When more data is not enough: instrumental calibration challenges in next-generation cosmology

Presented by Thierry Souverin

24/04/2026

What is cosmology ?

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

General relativity, 1915

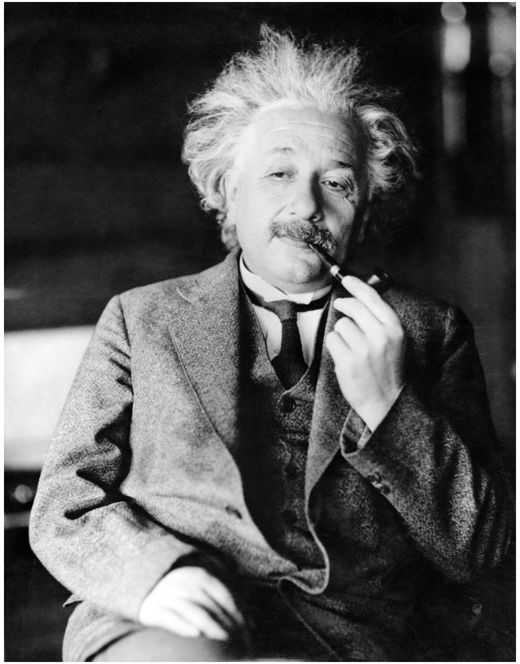
Einstein equation:

Newtonian gravitational constant

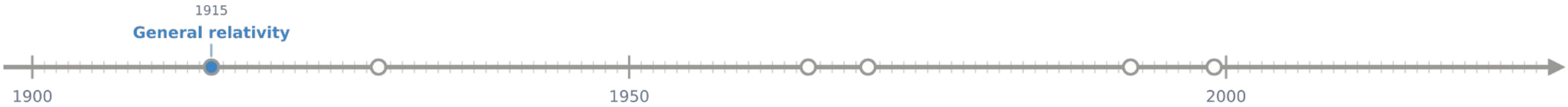
$$G_{\mu\nu} = \frac{8\,\pi\,G_N}{c^4}\,T_{\mu\nu}$$

4D spacetime curvature

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



Albert Einstein, pipe smoking



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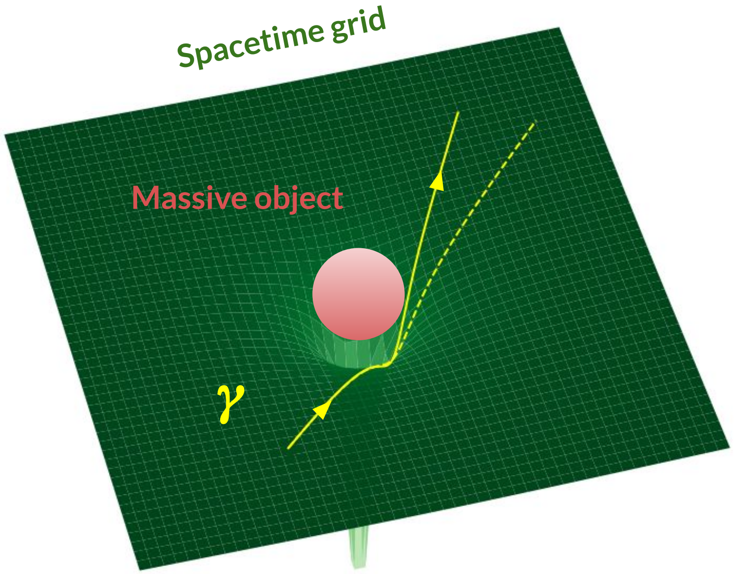
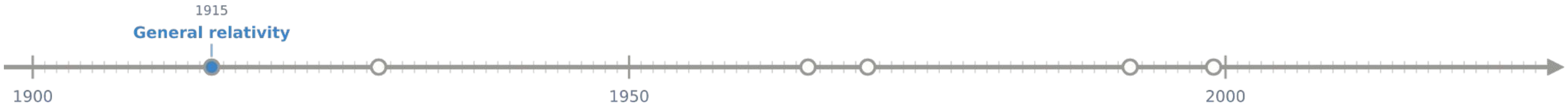


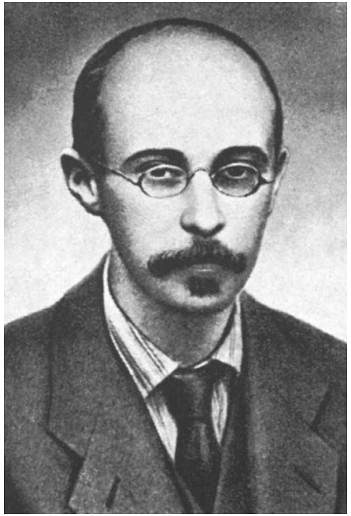
2D representation of spacetime deformed by a massive object



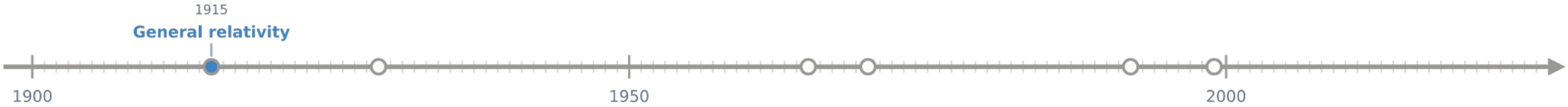
Cosmological principle

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

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



Aleksandr Friedmann, not pipe smoking



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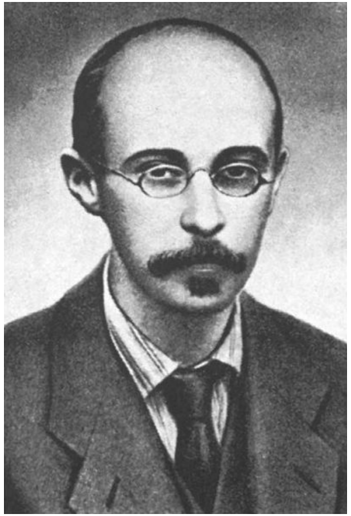
Friedmann's equations (solution to Einstein equation)

Scale factor

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

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



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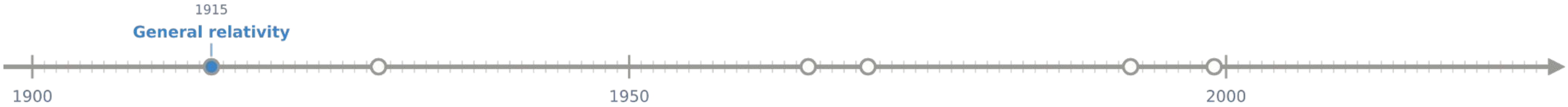
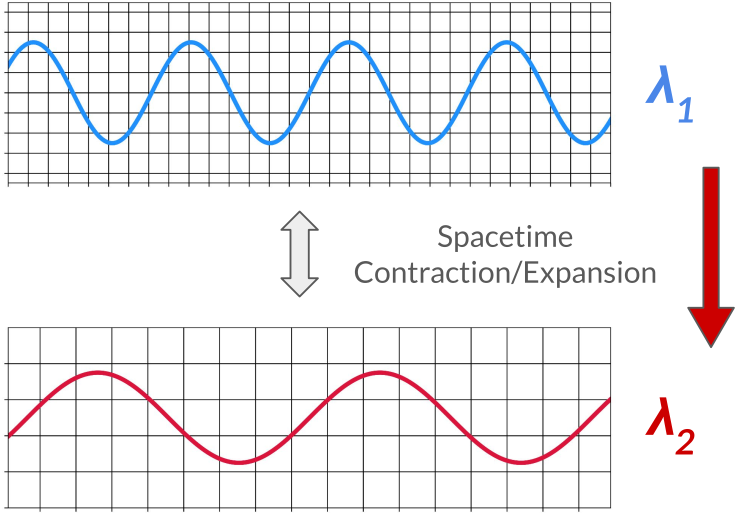
⇒ links the **dynamic behavior** of the Universe with its **energy content**



Redshift definition

$\lambda_1 < \lambda_2$



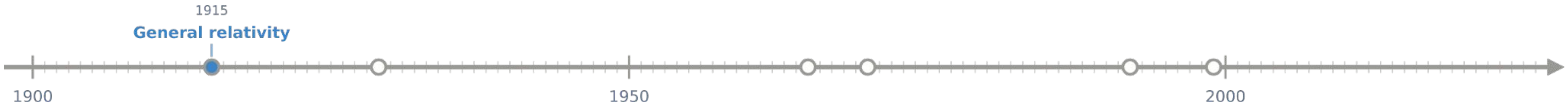
λ_1

Spacetime
Contraction/Expansion

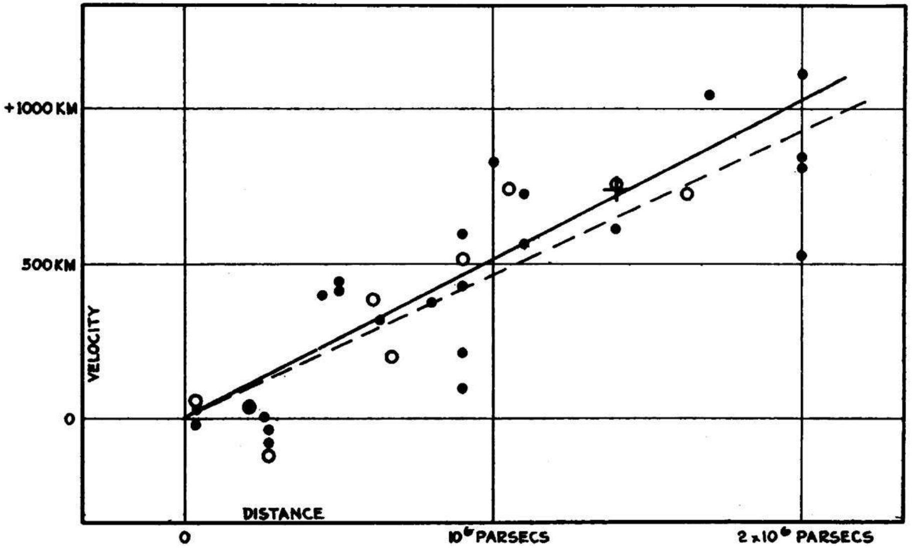
λ_2

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

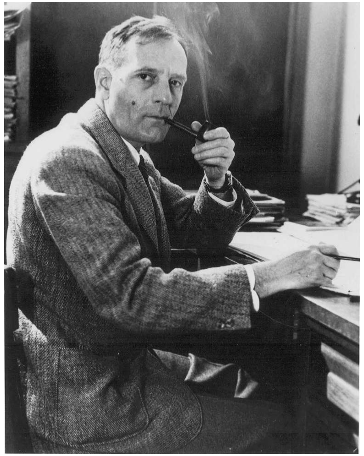
Wavelength is affected by spacetime distorsion ⇒ **The redshift *z* tracer spacetime evolution**



Expansion of the Universe, 1929



Galaxy velocities against their distances
(Hubble, 1929)



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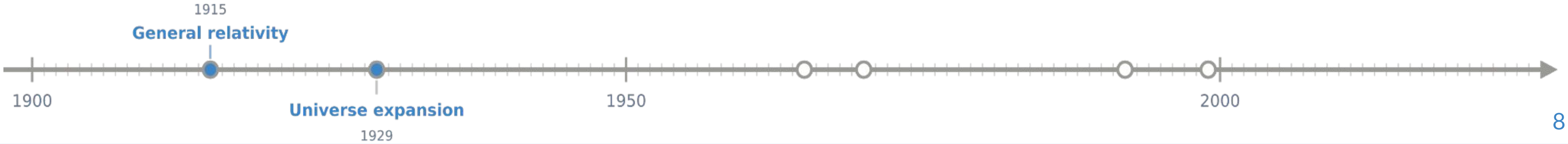

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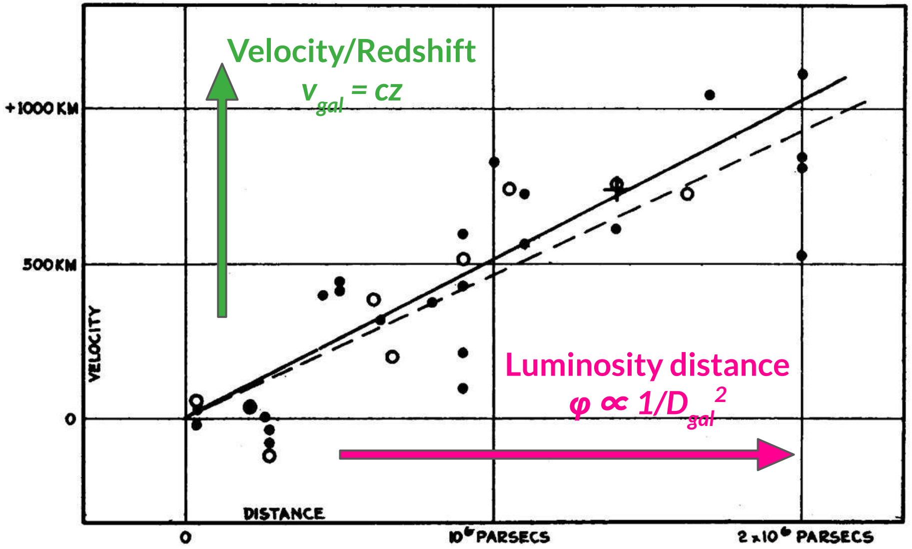

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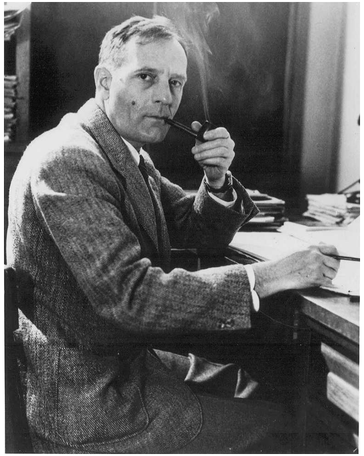

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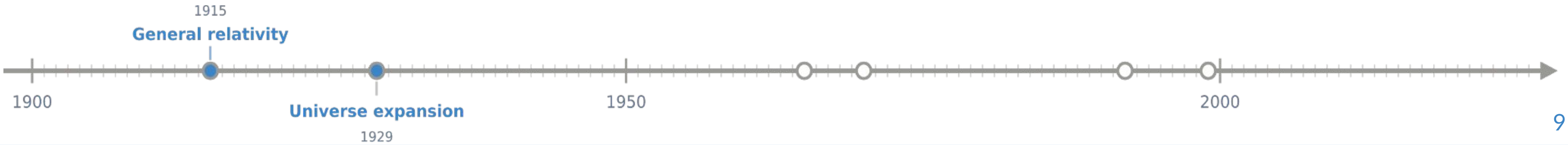
$$v_{\text{gal}} \propto D_{\text{gal}}$$

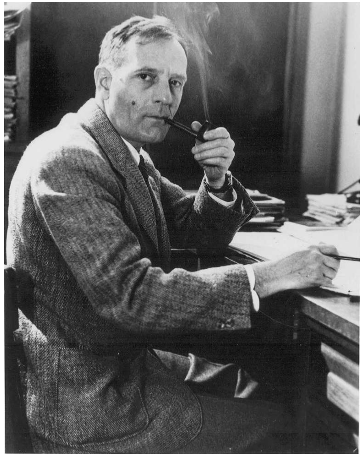
$$\Longleftrightarrow$$

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



Expansion of the Universe, 1929

- Only 22 sources observed
- Poor photometric calibration
- Confusion between gas clouds and galaxies



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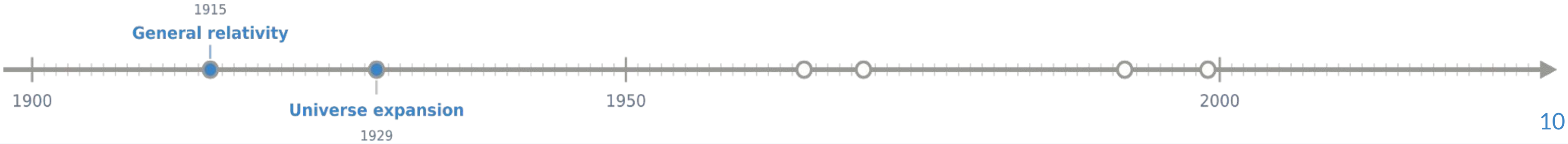

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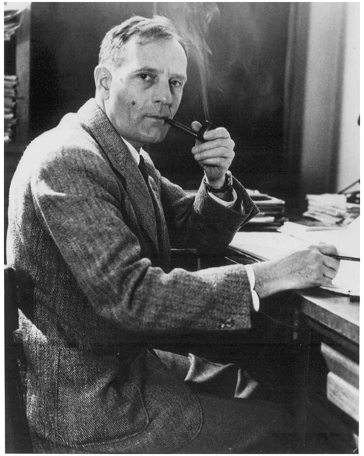
Factor ~7 between Hubble and current estimation:

$$H_{0,\text{Hubble}} \simeq 500\text{km}^{-1}.\text{s}^{-1}.\text{Mpc}^{-1} \quad ; \quad H_{0,\text{current}} \simeq 71 \pm 3\,\text{km}^{-1}.\text{s}^{-1}.\text{Mpc}^{-1}$$



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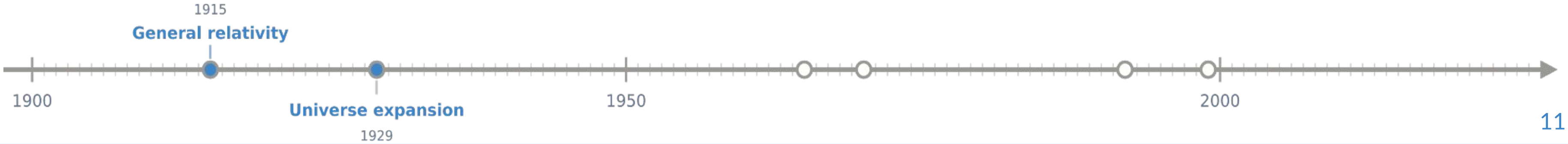

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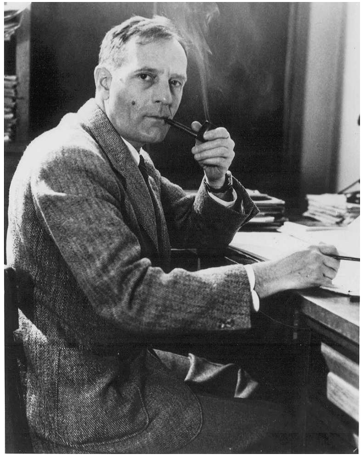

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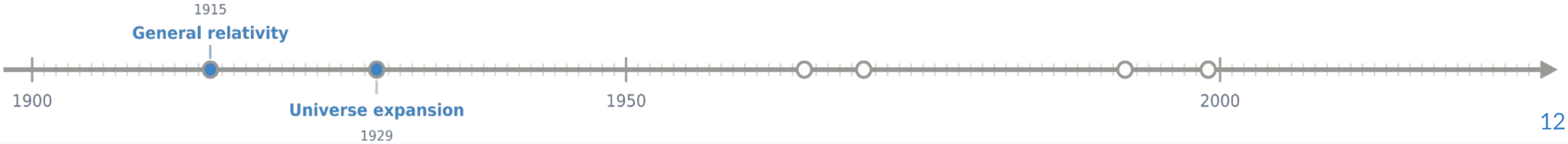
But:

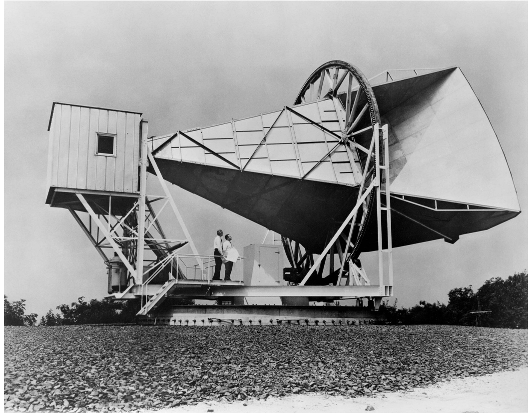
- Clear linear correlation between redshift z and galaxy distance D_{gal}

⇒ **First evidence of the Universe's expansion**

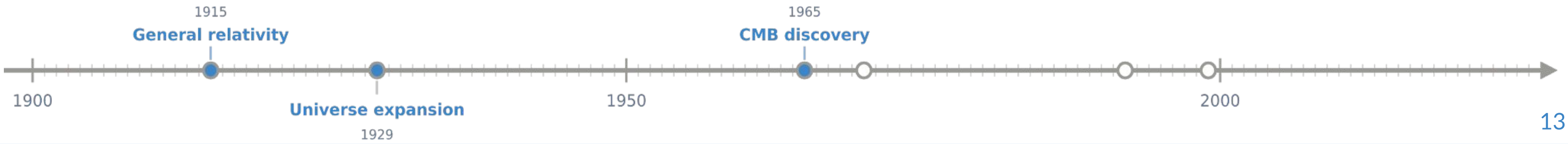


Cosmic Microwave Background discovery, 1965

Several models to explain the Universe’s expansion, including the **Big Bang theory** ⇒ need for observational confirmation



A. Penzias and R. Wilson, not pipe smoking, standing on the Holmdel Horn Antenna



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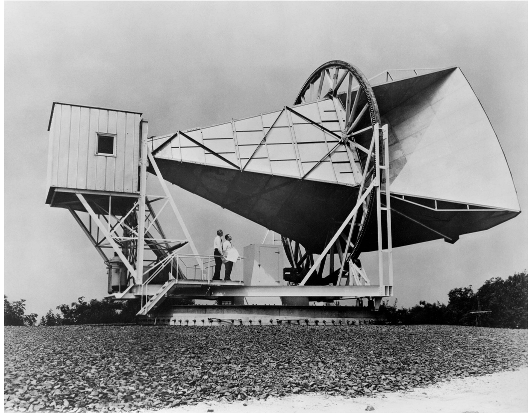

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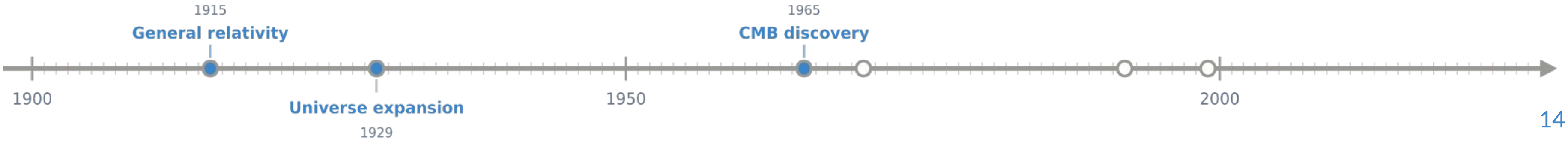

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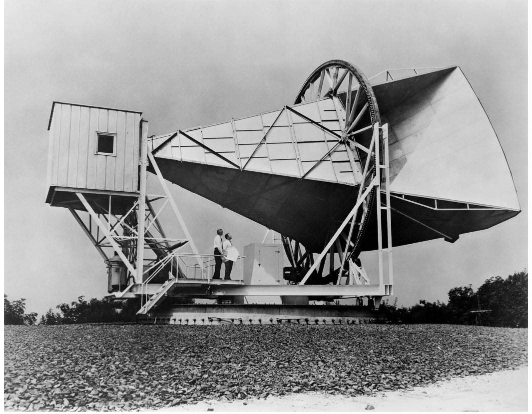

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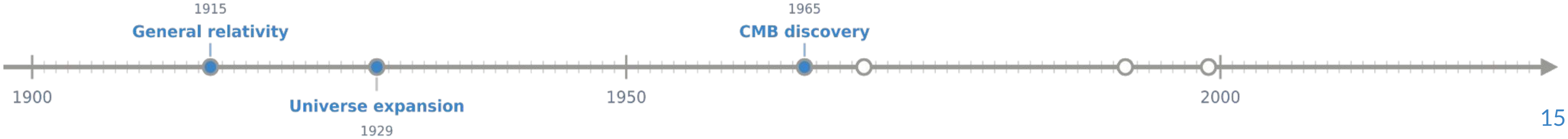

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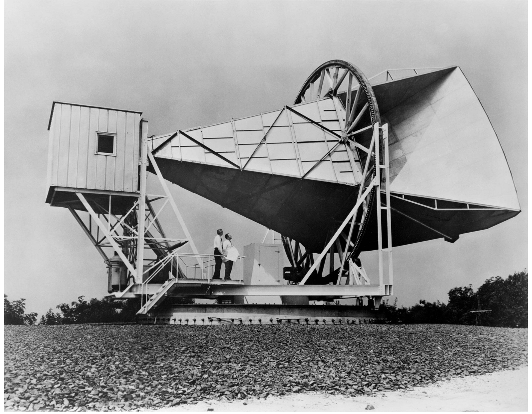

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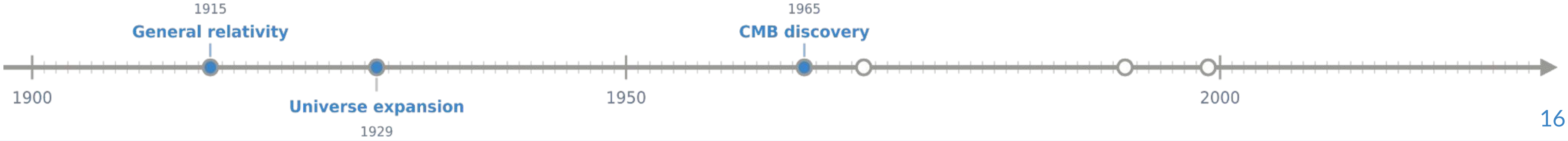

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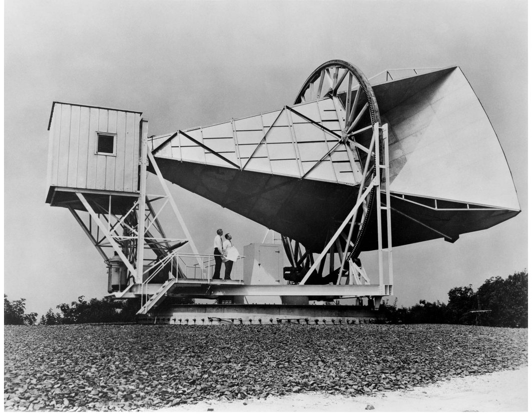

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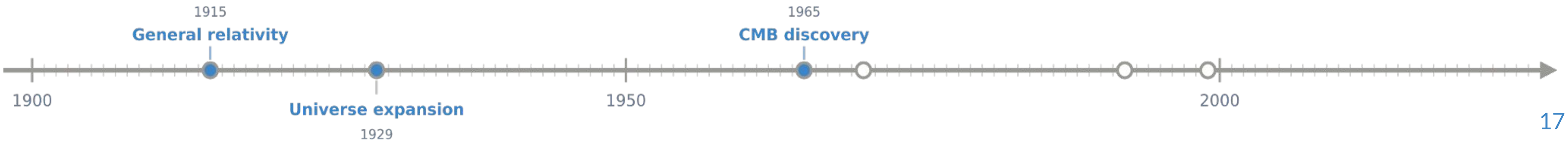

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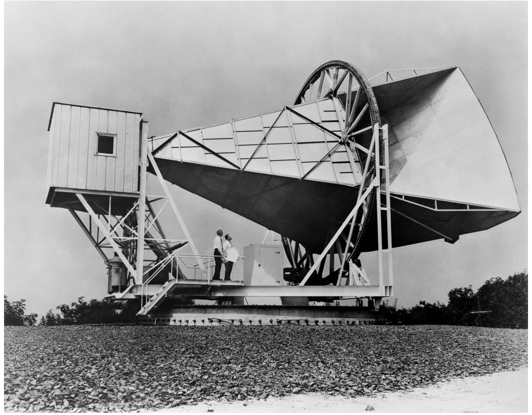

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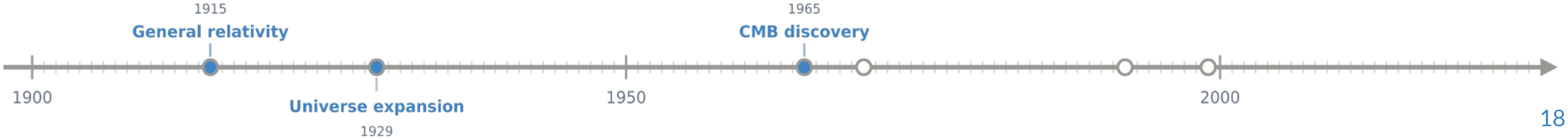

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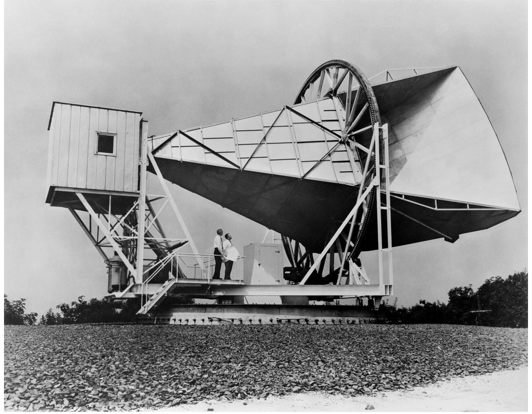

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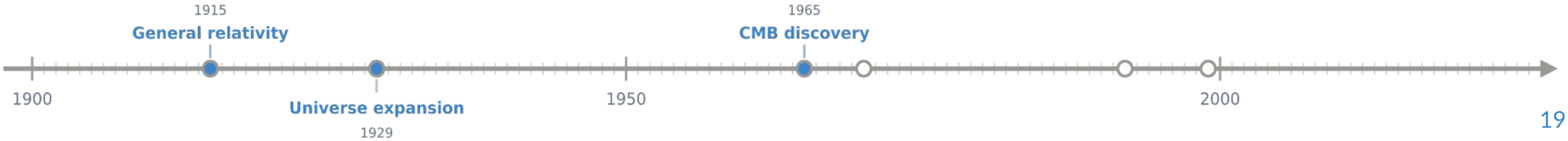

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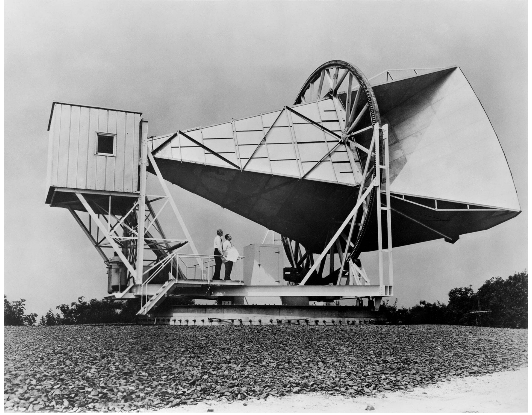

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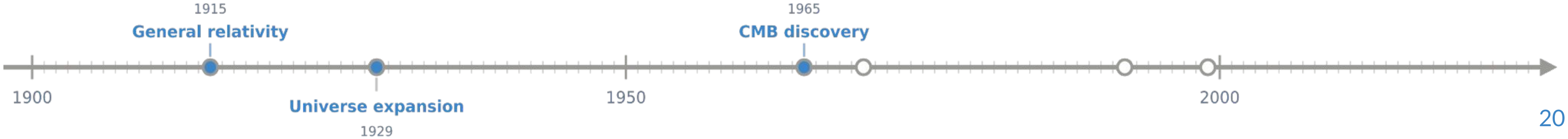

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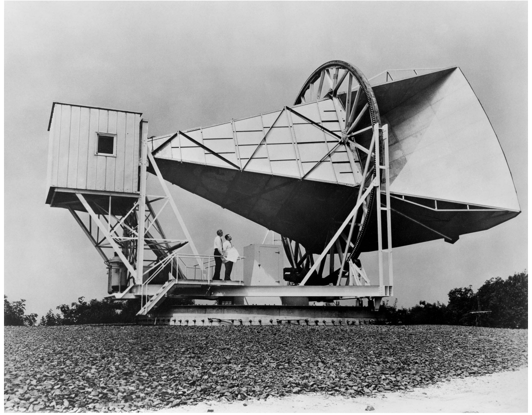
  ⇒ isotropic thermal source of 2.7K



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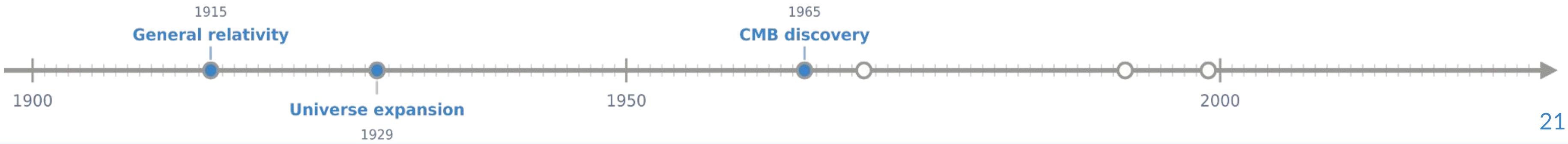

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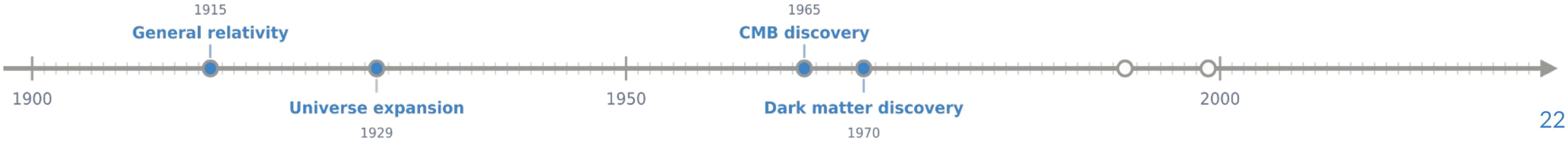
Dark matter discovery

Studies for galaxy dynamics:

- **1 galaxy** observed : **Andromeda**
- **67 gas region** observed inside

Vera Rubin, not pipe smoking, measuring spectra



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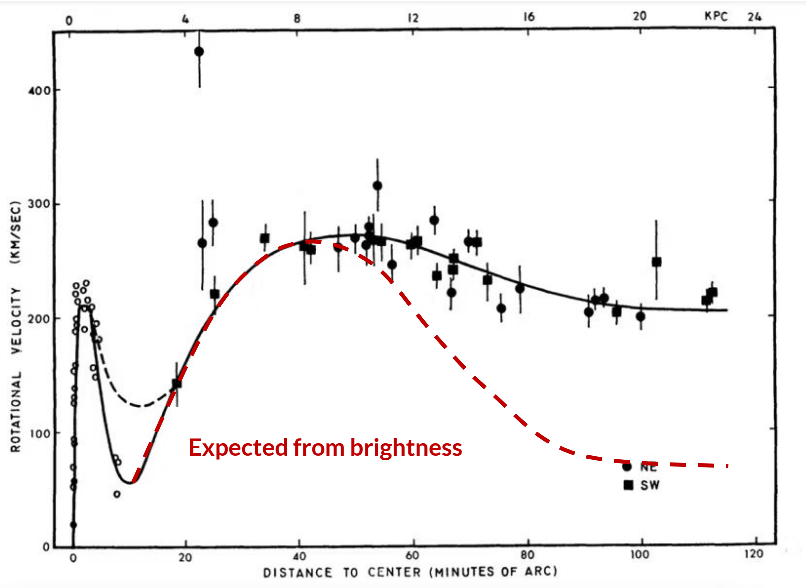
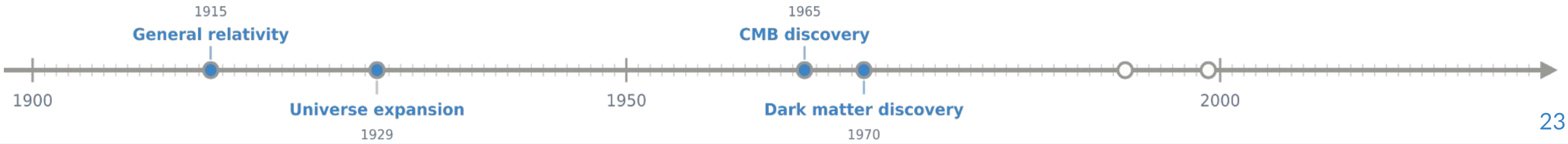


HII gas region velocity against distance from nucleus of Andromea galaxy (Rubin, 1970)



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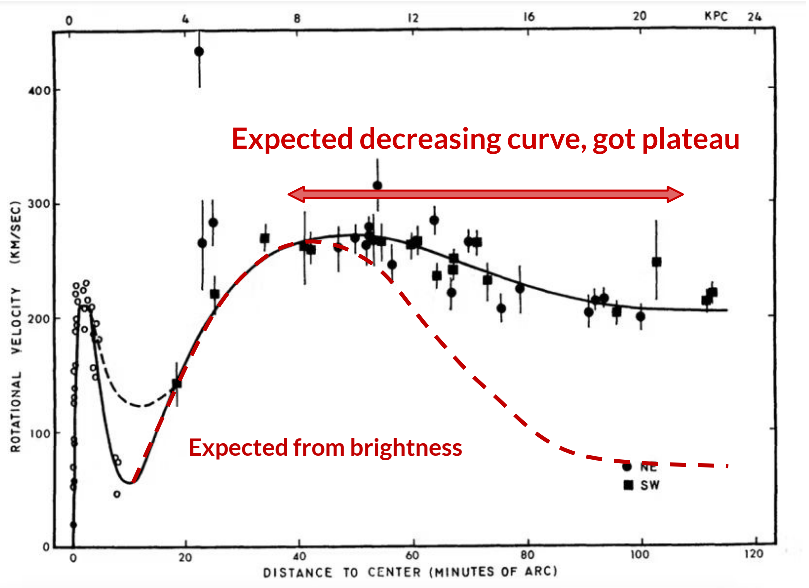
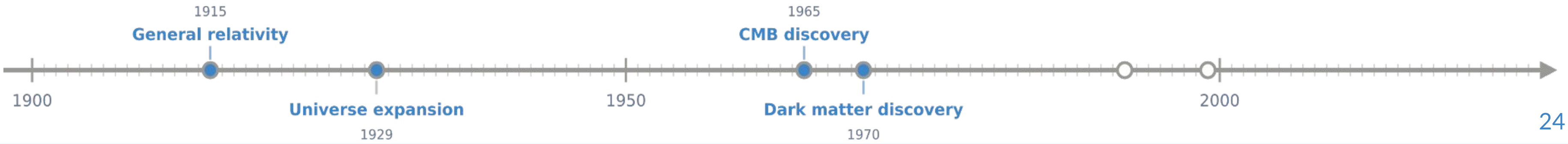


Expected decreasing curve, got plateau

Expected from brightness

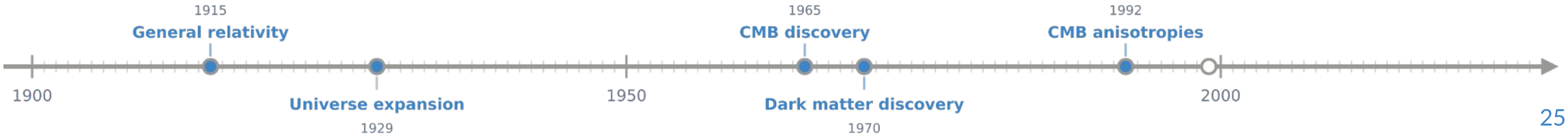
HII gas region velocity against distance from nucleus of Andromea galaxy (Rubin, 1970)

Hints for **halo** of invisible mass
⇒ First evidence of **dark matter**



CMB anisotropies measurements

Is the CMB truly isotropic ? Ground and balloon-borne experiments tried to measure anisotropies ⇒ but were limited by **atmospheric** and **instrumental noise**



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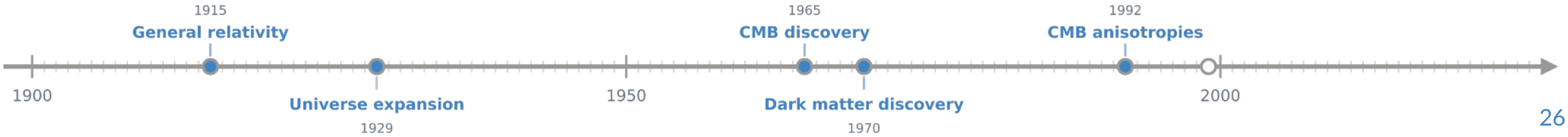

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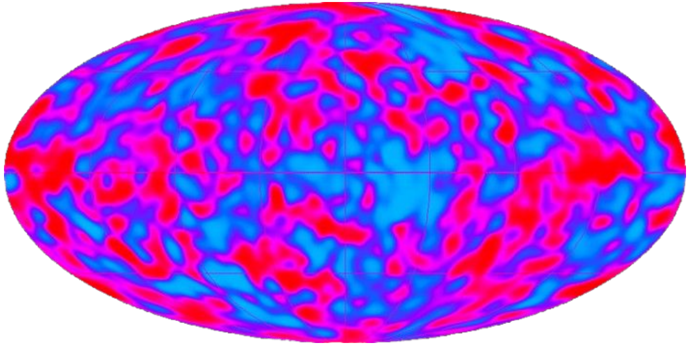
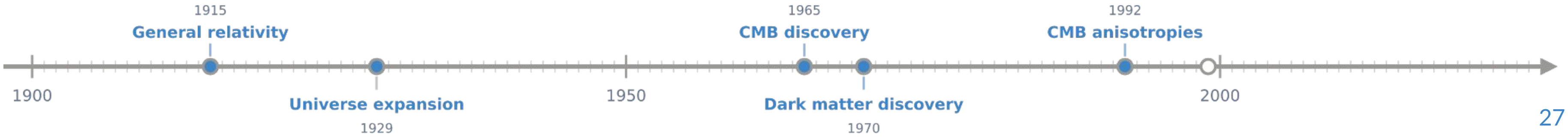
Artist's concept of the COBE spacecraft



Temperature map of the CMB obtained with 2-year observations from COBE

CMB anisotropies detection: **± 30 μK**

⇒ same order of magnitude as instrumental noise

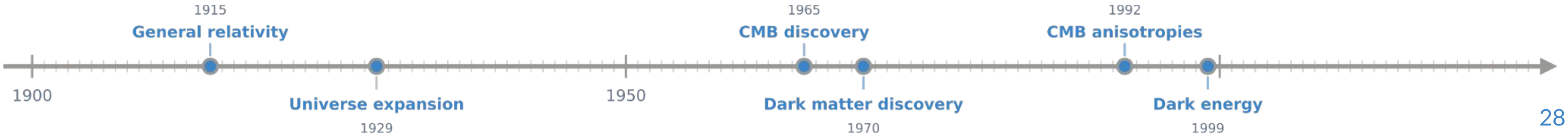


Dark energy

SNe Ia observations for Universe's expansion study:

- High-Z Supernova Search Team: 16 + 34 others
- Supernovæ Cosmology Project (SCP): 42 + 18 others

⇒ Both did joint analysis with Calán-Tololo survey (and others)



Dark energy

SNe Ia observations for Universe’s expansion study:

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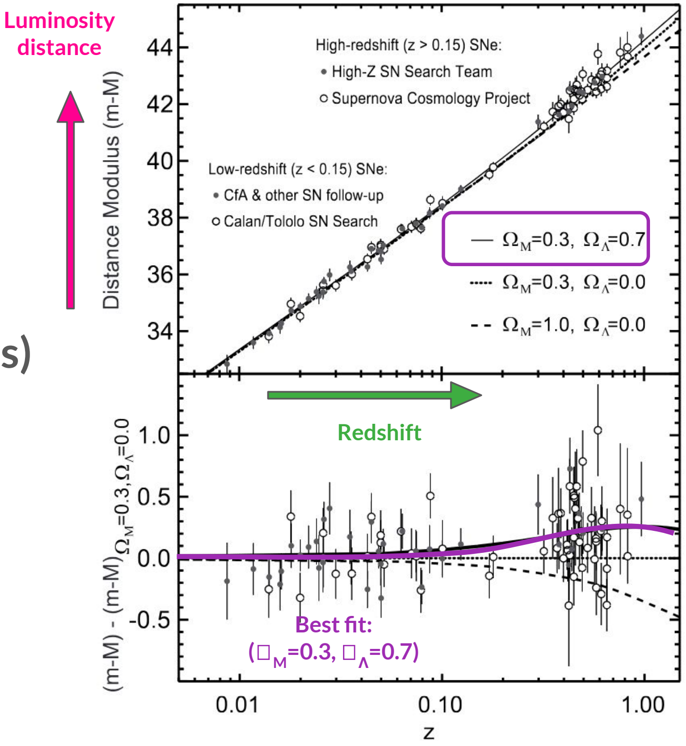
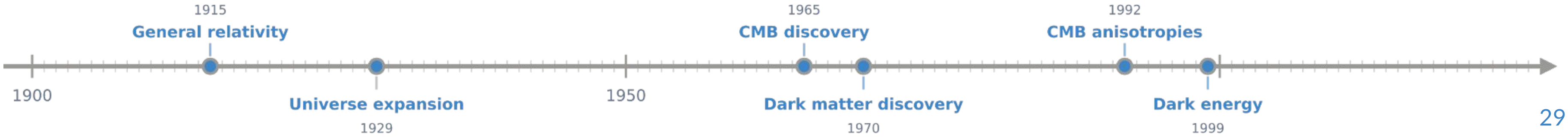


Hubble diagram combining High-Z Supernova Search Team and SCP (Perlmutter and Schmidt, 2003)



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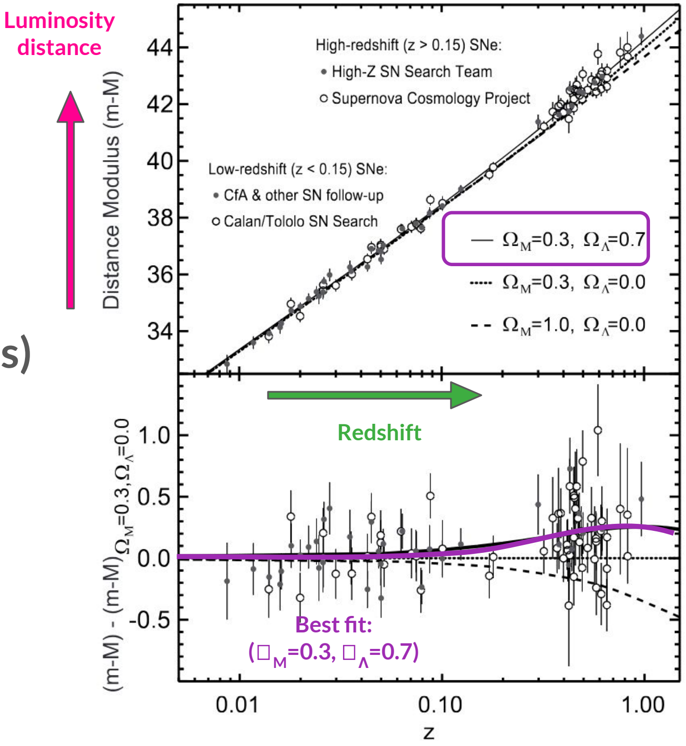
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\,\pi\,G_N}{c^4}\,T_{\mu\nu}$$

Cosmological constant

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



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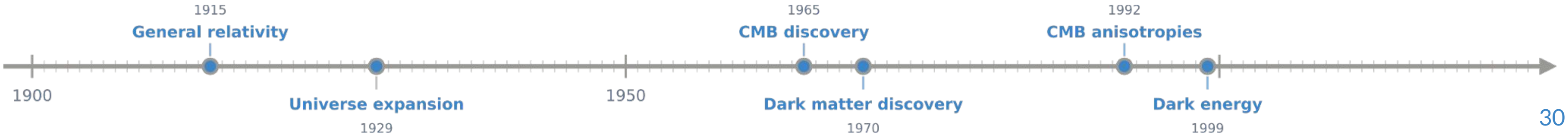

1915
General relativity

1929
Universe expansion

1965
CMB discovery

1970
Dark matter discovery

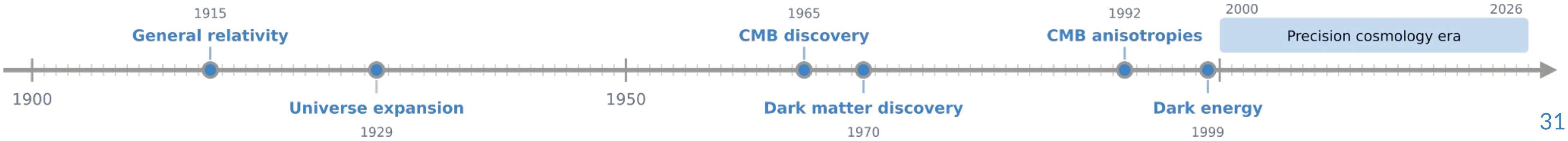
1992
CMB anisotropies

1999
Dark energy

Precision cosmology era

The contemporary cosmology has reached a high-precision era:

- SNe Ia:
  - ~10^4 observations (ZTF) → ~10^5 within the next decade (LSST)
  - Joint analysis with ~10^3 observations & up to 24 different datasets



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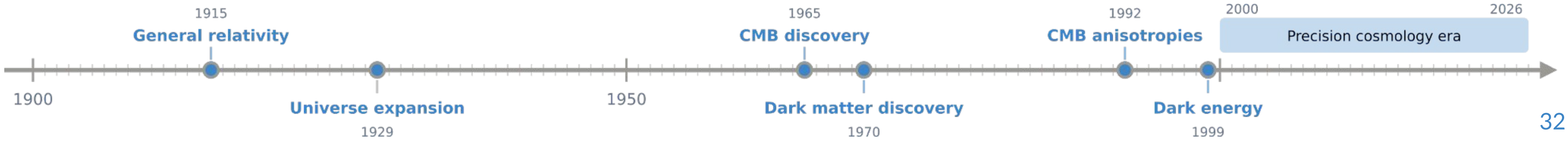
  - Temperature precision of few μK
  - Polarization measurements of ~1°



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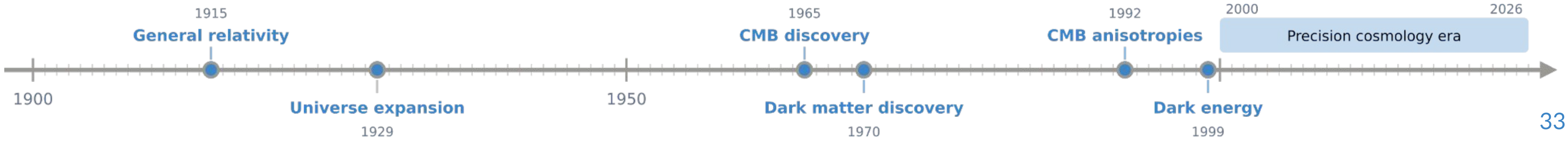
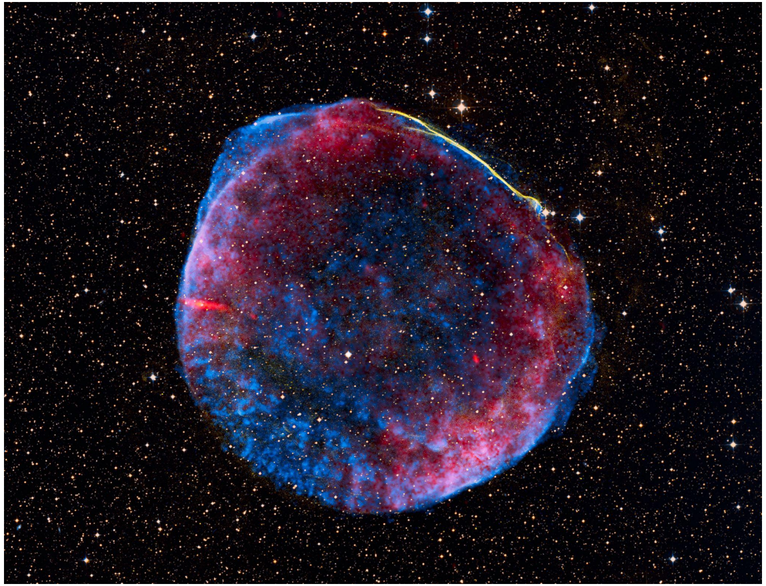
⇒ Surveys become more sensitive, with bigger datasets



Type Ia supernovae cosmology

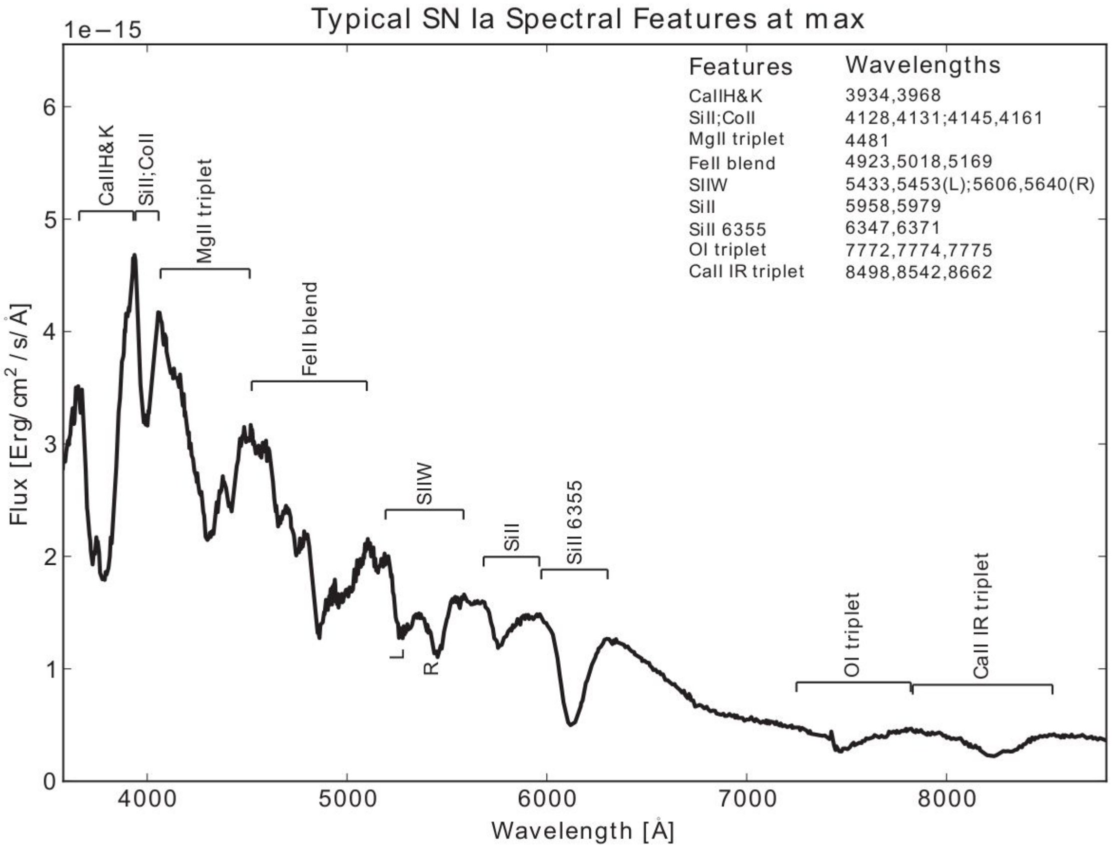
Explosion mechanism

- 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



Features	Wavelengths
CaIIH&K	3934,3968
SiII;CoII	4128,4131;4145,4161
MgII triplet	4481
FeII blend	4923,5018,5169
SIIW	5433,5453(L);5606,5640(R)
SiII	5958,5979
SiII 6355	6347,6371
OI triplet	7772,7774,7775
CaII IR triplet	8498,8542,8662

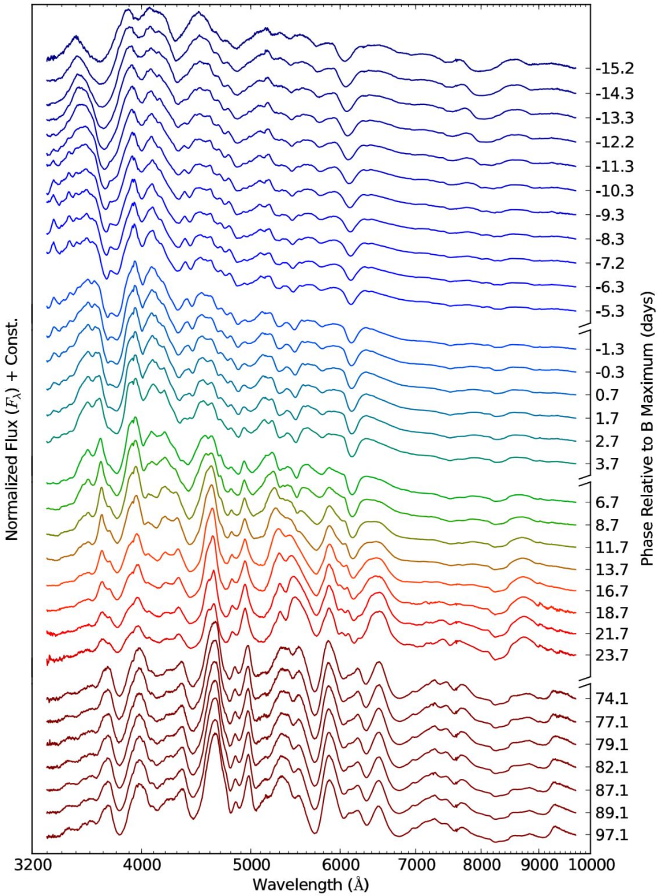
SN Ia spectrum (Chotard, 2011)

Characteristics:

- 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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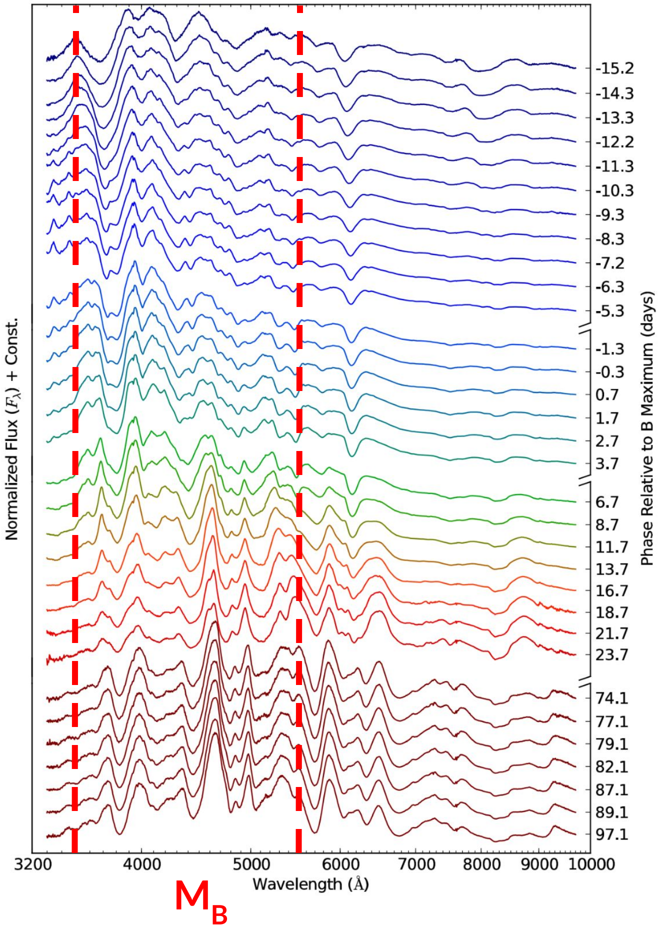
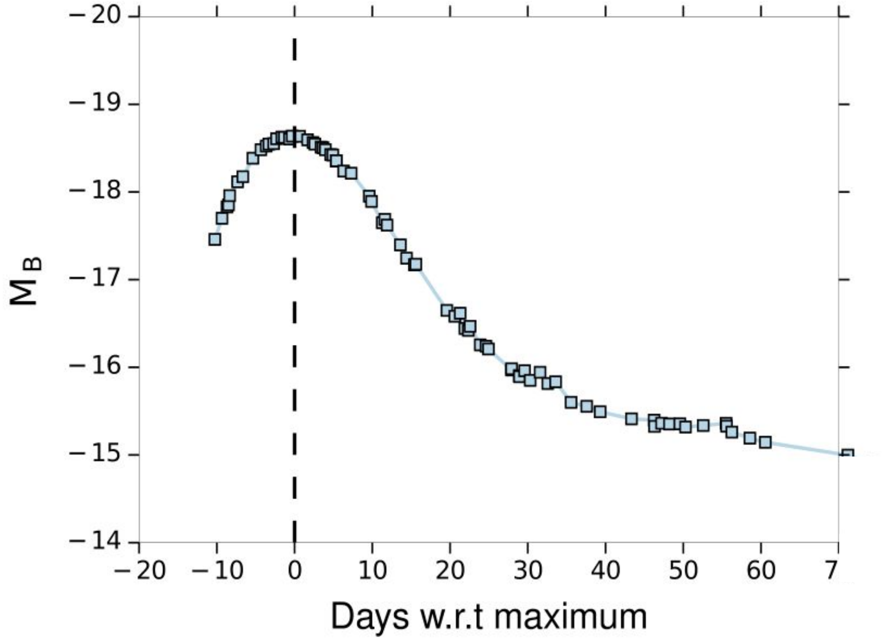


SNe Ia light curve

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



Restframe B band

Spectrum temporal evolution of SN2011fe
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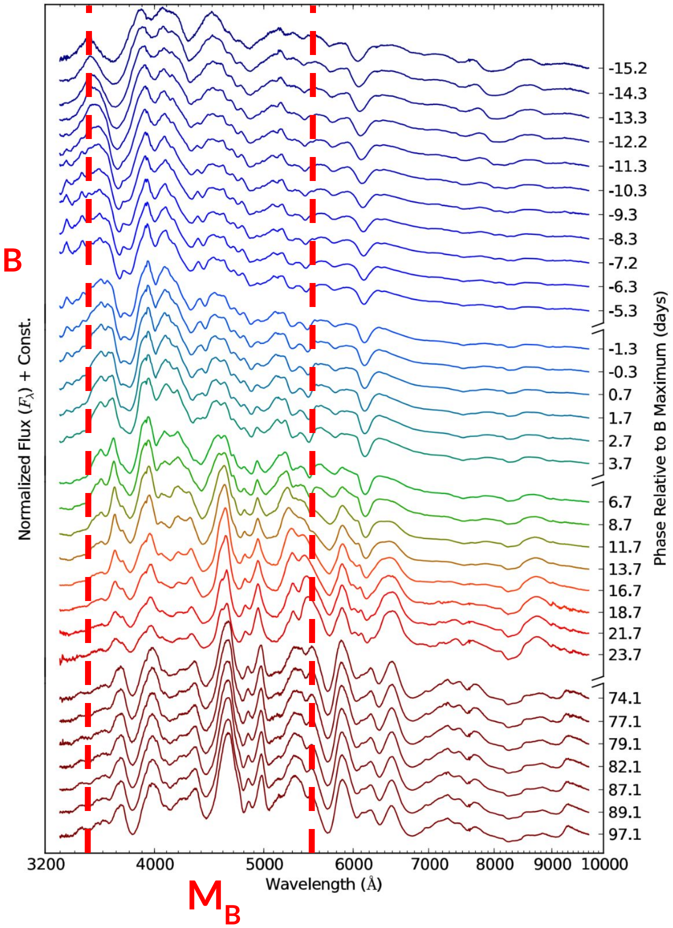

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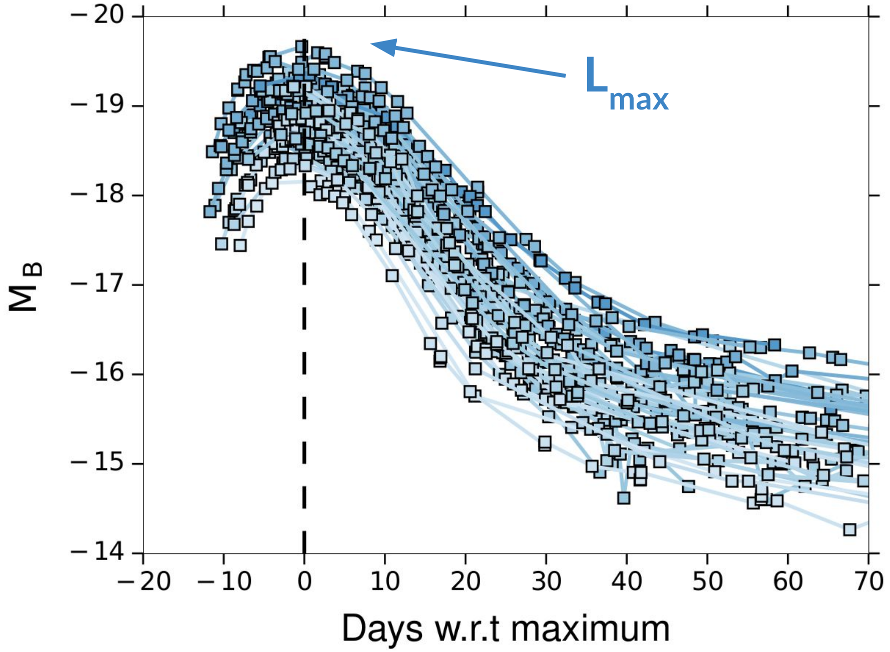

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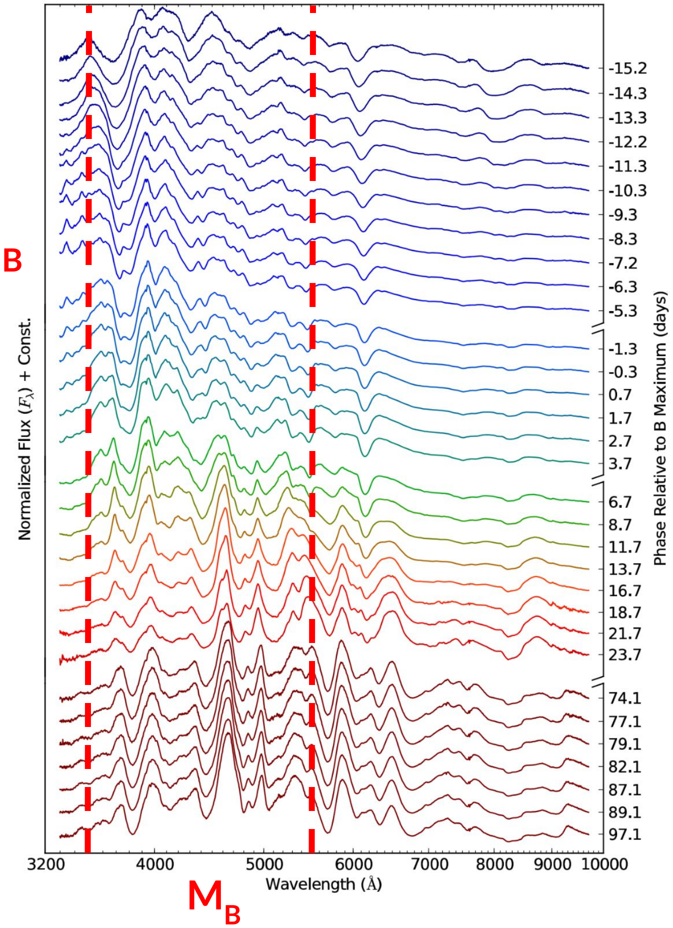

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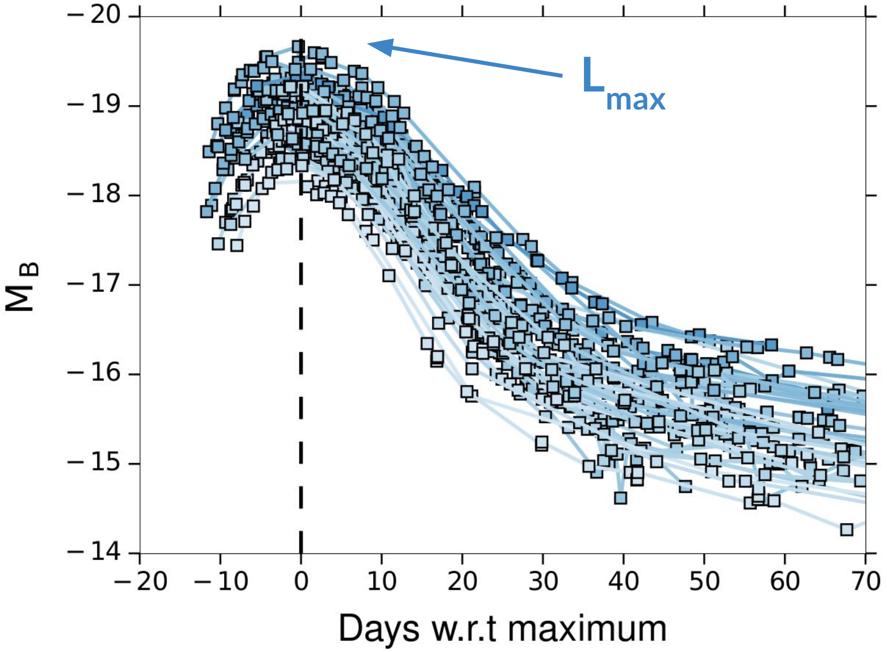

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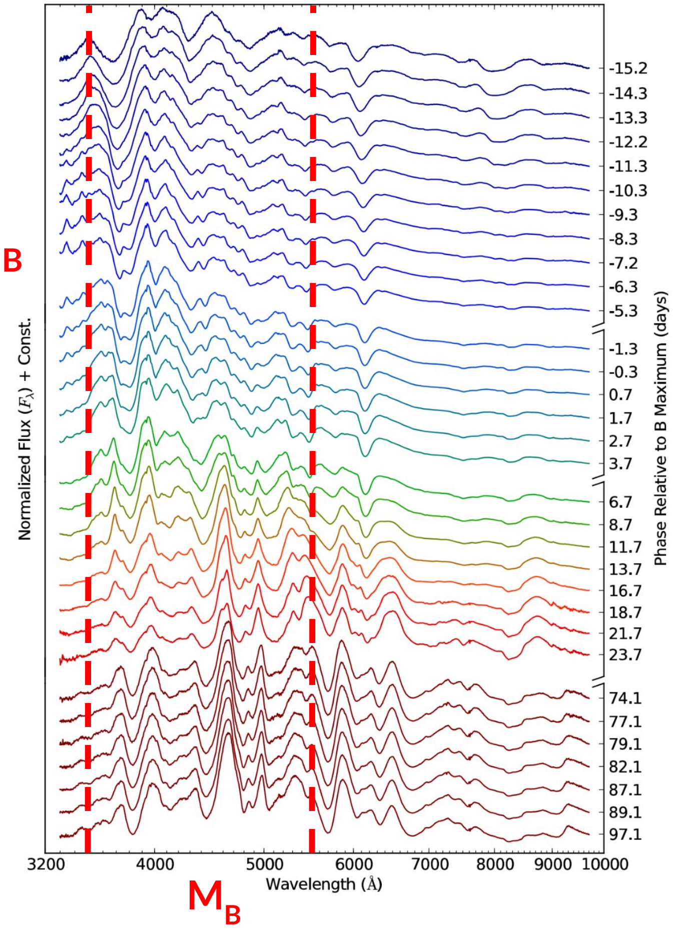


Luminosity distance:

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

Hubble diagram

Plot μ against z → Hubble Diagram

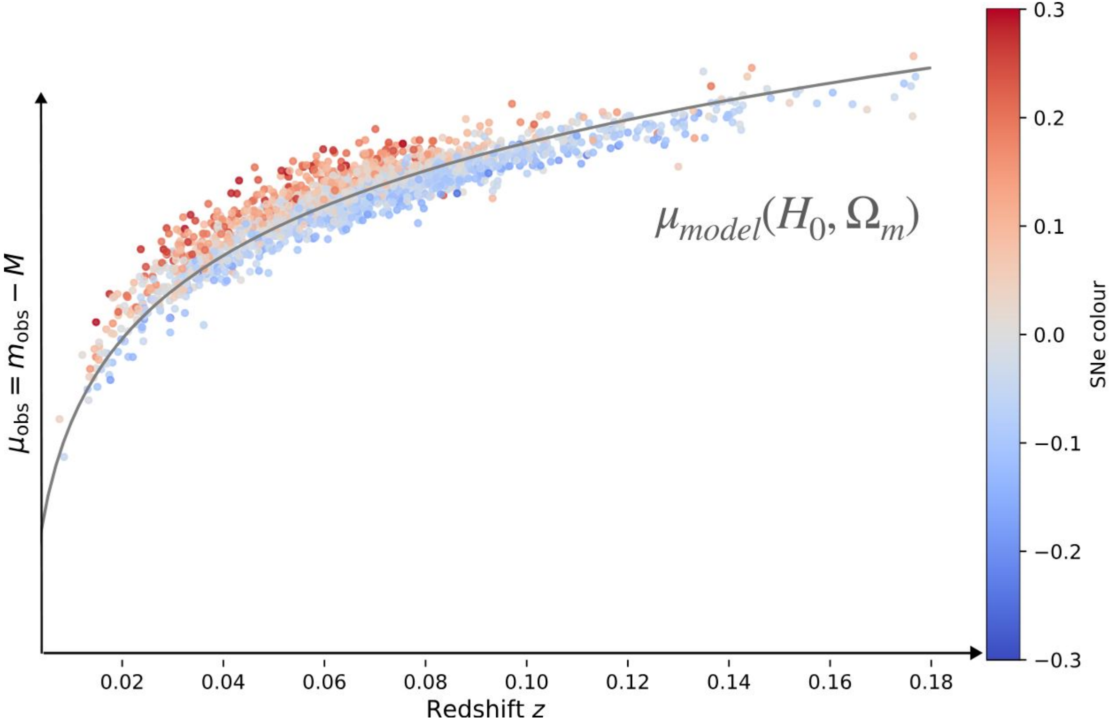
Distance modulus:

$$\mu = \boxed{m_B^\star} - \boxed{M_B}$$

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

Standardization parameters
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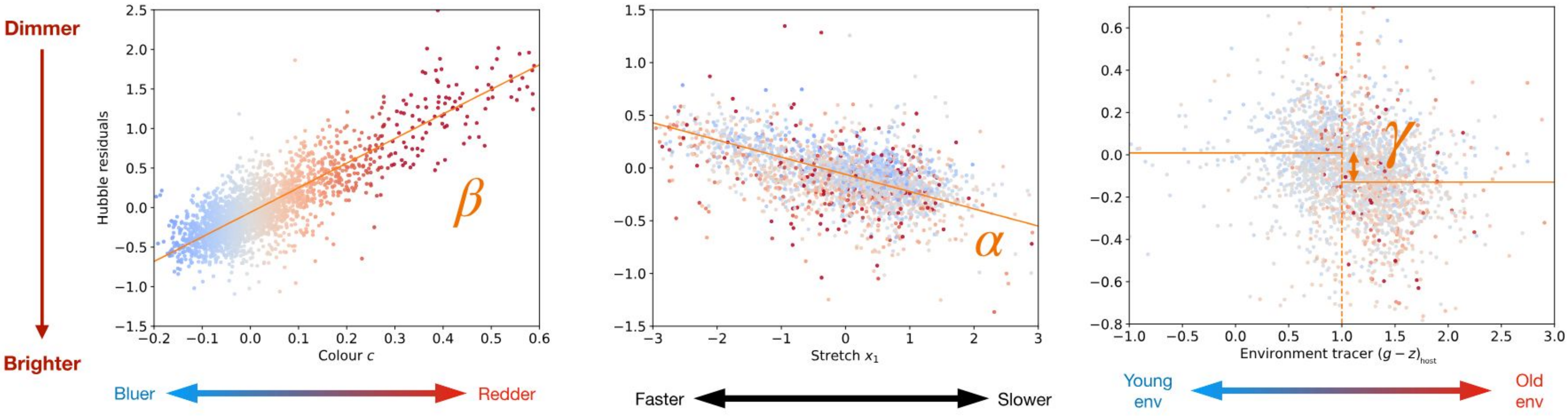

$$\mu = m_B^\star - M_B - \beta c + \alpha x_1 - \gamma p$$

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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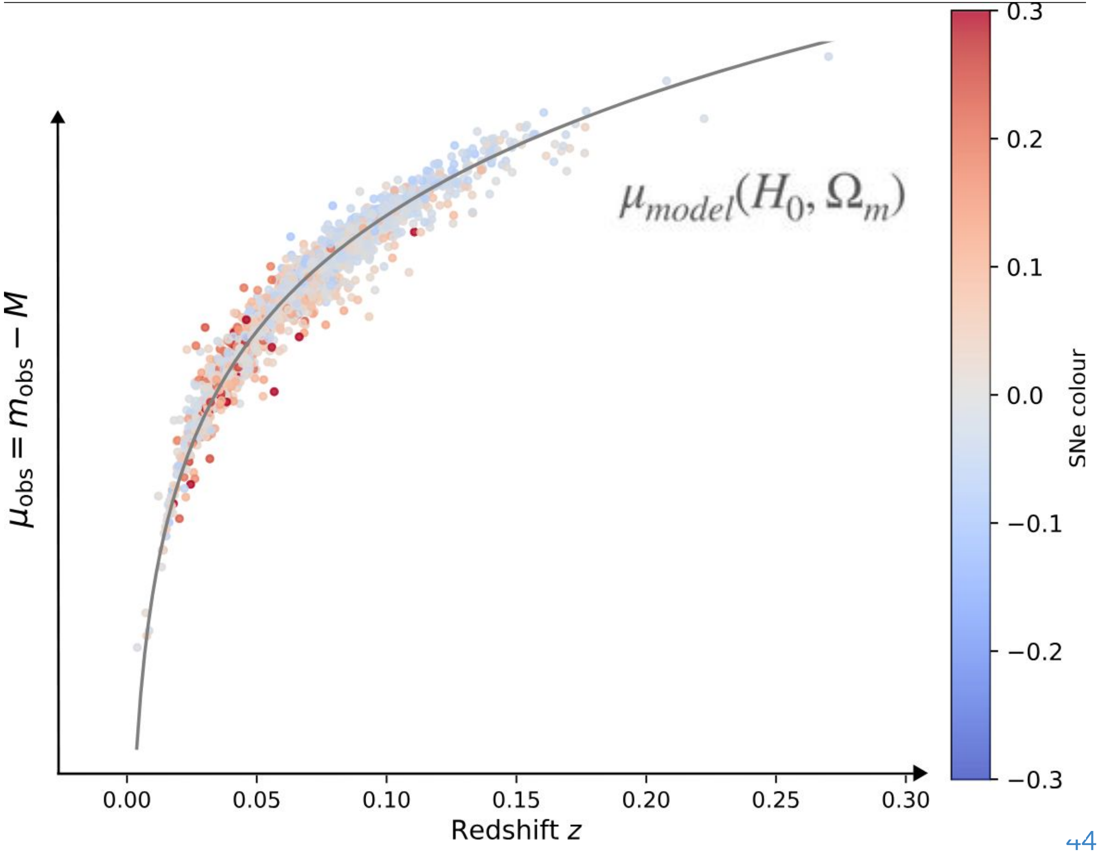


Standardized Hubble diagram

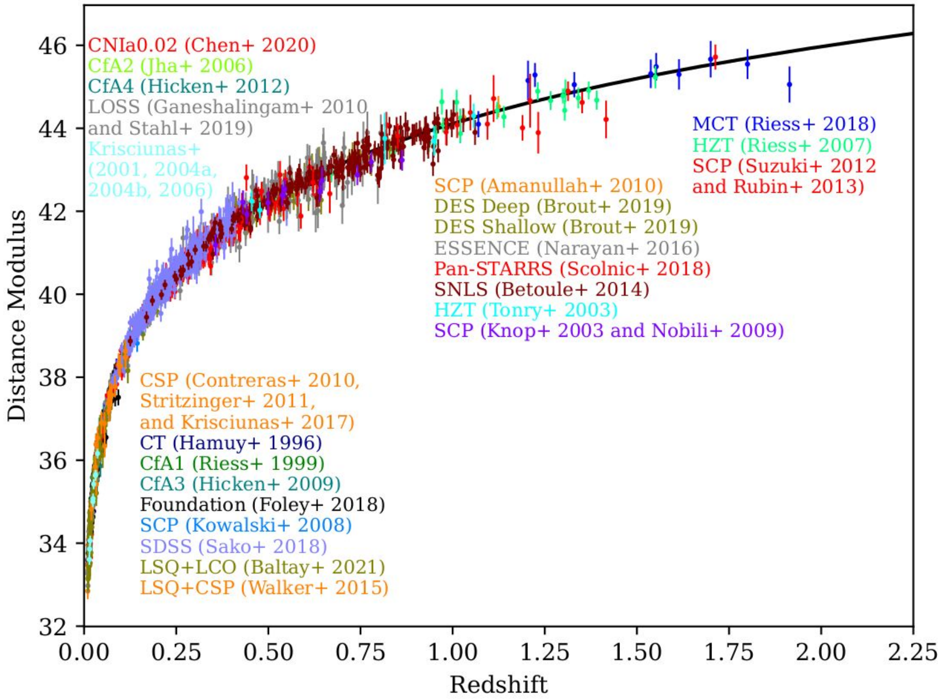
Distance modulus:

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

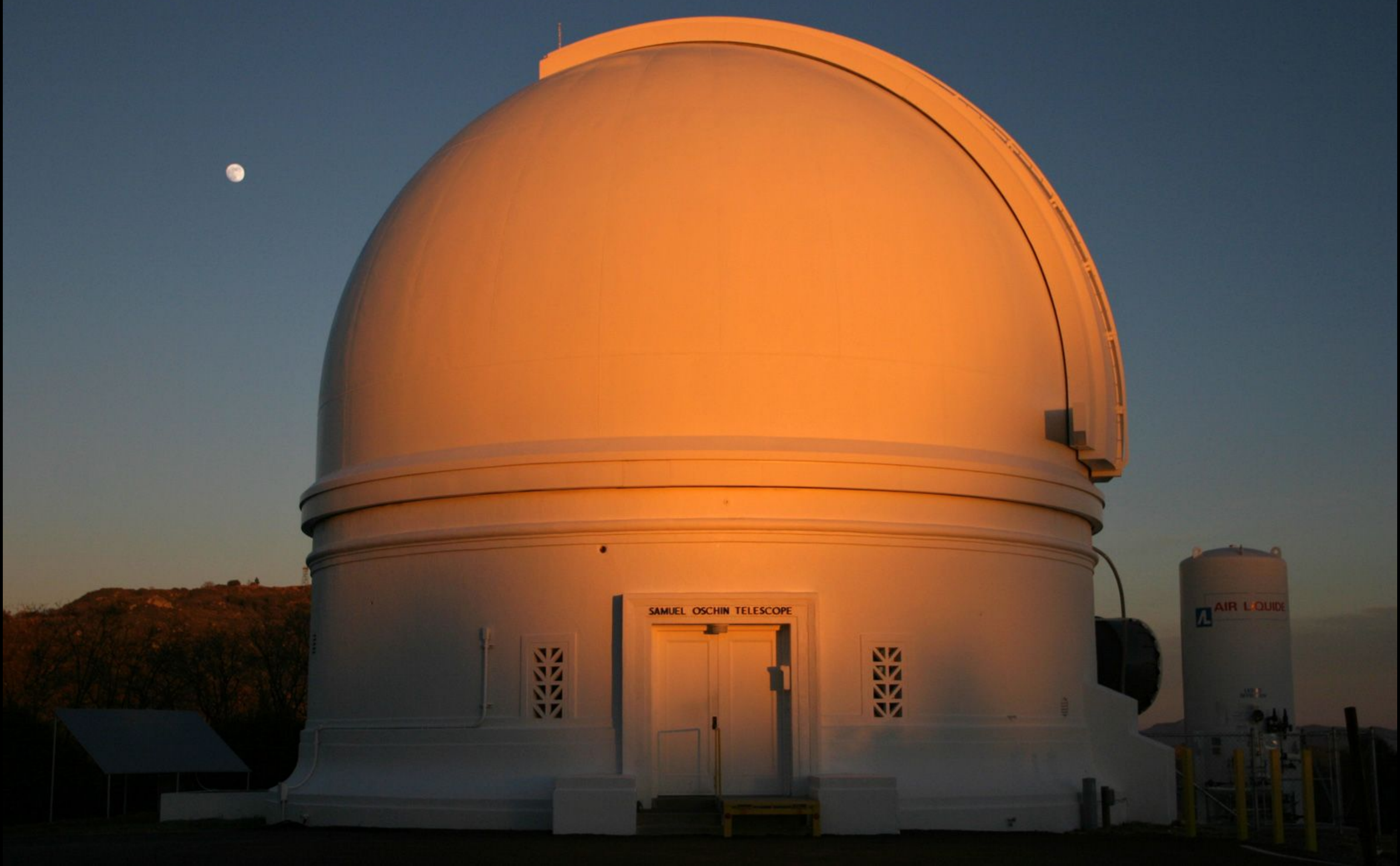
⇒ $\boldsymbol{\mu}$ dispersion reduced to ~14%

⇒ Infer constraints on cosmological parameters such as $\boldsymbol{w}$

Union Hubble diagram (Rubin et al., 2023)

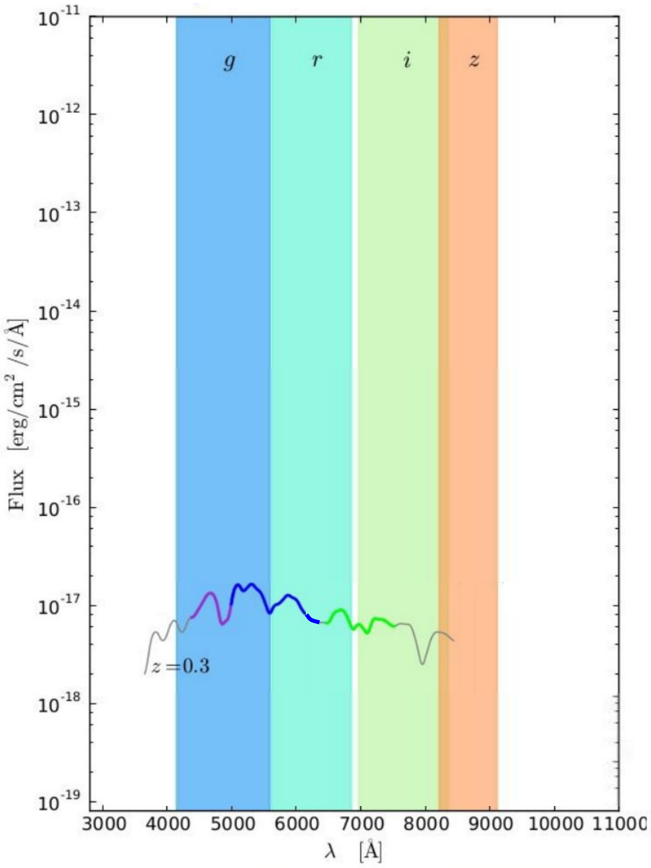


Photometric calibration


SAMUEL OSCHIN TELESCOPE
AIR LIQUIDE

SNe Ia flux measurement

SN Ia spectrum observed through telescope filter



SN spectrum

X filter transmission

Atmosphere transmission

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

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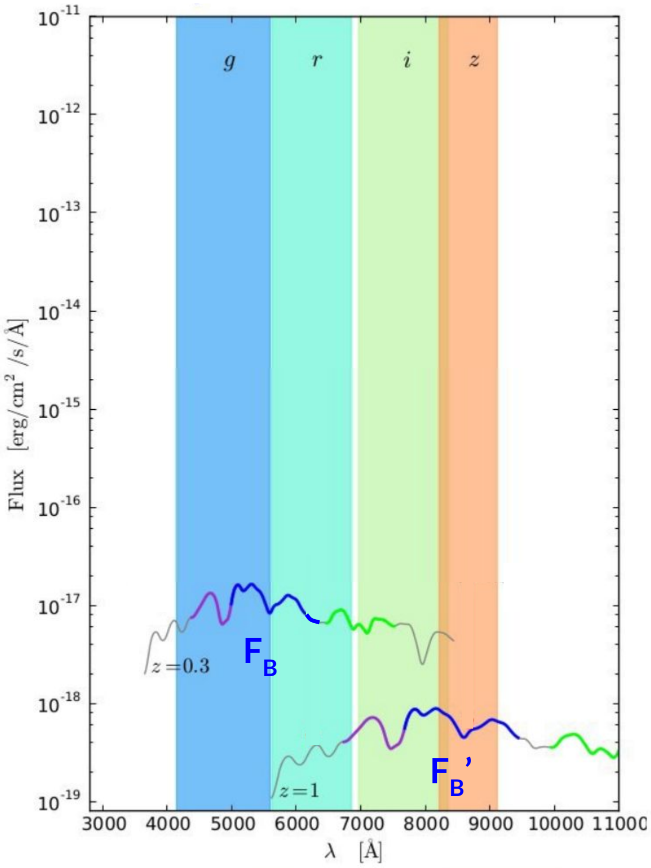

Goal : Measure relatively $\mathbf{F_B}$ of SNe spectra at different redshift **z**

But :

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

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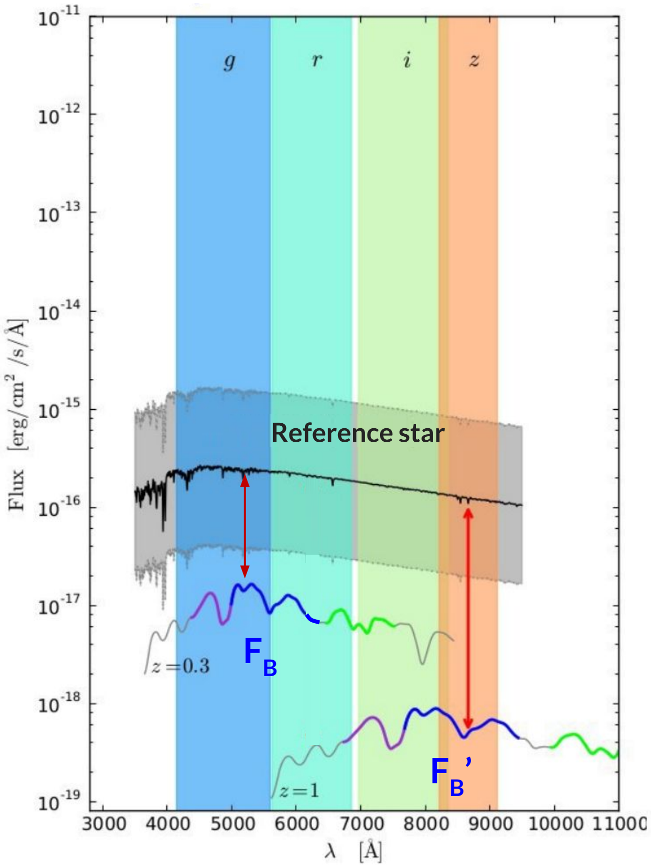

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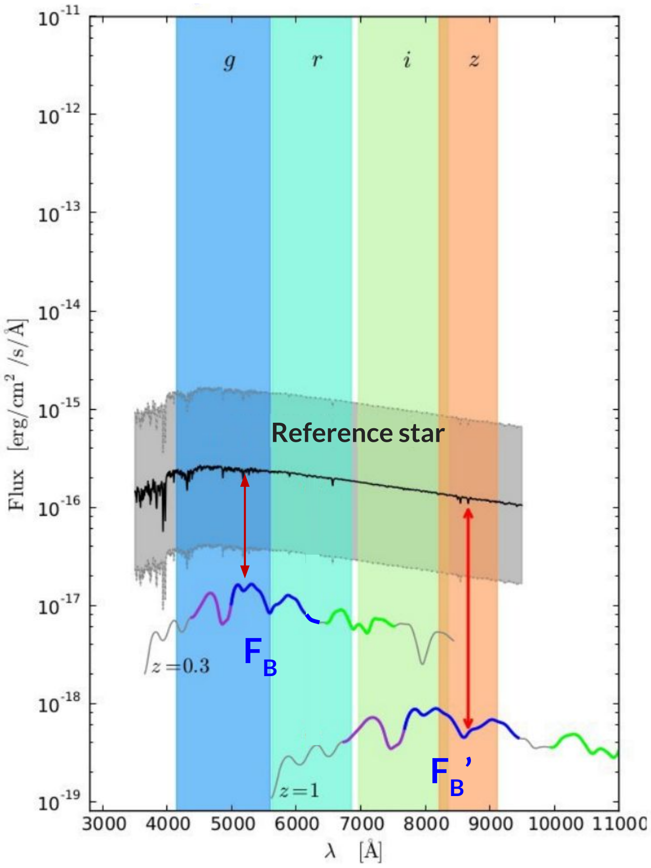

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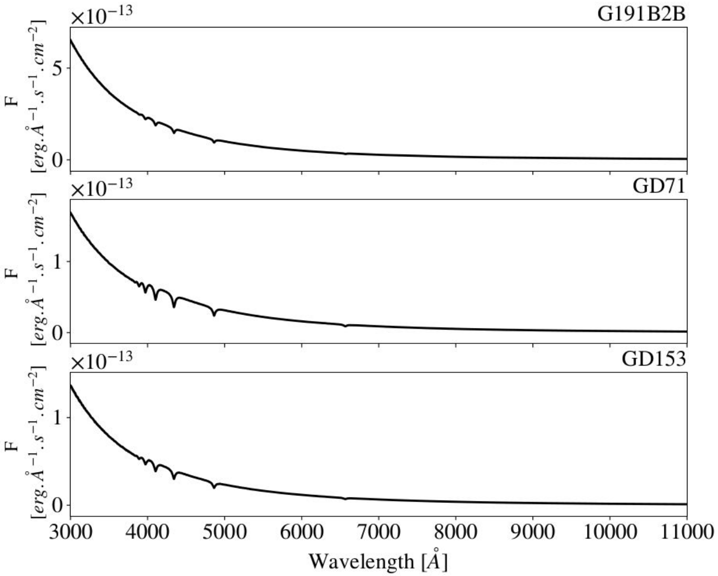
⇒ CALSPEC calibration

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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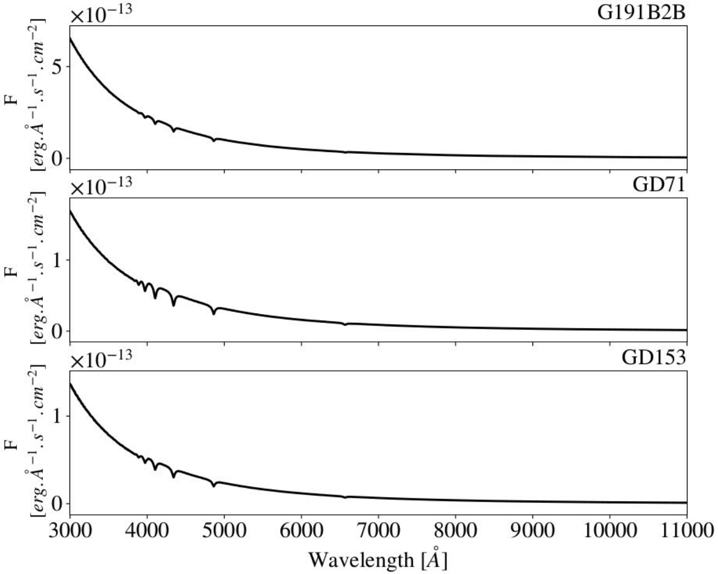
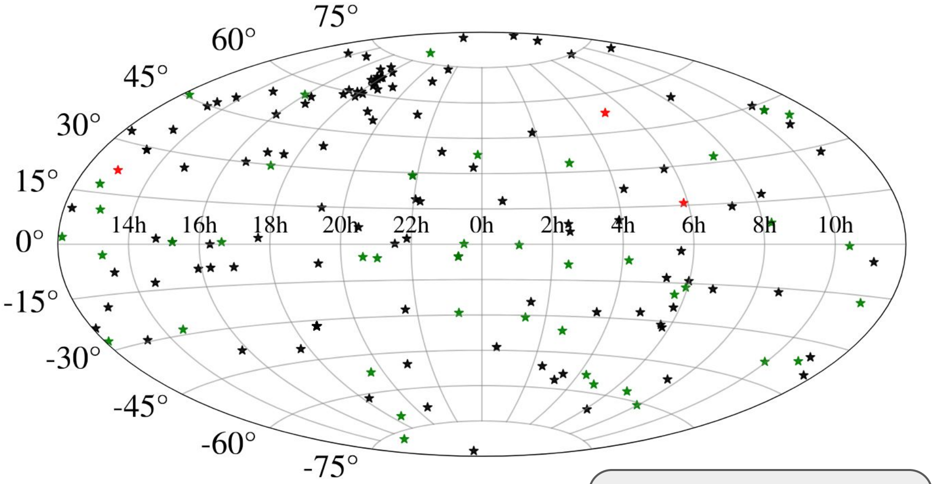


Sky map of the CALSPEC network



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

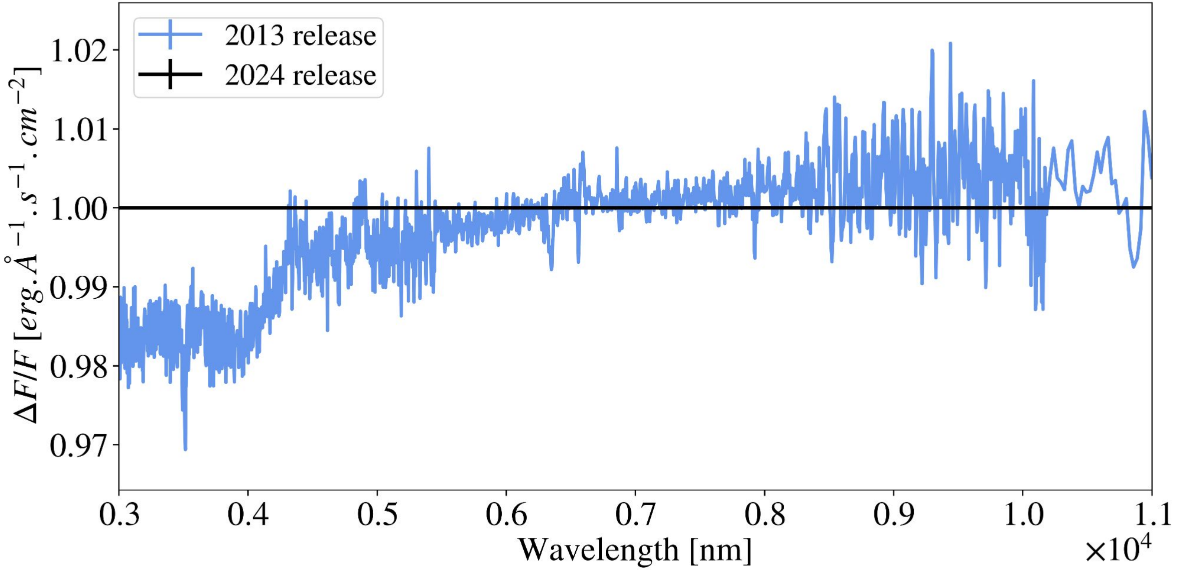
⇒ Network of calibrated sources covering the full sky

⇒ **~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

CALSPEC model variation of G191B2B



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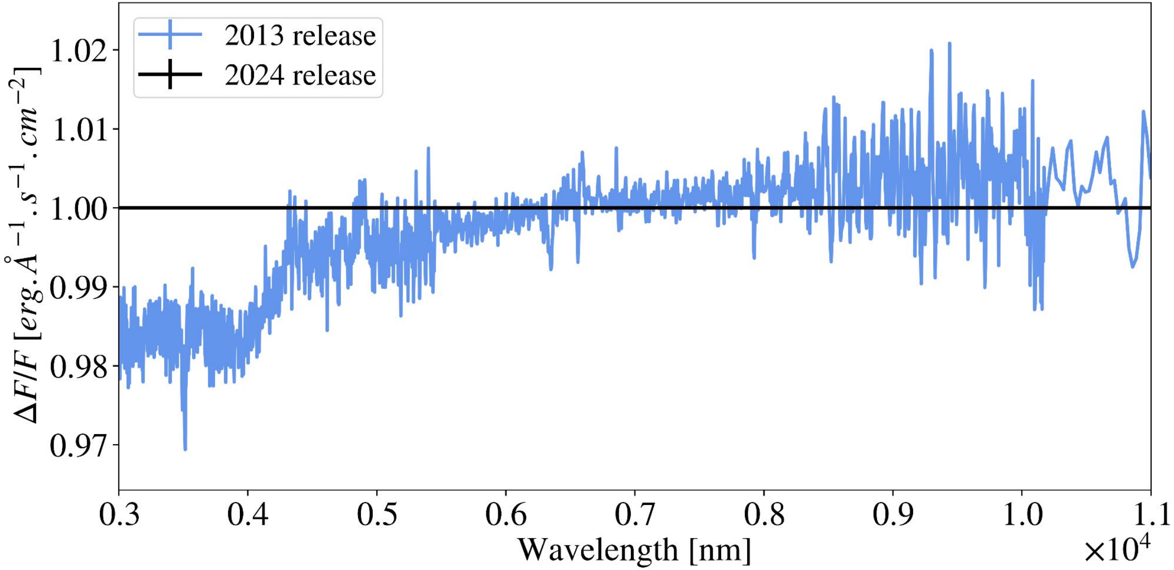
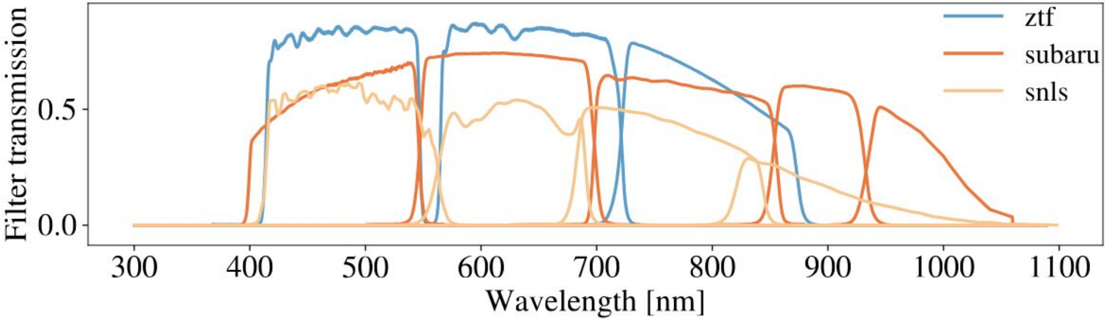


Impact cosmological parameters inference? ⇒ Hubble diagram with simulated SNe Ia

Variations of CALSPEC model

CALSPEC calibration differences simulated
(LEMAÎTRE joint analysis)



Simulation of 3 SNe Ia surveys:

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

- Calibration of the bandpass with each CALSPEC release

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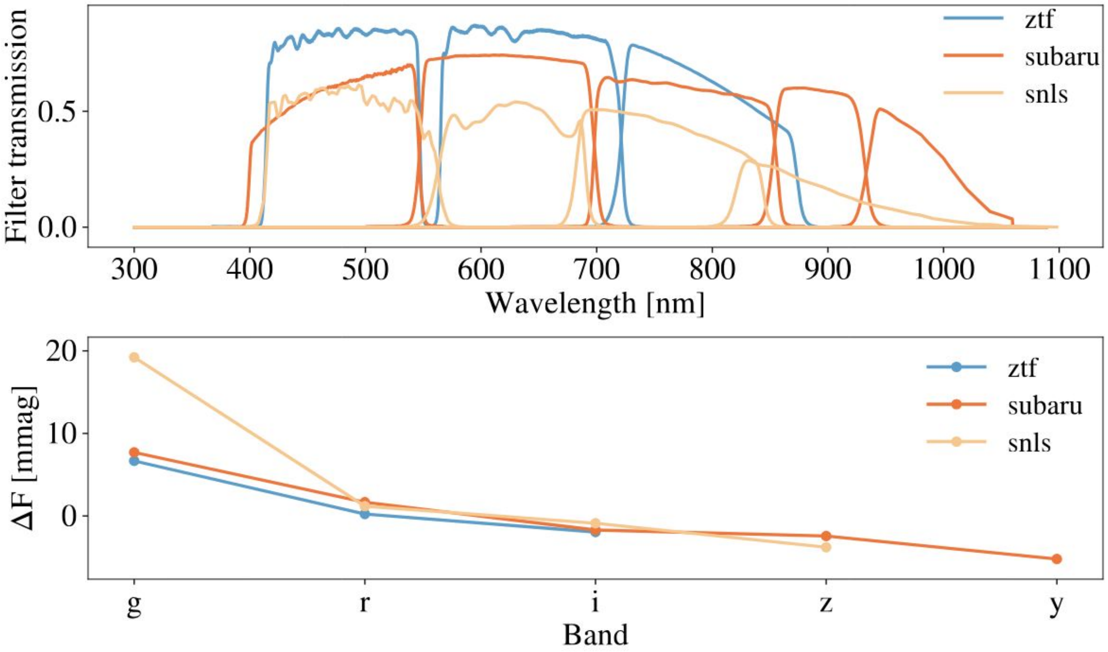

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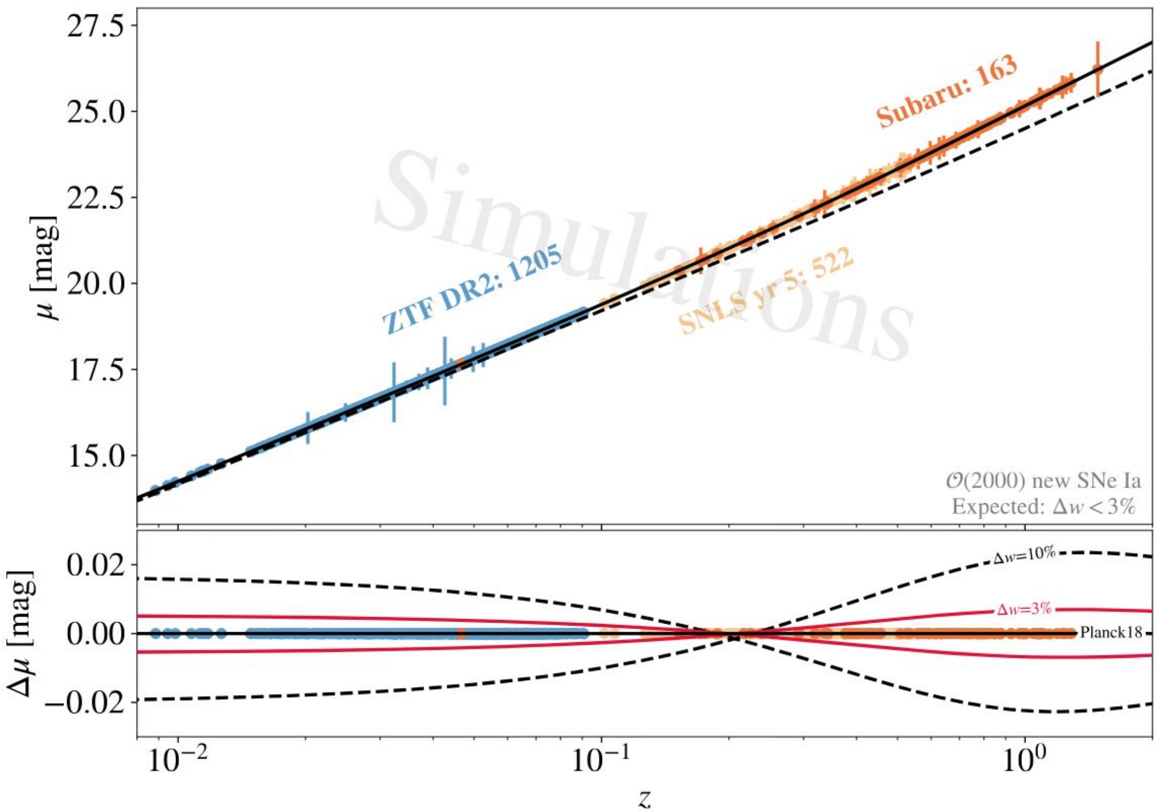
⇒ up to **20 milli-mag** difference

Variations of CALSPEC model

Hubble diagram obtained with LEMAÎTRE simulations



- Fitting distance moduli μ of simulated SNe Ia

⇒ Hubble diagram

Variations of CALSPEC model

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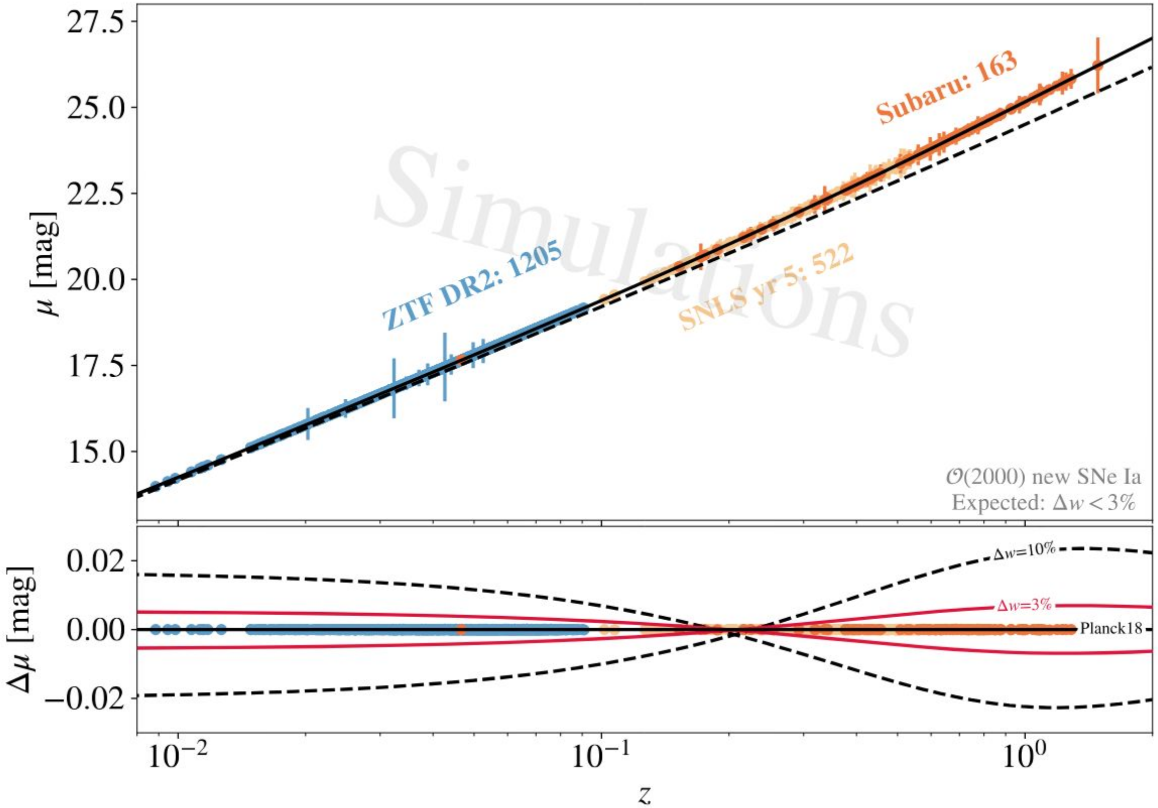


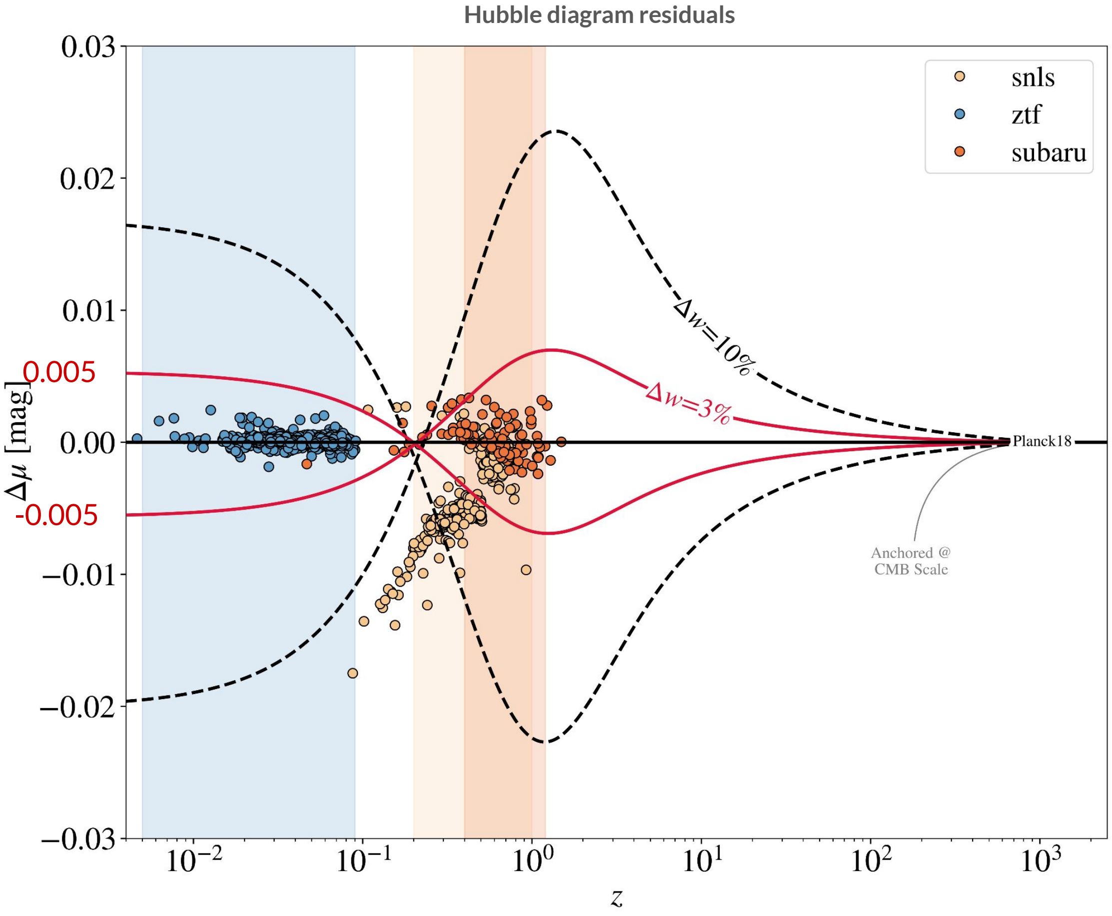
- Fitting distance moduli μ of simulated SNe Ia

⇒ Hubble diagram

- Adding flux calibration bias estimated with CALSPEC releases

⇒ focus on the residuals to the ΛCDM model

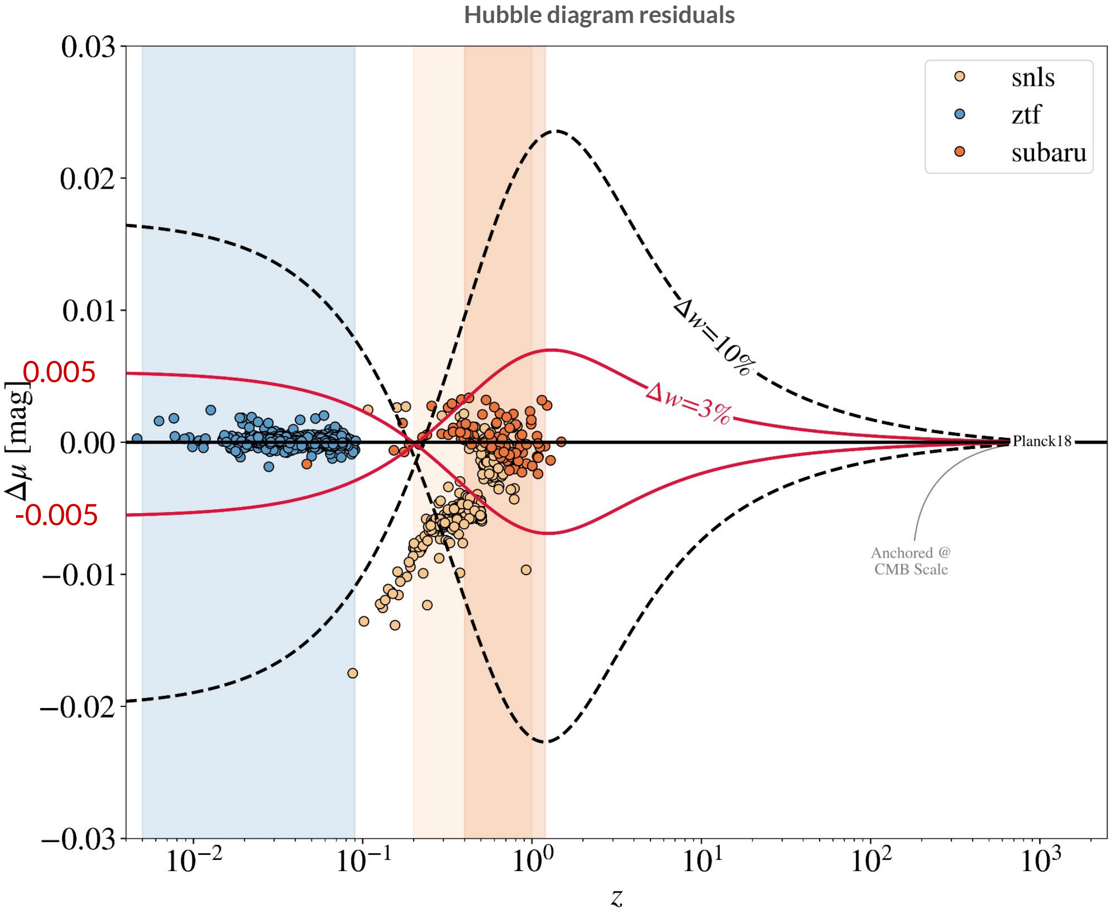
Variations of CALSPEC calibration



- **3% deviation of w from ΛCDM**

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

▢ Variations of CALSPEC calibration



- **3% deviation of *w* from ΛCDM**

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2% chromatic bias ⇒ Δμ > 0.005 mag

⇒ deviation similar than Δ*w* > 3%

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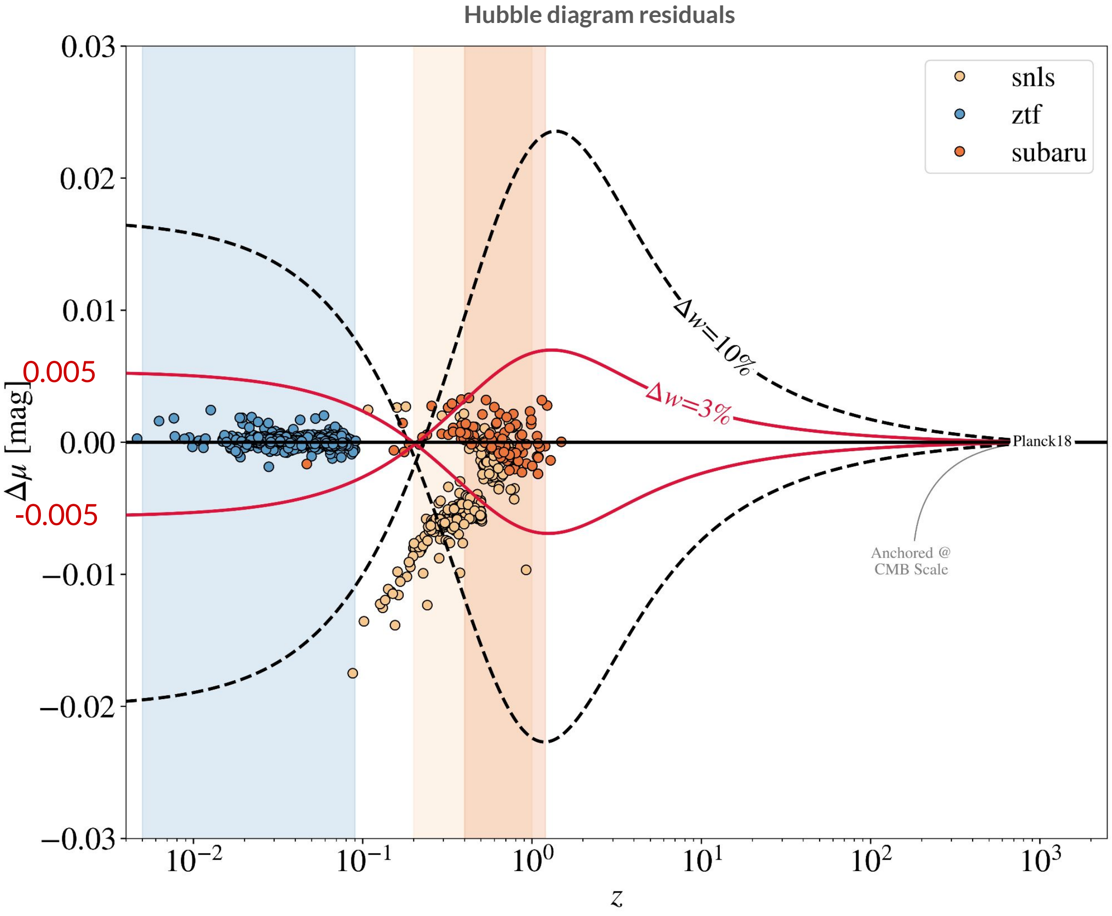

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How much confident are we about WD atmosphere models ?

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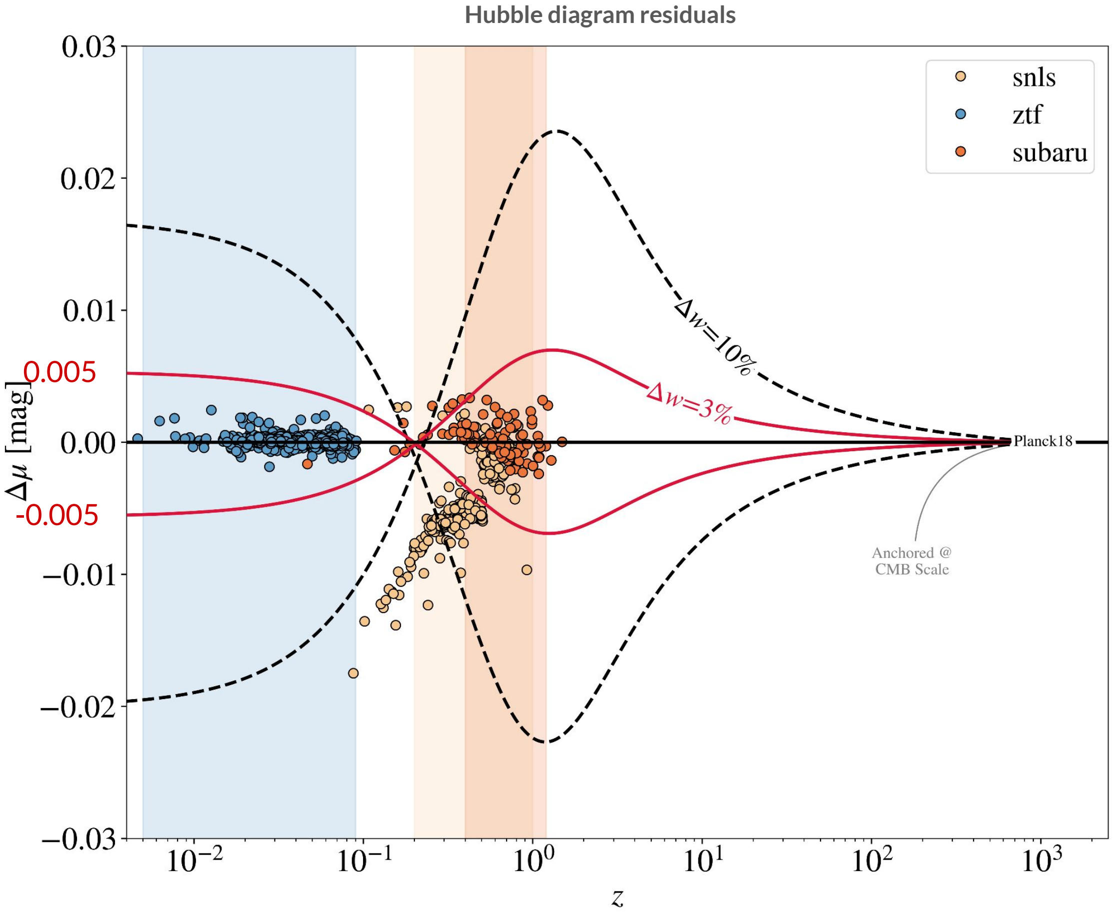

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How much confident are we about WD atmosphere models ?

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

The StarDICE experiment

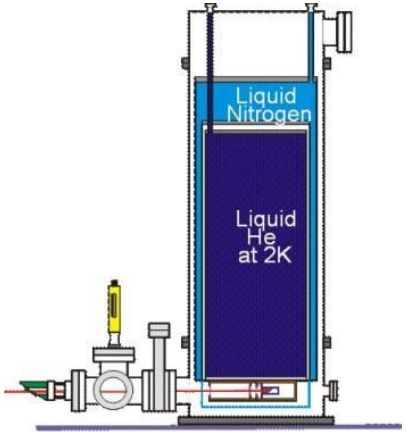
Photometric calibration transfer

Standard watt
(NIST)

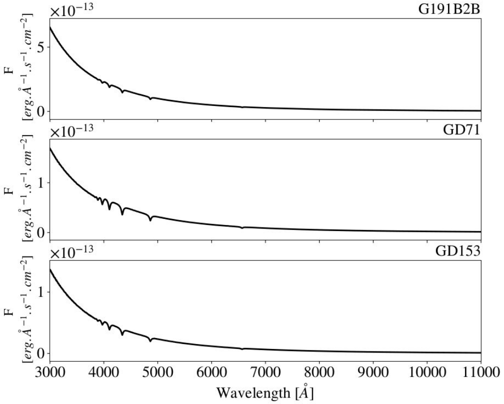
???

CALSPEC
standard stars

1 W

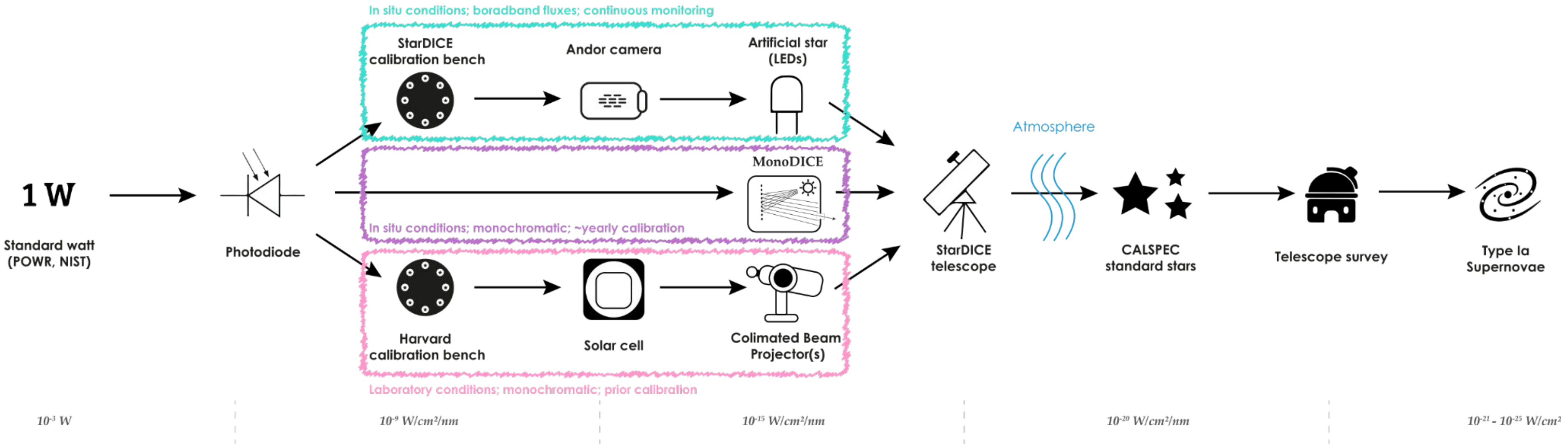


POWR facility
Houston et al. 2006

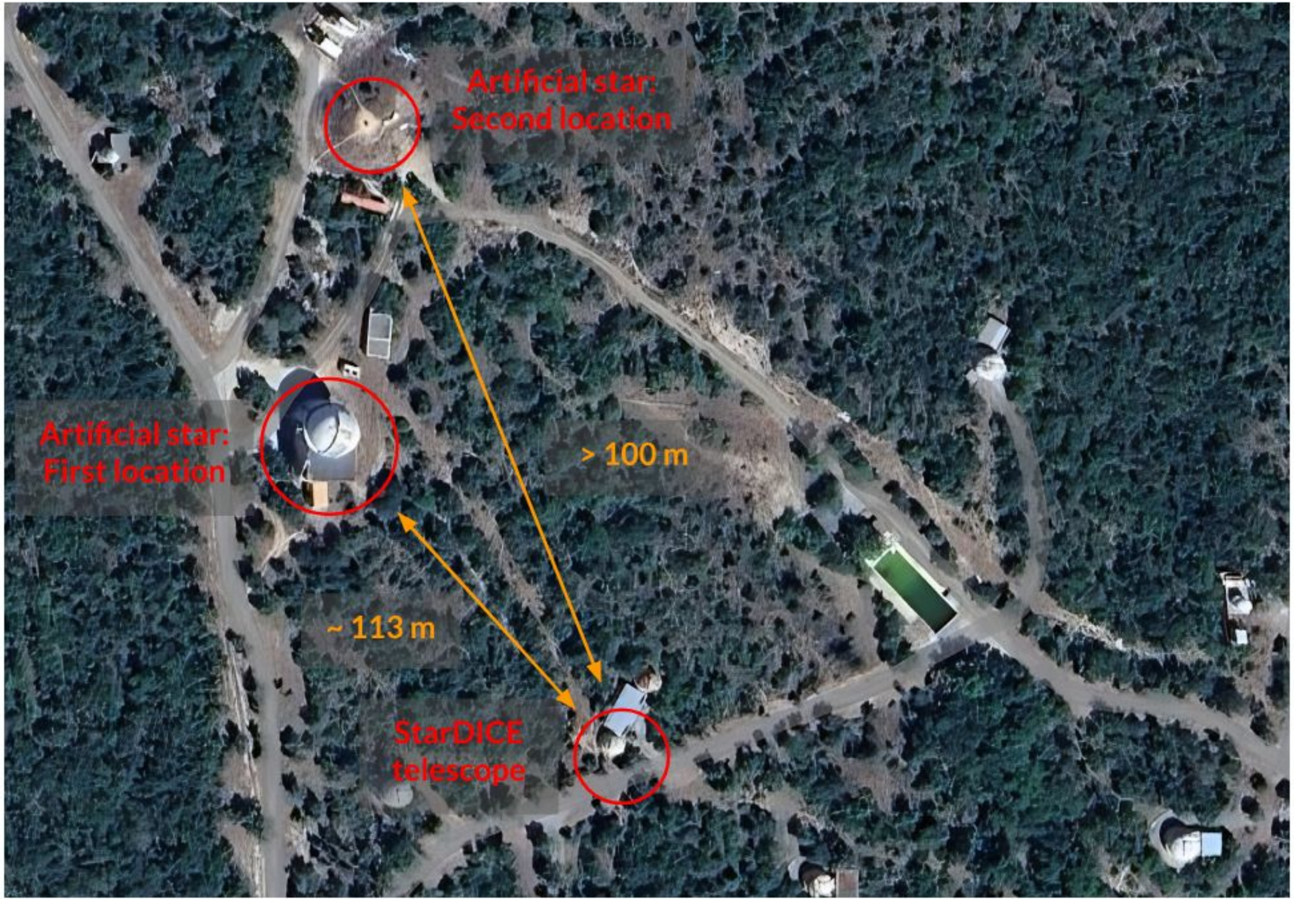


CALSPEC primary standard stars

Photometric calibration transfer chain



Observatory of Haute-Provence



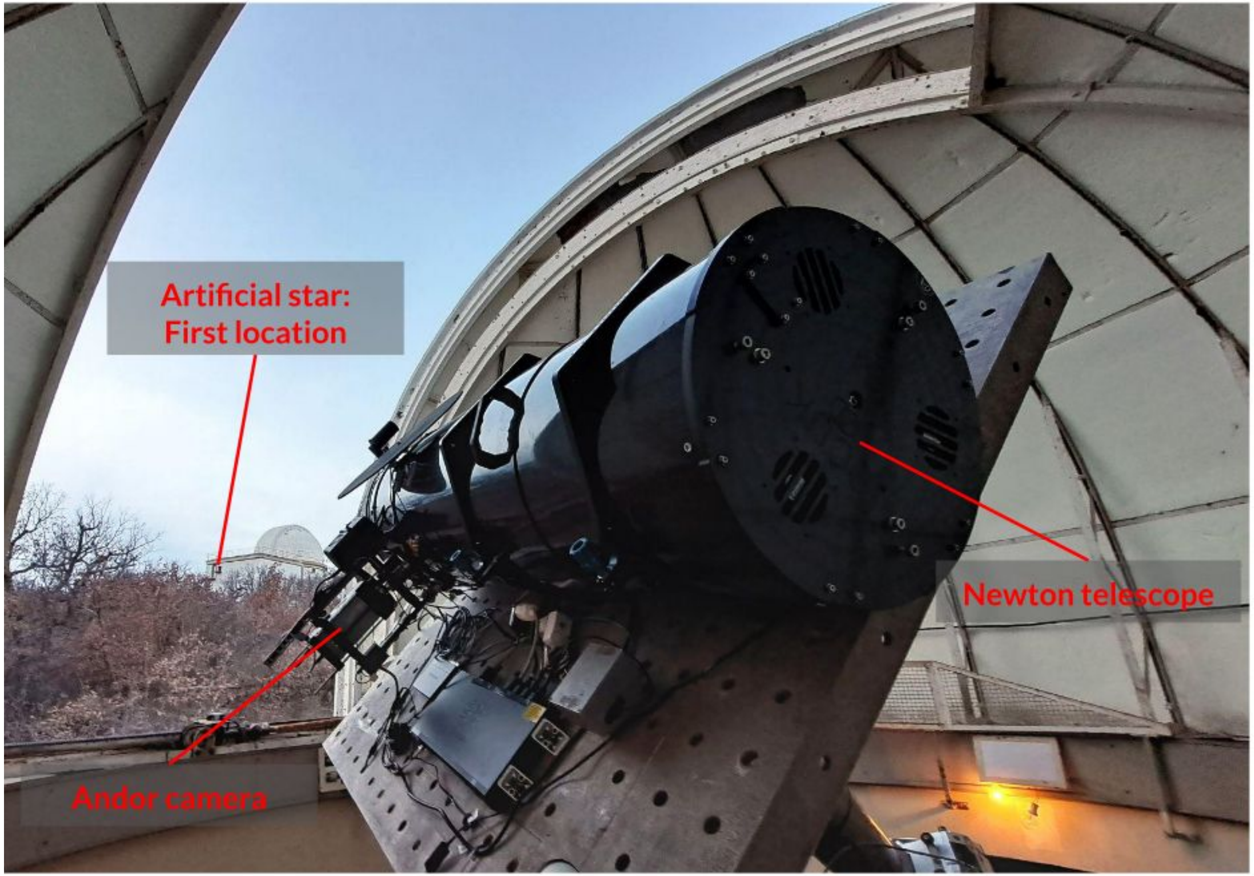
Observatoire de Haute-Provence satellite view

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



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Filterwheel:

- “ugrizy” photometric filters
- Diffraction grating

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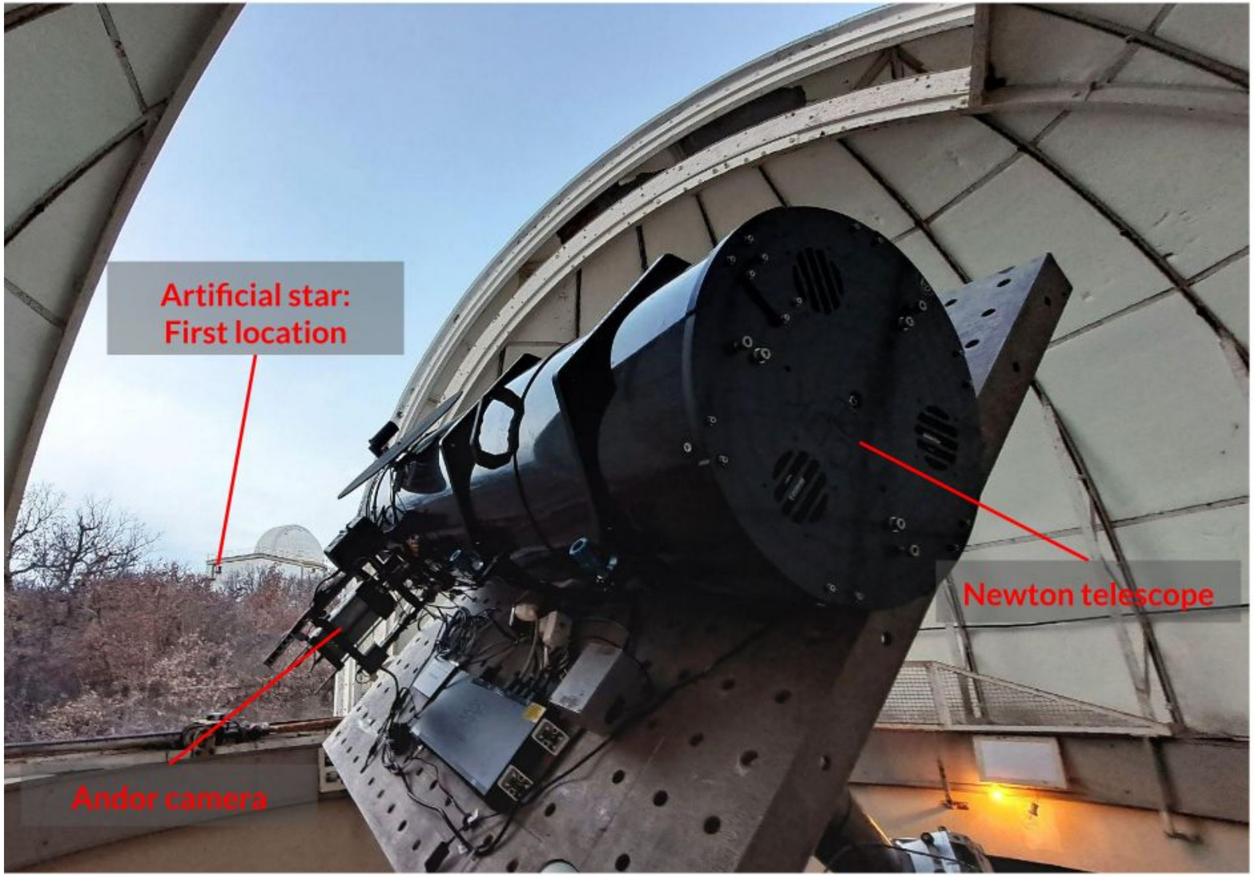

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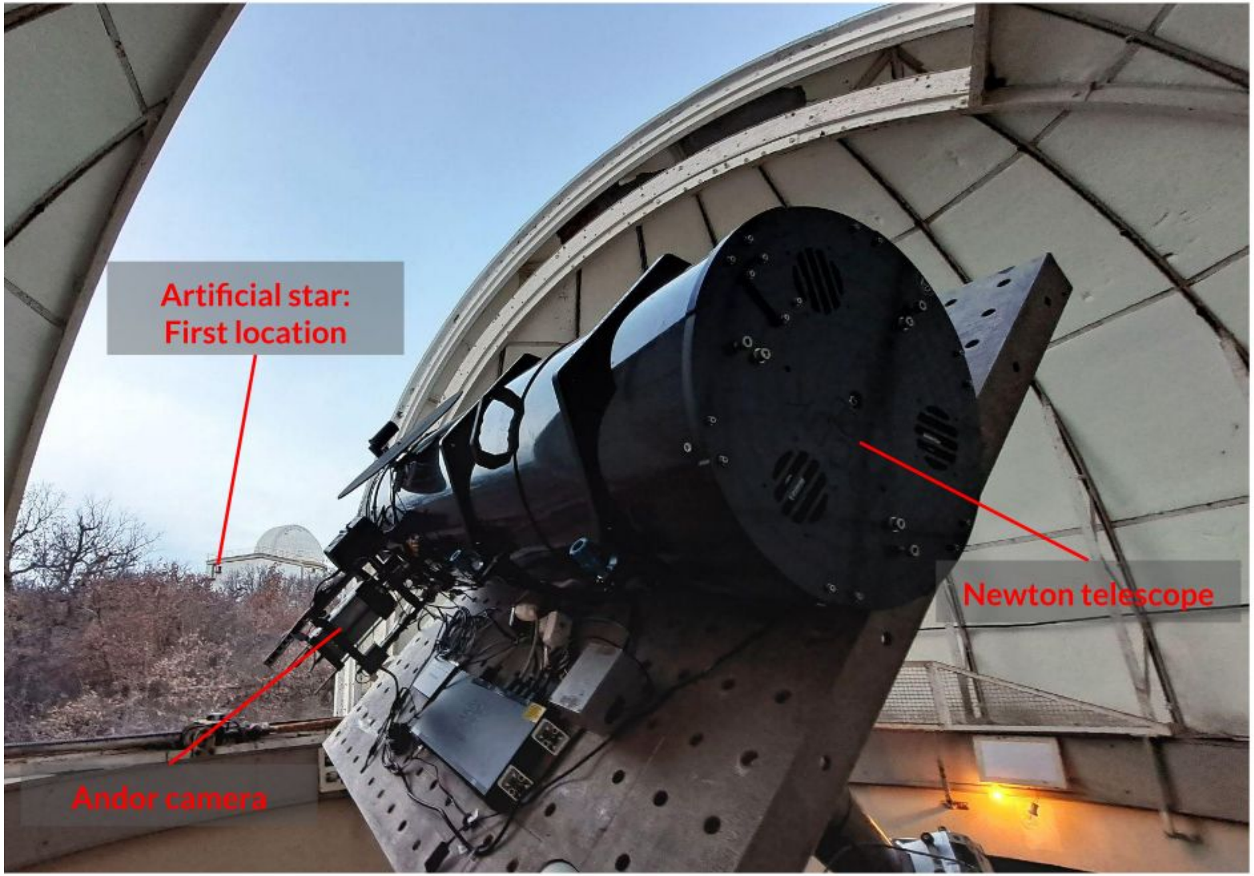
Monitoring instruments:

- Hygrometer
- Thermometers
- Barometer
- Rain detector

StarDICE telescope on its mount



StarDICE telescope

Newton telescope:

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

Filterwheel:

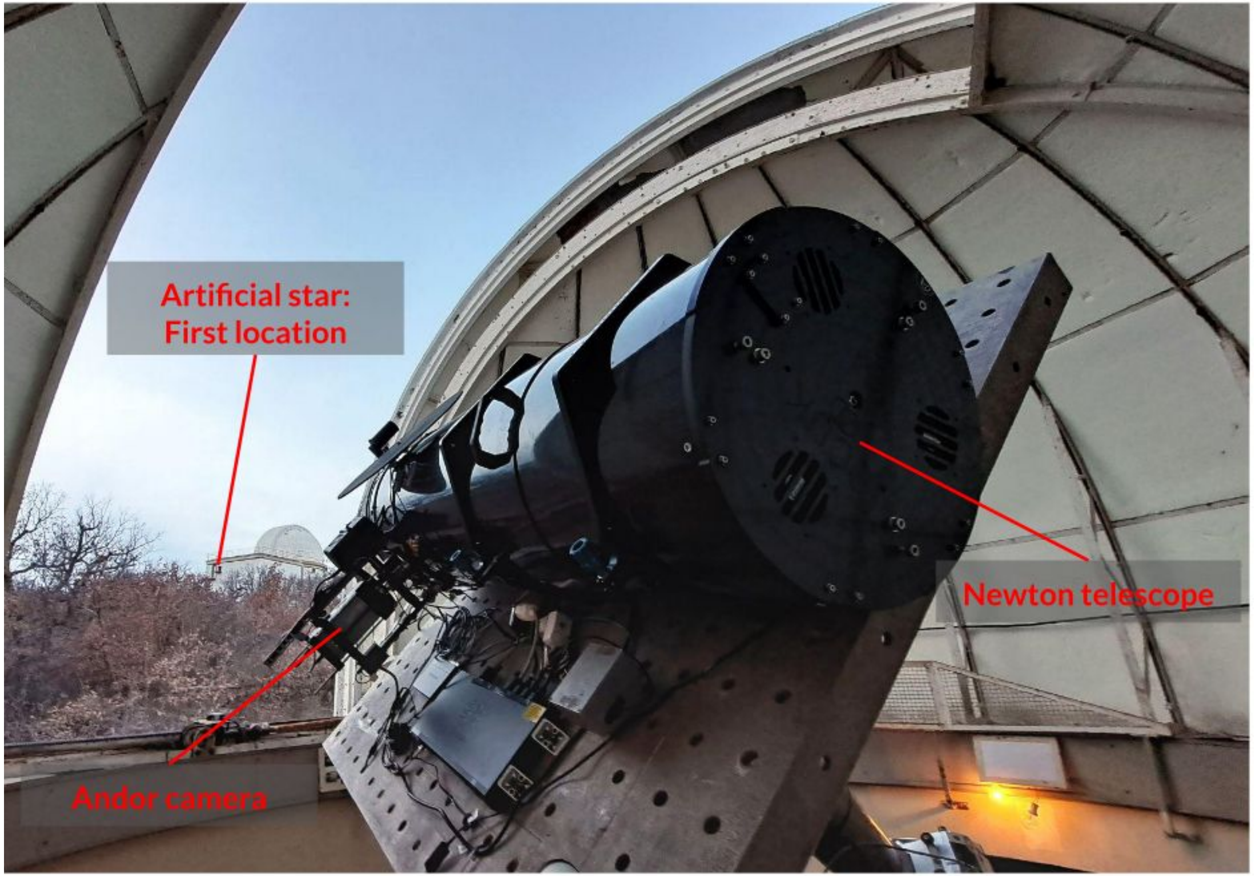
- “ugrizy” photometric filters
- Diffraction grating

Monitoring instruments:

- Hygrometer
- Thermometers
- Barometer
- Rain detector

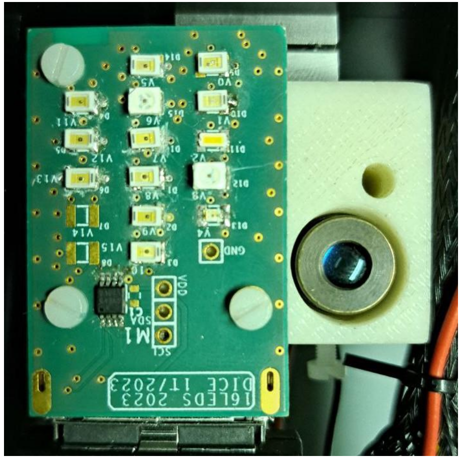
Fully robotic

StarDICE telescope on its mount



Artificial star

- 16 LEDs covering visible and near-IR range
- Flux calibrated in laboratory

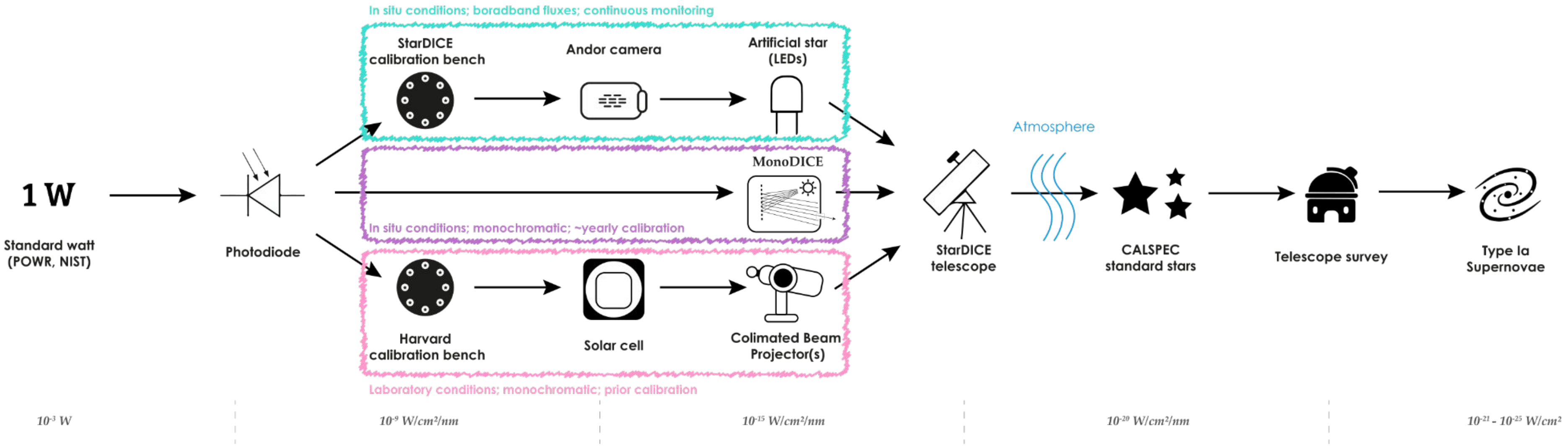


Artificial stars LEDs off

Artificial stars LEDs on

Helmet enclosing the artificial star

Photometric calibration transfer chain



In situ conditions; boradband fluxes; continuous monitoring

StarDICE calibration bench

Andor camera

Artificial star (LEDs)

In situ conditions; monochromatic; ~yearly calibration

MonoDICE

Laboratory conditions; monochromatic; prior calibration

Harvard calibration bench

Solar cell

Colimated Beam Projector(s)

1 W

Standard watt (POWR, NIST)

Photodiode

StarDICE telescope

Atmosphere

CALSPEC standard stars

Telescope survey

Type Ia Supernovae

10^{-3} W

10^{-9} W/cm²/nm

10^{-15} W/cm²/nm

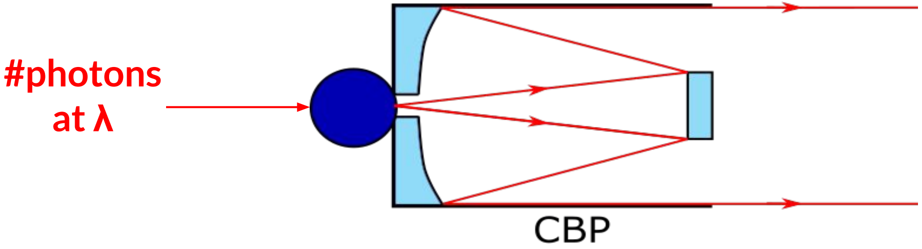
10^{-20} W/cm²/nm

10^{-21} - 10^{-25} W/cm²

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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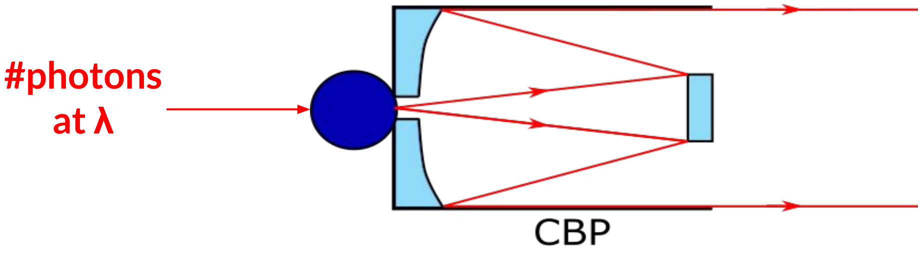

Two purposes:

- **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

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Ingredients:

- A tunable laser
- A mounted-backward telescope to recreate a parallel beam from a point source

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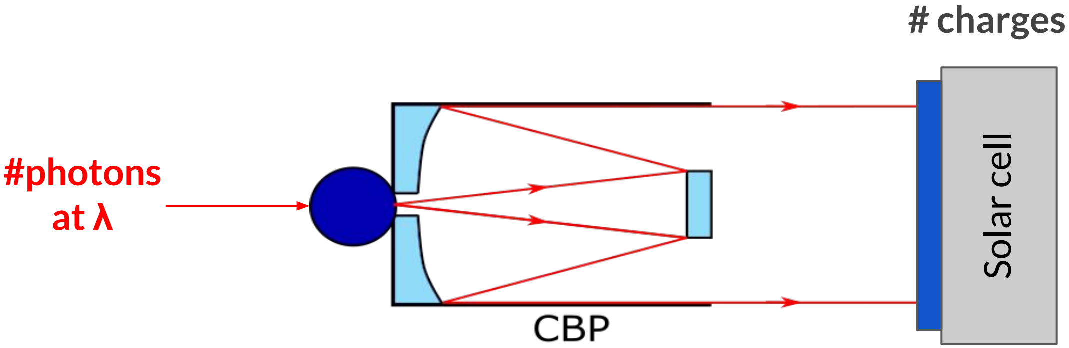
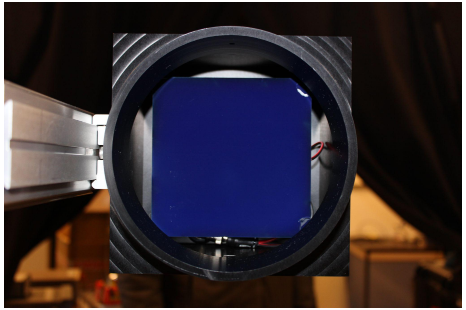
Recipe:

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





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Recipe:

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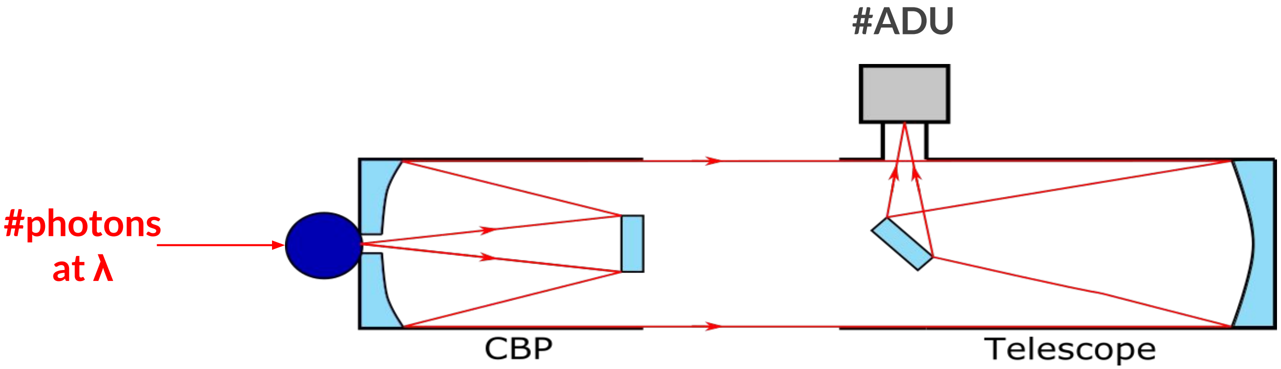
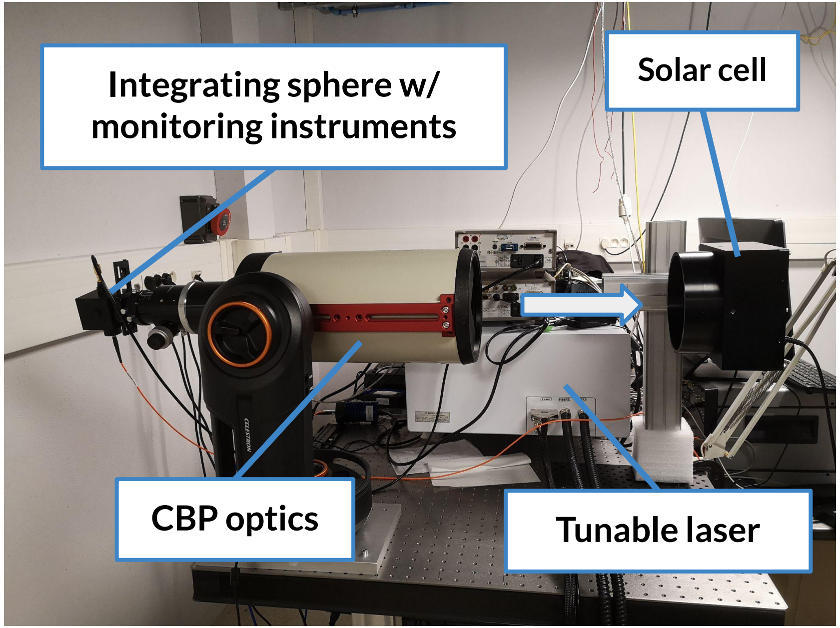
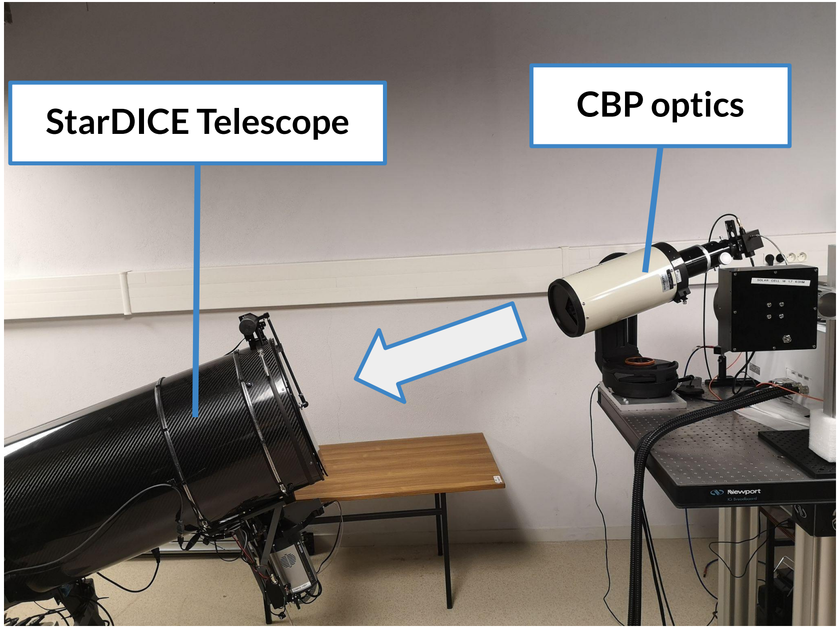
(2) Shoot light inside the instrument to calibrate, using R_{CBP}



Setup device

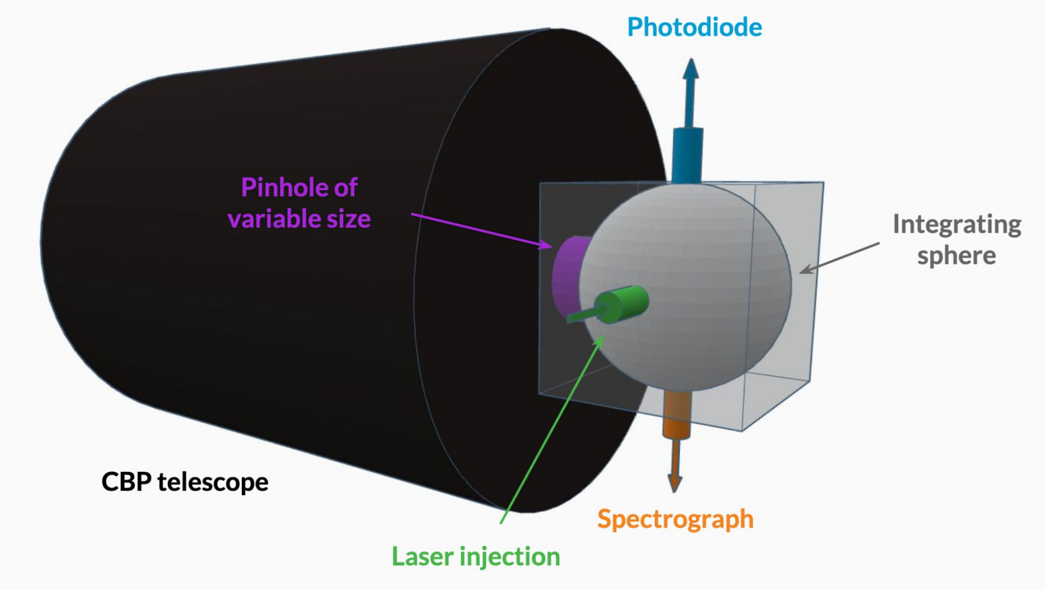




(1) CBP response measurement

(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} $[\gamma.C^{-1}]$

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

(2) StarDICE response R_{SD} $[ADU.\gamma^{-1}]$

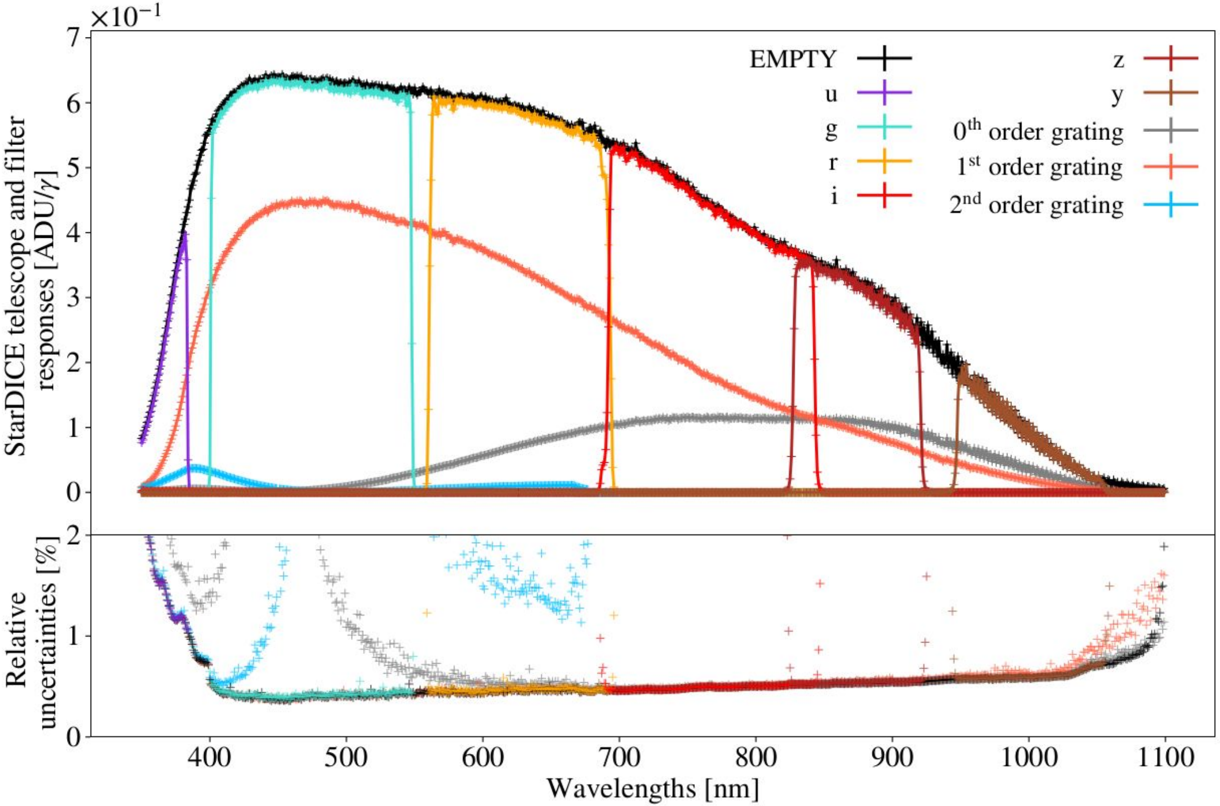
$$\boxed{R_{\mathrm{tel}} = \frac{Q_{\mathrm{ccd}}}{Q_{\mathrm{phot}} \times R_{\mathrm{CBP}}}}$$

- Q_{solar}: solar cell charges [C]
- Q_{phot}: photodiode charges [C]
- Q_{ccd}: stardice charges [ADU]
- ϵ_{solar}: solar cell quantum efficiency $[\gamma^{-1}]$
- $e = 1.6\text{x}10^{-19}$ [C]

StarDICE filters transmission

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

- ~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

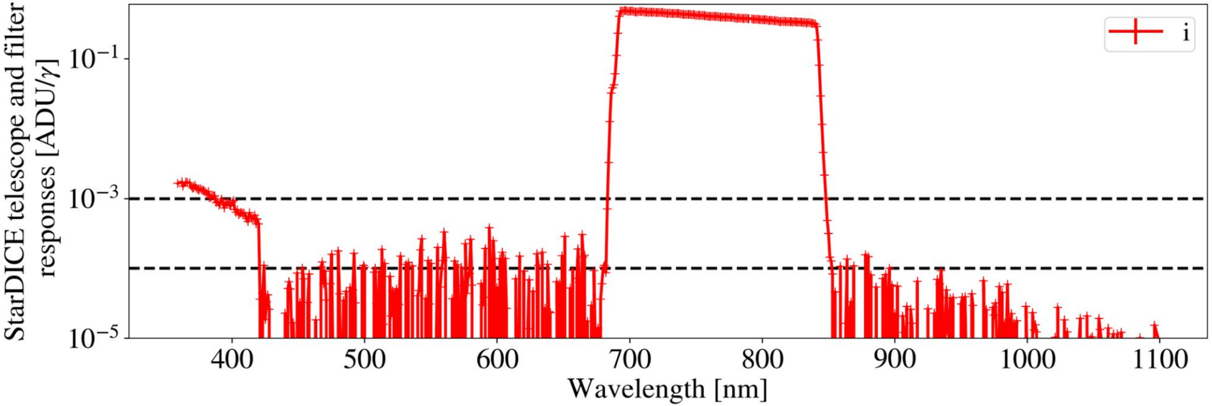


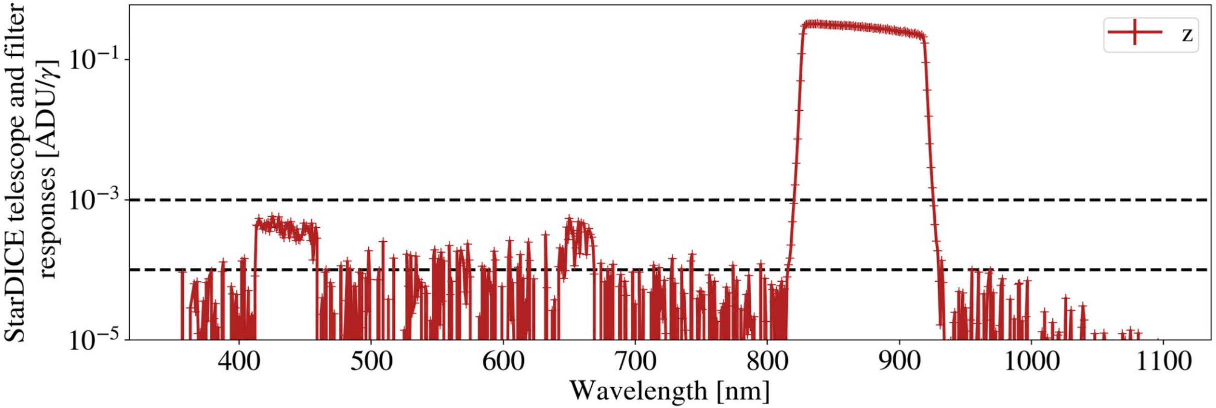
Filter leakages

Example of i and z filters:

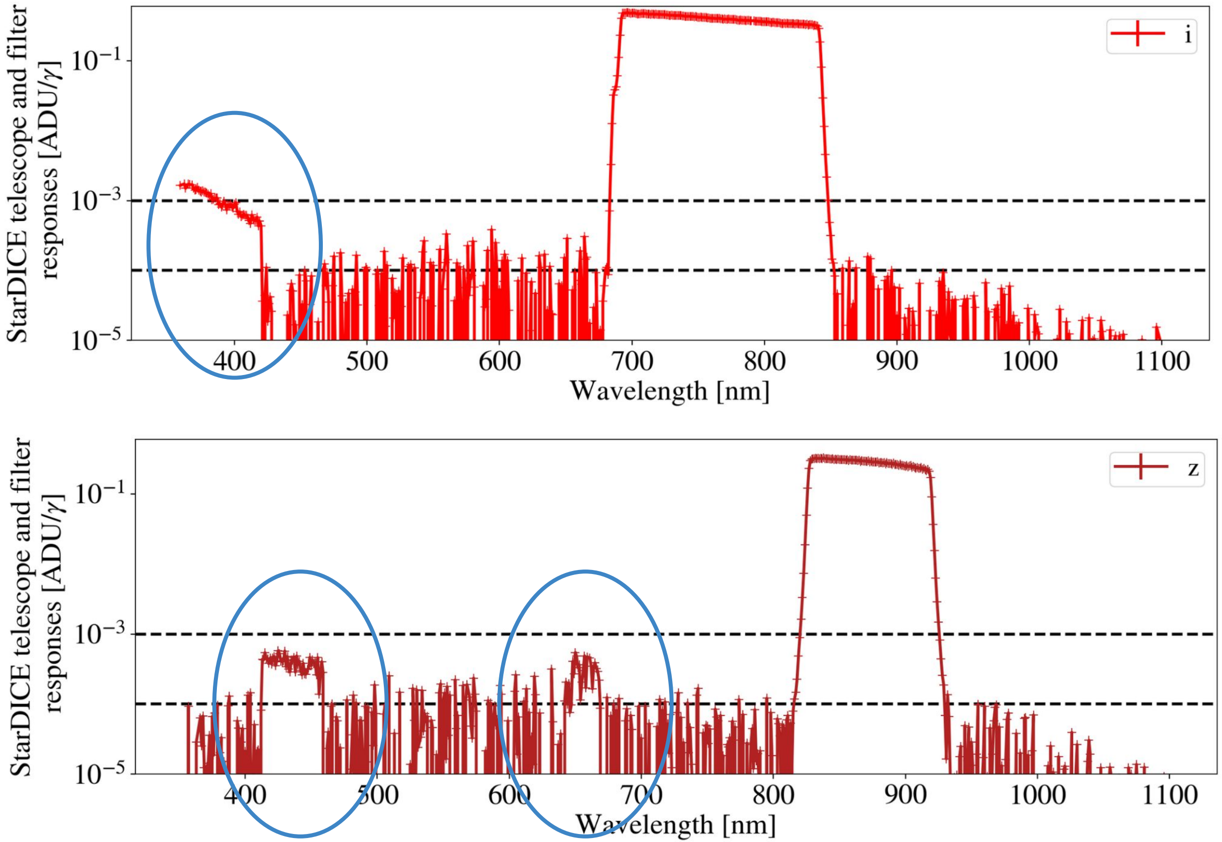
Detection of out-of-band leakages below **0.1%** level

→ **crucial for accurate photometric measurement**





Filter leakages



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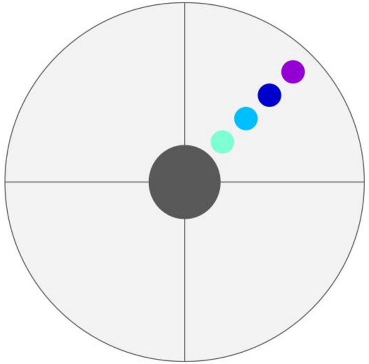
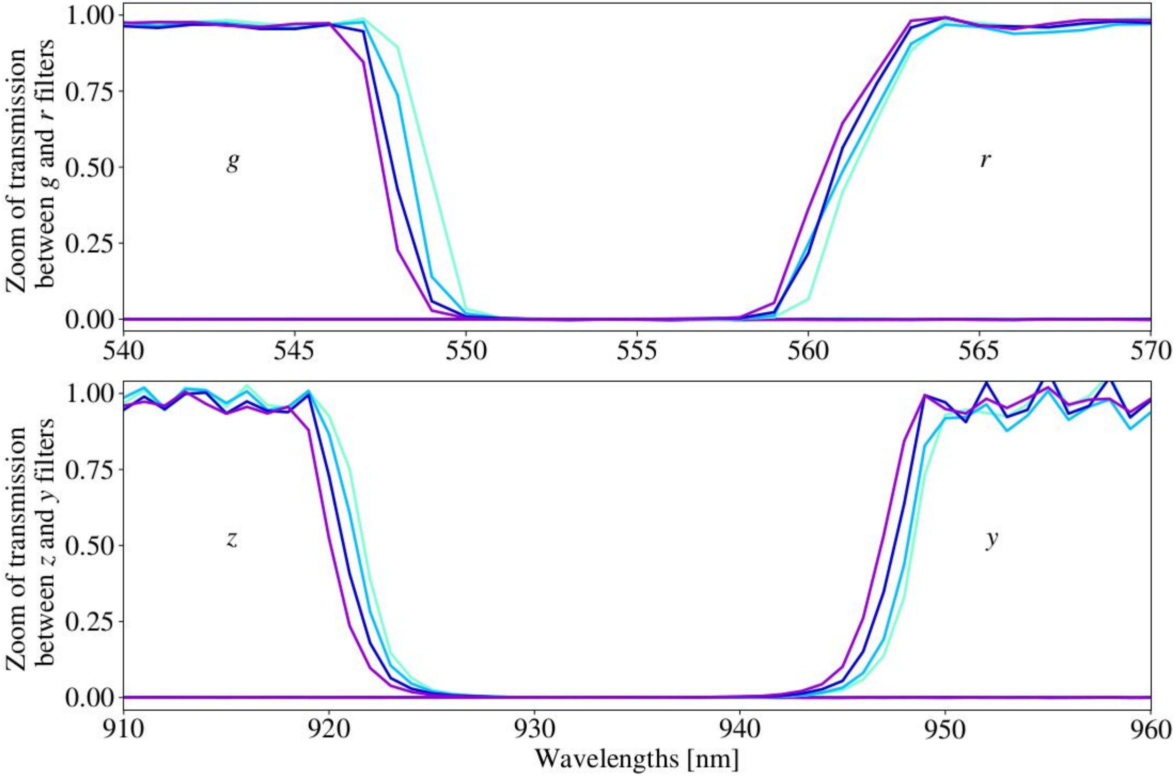
▢ Filter edges : blueshift

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

Blue-shift of filter edges when high incident angles





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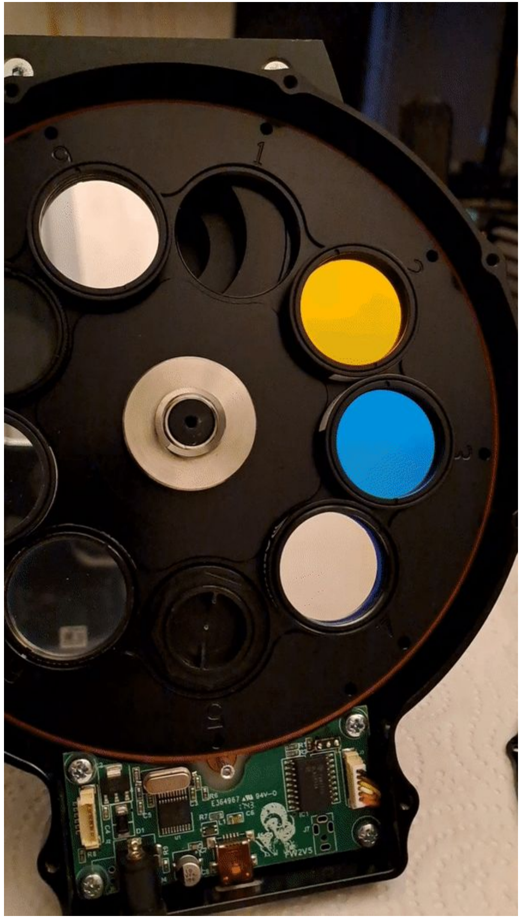

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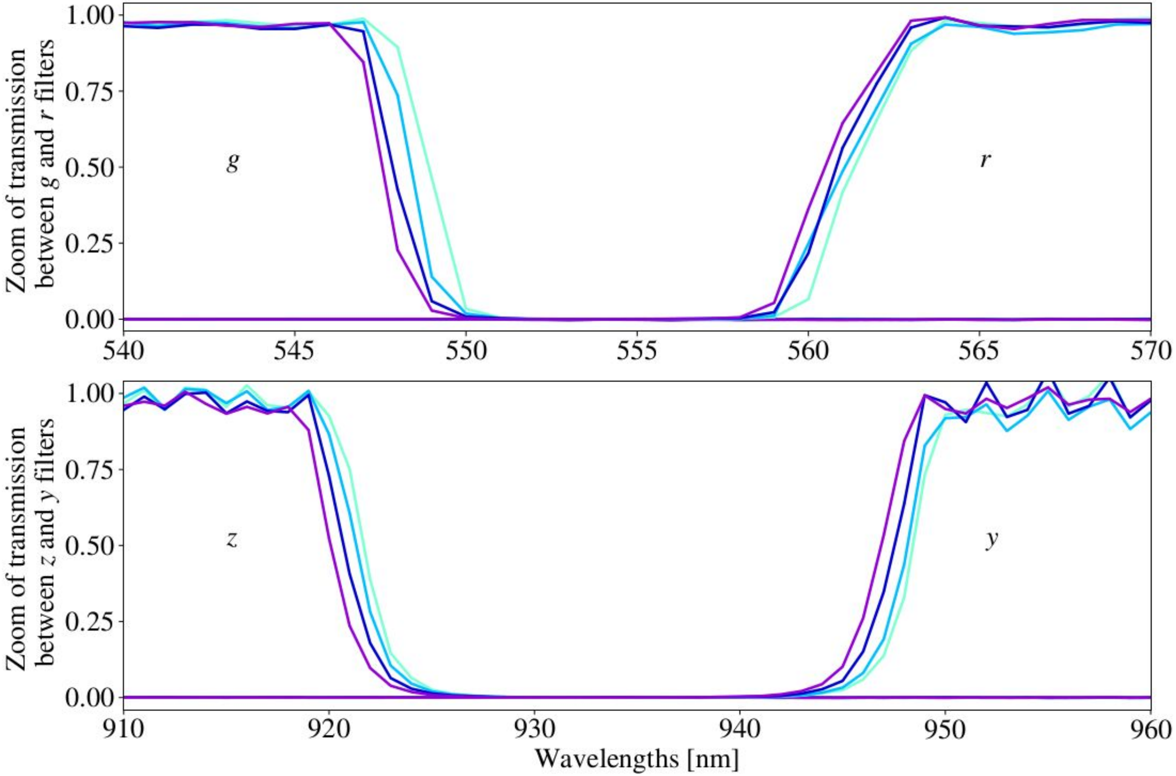
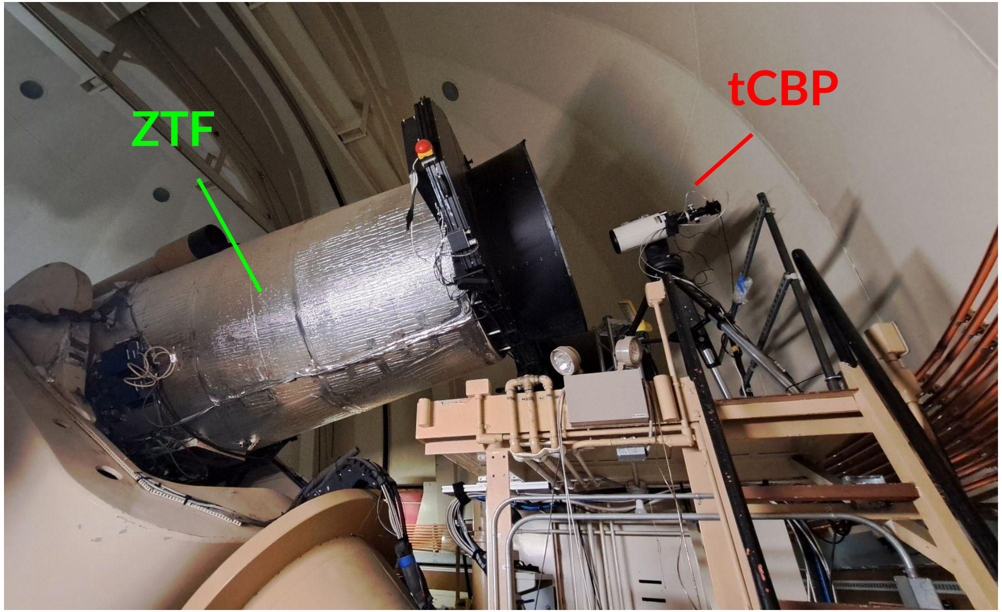
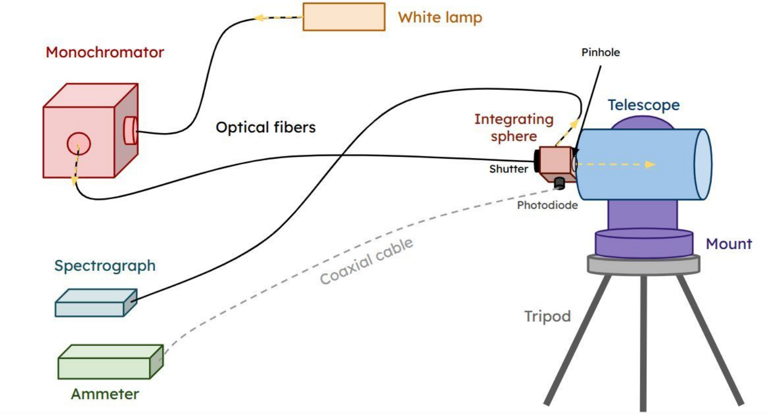


Traveling-CBP with ZTF



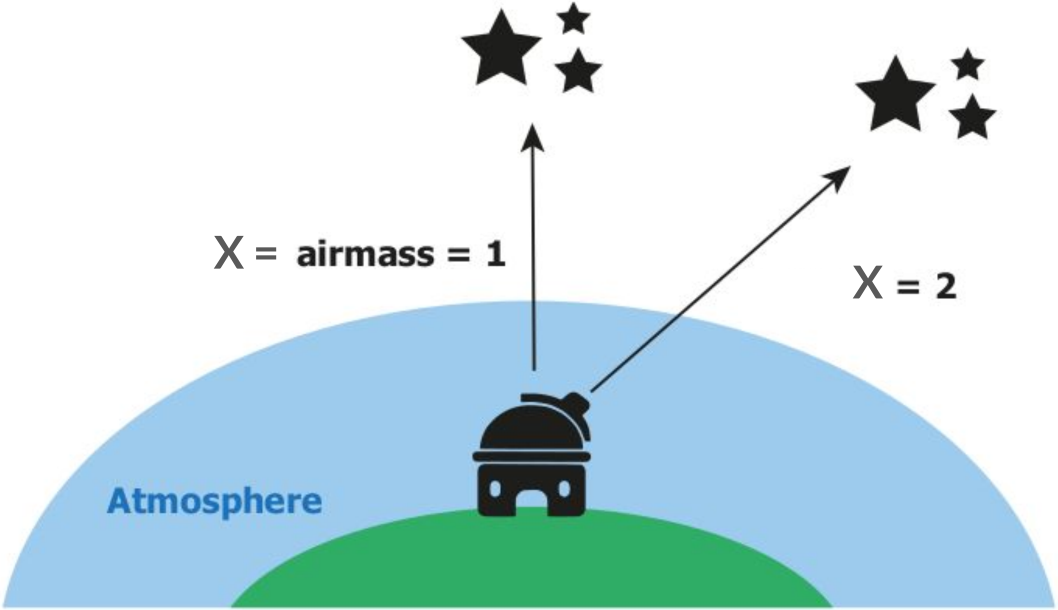
Picture of the tCBP shooting in the ZTF telescope



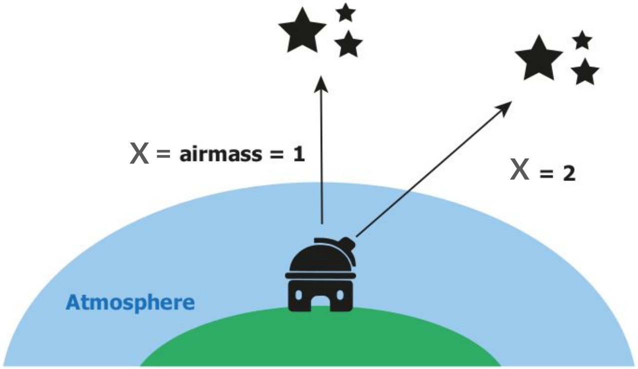
tCBP schematic
(Credit: E. Van Den Abeele)

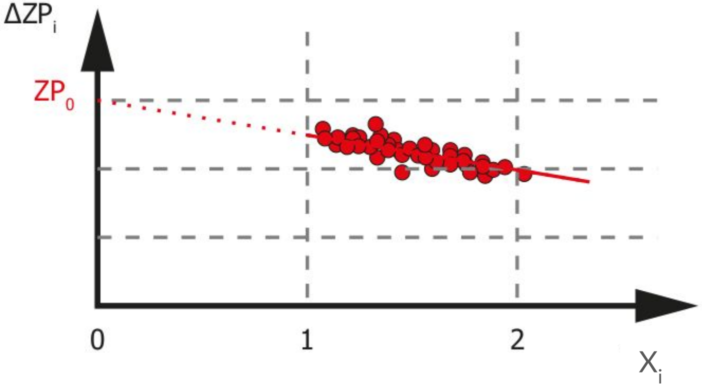
Photometric analysis

Airmass



Atmospheric considerations

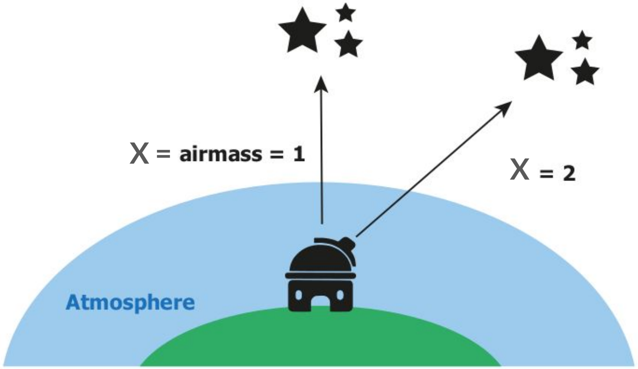


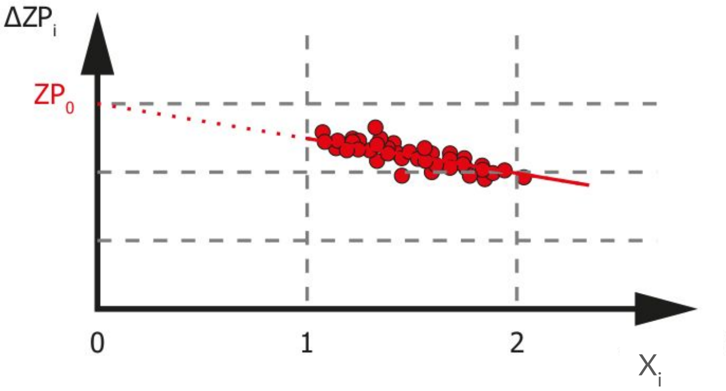


Airmass regression:

- 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





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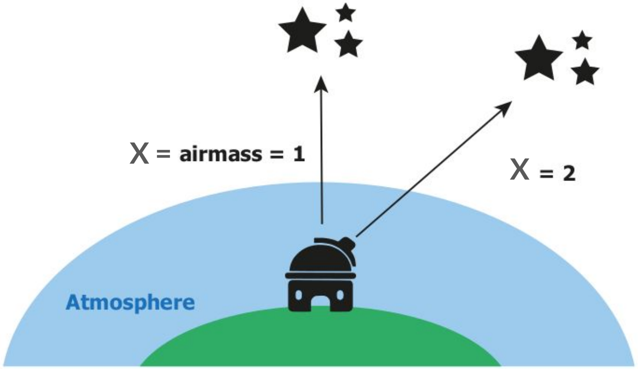

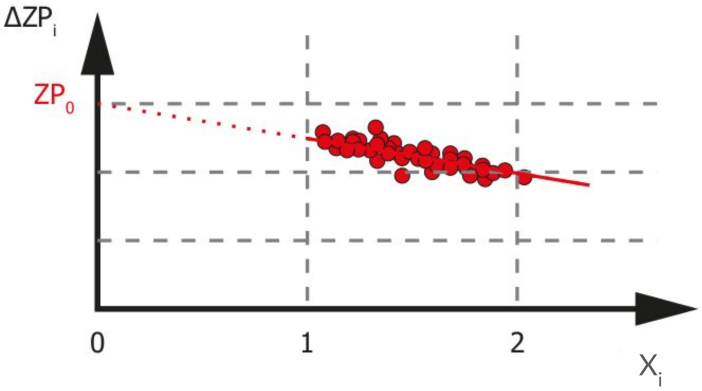

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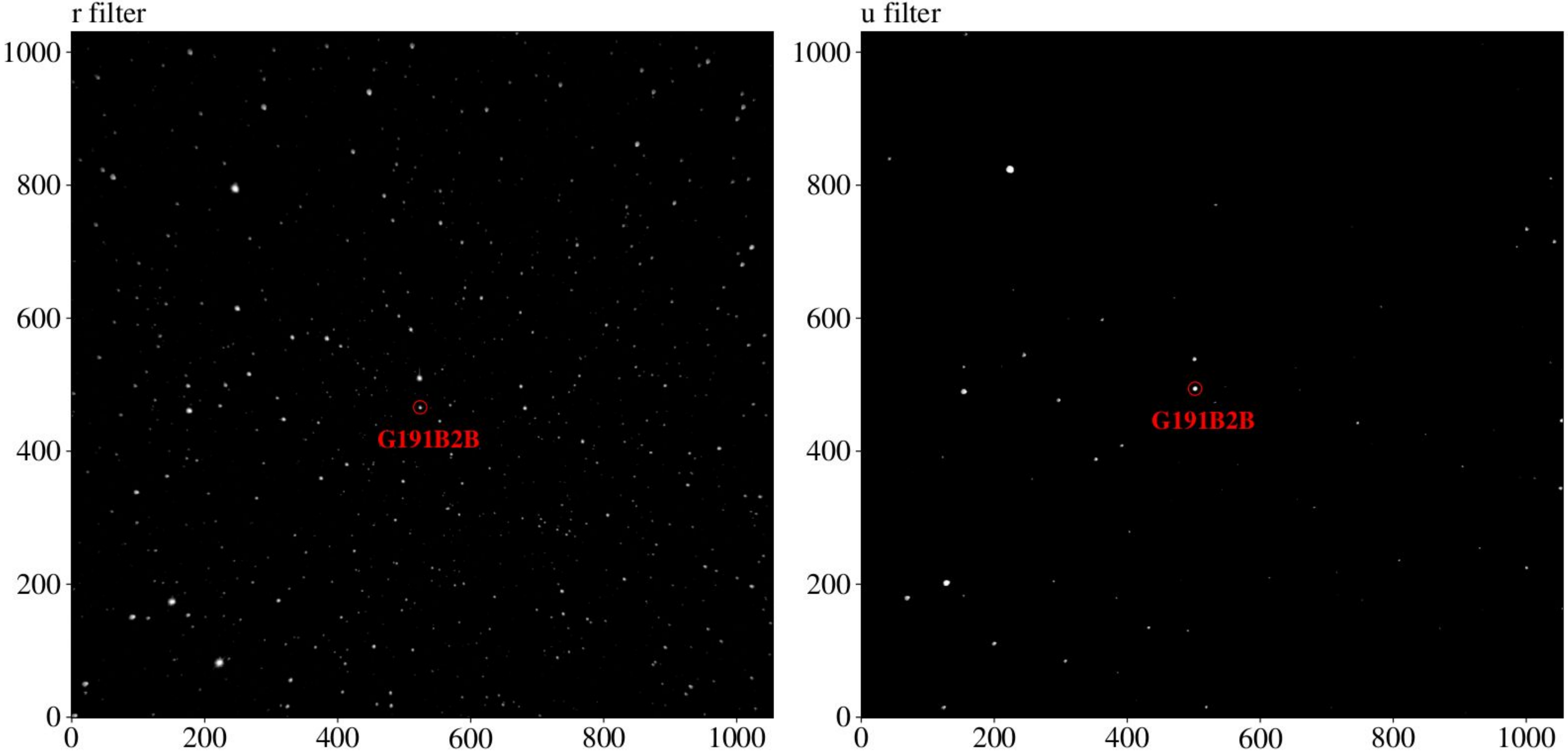
This analysis:

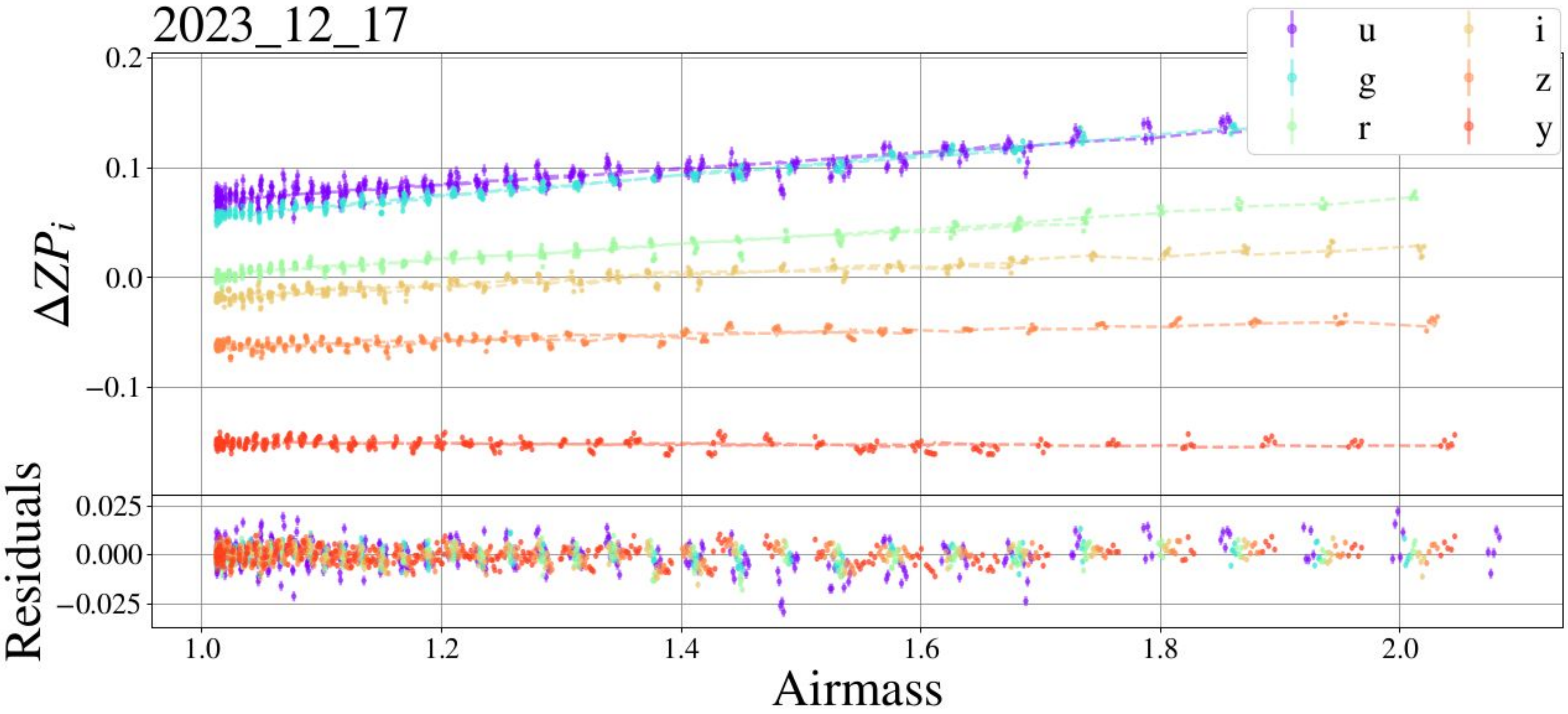
- Estimate the StarDICE performance of refining the $\mathbf{ZP_0}$ with a 2-year survey

Examples of image



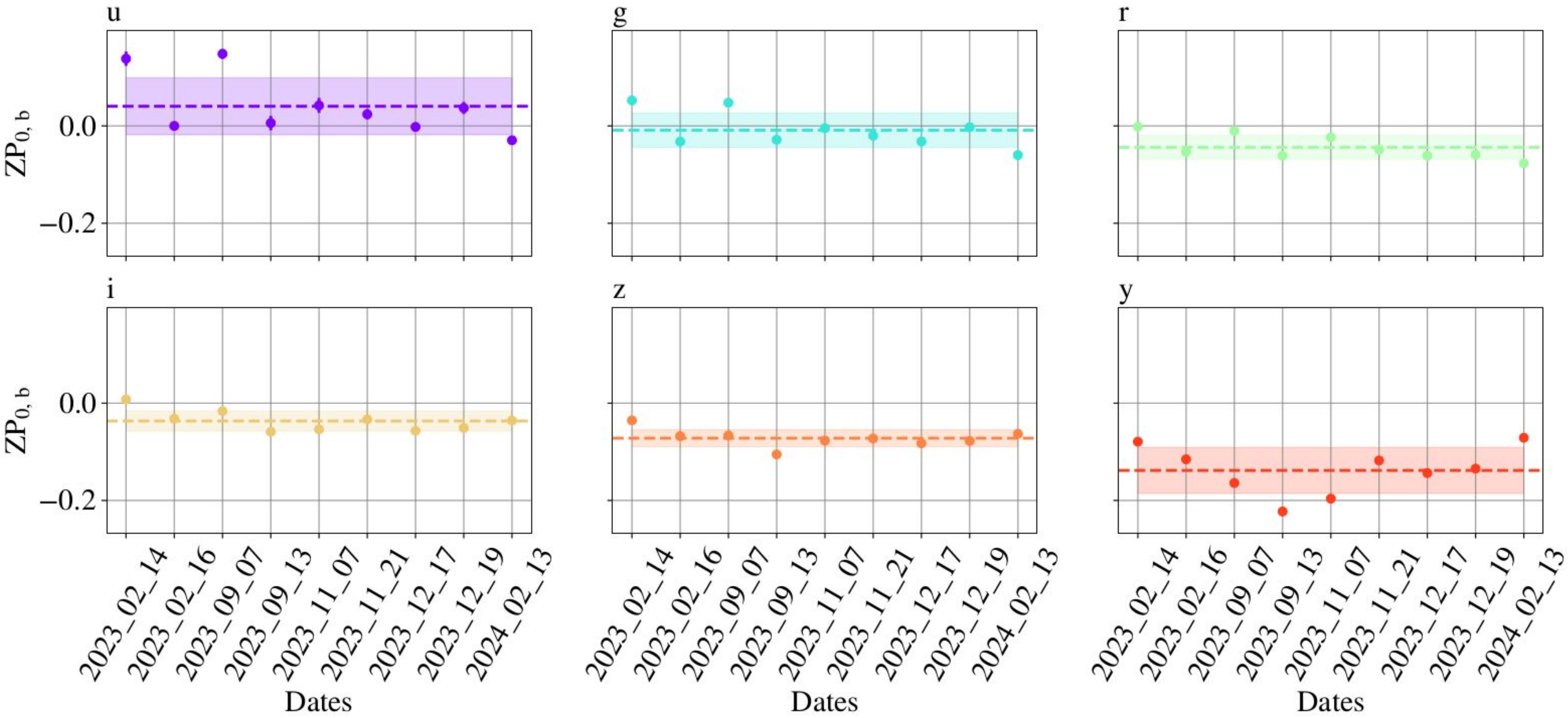
Pre-survey: 23 observation nights of the CALSPEC primary standard G191B2B

▢ ΔZPi vs airmass

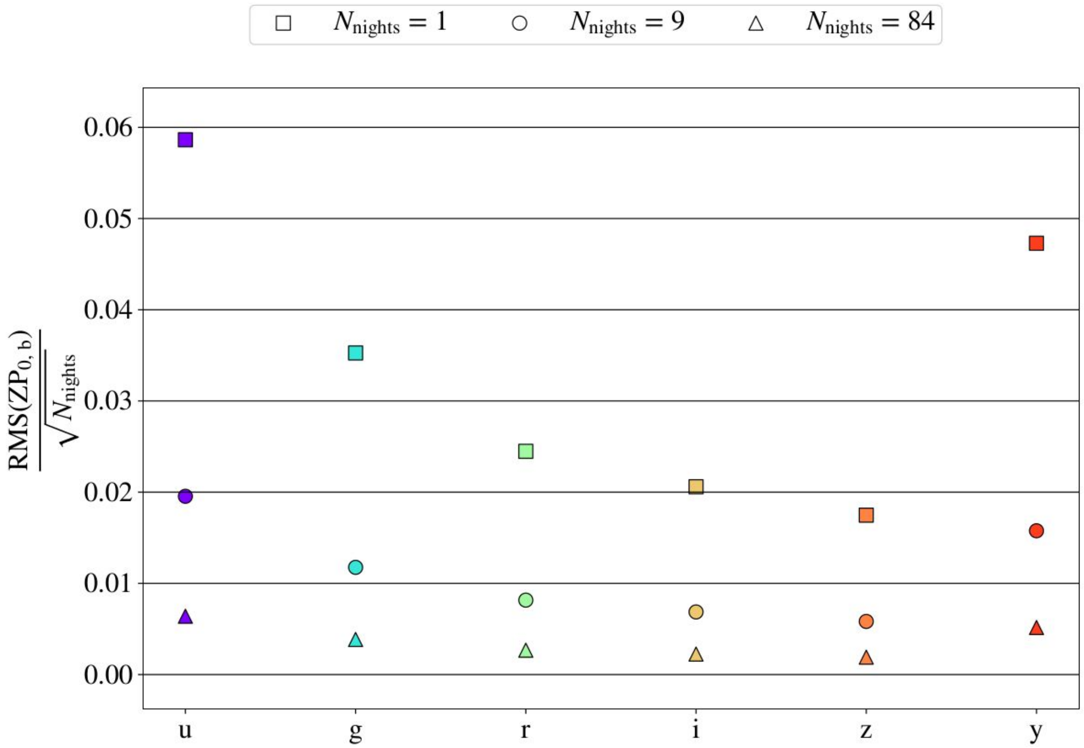


$$\Delta ZP_{\mathrm{b},\,i}(X) = k_{\mathrm{b}} X_i + ZP_{0,\mathrm{b}}$$

Results


u
g
r
i
z
y
$ZP_{0,\,b}$
$ZP_{0,\,b}$
0.0
−0.2
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
Dates
Dates

StarDICE performances projection



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

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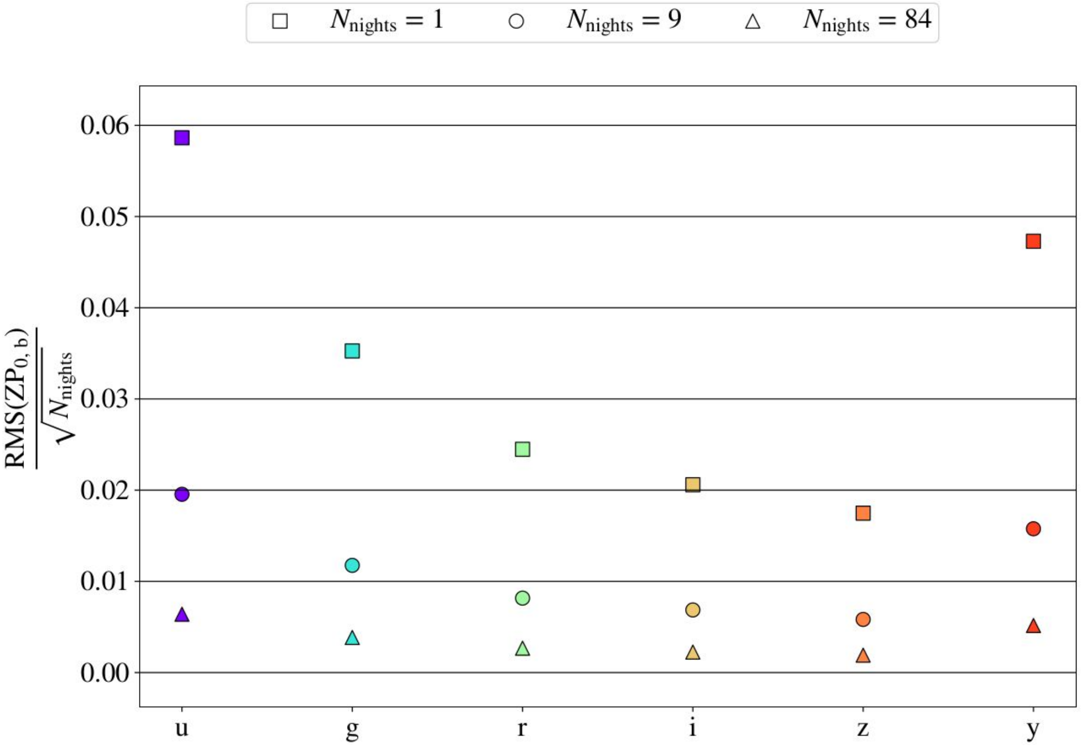

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⇒ 2 to 4 times the suitable value to fully exploit the future LSST SNe Ia dataset

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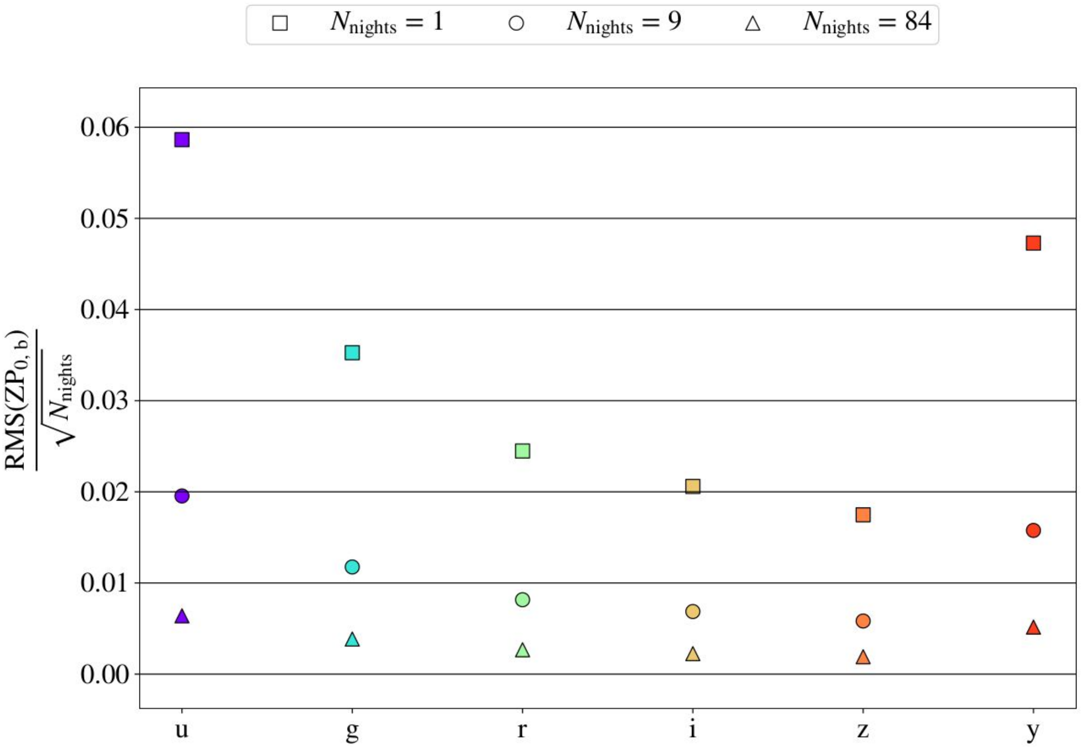

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- **~0.2 to 0.4% uncertainty**

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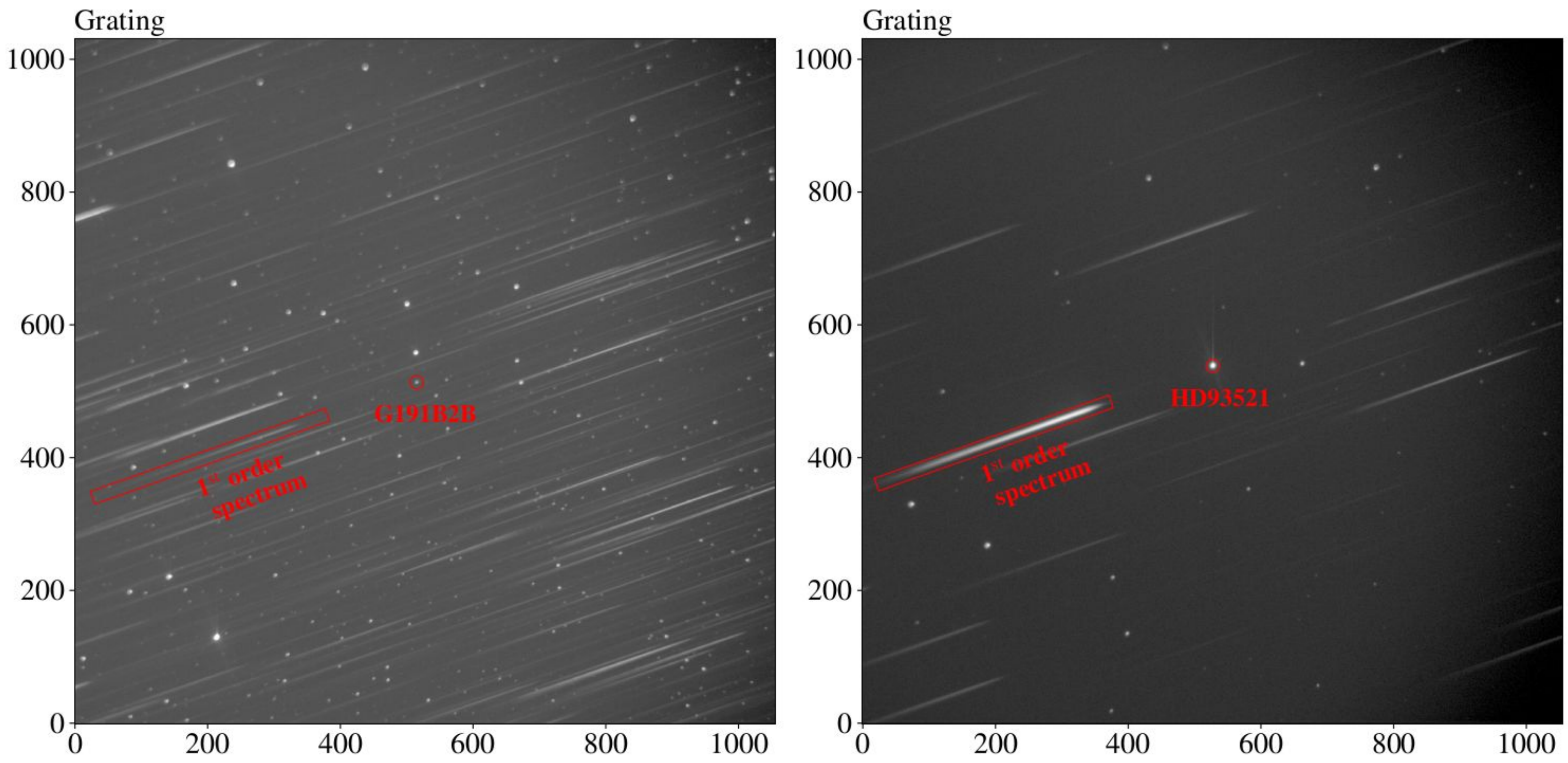
⇒ Improve the atmosphere transmission prior by fitting live parameters

Grating images



CMB polarization & the POLOCALC experiment

POLOCALC project

(slides from A. Novelli, Moriond 2026)

- An ERC-funded project to build a drone-based calibration source for CMB telescopes

POLOCALC: F. Nati
arXiv:1704.02704

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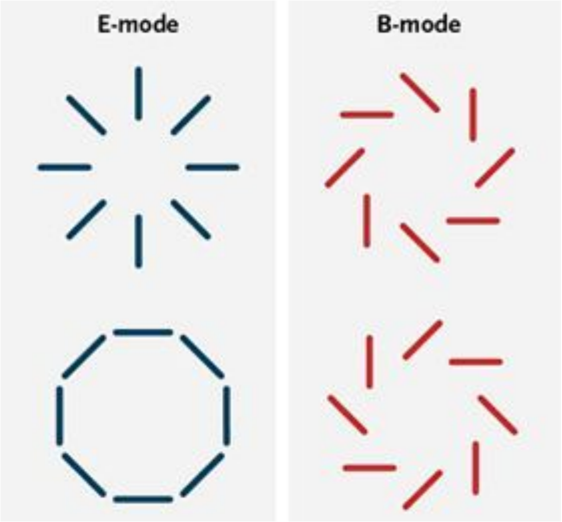
- Main goal: absolute polarisation angle calibration in the range 0.1° and 0.01°
    - Necessary to disentangle E-modes and B-modes

$\alpha \rightarrow$ rotation in the line of ishgt

$$\begin{cases} C'_{TT} = C_{TT} \\ C'_{BB} = C_{BB}\cos^2(2\alpha) + C_{EE}\sin^2(2\alpha) \\ C'_{EE} = C_{BB}\sin^2(2\alpha) + C_{EE}\cos^2(2\alpha) \end{cases}$$



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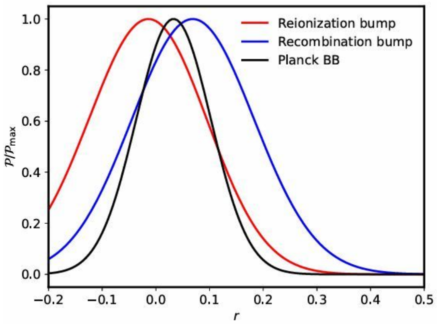

ArXiv:2010.01139

POLOCALC project

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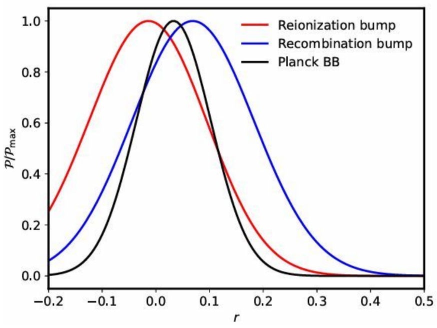
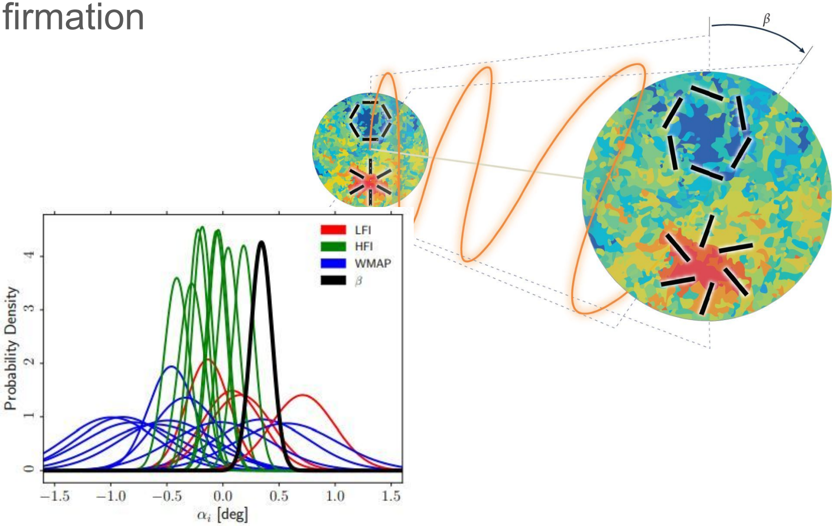
    - Test cosmic birefringence theories



ArXiv:2010.01139



ArXiv:2205.13962

POLOCALC project

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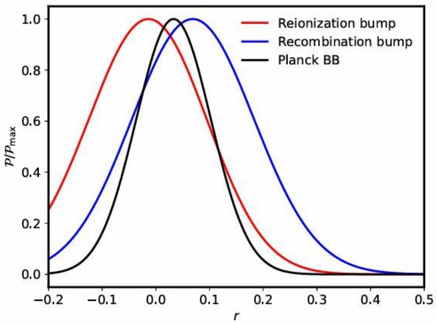
- Main goal: absolute polarisation angle calibration in the range 0.1° and 0.01°
  - Necessary to disentangle E-modes and B-modes
    - Allows to constrain r<0.01 ⇒ inflation confirmation
    - Test cosmic birefringence theories
    - Detect the presence of primordial magnetic fields



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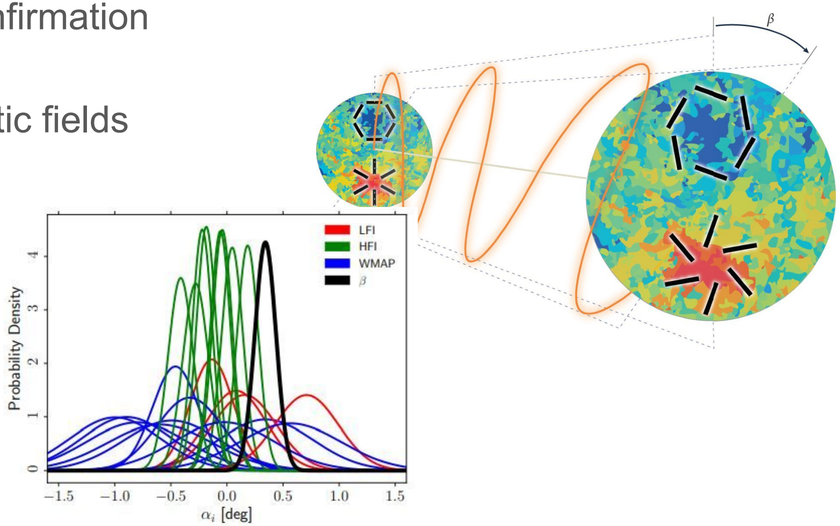

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POLOCALC project

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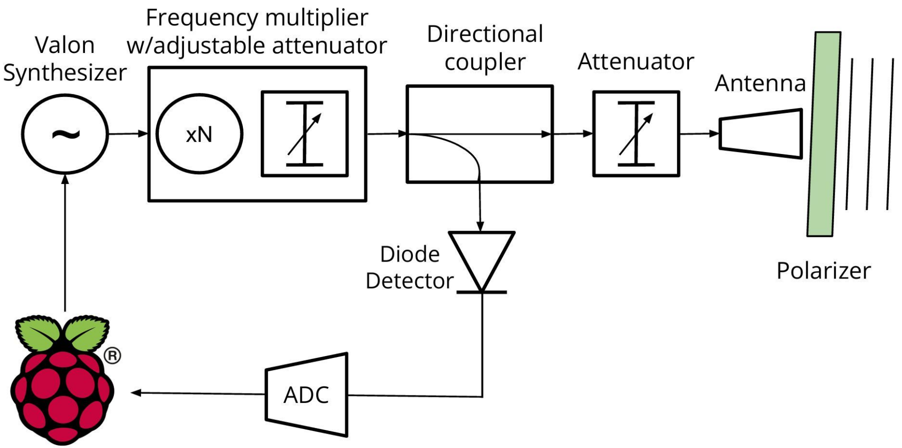
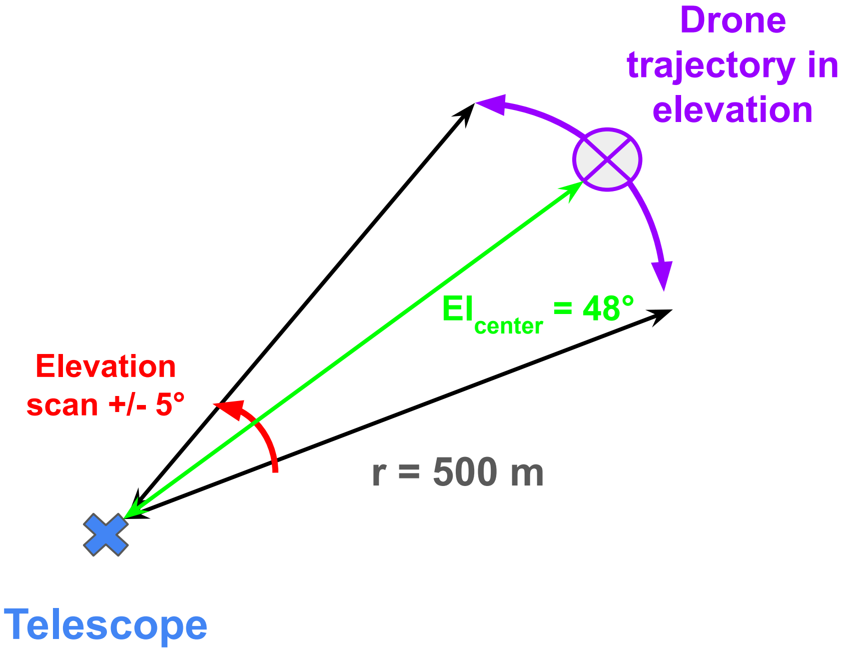
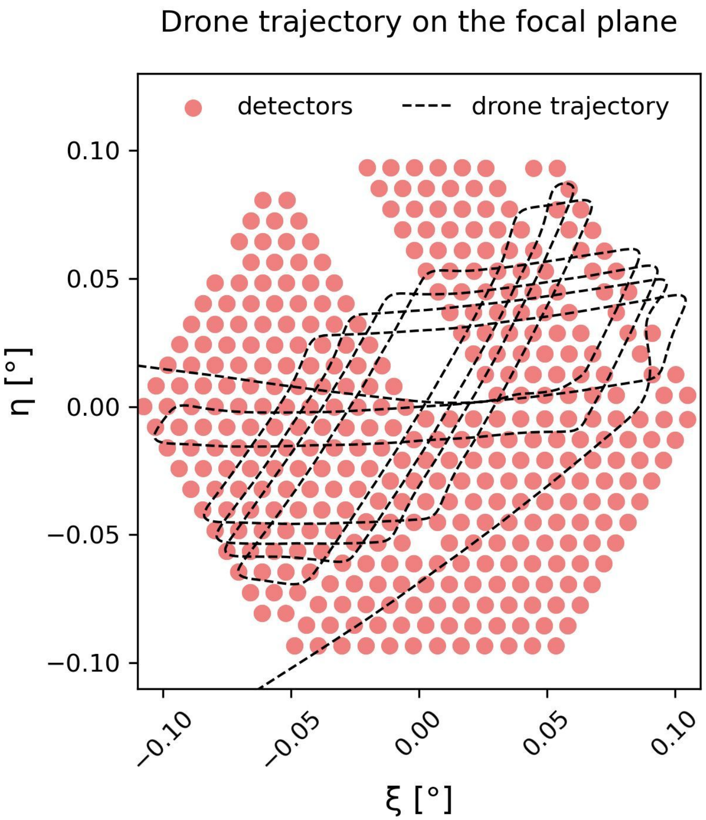


- Polarizer orientation calibrated in laboratory
- Attitude reconstruction of the drone (GPS + photogrammetry)

POLOCALC project



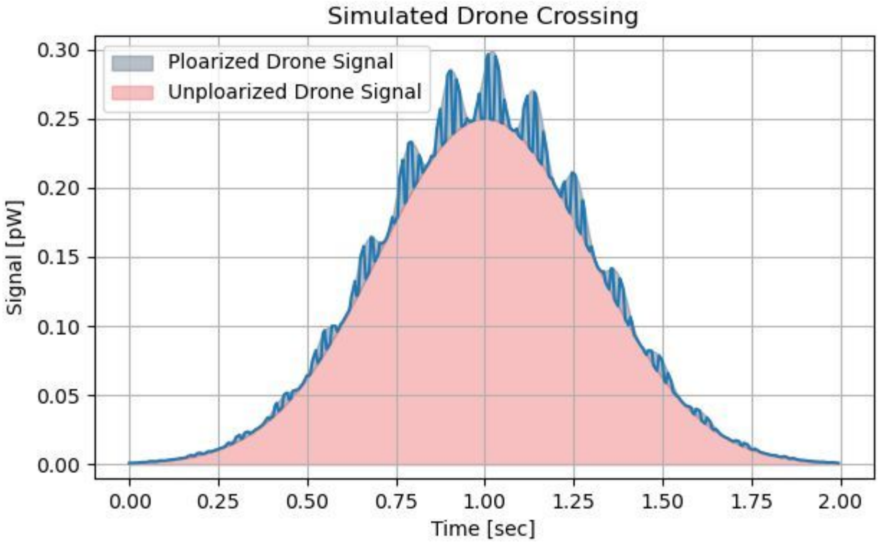


POLOCALC project

(slides from A. Novelli, Moriond 2026)

Our data model for each crossing is composed of:

- drone thermal emission
- source's chopped polarised emission
- noise



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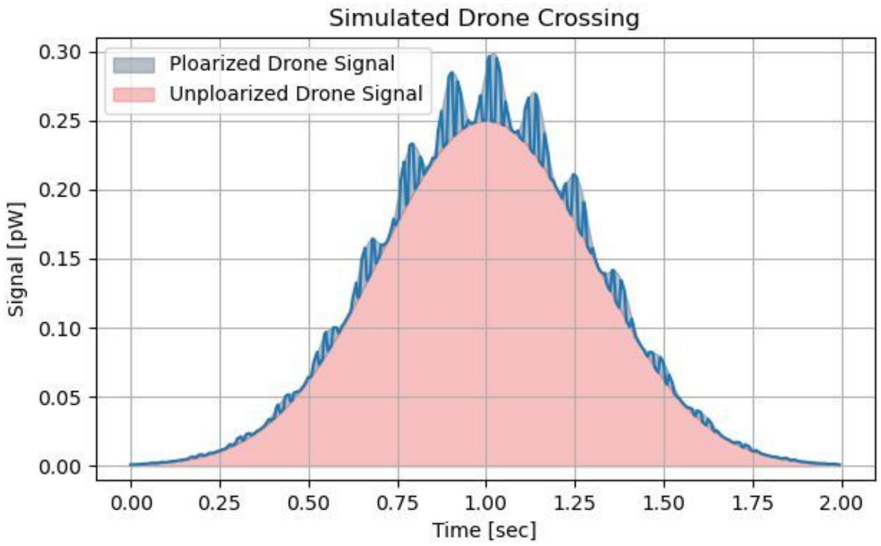
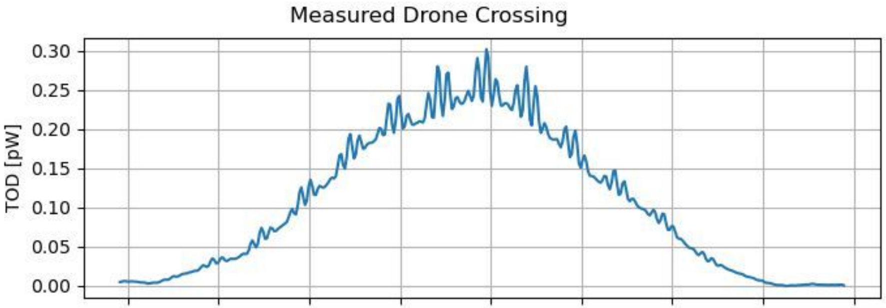
Our data model for each crossing is composed of:

- drone thermal emission
- source’s chopped polarised emission
- noise

⇒ Through double demodulation from each crossing we can extract the Θ_{POL} of the source as seen by the detectors





Conclusion

Since ~20 years, cosmology has entered a high-precision era where datasets keep getting bigger, and instruments keep getting more sensitive

With statistical uncertainties diminishing, and S/N ratio increasing, systematics uncertainties arise to become new dominants noise source

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But most important…

Thank you for your attention