Final design and future upgrades of the Stellar Intensity Interferometry Instrument (SI3) for the ASTRI Mini-Array

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for the ASTRI-SI3 team and the ASTRI Project

Stellar Intensity Interferometry Workshop 2024, Porquerolles (France)
13 September 2024

ASTRI SI3 Team

SI³ – Organization Chart
PI: L. Zampieri

Mechanics Sub-system (C. Gargano)	Optics Sub-system (G. Rodeghiero)	Detector+ PRE-FEE Sub-system (G. Bonanno)	FEE+ VDB+CCU Sub-system (Paoletti/Romeo)	Acquisition and control Sub-system (P. Bruno)	BEE Sub-system (M. Fiori)	Science data processing Sub-system (L. Zampieri)	AIV (G. Naletto)
C. Gargano	G. Naletto	G. Bonanno	G. Bonanno	P. Bruno	M. Fiori	M. Fiori	M. Fiori
L. Lessio	C. Pernechele	A. Grillo	A. Grillo	M. Fiori	G. Naletto	A. Spolon	T. Forte
	G. Rodeghiero	G. Occhipinti	G. Occhipinti	D. Impiombato	L. Zampieri	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

CTAO SII Science Working Group

➔ The CTAO SII Science Working Group is an open discussion 'forum' on SII science and potential SII implementations on CTA

WG Coordinator: LZ

WG Deputy Coordinator: Mike Lisa

➔ Recent activities include:

- Drafting a White Paper on SII science cases with CTAO and potential SII implementation modes on CTAO
- Internal presentations of SII results/simulations from current/future IACTs installations (MAGIC, HESS, VERITAS, ASTRI Mini-Array)
- Advertizing SII and presenting SWG activities at conferences (CTA Symposium, EAS 2024, IAU 2024)
- Setting up a SII Science Data Challenge with simulated data

If you want to join, you are welcome to do so!
Just send an e-mail to: **cta-wg-phys-int@cta-observatory.org**

CTAO SII Science Working Group

What can be done with CTA
SII observations of solar-type stars

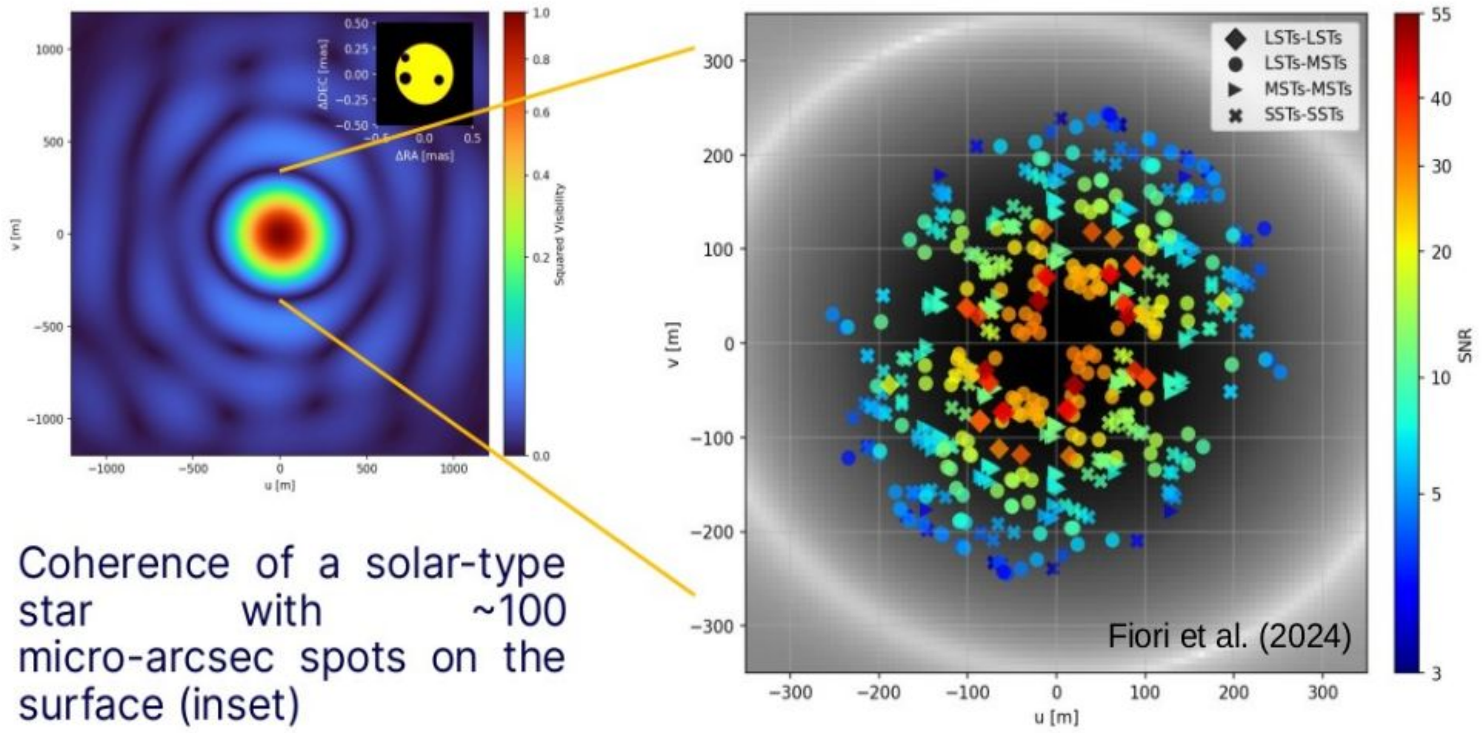
CTAO

Measurement of basic quantities (stellar diameters, surface spots, mass-and-radius in binaries) will have a low-key but **all-pervasive impact on stellar astrophysics**

Solar-type stars are crucial for understanding the properties of the Sun in relation to other stars and for exploring the habitability conditions of exo-planets around stars similar to the Sun (e.g. Soderblom and King 1998; Charbonneau 2014; Ragulskaya 2018)

~100 G-type stars with **V < 5 mag** visible from each CTAO site

Simulated coherence on (U,V) plane of **F/G-type stars with spots**:



Coherence of a solar-type star with ~100 micro-arcsec spots on the surface (inset)

Several telescope pairs at CTA-South give measurements with a signal-to-noise ratio larger than 3 in 10 hours

Allow for 2D model fitting of the coherence and hence the determination of the **star diameter and spots size**

Unique capabilities of CTAO in terms of coverage of the U-V plane and angular resolution

How to do it on CTA?
SII implementation modes

CTAO

Digital SII Measurements at **high photon rates**: photon counting detectors *in integration mode*

Continuously sampling and digitizing the photo-currents (at ~ 1 GHz)

'Counts'/waveforms directly proportional to the instantaneous light intensity/number of photons per time bin (with Direct Current coupling)

Coherence computed by **cross-correlating synchronized waveforms from two telescopes** (a la` Hanbury Brown & Twiss)

Suitable for bright targets with the LSTs/MSTs

Strengths: Possibility to use pixels of the Cherenkov camera as detectors, in post-processing checking for systematics and tuning the analysis

Photon Counting SII Measurements at **low photon rates**: photon counting detect. *in single-phot-counting mode*

Continuously sampling and time-tagging photon-events with a time-to-digital converter (at ~ 1 ns)

Exploiting the quantum properties of the star light (bosons giving a joint detection probability greater than that for two independent events)

Coherence computed by **counting simultaneous detections at two telescopes**

Suitable for SSTs, and LSTs/MSTs observing weak targets or equipped with narrow band filters

Strengths: Spectrally resolving SII (~ 1 nm), boosting sensitivity with channel multiplexing, checking for systematics and tuning the analysis, computing the correlations among three or more telescopes

Outline

→ Stellar Intensity Interferometry (SII) and Photon Counting SII (PC-SII)

→ SII Instrument (SI3) for the ASTRI Mini-Array
- SI3 Version 2
  - Rationale and advantages
  - Instrument modules and subsystems
- SI3 Version 2 (3)
  - Potential future upgrades

→ Michele Fiori: *Assembly, Integration, and Verification of the laboratory prototype of ASTRI SI3*

→ Alessia Spolon: *Simulations and analysis of ASTRI SI3 data*

Stellar Intensity Interferometry (SII)

ASTRI Mini-Array

SII consists in a measurement of the **spatial correlation of the intensities of the light from a star with two telescopes** at distance **d** (Hanbury Brown & Twiss 1957, 1958)

Photon counting SII

If photons are detected with a **sampling time dx in N intervals**, then the **2nd order degree of coherence $g^{(2)}$** is calculated from:

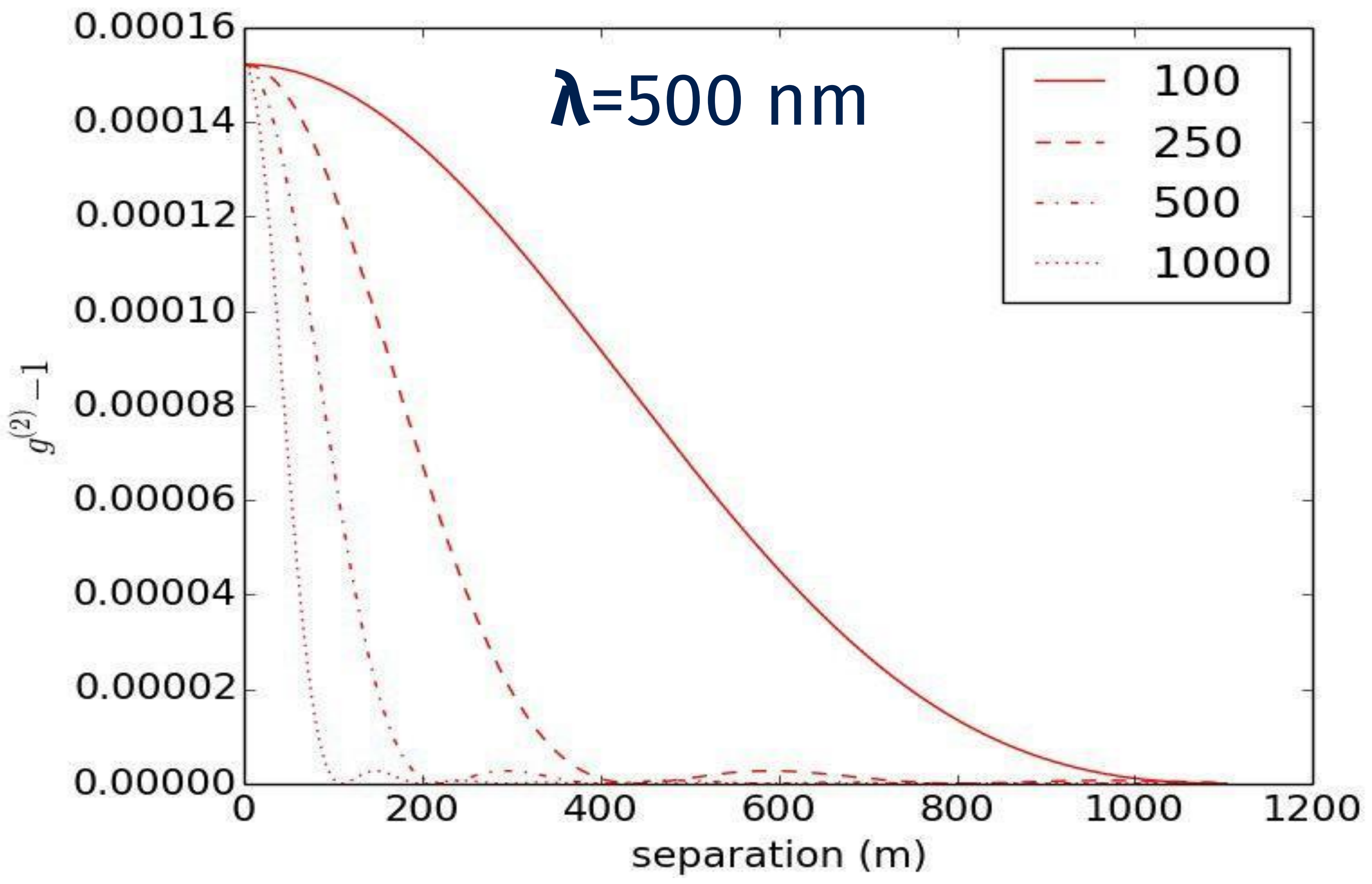
$$g^{(2)} = N_{12} N / (N_1 N_2) = < I_1 I_2 >/[<I_1><I_2>]$$

N_1, N_2 = number of photons detected at D1 and D2 in time **T**

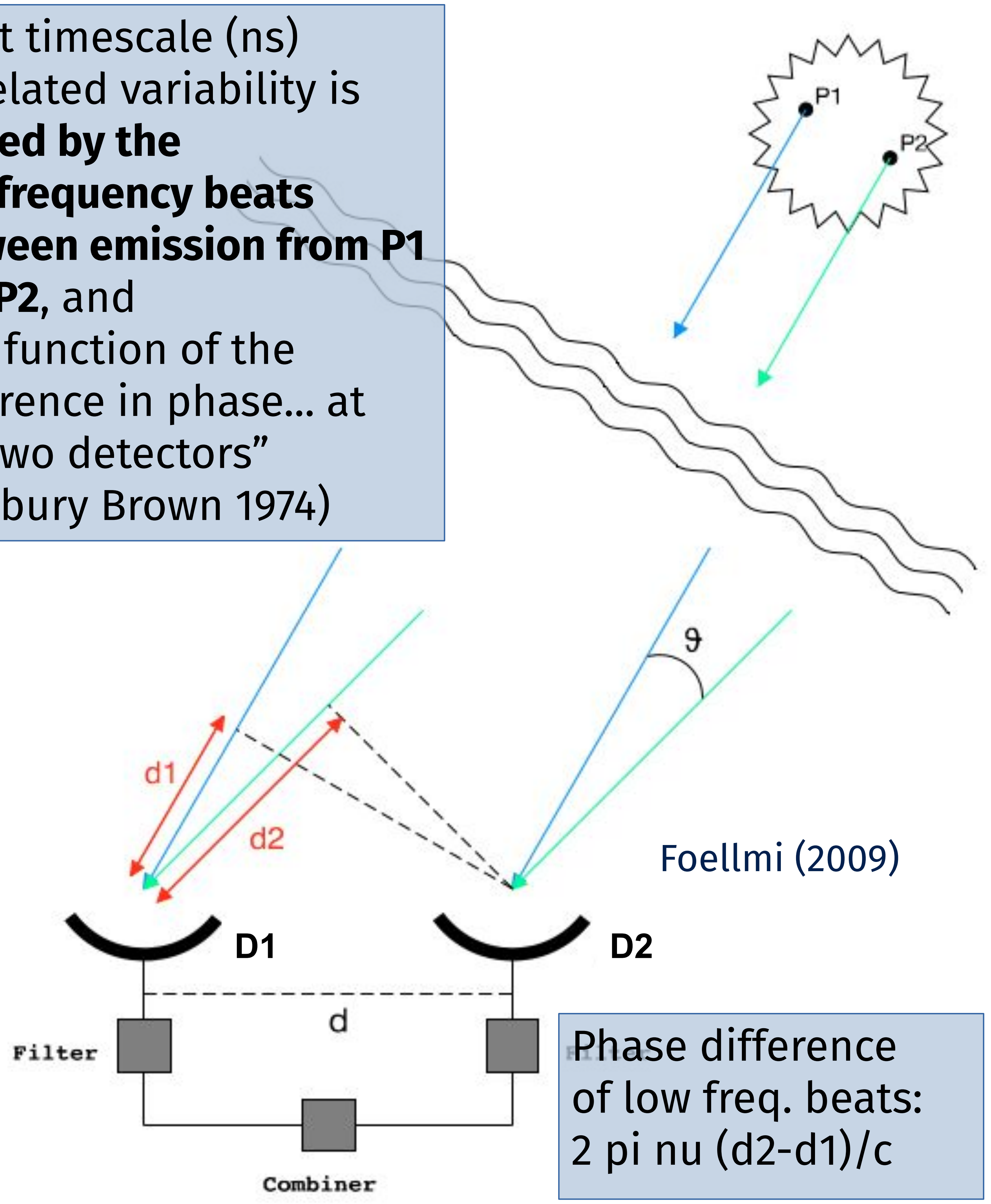
N_{12} = number of simultaneous detections in bins **dx** (random + quantum excess)

N = number of intervals (**T**/**dx**)

Short timescale (ns) correlated variability is **caused by the low-frequency beats between emission from P1 and P2**, and "is a function of the difference in phase… at the two detectors" (Hanbury Brown 1974)



Discrete degree of coherence of a source (uniform disc approx.) with angular size θ (in μarcsec) as a function of the telescope separation



Foellmi (2009)

Phase difference of low freq. beats: 2 pi nu (d2-d1)/c

Photon Counting Stellar Intensity Interferometry (PC-SII)

Mini-Array

Time averaged cross-correlation of the electric field (amplitude/phase interferometry):

$$\Gamma(u,v,\tau) = \lim (1/2T) \int E_1(t)\, E_2^*(t-\tau)\, dt$$

Time averaged cross-correlation of the intensities (intensity interferometry):

$$< I_1 I_2 > = \lim (1/2T) \int I_1(t)\, I_2(t-\tau)\, dt$$

Under quite general assumptions:

$$< I_1 I_2 > - < I_1 >< I_2 > = ½\, |\Gamma(u,v)|^2$$

Complex **Visibility**

In terms of **correlation functions** (Glauber 1963):

$$G2(1,2,2,1) - G1(1,1)G1(2,2) = G1(1,2)G1(2,1)$$

2nd order corr. **1st order corr.**

2nd order degree of coherence

$$g^{(2)} = G2(1,2,2,1)/G1(1,1)G1(2,2) = < I_1\, I_2 >/[<I_1><I_2>]$$

$$g^{(2)} - 1 = G1(1,2)G1(2,1)/G1(1,1)G1(2,2)$$

Zampieri et al., MNRAS, Vol. 506, Issue 2 (2021)

If **dx** is the sampling time bin, measurements in interval **[τ-dx/2, τ+dx/2]** are averaged out:

$$(1/dx) \int g^{(2)}\, dx = 1 + (Q/N) / [(N_1/N) (N_2/N)] = 1 + Q\, N / (N_1\, N_2) = N_{12}\, N / (N_1\, N_2)$$

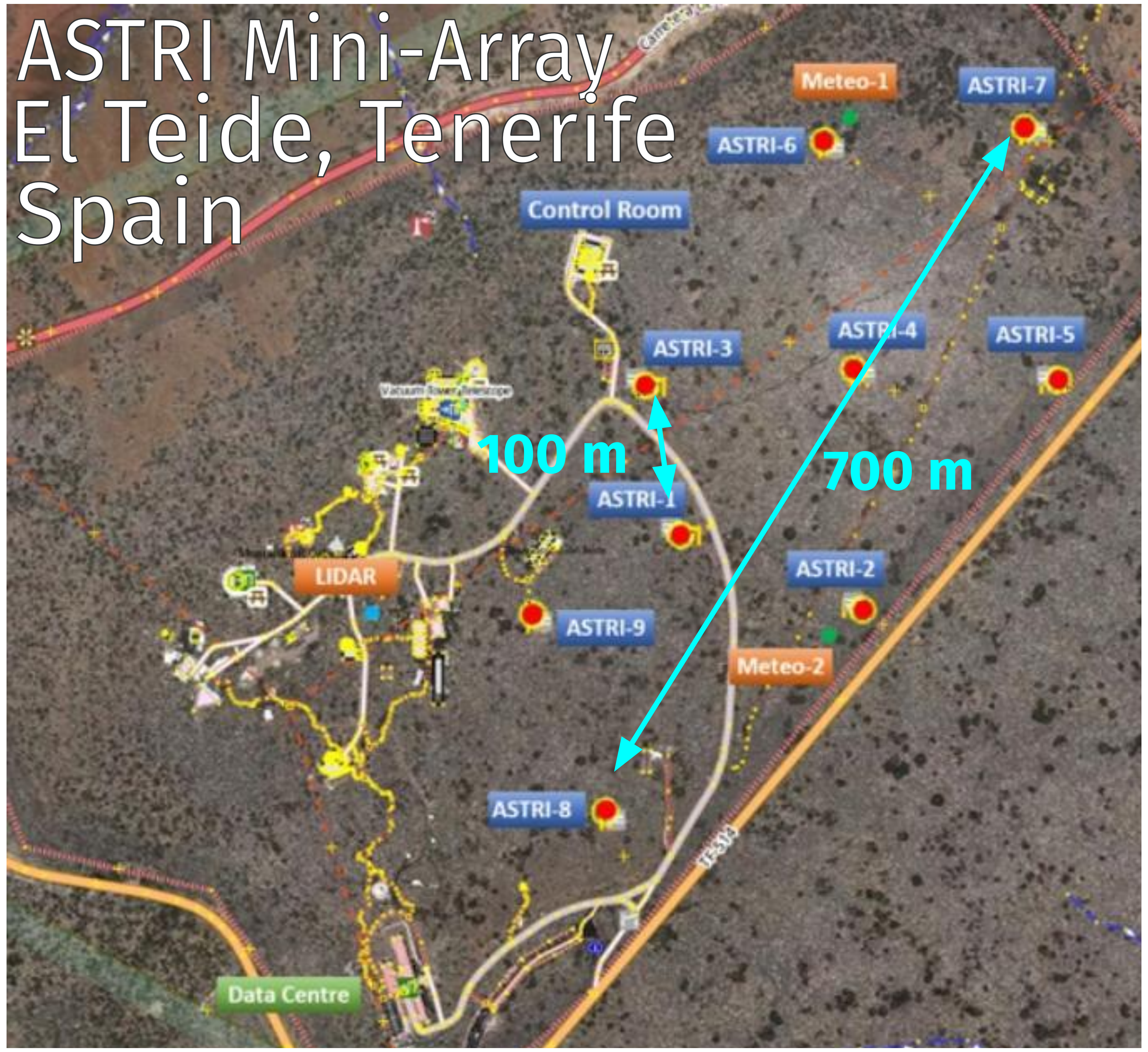
where: N_{12} = $(N_1\, N_2)/N$ + Q

Random joint detections **Extra joint detections (boson statistics)**

$G1(1,1) = N_1/N$ $G1(2,2) = N_2/N$
prob. of detecting a photons at 1 or 2 in dx
$G1(1,1)G1(2,2) = (N_1/N)\,(N_2/N)$
prob. of random joint detections at 1 and 2
$G1(1,2)G1(2,1) = Q/N$
prob. of extra joint detections at 1 and 2

ASTRI SII Instrument (SI^3)

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**

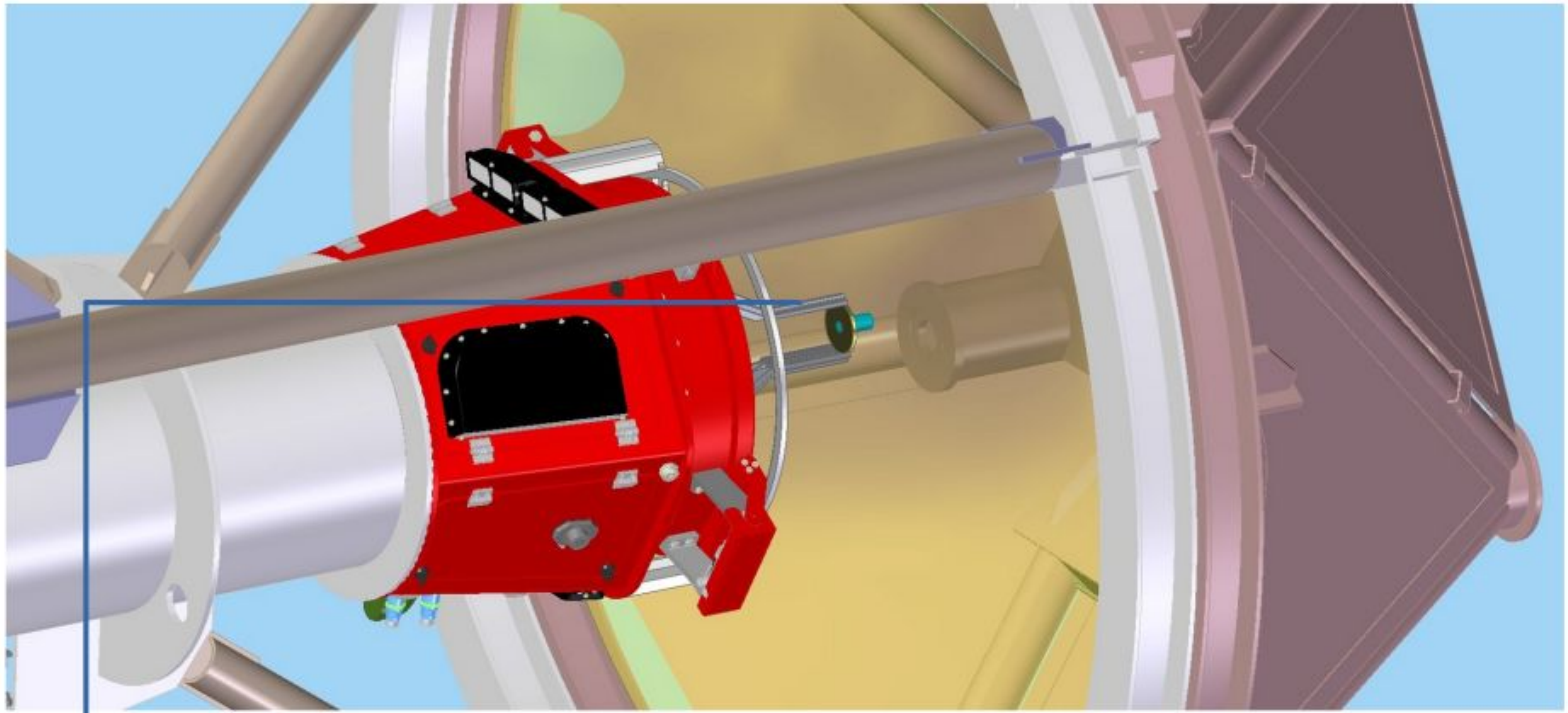


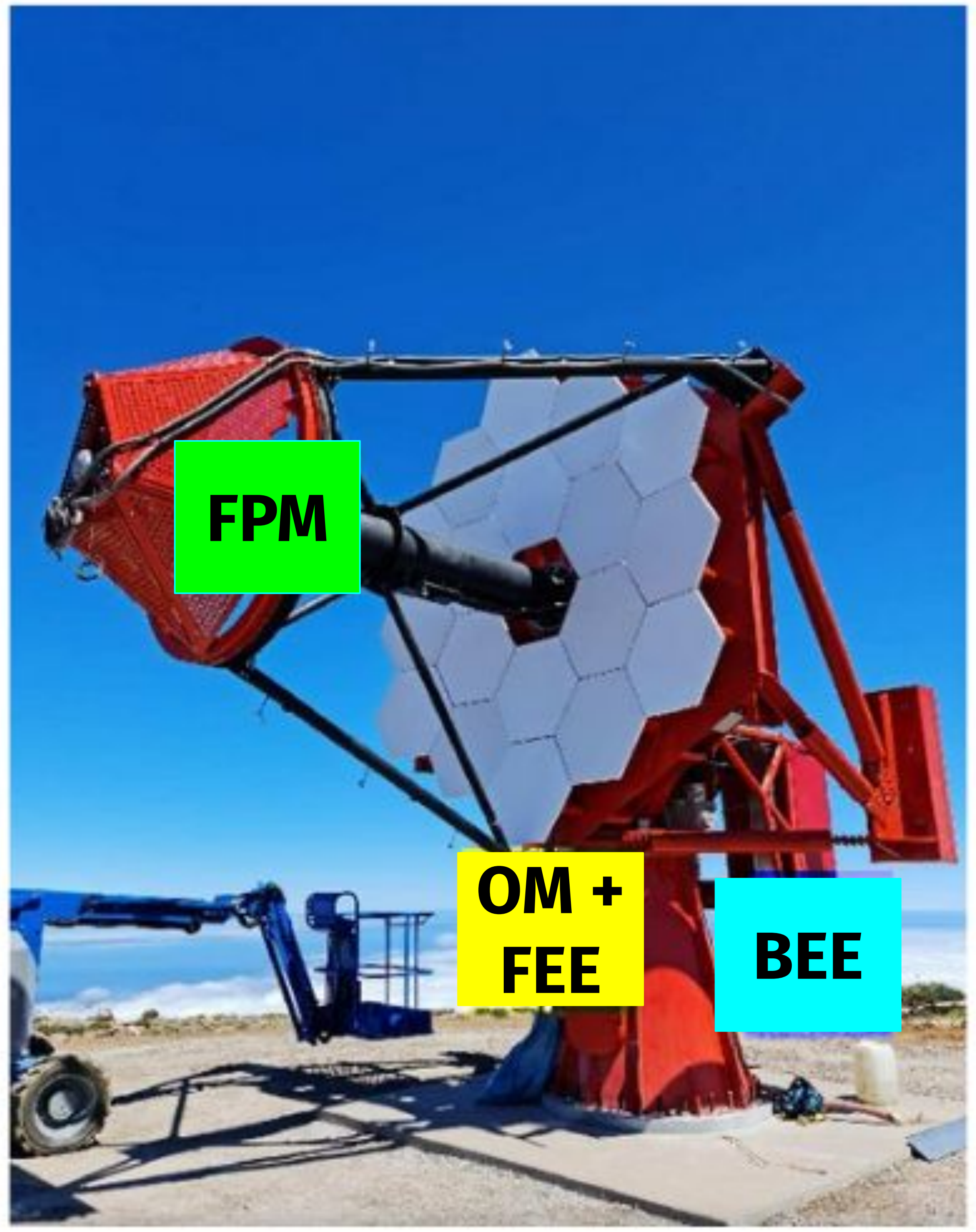
Stellar Intensity Interferometry with ASTRI

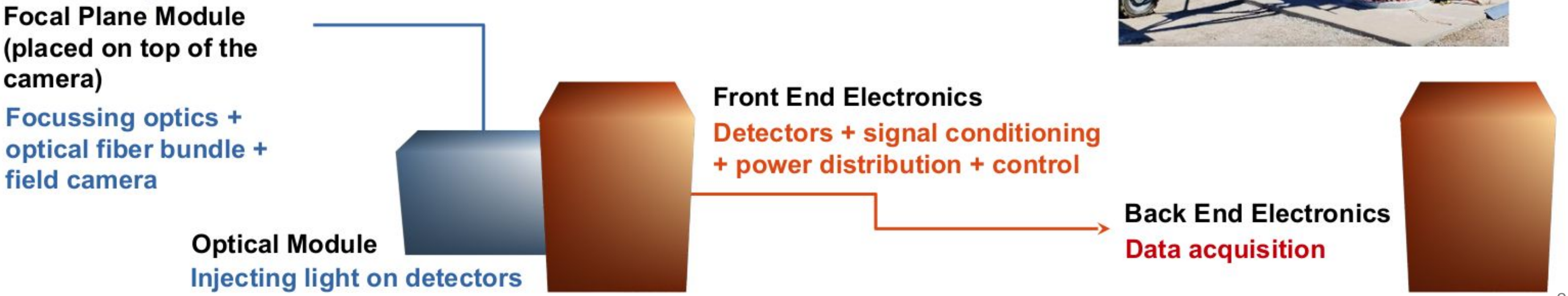
The ASTRI Mini-array provides a suitable infrastructure for performing SII measurements at sub-milliarcesec level

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

SI^3 Version 2
Instrument Design





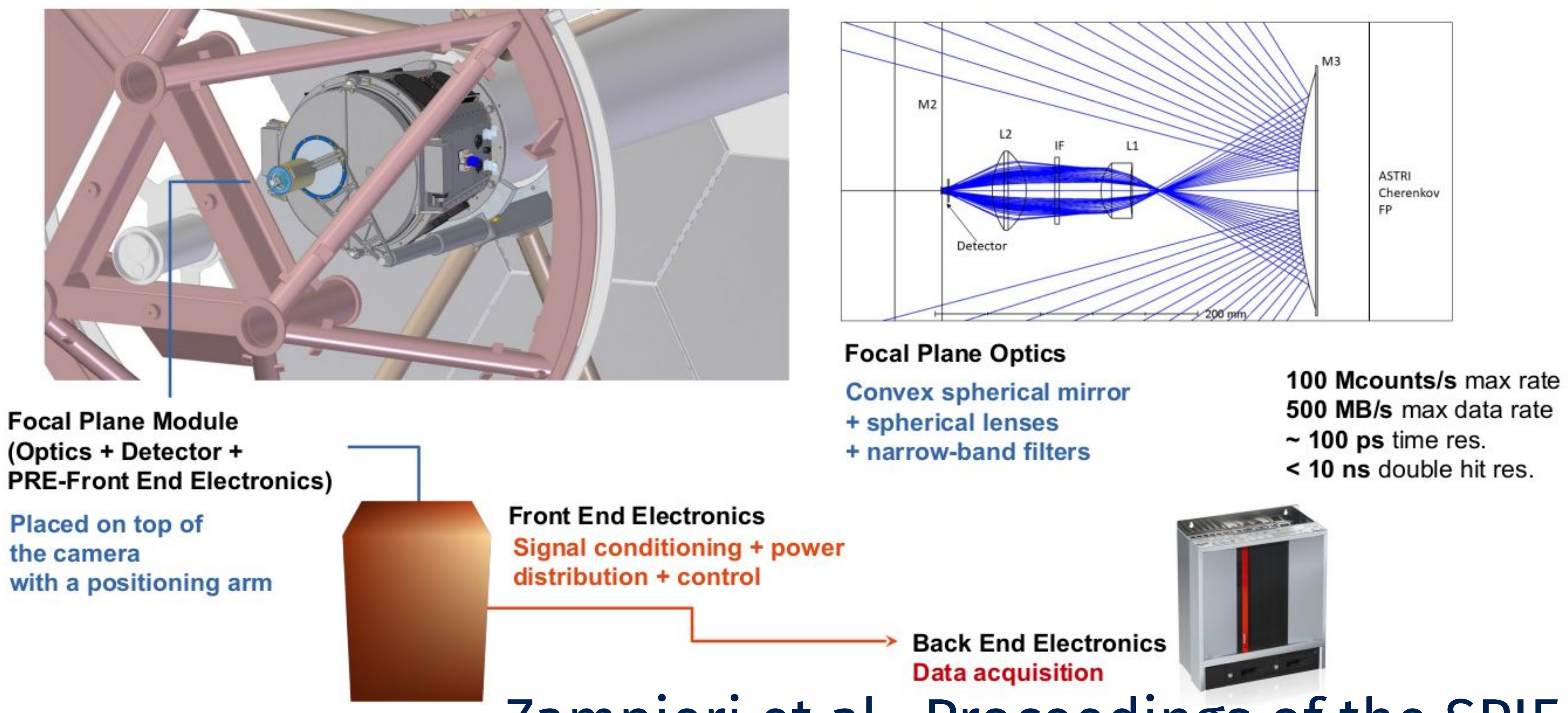


Zampieri et al. (2024)

SI^3 Version 1 vs 2
Rationale and advantages

Columbus SII Workshop 2023

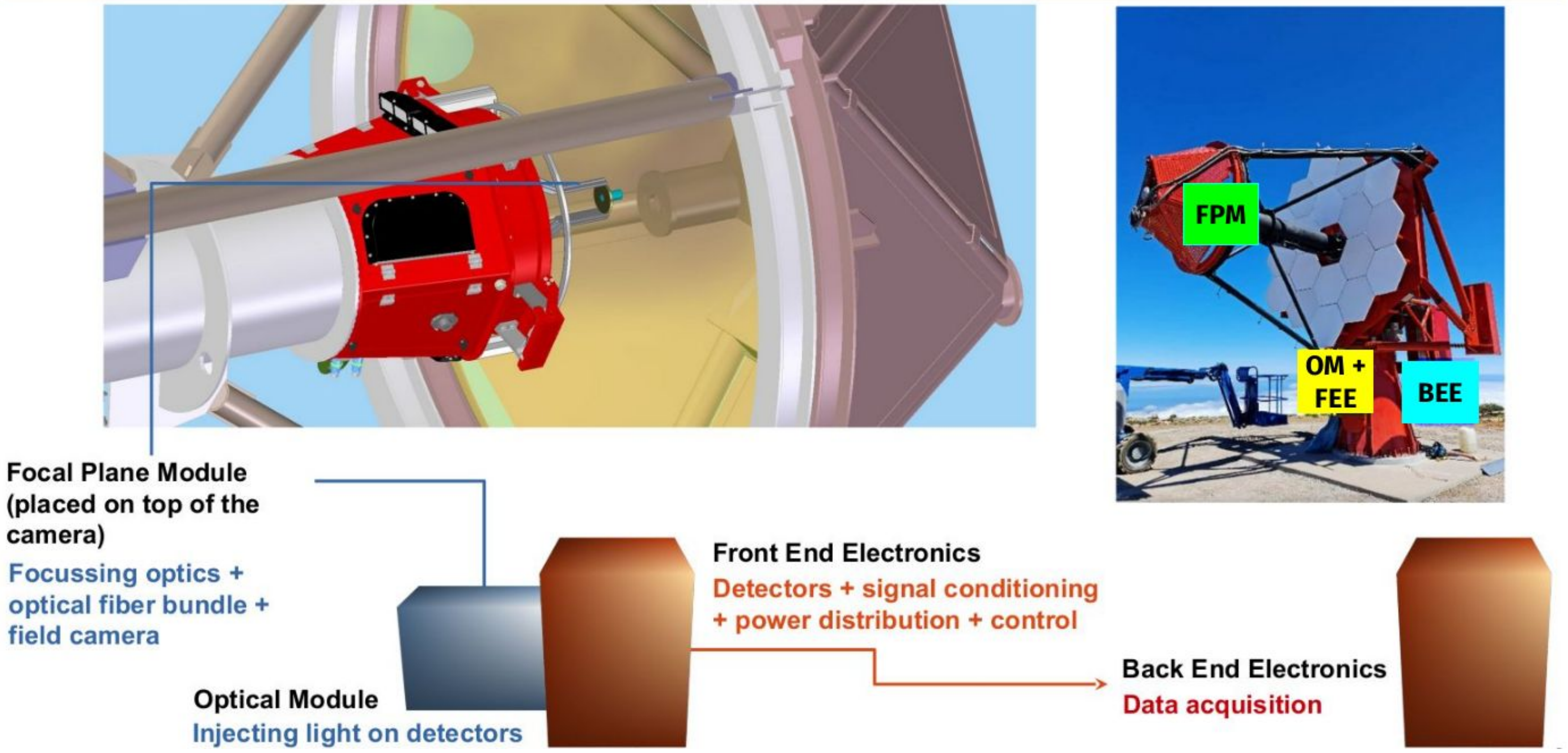
ASTRI SI3 – v. 1.0



Zampieri et al., Proceedings of the SPIE, Vol. 12183, id. 121830F (2022)

SI^3 Version 2
Instrument Design

Porquerolles SII Workshop 2024



Zampieri et al., Proceedings of the SPIE, Vol. 13095, id. 130950J-1 (2024)

Pros

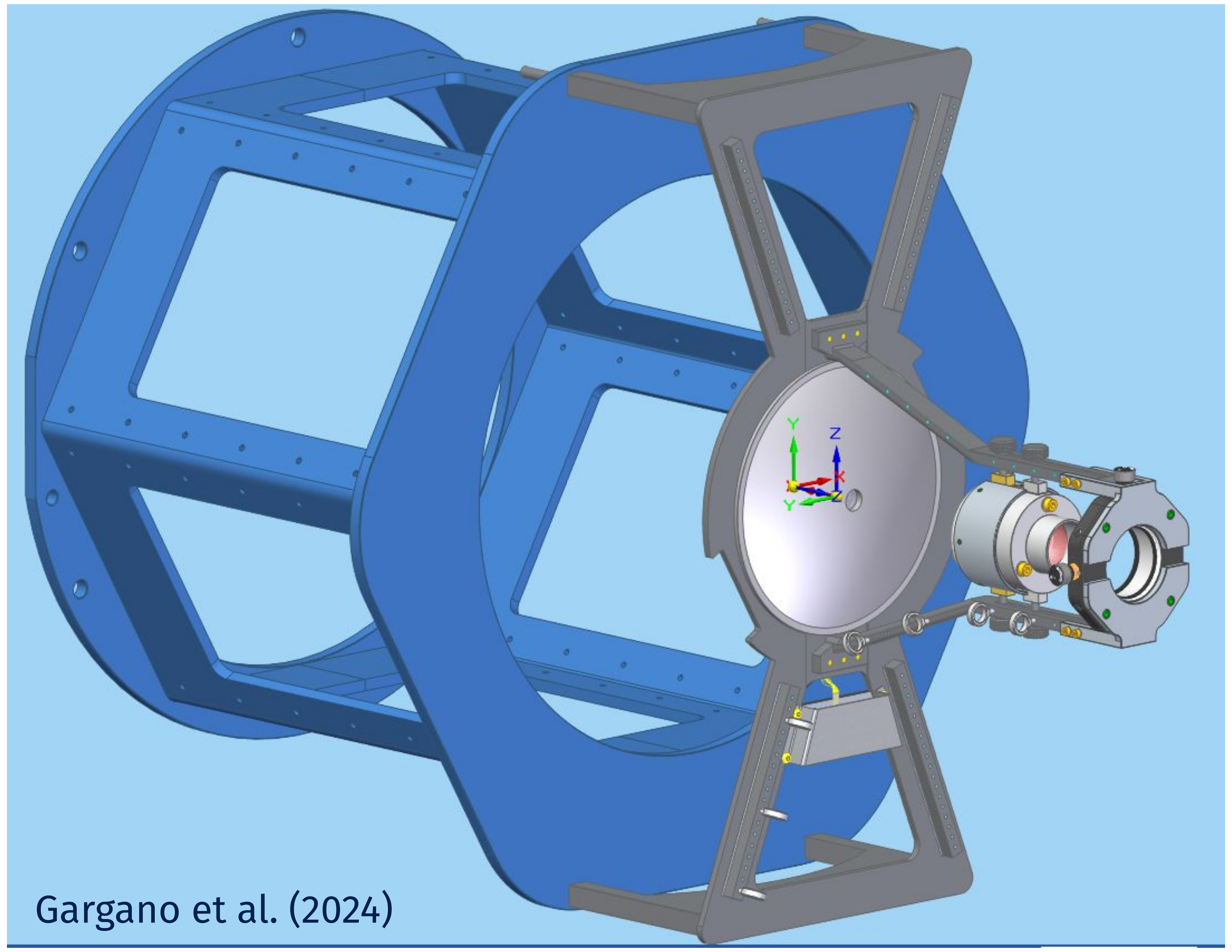
- Removing pre-FEE from focal plane
  Issues solved: potential sources of electronic noise, heat dissipation, PRE-FEE weight and size, electric/electronic cable harness
- Removing filters/filter wheel from focal plane - *Issues solved*: vignetting, Angle of Incidence (too large for a fraction of the rays)
- Placing pointing camera at focal plane - *Issue solved*: checking pointing accuracy
- Adding secondary optical module - *Issue solved*: Having a well collimated portion of the optical beam
- Changing BEE hardware - *Issues solved*: no jump in TDC clock cycles, reaching needed maximum count rate

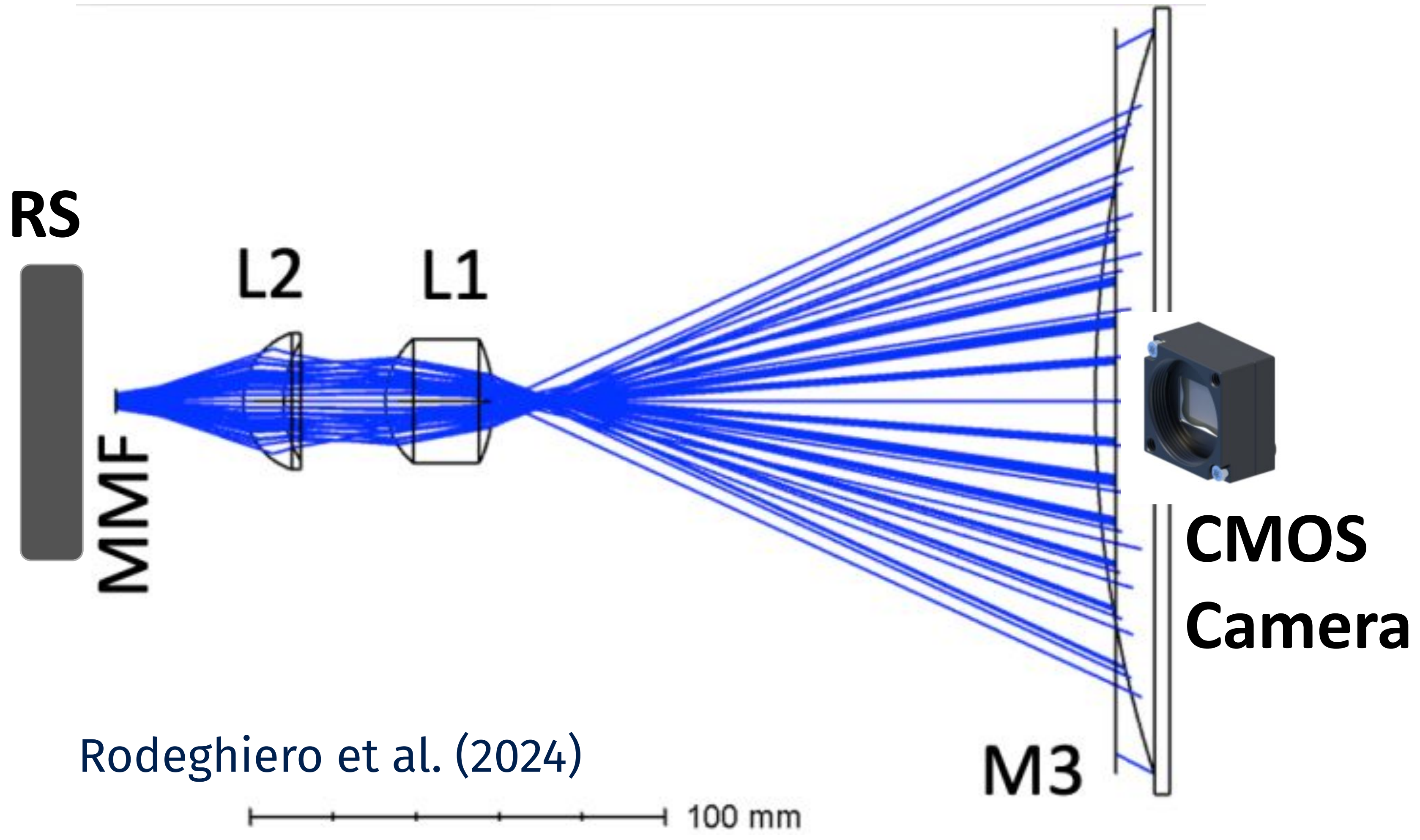
Cons

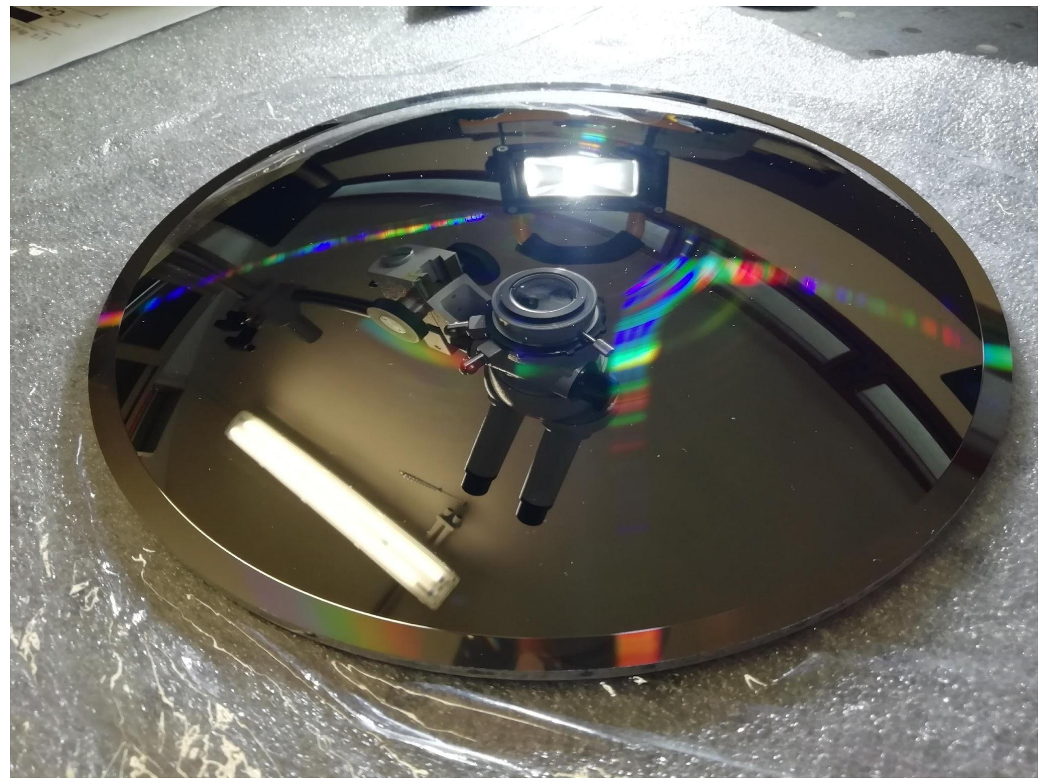
- Adding multimode optical fiber bundle - *Issue*: slight decrease of overall optical efficiency

SI3 Version 2
FPM: Focal Plane Module

Mini-Array



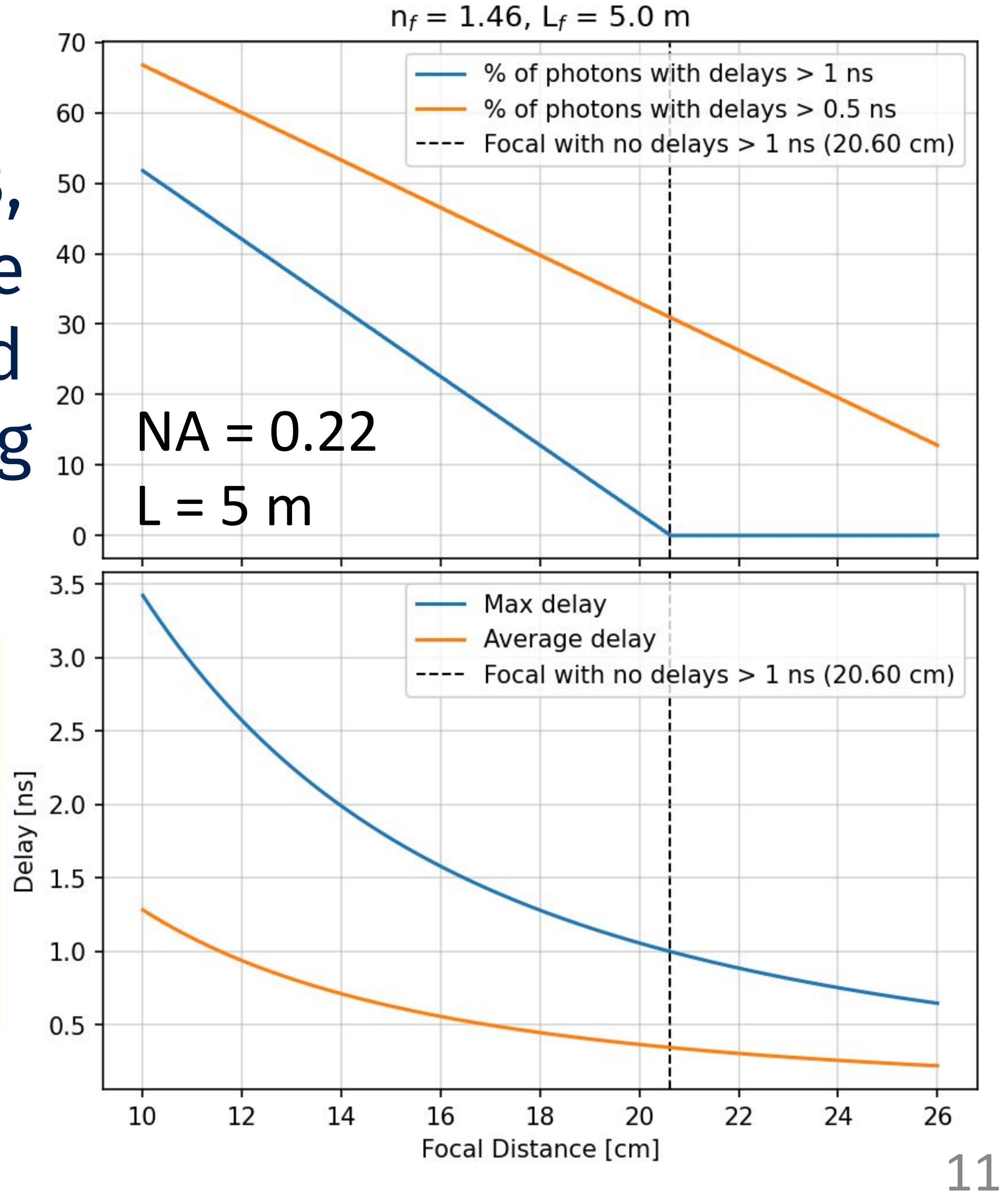


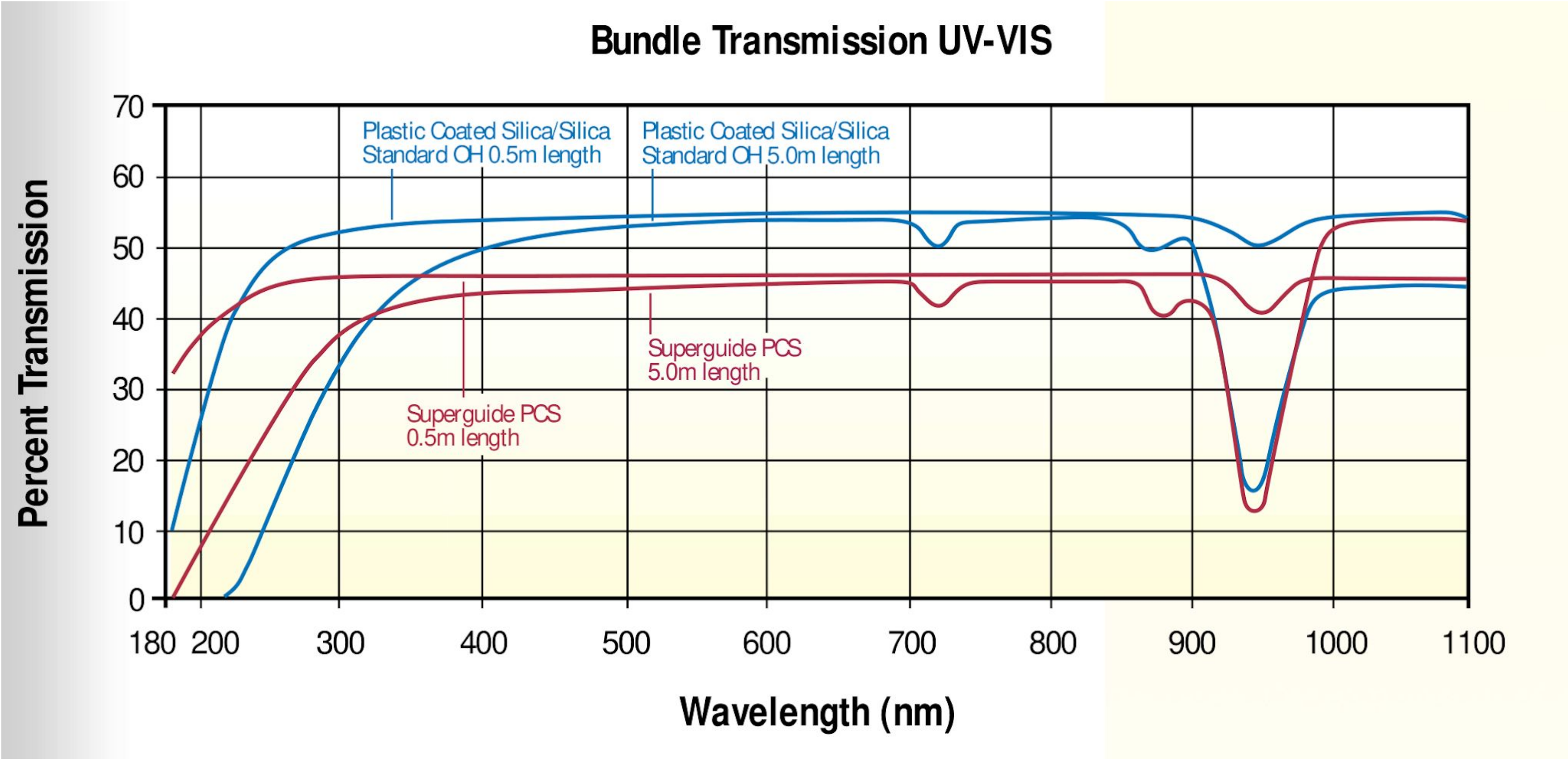


M3 Aluminum mirror

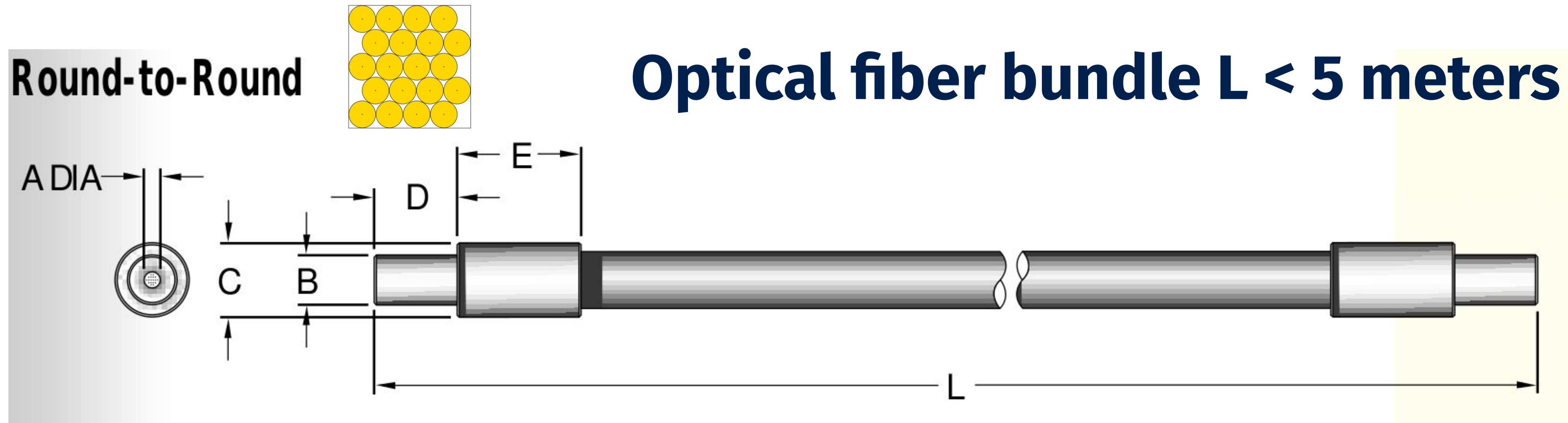
Prefocal catadioptric system

The beam from the telescope is reflected off M3, collimated by L1 and refocused by L2 on a multimode optical fiber bundle (MMF). A CMOS camera is placed on axis, at the center of M3, for checking the pointing using the reflected light from mirror RS





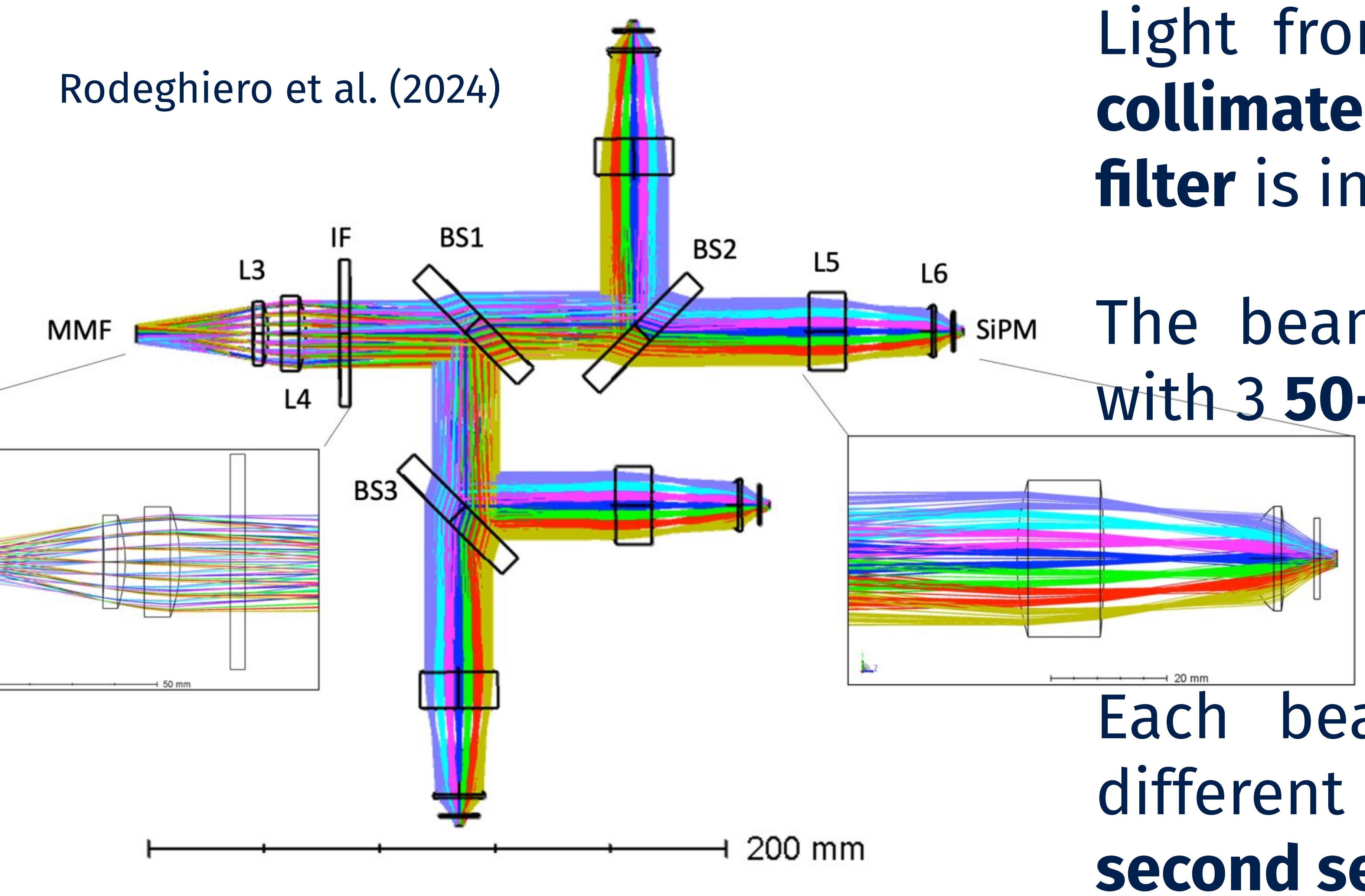
Optical fiber bundle L < 5 meters



Credit: Fiberguide
https://www.amstechnologies-webshop.com/media/pdf/0b/85/f7/Bundled-Assemblies-Fiberguide-Datasheet.pdf

SI3 Version 2
OM+FEE: Optical Module with detectors and Front End Electronics

Mini-Array



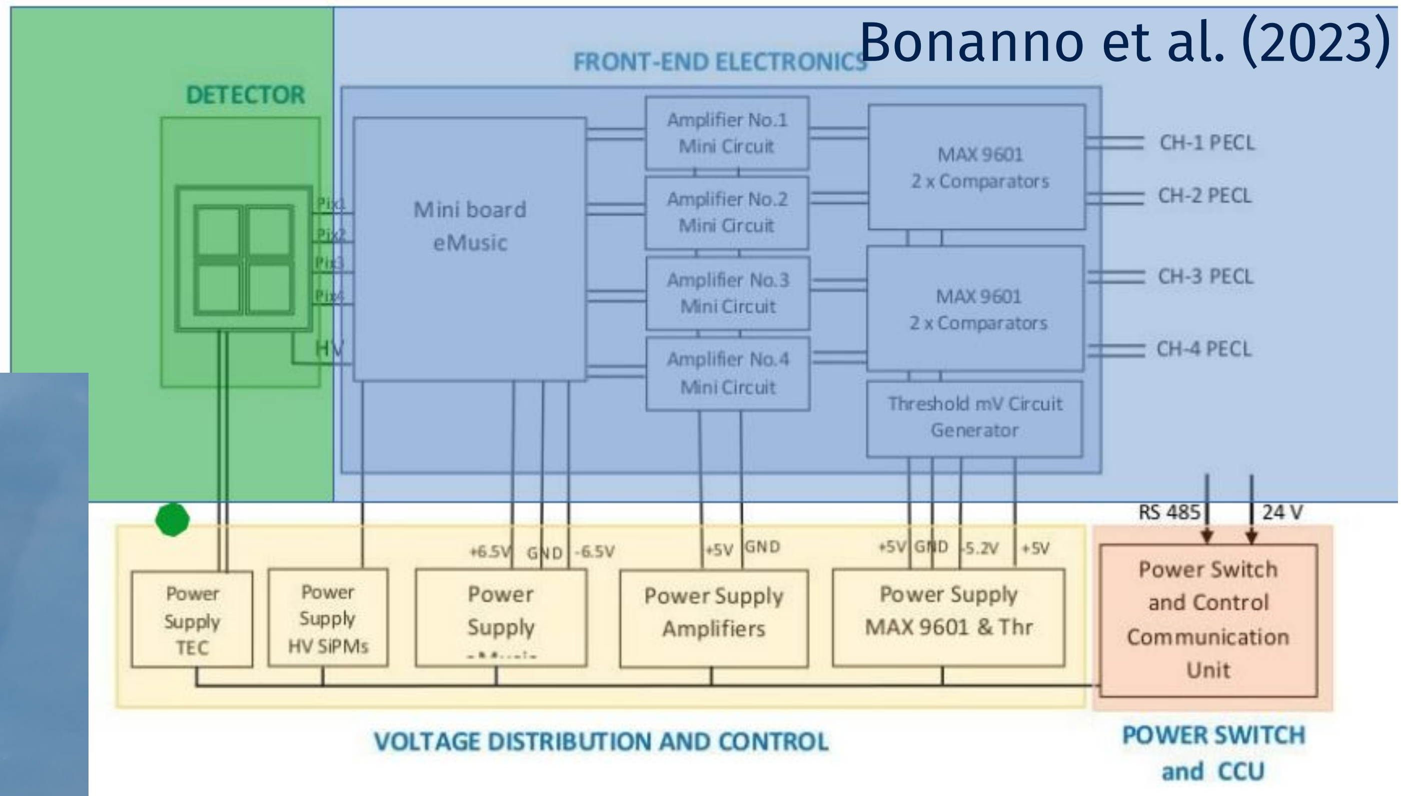
Rodeghiero et al. (2024)

Light from the optical fiber is **collimated** and a **narrow band filter** is inserted (1-8 nm)

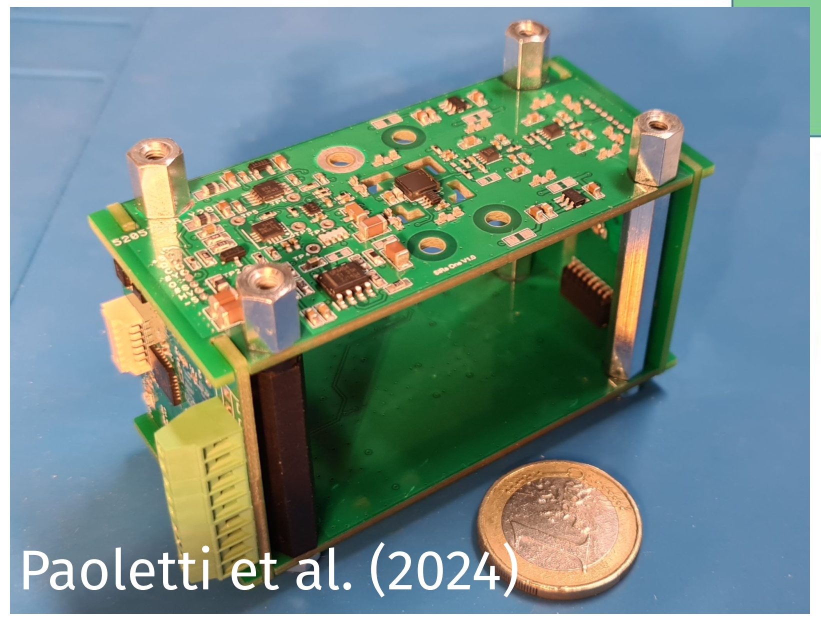
The beam is **split** in **4 paths** with 3 **50-50% beam splitters**

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

Custom SiPM Detector

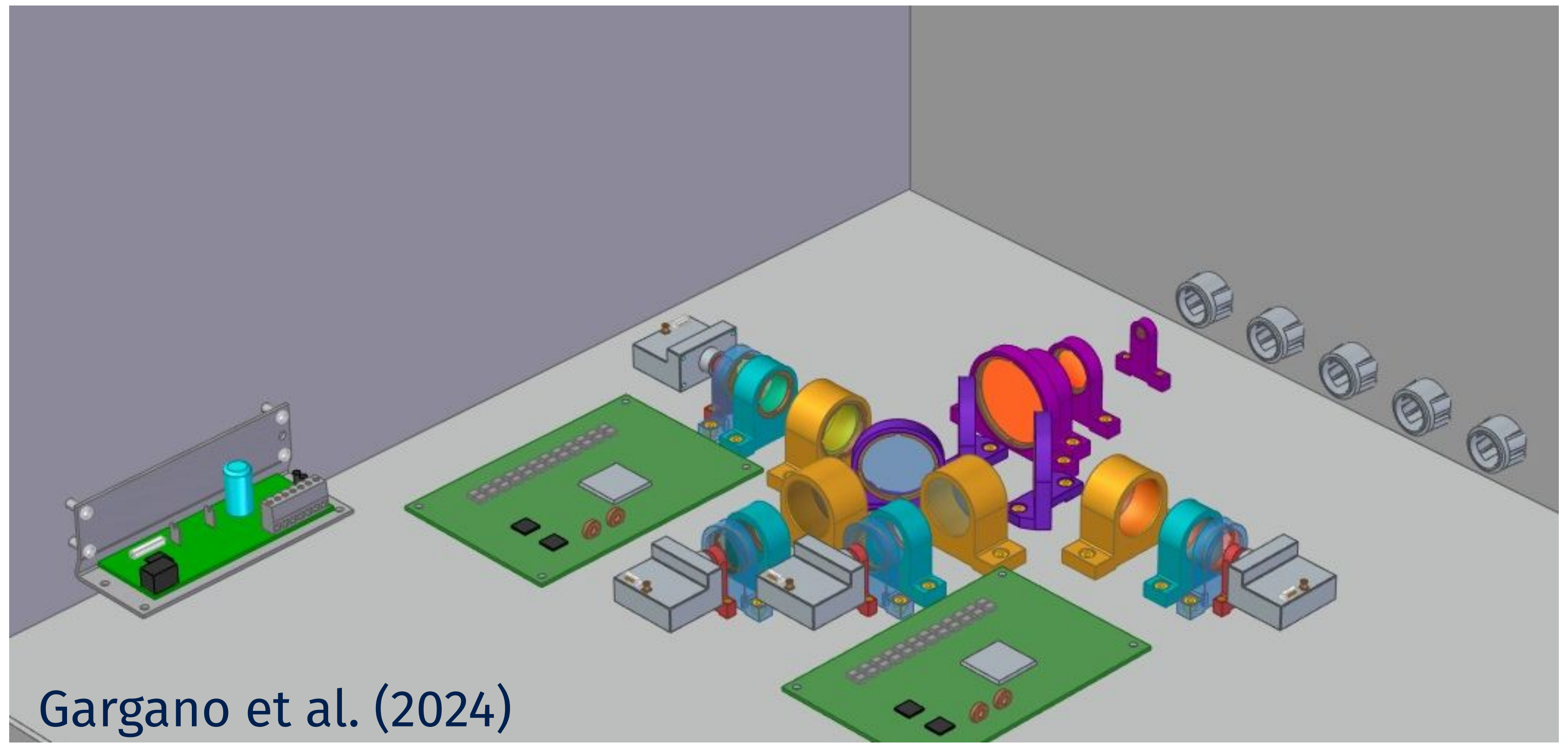


Bonanno et al. (2023)


Paoletti et al. (2024)

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

Under development

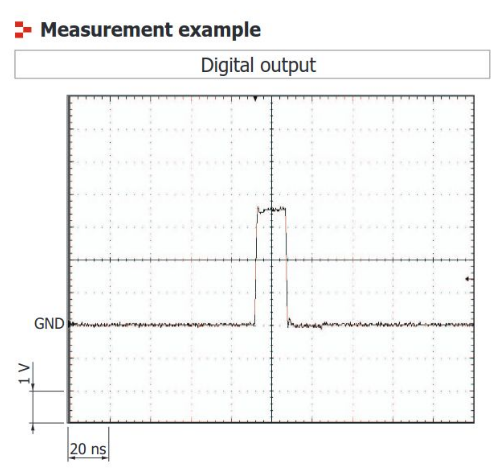

Gargano et al. (2024)

Commercial SiPM Detector

Hamamatsu MPPC C13852-3050GD

3 mm^2 photosensitive area, peak sensitivity 450 nm

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



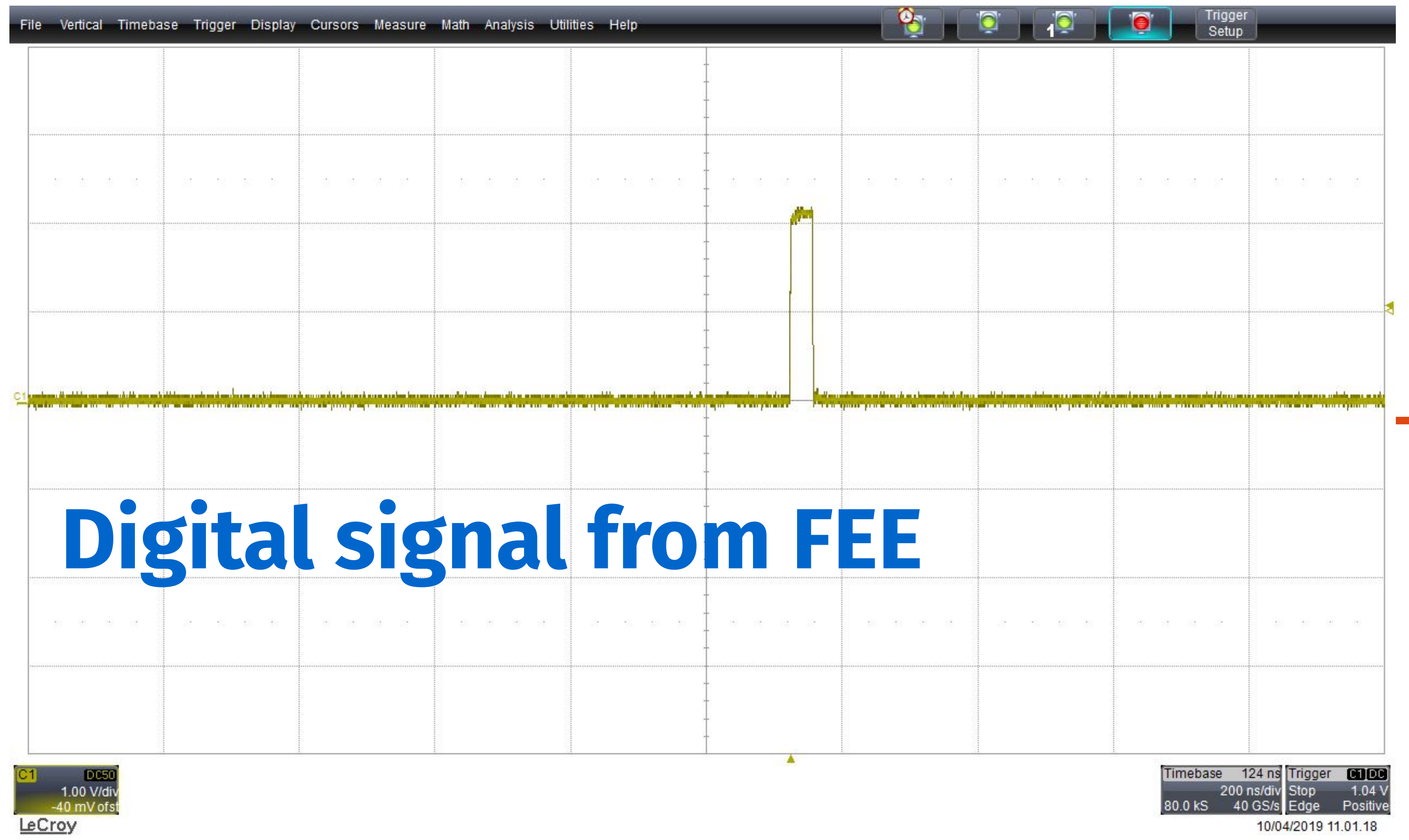
TTL-compatible digital output pulse

Max rate: ~17 Mct/s
Linearity preserved up to ~10 Mct/s
Jitter ~500 ps

For prototype phase

SI3 Version 2
BEE: Back End Electronics

ASTRI Mini-Array



Digital signal from FEE

x4

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

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

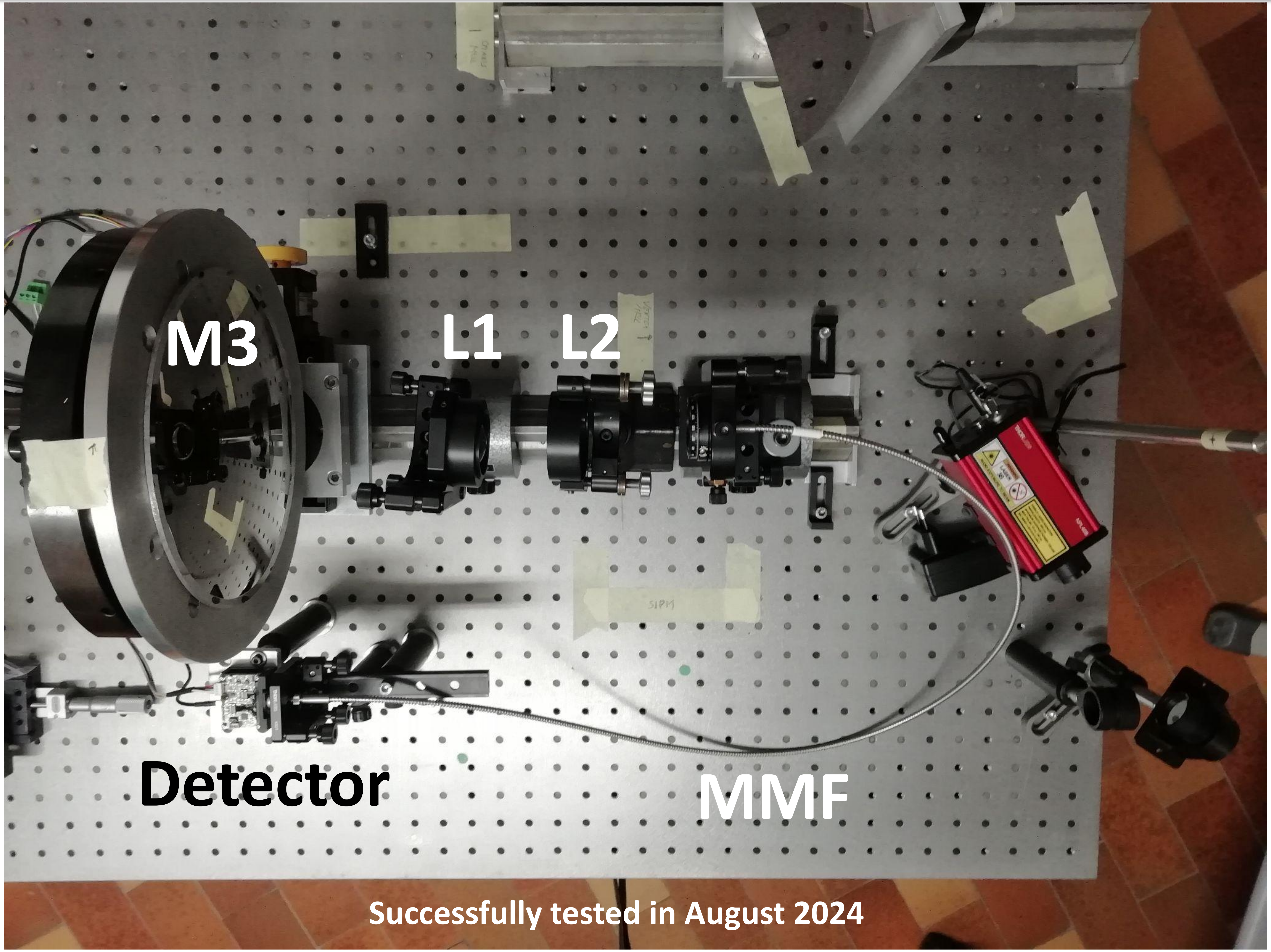
Workstation
Super Tower 732D3-903B
Supermicro

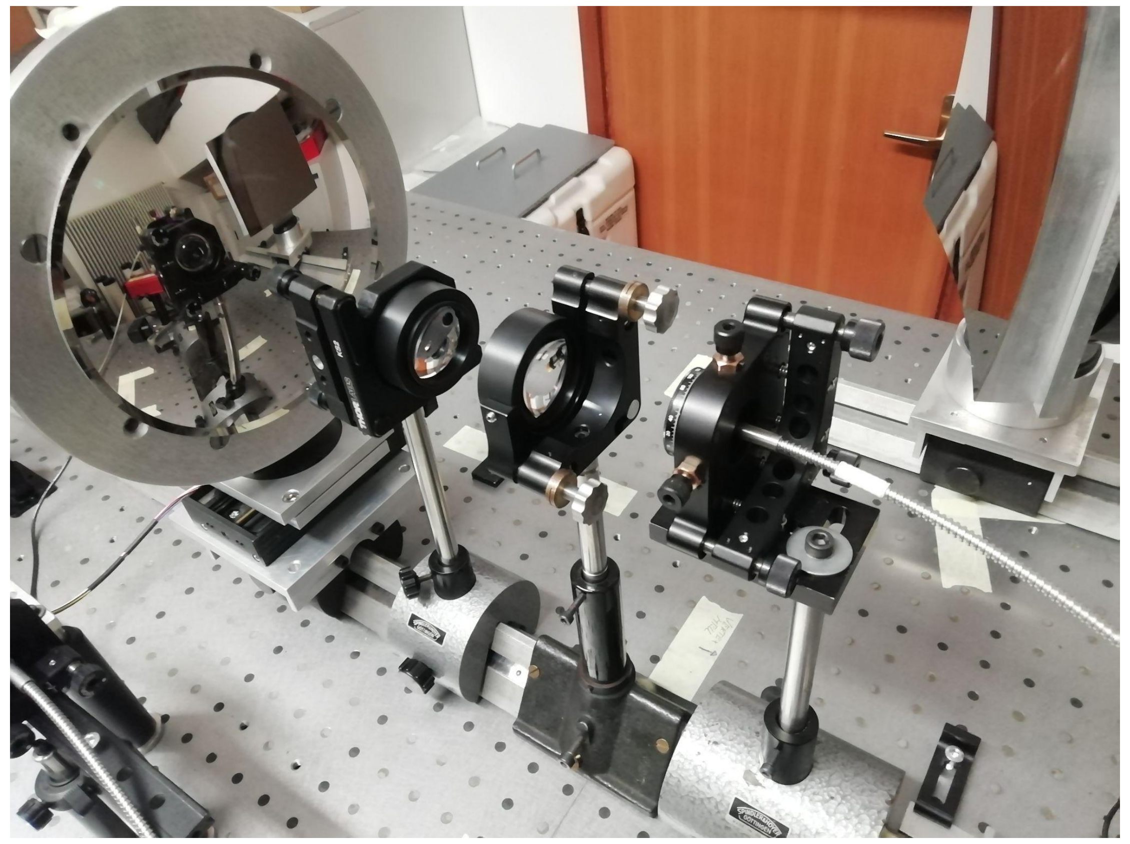
Time Distribution Unit (TDU)
White Rabbit system

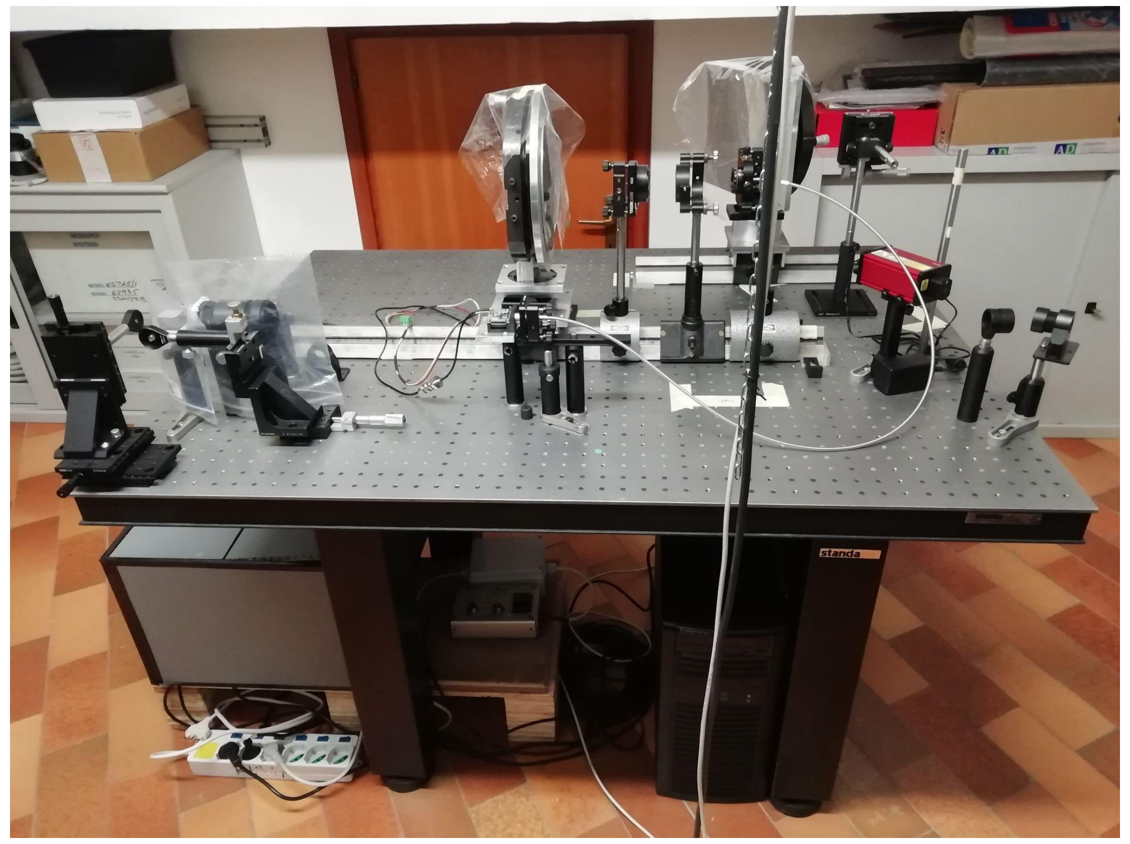
PPS signal + Clock reference signal

To Array Data Acquisition System
1.12 Gb/s max rate

SI^3 Version 2
Laboratory Prototype





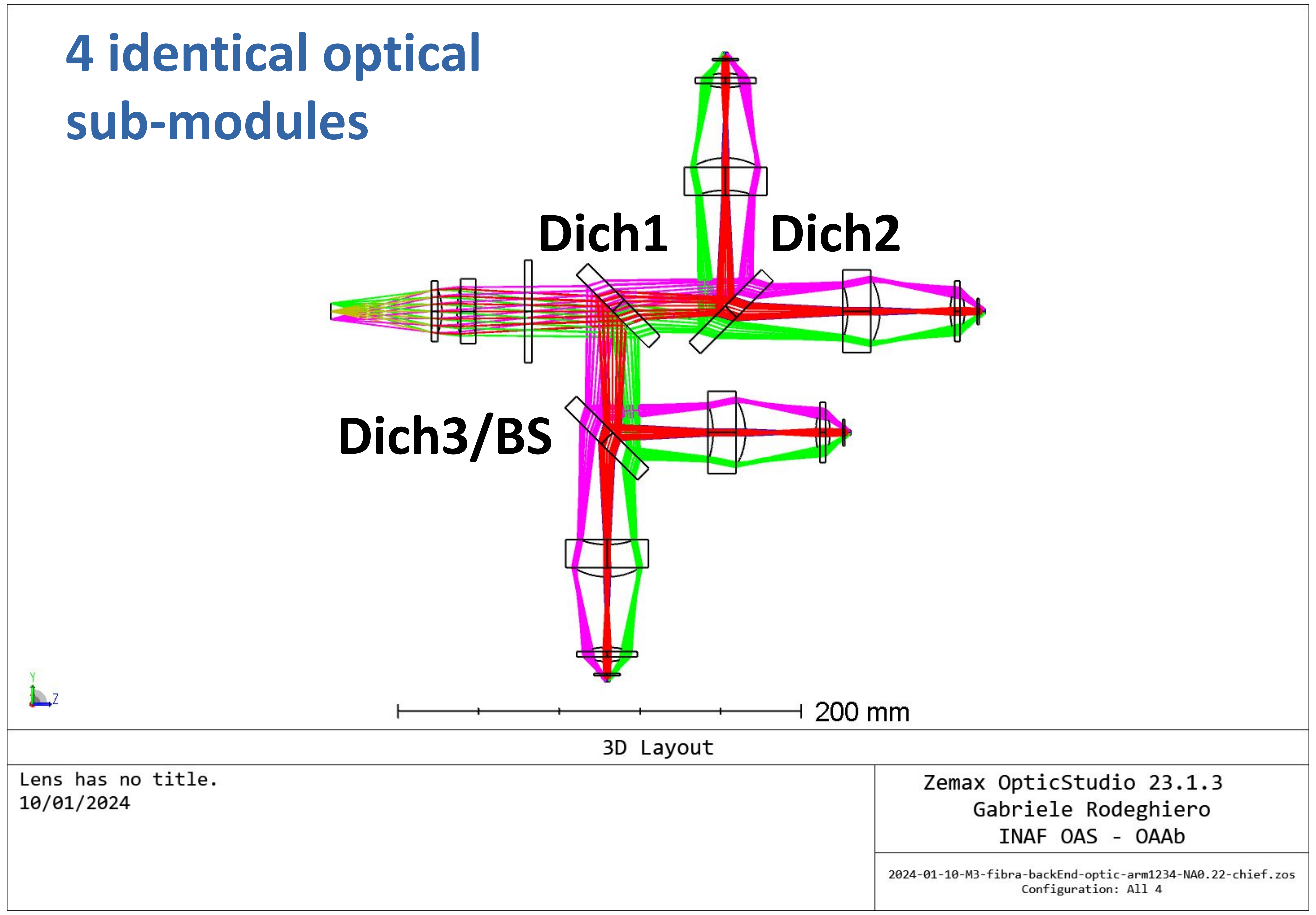


Zampieri et al. (2024)

SI³ Version 2 (3)
Potential future upgrades

Channel Multiplexing

- Inserting dichroics in 2/3 arms will allow us to perform simultaneous measurements in 3/4 bands
- 4 identical optical sub-systems can be accomodated in the Optical Module, leading to 12-16 channels and a boost in sensitivity up to a factor ~4



Custom SiPM-based detectors and FEE

- Will reach higher maximum rate better preserving linearity

Strengths of PC-SII on Cherenkov telescopes when combined with data storage and an adequate handling of the optical beam

- *Spectrally resolving SII*: observations with ~1 nm (up to 0.3 nm) resolution, simultaneous measurements in more bands
- *Channel multiplexing*
- *Post-processing analysis/re-analysis*: checking for systematics and tuning the analysis, computing the correlations among three or more telescopes
- *Synergies with optical telescopes*

Conclusions

Mini-Array

- **SI3** will be mounted **on the ASTRI Mini-Array** that provides **36 baselines between 100 m and 700 m**, enabling detailed observations of stellar surfaces of bright stars and their surrounding environments with angular resolution below 100 micro-arcsec

- Designed to perform accurate **measurements of single photon arrival times (1 ns) in a narrow optical bandwidth (1-8 nm)**

- During 2023 **SI3** underwent a significant **redesign**: focal plane detectors replaced by an **optical fiber bundle** (**FPM**); detectors fed by the fiber bundle and placed in a separated **injection module** (**OM+FEE module**); **new BEE**

- **Laboratory Prototype** completed and working

- Potential future upgrades: **Channel Multiplexing**

SI^3

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