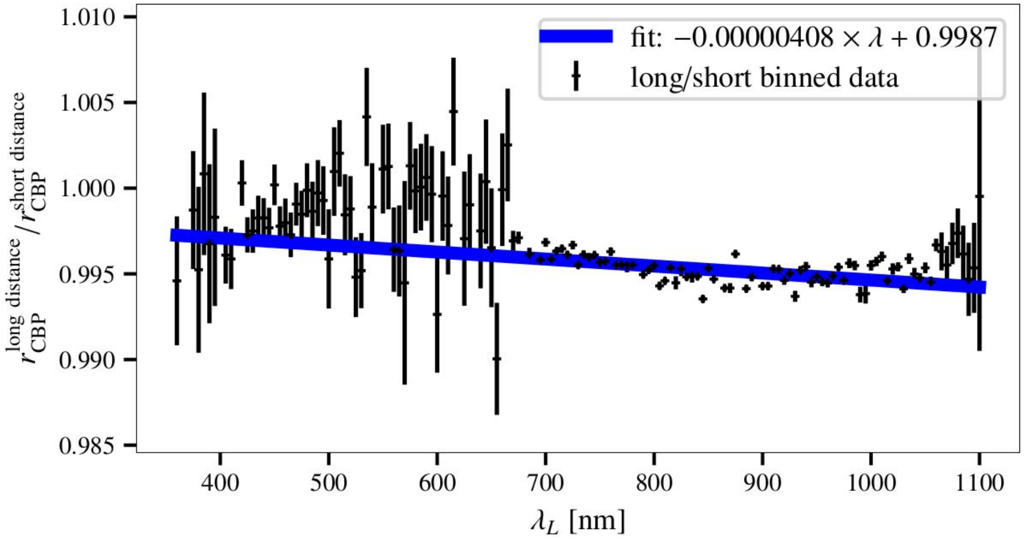
Ratio of two runs at different laser powers (different by a factor 2)

⇒ once corrected by the background, ratio contained below the per mil

$$Q_{\mathrm{solar}}^{\mathrm{cal}} = Q_{\mathrm{solar}}^{\lambda_L} - r_{\mathrm{CBP}}^{\mathrm{dark}} \times Q_{\mathrm{phot}}$$

Scattered light

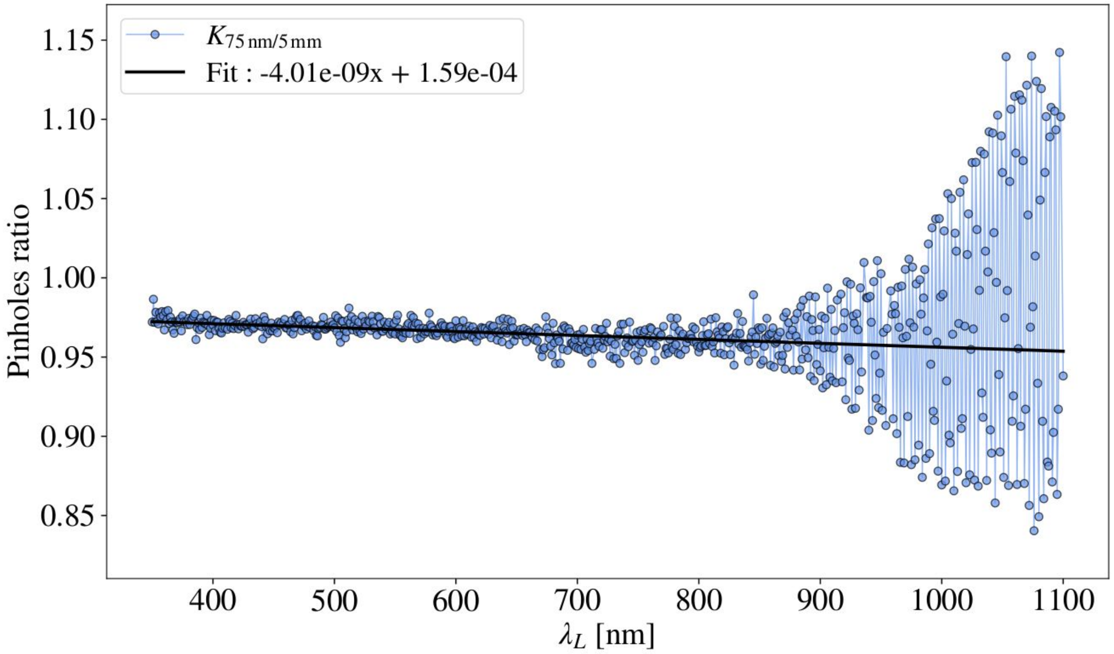




Ratio of two run at different distance between the CBP and the Solar Cell (~ 16cm)

- Decrease of 2.5‰ of light flux in [350 - 1100]nm
- Dominant systematics for CBP throughput

Intercalibration 5mm/75µm



$$K_{75\mu m/5mm}(\lambda) = \frac{R^{5mm}_{\mathrm{CBP}}(\lambda)}{R^{75\mu m}_{\mathrm{CBP}}(\lambda)} \quad \Rightarrow \quad \text{Infer } R^{75\mu\mathrm{m}}_{\mathrm{CBP}}(\lambda) \text{ from } R^{5\mathrm{mm}}_{\mathrm{CBP}}(\lambda)$$

Ghost contamination

PSF fit with successive aperture photometry with radius *r*:

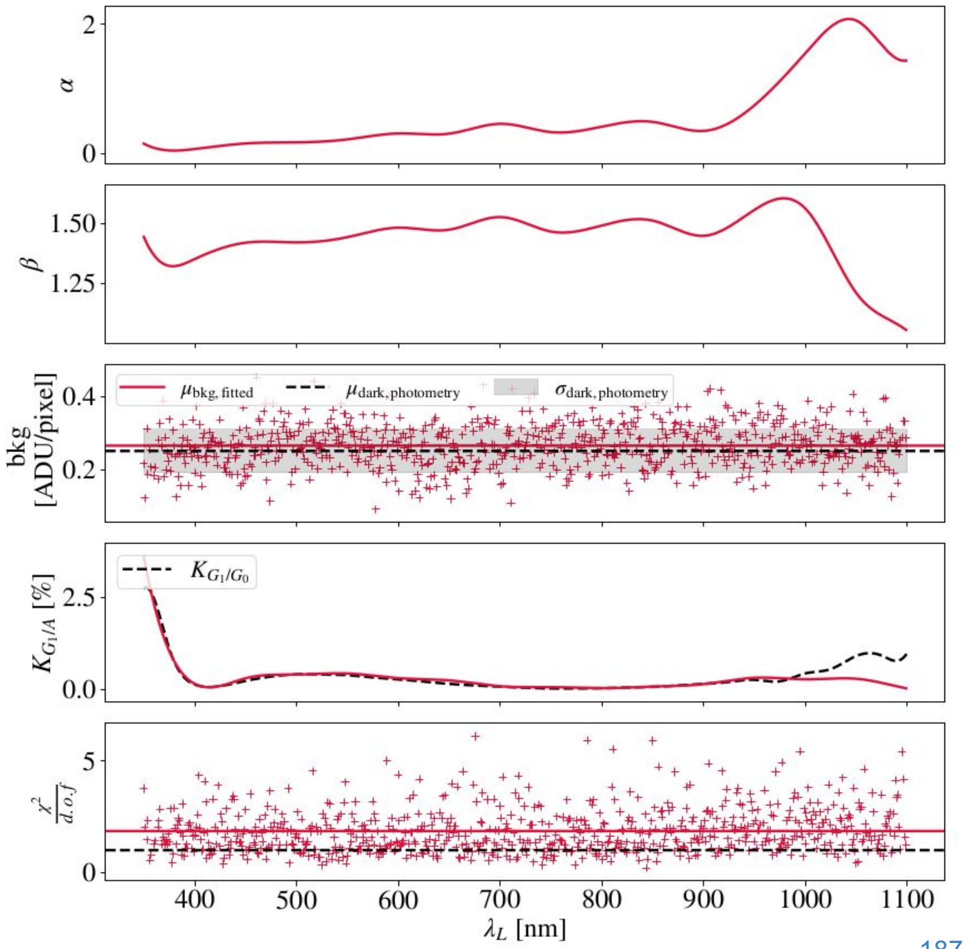
Moffat distribution — Ghost contribution — Background

$$F(r,\lambda) = A(\lambda) \times \frac{M(r,\lambda) + K_{G/A}(r,\lambda)}{1 + K_{G/A}(+\infty,\lambda)} + \mathrm{bkg}(\lambda) \times \pi r^2$$

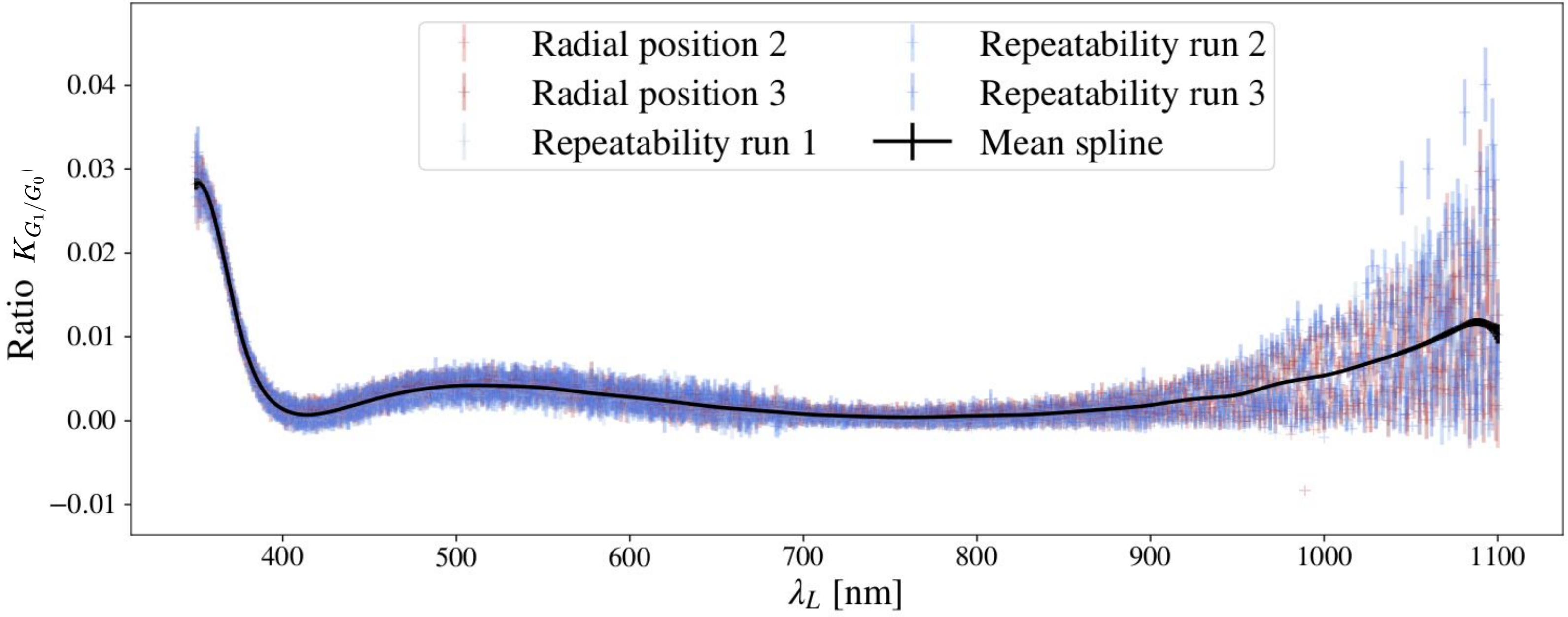
Fit results consistent with ghost photometry:

$$K_{G_1/G_0}(\lambda) = \frac{G_1(\lambda)}{G_0(\lambda)}$$

⇒ Ghost contribution well characterized with wavelength

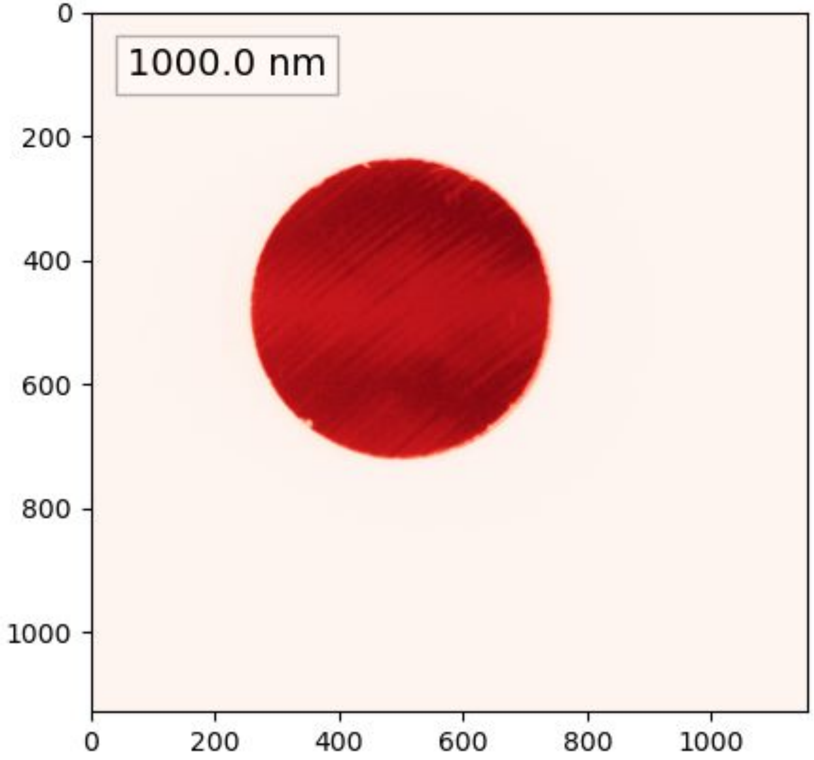


Ghost contamination in StarDICE

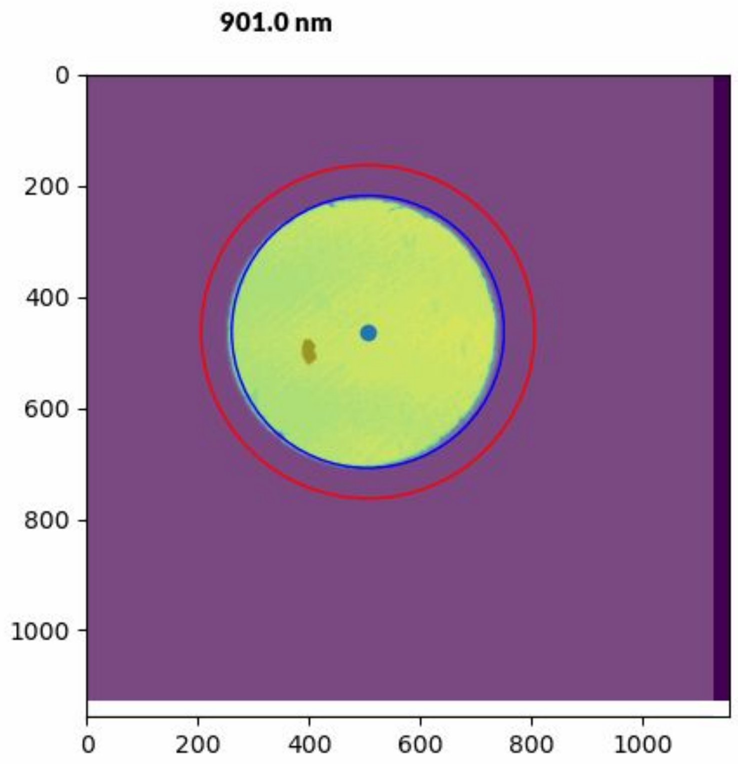


$$K_{G_1/G_0}(\lambda) = \frac{G_1(\lambda)}{G_0(\lambda)}$$

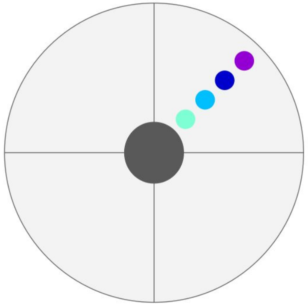
Fringing depending on position

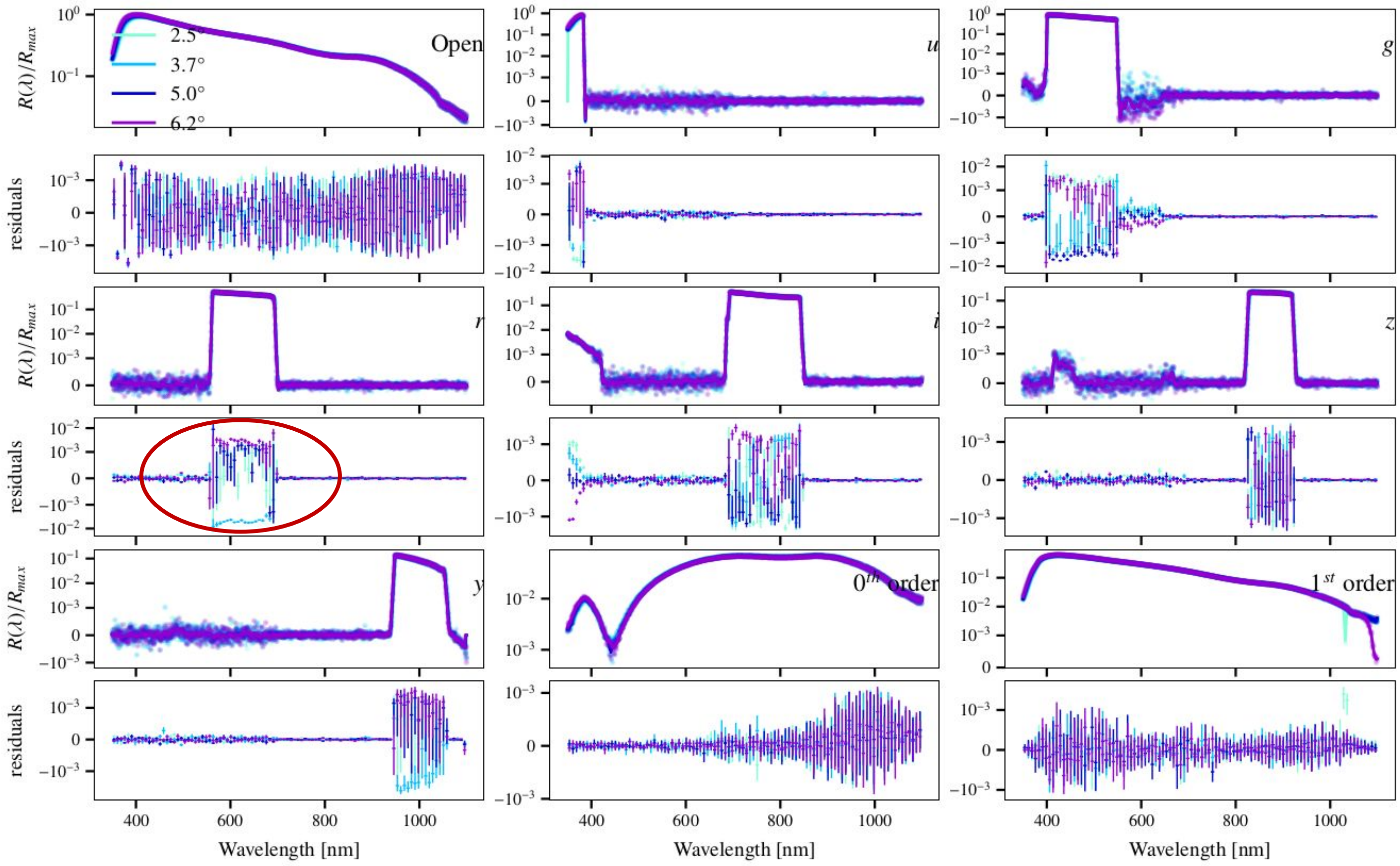


Ghost photometry : IR oscillations

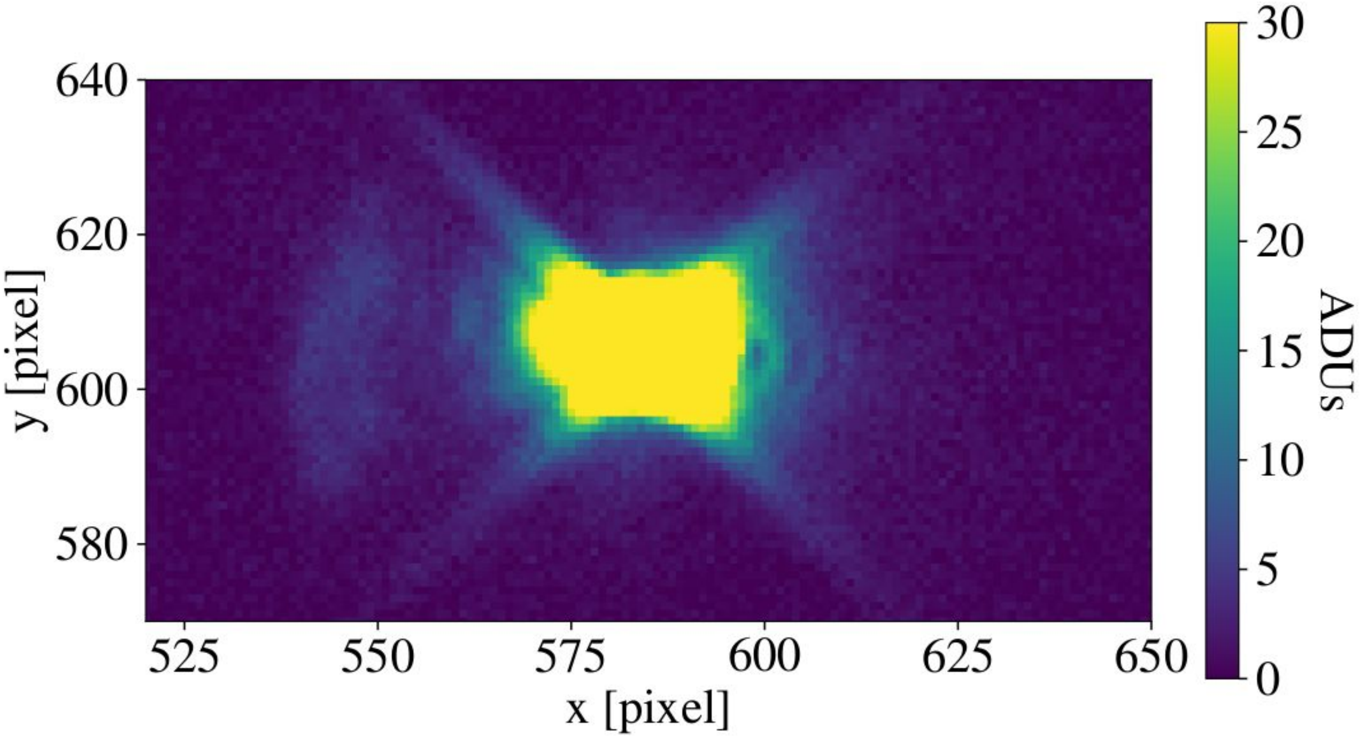


Pupil stitching



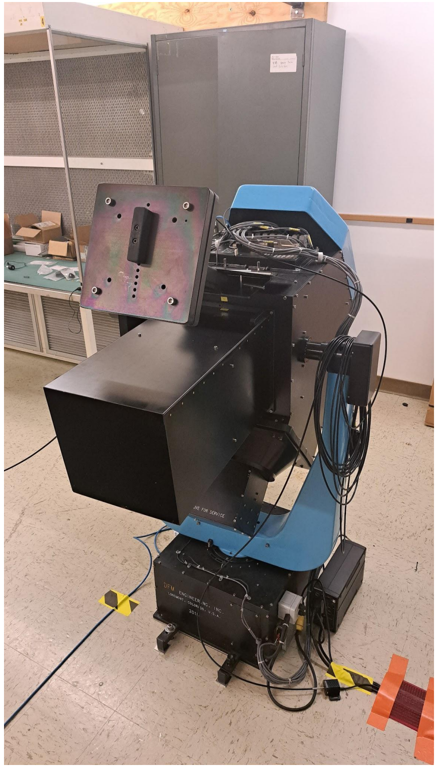


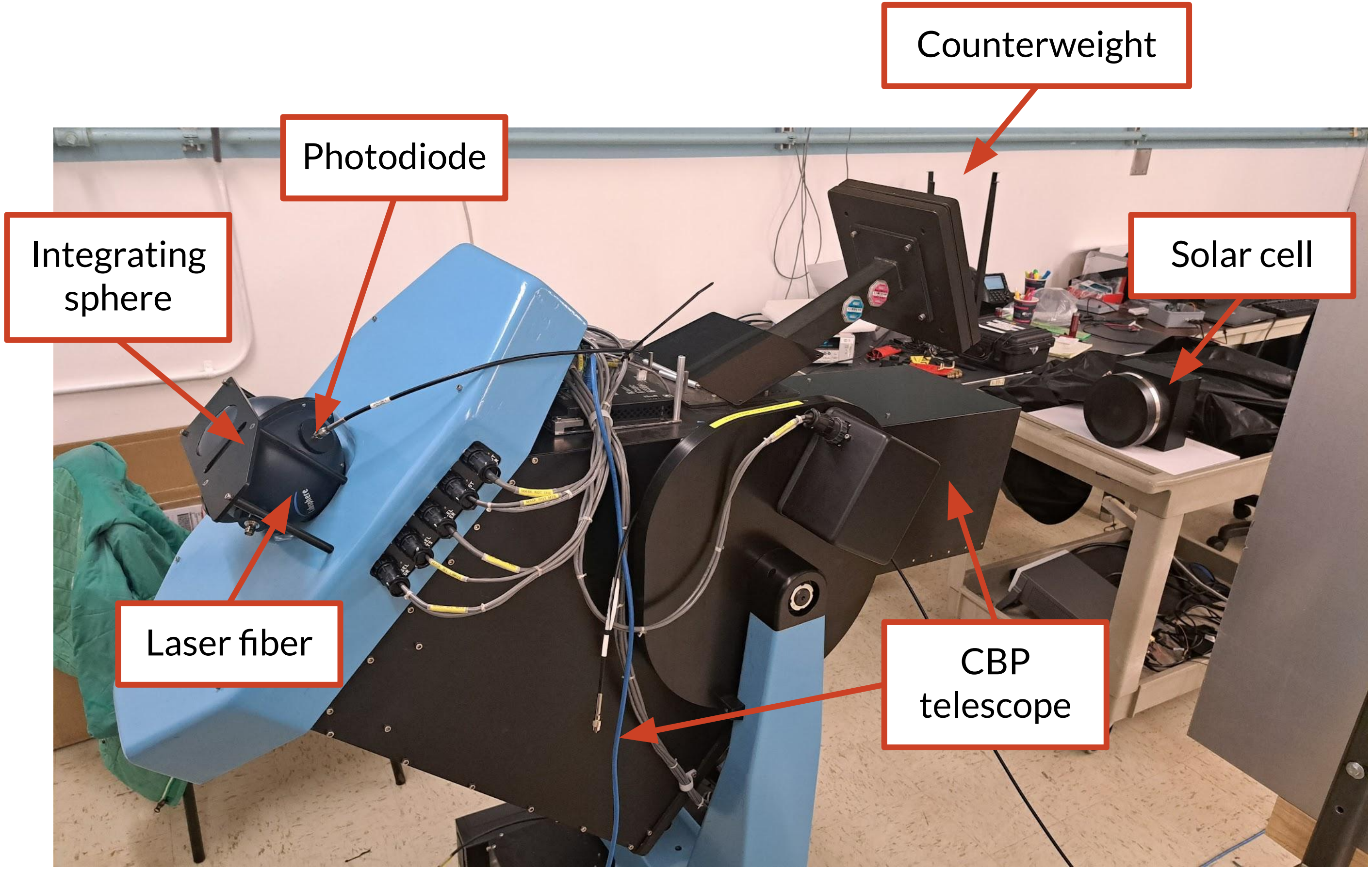
Dust on the filter



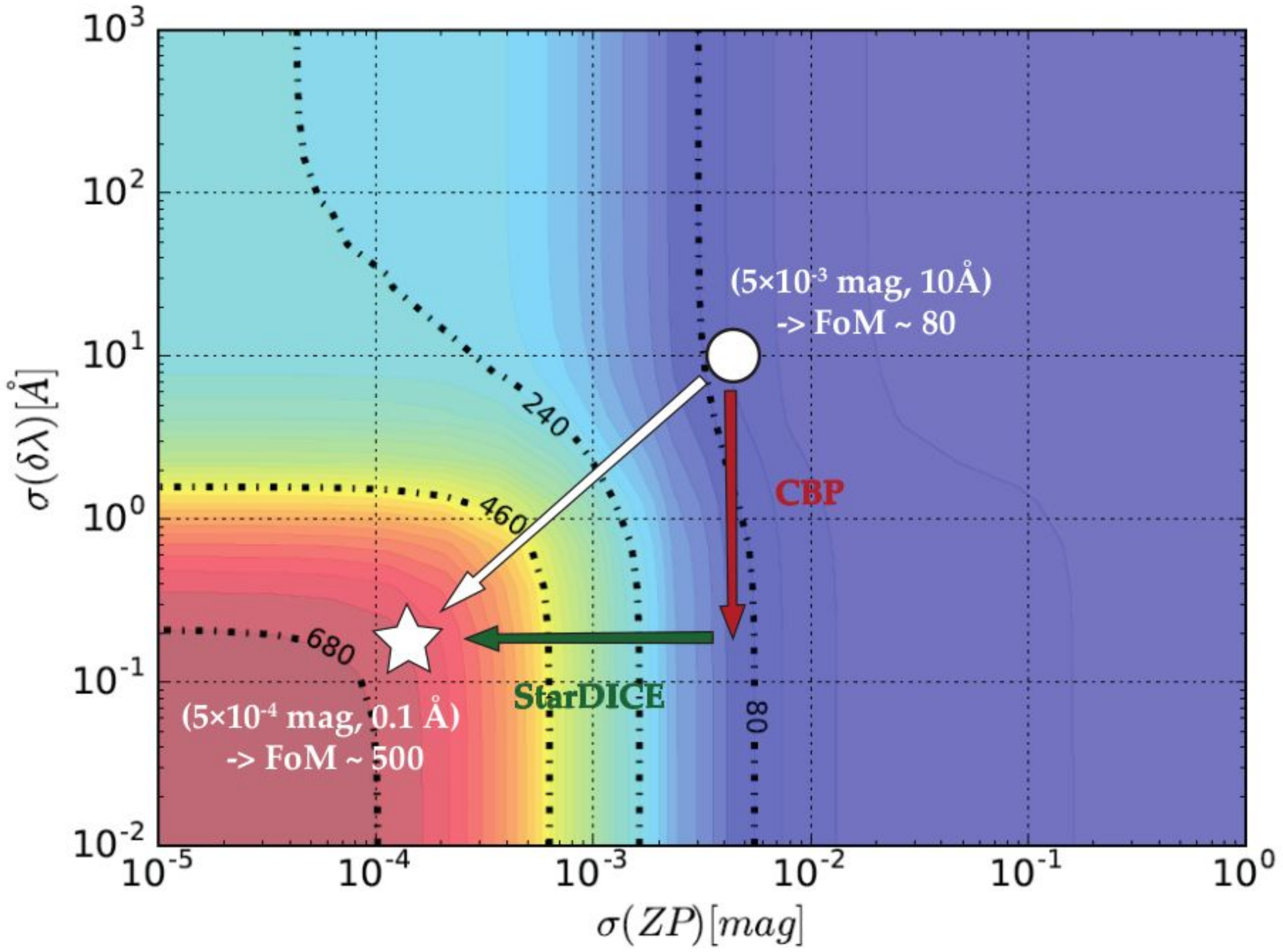
Dust particle of about 200-300 μm diameter intercepting the CBP beam
⇒ **consistent with the flux discrepancy**

Rubin CBP





Counterweight
Photodiode
Integrating sphere
Solar cell
Laser fiber
CBP telescope



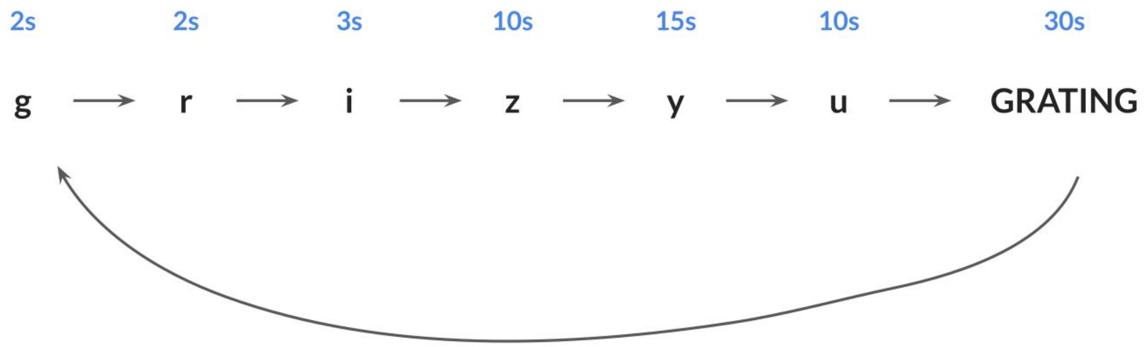
(5×10-3 mag, 10Å)
-> FoM ~ 80
CBP
StarDICE
(5×10-4 mag, 0.1 Å)
-> FoM ~ 500
240
460
680
80
σ(δλ)[Å]
σ(ZP)[mag]

Photometry

Dataset description

Follow-up of the CALSPEC primary standard G191B2B

- 23 observation nights
- ~3000 images by filter → total of ~20 000 images
- Observations in “ugrizy” filters + “grating”
- ~800 stars studied in the field



Fitting zero points

Fit initialization for every star *s* in every image *i*:

$$\Delta\hat{m}_{i,\,s} = m_{i,\,s}^{\mathrm{obs}} - m_{i,\,s}^{\mathrm{synth}} = -2.5 \times \log_{10}\left(\frac{F_{i,\,s}^{\mathrm{obs}}}{F_{i,\,s}^{\mathrm{synth}}}\right)$$

Magnitude variation model:

Image variations — Average offset synth/obs — Variance model

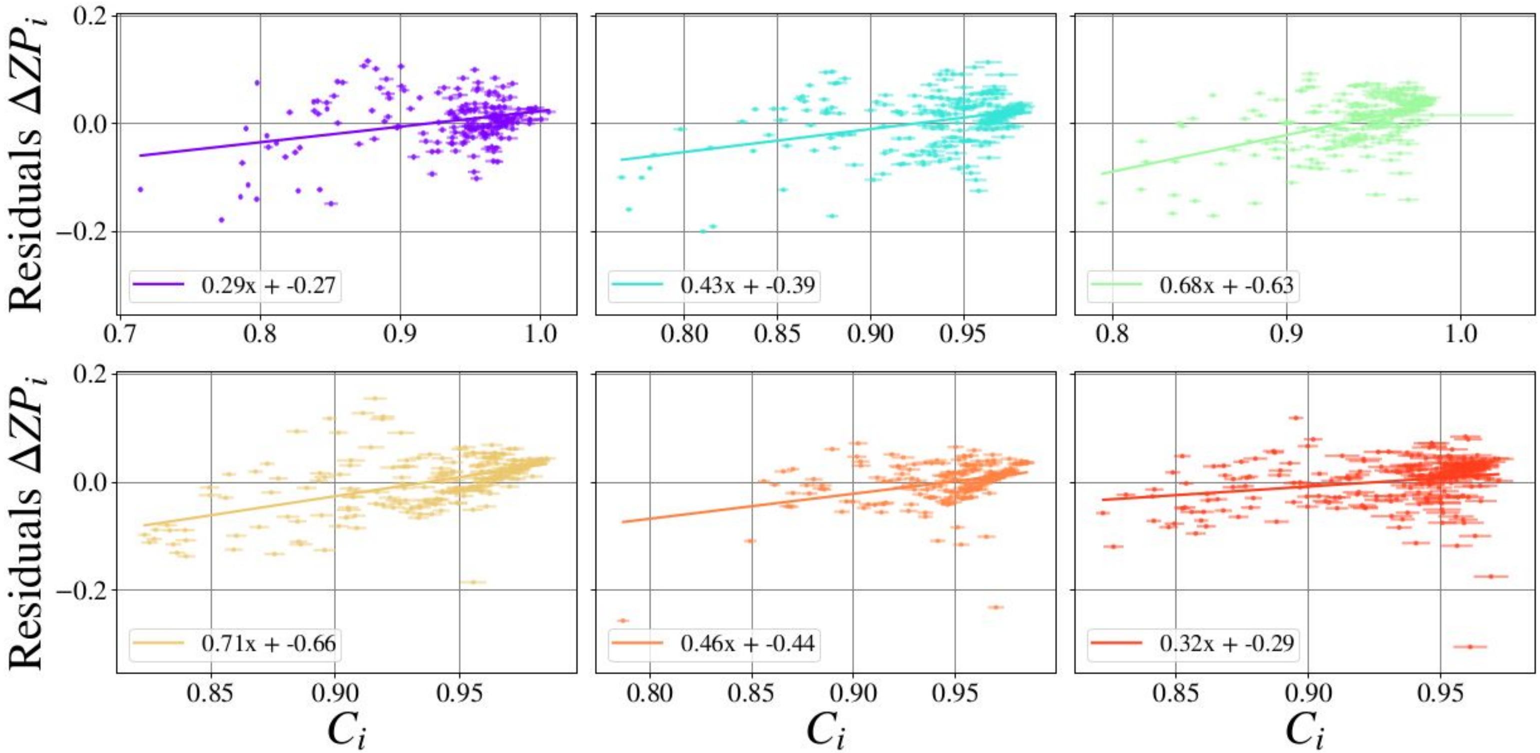
$$\Delta m_{i,\,s} = \Delta \mathrm{ZP}_i + \Delta m_s + \epsilon_{i,\,s}$$

Zero point model per band:

Atmosphere — Out-of-atmosphere zero point

$$\Delta ZP_{\mathrm{b},\,i}(X, C) = k_{\mathrm{b}} X_i + \alpha_{\mathrm{b}} C_i + ZP_{0,\mathrm{b}}$$

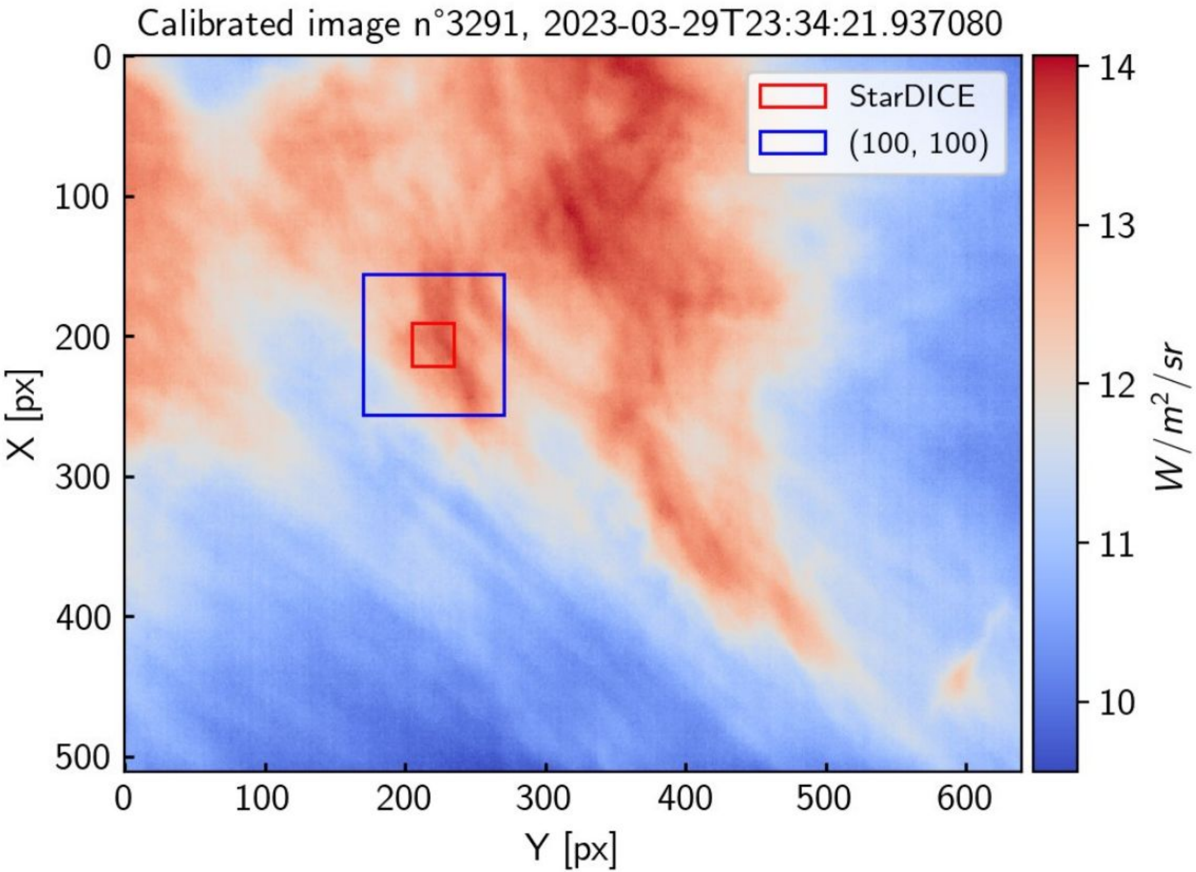
Aperture photometry



Residuals ΔZP_i
0.2
0.0
−0.2
0.29x + -0.27
0.43x + -0.39
0.68x + -0.63
0.7
0.8
0.9
1.0
0.80
0.85
0.90
0.95
0.71x + -0.66
0.46x + -0.44
0.32x + -0.29
C_i

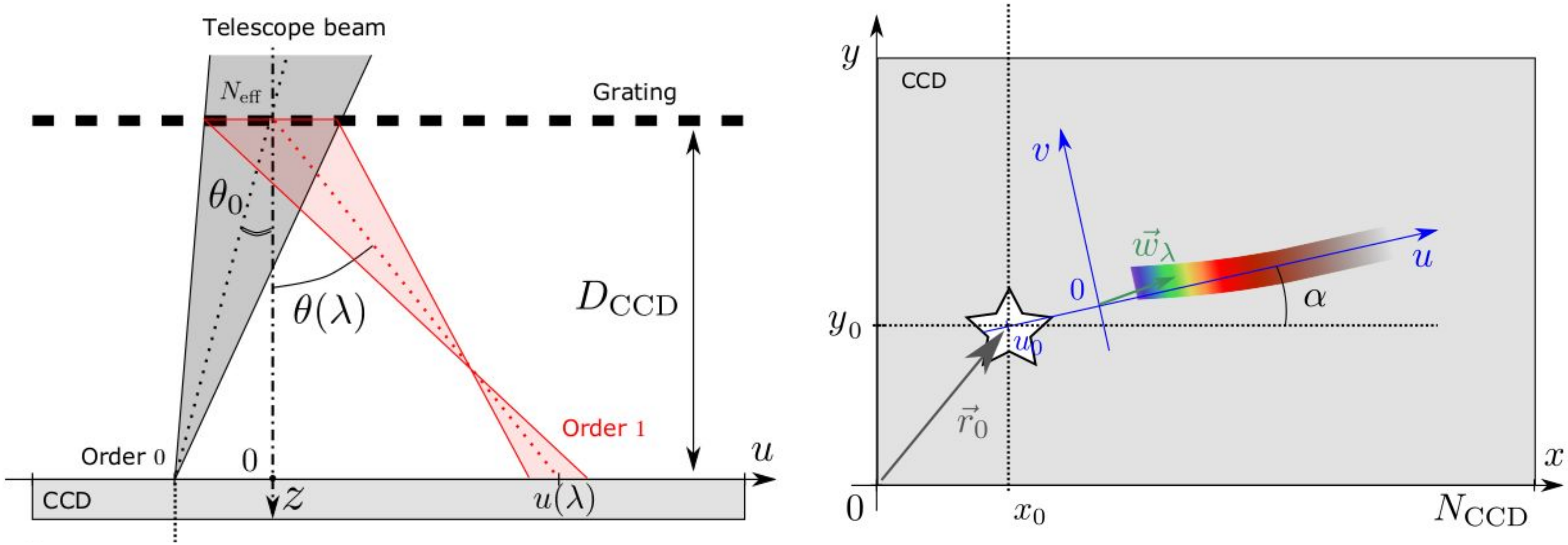
```
Δm_{i,s} = fit_init(F_{is}^{obs}, F_{is}^{synth})
σ_F = vect(1)
Δm_s = vect(0)

for p in range(N_p)
    for q in range(N_q):
        ΔZP_i, Δm_s = mag_variation_model(Δm_{i,s}, Δm_s, σ_F)

    r_{i,s} = Δm_{i,s} - (ΔZP_i + Δm_s)
    σ_F = error_model_variance(r_{i,s})

k_b, ZP_{0, b}, α_b = zero_point_model(ΔZP_i, X_i, C_i)
```

Infrared image



Spectrophotometry

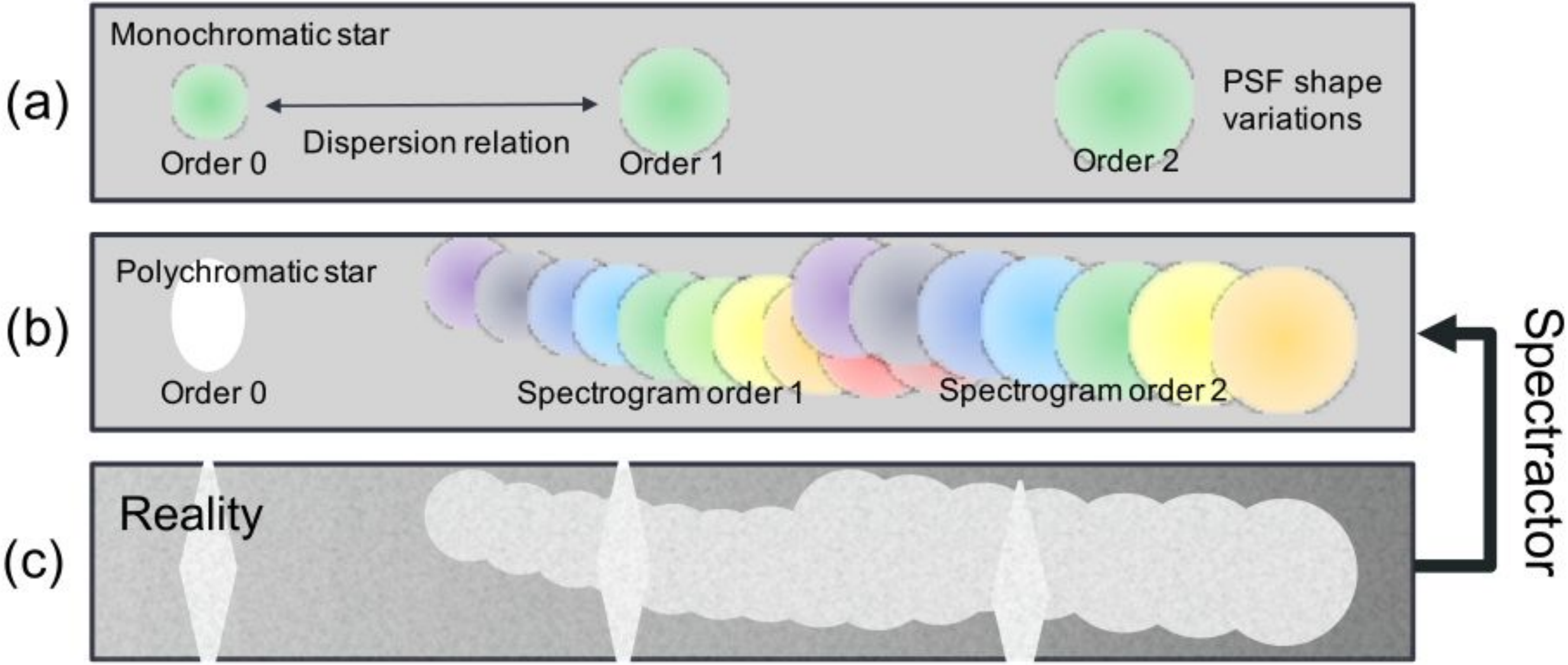
Grating dispersion

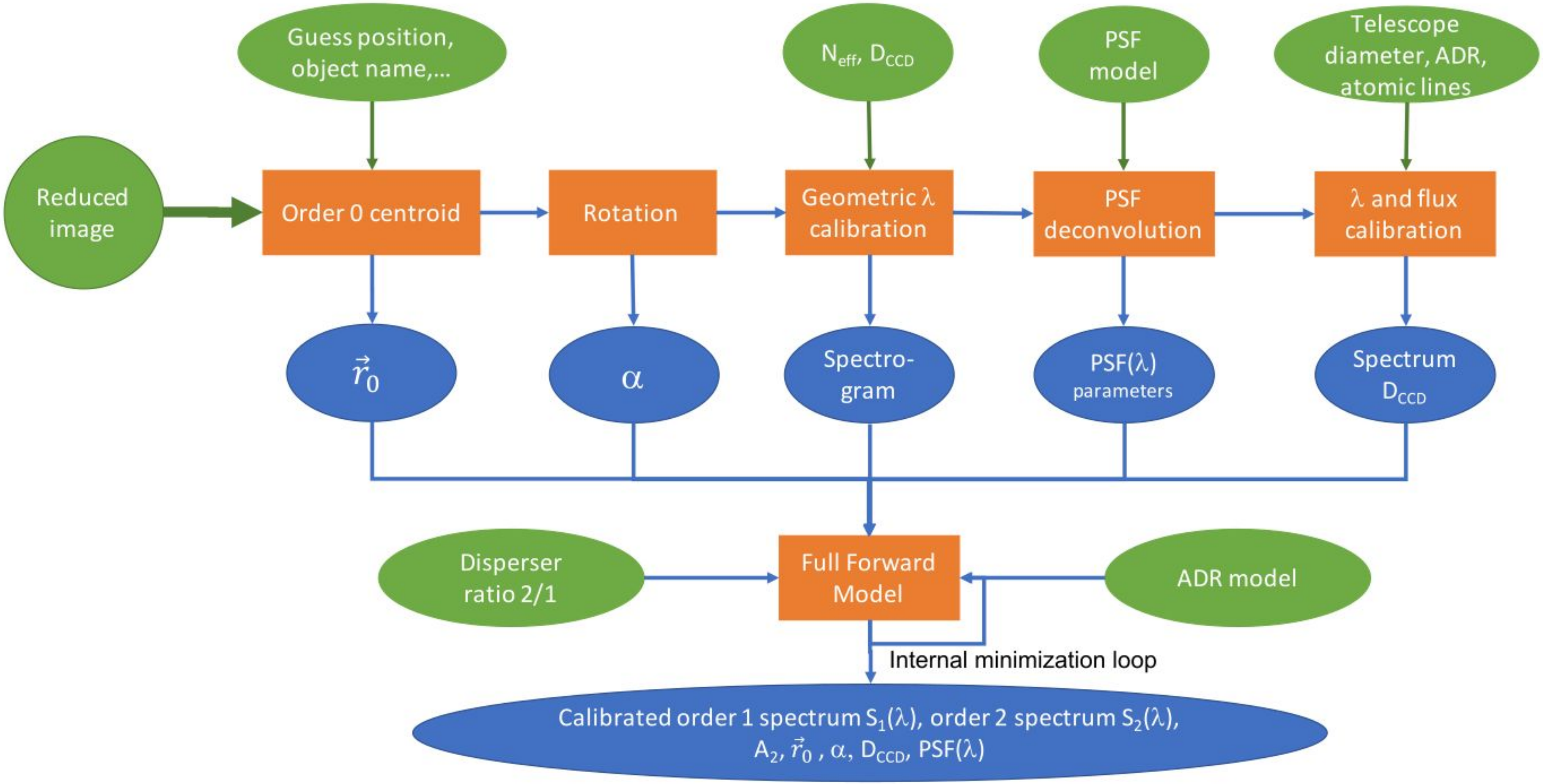


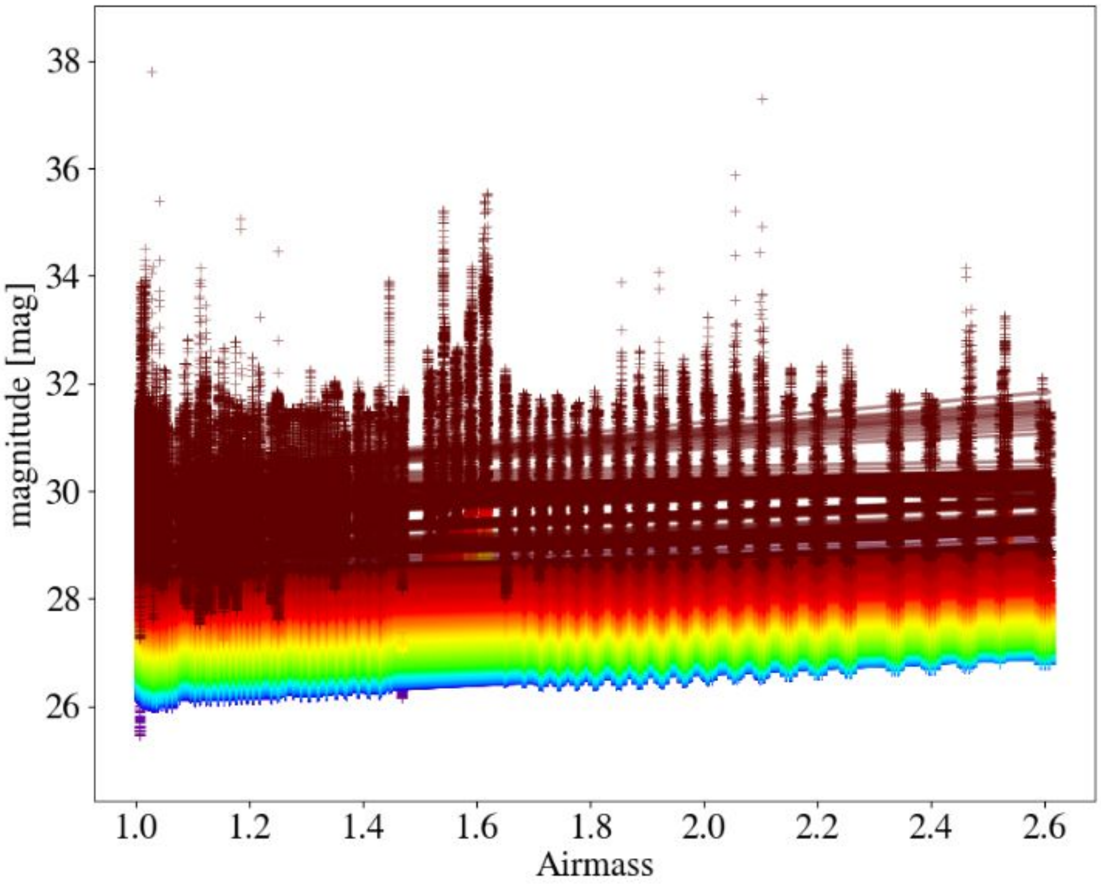
⇒ Disperse the light of the entire field of view on the camera

Spectractor

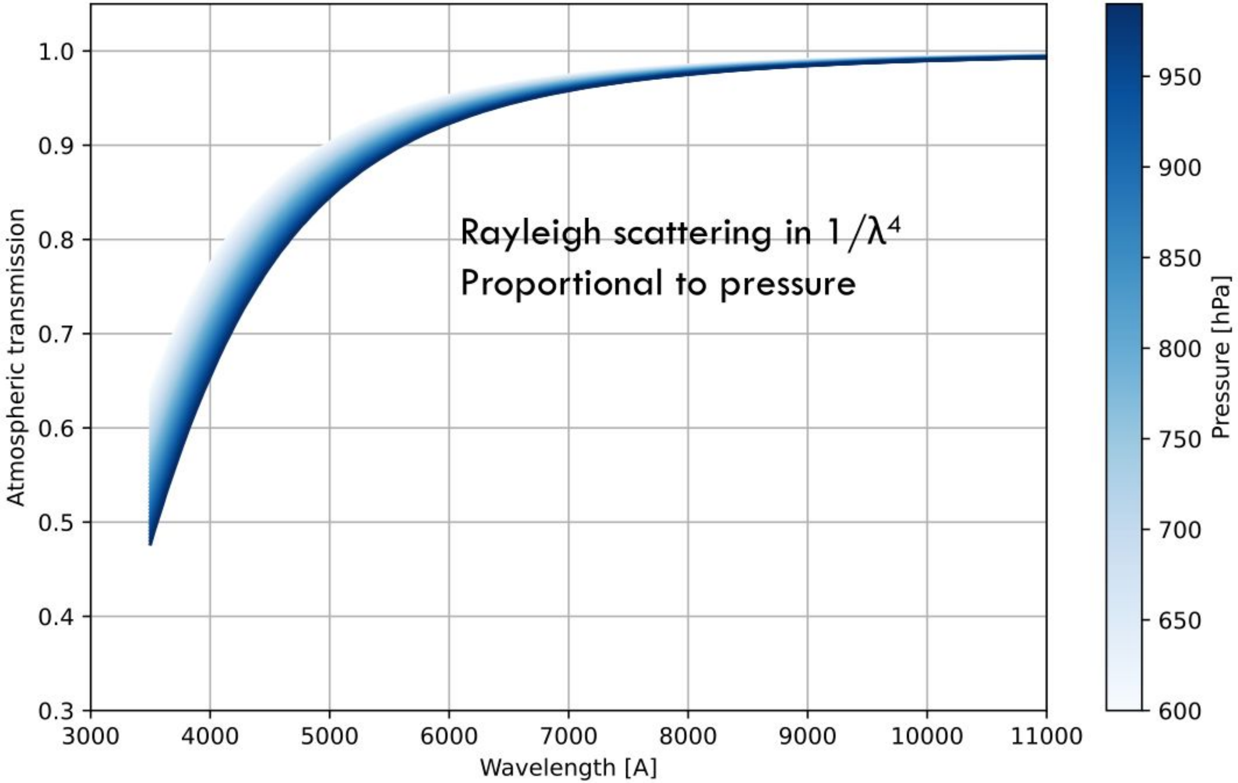
Spectractor software (Neveu et al. 2021)




Guess position, object name,...
N_eff, D_CCD
PSF model
Telescope diameter, ADR, atomic lines
Reduced image
Order 0 centroid
Rotation
Geometric λ calibration
PSF deconvolution
λ and flux calibration
$\vec{r}_0$
α
Spectro-gram
PSF(λ) parameters
Spectrum D_CCD
Disperser ratio 2/1
Full Forward Model
ADR model
Internal minimization loop
Calibrated order 1 spectrum $S_1(\lambda)$, order 2 spectrum $S_2(\lambda)$,
A_2, $\vec{r}_0$, α, D_{CCD}, PSF(λ)

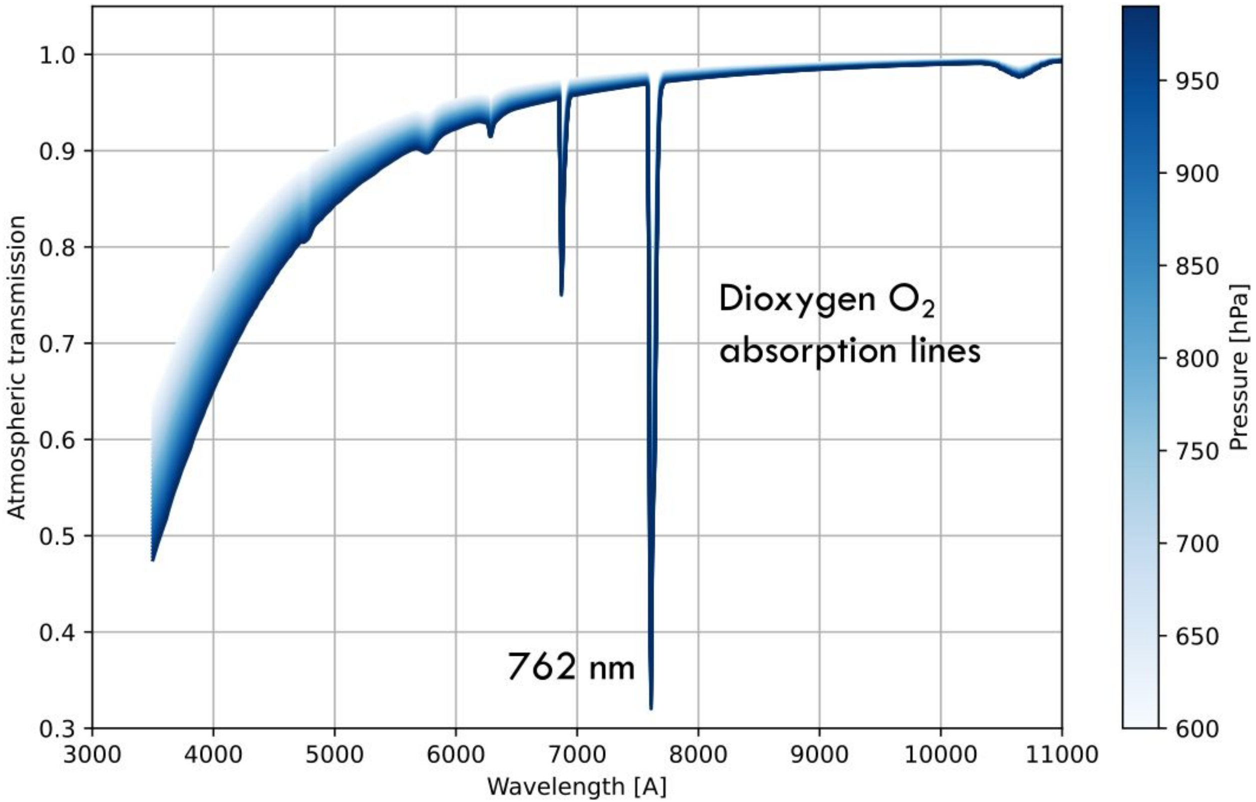

38
36
34
32
30
28
26
magnitude [mag]
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
Airmass

(1)



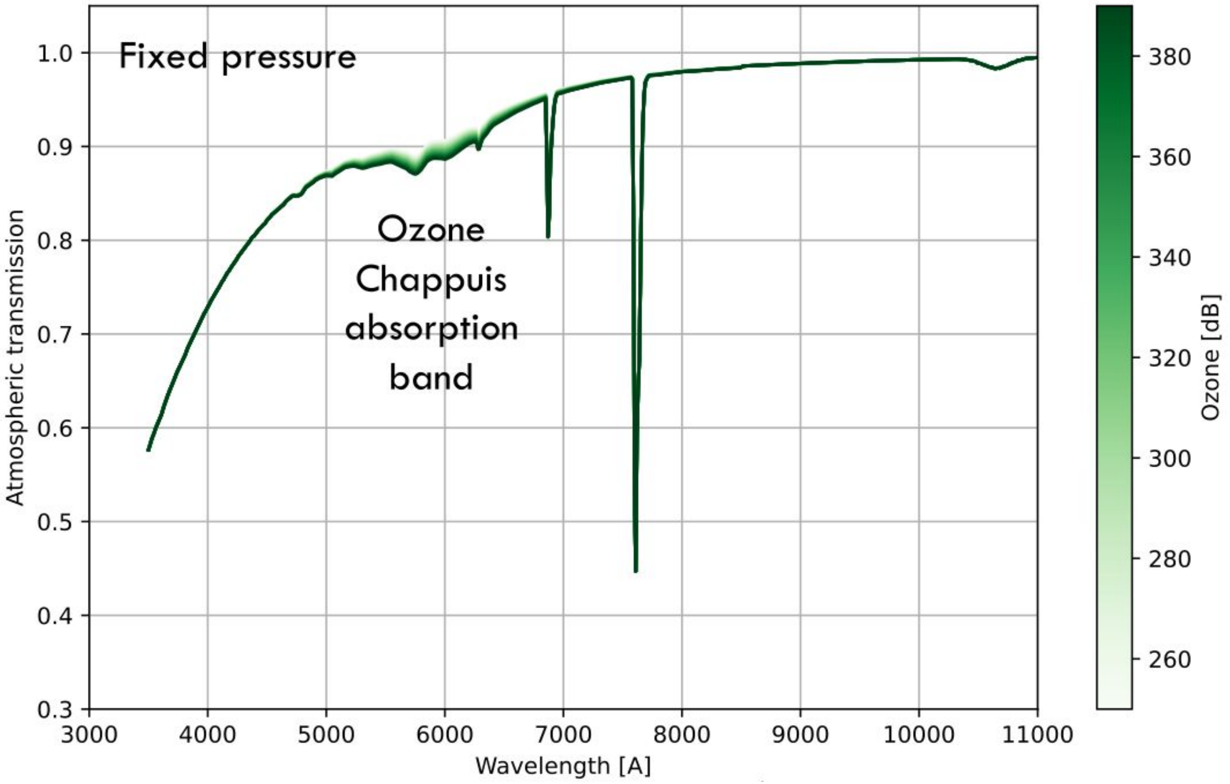
Rayleigh scattering in 1/λ⁴
Proportional to pressure
Atmospheric transmission
Wavelength [A]
Pressure [hPa]
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
3000
4000
5000
6000
7000
8000
9000
10000
11000
950
900
850
800
750
700
650
600

(2)



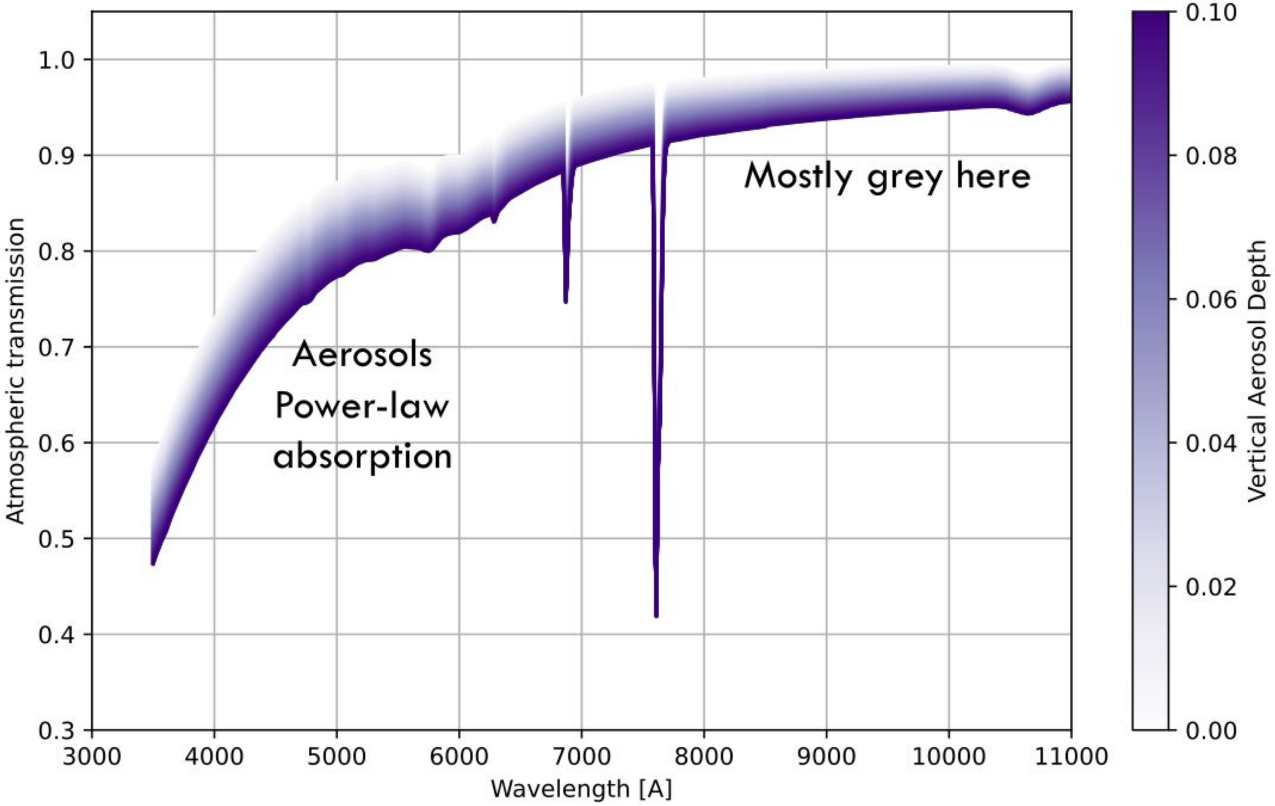
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Atmospheric transmission
3000
4000
5000
6000
7000
8000
9000
10000
11000
Wavelength [A]
Dioxygen O_2
absorption lines
762 nm
950
900
850
800
750
700
650
600
Pressure [hPa]

(3)



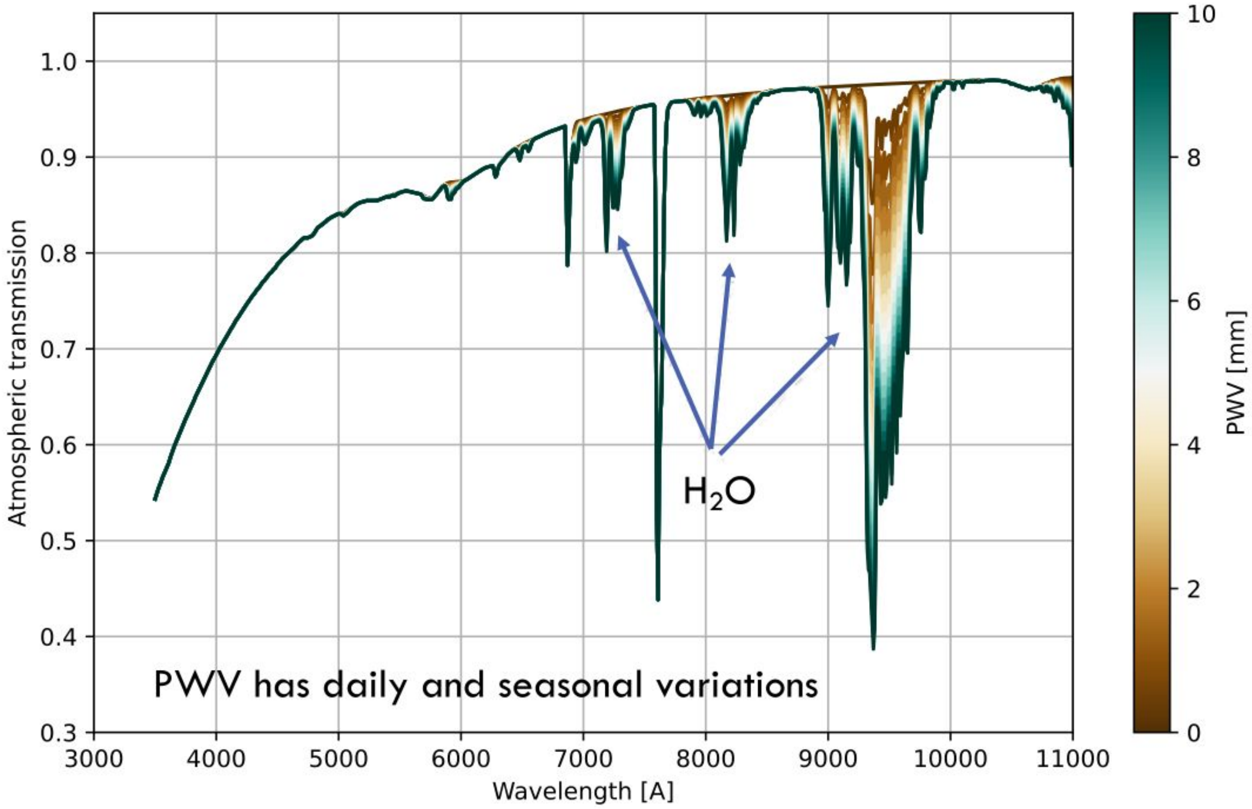
Fixed pressure
Ozone
Chappuis
absorption
band
Atmospheric transmission
Wavelength [A]
Ozone [dB]
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
3000
4000
5000
6000
7000
8000
9000
10000
11000
380
360
340
320
300
280
260

(4)



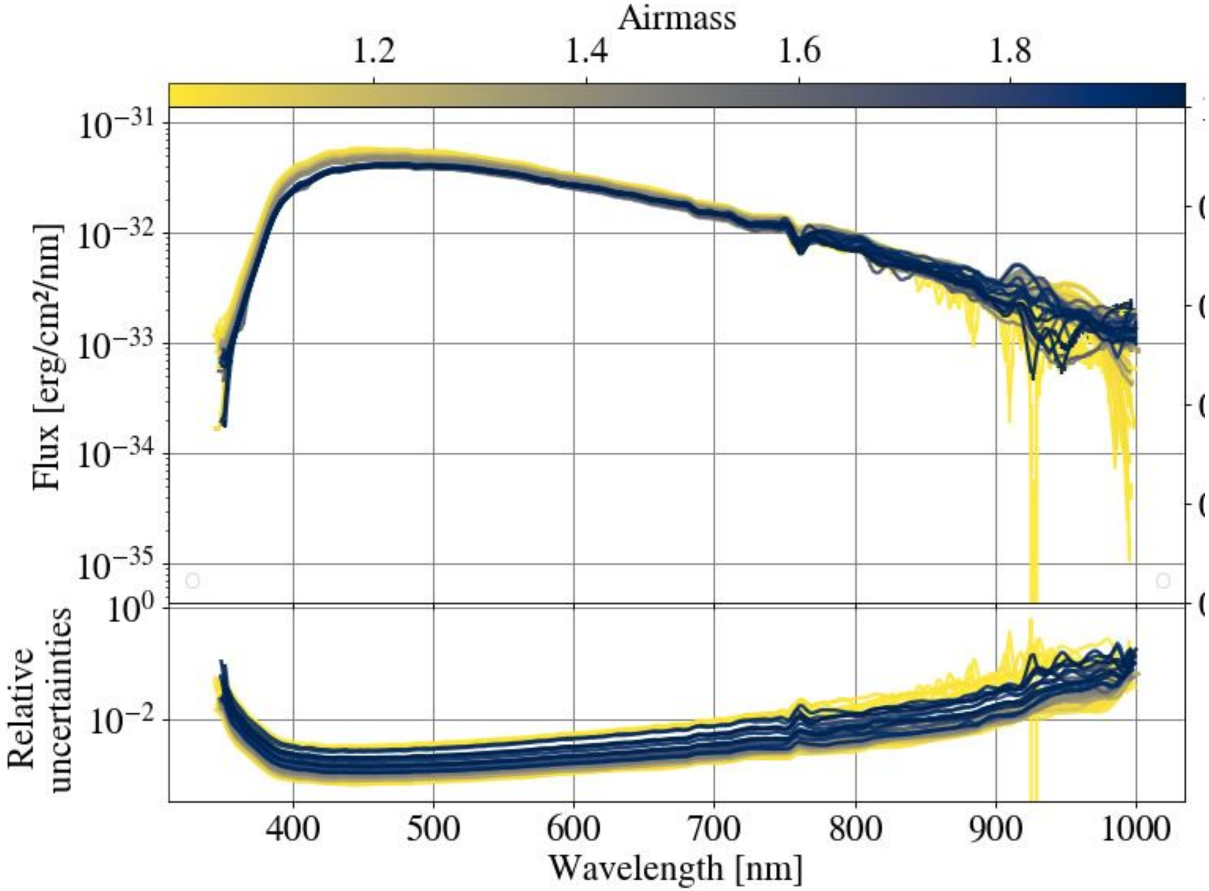
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Atmospheric transmission
3000
4000
5000
6000
7000
8000
9000
10000
11000
Wavelength [A]
Aerosols
Power-law
absorption
Mostly grey here
0.10
0.08
0.06
0.04
0.02
0.00
Vertical Aerosol Depth

(5)



Atmospheric transmission
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
3000
4000
5000
6000
7000
8000
9000
10000
11000
Wavelength [A]
H_2O
PWV has daily and seasonal variations
PWV [mm]
10
8
6
4
2
0

FFM



Airmass
1.2
1.4
1.6
1.8
Flux [erg/cm²/nm]
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
Relative uncertainties
10^{0}
10^{-2}
400
500
600
700
800
900
1000
Wavelength [nm]

Field simulation