# Calibrating the LSST Hubble diagram with StarDICE

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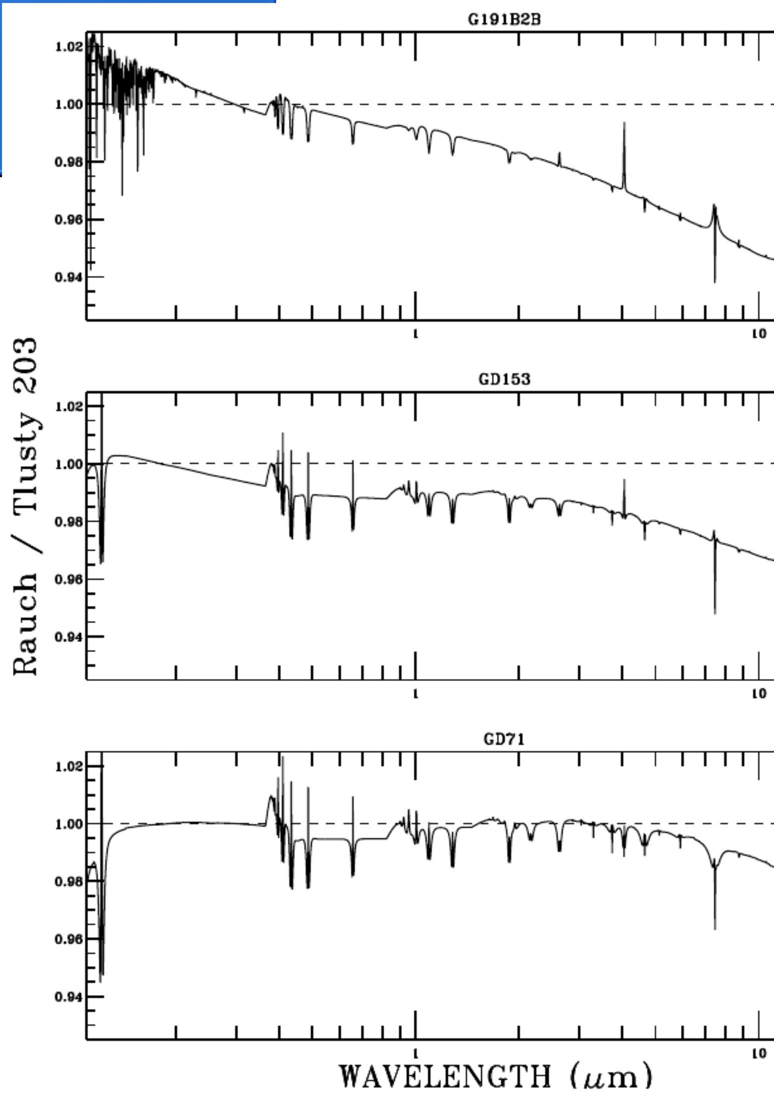
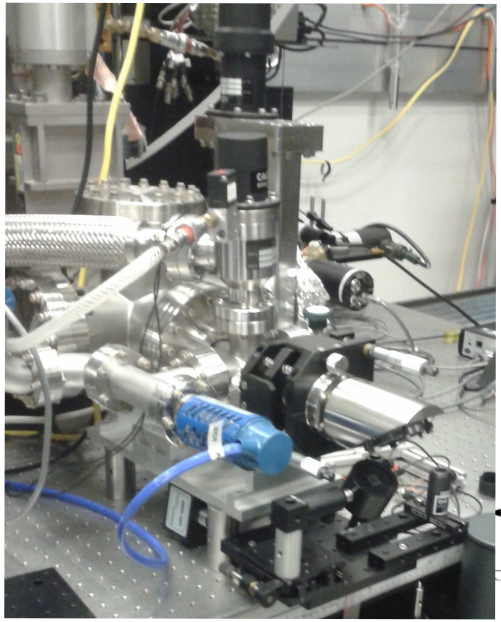
# Current calibration standard
# The CALSPEC system

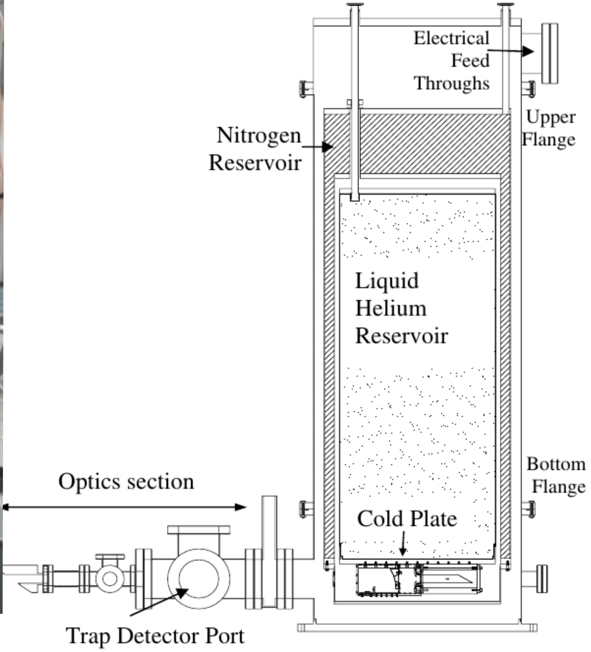
- Numerical model of 3 mag 13 stars
- Solving the radiative transfer equation in the star atmosphere requires:
  - Atmospheric composition (pure Hydrogen, or something more sophisticated)
  - Temperature and density profile
- Advantage: Readily observables
- Drawback: Uncertainties associated to
  - Numerical assumptions (LTE/NLTE…)
  - Physical assumptions (Turbulence …)
  - Measurement uncertainties on the simulation parameters
- Claimed accuracy ~0.5% in the 350-1000nm range

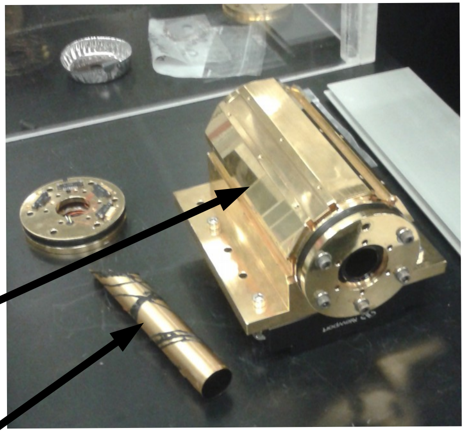


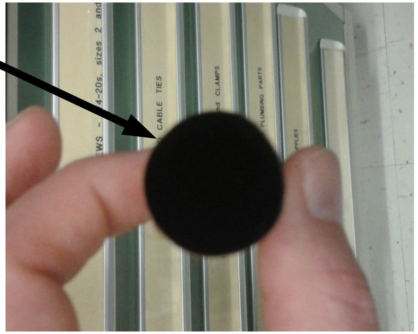
# The alternative standard

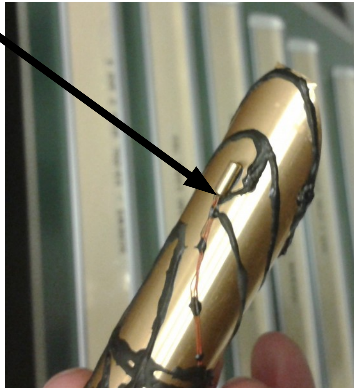
POWR: the Primary Optical Watt Radiometer (Brown et al. 2006, Houston et al. 2006) high-accuracy electrical substitution cryogenic radiometer









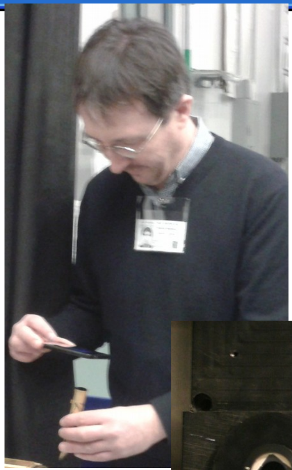
Cryogenic shelter

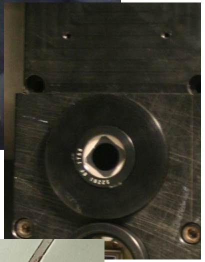
Black absorbing cavity

Germanium resistance thermometer

Claimed accuracy at the $10^{-4}$ level

# The proposed calibration path





NIST POWR

$10^{-3}$W

NIST SCF

$10^{-6}$W

NIST Photodiodes

$10^{-13}$ W/cm²/nm

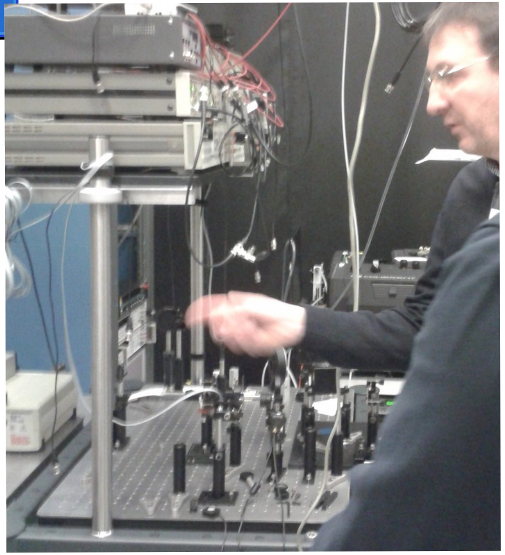
Narrow spectrum LEDs with stable drive elec

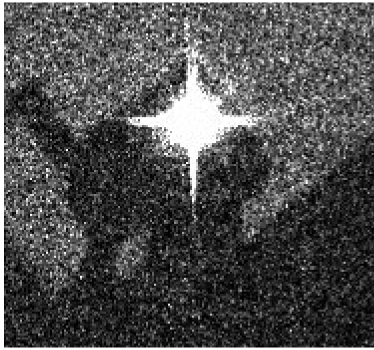
$10^{-17}$ W/cm²/nm

Small aperture telescope

$10^{-19}$W/cm²/nm

Spectrophotometric standard stars

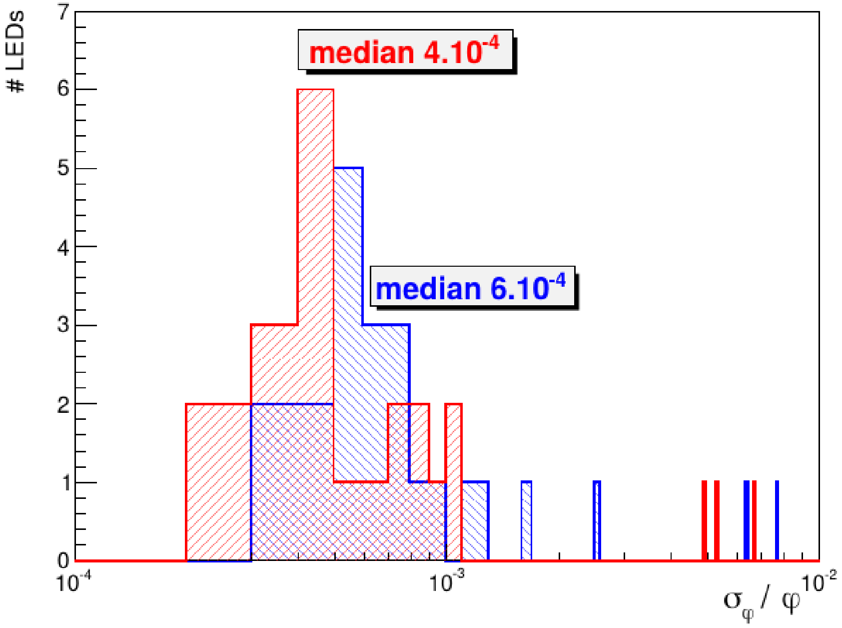




# The idea of using narrow spectrum LEDs: The history of DICE

- Successful demonstration of a calibrated and stable light source in Regnault et al. 2015

Stability of 24 LEDs measured over 30 days




24 narrow spectrum LEDs to cover 300-1000nm

LEDs require a «standardisation»
- Flux (and spectrum) at a given intensity depends on junction temperature
- Measuring the junction temperature is required to predict the emitted flux

After standardization, most LEDs below 1mmag over 3 weeks

# Making the star and calibration beams similar

DICE@CFHT

Calibration and star beams differs

Results are dependent on a good model of the optics including:

- Reflections
- Diffraction/diffusion on optics defects
- Mirrors reflectivity variations...

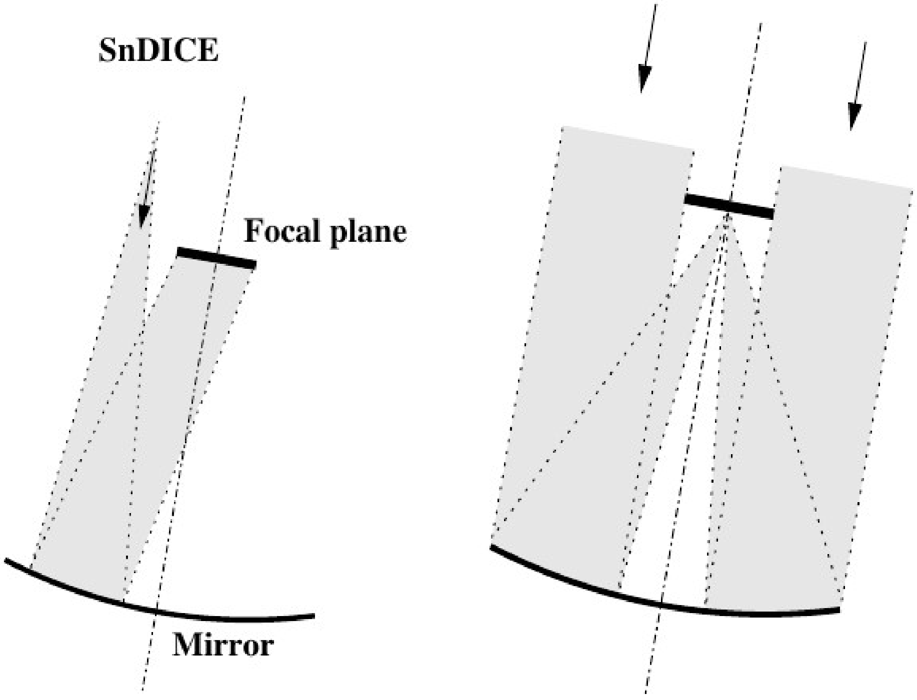
StarDICE@OHP

It is easy to make a good point-like source for an instrument with

- small aperture ~ 10''
- short focal lens ~ 1 m

For such an instrument a 250µm LED junction at 100m appears:

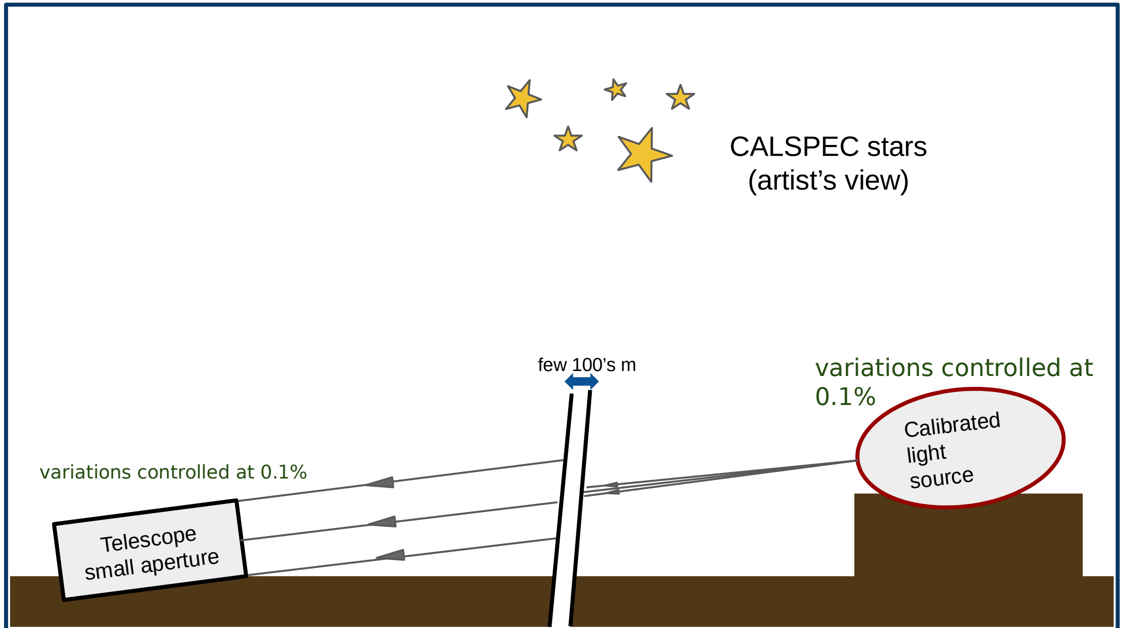
- Unresolved
- in Focus 1cm away from infinity




(a) DICE beam (b) Science beam

# Goal in short : mmag instrumental calibration of broadband colors

- **1 mmag** accuracy on **broadband colors (50x better than state of the art)**
- Proof of concept: Quick test of all steps at lower accuracy




Steps:

- Build a **stable light source** calibrated on **NIST** photo-diodes
- Use it as an artificial star to calibrate a **small aperture** telescope
- Follow spectrophotometric standards with the calibrated telescope for a sufficiently **long duration** to average out errors in the atmospheric regression

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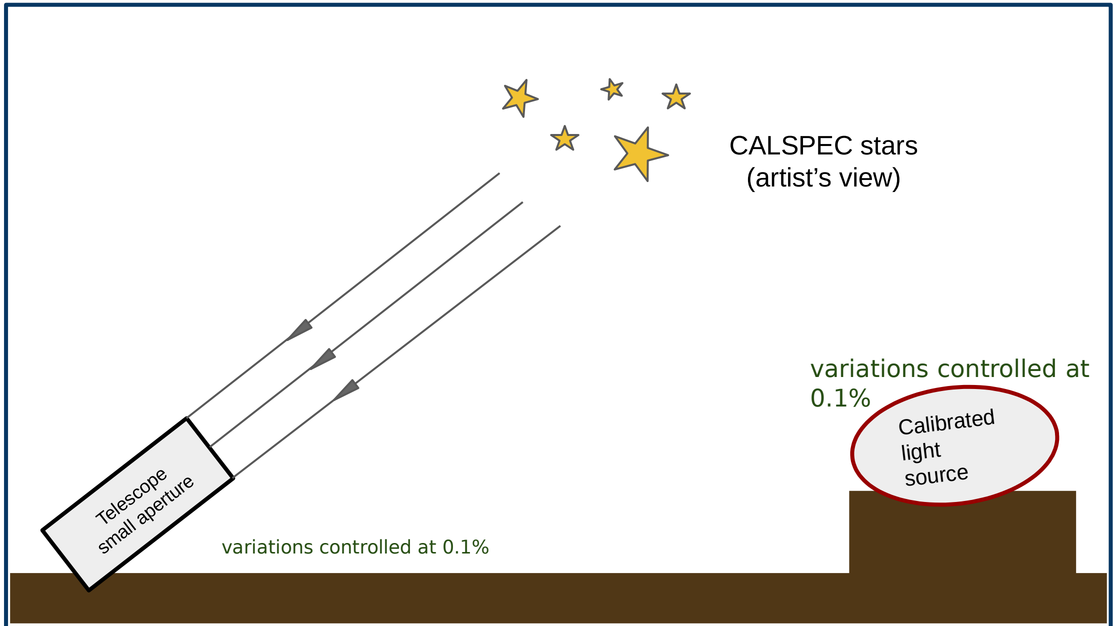


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# Proof of concept:Testing the design ideas with existing hardware

- Testing all steps:
  - Find a couple of sites which can host the source and the telescope in sight of each other
  - Decrease the luminosity of the existing LED source by x10000
  - Calibrate the low luminosity light source to NIST
  - Assemble a small aperture telescope setup
  - Conduct calibration observations
  - Follow CALSPEC stars

# Proof of concept milestones

- 7 Déc 2015: Concept proposed to LSST France, interest from LPNHE, LUPM, CPPM, OHP
- Mai-June 2016: First tests on site
- March 2017: Final site chosen
- June 2017: Low flux version of the DICE electronic finished
- July 2017: Installation starts OHP
- December 2017: First light
- January 2018: First usable night
- January 2018-July 2018 : Working on setup automation, data taking for a week every 2 new moon (weather permitting)
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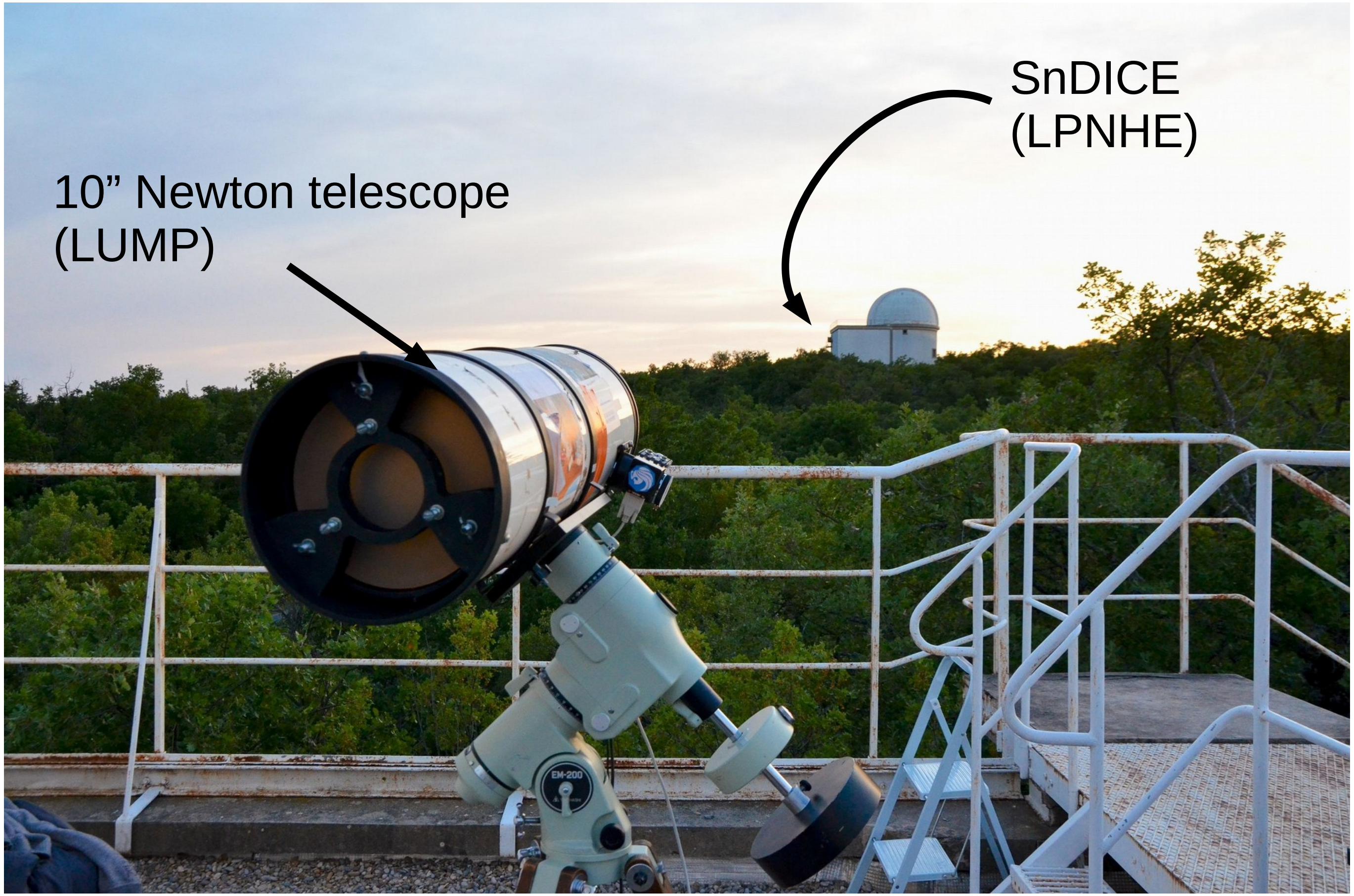
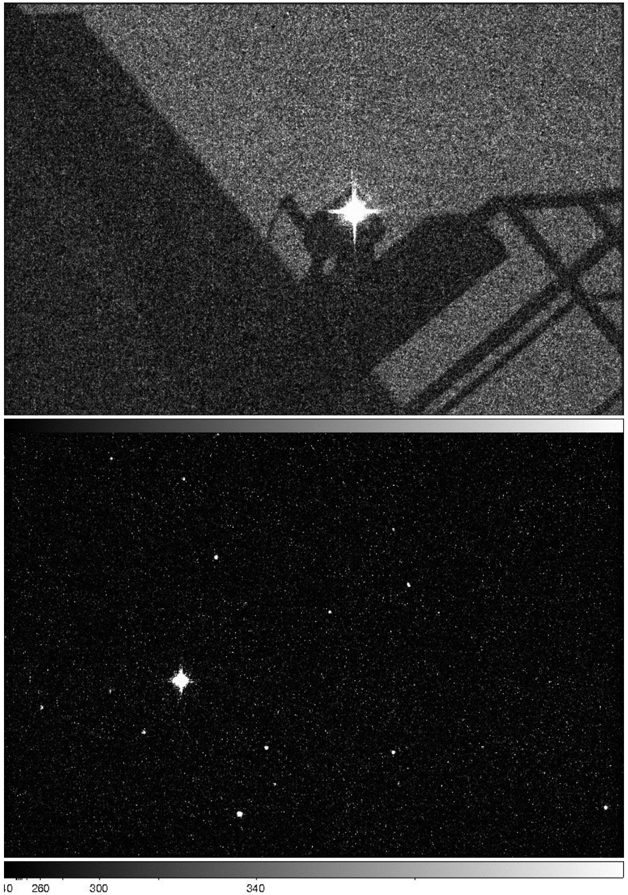
- January 2019: Final takedown

# Very first test @OHP

- Telescope on the roof of a building
- Source in the window of another building
- Check optical formula, flux level, noises



# First pictures of the artificial star

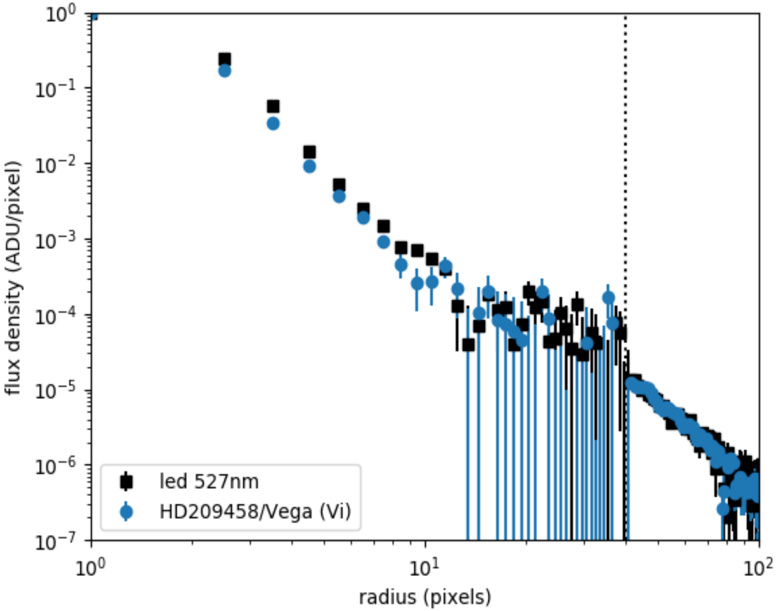



The artificial light source and a real bright stars seen by the same instrument on Top and bottom pictures

A comparatively easy way to build a point-source

The only visible difference is an easy-to-subtract structured background

PSF of artificial and real stars similar over 7 orders of magnitude in flux




Need for a stable semi-permanent installation to go further and test stability and transfert to stars

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# Choosing a couple of sites at OHP


>250 photometric nights per year
Many combination possible
On site monitoring of atmospheric transmission

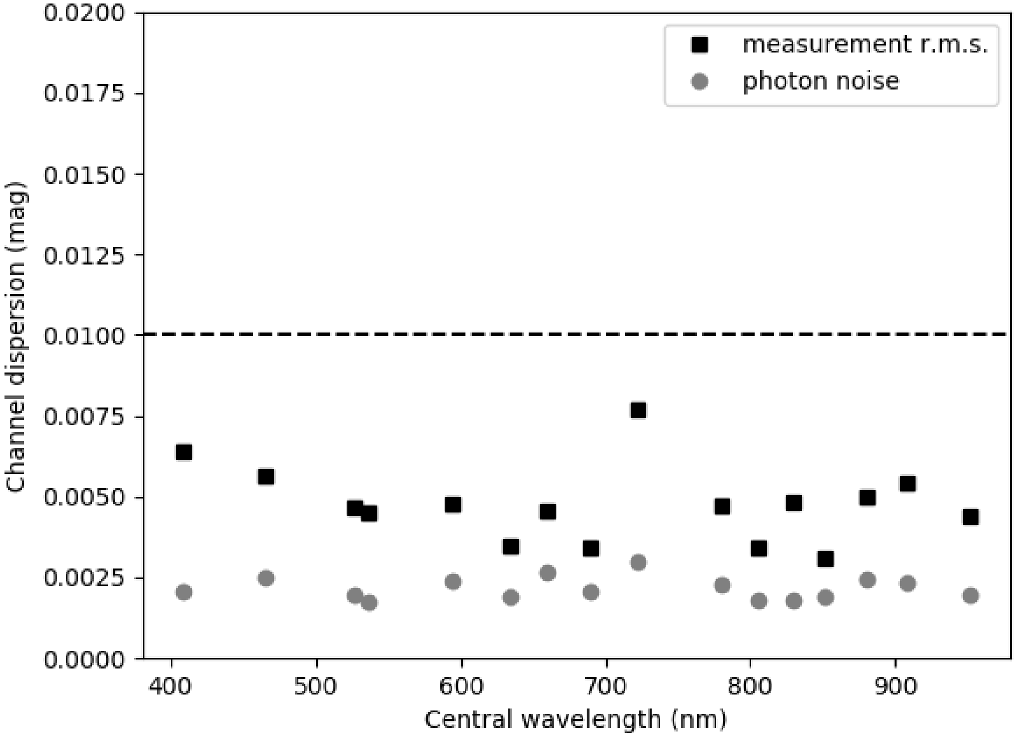
NOTE: Relatively easy to get 4 significative digits on the source/telescope distance with commodity hardware

# One seen by the other

Source seen by the telescope

Telescope seen by the source

# Relative stability over 3 monthes



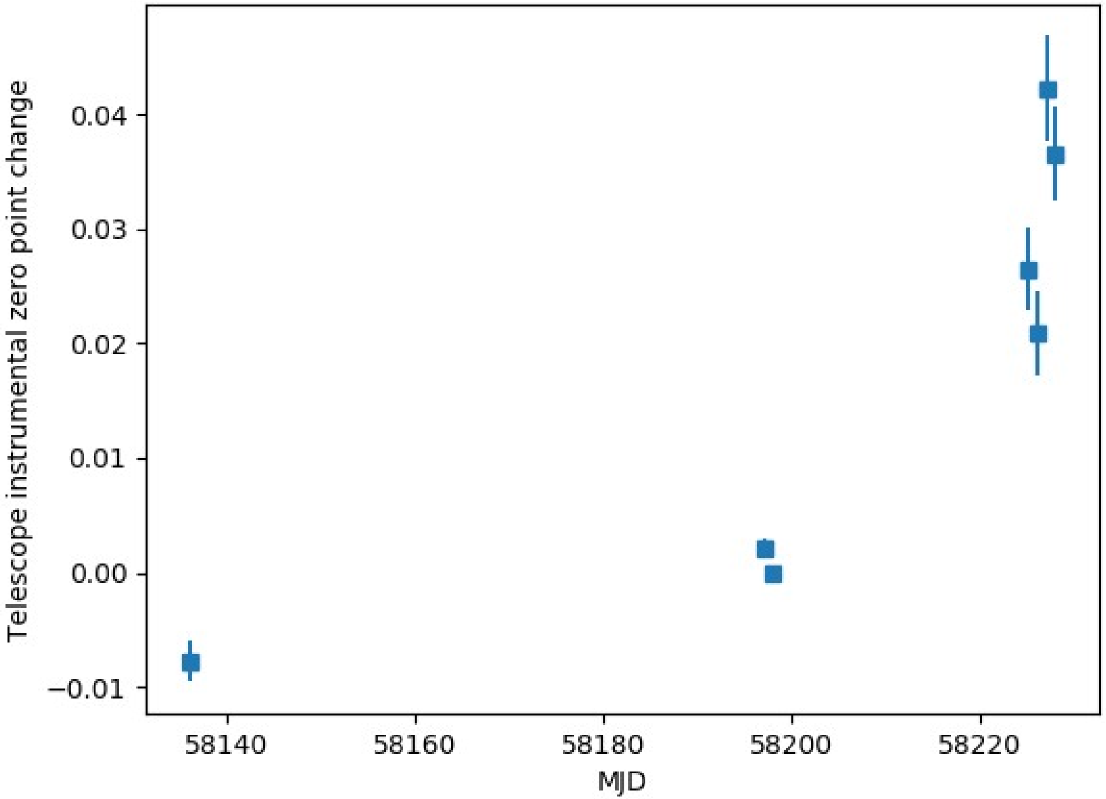

Measured flux / predicted LED flux gives an absolute zero point per channel

RMS of zero point measurement by LED channel after:
- standardization by temperature
- fit of a global instrument zero point per night

Mean dispersion is 4.8 mmag
Best channel ~ 2.8mmag

This encompass everything:
- Measurement noise
- Potential variations of the instrument
- Line of sight transparency variations
- relative led variations

# Instrumental determination of the ‘gray’ zero point of the instrument




1-4mmag uncertainty on nightly zero point determination

Uncertainty dominated by uncertainties in the temperature standardization

Zero point change compatible with expected contamination by dust

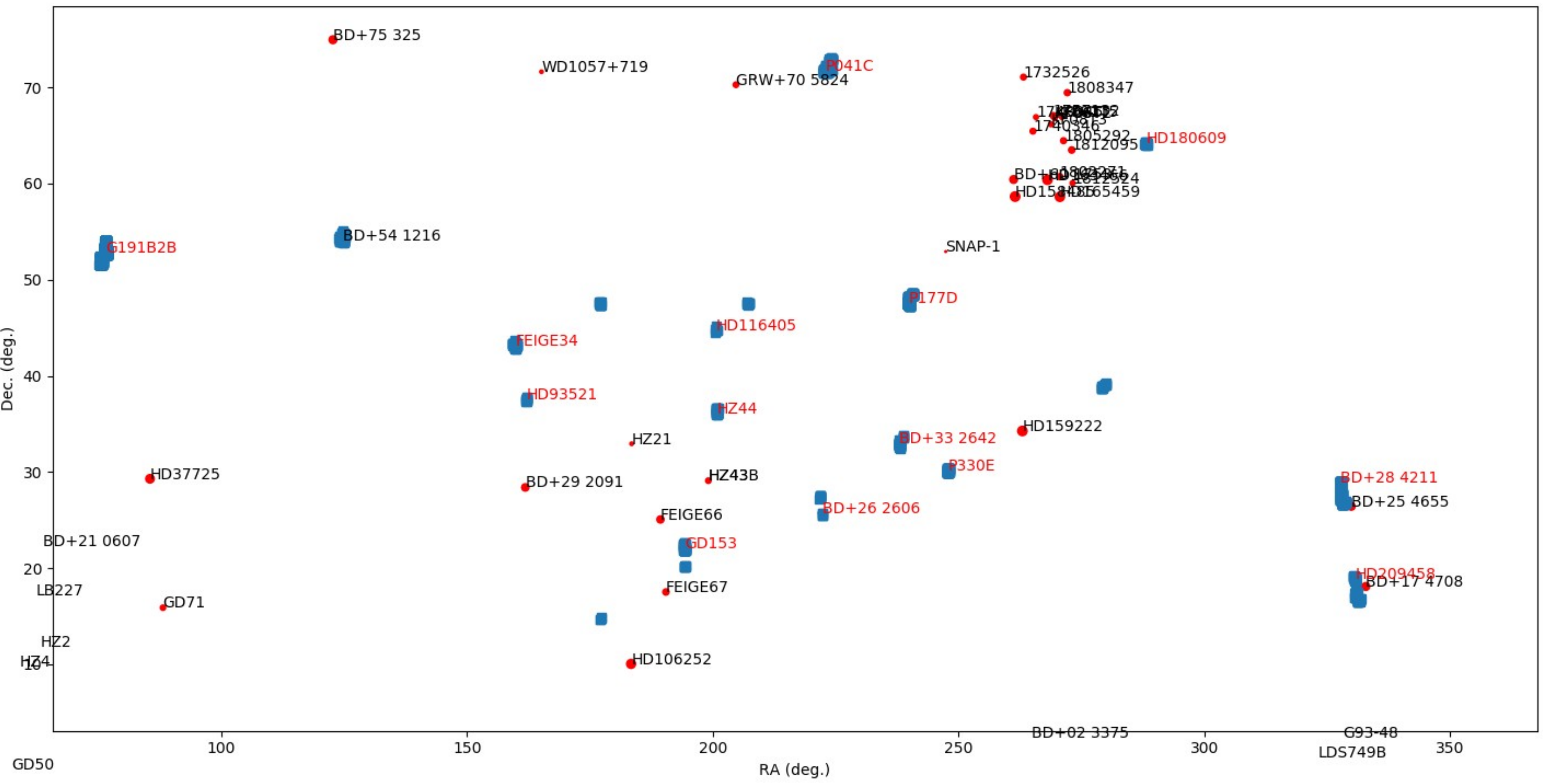
# What about July ?

The protection cover of the LED Head fell at some point during the May-June break of the observations

Biological contamination of the LED head (Hornets)
- A few channels obstructed
- Erratic behavior
- Temperature monitoring lost

We completed the observation week and bring back the source for cleaning, examination and calibration

# Stellar observations




- A subsample of 14 spectrophotometric standards from the CALSPEC database observed
- 2/3 primary standards
- Nightly determination of the atmospheric transmission with an uncertainty of 2-3%
- A monitoring of gray extinction is necessary to decrease this uncertainty.

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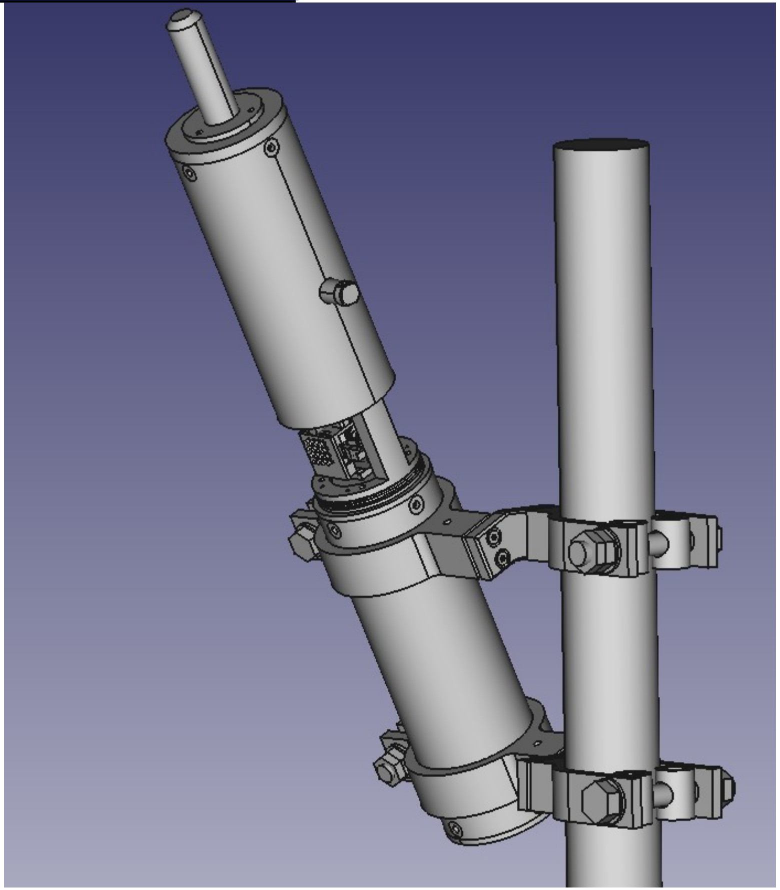
# LESSONS learned

- At first order the basic concept is working fine
  - The source delivers perfect point like illumination
  - Resulting calibration is stable and fast
- At second order a number of improvements are needed
  - A better protection of LEDs against contamination (Done)
  - A slightly larger, much more stable telescope with controlled vignetting (ongoing)
  - A better temperature proxy for LEDs (ongoing)
  - A two step transfer of calibration from NIST to LEDs (ongoing)
  - A monochromatic monitoring of telescope transmission (Collaboration with Harvard)
  - A monitoring of time changes in the atmosphere (still in discussion)

# A better protection of LEDs against contamination

- Hardware designed and build at CPPM
- Currently in test at LPNHE
- Second version with tunable LED orientation in prep.

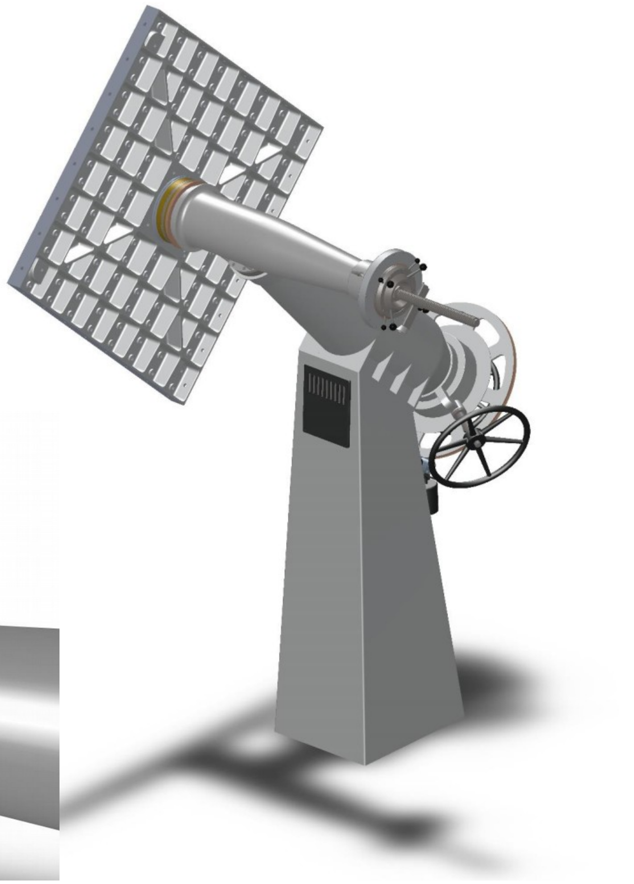


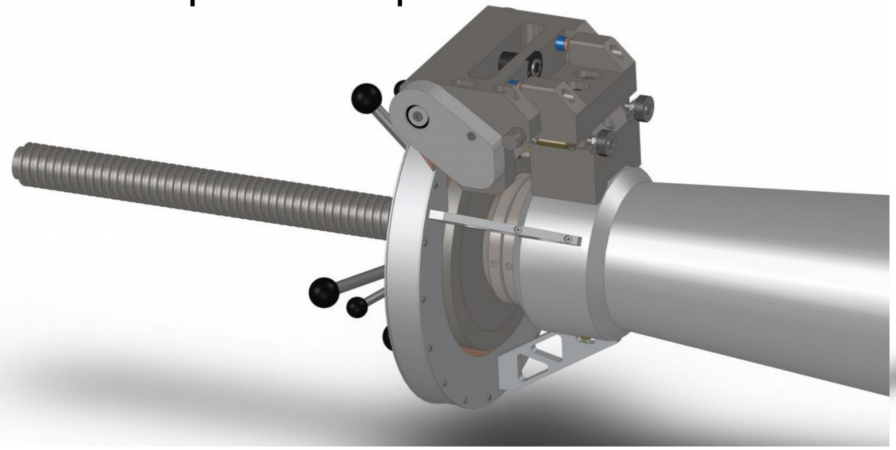
# Telescope/mount upgrade

Equatorial table motorized and automated mid-July
- Highly flexible
- Not as fast as originally required (110x sidereal speed)

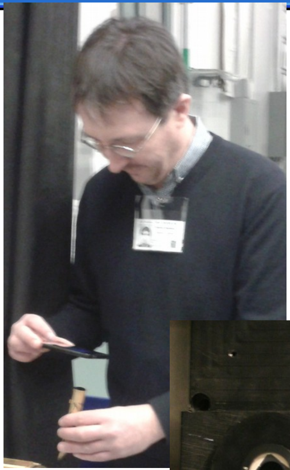
Tube delivered mid-June
- 40cm f/4 carbon tube
- Custom secondary size (11cm)
- Custom dust cover
- Some amount of mechanical adaptation expected

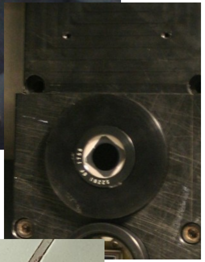
EEV Deep depleted back illuminated CCD
- Already delivered
- To be calibrated on the new transfer bench
- Waiting for filter wheel (mid-June)

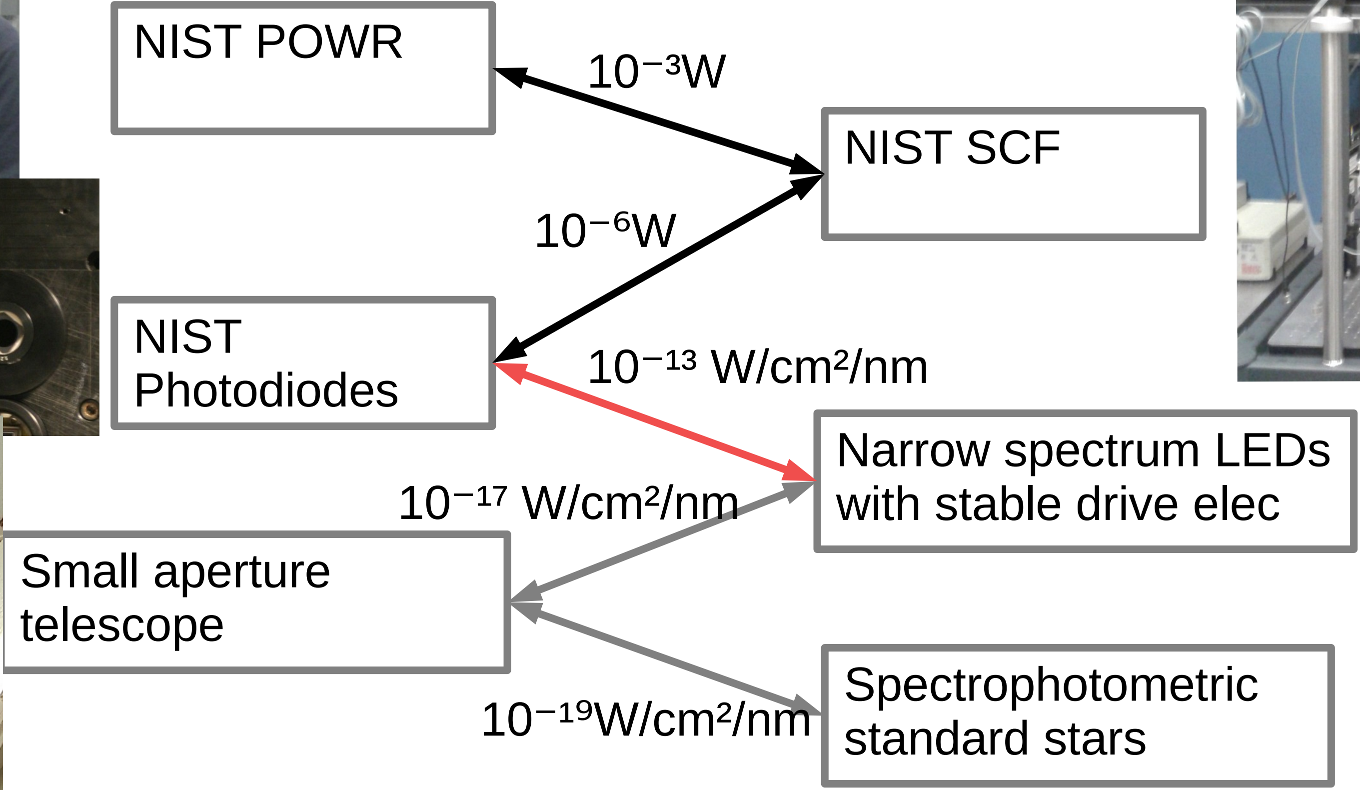


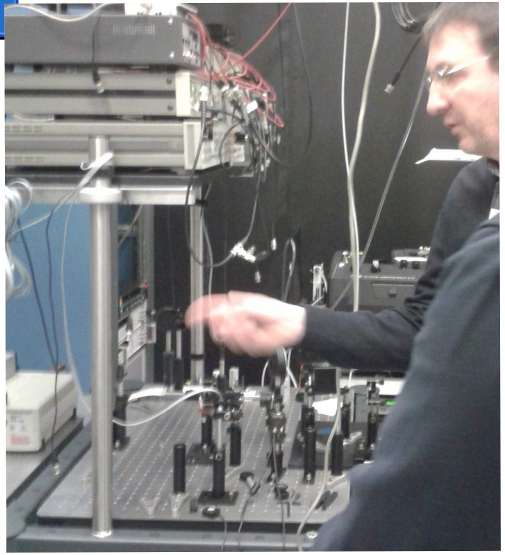


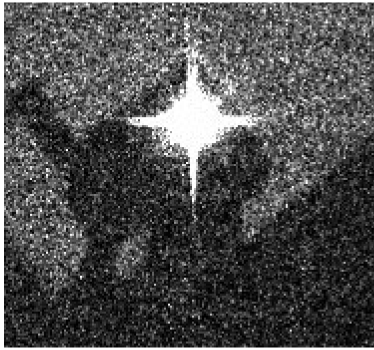
# The proposed calibration path





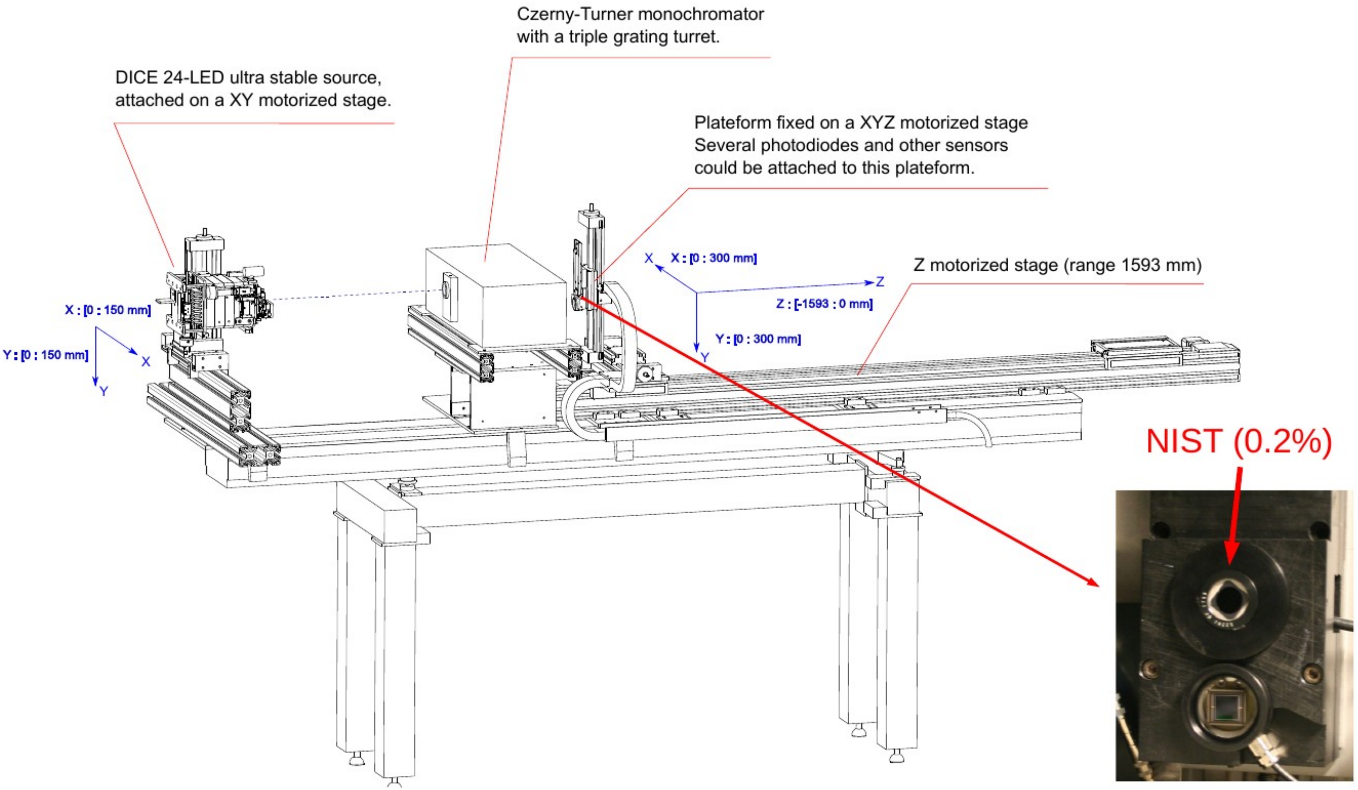


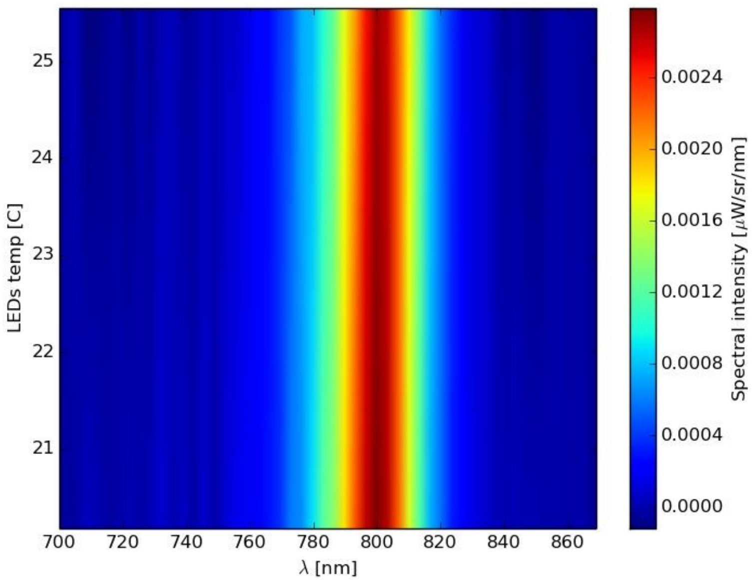





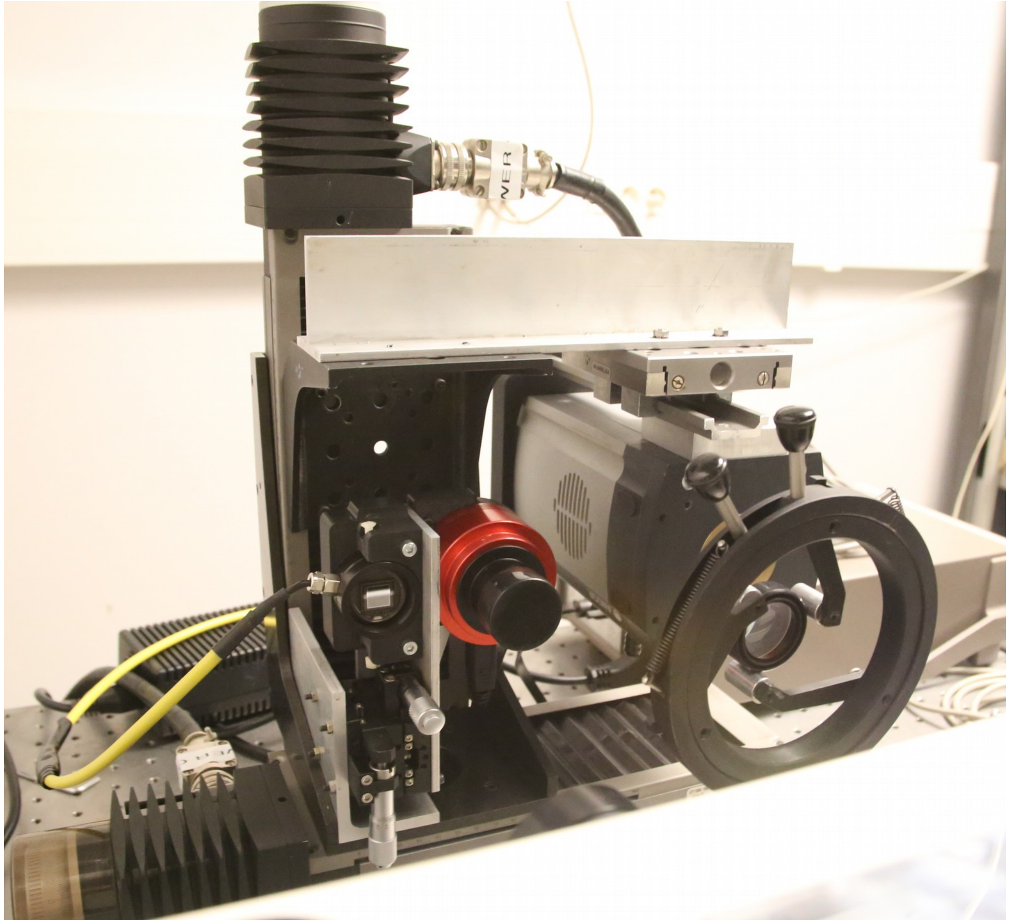
# The upgraded DICE spectrophotometric calibration bench

- Mesure the absolute LED flux as a function of wavelength and temperature
- Mmag accuracy on integrated flux temperature law reached in January
- SNR still insufficient to get spectra for the 10000x smaller fluxes



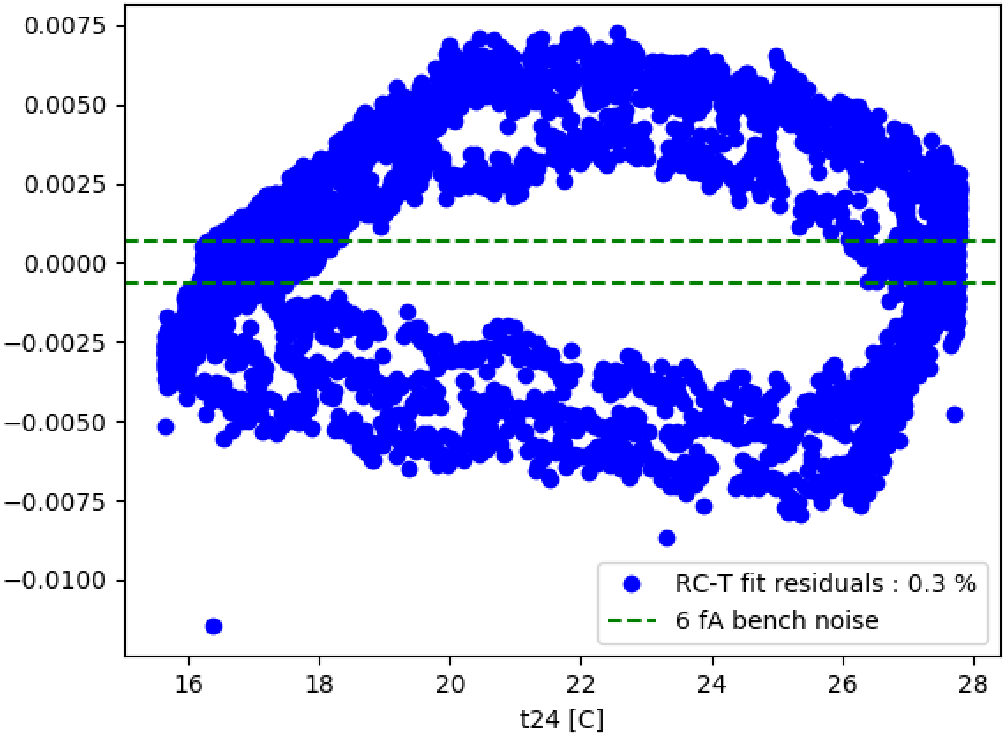



# New spectrophotometric calibration transfer bench at LPNHE



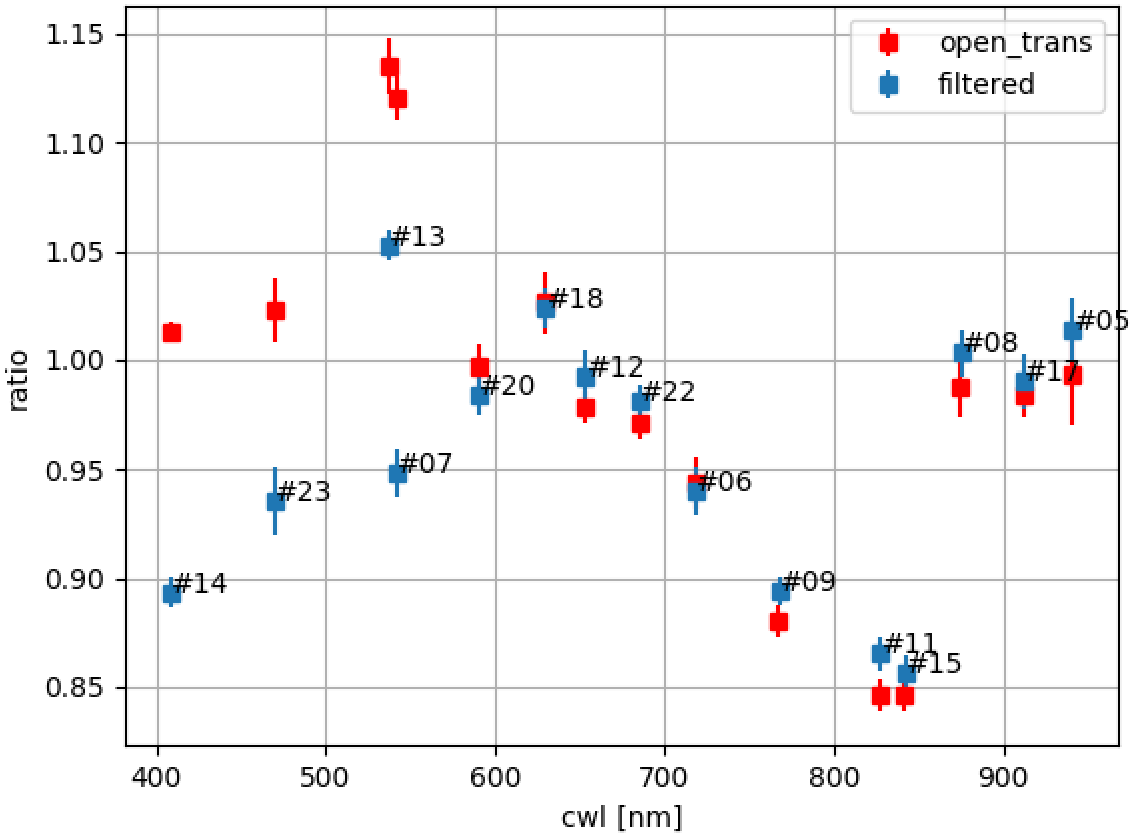
- Transfer NIST photodiode calibration to cooled charge collection detector (CCD or CMOS)
- Exact reproduction of NIST photodiodes calibration beam

# Improving the temperature proxy



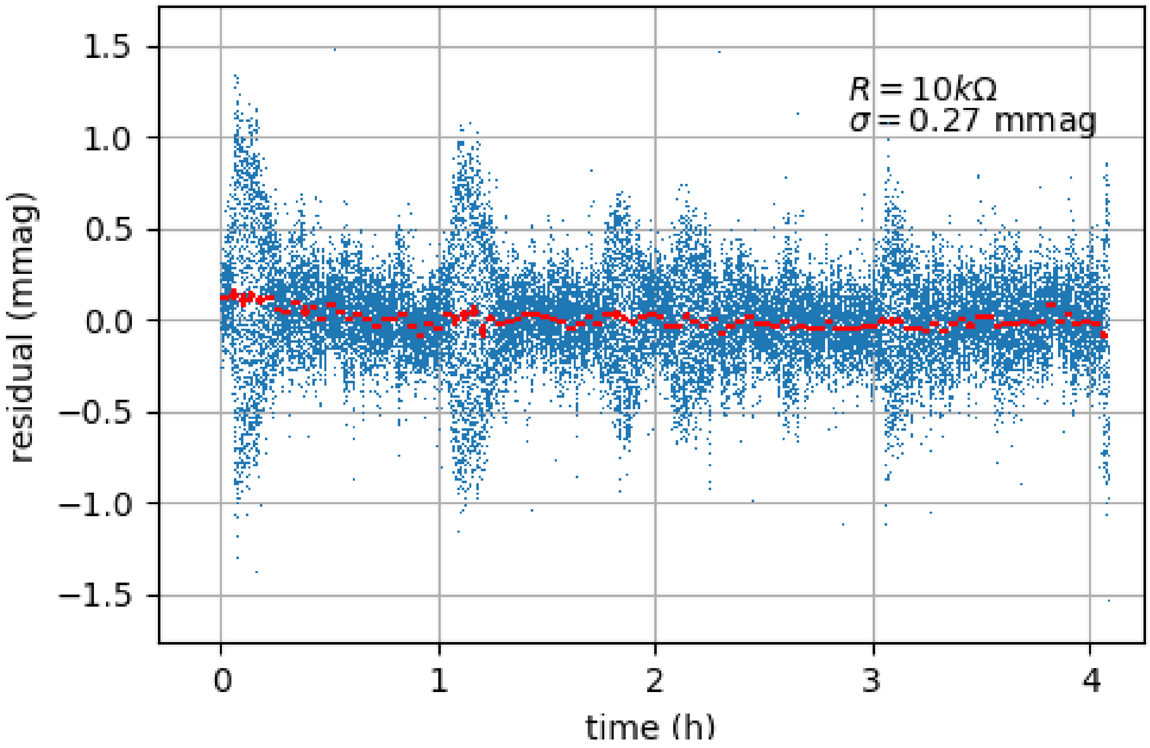

- The hysteresis of the current temperature proxy can exceed 0.1% if the temperature is changing fast

# Improved measurement of monochromatic transmission




- The monochromatic transmission curves is needed to interpolate between led points
- Comparing the monochromatic model we had so far with LED measurement showed discrepencies too large to use the model (even for interpolation)
- This triggered collaboration with Harvard CBP

# Major upgrade of the LED drive




Prototype of drive electronique to monitor LED junction temperature directly through its forward voltage.

Development led by Eduardo

Demonstrate stability at $10^{-4}$ over 4 hours and 12 cycles between 5 and 20°C

# Conclusion

- Proof of concept has completed
- Proof of concept analysis ongoing with two hard points:
  - Low flux LED spectroscopy
  - Monochromatic instrument transmission
- Upgrade has started
- International context is changing (collaboration au sein de LSST → consortium France-Berkeley-Harvard-Berlin)
- An attractive experiment for student:
  - 1 thèse et 7 stages