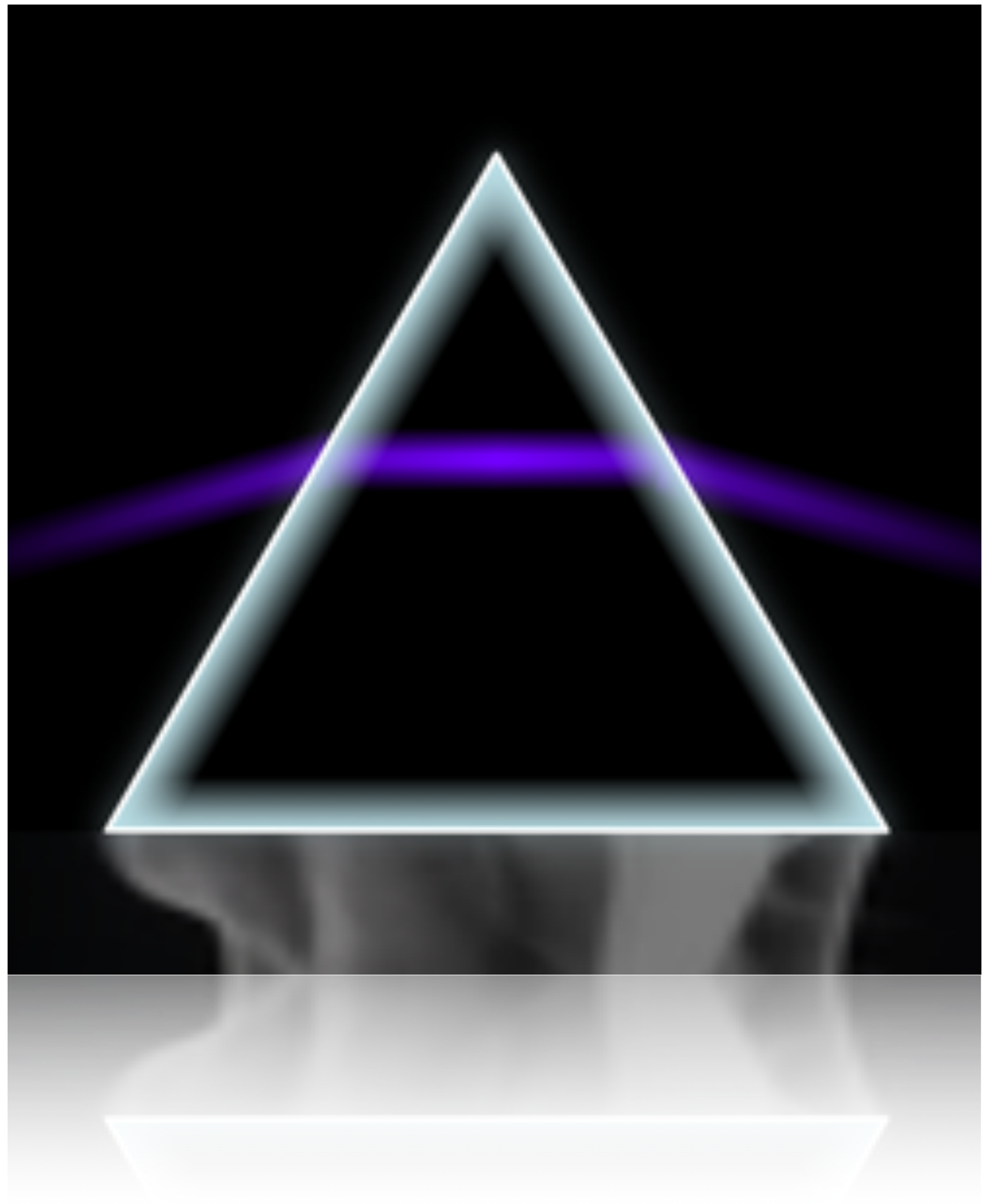
LArRI:

A new setup for Liquid Argon Refractive Index measurement



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LArRI: Liquid **Ar**gon **R**efractive **I**ndex measurement

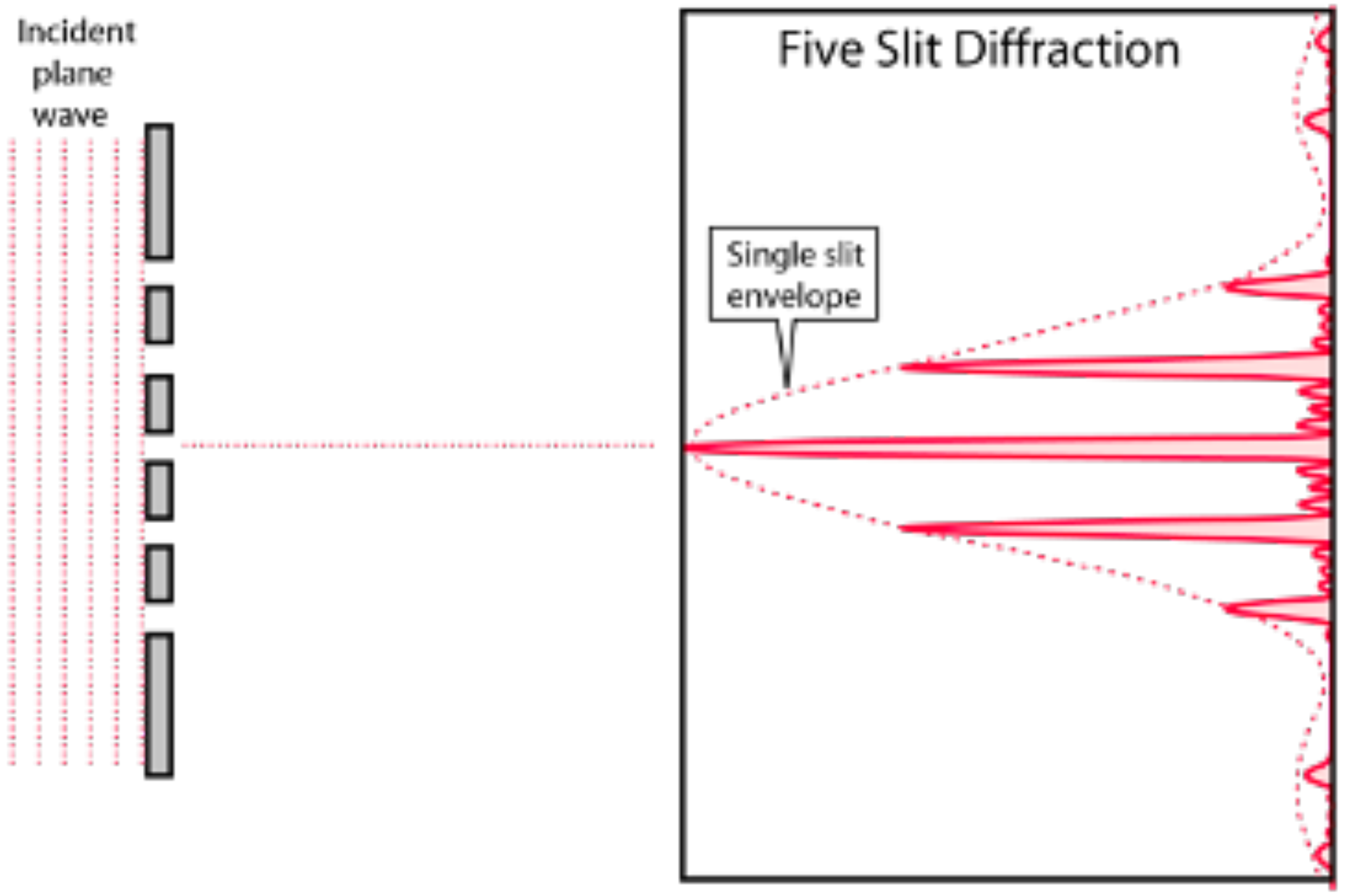
- Liquid Argon (LAr)
  - widely used in particle physics experiments (ν studies, dark matter searches, …)
  - low cost, high availability, good scintillator
  - Xenon-doping to increase uniformity and collected light: scintillation peak @ 175 nm
  - Measuring its optical properties is crucial
- LArRI main goal:
  - direct measurement of LAr refractive index at $\lambda \simeq$ 175 nm
  - development of optical systems, i.e. lenses for Xe-doped LAr imaging
  - Secondary targets:
    - Same measurement at $\neq$ wavelengths (dispersion relation)
    - Measurement of the attenuation length
    - Characterization of optical properties of other noble gases

LArRI: measurement strategy

- Key idea is to measure the LAr refractive index by **comparing the diffraction patterns** generated when light propagates in vacuum and liquid argon by means of a **diffraction grating**:

The position of the diffraction peaks depends on $\lambda_L = \frac{\lambda_0}{n}$

- λ_0: wavelength in vacuum
- n: LAr refractive index
- λ_L: wavelength in liquid

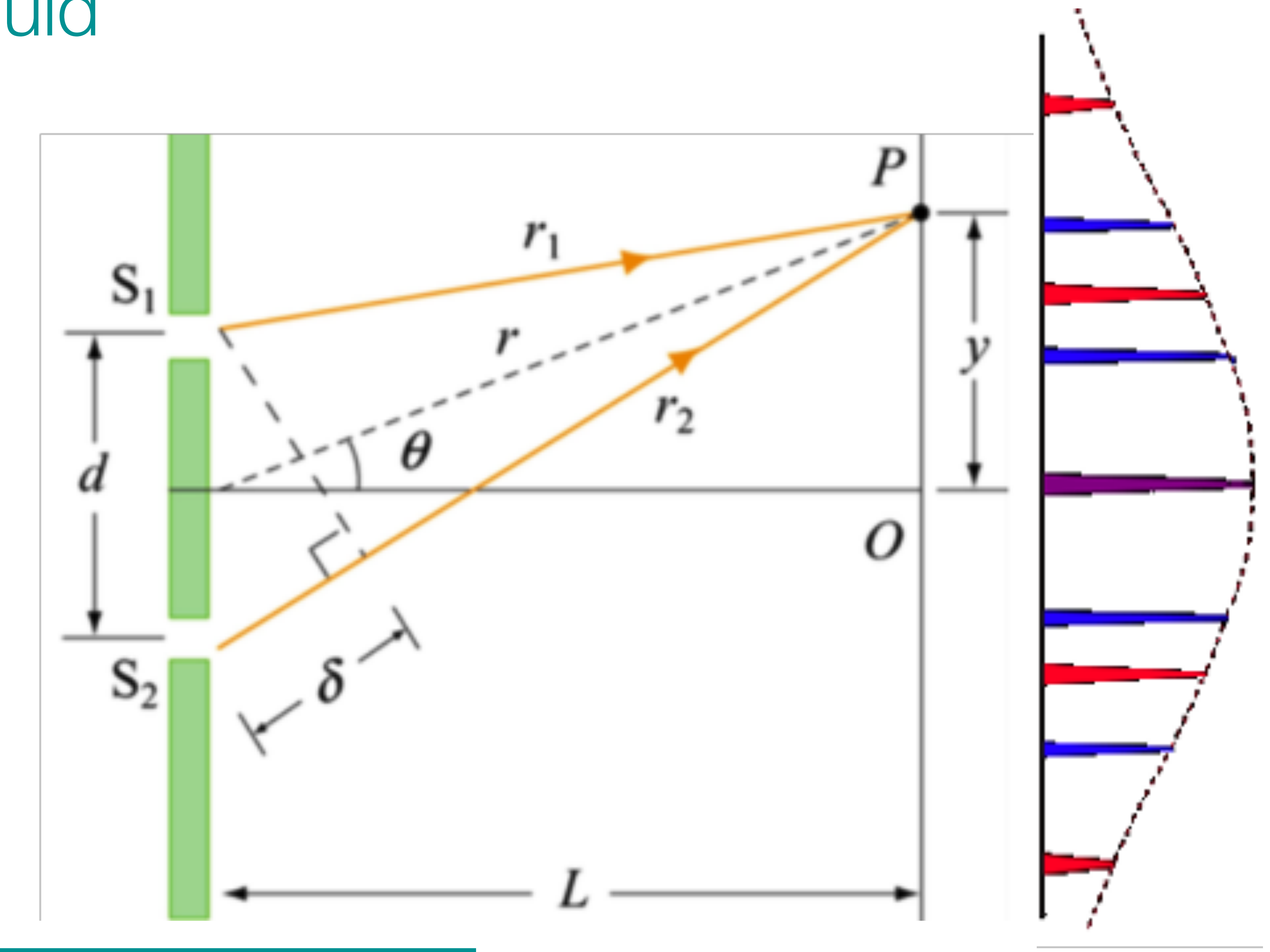


Max in vacuum:

$$d \sin\theta_0 = \lambda_0$$

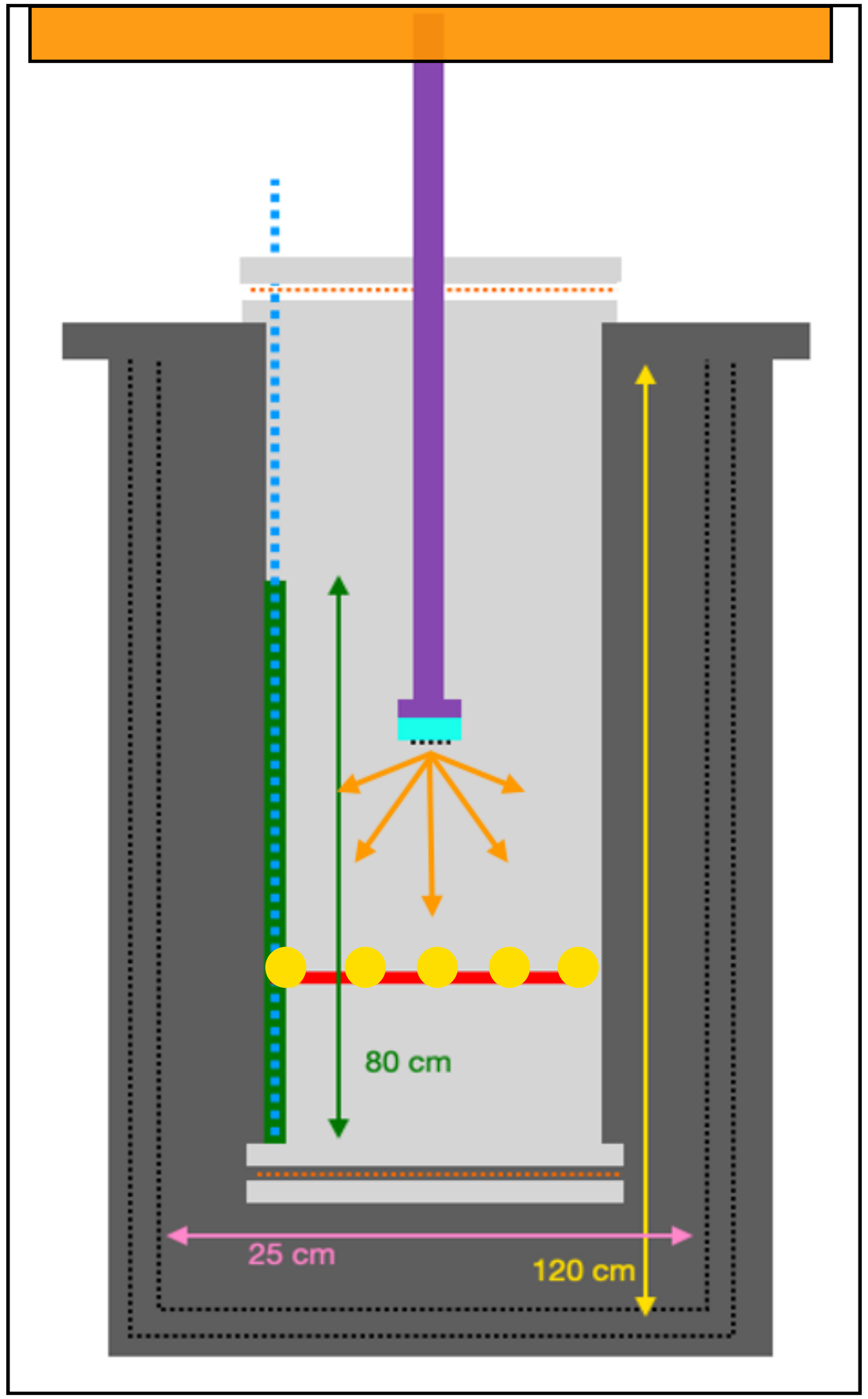
Max in LAr:

$$d \sin\theta_L = \lambda_L = \frac{\lambda_0}{n}$$

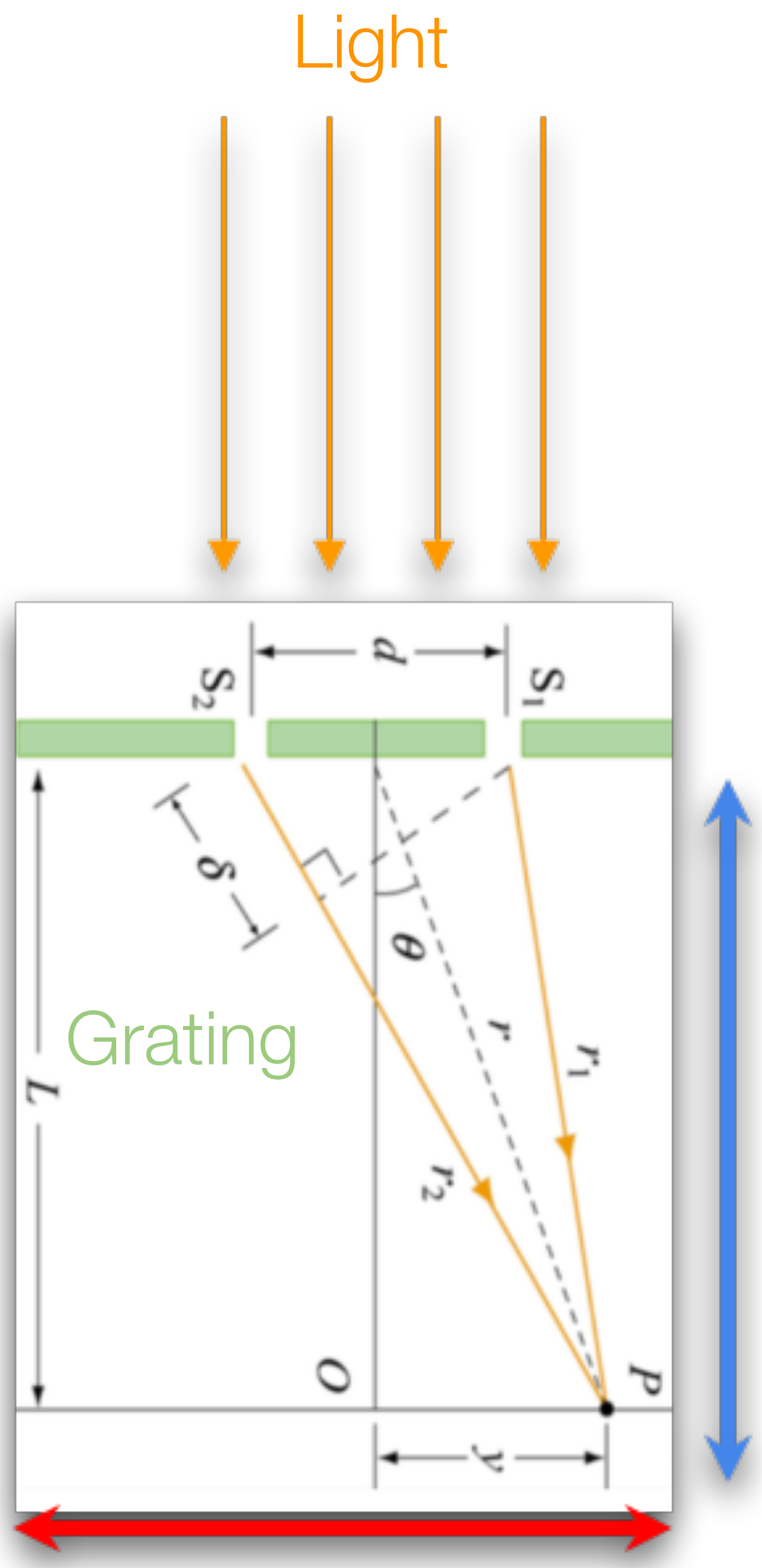


We need a source of coherent and monocromatic light

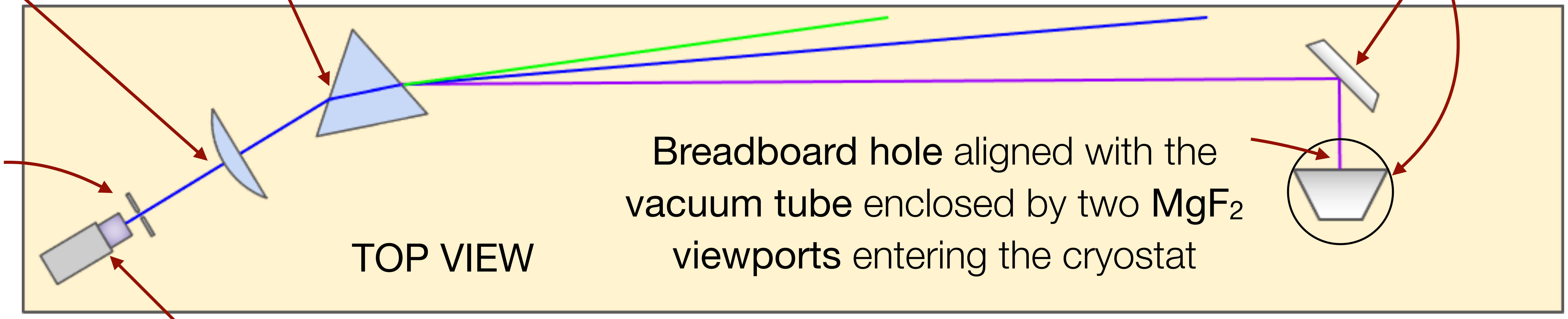
LArRI: measurement strategy and setup



- The core of the setup consists in:
  - optical apparatus to generate coherent, monocromatic light @175 nm, light enters from the top into the chamber
  - a cylindrical chamber that can be evacuated or filled with liquid argon contained in a cryostat to thermalize the system at low T
  - Silicon photomultipliers (SiPMs) located on a movable stand record the diffraction pattern in vacuum and liquid argon
  - **Diffraction peaks** are **scanned** along the **vertical axis**, i.e. the side opposite to the grating to <u>compact the apparatus</u>



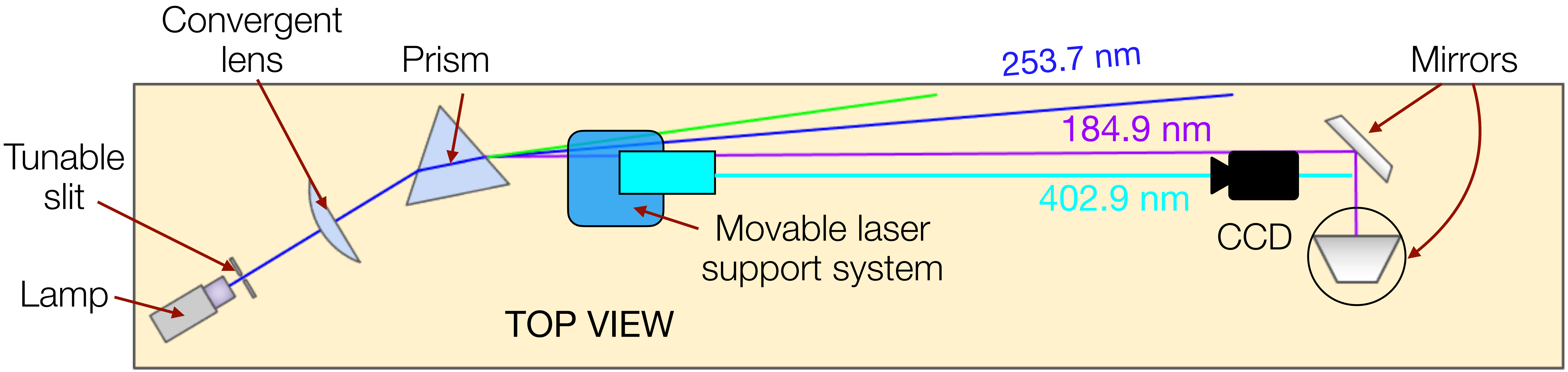
LArRI detector: warm part - optical setup



Emission peaks at 253.7 nm and 184.9 nm

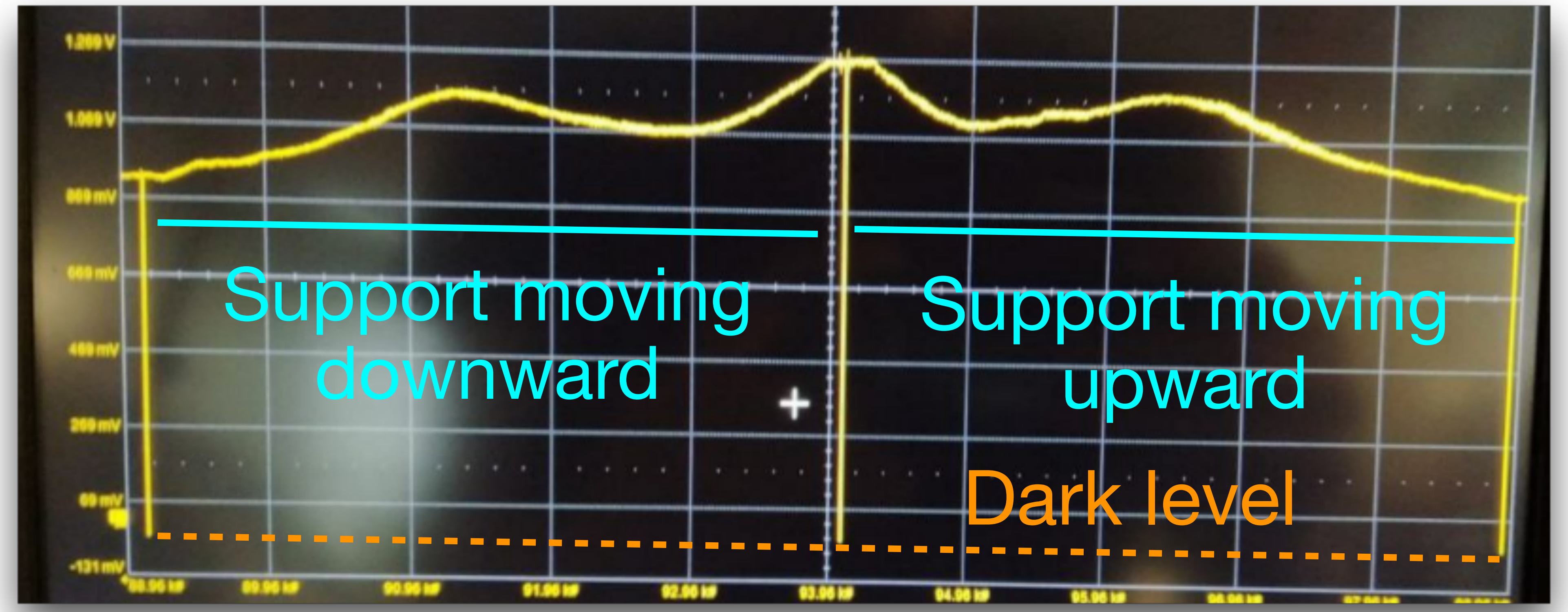
- All the optical assembly is mounted on a breadboard on top of the cryostat, a hole connects the collimated light beam with the entrance of the cold chamber and sends it towards the grating
- The light source is a low pressure mercury lamp with an emission peak at 253.7 nm and at 184.9 nm, used as a proxy for the LXe-doped scintillation light
- All the optical setup is in air, this results in a ~50% light loss at 184.9 nm

LArRI setup: light source/chamber alignment



- The 185 nm peak has very **low intensity**: it is impossible to do the alignment with the beam only
- We developed a **two-step procedure** relying on an additional **402.9 nm laser**:

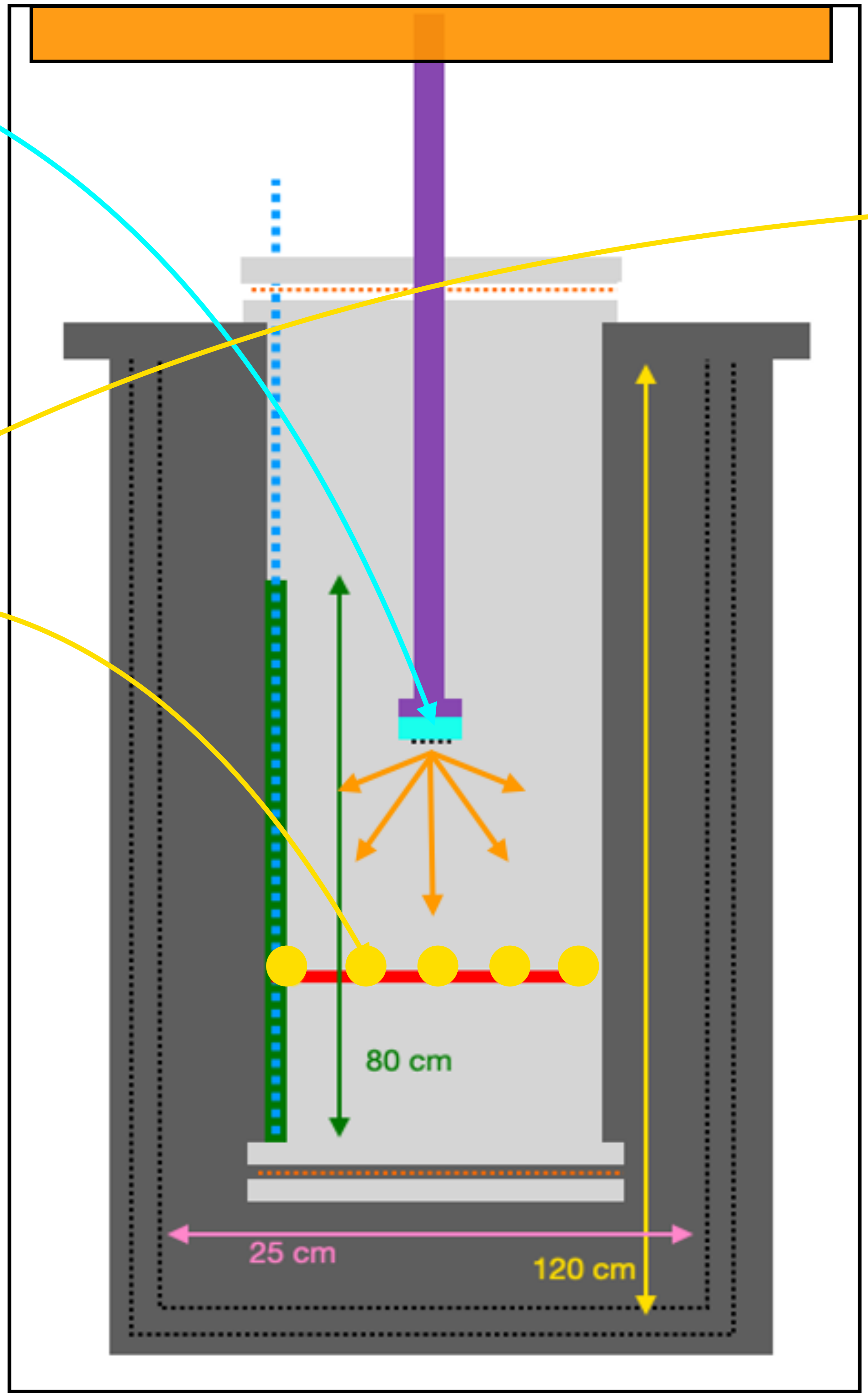
1. Align the 184.9 nm to the laser using a movable CCD
2. Remove the CCD and align the laser with the central SiPM by tuning the orientation of the mirrors: this is done moving the light detectors from top to bottom of the chamber to guarantee the maximum SNR for the entire scan

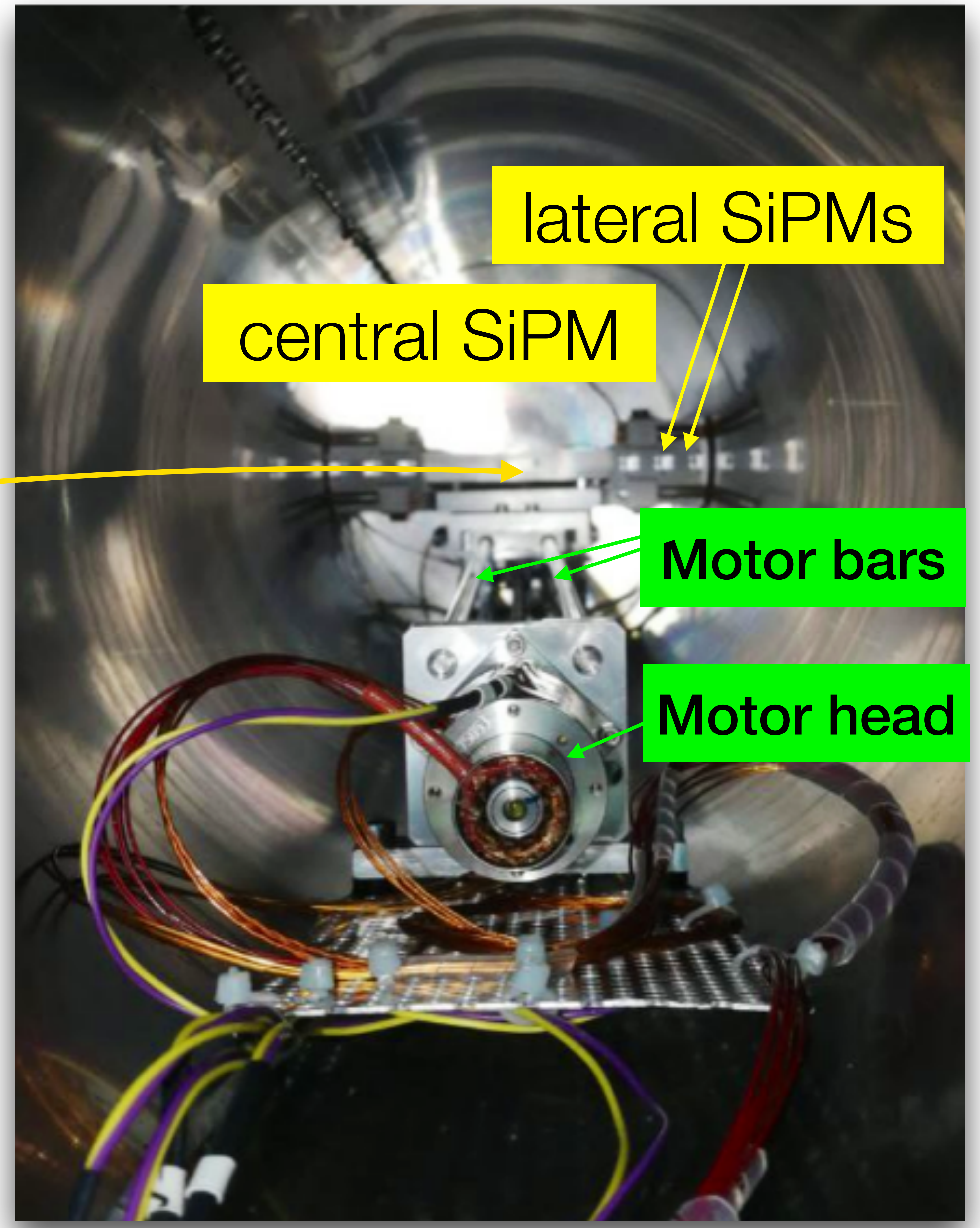


Integrated SiPM signal is constant within 30% and reproducible in the two directions

LArRI detector: cold part

- **Diffraction grating:** Aluminum deposited on a thin fused silica substrate, pitch is 723 nm
- **Motor** by VacuumFab capable to operate both in vacuum and immersed in cryogenic liquids that is used to lift the supports that houses the SiPMs
- **Light detectors:** 5 Hammamatsu (S13370-3075CN) **silicon photomultipliers** (3 x 3 mm^2), 4 symmetrically mounted on the movable stand, 1 at the center used for the alignment procedure and to guarantee that the light beam reaches LArRI chamber





Inner part of the chamber

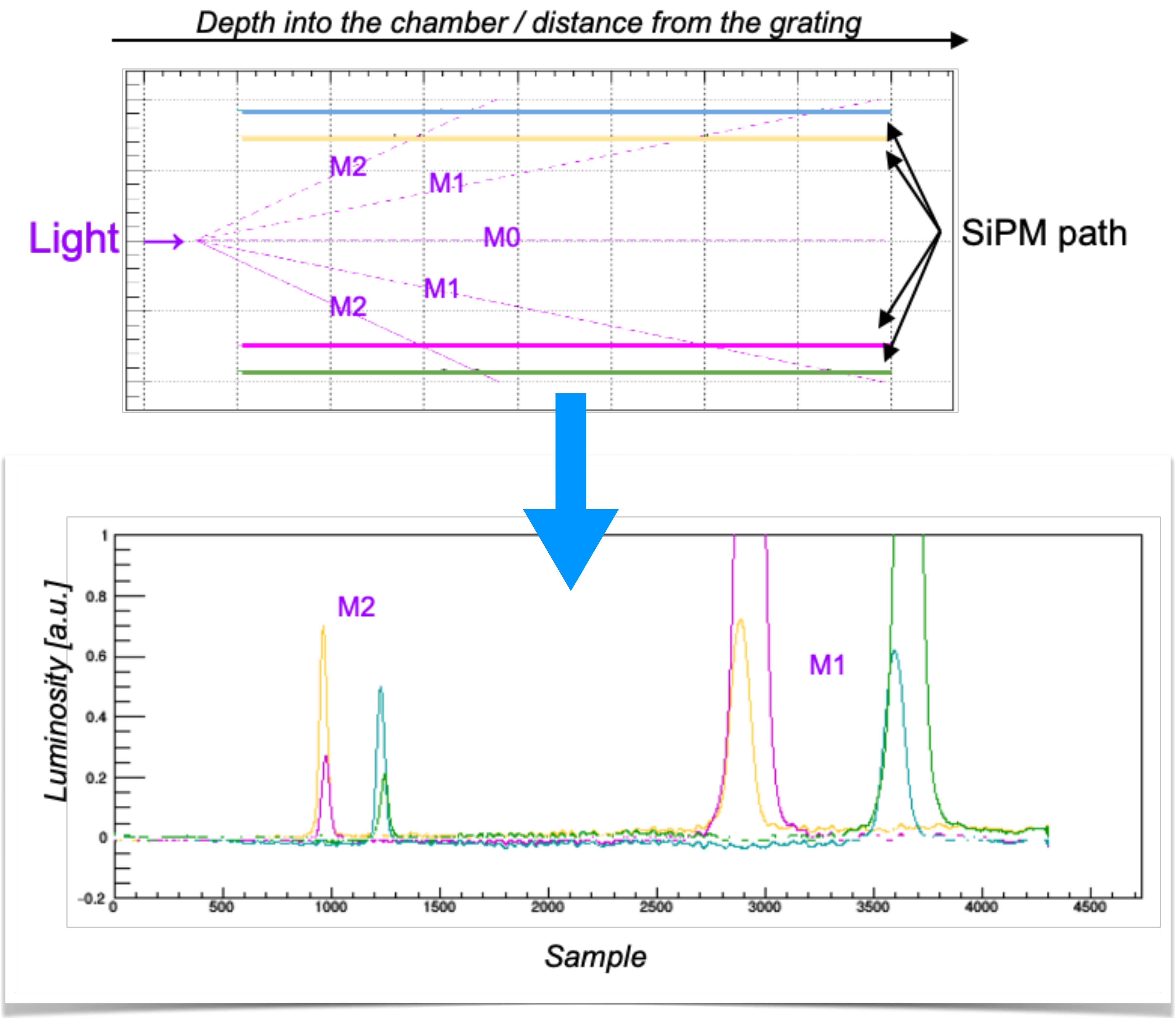
- **3 RTDs** to monitor temperature and liquid level

LArRI: DAQ system and electronics

- Two custom made front end boards positioned outside the cryostat at room temperature route the bias voltage to the SiPMs and integrate their current signal ($\tau \simeq 100$ ms)

- The signal is then acquired with a Teledyne Lecroy scope in 100 ms long windows at typically rates of 2-10 Hz

- The signal of a single acquired window (a motor scan) is averaged to obtain the luminosity sample used for the analysis

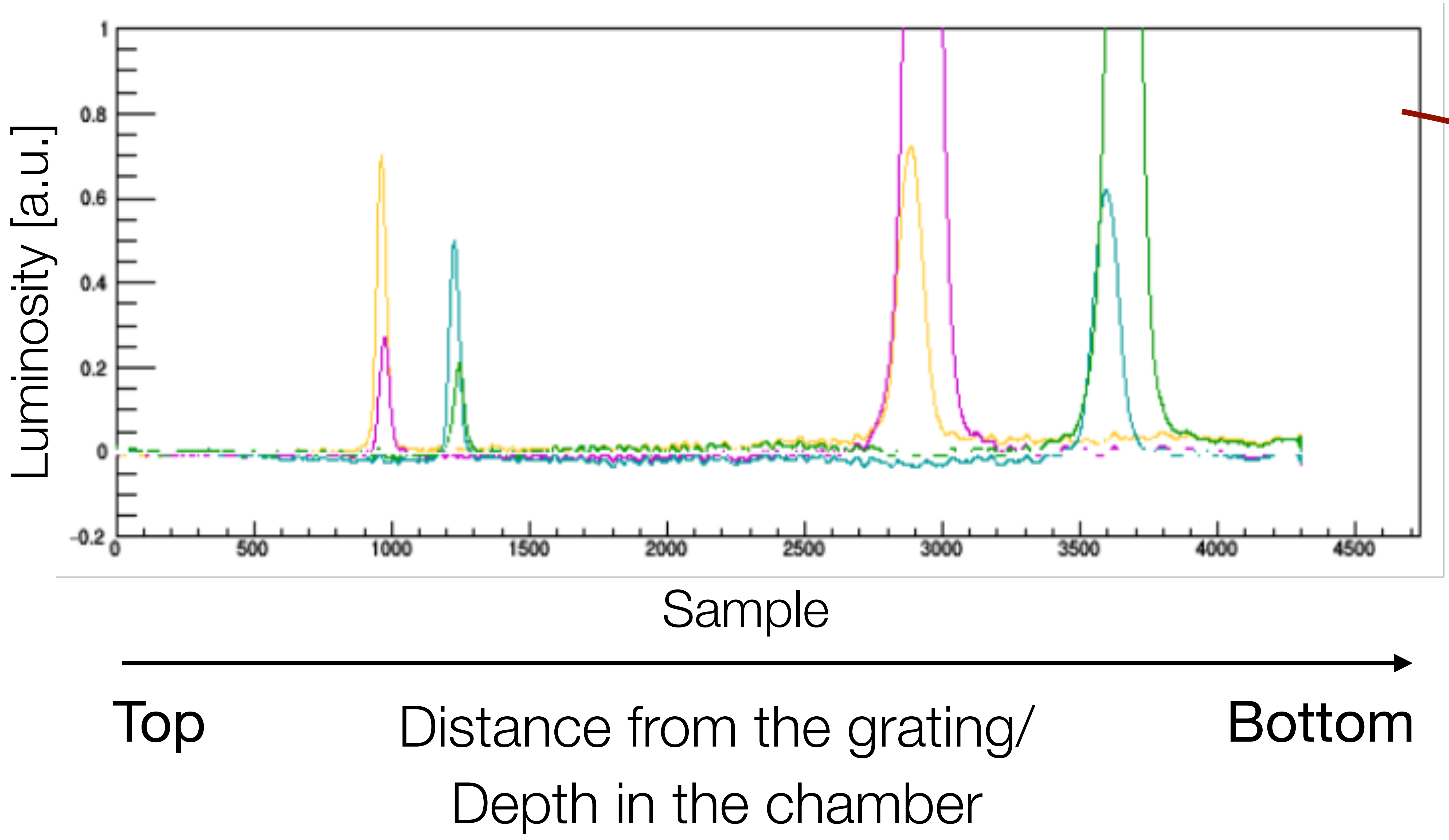


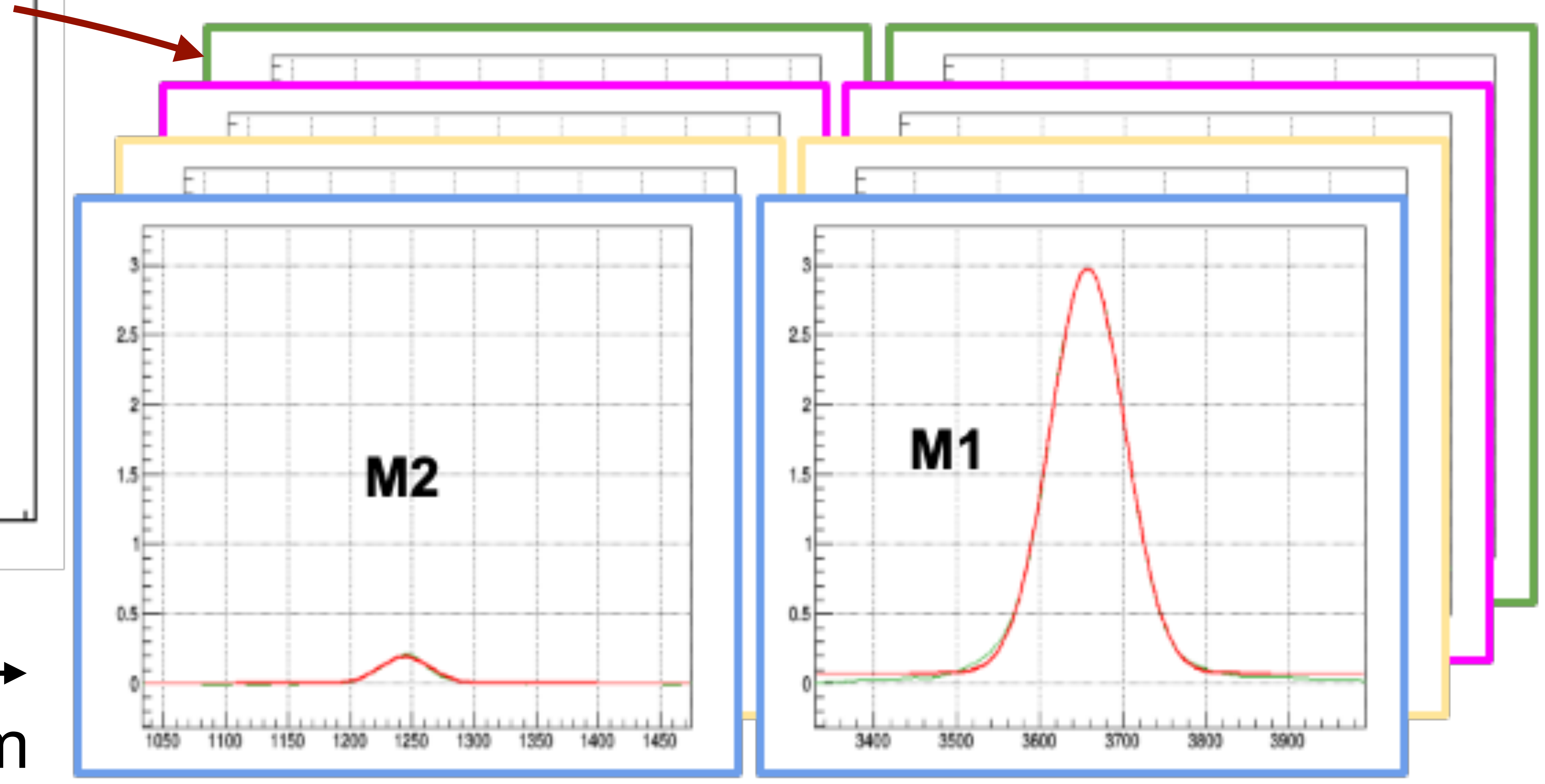
SiPM signal while motor goes downward

LArRI: First step of data analysis

- A single scan (either in vacuum or in LAr) is considered and the 8 luminosity maxima corresponding to M_1 and M_2 diffraction peaks intercepted by the 4 lateral SiPMs are fit with a Gaussian to extract the mean

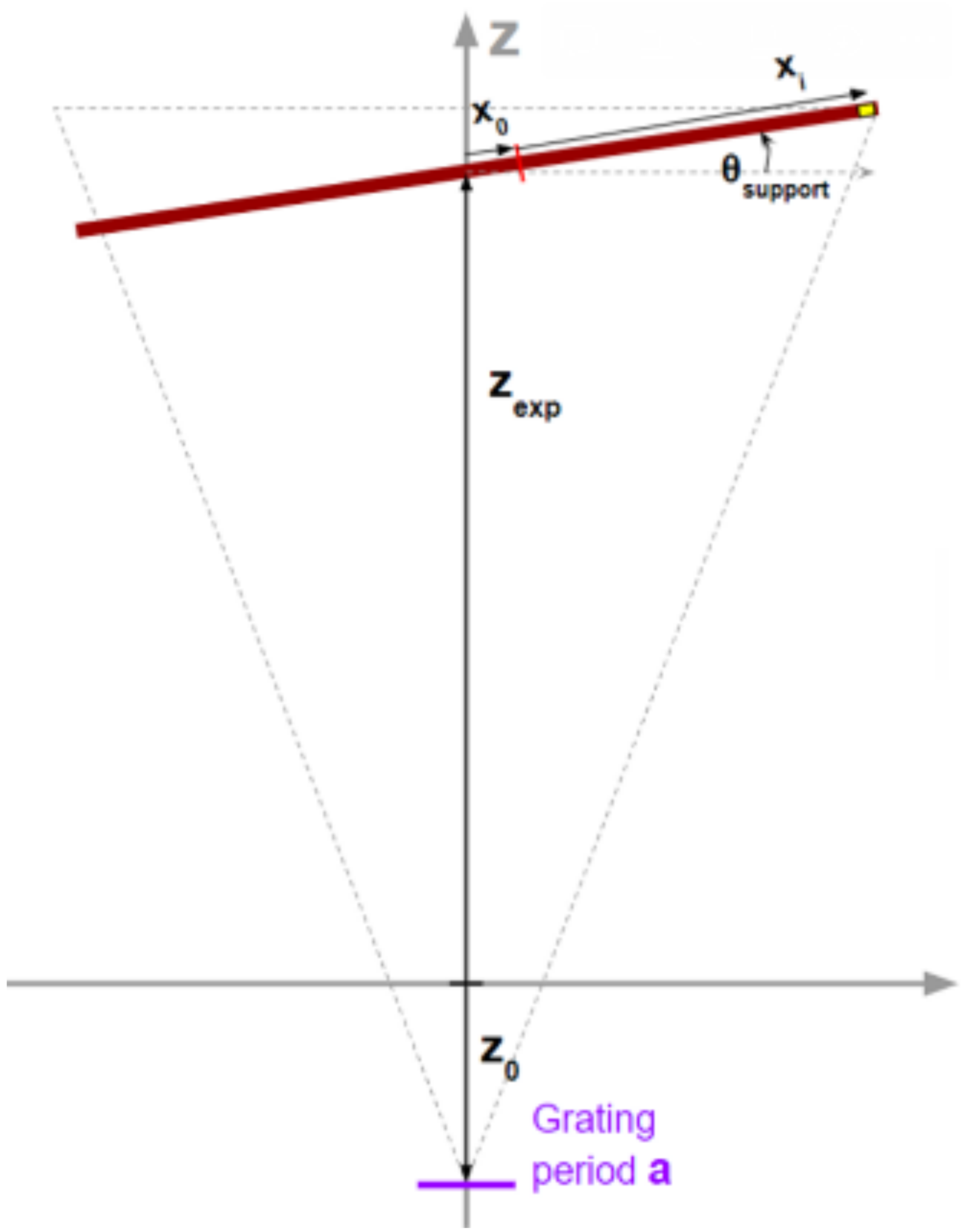
- We use the position of the motor at the beginning (top) and end (bottom) of the scan (chamber) to extract the position of the diffraction maxima for each of the light detectors





LArRI: Second step of data analysis

- Simultaneous fit of the 16 maxima acquired in two scans (one with the chamber in vacuum and the other with LArRI filled with liquid argon) to measure the LAr refractive index
  This helps us reducing systematic effects due to the geometrical non idealities of the setup



$$z_{exp} = \frac{(x_i + x_0)\cos\theta_s}{\tan\arcsin\frac{m\lambda}{an}} - (x_i + x_0)\sin\theta_s - z_0$$

x_i positions of the 8+8 diffraction maxima, $m = 1,2$

Free parameters include:

z_0 the initial position of the SiPM support along the motor axis

θ_s the angle between motor axis and SiPM movable support

x_0 offset on the position of the SiPM slots along the support

a grating periodicity

n liquid argon refractive index

LArRI: Consistency checks and analysis validation

$$z_{exp} = \frac{(x_i + x_0)\cos\theta_s}{\tan\arcsin\frac{m\lambda}{an}} - (x_i + x_0)\sin\theta_s - z_0$$

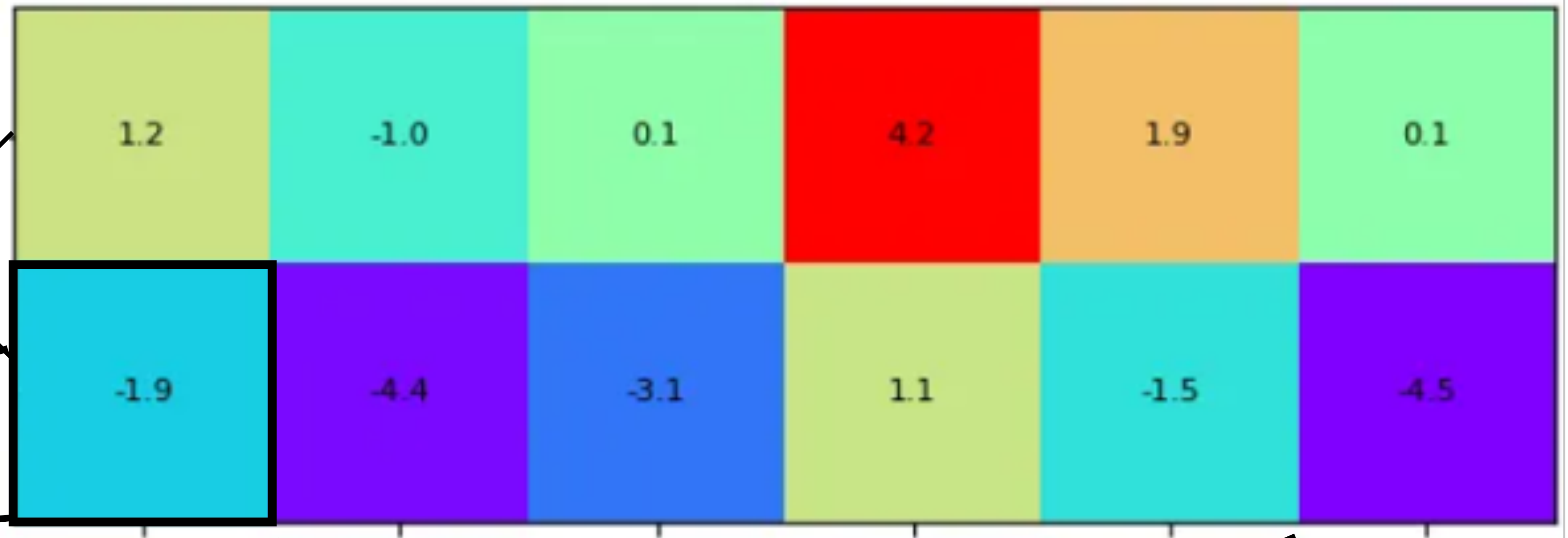
- In alternative to considering data from the same wavelength in different conditions (vacuum and LAr filling), since there is a degeneracy between λ and n we can do the simultaneous fit of measurements with **two different wavelengths** in **vacuum**: the analysis is the same, but in this case the contraction factor is given by the ratio between the two wavelengths, i. e. $n = \frac{\lambda_2}{\lambda_1}$
- We compare 2 scans at 402.9 nm (laser) and 6 (5 scans + one dataset made by the mean, peak by peak, of the maxima positions) at 253.7 nm (mercury lamp)

Expected “n"= 1.5884 = 402.9 nm/253.7 nm

We observe compatibility within few parts per thousand

$\left(n_{meas} - n_{exp}\right) \cdot 10^3$

Laser scan



253.7 runs

LArRI: Preliminary measurements in liquid argon

First measurements in liquid nitrogen

$$n_{LN_2}(253.7\ \mathrm{nm}) = (1.24 \pm 0.01)$$ 8 x 8 scans

$$n_{LN_2}(402.9\ \mathrm{nm}) = (1.24 \pm 0.01)$$ 2 independent measurements

Preliminary measurements in liquid argon

$$n_{LAr}(402.9\ \mathrm{nm}) = (1.24 \pm 0.01)$$ 2 x 1 scans

$$n_{LAr}(253.7\ \mathrm{nm}) = (1.24 \pm 0.01)$$ 1 measurement

$$n_{LAr}(184.9\ \mathrm{nm}) = (1.29 \pm 0.05)$$ 2 x 1 scans

Measurement in liquid argon are based on data acquired with 2/4 SiPMs operational

LArRI: Conclusions and next steps

- The system is fully operational since 2023 and we were able to acquire measurements both in cold vacuum cryogenic liquids (scan performed both in LN_2 and LAr)

- The analysis structure is ready and working as we demonstrated with our consistency checks

- We took our first measurements in liquid argon with 2/4 SiPMs

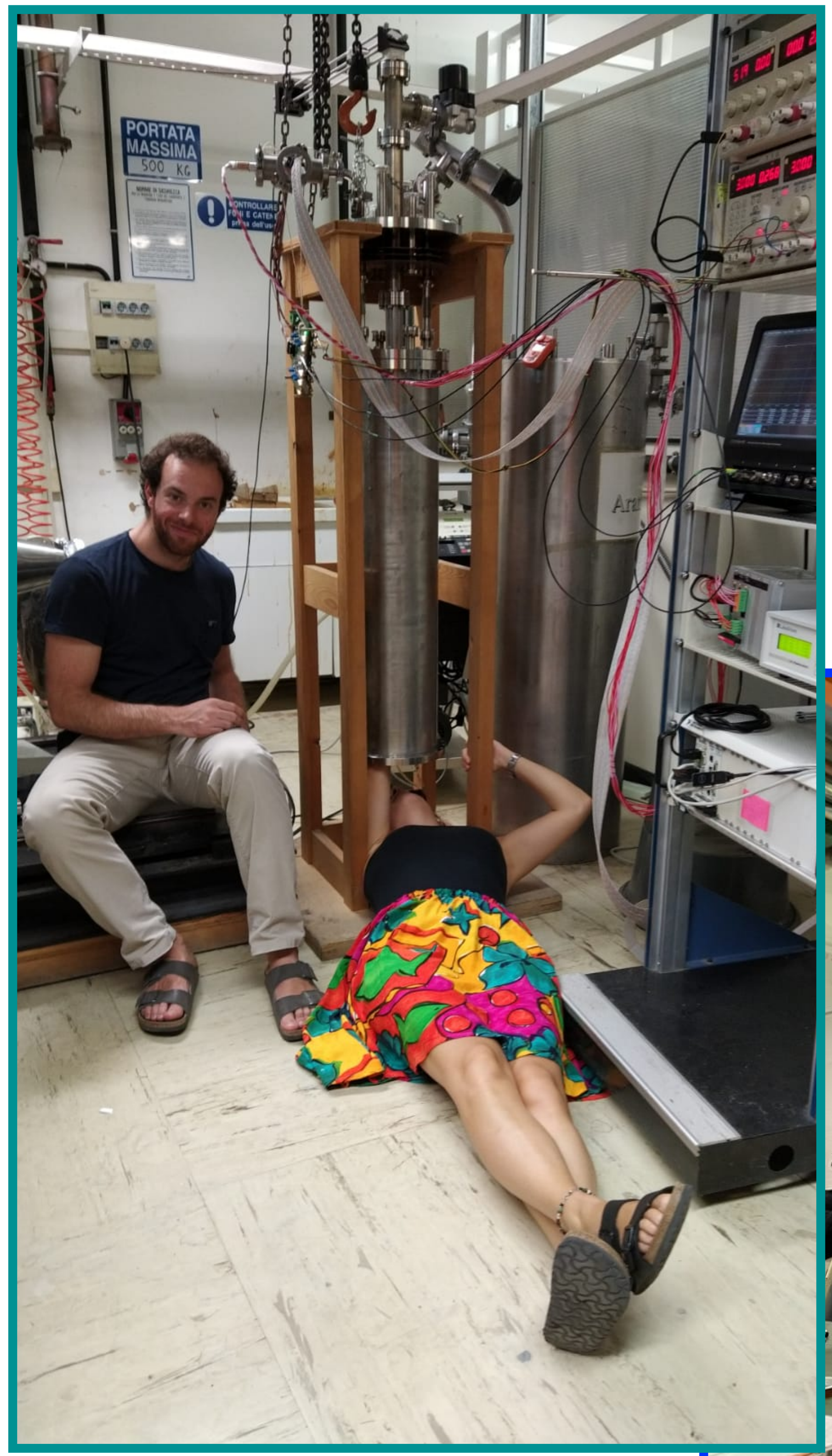
Our steps moving forward include:

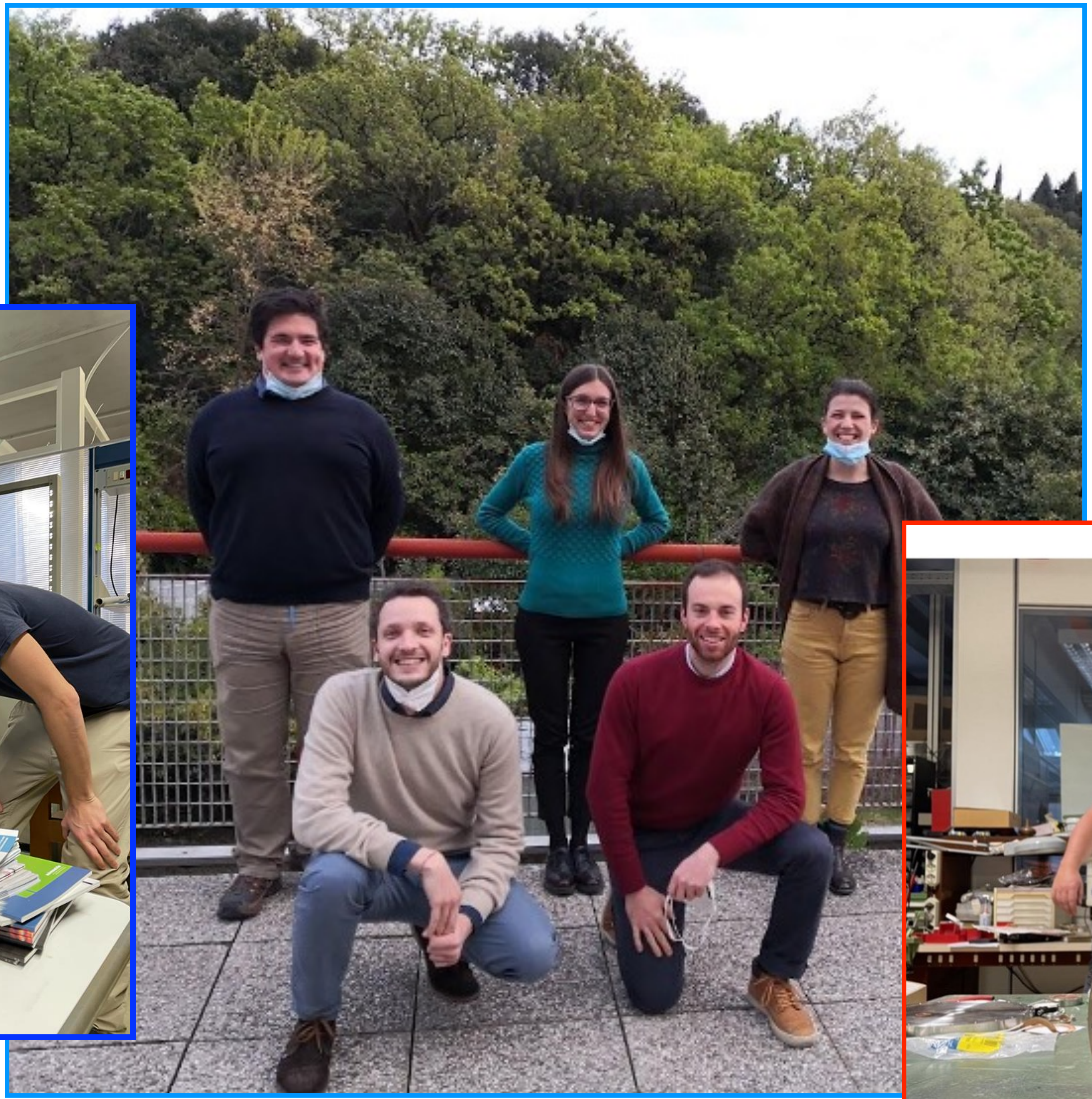
  - Dedicated studies to evaluate the systematic effects that affect our measurement (optical system, grating, …)

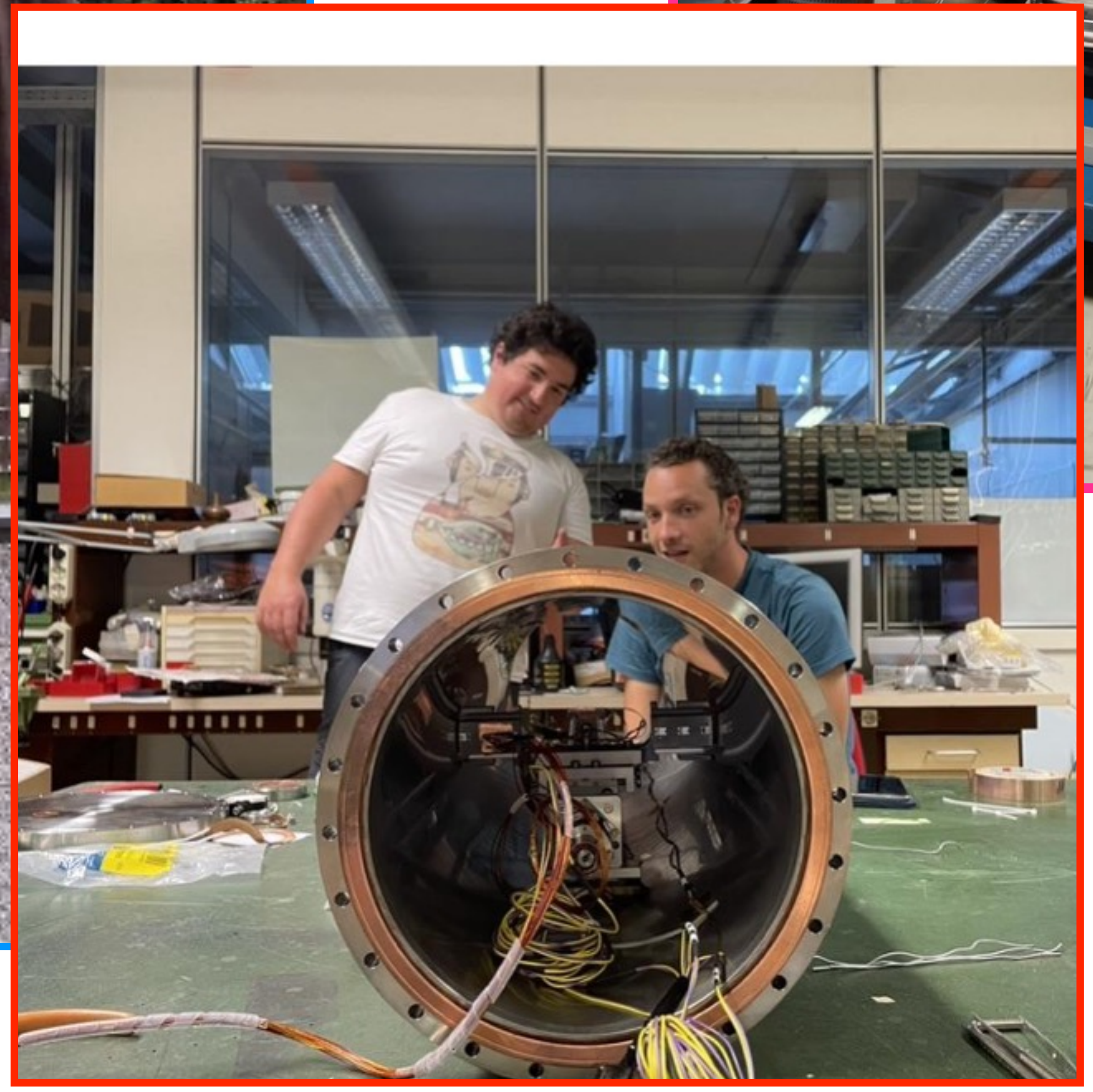
  - Improve our measurements at $\lambda = 184.9$ nm

  - Repeat the measurement in liquid argon with the full set of light detectors to achieve our main target

Thank you for your attention on behalf of *LArRI*





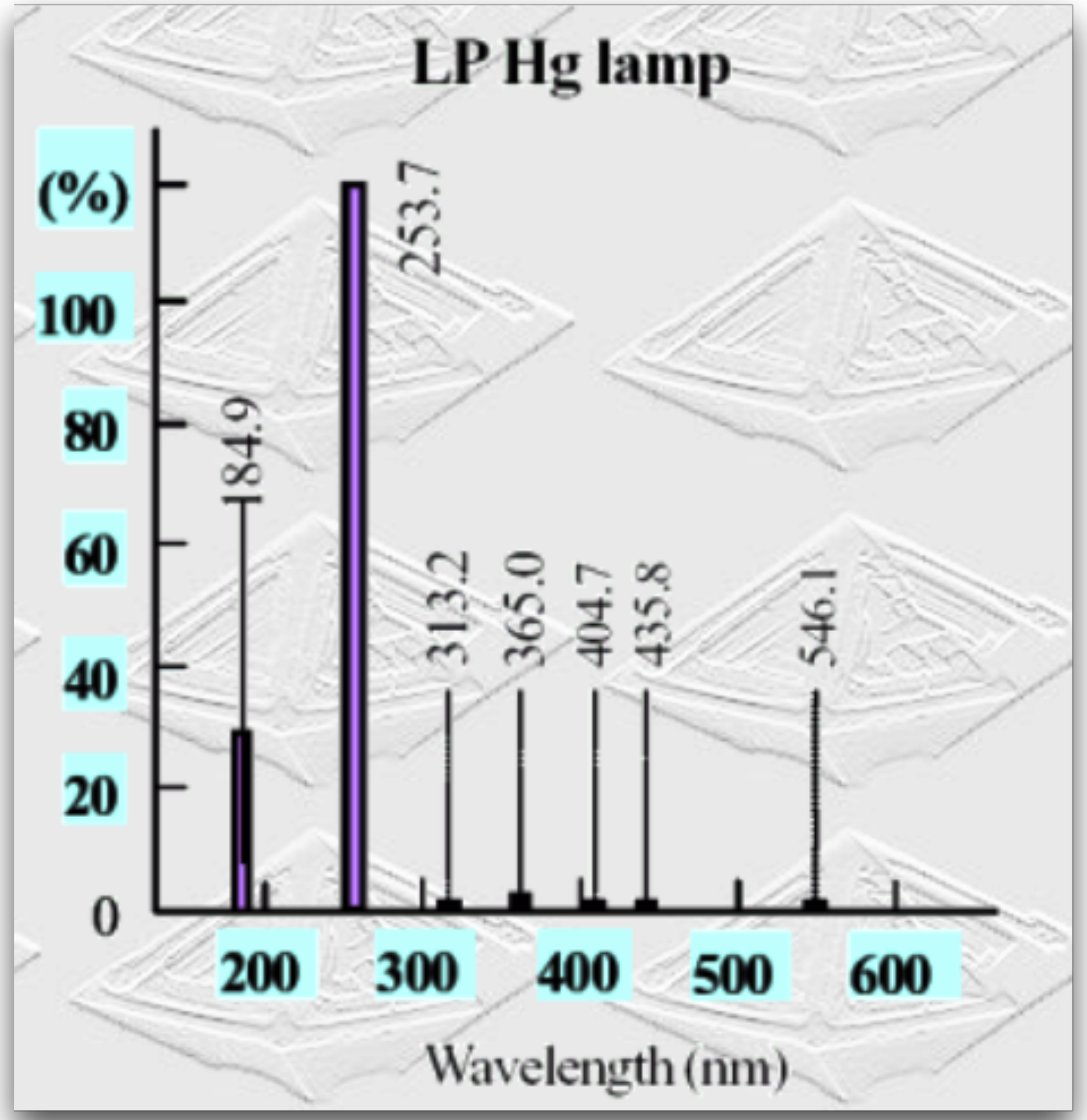


Back up slides

LArRI: choice of the light source

The choice to use a low pressure mercury lamp was guided by the following factors:

- **Emission peak close** to 178 nm
- **Coherence length** (184.9 nm peak is narrow)
  defined as the maximum longitudinal distance allowed between two points to preserve correlated phase
  the minimum requirement is
  $$L = N \cdot m \cdot \lambda \simeq 1000 \cdot 2 \cdot 190 \text{ nm} \simeq 380 \ \mu\text{m}$$
  with N slits in the lattice, m maximum interference order we want to observe
- Emittance (source size and collimation)



Peak at 185 nm and 254 nm have a power ratio of about 1:5

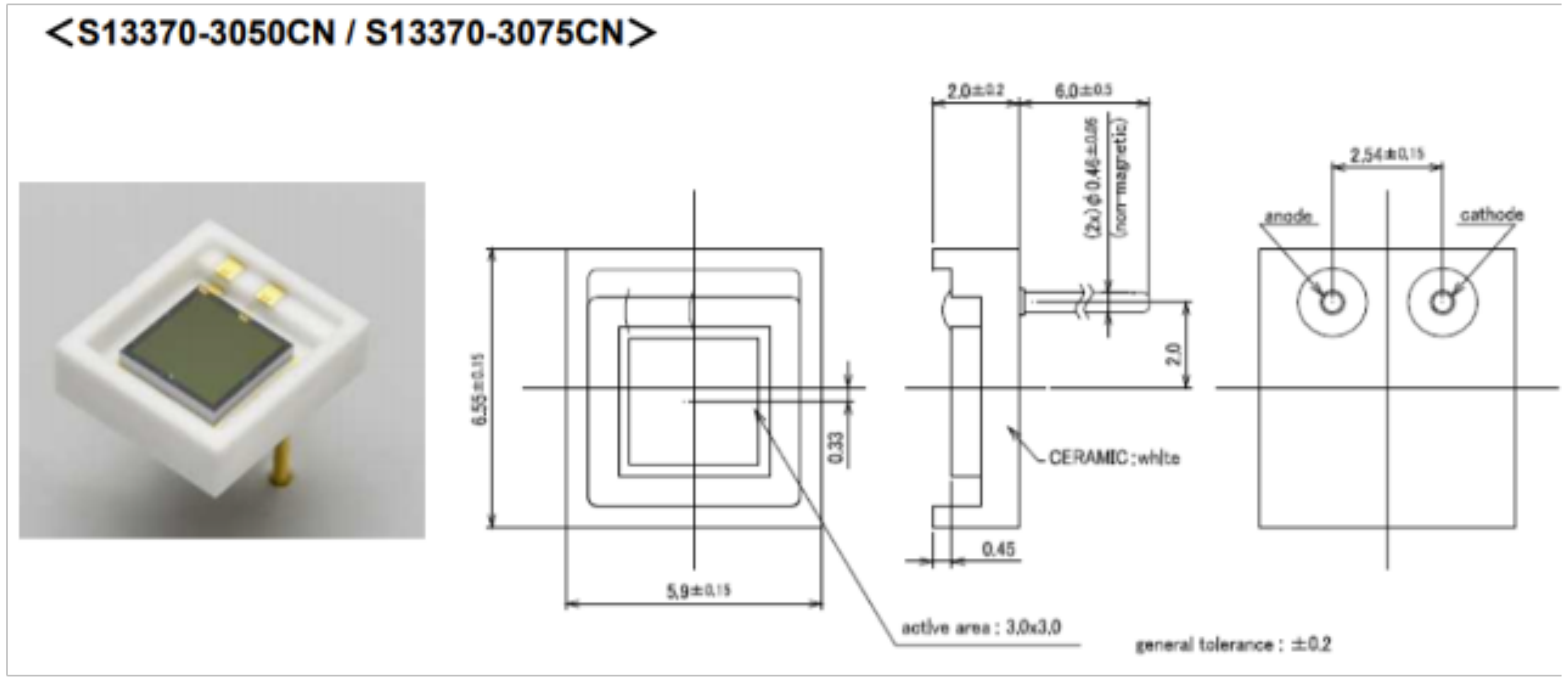
LArRI: VUV sensitive SiPMs

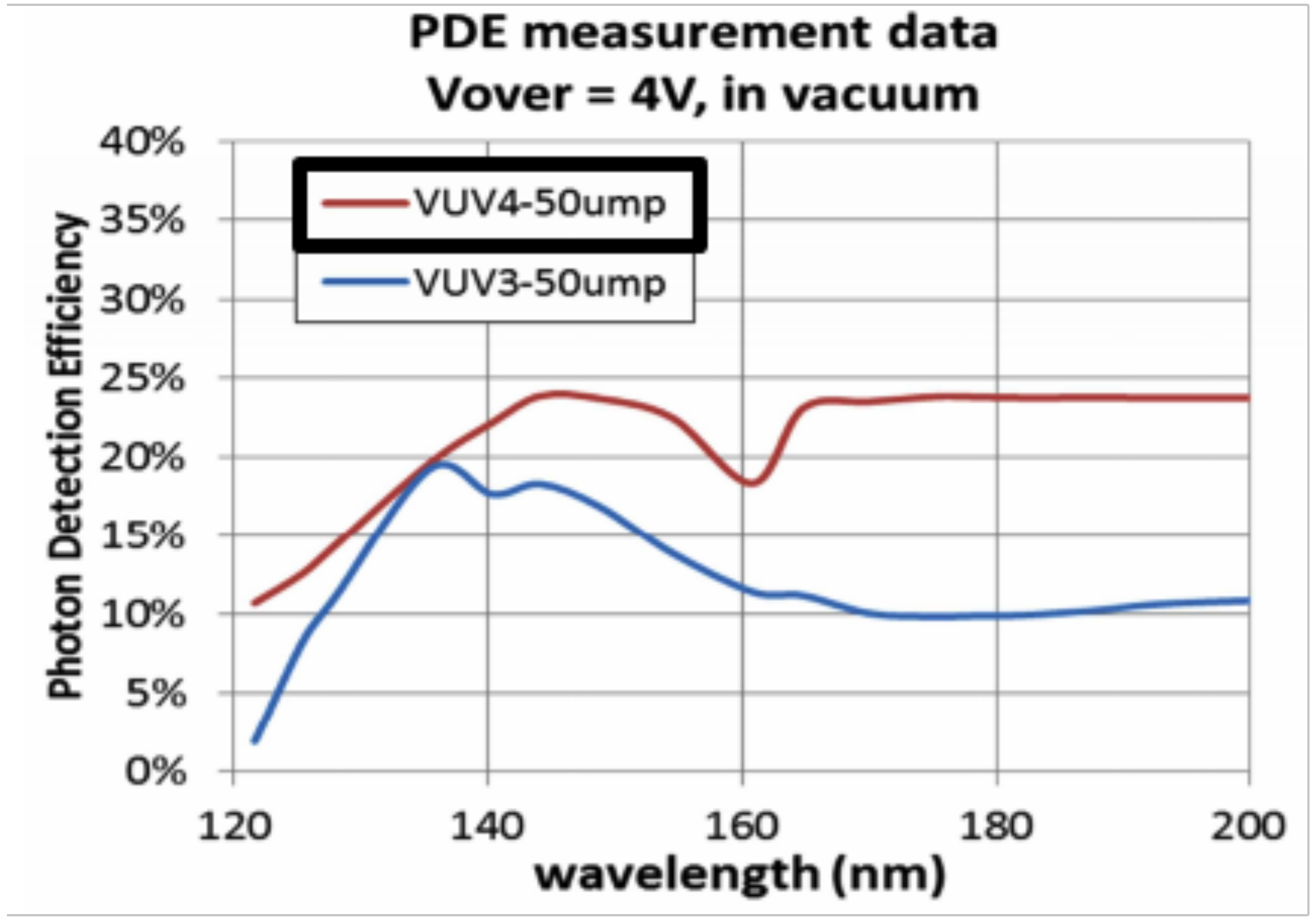
Hamamatsu S13370-3075CN (9 mm^2)

DCR: < 1 Hz/mm^2 @ 165 K

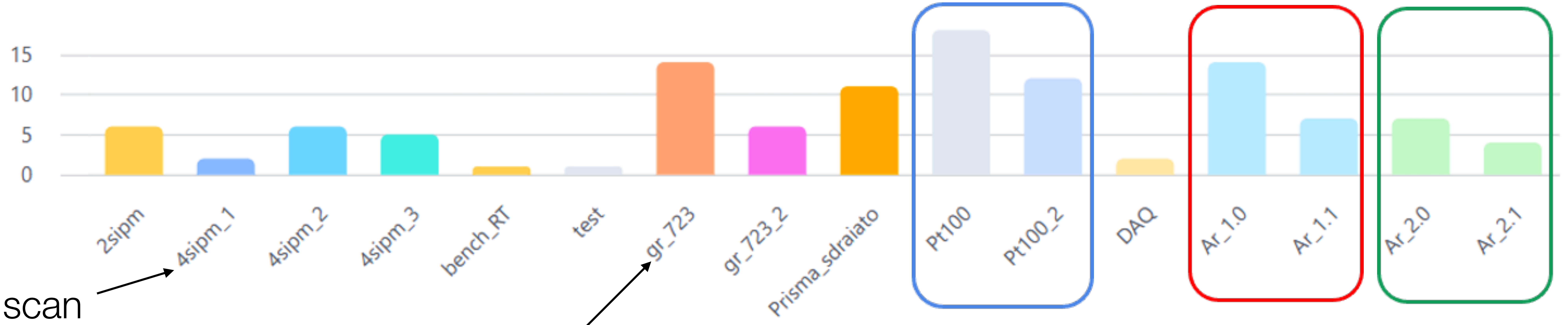
< 25 mHz/mm^2 @ 77K (S13360-DUNE)

PDE: 24% @ 178 nm (nominal)





LArRI: commissioning phases of the setup



First scan with 4 SiPMs

First run with the 723 nm grating

Runs with LN_2

First tests in LAr

First measurements in LAr

- Six months of work on the optical setup
- ~1 year of work on the electronics and mechanics of LArRI
- First scans acquired in summer 2022
- First runs in cryogenic liquid (LN_2) in spring 2023
- First measurement in liquid argon in November 2023