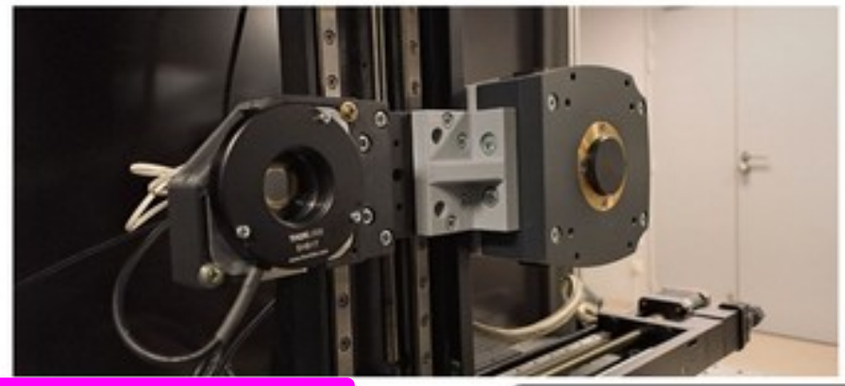
M. Betoule, P.E. Blanc, S. Bongard, J.C. Tanugi, S. Dagoret-Campagne, F. Feinstein, D. Hardin, C. Juramy, L. Le Guillou, A. Le Van Suu, M. Moniez, J. Neveu, E. Nuss, B. Plez, N. Regnault, E. Sepulveda, K. Sommer, T. Souverin

Seb parlant pour StarDICE

THE GOAL

Providing lab calibrated Standard Stars for LSST



NIST Photodiodes

CCD/CMOS

StarDICE telescope

1e-12W

1e-12W/cm²

1e-12W/cm²

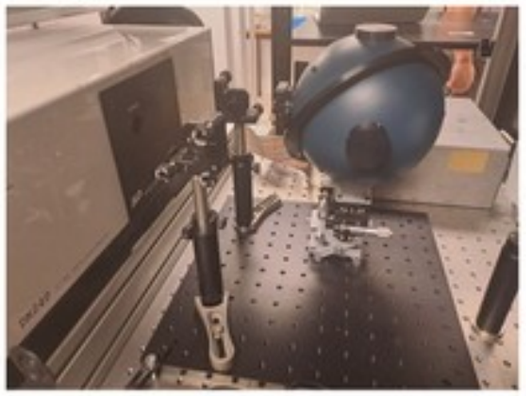
1e-16W/cm²

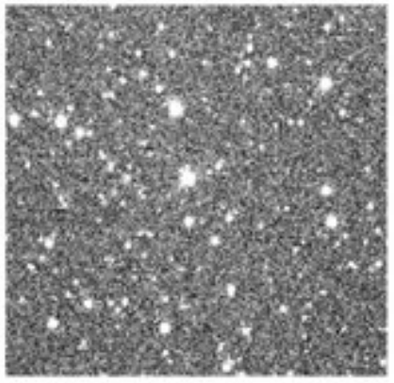
1e-19W/cm²/nm

ArDICE

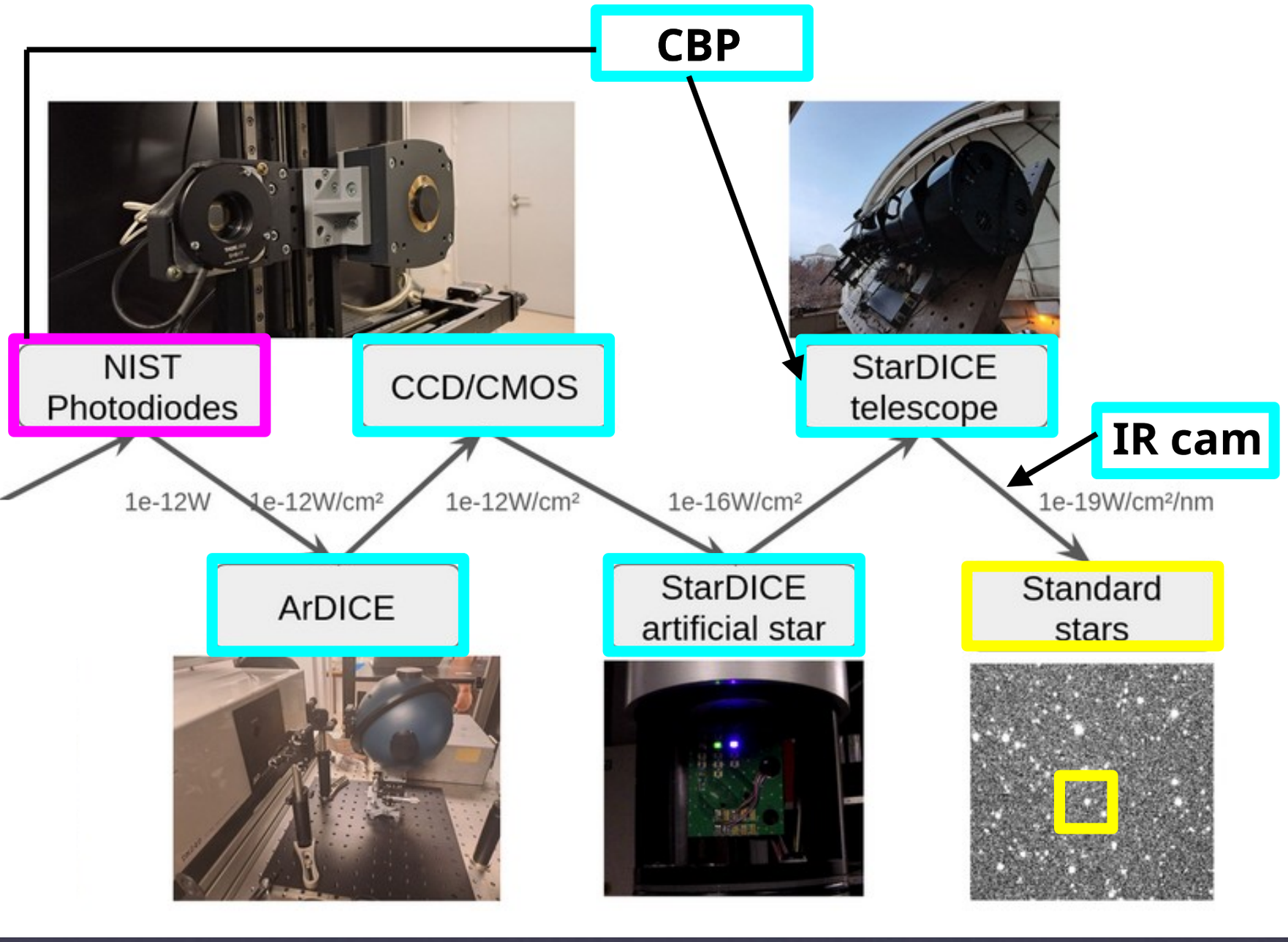
StarDICE artificial star

Standard stars





THE GOAL → Reality

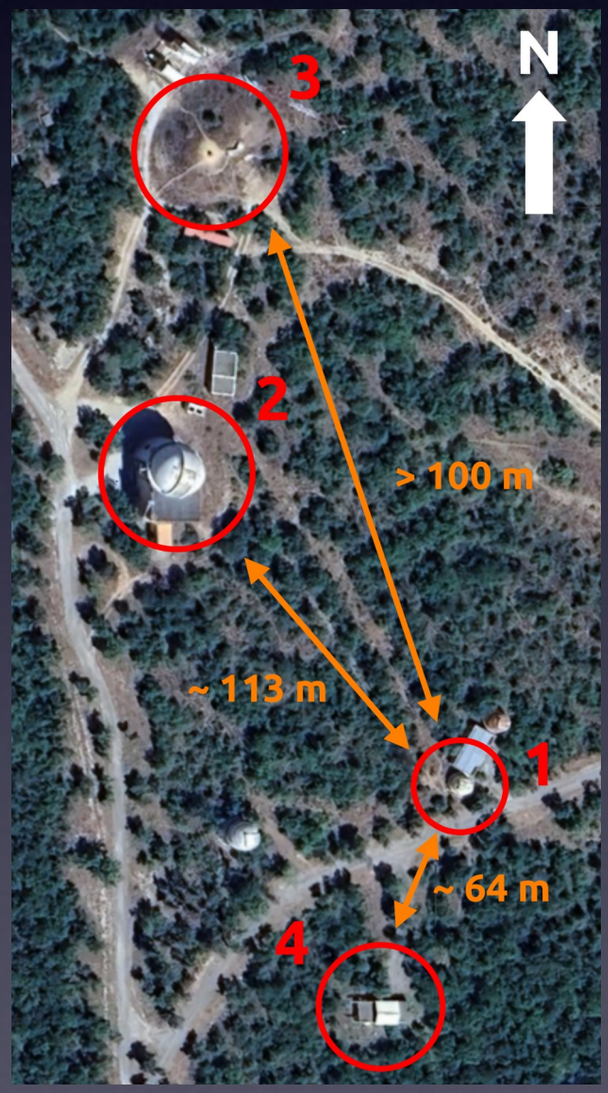


2 calibration benches @ LPNHE + 1 CBP @ LPNHE
1 artificial star @ OHP
1 Robotic telescope @ OHP
1 IR camera + optical camera @ OHP

Providing lab calibrated Standard Stars for LSST

↓

A **dedicated calibration facility** linking Lab Calibrated Photodiodes to Standard Stars



towards

THE GOAL

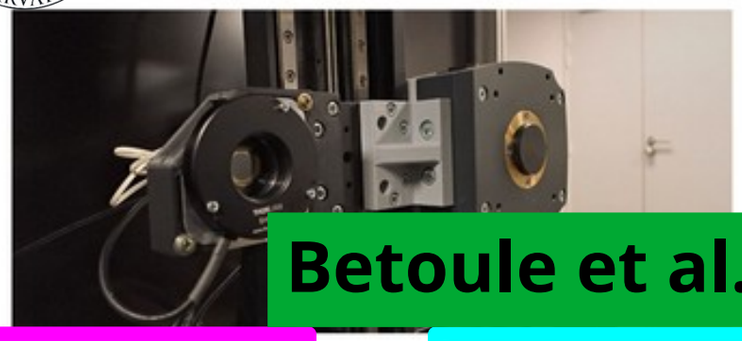
tCBP

LSST-CBP

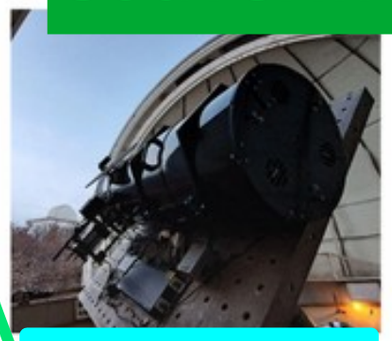
Brownsberger et al.

CBP

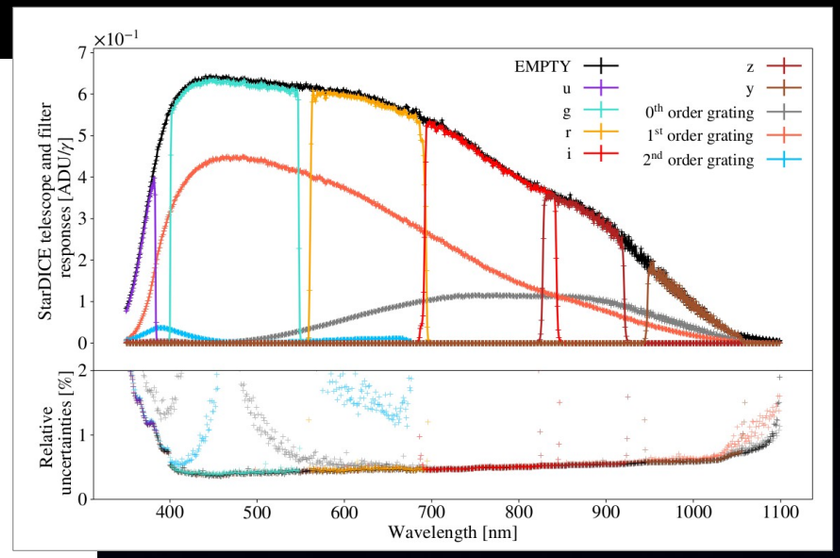
Souverin et al.



Betoule et al.



Sommer et al.



NIST Photodiodes

CCD/CMOS

StarDICE telescope

IR cam

1e-12W

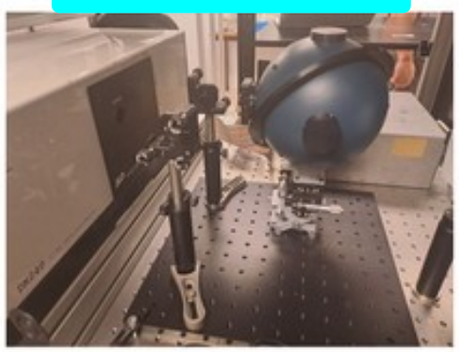
1e-12W/cm²

1e-12W/cm²

1e-16W/cm²

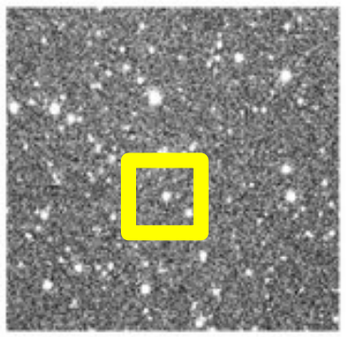
1e-19W/cm²/nm

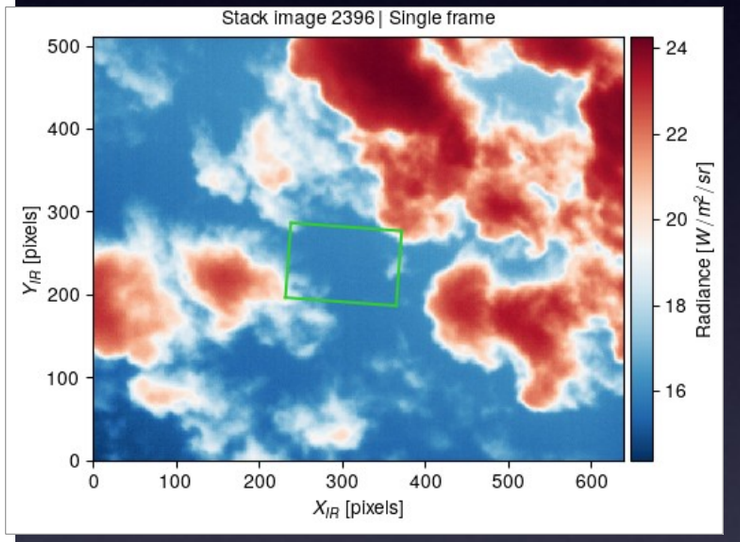
ArDICE



StarDICE artificial star

Standard stars





2 PhD

Kelian Sommier : IR measurement of cloud coverage

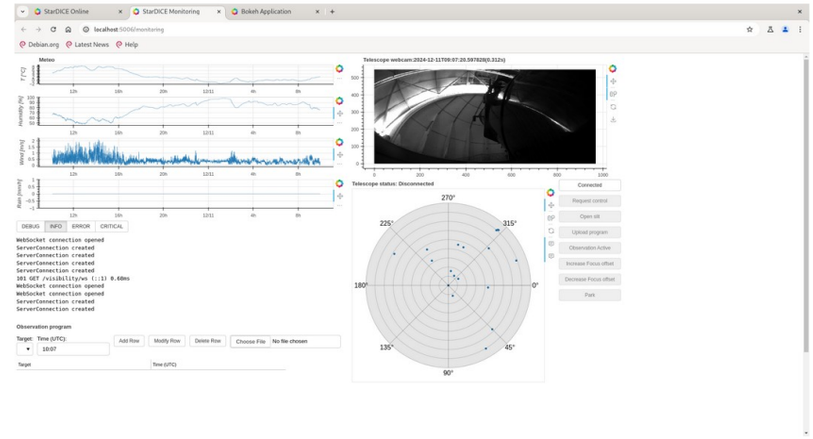
Thierry Souverin : StarDICE telescope transmission measurement and Stellar Photometry

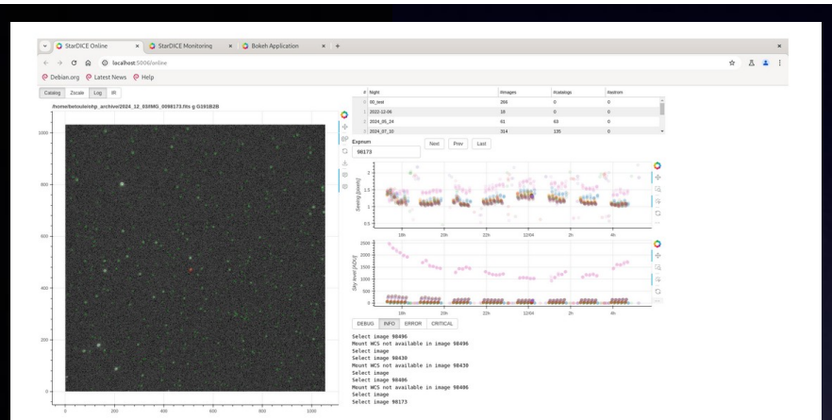
3 papers + 1 in prep

Remote controlled dedicated facility

Operates remotely with
OHP emergency support

REMOTE OPERATIONS



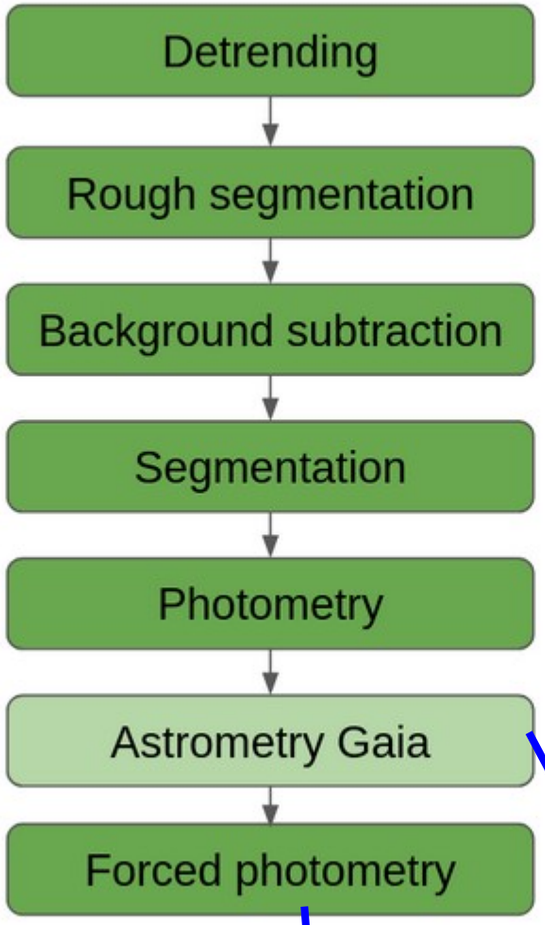


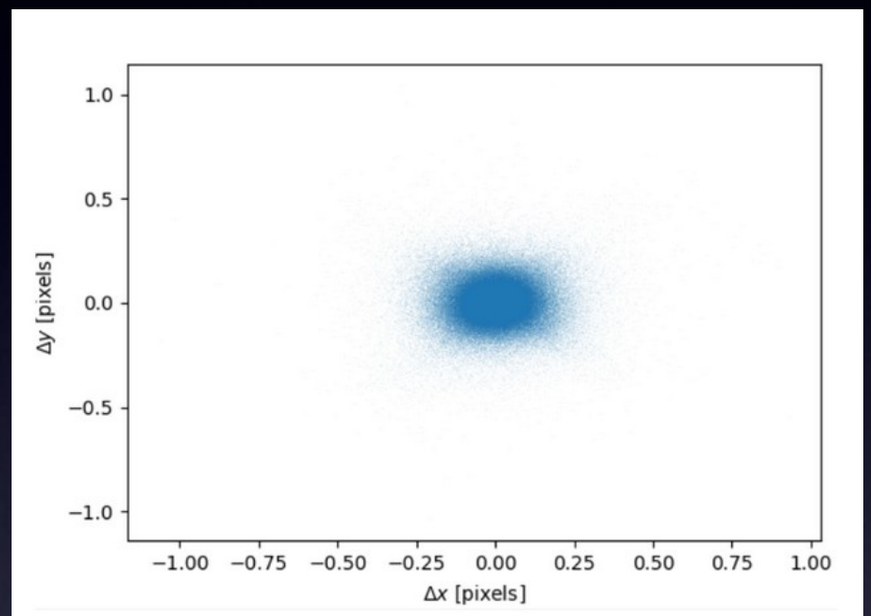
GATHERED DATA

Target	#images	%astro	#nights	ΔX > 0.2
G191B2B	35378	73	37	35
BD+28 4211	8302	63	17	14
GD153	8036	0	10	10
Delta Umi	4419	0	2	2
HD93521	3841	0	3	2
Eta Uma	3511	0	1	1

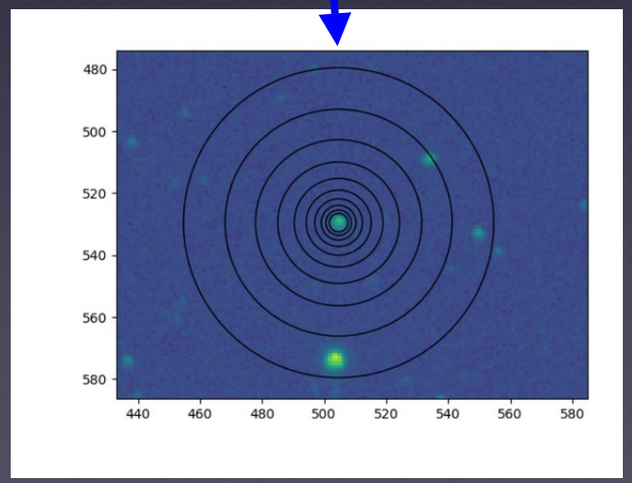
The stars

Processing pipeline





RMS residuals
X ~ 0.1 pix
Y ~ 0.1 pix
→ enough for forced photometry



Analysis: comparison with GAIA

OBSERVATION MODEL

$$\phi = \int T(\lambda) A(\lambda) S(\lambda) \frac{\lambda d\lambda}{hc}$$

- T: from CBP measurement
- S: low resolution spectrum from gaia
- A: 4 free parameter model, pressure from meteo station, airmass computed for each star, templates from Buton et al. 2013

Accounts for seeing variations

APERTURE CORRECTION MODEL

$$\frac{\Phi_{3.00}}{\Phi_{4.10}} = a_e + \alpha_b |\vec{x} - \vec{x}_b|^2$$

- Small aperture to minimize contamination and maximise the lever arm
- a_e One scale parameter per exposure
- One fix pattern per band

Computationally efficient

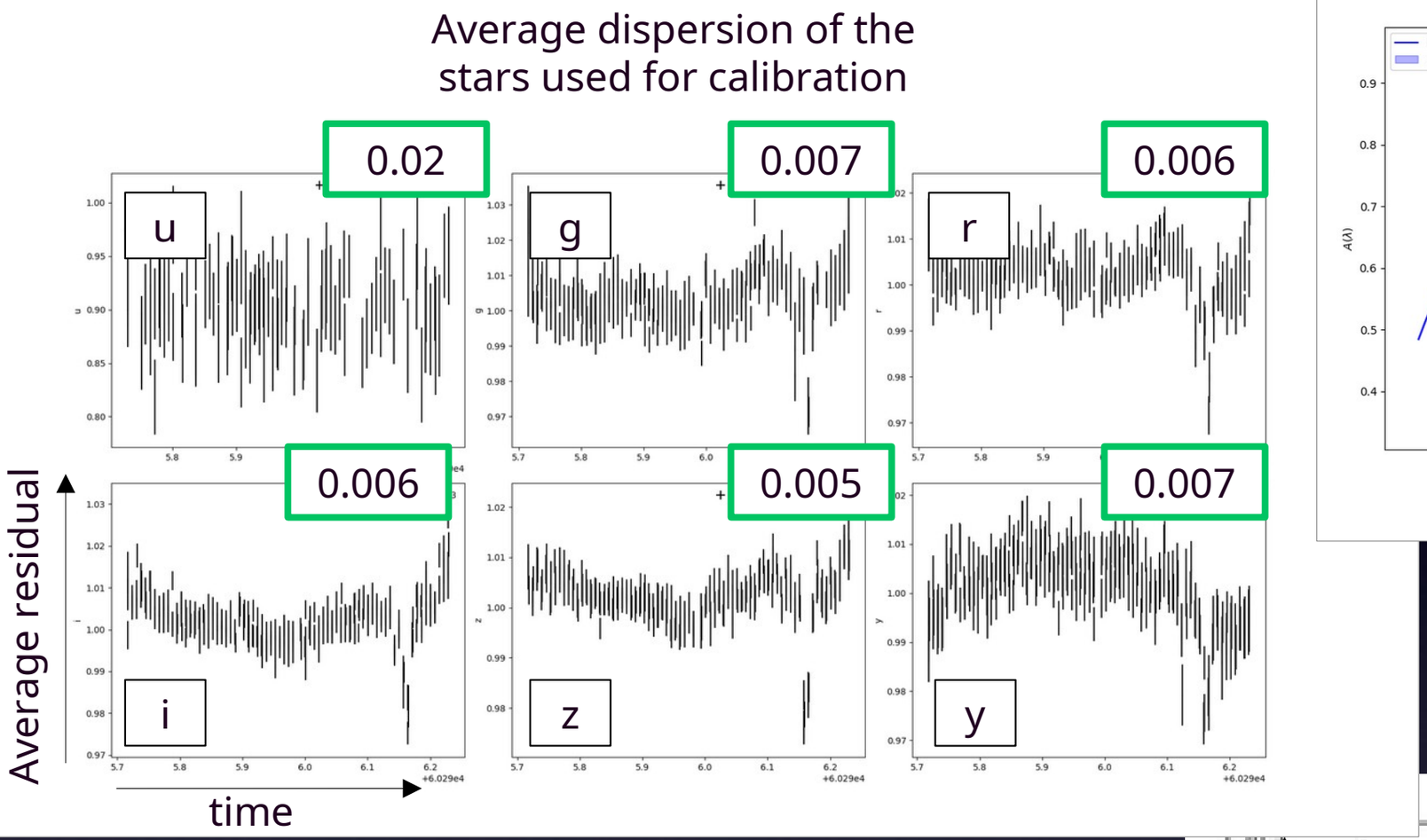
JAX IMPLEMENTATION

```
def synthetic_mag(starid, bandid,
                  airmass, pressure, ozone_column=300,
                  aerosol_optical_depth=1e-2, aerosol_exponen
                  H2O_intensity=1, gray=0):
    T = trans[bandid]
    atm = atmosphere.atmospheric_transmission(
        airmass, pressure, ozone_column, aerosol_optical_dept
        aerosol_exponent, H2O_intensity, gray)
    spectrum = flux[starid, :]
    return (T * atm * spectrum).sum()

smag = jax.jit(jax.vmap(synthetic_mag,
               in_axes=(0, 0, 0, 0, None, None, None, None, N
```

450000 magnitudes takes 625ms (@2nm res). Jacobian with respect to 5 atmospheric parameters takes 920ms.

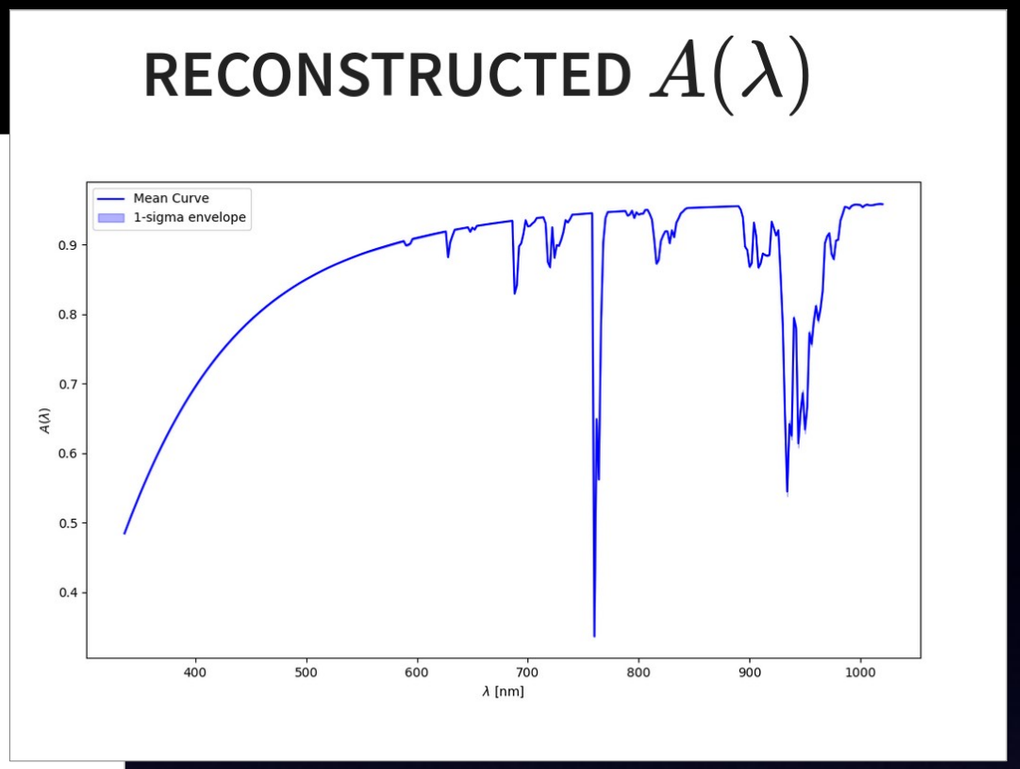
The stars

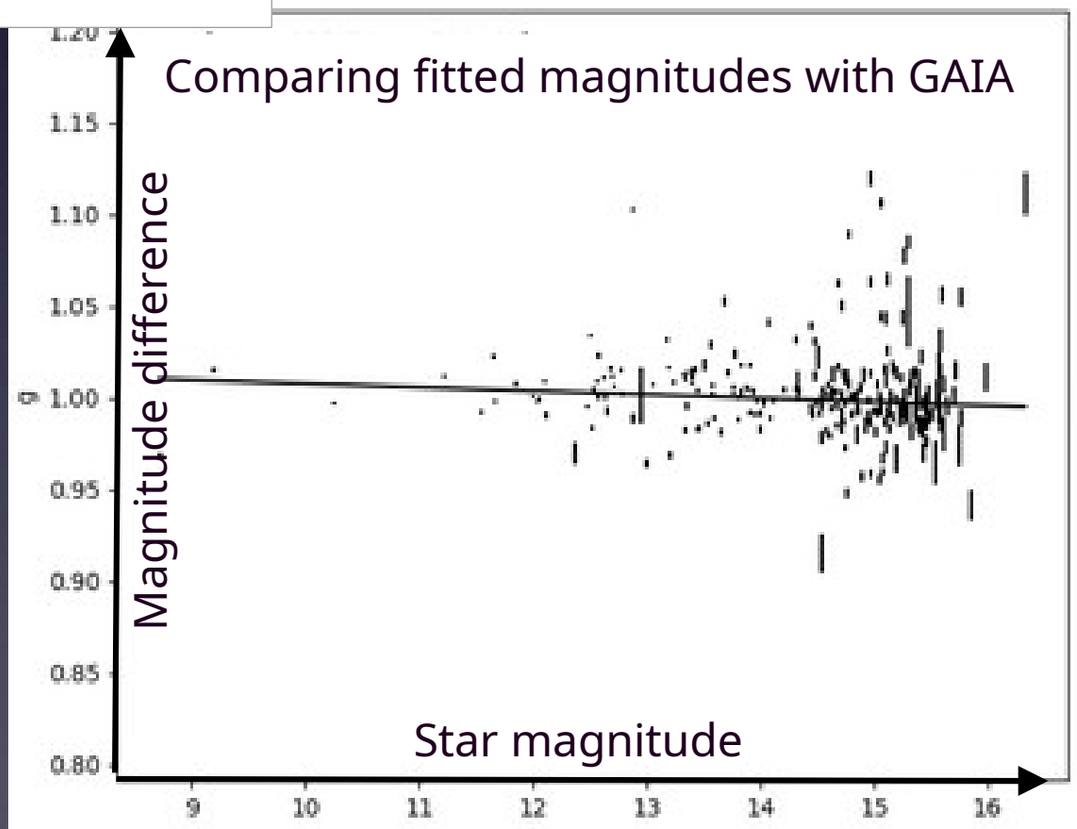


Average variability per star
A few per mil

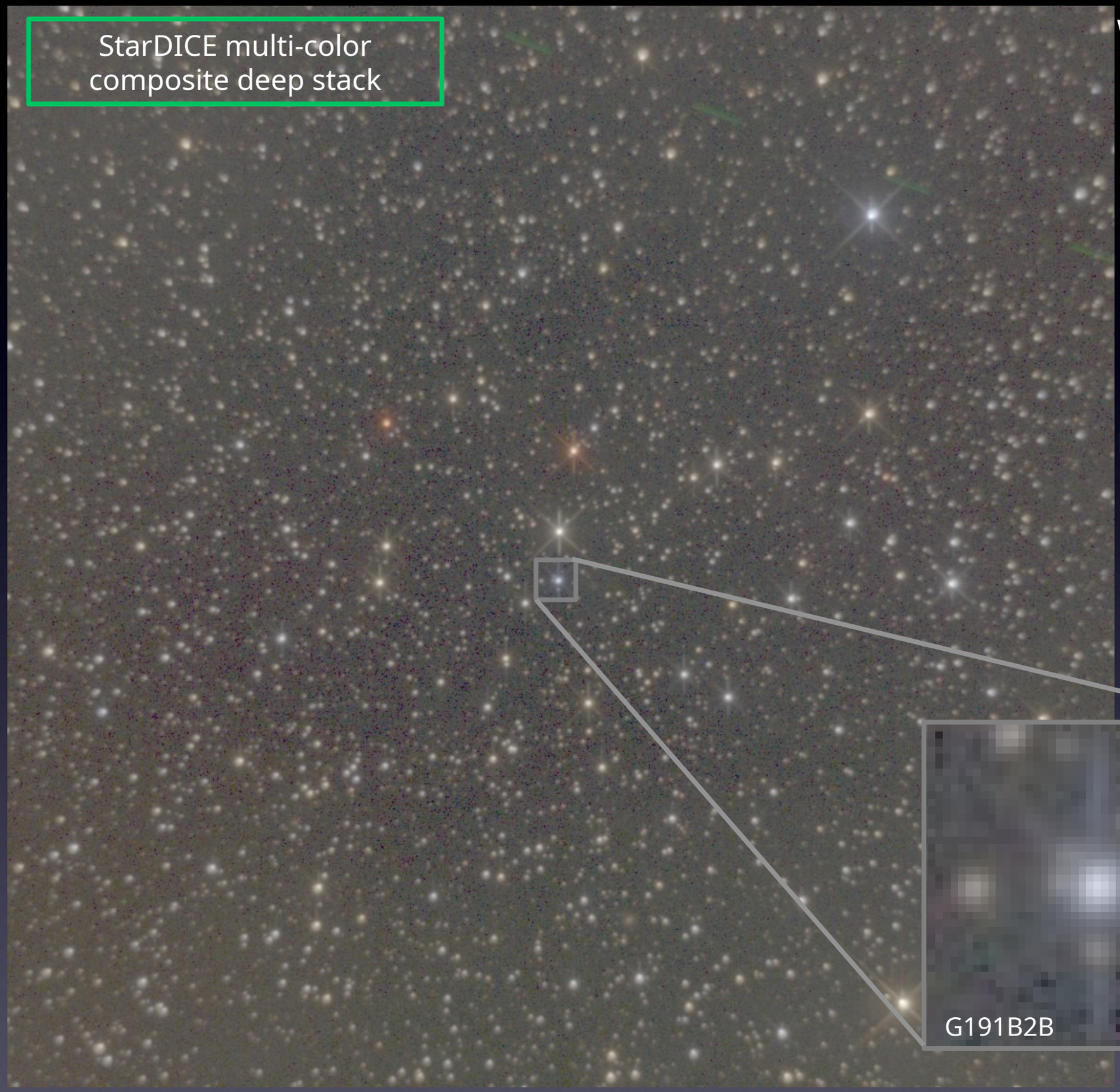
Stars are well measured
Dispersion larger for faint stars
A slight slope with magnitude

→ Main suspect is **aperture contamination**





Next steps with the stars:



Where we are:

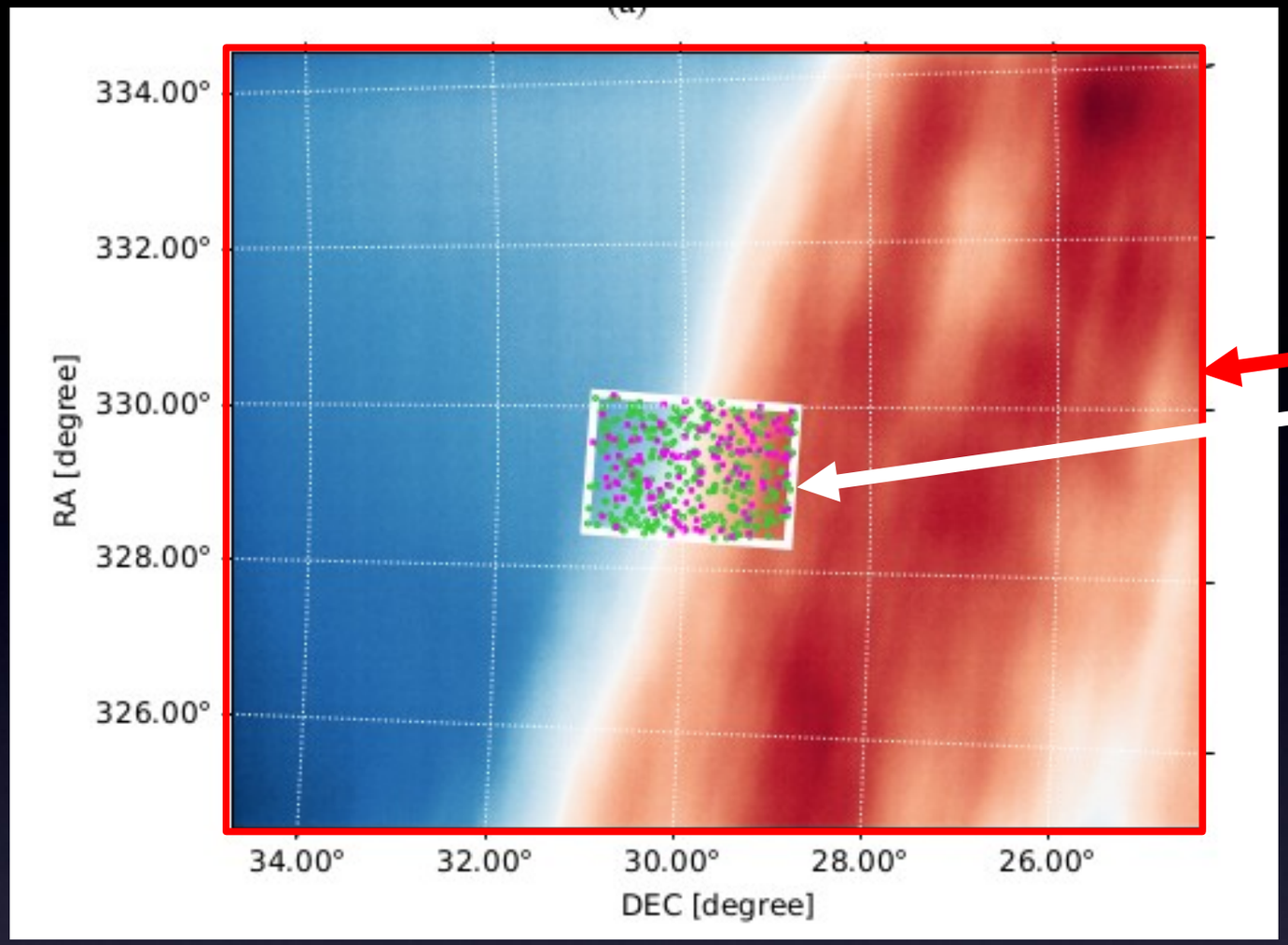
- Beautiful star transits
  - ugriz
  - EMPTY
  - Slitless spectroscopy
- Stars dispersion of a few per mil
- A systematic of 3% due to apperture contamination

Next steps:

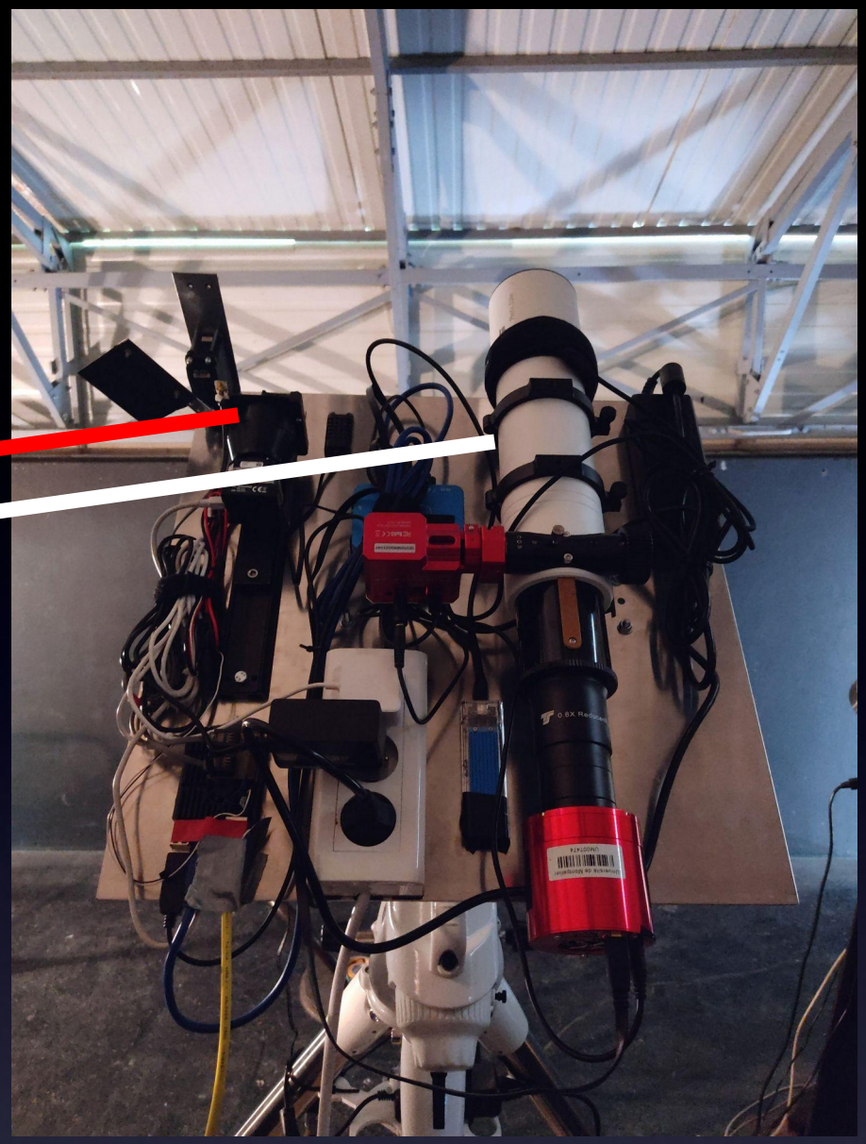
- Crowded field photometry
- Choose secondary standards with less crowded fields

aperture contamination

IR camera



Clouds in the sky add photometric noise

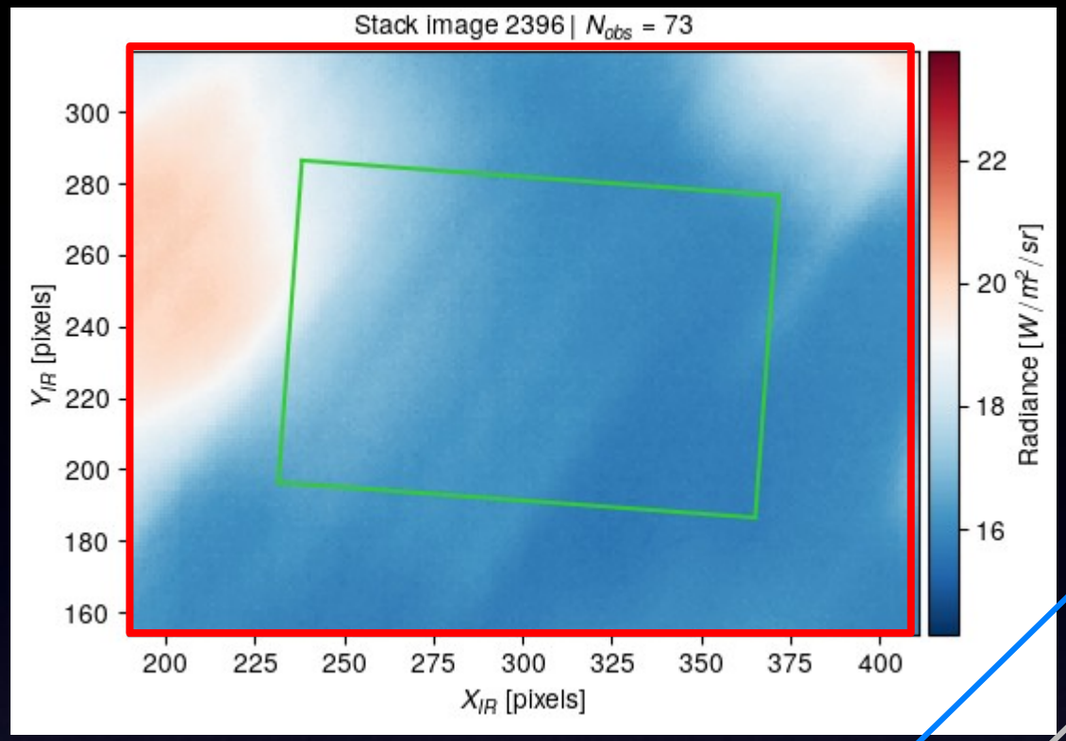


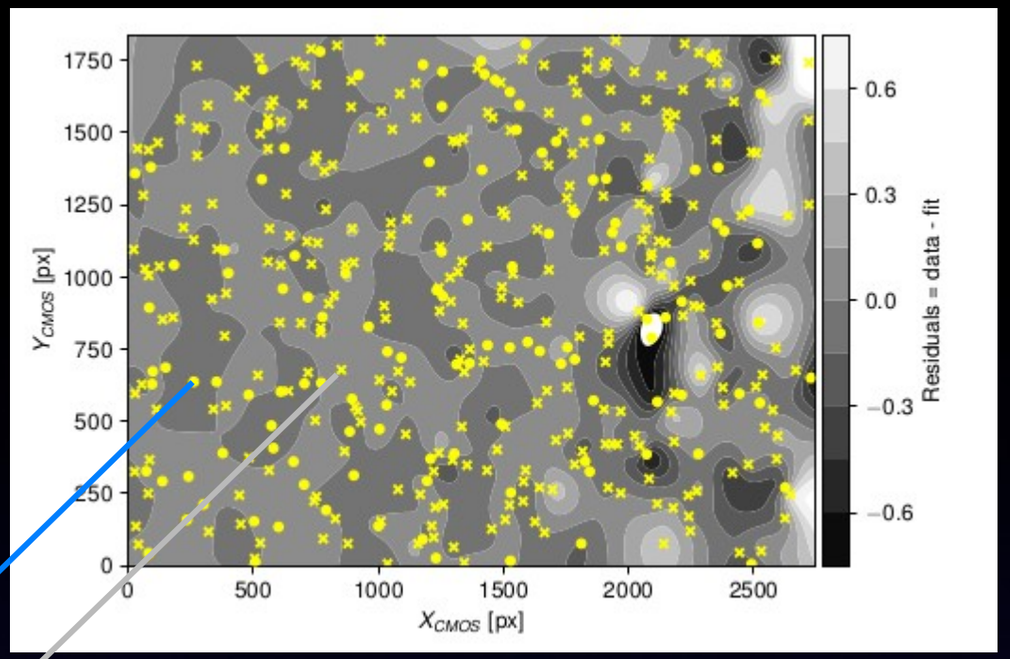
A prototype facility @ Satino @ OHP
- A photometric camera
- An IR FLIR Tau2 camera

Monitor jointly the **stars in r band**
And
The **sky radiance in IR** (11-14 microns)

First prototype @ StarDICE
→ demonstrator in a different location to avoid background radiation of the dome

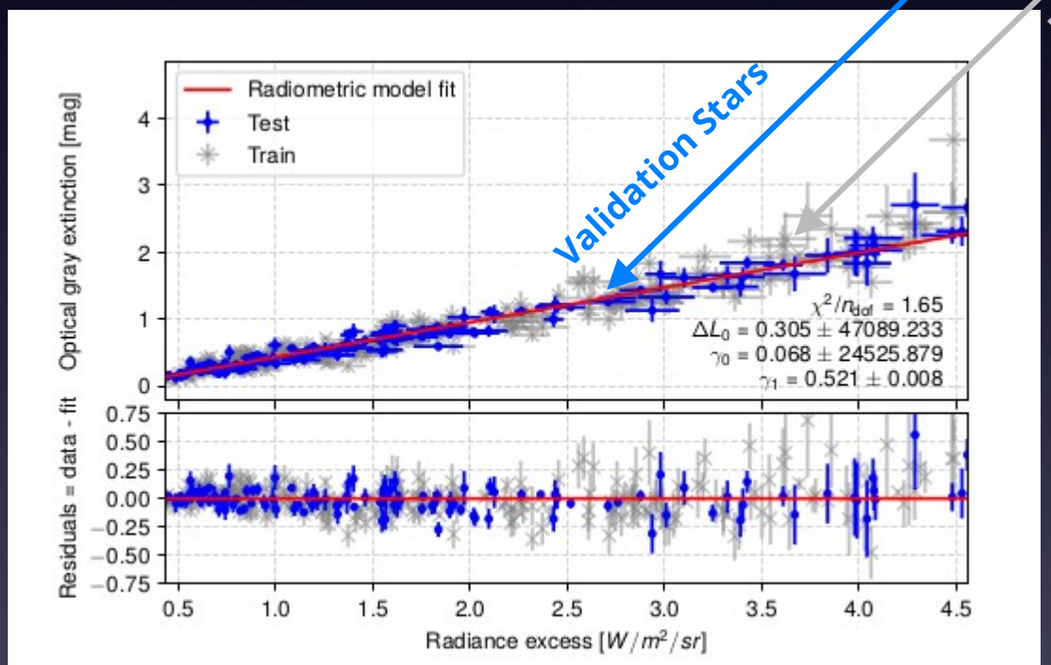
IR camera





Training Stars

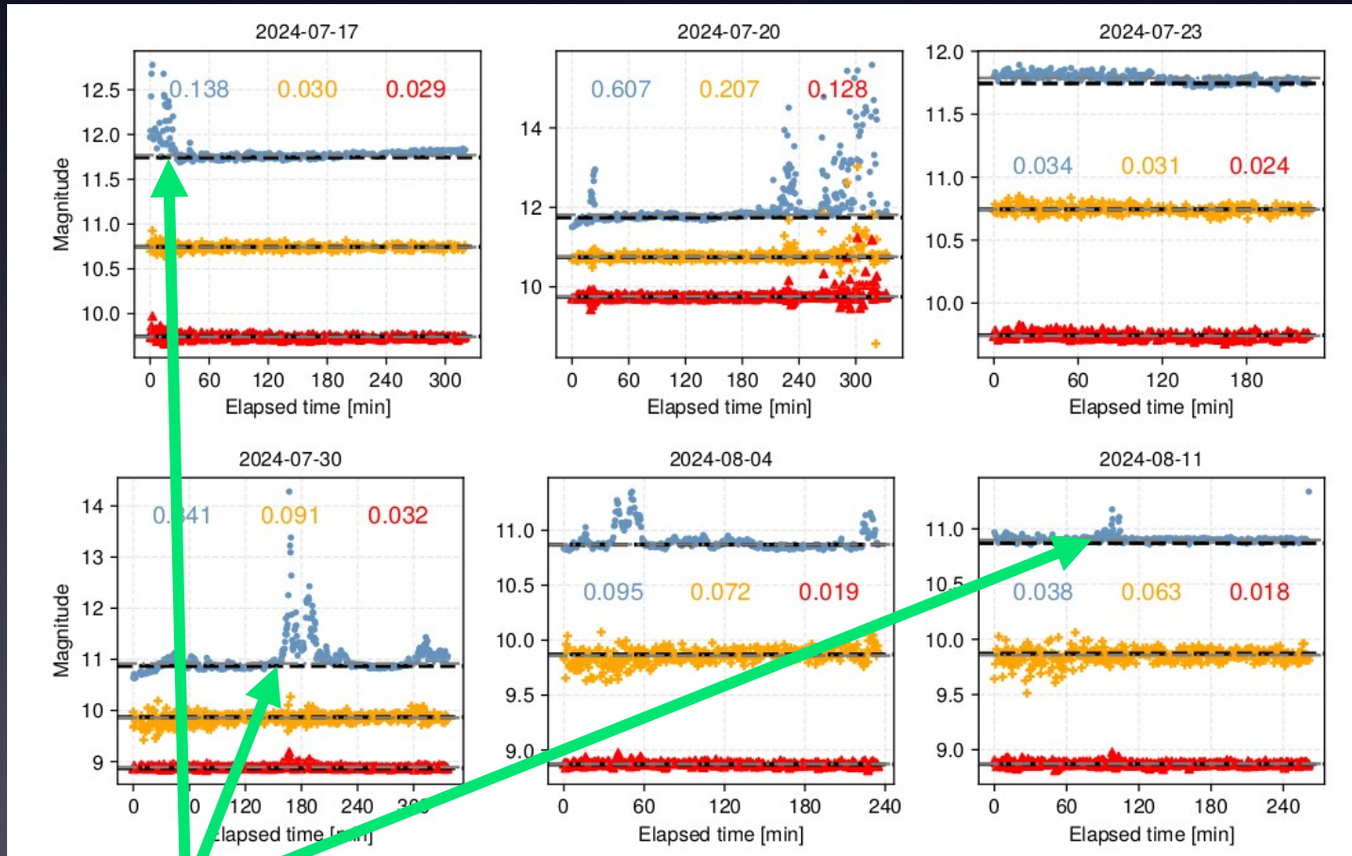
Validation Stars



$$\Gamma_i^{\text{gray}} = \begin{cases} \gamma_0 & \text{for } \Delta L_{s,i} < \Delta L_0, \\ \gamma_0 + \gamma_1 \times (\Delta L_{s,i} - \Delta L_0) & \text{for } \Delta L_{s,i} \geq \Delta L_0. \end{cases}$$

Fits the variations of the photometric flux w.r.t the corresponding IR flux in the field.

Allows to correct gray extinction to a few %



Very powerful transient cloud vetting / correction

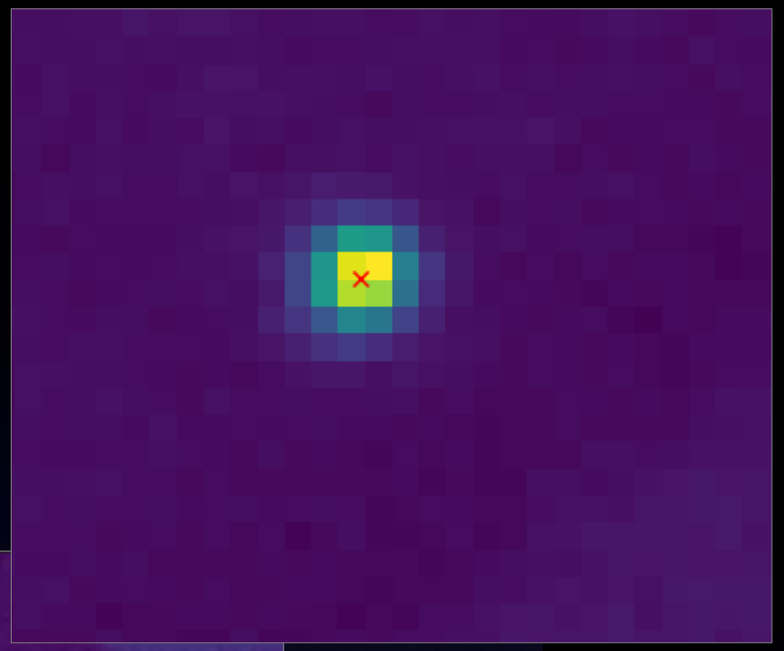
Star152: the first on site artificial star

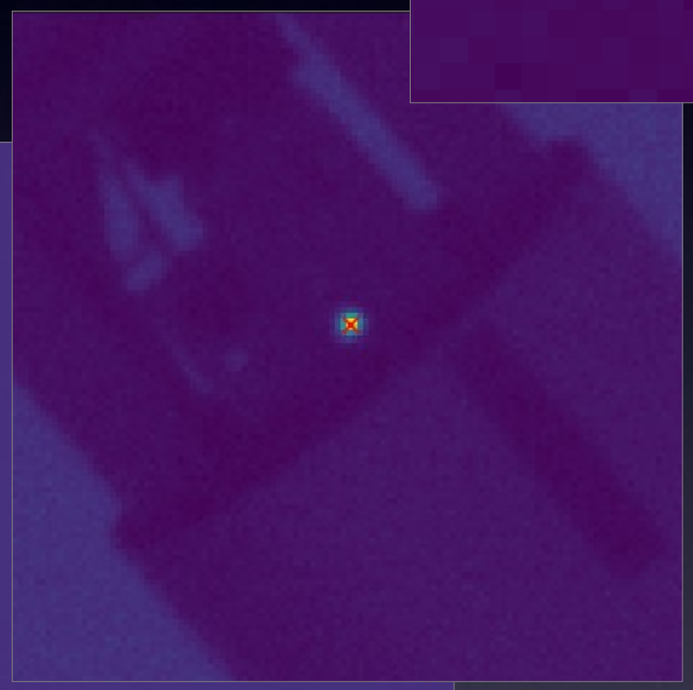
On site installation: July 2024

Star152:

Since July 15 nights of data

Observations EMPTY
u, g, r, i, z, y
slitless spectroscopy





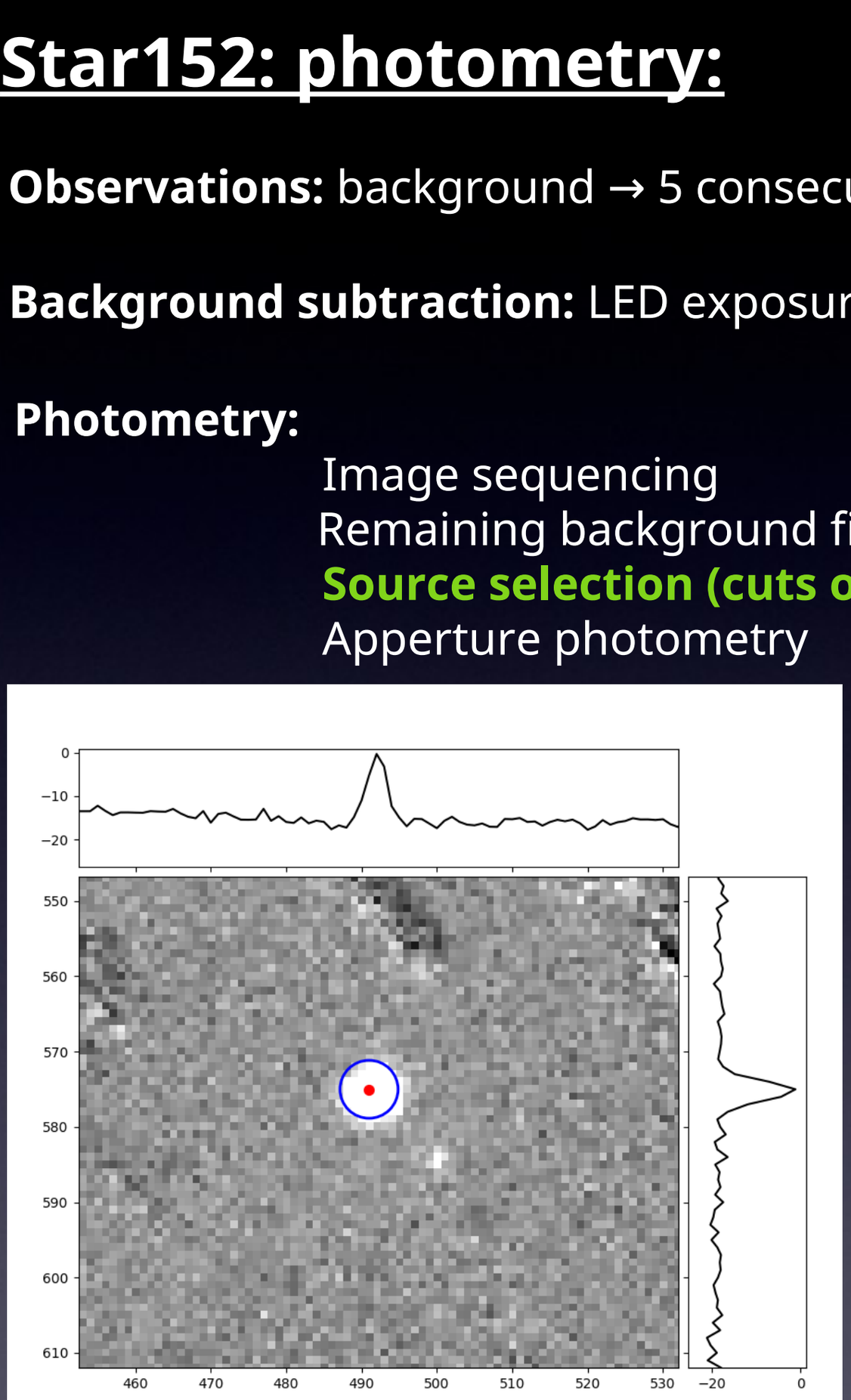
Star152: photometry:

Observations: background → 5 consecutive LED exposures → background

Background subtraction: LED exposure – preceding background

Photometry:

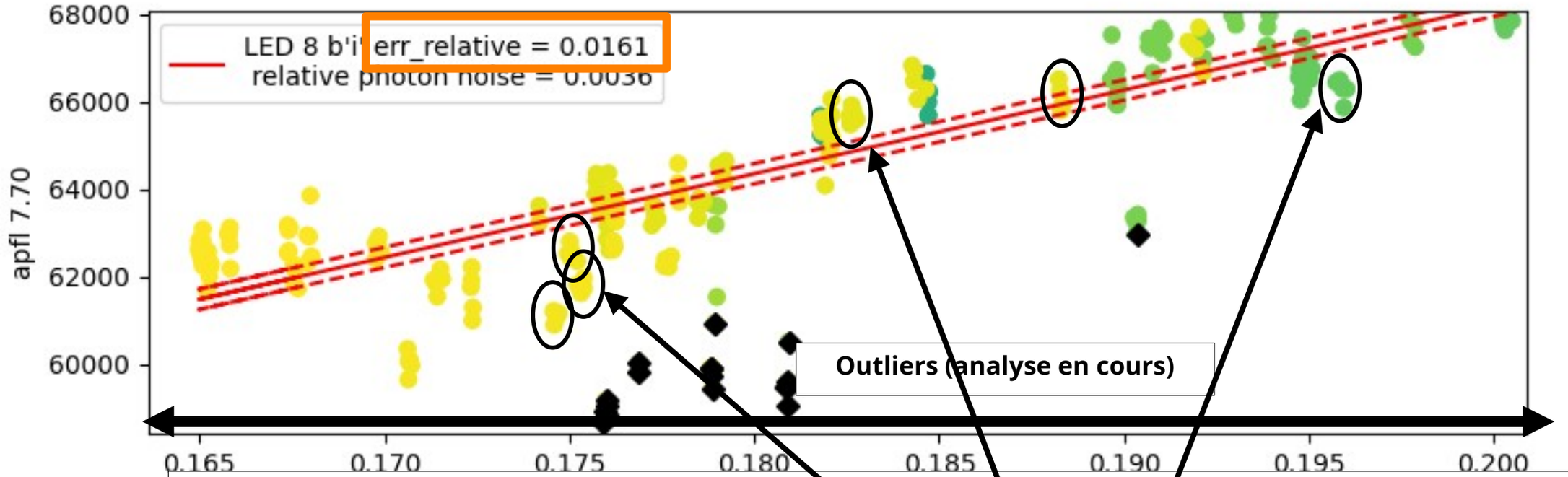
Image sequencing
Remaining background fit
Source selection (cuts on size and position)
Apperture photometry



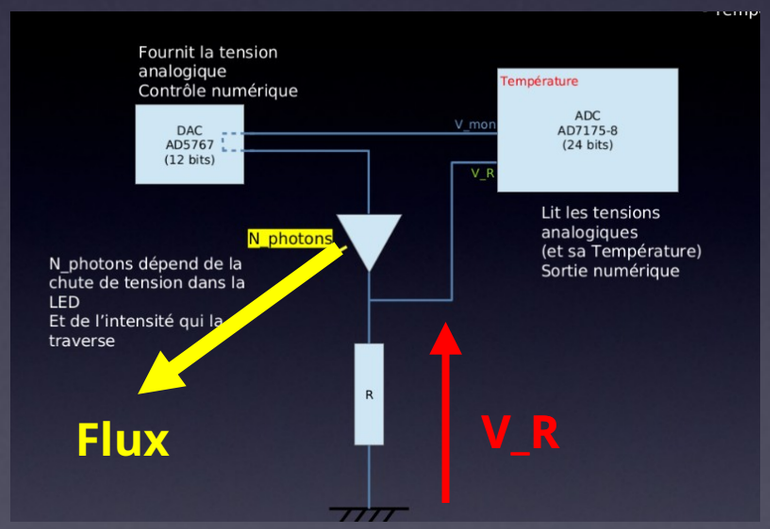
Refinements to come:
- **Study background variability**
- **Aperture corrections**

Star152: standardization

Robust linear fit with 3 sigma outlier rejection

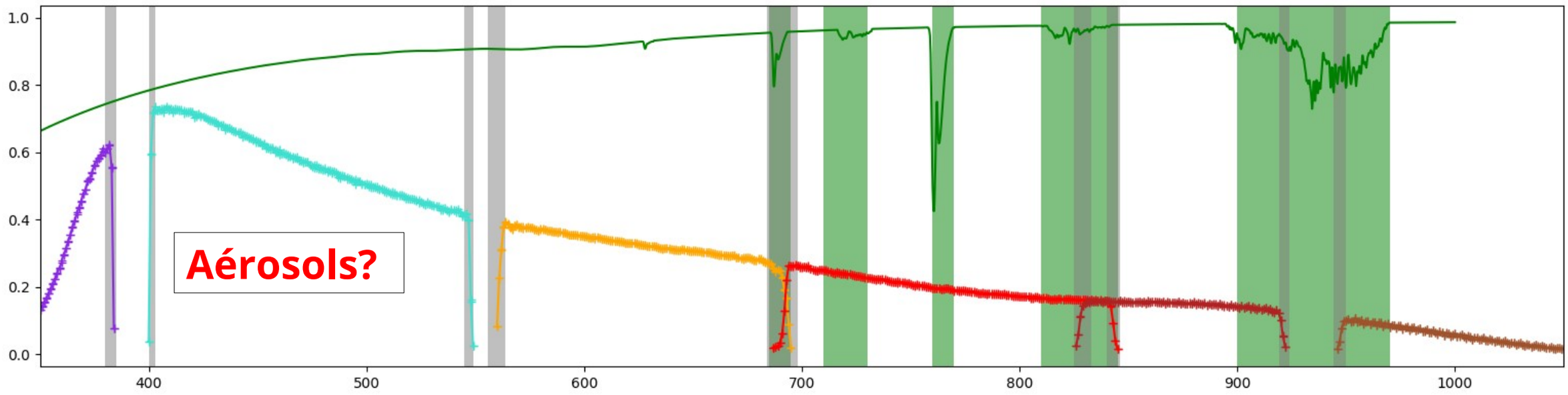


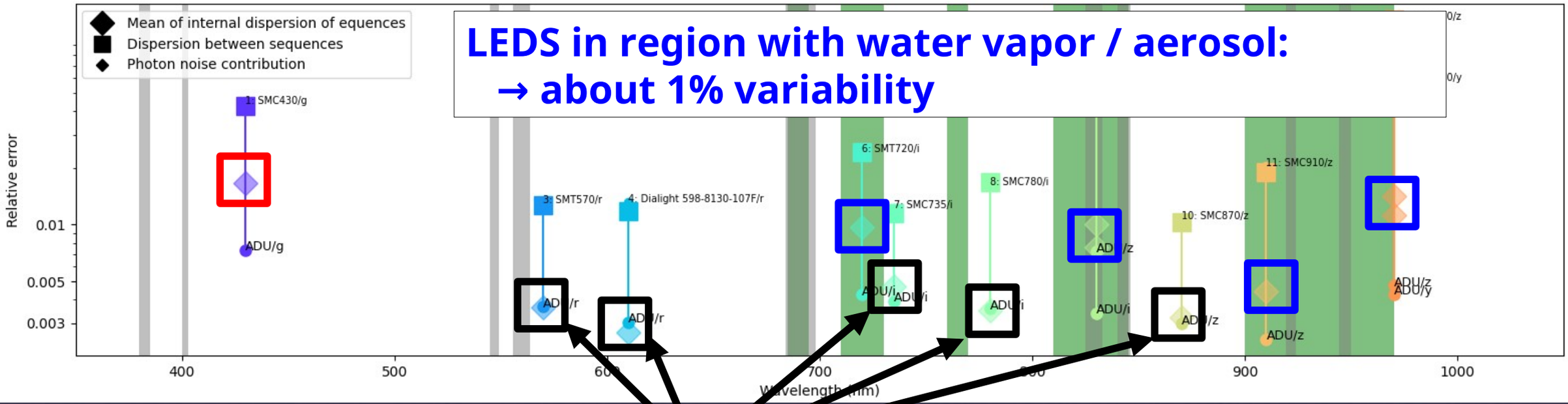
Full inter-night calibration: a few %



Dispersion in a LED sequence: a few per mil

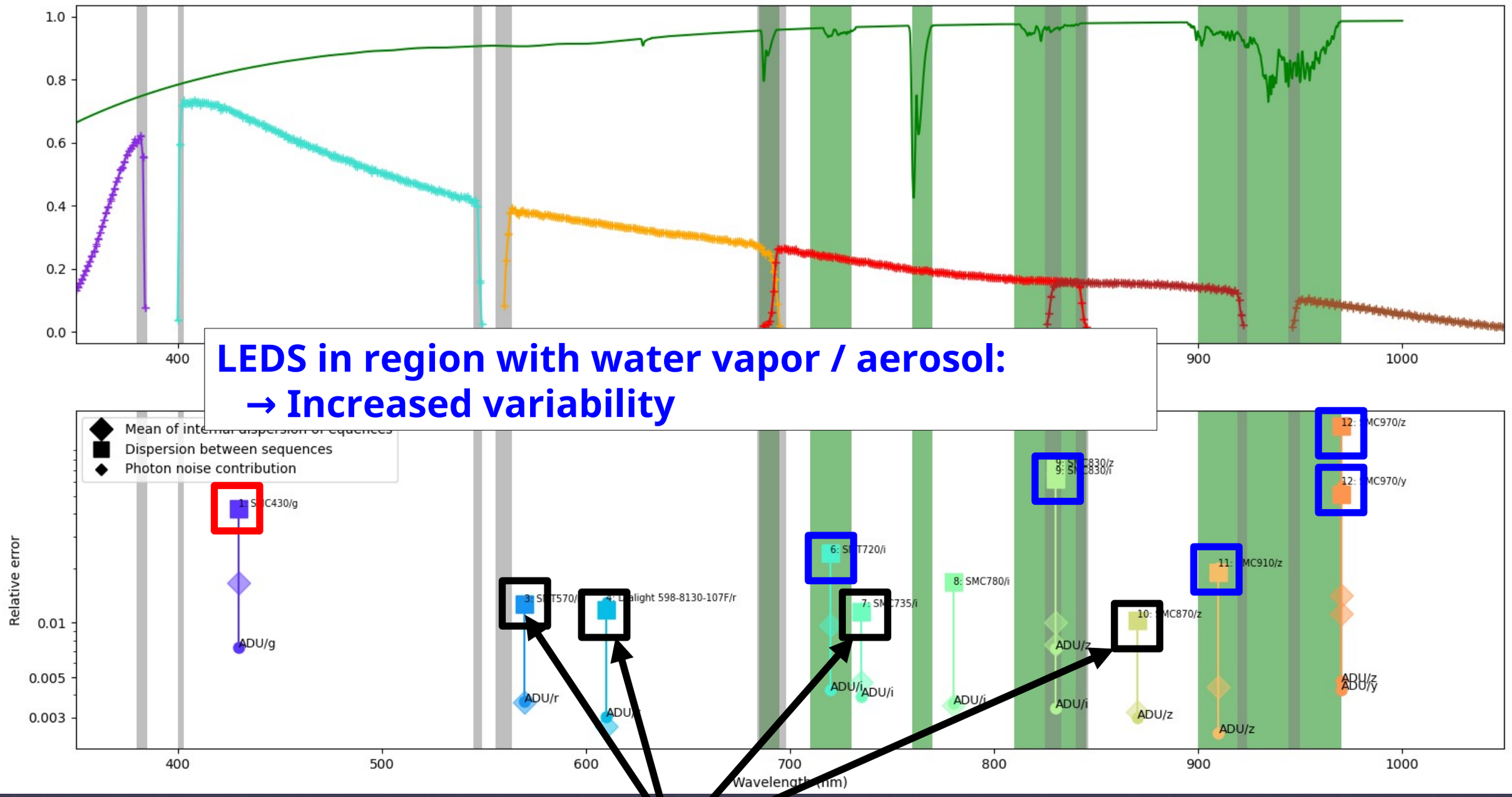
Star152: behavior of LEDs inside of a sequence





LEDs in regions with little atmospheric absorption
→ standardized to a few per mil
→ reach the photon noise limit

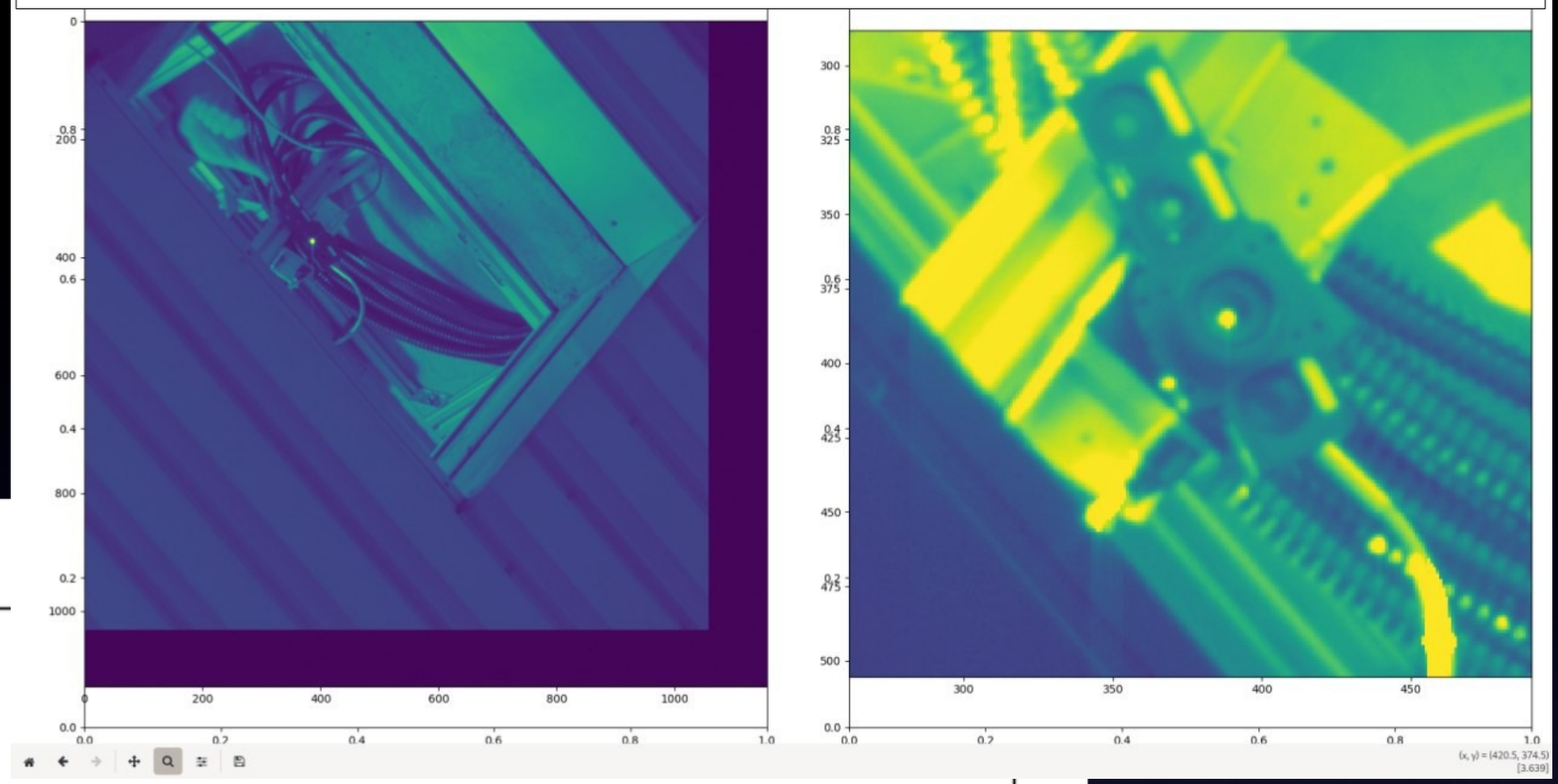
Star152: behavior of LEDs between sequences

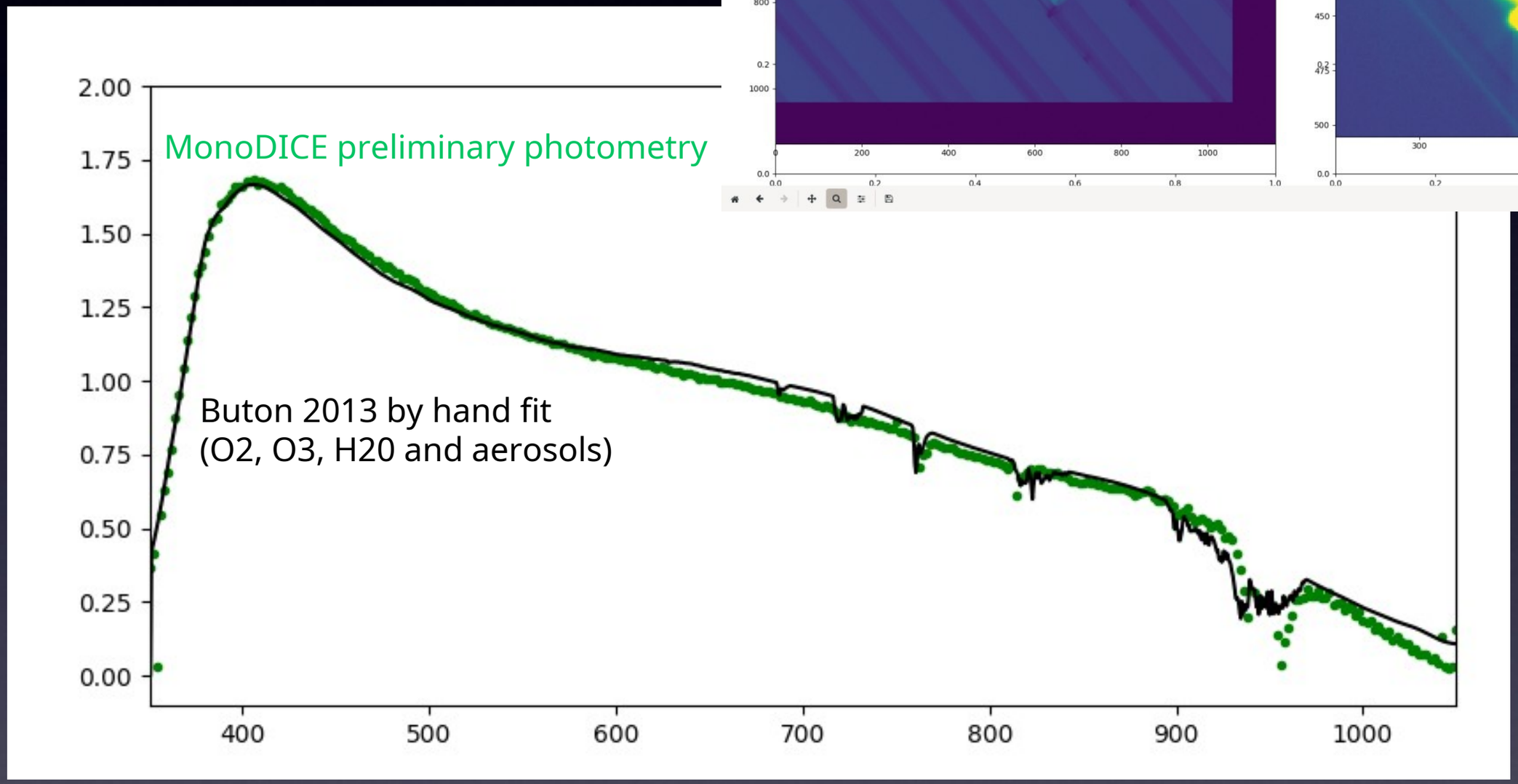


Monodice

An alternative source:
the tCBP monochromatic source
without the telescope

Window of T152 observed with StarDICE pinhole





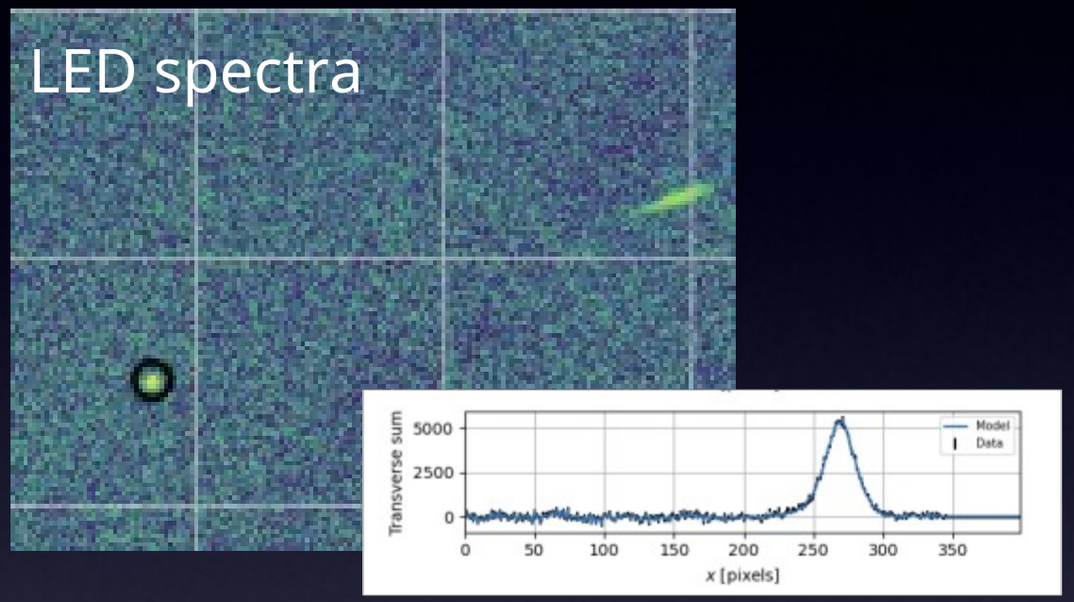
Don’t overinterpret the “fit”…

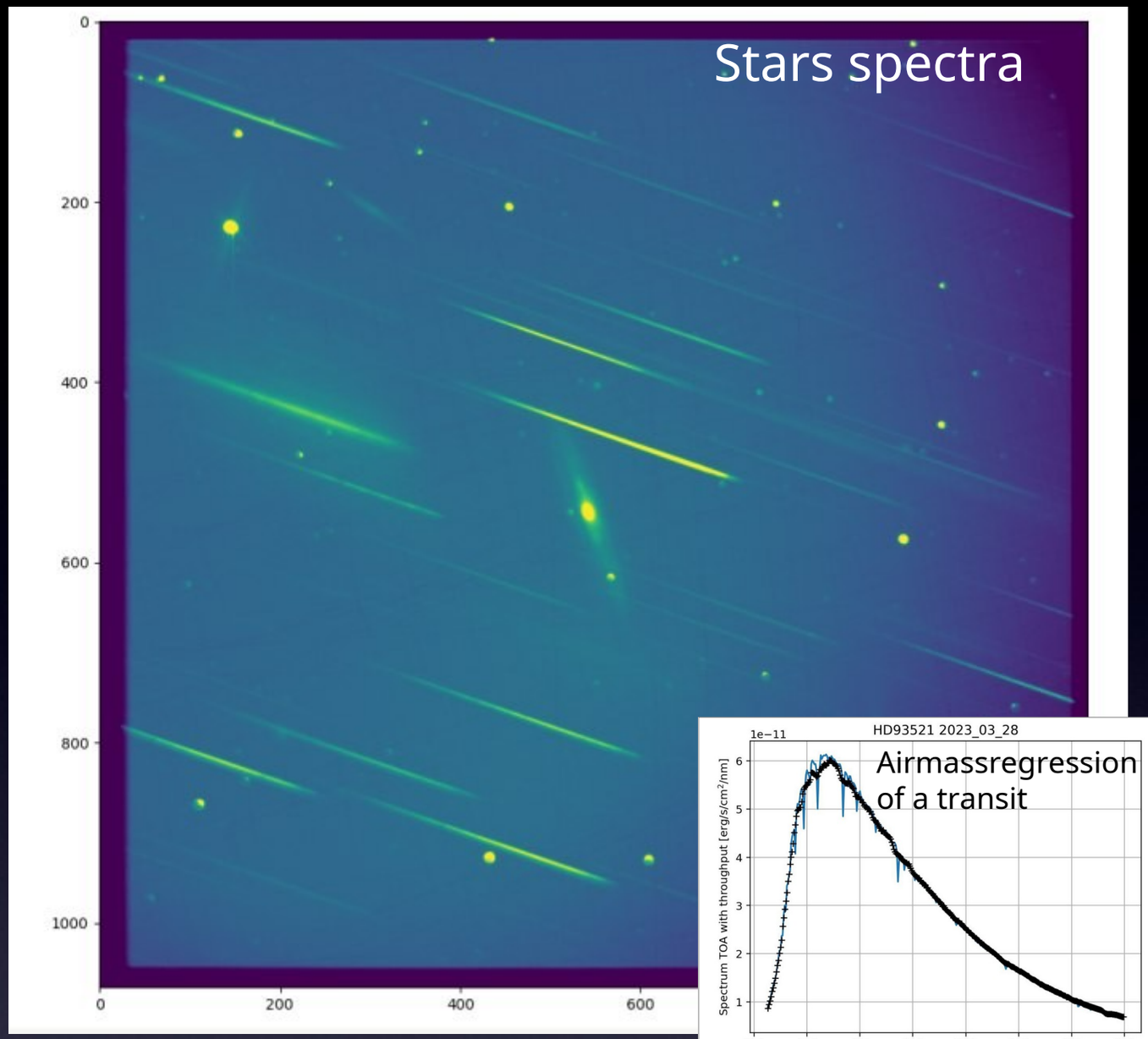
… But we do see atmospheric lines on the ~135 m line of sight

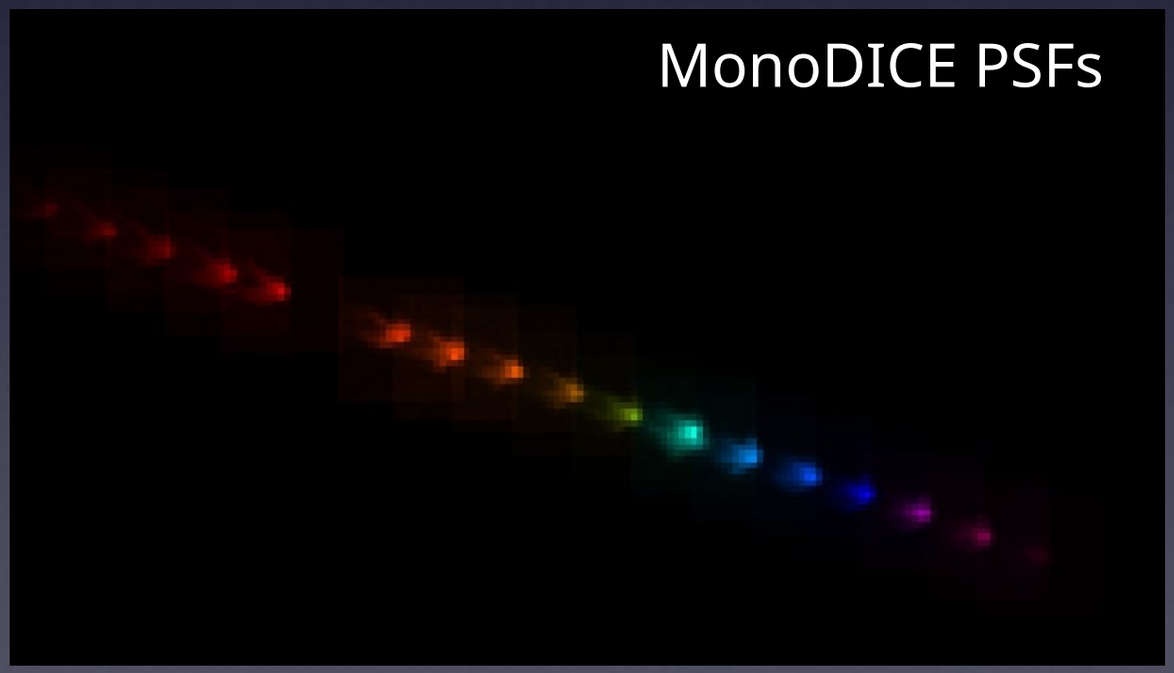
Slitless spectro

StarDICE also has a raunchy grating

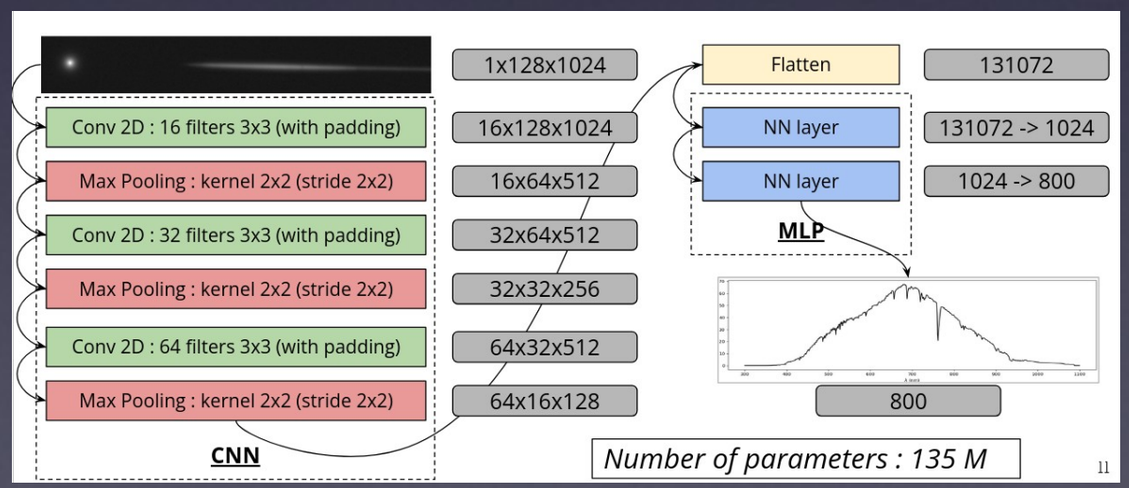
+ spectrograph transmission (CBP)
+ Spectractor







And a PhD



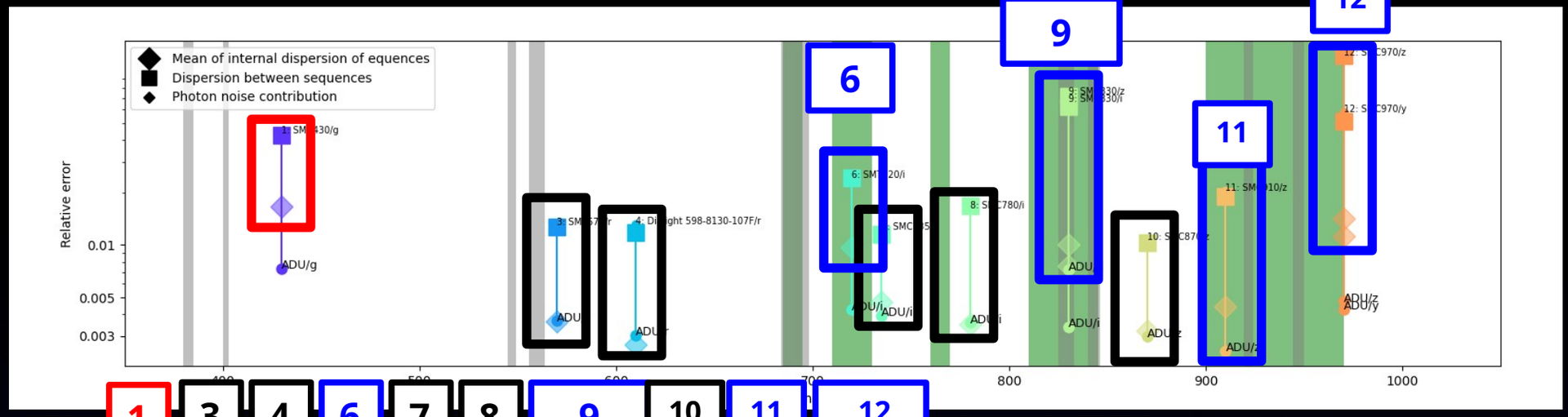
Conclusion:

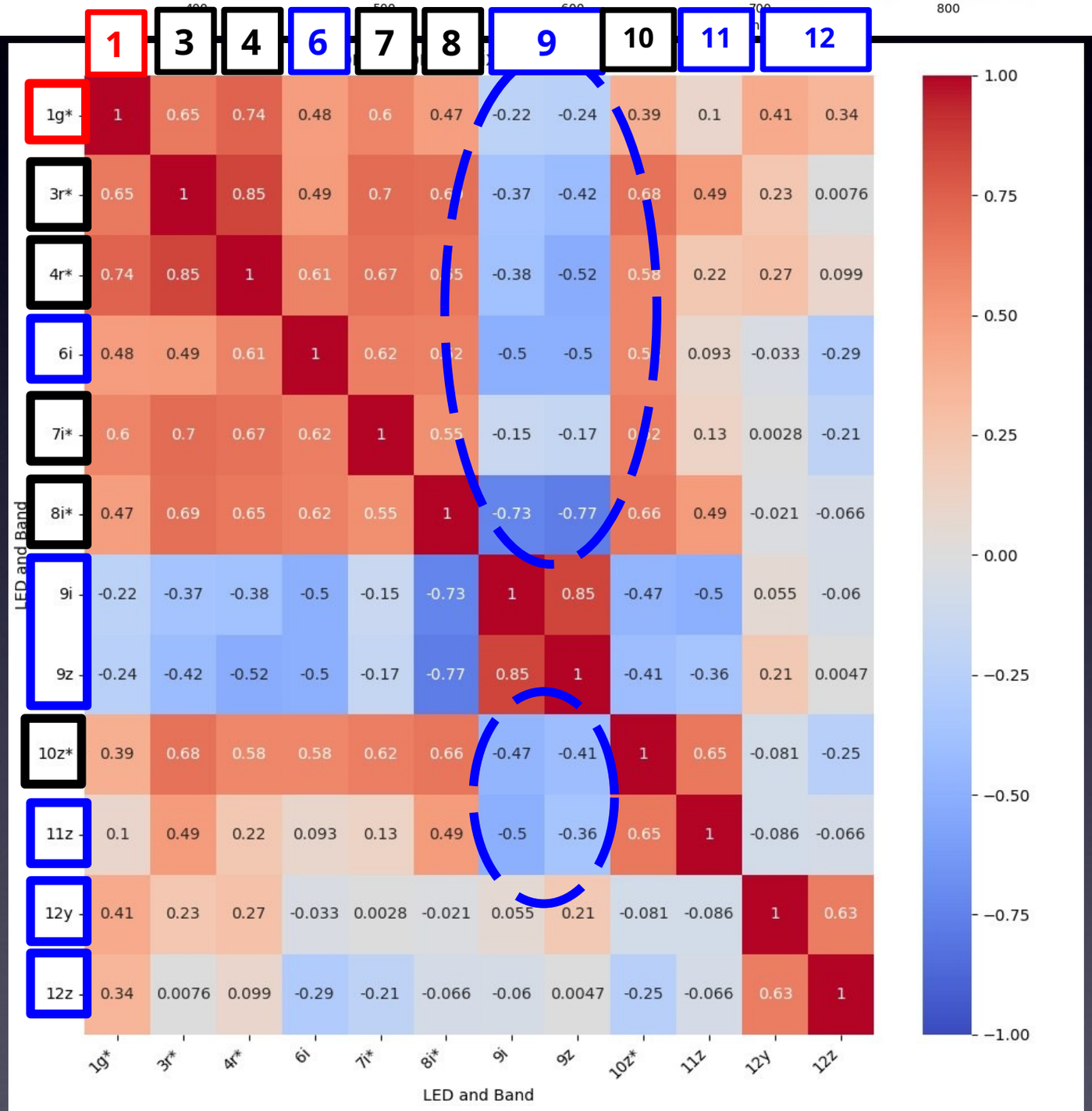
An operational dedicated facility
Presurvey data being analysed

Current status:
- Stars calibration to a few per mil
  → need to account for crowded field
- LEDs stable to a few per mil
  → need to account for atmospheric transmission variations
- Demonstration of cloud vetting/gray extinction mitigation with IR camera

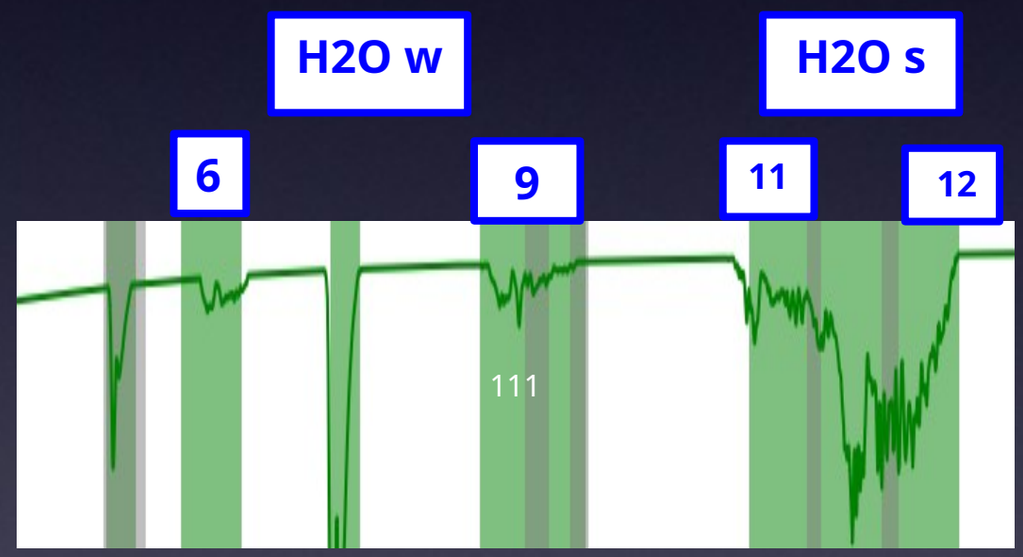
Next steps:
- Lab calibration of Star152 → close the full calibration loop
- Joint operations with IR camera

- Acquire more data: standard star in less crowded field
- Slitless spectroscopy
- Source for a 2nd line of sight





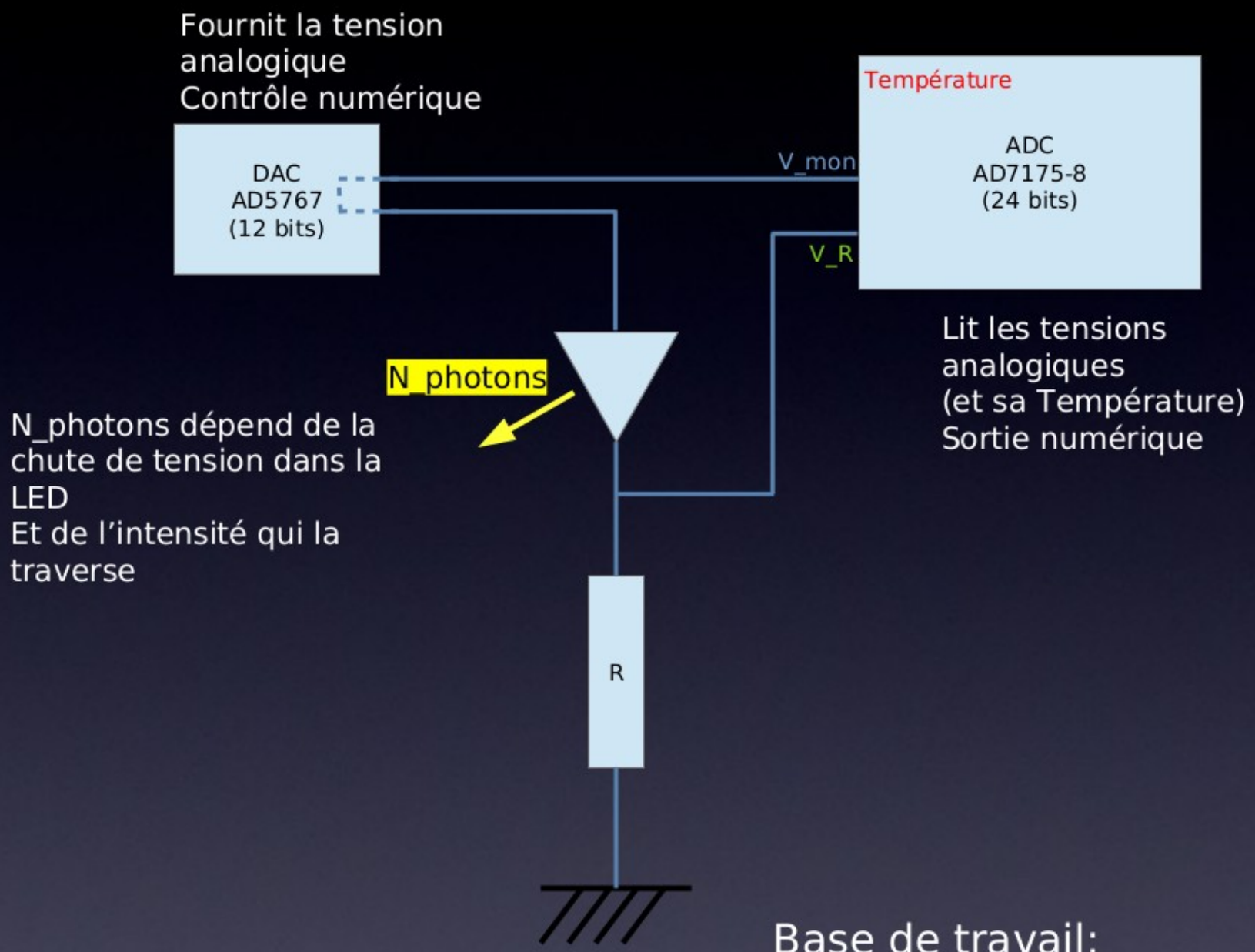
Strong correlation of lines without H20
Stronger in UV
→ Hints at gray / aerosol component



Anti-correlation of 9 due to water ?

Principe de l'Étoile Artificielle

Pilotage par Pi
- Réglage de V_Mon
- Température de l'ADC
- Température des LEDs



Base de travail:
V_mon stable

R stable → **Augmentées ~ 100kOhms**

V_R monitore la variabilité