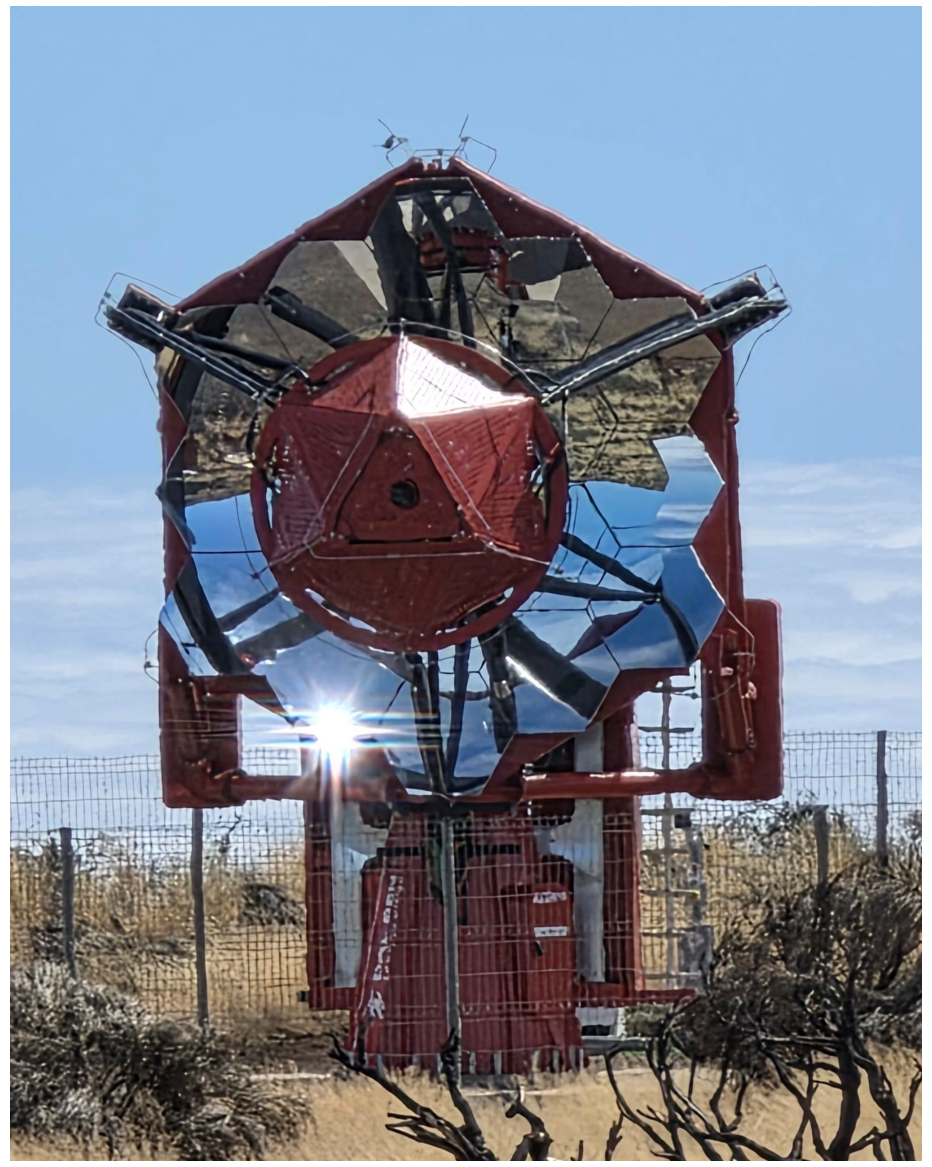
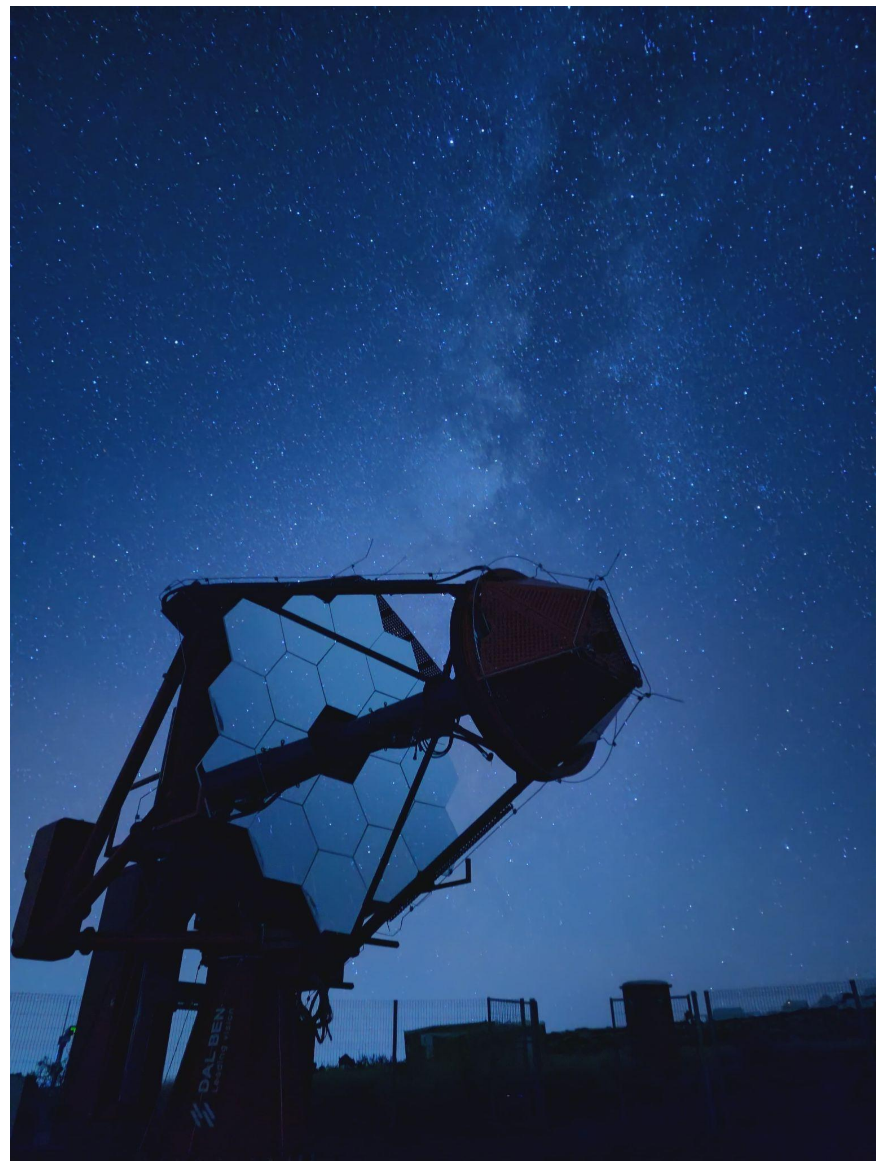
Sub-nanosecond, very narrow band intensity interferometry with the ASTRI Mini-Array

Luca Zampieri, Michele Fiori, Alessia Spolon, Luigi Lessio, Gabriele Rodeghiero, Pietro Bruno, Carmelo Gargano, Giampiero Naletto, Giovanni Pareschi, Salvatore Scuderi, Gino Tosti

for the ASTRI-SI3 team and the ASTRI Project

Stellar Intensity Interferometry Workshop (Waischenfeld, Germany) - October 13-17, 2025



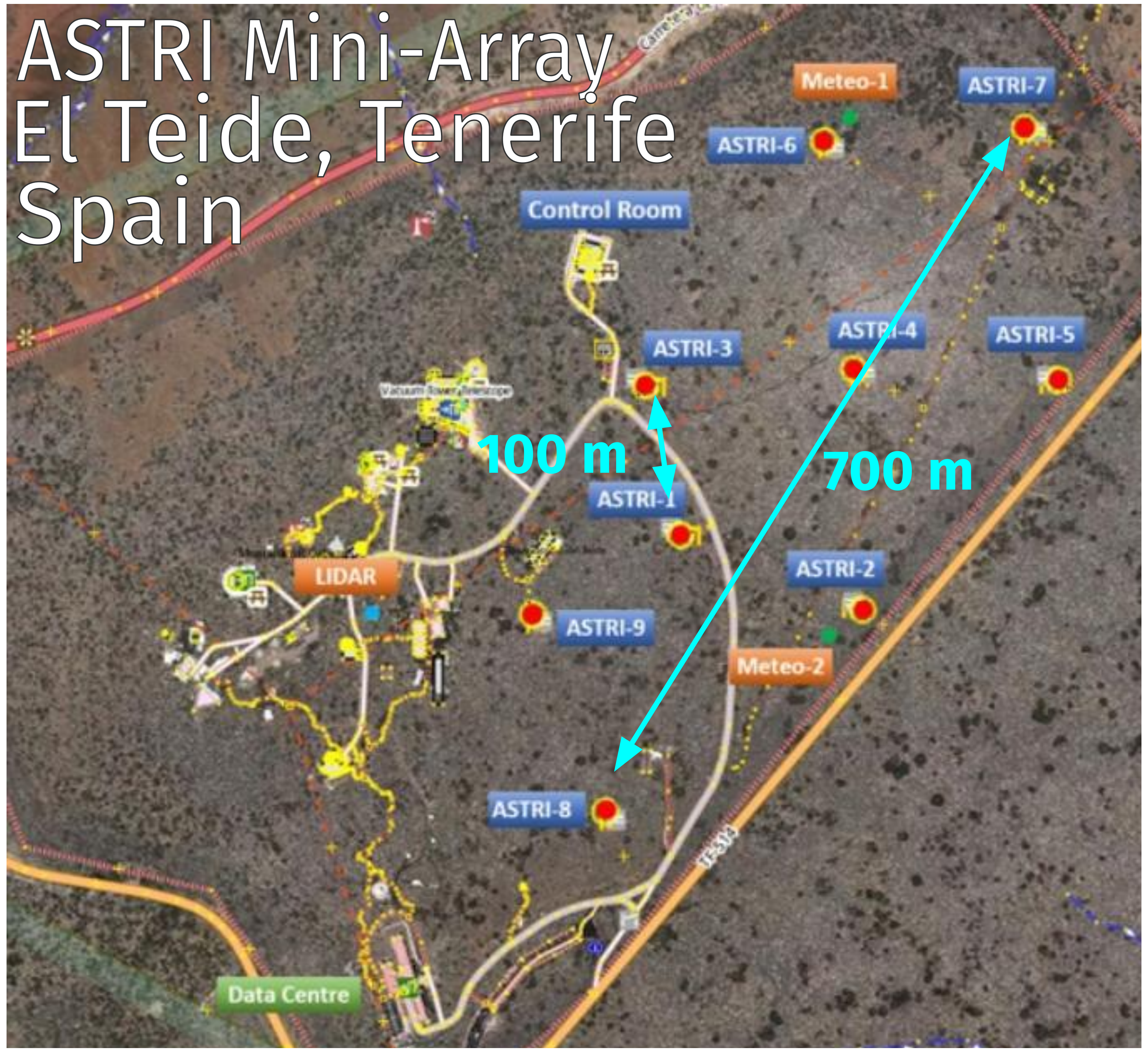


Outline

- The ASTRI Mini-Array
- Basic concept and design of the Stellar Intensity Interferometry Instrument (SI3)
- Assembly of the first instrument (Jul-Oct 2025)
- First time demonstration of the SI3 capabilities with a prototype version fully tested in the laboratory

ASTRI SII

The **ASTRI Mini-Array** is an International collaboration, led by the Italian National Institute for Astrophysics (INAF), that is constructing and operating an array of nine Imaging Atmospheric Cherenkov Telescopes to study gamma-ray sources at very high energy (TeV) and **perform optical stellar intensity interferometry observations**

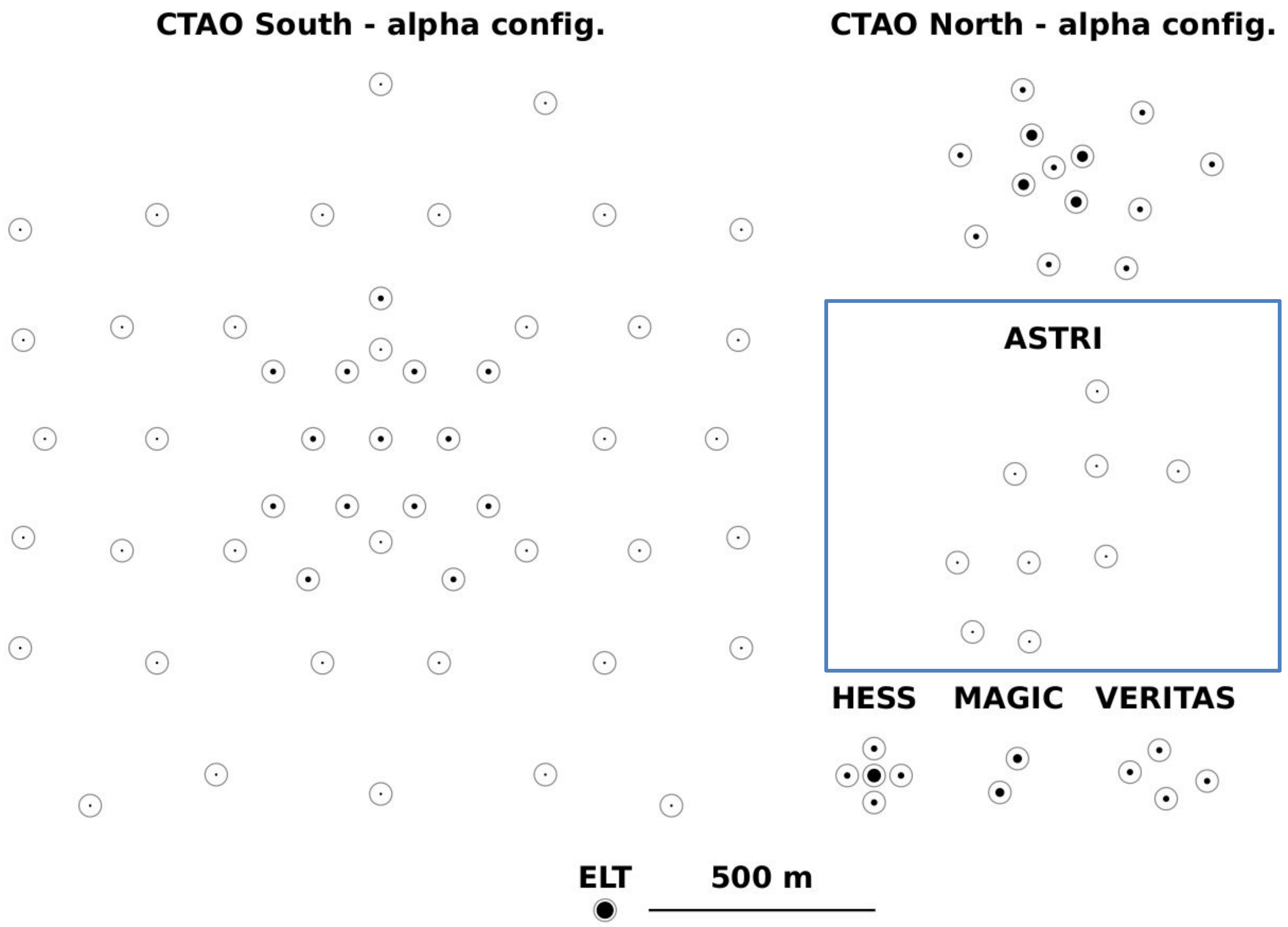


Stellar Intensity Interferometry (SII) with ASTRI

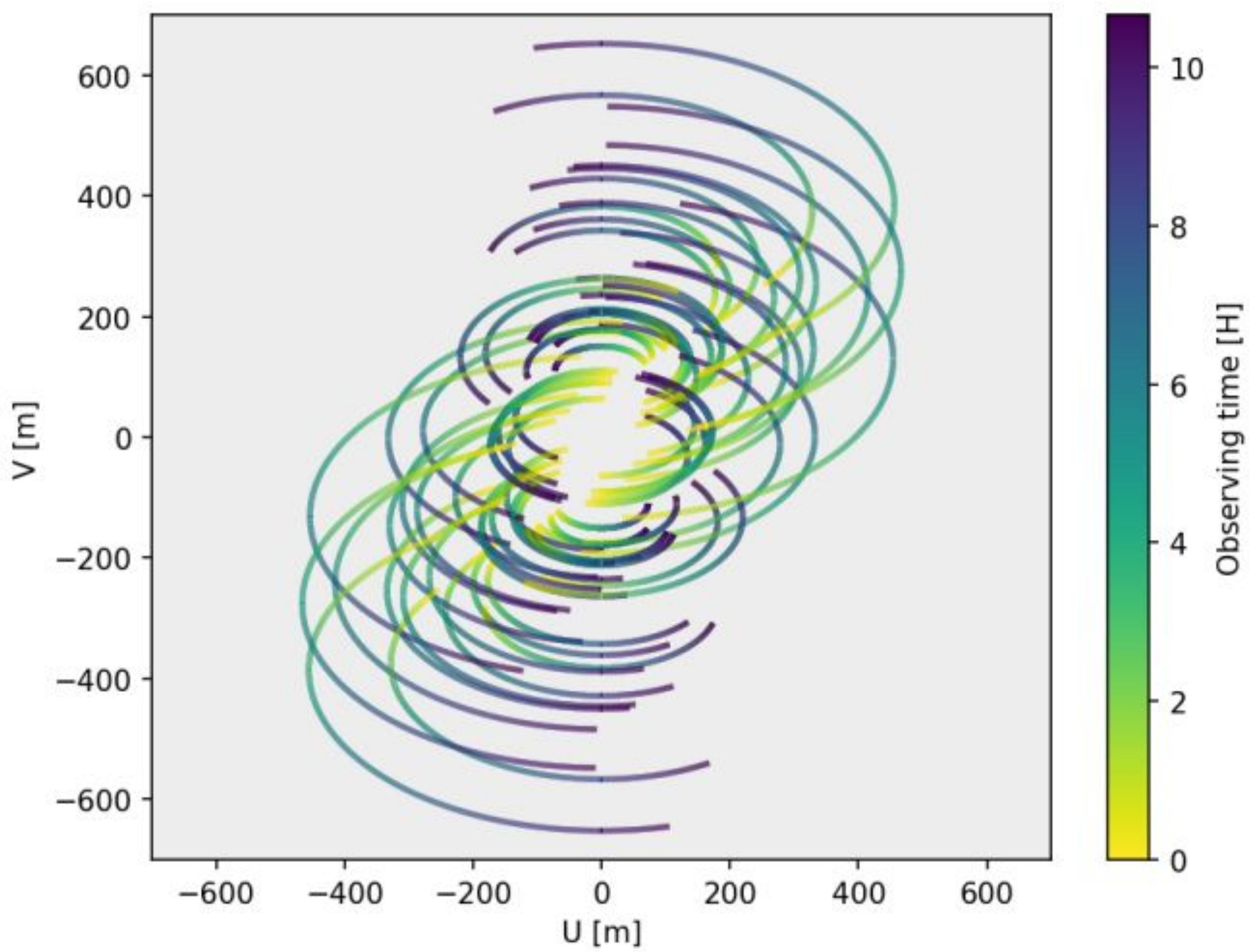
The ASTRI Mini-array provides a suitable infrastructure for performing SII measurements at sub-milliarcesec level

Ultimate goal: using the **long (up to ~700 m) multiple baselines (36)** of up to 9 ASTRI Mini-Array telescopes to do image reconstruction with resolution of **~100 microarcseconds**

ASTRI Mini-Array
Baselines and angular resolution



Example of **ASTRI U-V plane 1 night coverage for the full Mini-Array**



Angular resolution ~< 100 microarcsec

36 different baselines with dense coverage

ASTRI Mini-Array
Telescopes on site

ASTRI
Performing sub-ns, very narrow band SII measurements

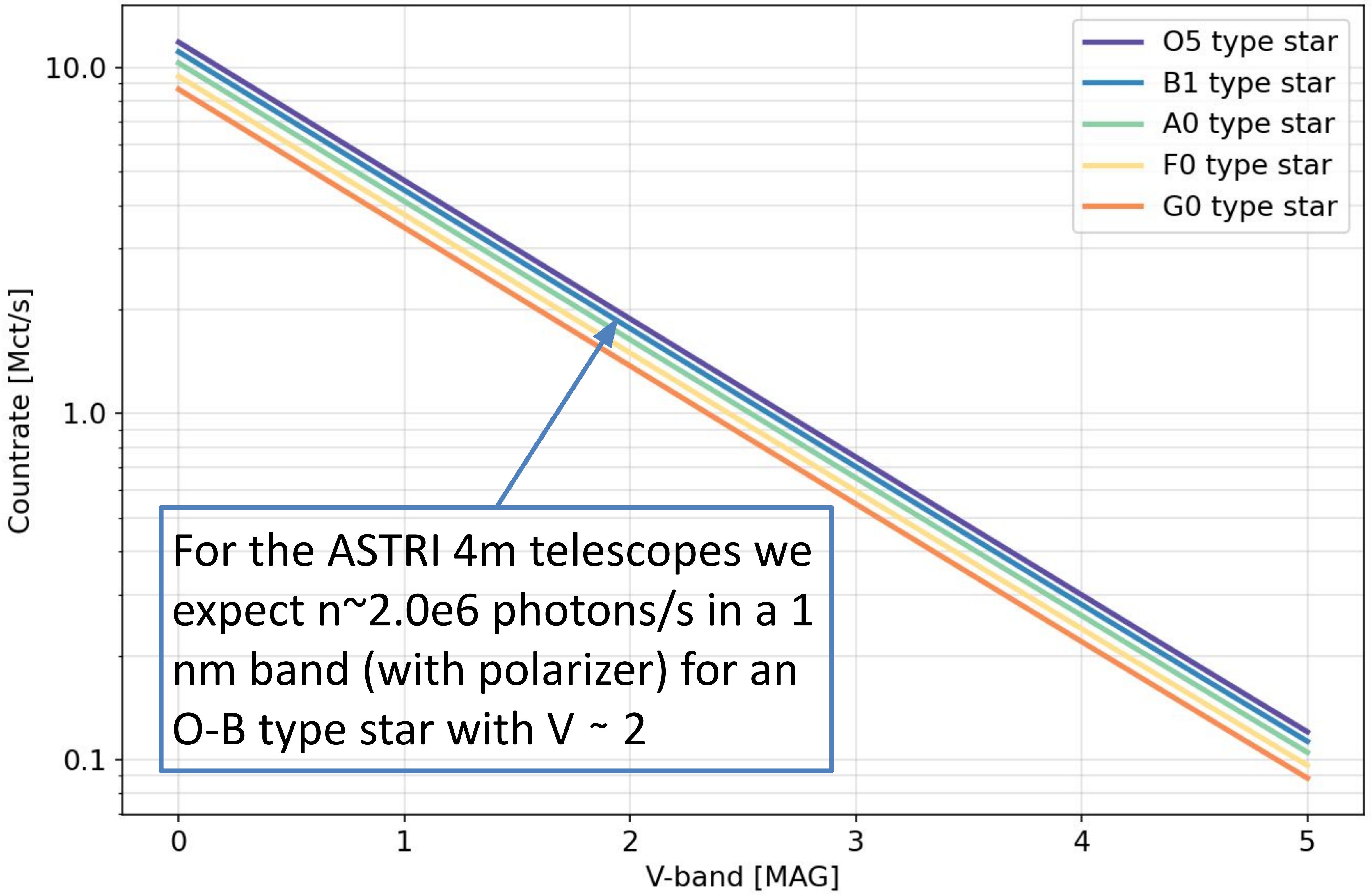
Mini-Array

S/N ratio in Photon Counting SII

$$S/N = \frac{N_{12,s}}{\sigma_{N_{12}}} \simeq \frac{QN_1N_2/N}{\sigma_{N_{12,r}}} = Q\sqrt{\frac{N_1N_2}{N}}$$

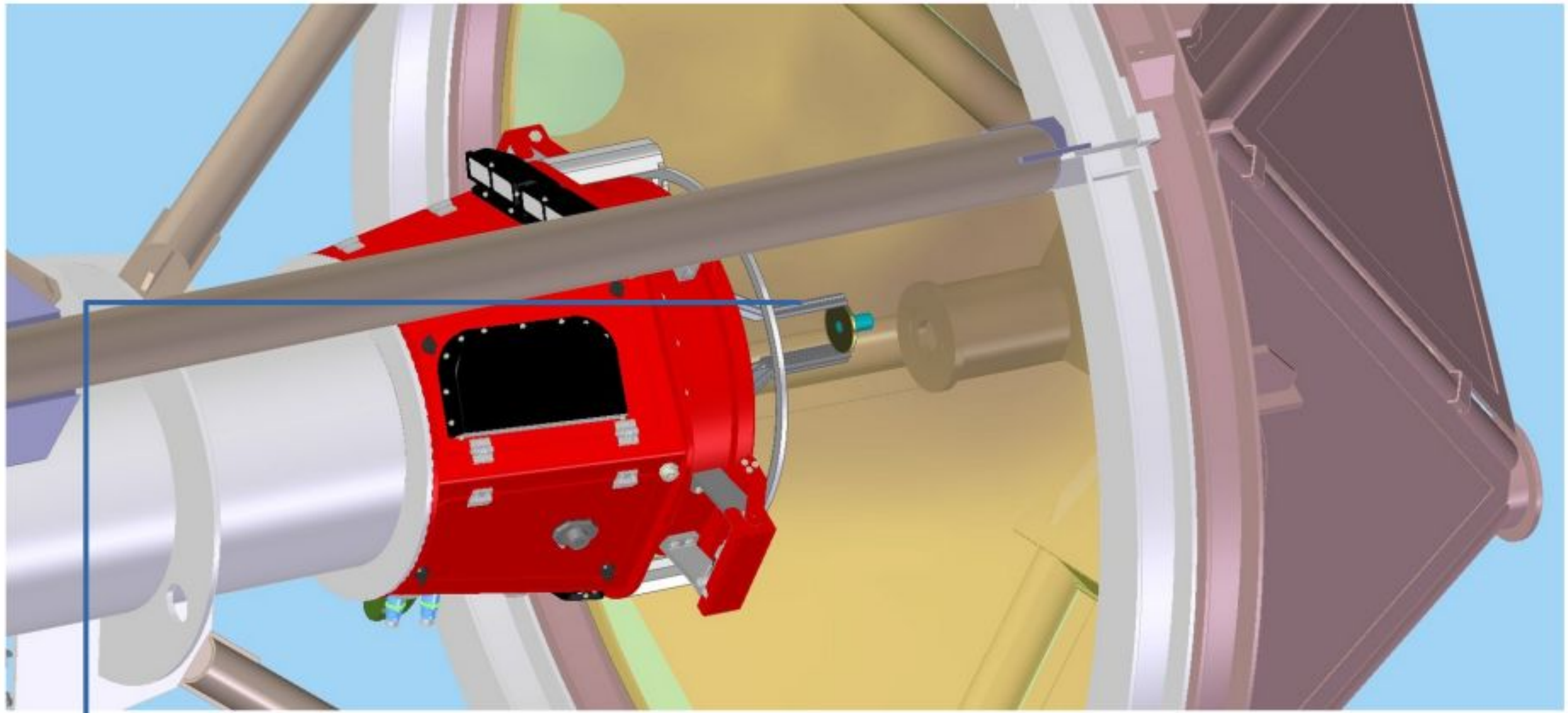
$$S/N = 7\,|\gamma|^2 \left(\frac{n}{2\,\mathrm{Mc/s}}\right)\left(\frac{\lambda}{500\,\mathrm{nm}}\right)^2\left(\frac{\Delta\lambda}{1\,\mathrm{nm}}\right)^{-1} \times \left(\frac{d\tilde{t}}{500\,\mathrm{ps}}\right)^{-1/2}\left(\frac{T}{5\,\mathrm{hr}}\right)^{1/2}.$$

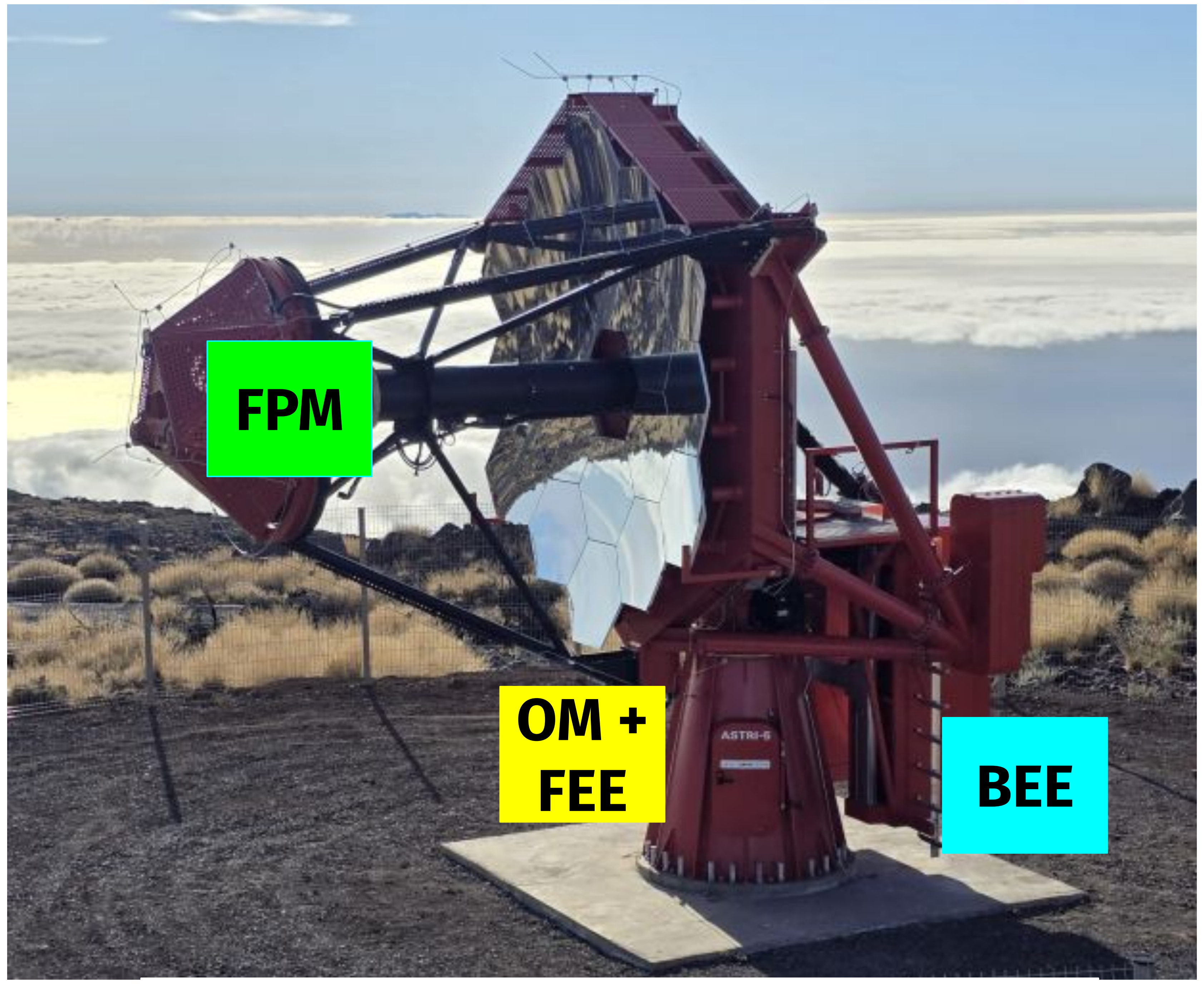
These number guided us in designing a **sub-ns, very narrow band (1-3 nm)** implementation



Basic idea: use SiPM detectors that have *hundreds of ps resolution* along with an *adequate sensitive area* (square mm), fed by a *fiber bundle* after which the beam can be *collimated* and the *spot size reduced*

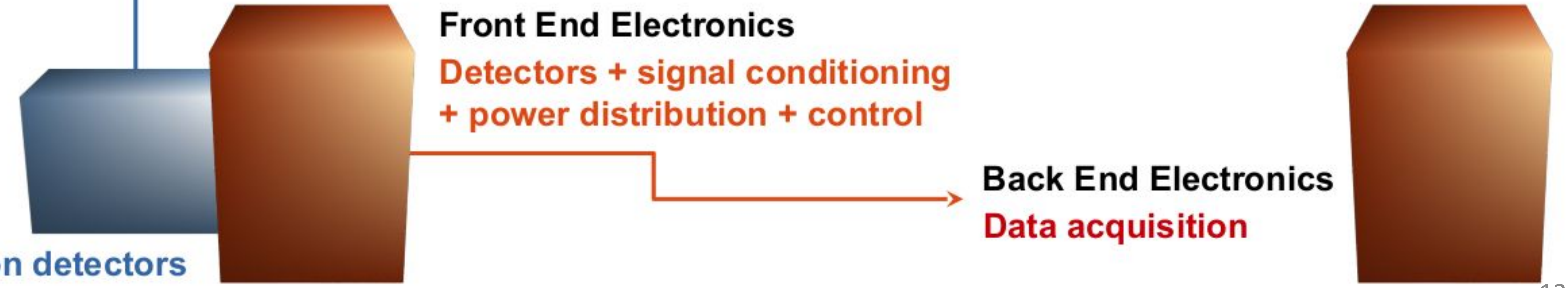
ASTRI Stellar Intensity Interferometry Instrument (SI3)
Instrument Design





Focal Plane Module (placed on top of the camera)

Focussing optics + optical fiber bundle + field camera



Front End Electronics

Detectors + signal conditioning + power distribution + control

Optical Module

Injecting light on detectors

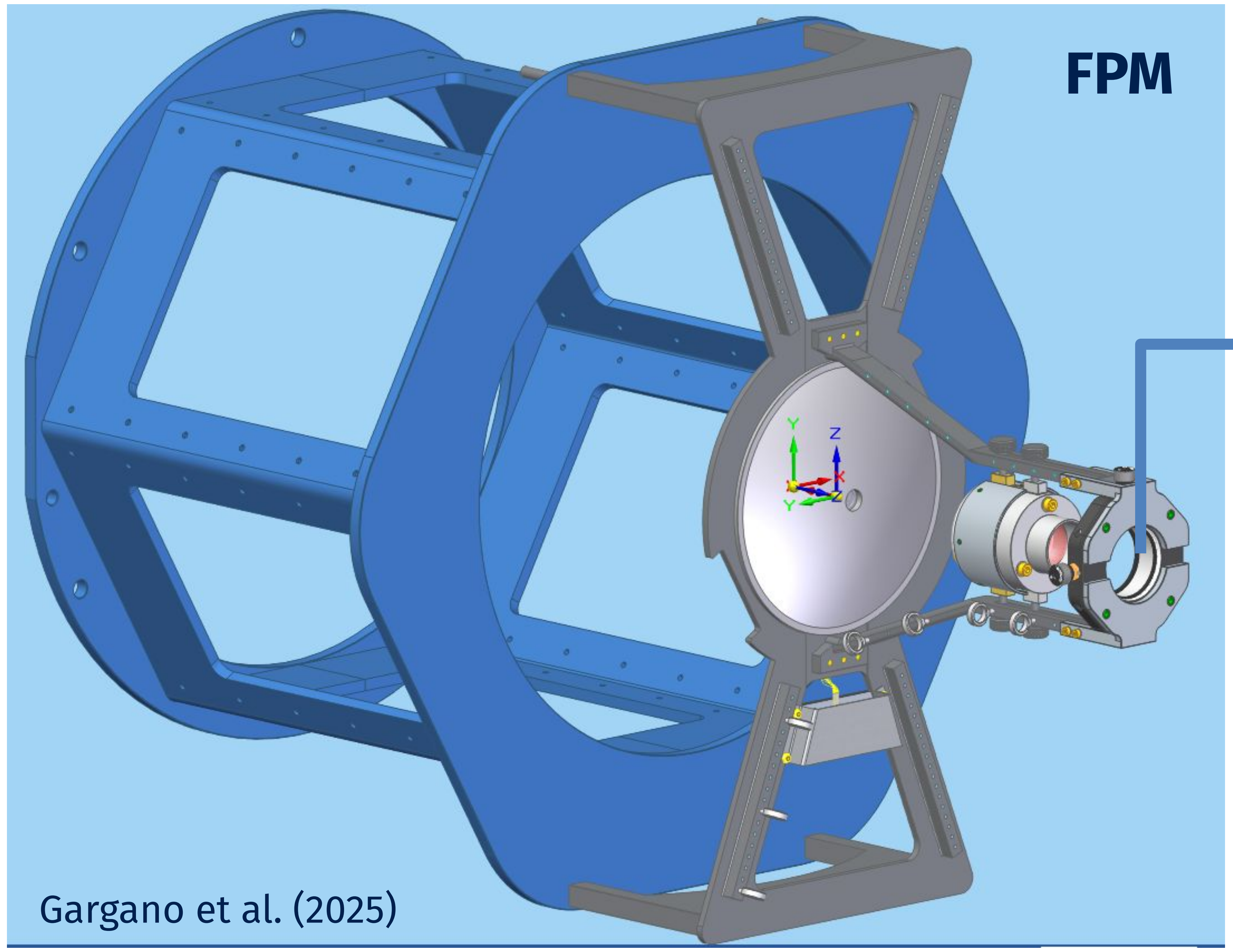
Back End Electronics

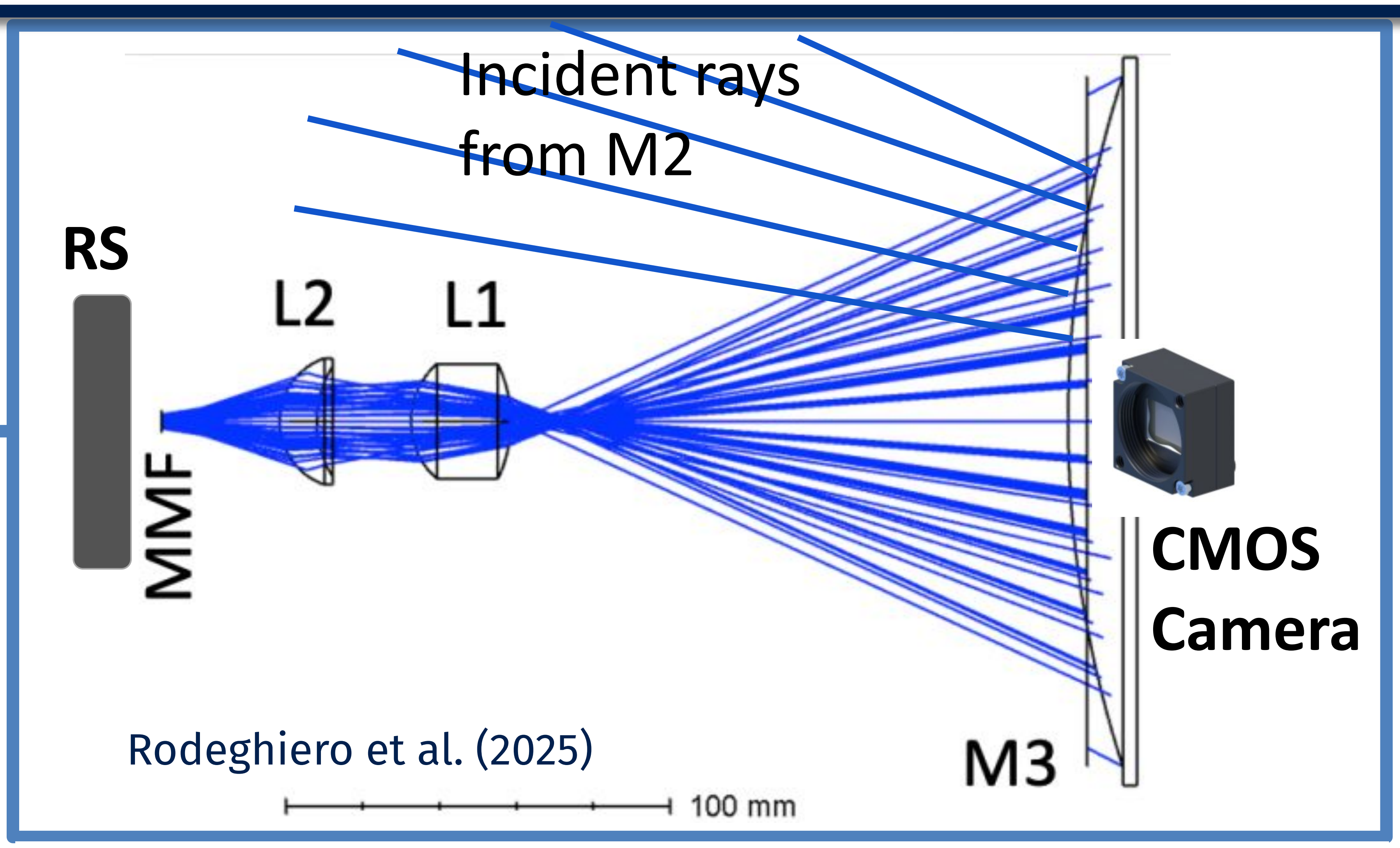
Data acquisition

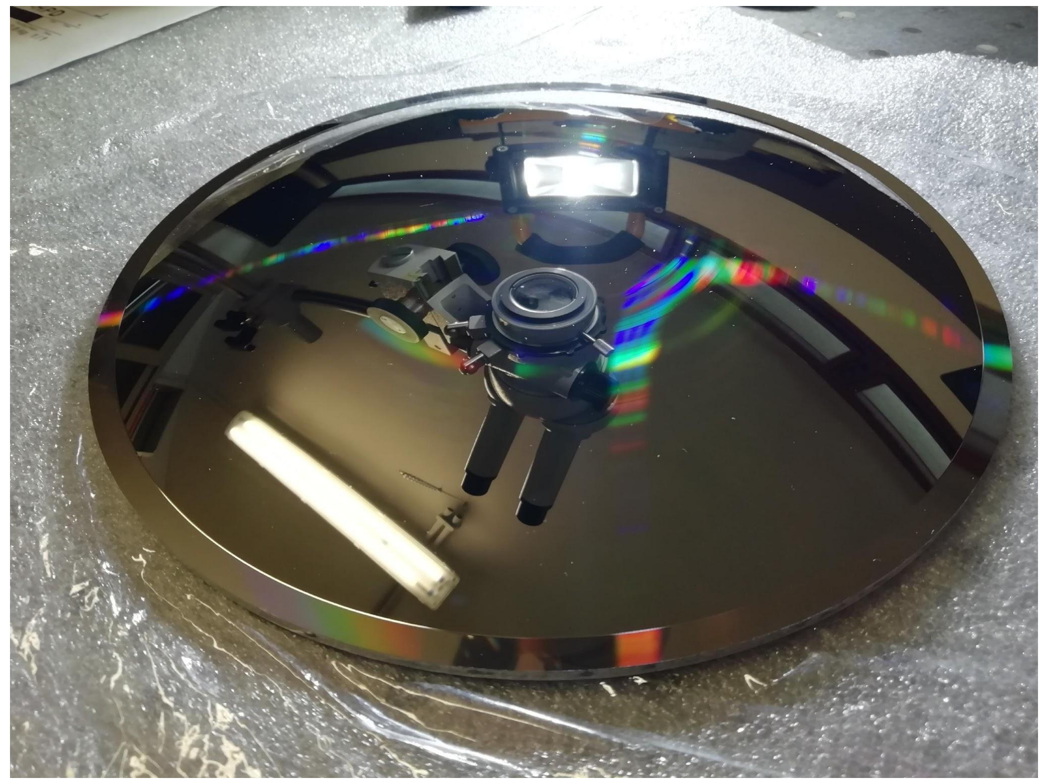
Zampieri et al. (2024)

ASTRI SI3
FPM: Focal Plane Module

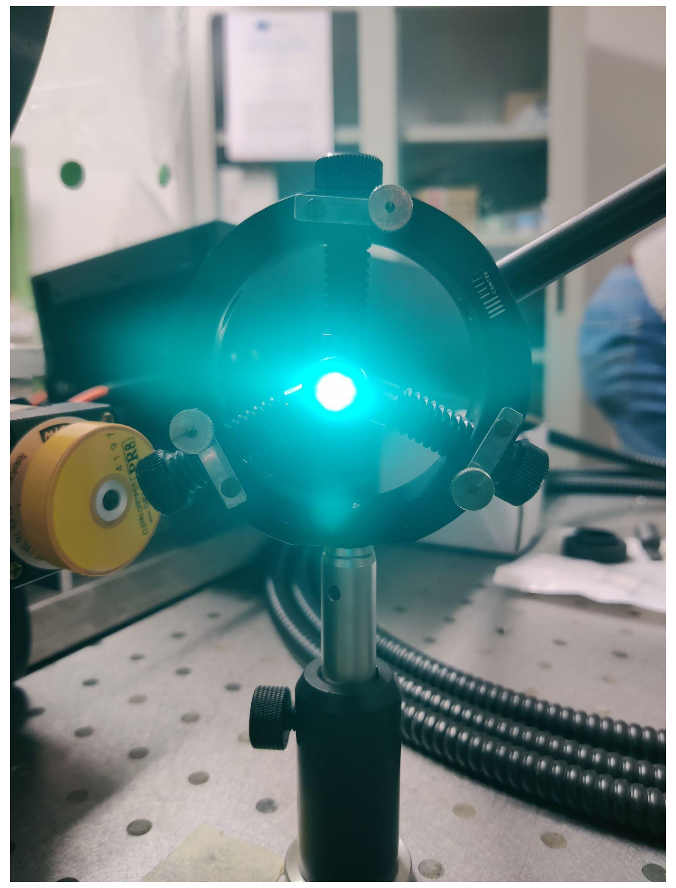
Mini-Array







M3 Aluminum mirror



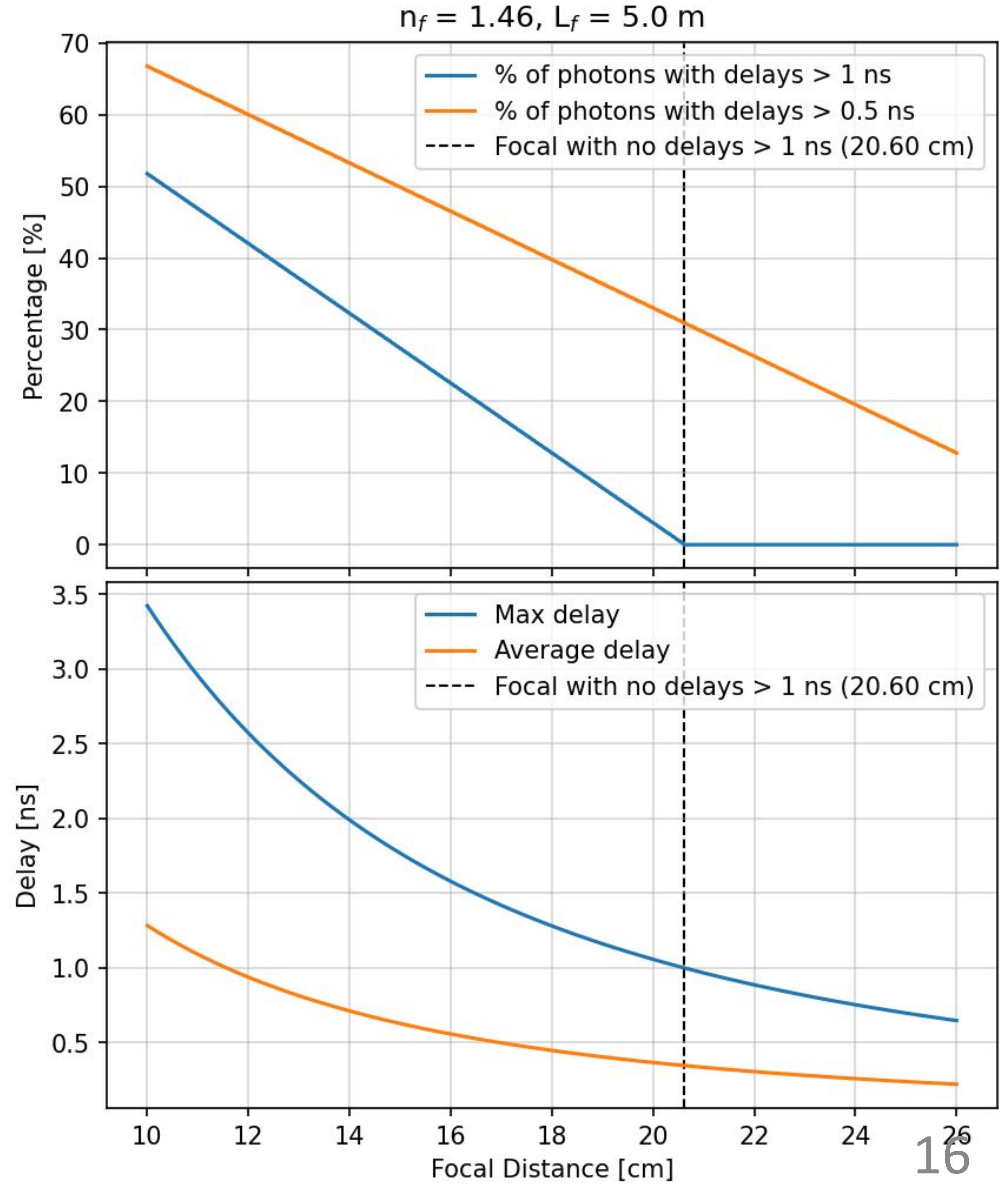
Focal Plane Optics:
Prefocal catadioptric system

Beam from telescope reflected off M3, collimated by L1 and refocused by L2 on a multimode optical fiber bundle (MMF)

CMOS camera on axis, at the center of M3, for checking the pointing using the reflected light from mirror RS

Focal Plane Optics: Optical fiber bundle (MMF)

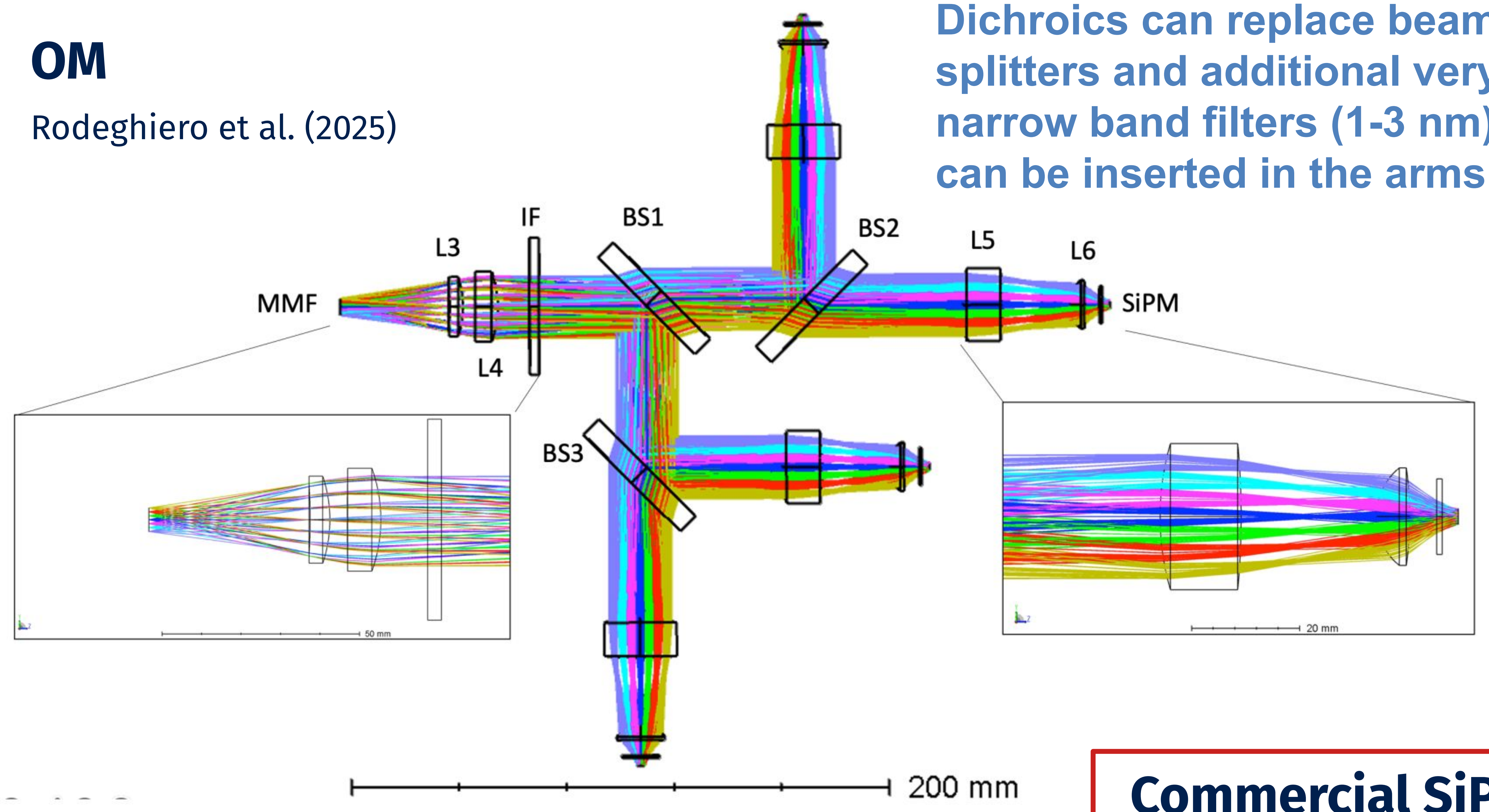
L = 5 meters
NA = 0.22
Transmission efficiency (tested): ~60%



ASTRI SI3
OM+FEE: Optical Module with detectors and Front End Electronics

OM
Rodeghiero et al. (2025)

Dichroics can replace beam splitters and additional very narrow band filters (1-3 nm) can be inserted in the arms

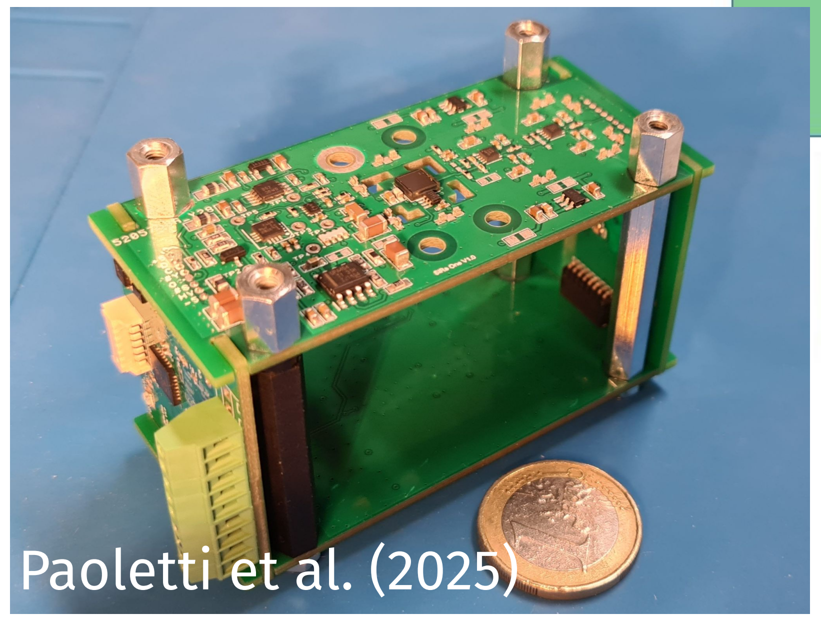


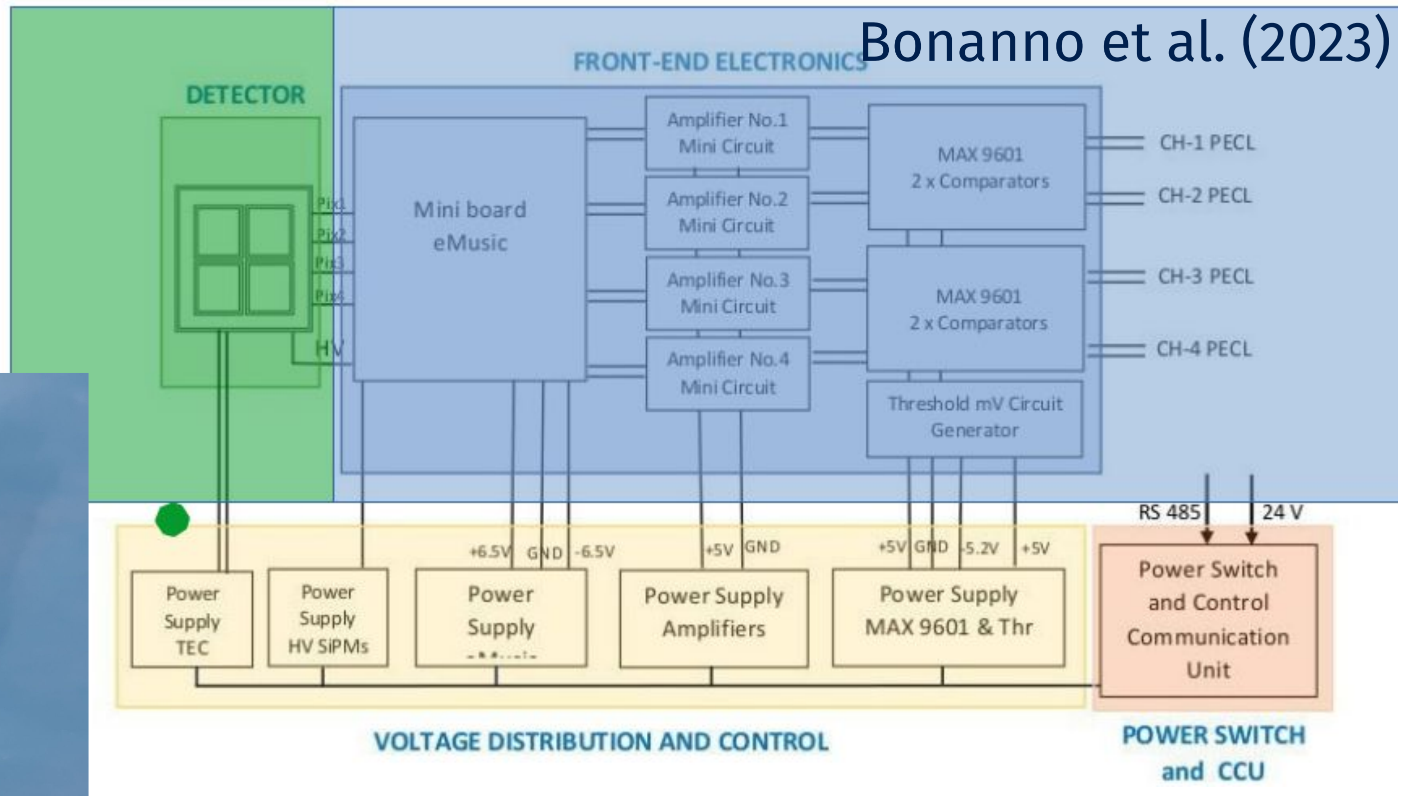
Light from the optical fiber is **collimated** and a **narrow band filter** is inserted

The beam is **split** in **4 paths** with 3 **50-50% beam splitters**

Each beam is **focused** on a different **SiPM detector** with a **second set of lenses**

Custom SiPM Detector





Maximum count rate (~25 Mct/s)
Linearity preserved up to ~20 Mct/s
Jitter < 500 ps

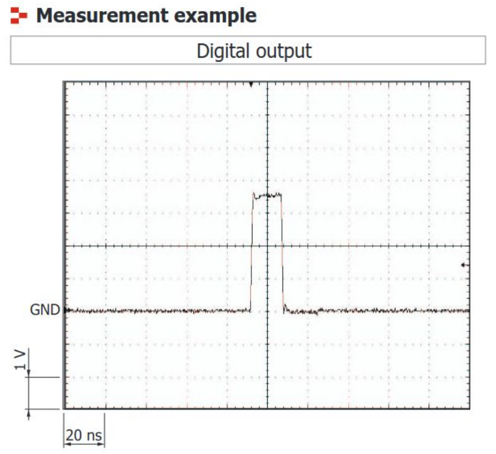
Under development

Commercial SiPM Detector

Hamamatsu MPPC C13366-3050GD

3 mm^2 photosensitive area, peak sensitivity 450 nm

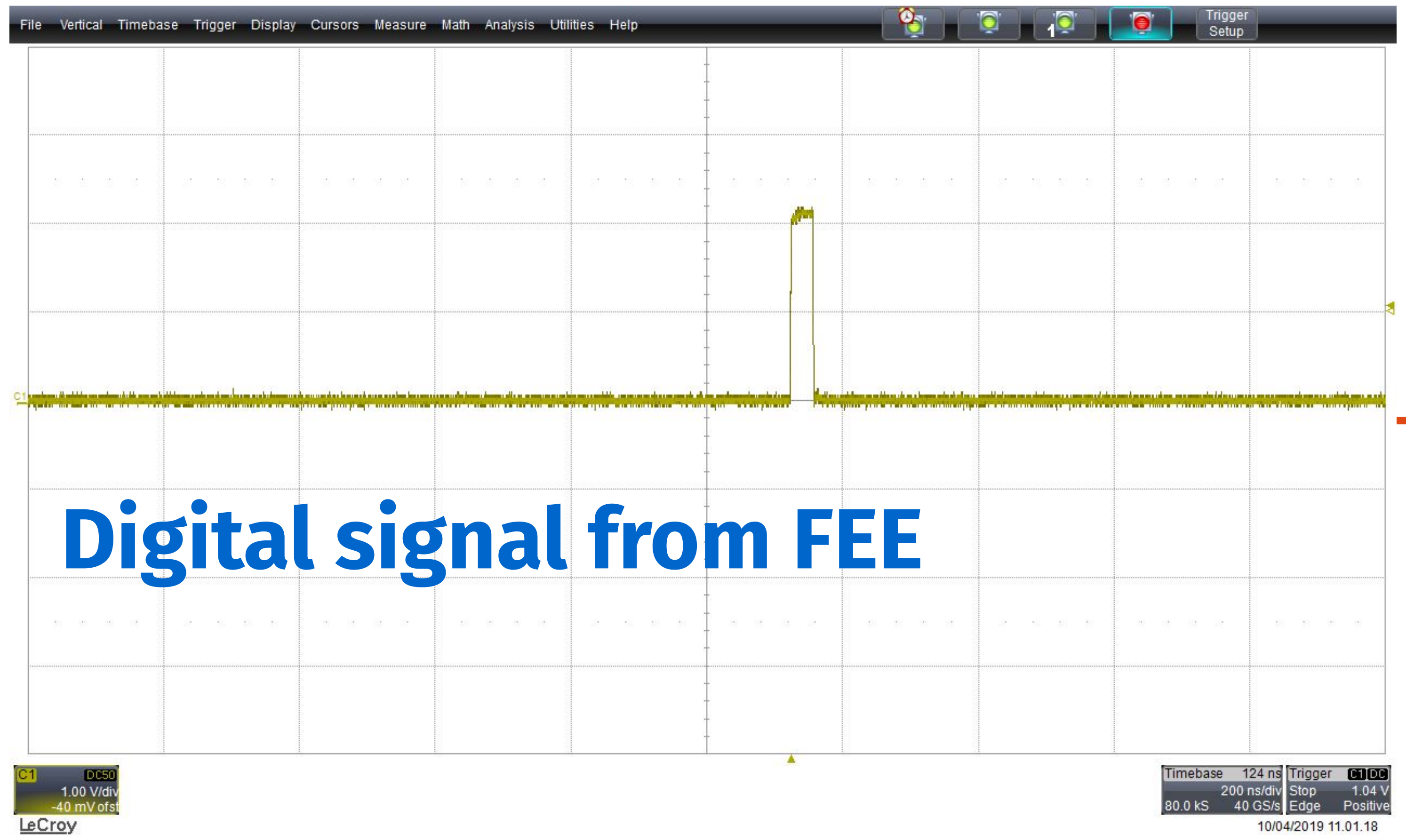
TE-cooled, onboard amplifier, comparator circuit, high-voltage power supply circuit, temperature control circuit



TTL-compatible digital output pulse

Max rate: ~8 Mct/s
Linearity preserved up to ~5 Mct/s
Jitter ~500 ps

ASTRI SI3
BEE: Back End Electronics



Digital signal from FEE

x4

Time-to-Digital Converter (TDC)
Time Tagger Ultra
Swabian Instruments

80 Mcounts/s max rate
160 MB/s max data rate
< 10 ps time resolution

Workstation
Super Tower 732D3-903B
Supermicro

Time Distribution Unit (TDU)
White Rabbit system

PPS signal + Clock reference signal

To Array Data Acquisition System
1.12 Gb/s max rate

Zampieri et al. (2024)

An Italian saying applies here:

Tra il dire ed il fare c'è di mezzo il mare…

Literally:

Between saying it and doing it, there is a sea…

There's a world of difference between saying and doing

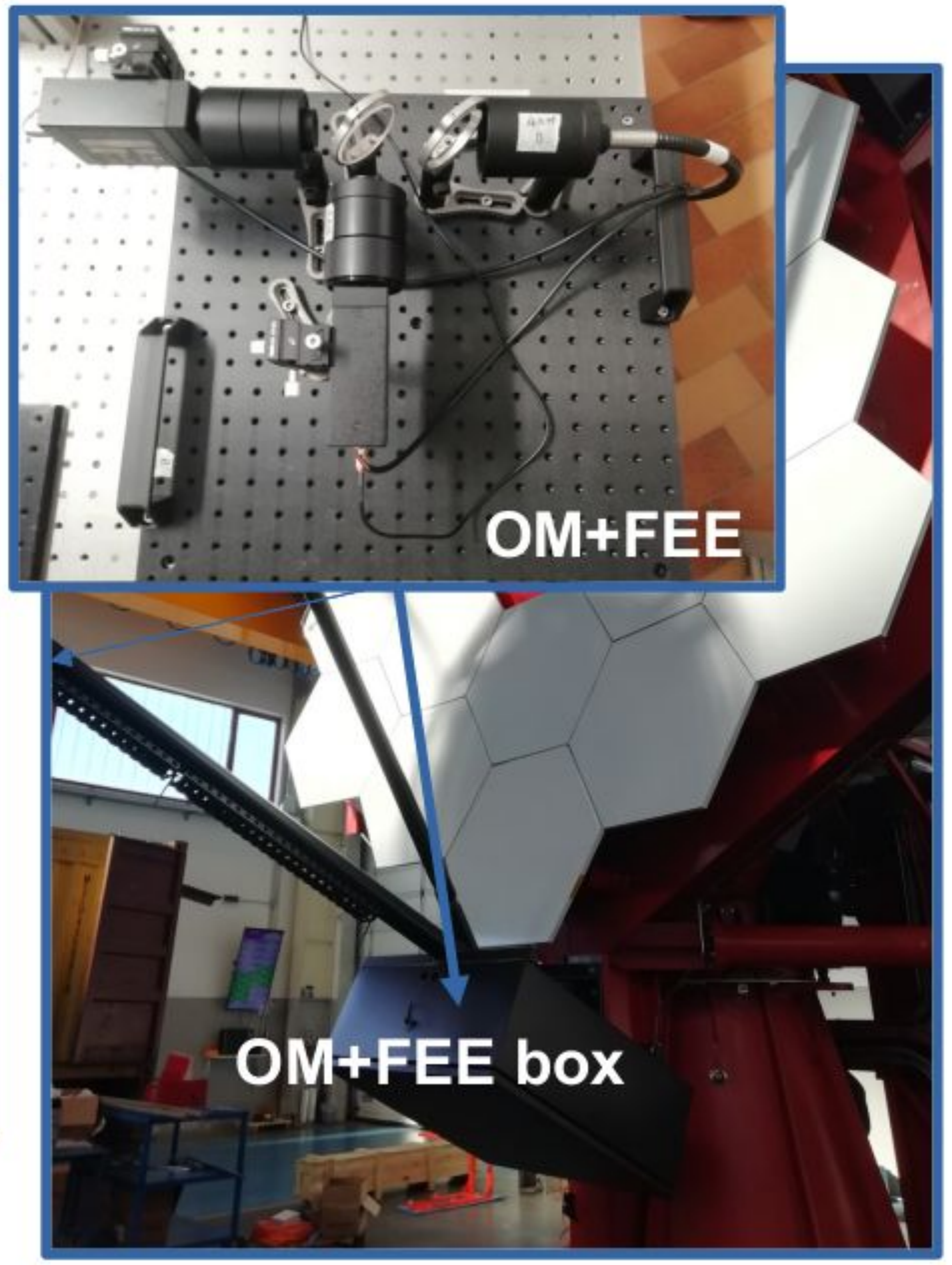
ASTRI SI3
SI3-1 fully assembled and ready for shipment!

ASTRI Mini-Array

Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA | INAF ISTITUTO NAZIONALE DI ASTROFISICA

WP 1450 - SI3-1

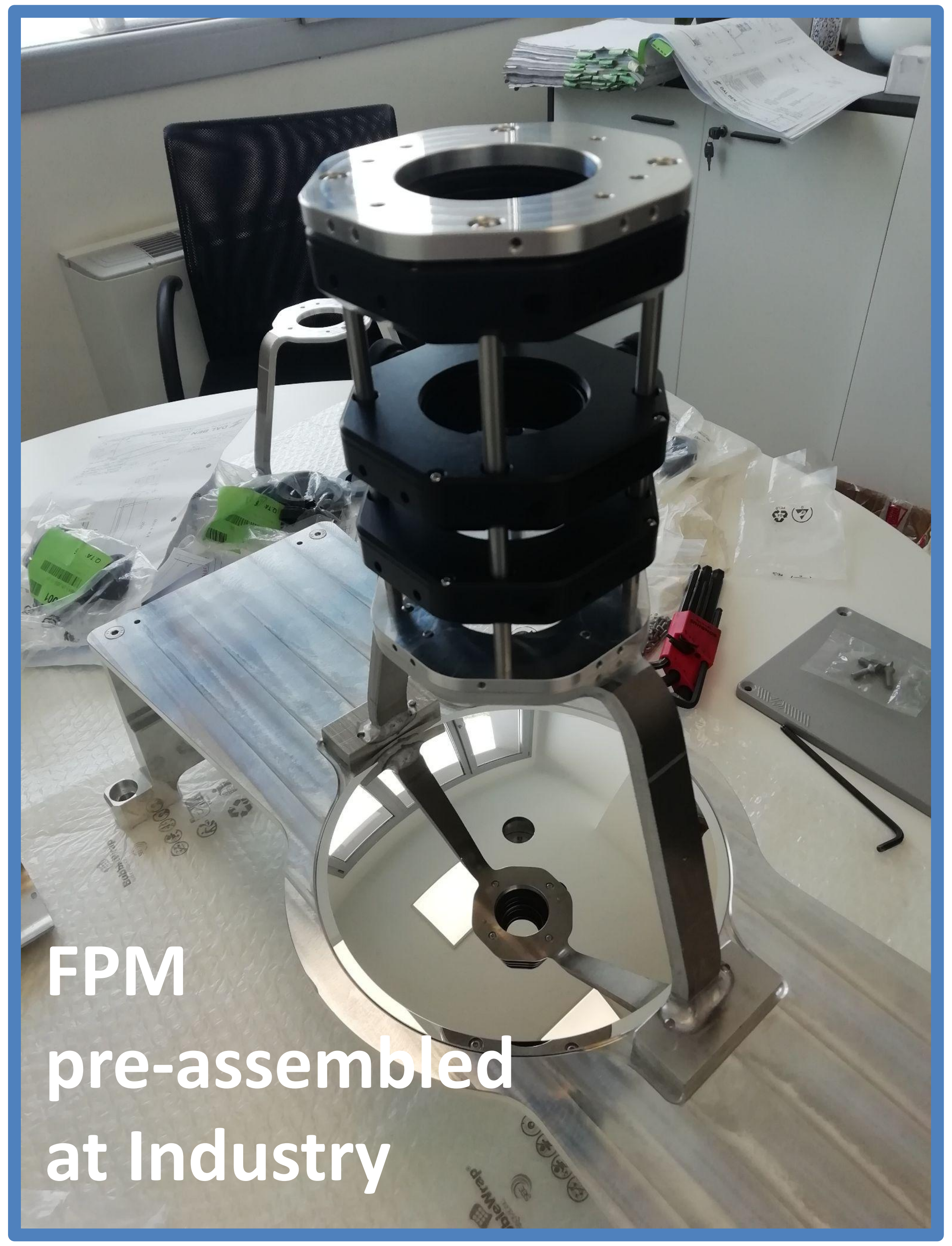
CTA+ Progress Meeting
Catania (Sep 22, 2025)



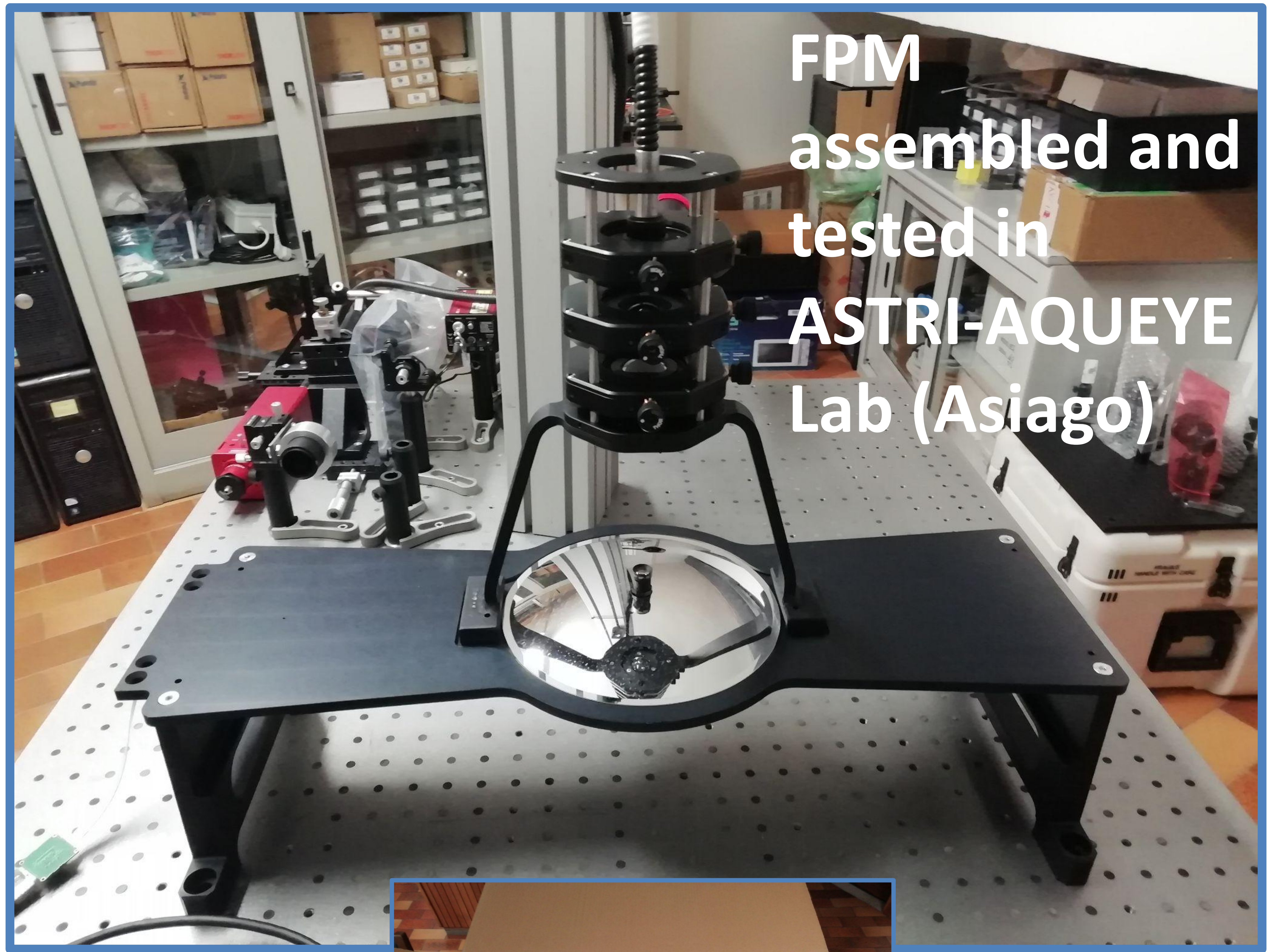
Progetto PNRR CTA+
Proposta IR0000012
CUP: C53C22000430006

Missione 4 Istruzione e Ricerca
Componente 2 Dalla ricerca all'impresa
Linea di investimento 3.1

ASTRI SI3 - First Instrument
Fabrication and Assembly of **FPM** (Jul-Sep 2025)



FPM
pre-assembled
at Industry

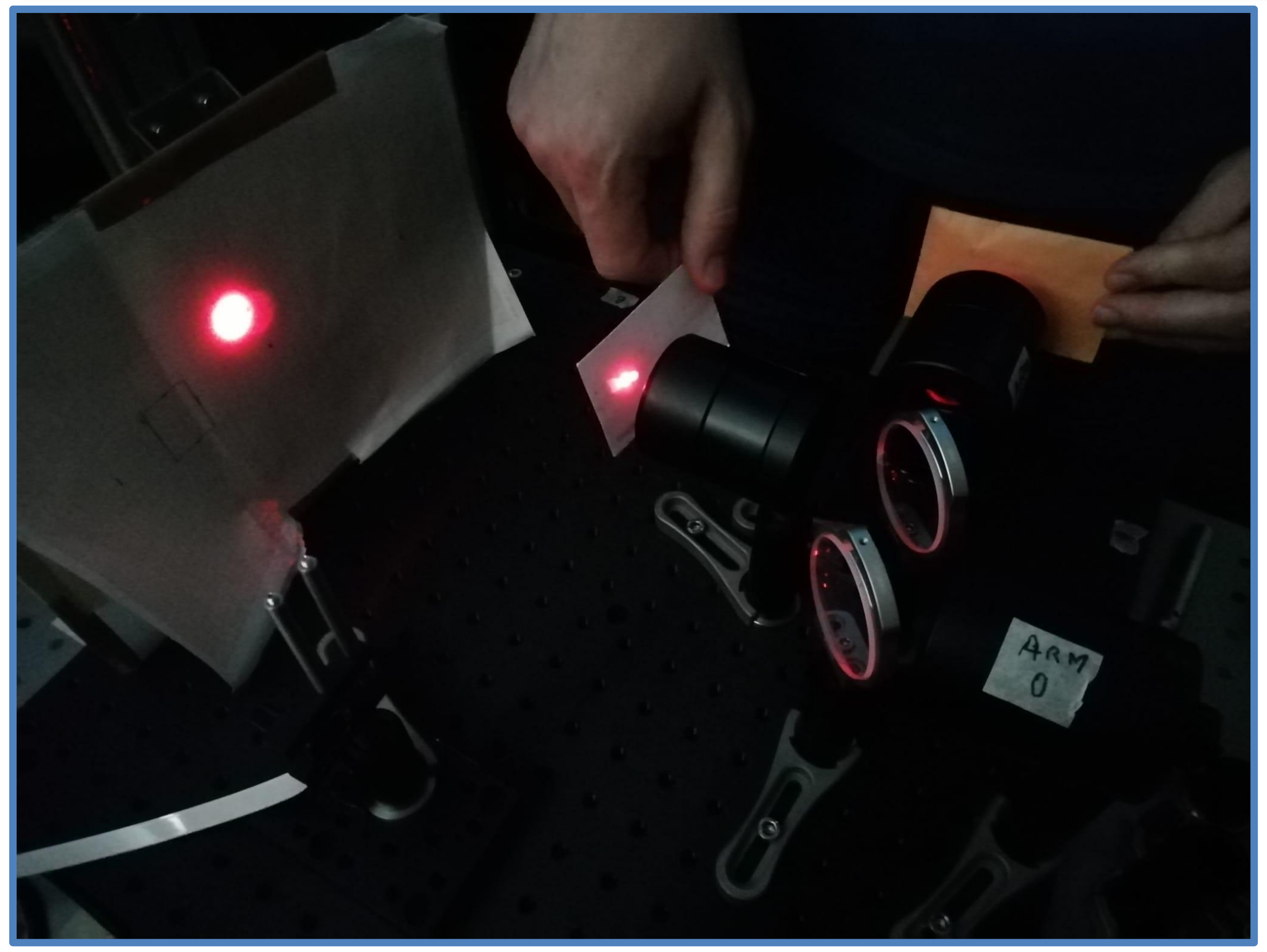


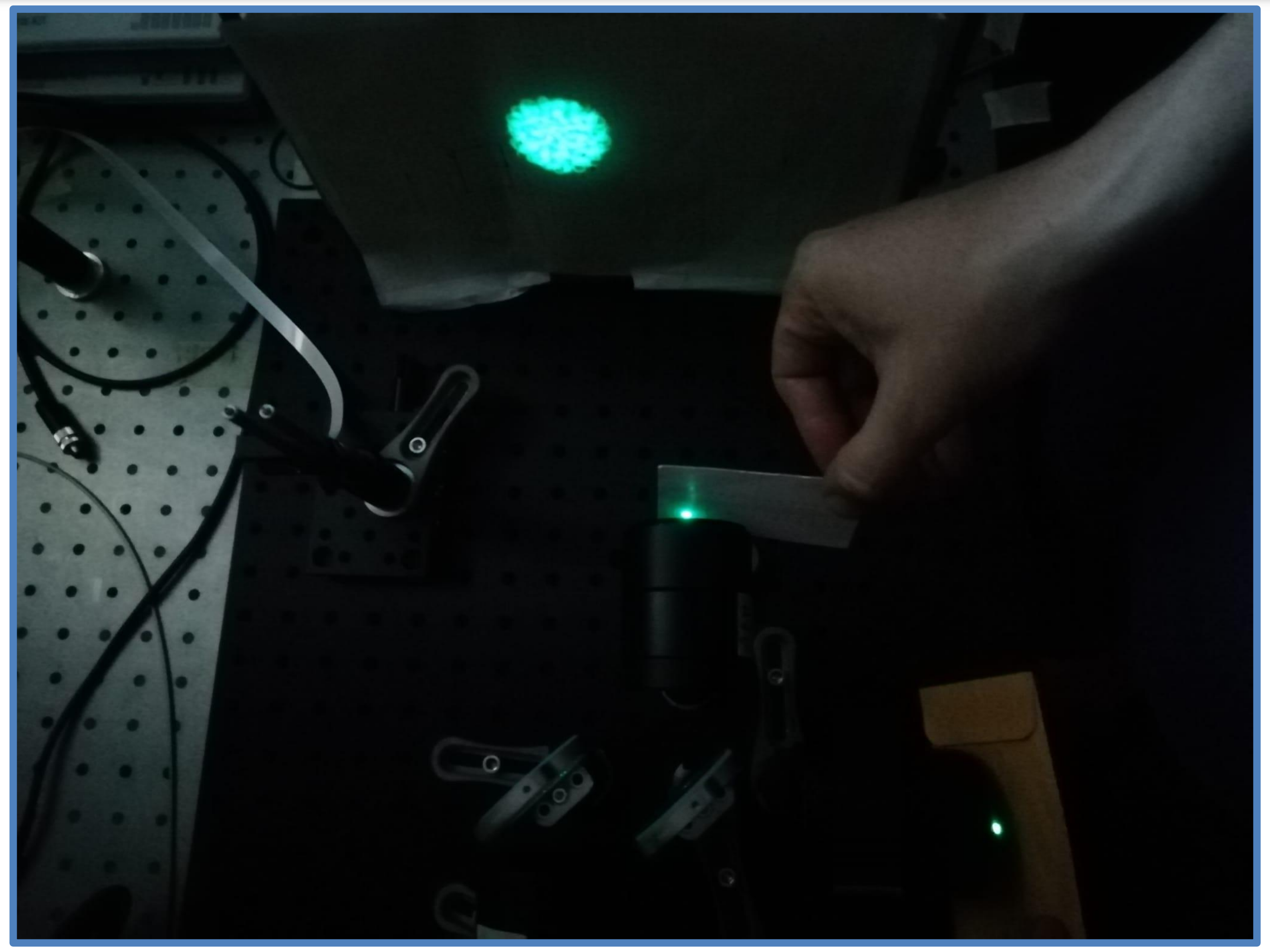
FPM
assembled and
tested in
ASTRI-AQUEYE
Lab (Asiago)

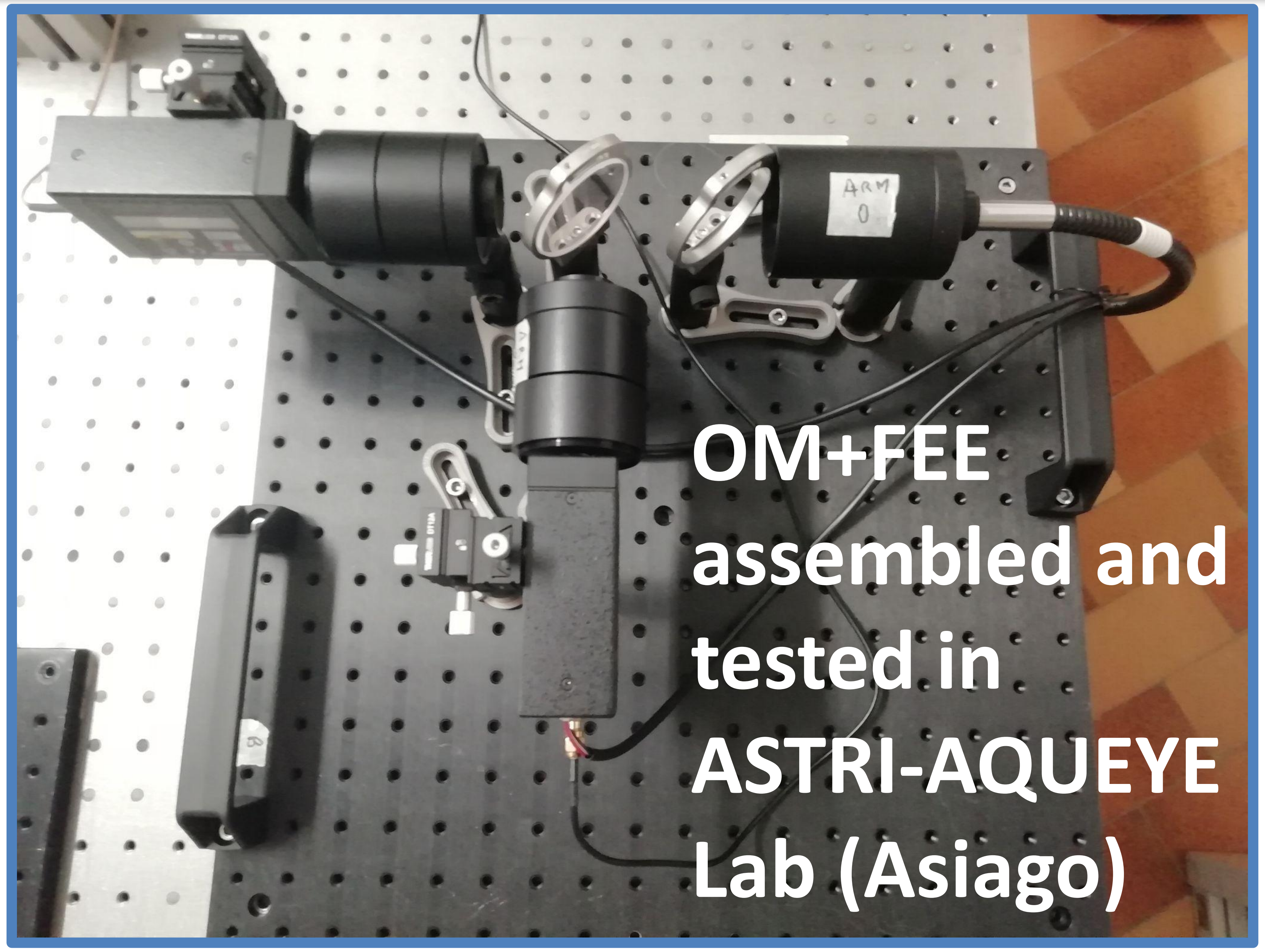
Companies:
Dal Ben,
Laboratorio BS,
Tecnottica,
Thorlabs, Ximea

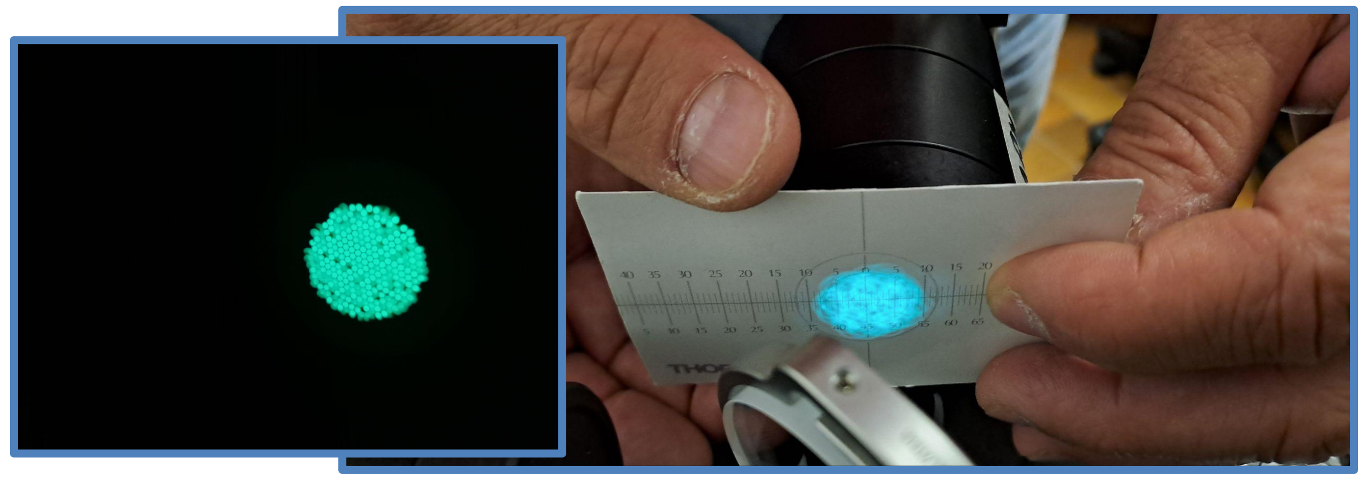
ASTRI SI3 - First Instrument
Fabrication and Assembly of **OM+FEE** (Jul-Sep 2025)

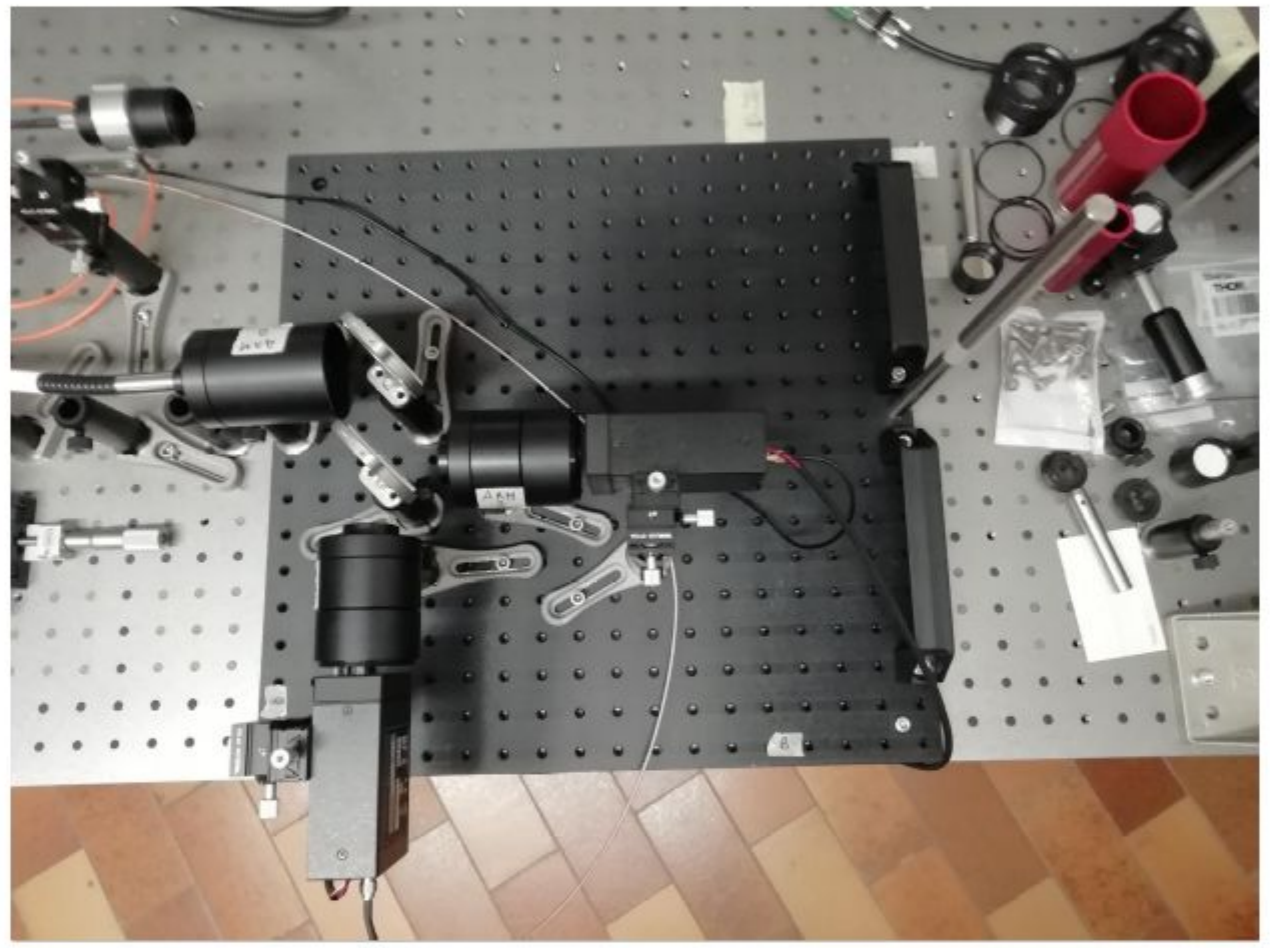
Mini-Array

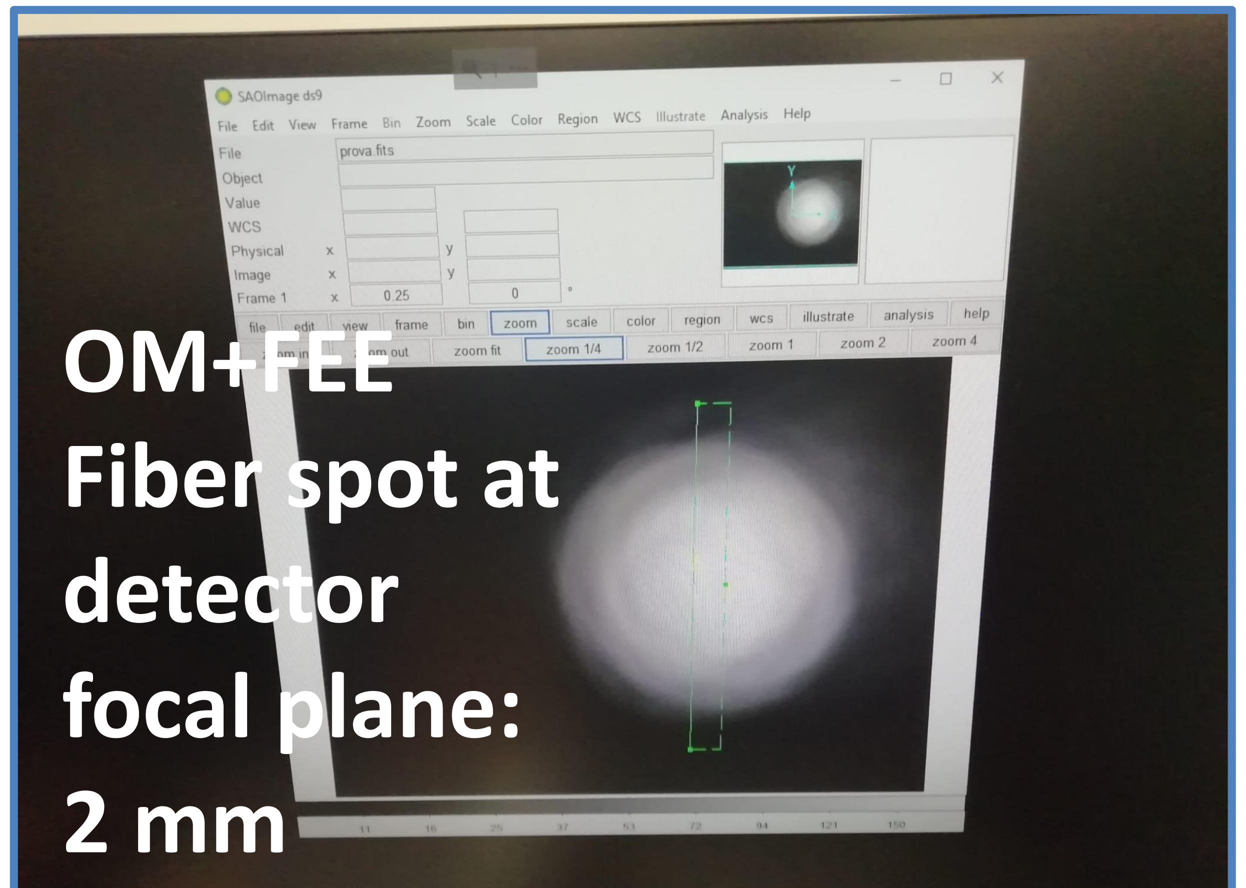


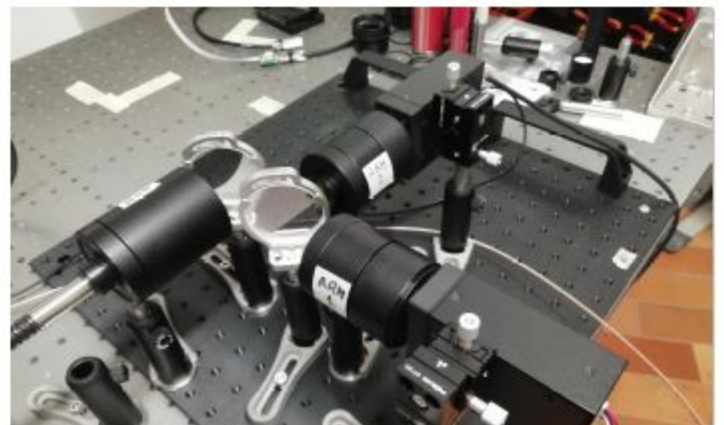


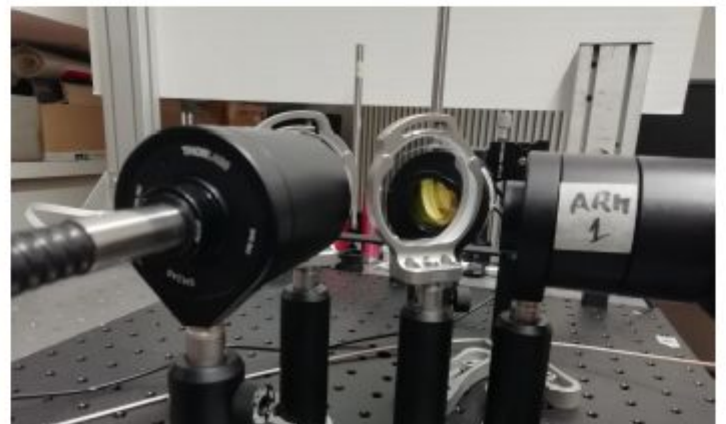




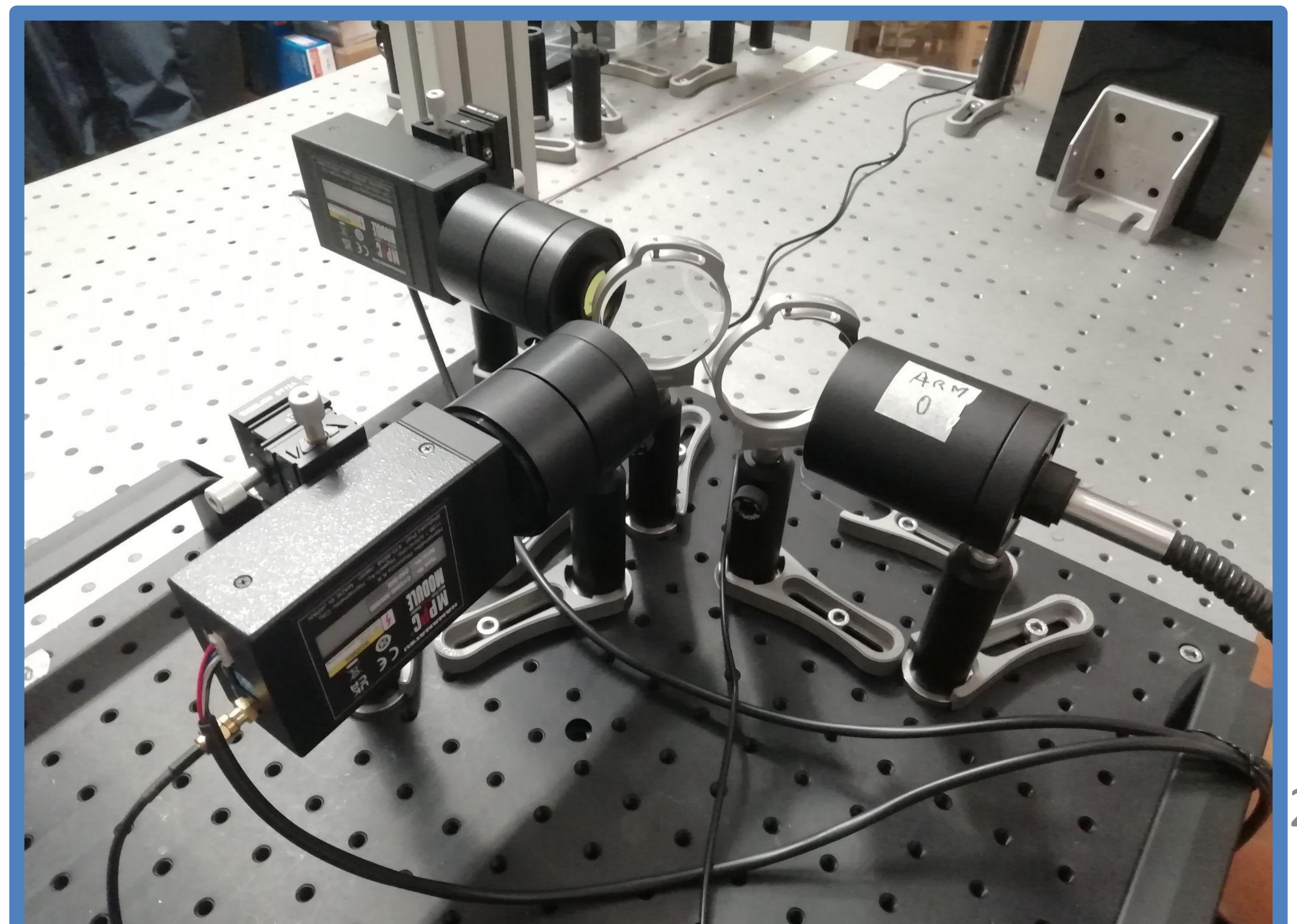






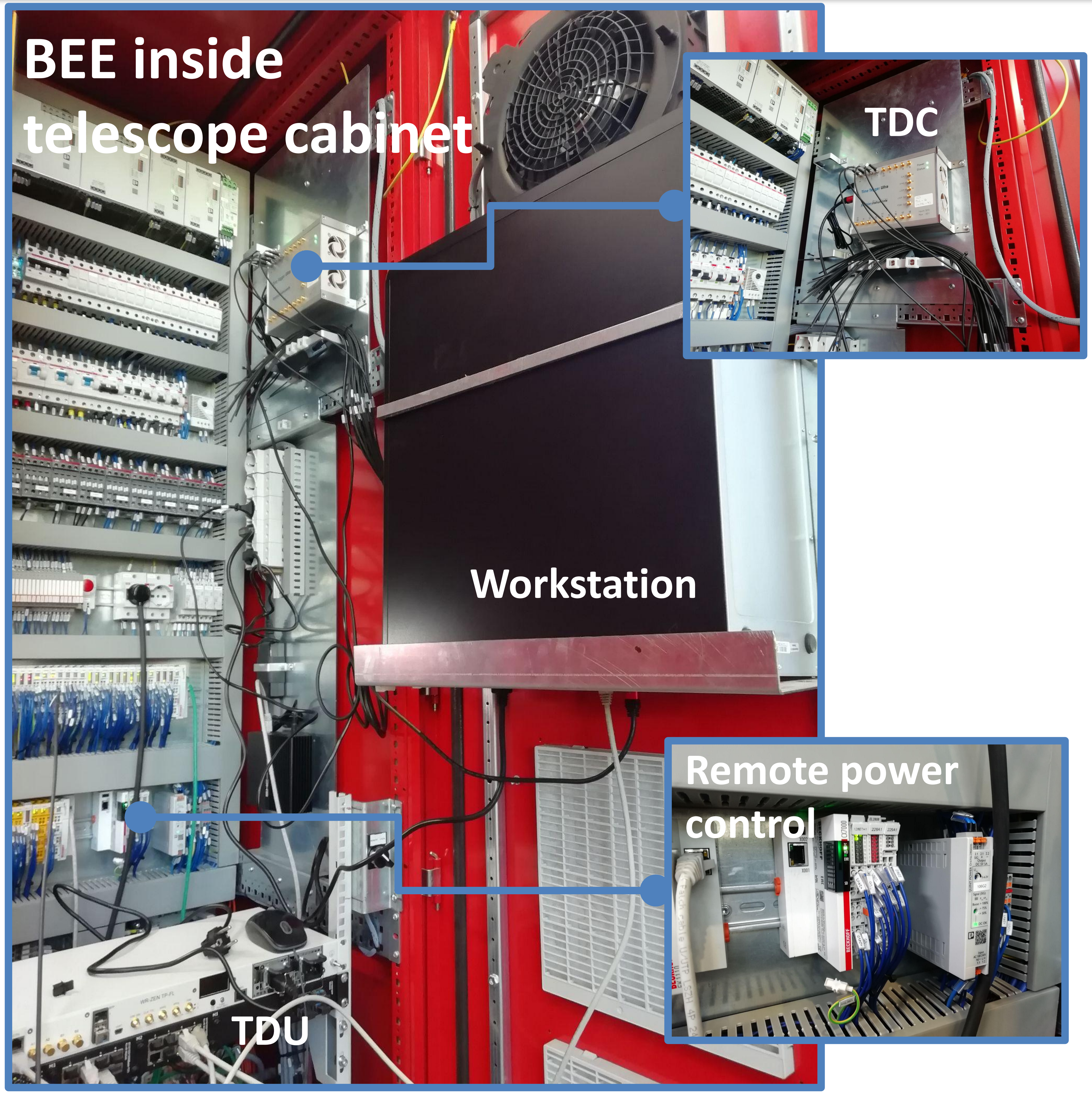


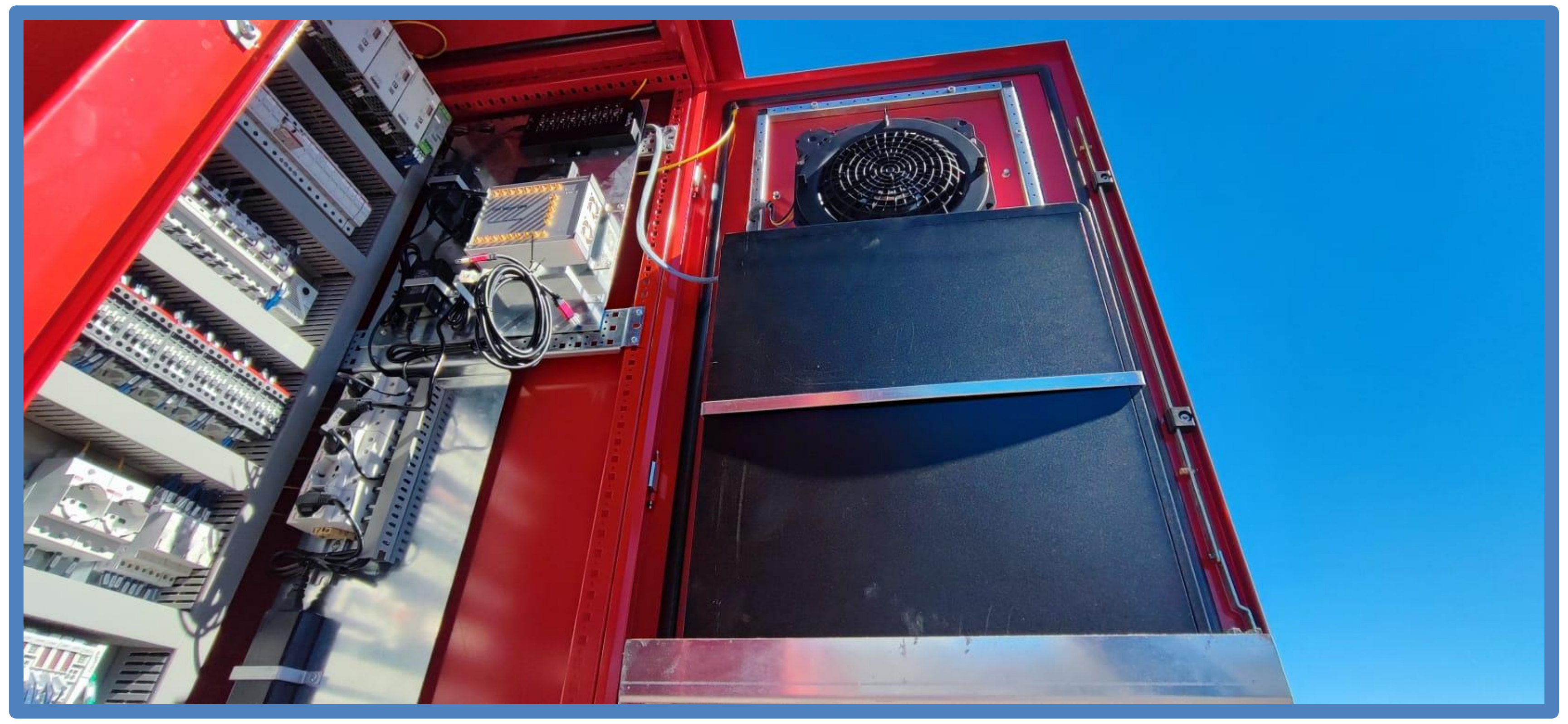
Companies:
Tecnottica,
Thorlabs,
Ceramoptec,
Hamamatsu



ASTRI SI3

Fabrication, Assembly and Integration of **BEE** (Nov-Dec 2024)

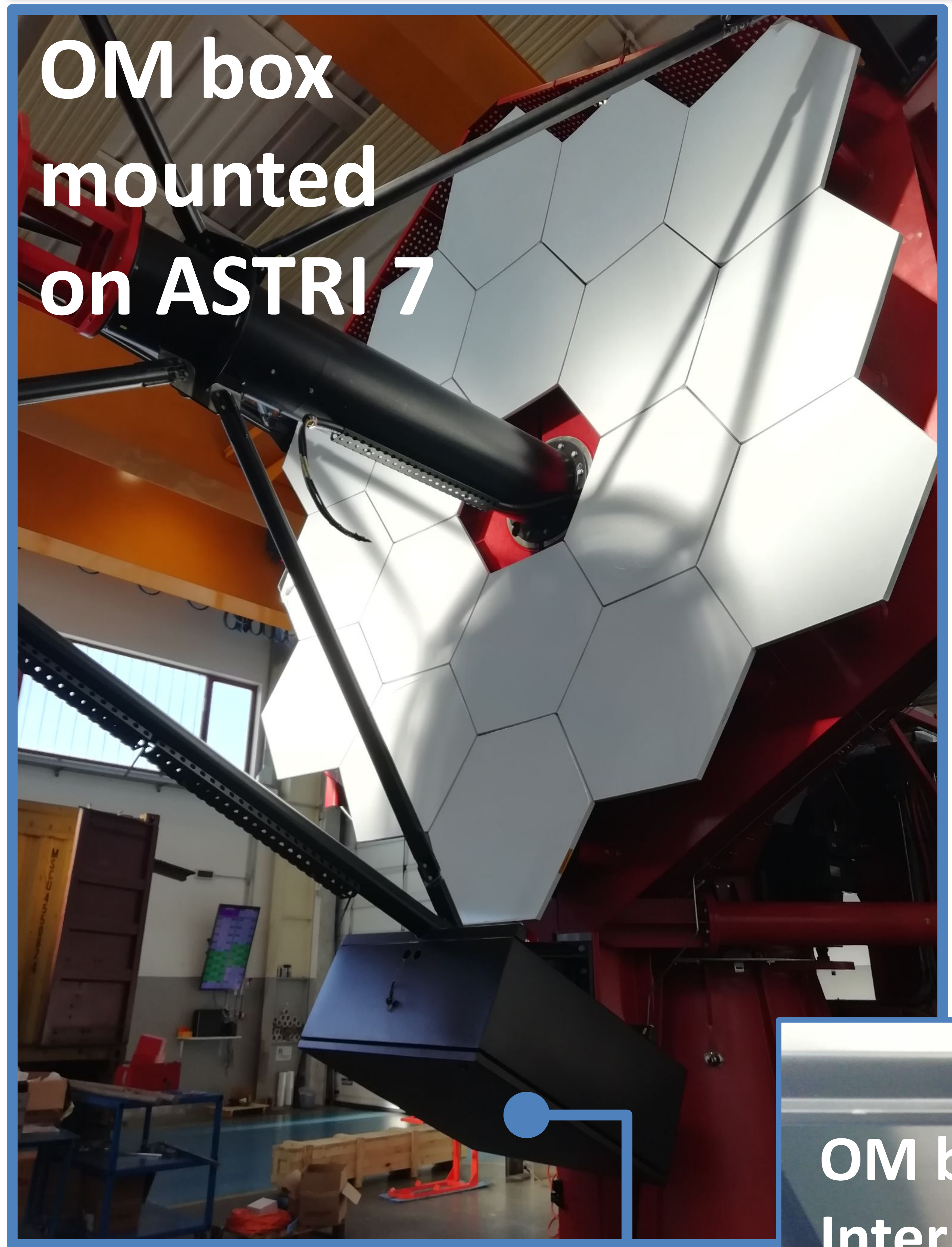


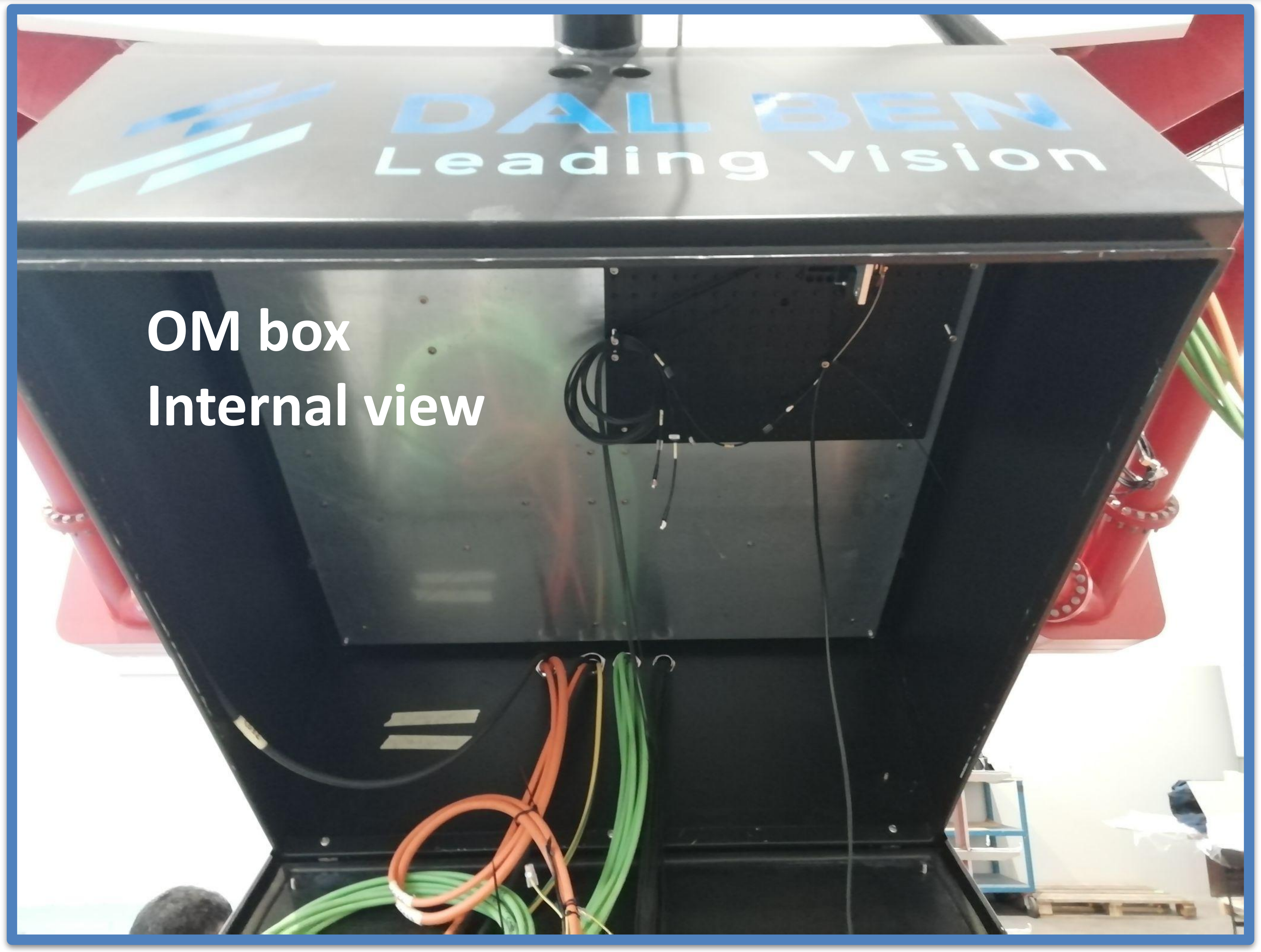


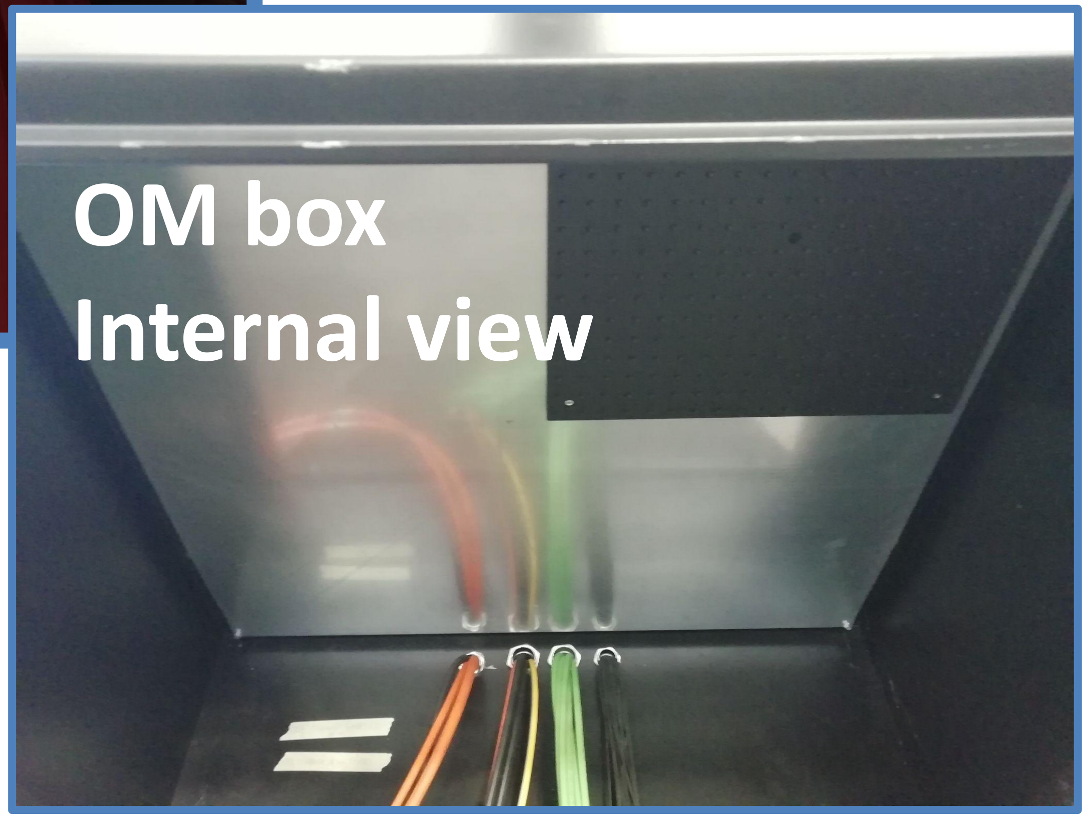
Companies:
Swabian Instruments,
Supermicro

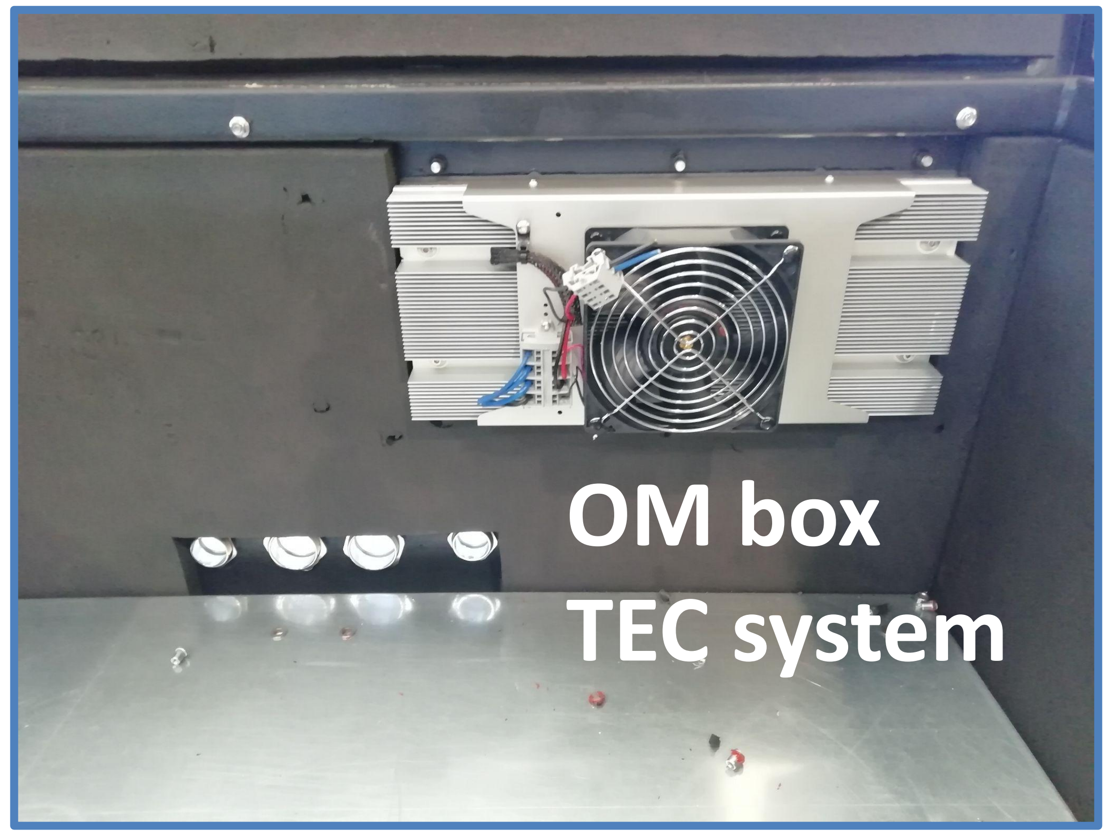
ASTRI SI3 - First Instrument
Fabrication and Assembly of **OM box** (Apr-Oct 2025)

Mini-Array



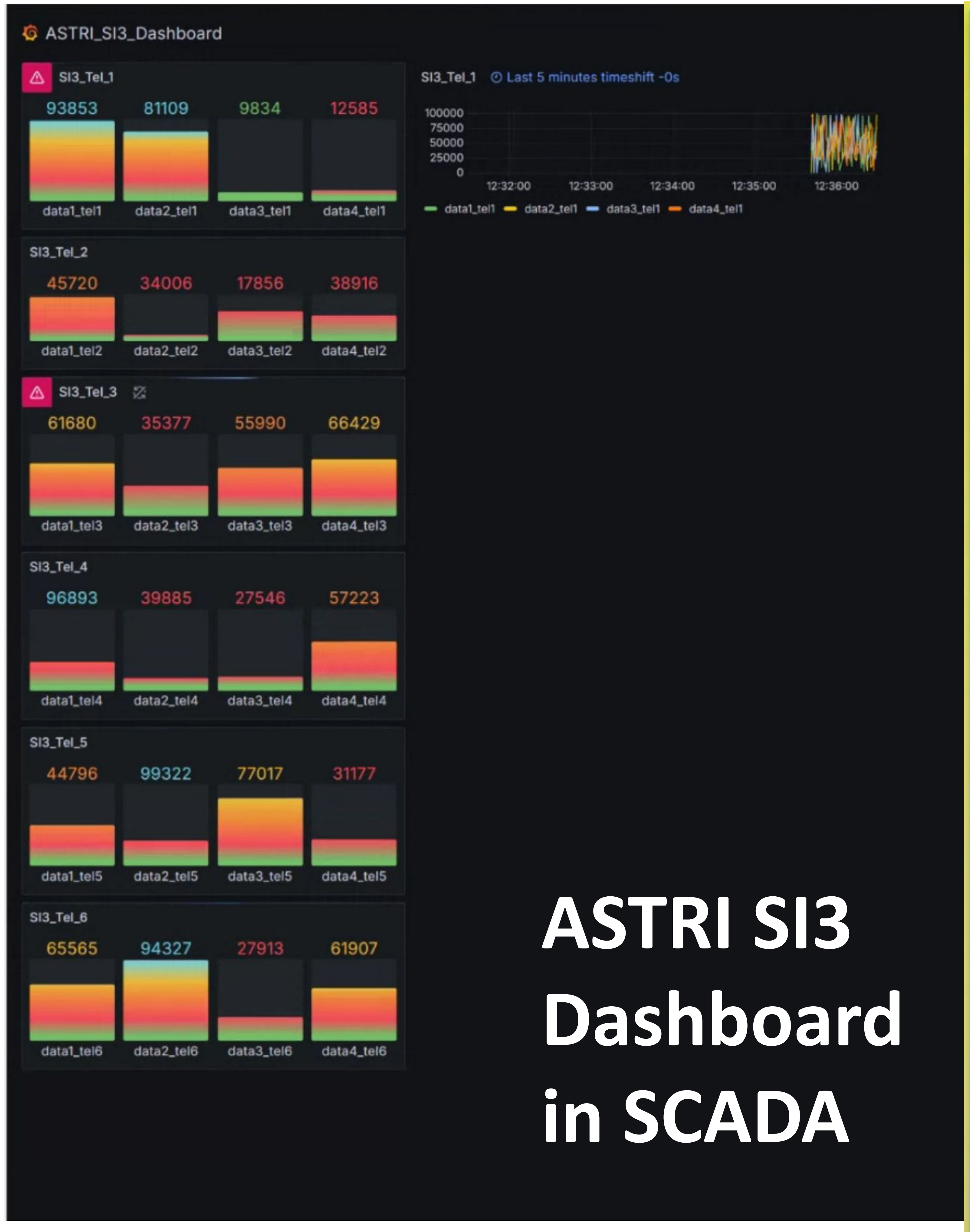






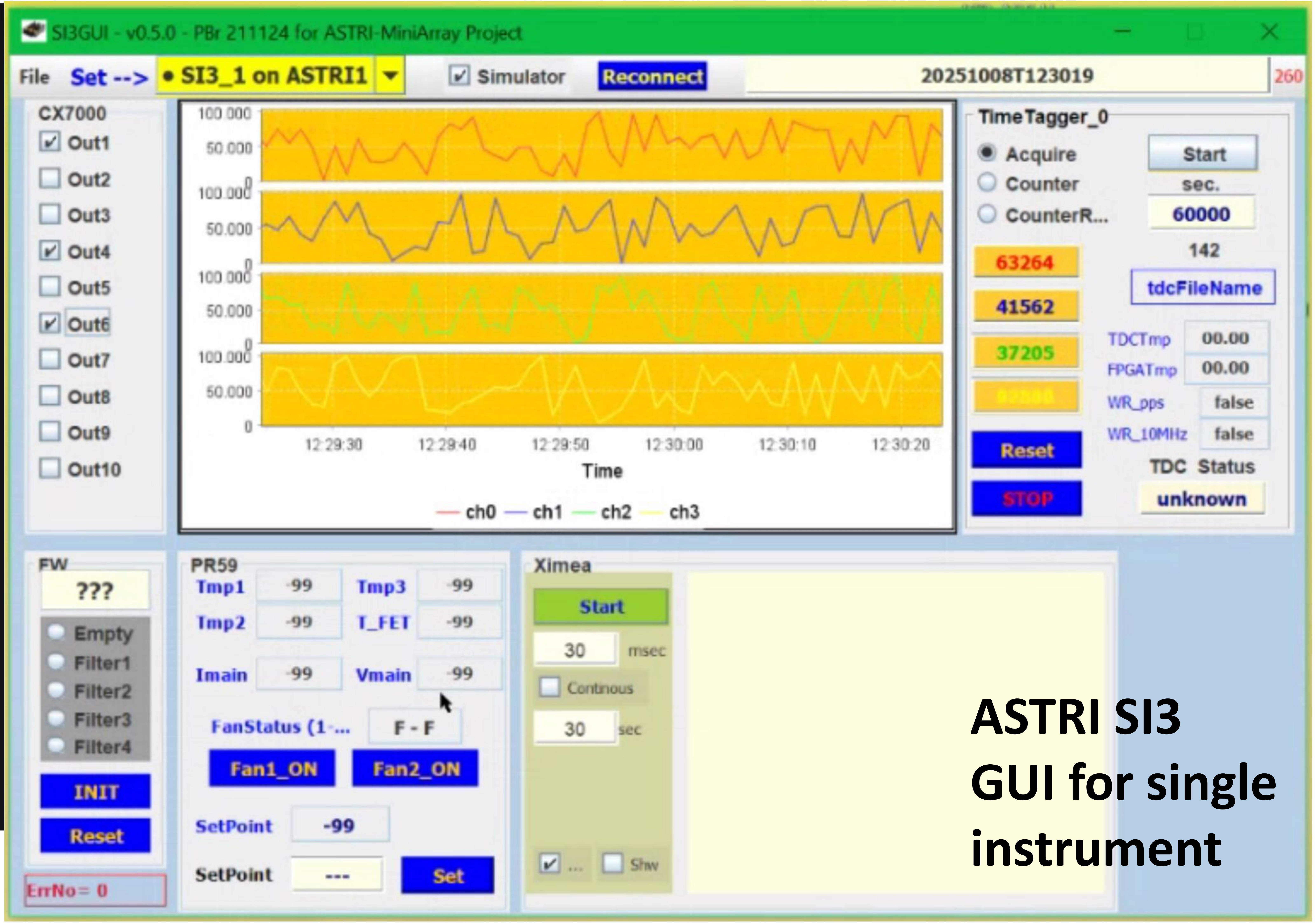
Company:
Dal Ben

ASTRI SI3
Local Acquisition/Control software



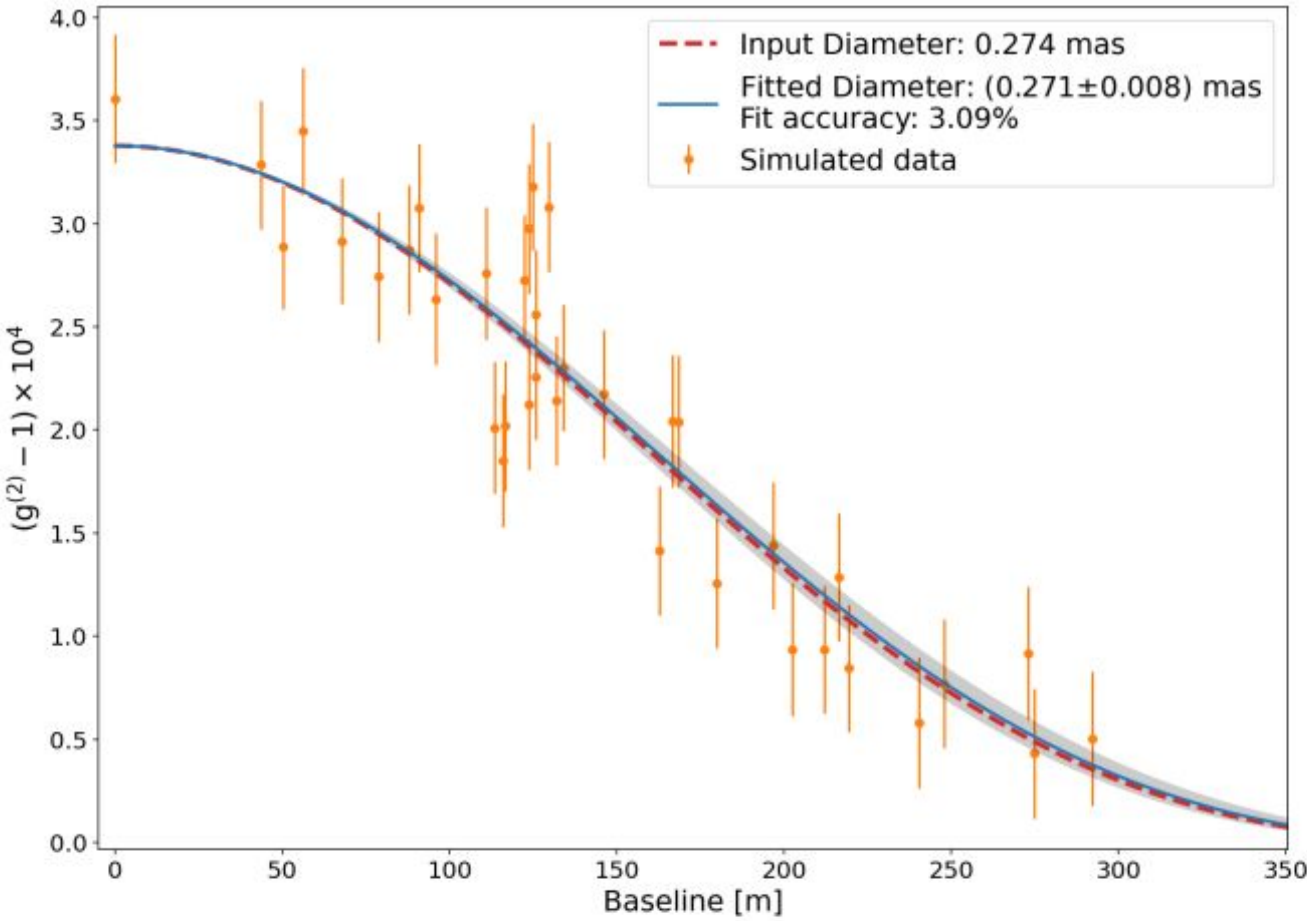
ASTRI SI3 Dashboard in SCADA

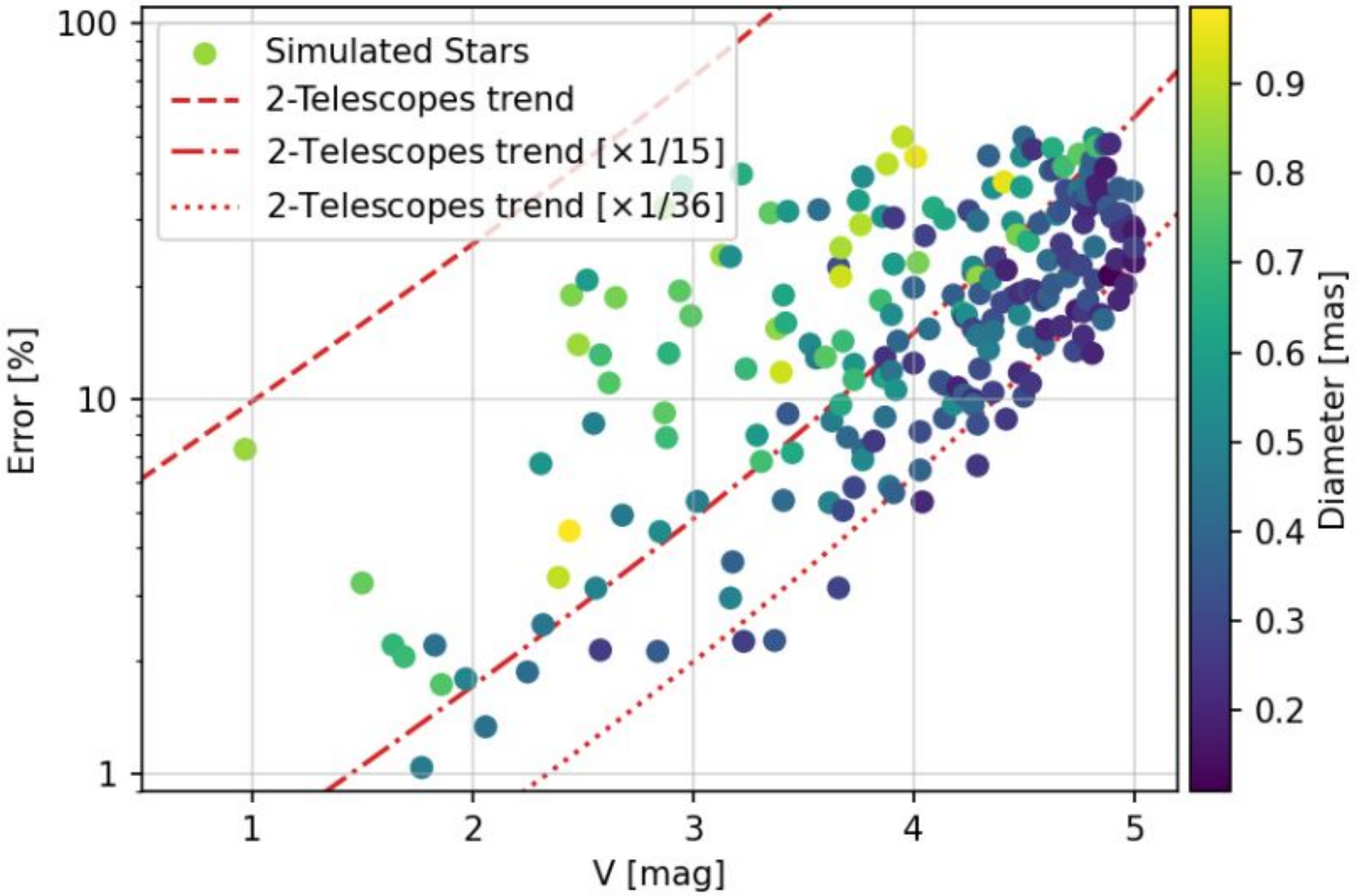
Bruno et al. (2025)



ASTRI SI3 GUI for single instrument

ASTRI SI3
Simulated measurements





Simulated measurements of g(2) for a B0-type star with V = 3.2, gathered with all 36 baselines in 20 hours

For small sources, all baselines contribute equally to sampling the coherence and improvement in sensitivity grows linearly with number of baselines

> 50 stars with error on radius < 10% (10 with V >~ 4)

ASTRI SI^3

Mini-Array

SI^3

Funded by the European Union – NextGenerationEU RFF M4C2 projects IR0000012 CTA+ and CN00000013 Centro Nazionale di Ricerca in High-Performance Computing, Big Data e Quantum Computing.

This work was conducted in the context of the ASTRI Project thanks to the support of the Italian Ministry of University and Research (MUR) as well as the Ministry for Economic Development (MISE) with funds specifically assigned to the Italian National Institute of Astrophysics (INAF).

Backup slides

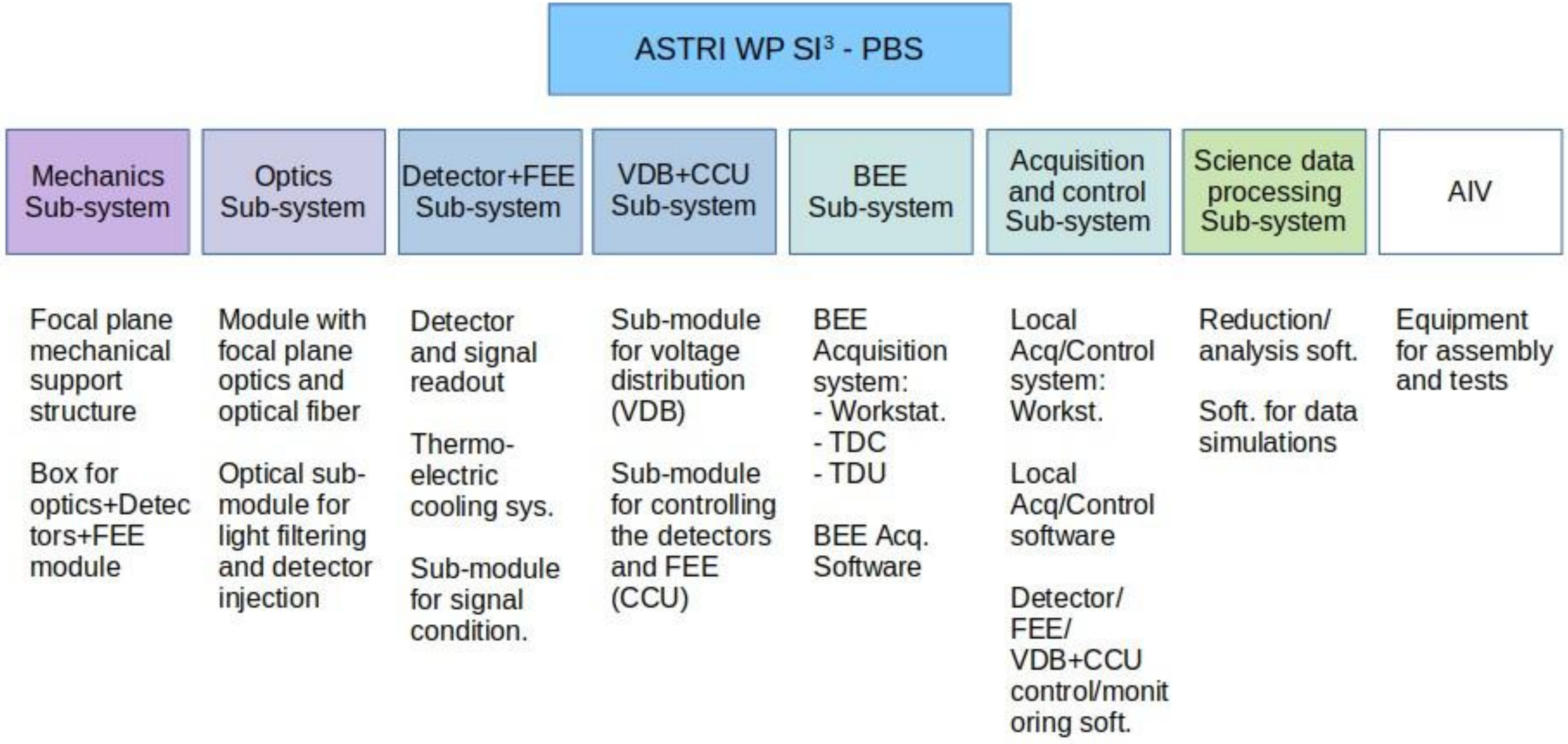
ASTRI SI3
Organization chart

SI³ – Organization Chart
PI: L. Zampieri
PM: M. Fiori

Mechanics Sub-system C. Gargano	Optics Sub-system G. Rodeghiero	Detector+FEE Sub-system G. Bonanno	VDB+CCU Sub-system Paoletti/Romeo	BEE Sub-system M. Fiori	Acquisition and control Sub-system P. Bruno	Science data processing Sub-system L. Zampieri	AIV G. Naletto
C. Gargano	G. Naletto	G. Bonanno	G. Bonanno	M. Fiori	P. Bruno	M. Fiori	M. Fiori
L. Lessio	C. Pernechele	A. Grillo	A. Grillo	G. Naletto	M. Fiori	A. Spolon	T. Forte
	G. Rodeghiero	G. Occhipinti	G. Occhipinti	L. Zampieri	D. Impiombato	L. Zampieri	L. Lessio
	L. Zampieri	L. Paoletti	L. Paoletti		L. Paoletti		M. Mosele
		G. Romeo	G. Romeo		+ members of the ASTRI Mini-array soft./hard. team		G. Naletto
		M. Timpanaro	M. Timpanaro				G. Rodeghiero
							L. Zampieri

PRE-FEE: Pre Front End Electronics
FEE: Front End Electronics
VDB: Voltage Distribution Board
CCU: Control and Communication Unit
BEE: Back End Electronics
AIV: Assembly Integration and Verification

ASTRI SI3
Product Breakdown Structure



ASTRI SI3
Publications

Zampieri et al. (2022), SPIE, 12183, id. 121830F: A stellar intensity interferometry instrument for the ASTRI Mini-Array telescopes

Fiori et al. (2022), Astronomy & Astrophysics, 666, id.A48: Investigating the accuracy achievable in reconstructing the angular sizes of stars through stellar intensity interferometry observations

Bonanno et al. (2022), SPIE, 12183, id. 1218322: Focal plane detector and front-end electronics of the stellar intensity interferometry instrument for the ASTRI Mini-Array telescopes

Bonanno et al. (2023), Sensors, 23, id.9840: Electronics and Detectors for the Stellar Intensity Interferometer of the ASTRI Mini-Array Telescopes

Zampieri et al. (2024), SPIE, 13095, id. 130950J: A new version of the stellar intensity interferometry instrument for the ASTRI Mini-Array telescopes

Spolon et al. 2024, SPIE, 12996, id. 129960Y: Towards image synthesis with photon counting stellar intensity interferometry

Zampieri et al. (2025), Nature Astronomy, in preparation: Narrow band, sub-nanosecond intensity interferometry in photon counting on Cherenkov telescopes