Stellar Intensity Interferometry with Cherenkov telescope arrays: the forthcoming ASTRI-SI^3 and prospects for the CTAO

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Outline

- → Stellar Intensity Interferometry (SII) and Photon Counting SII (PC-SII)
- → SII Instrument (SI^3) for the ASTRI Mini-Array
    - Instrument modules and subsystems
    - Assembly, Integration and Verification of the laboratory prototype
    - Simulations
    - Data processing
- → Potential future upgrades of ASTRI SI^3 (Version 3)
- → The Cherenkov Telescope Array Observatory (CTAO)
- → CTAO potential SII science and implementations
- → Conclusions

Stellar Intensity Interferometry (SII)

Mini-Array

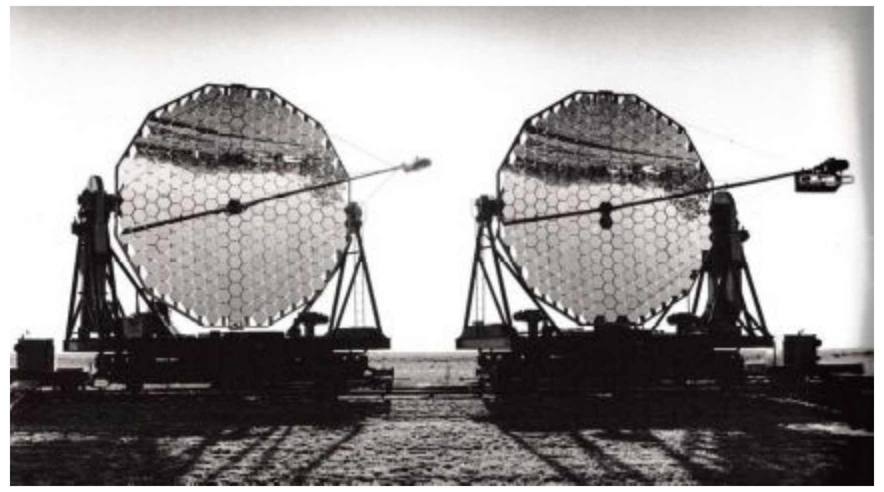
SII consists in a measurement of the **spatial correlation of the intensities of the light from a star with two telescopes** at distance **d** (Hanbury Brown & Twiss 1957, 1958)

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

The term on the right hand side is the square modulus of the **Complex Visibility** or time averaged cross-correlation of the electric field (amplitude/phase interferometry):

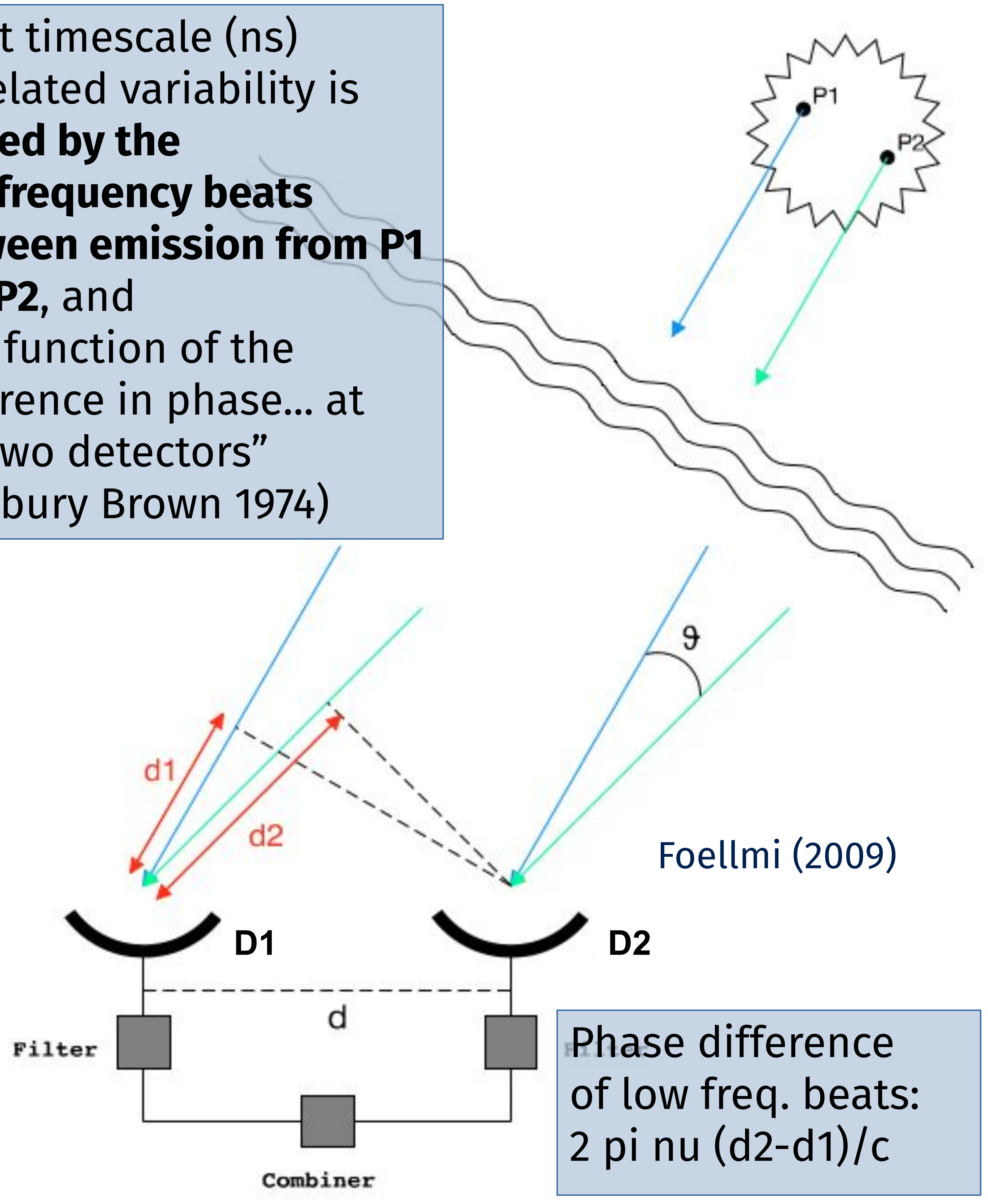
$$\Gamma(u,v,\tau) = \lim (1/2T) \int E_1(t) E_2^*(t-\tau)\, dt$$



The **first Intensity Interferometer** was built by Hanbury Brown & Twiss in Narrabri, Australia (Hanbury Brown 1956; Hanbury Brown & Twiss 1957, 1958)

Renewed interest for SII triggered by possibility to achieve diffraction-limited (sub-milliarcsec) resolution with ~km baselines **on IACTs** (LeBohec & Holder 2005) **and CTAO** (Dravins et al. 2012, 2013), not affected by atmospheric seeing

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)



Foellmi (2009)

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

Photon Counting Stellar Intensity Interferometry (PC-SII)

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

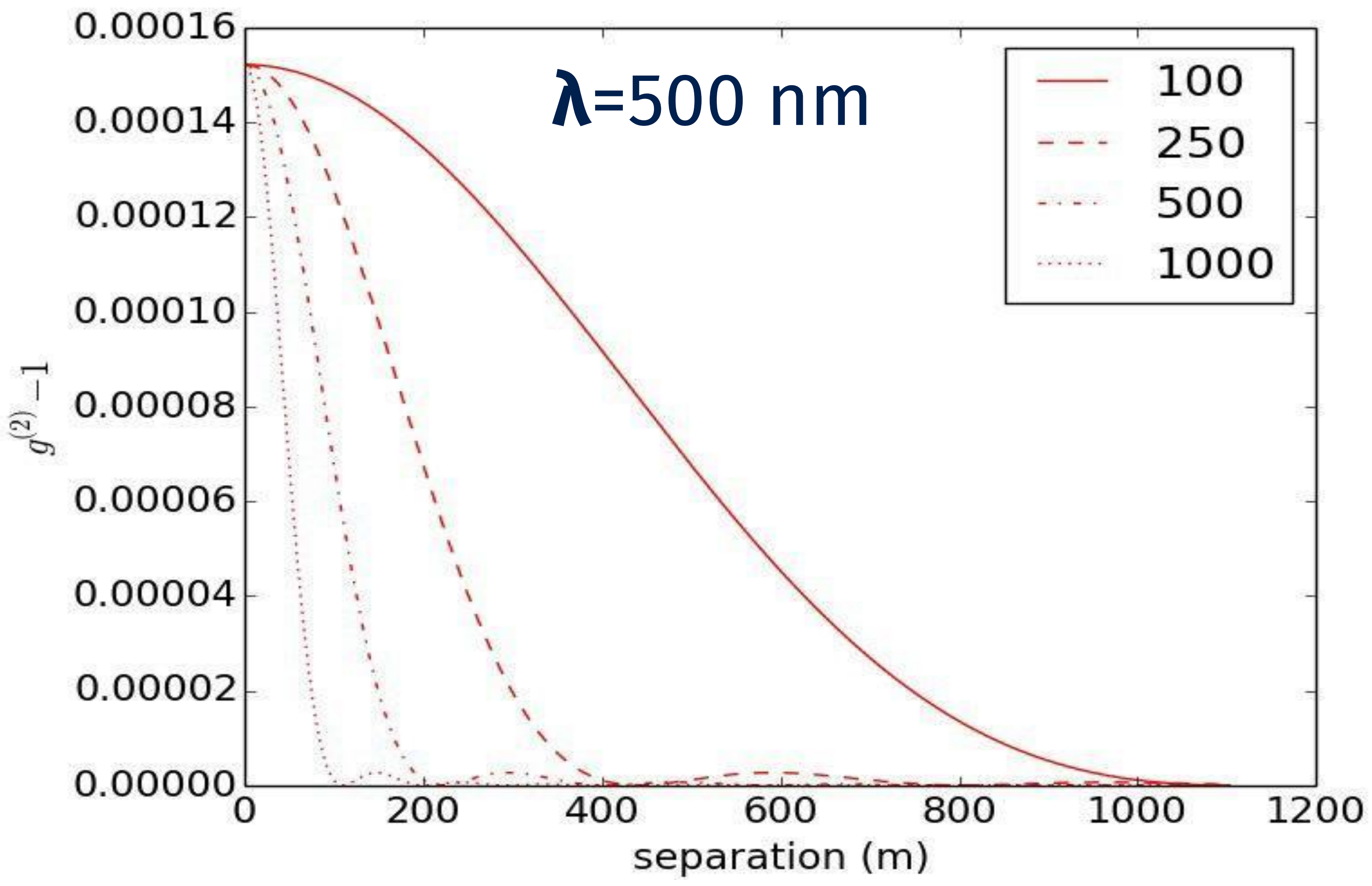
If photons are detected with a **sampling time dx in N intervals**, then the **2nd order degree of coherence $g^{(2)}$** is calculated from:

$$g^{(2)} = N_{12} N / (N_1 N_2) = \langle I_1 I_2 \rangle / [\langle I_1 \rangle \langle I_2 \rangle]$$

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

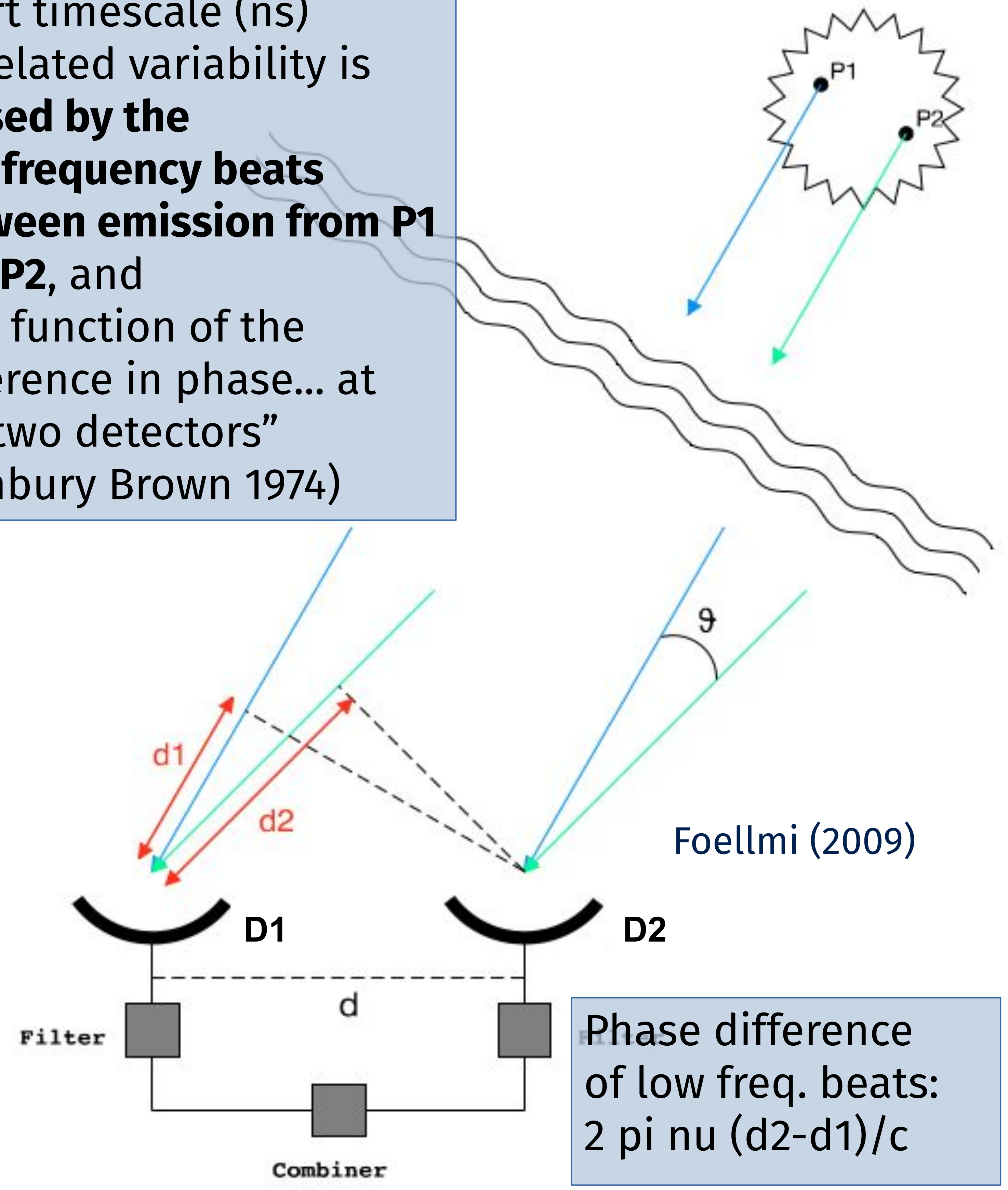
N_{12} = number of simultaneous detections in bins **dx** (random + quantum excess)

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



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

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)



Foellmi (2009)

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

SII Implementation modes

Mini-Array

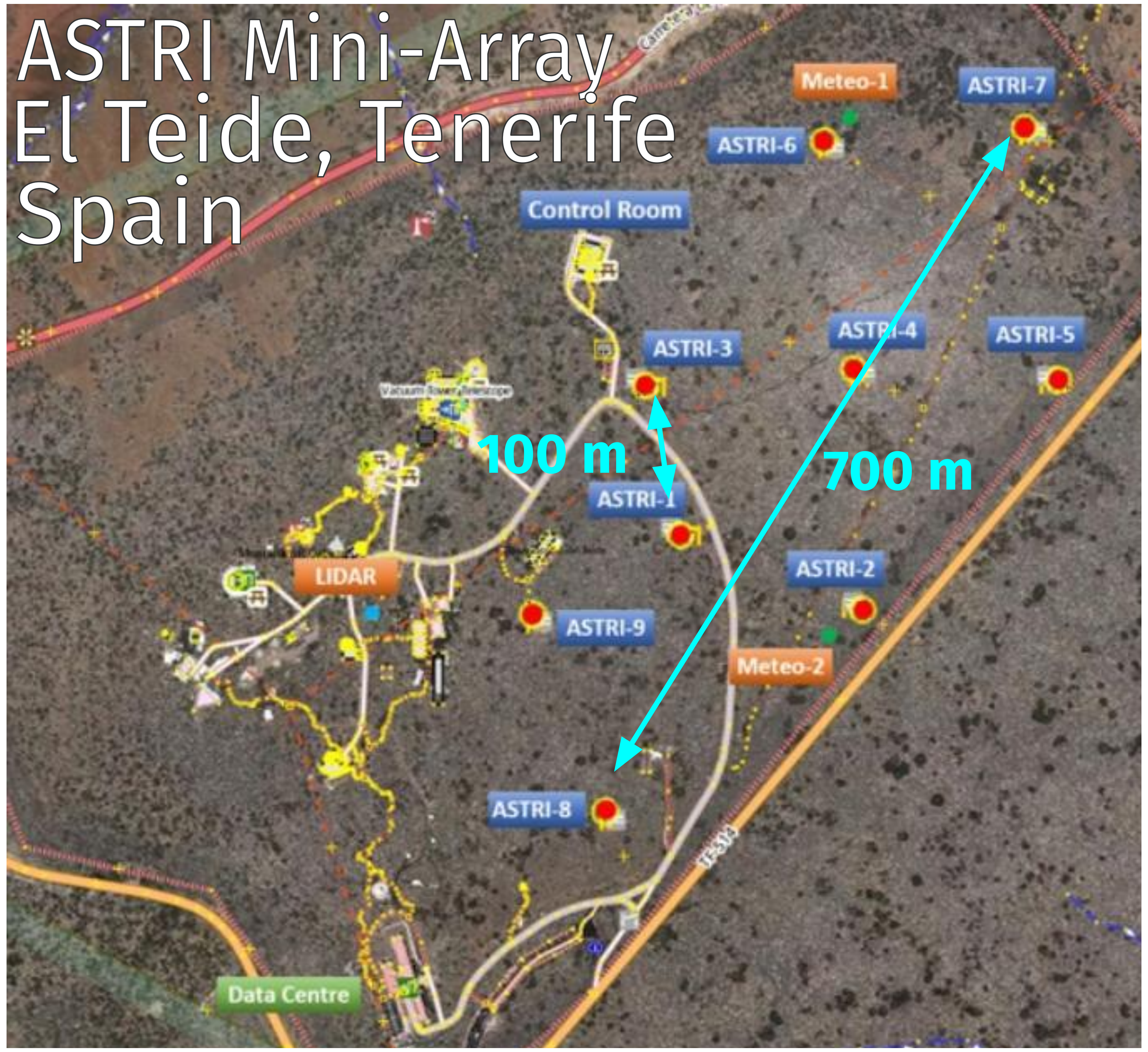
- **Two methods** to implement **SII**:
  - **Digital SII**: Similar to the original HBT experiment. Currents generated in two or more detectors are transformed into digital signals and then correlated.
  - **Photon-counting SII**: Exploiting quantum effects. Measuring the coincidence in the time of arrival of photons at different locations.
- **Correlation** can be computed **"on-line"** or **"off-line"** in the **time domain** or in the **frequency domain** (using to Fast Fourier Transform).

- **MAGIC (Cherenkov telescopes)**: **Digital SII**, **on-line correlation**, **frequency domain**
- **HESS (Cherenkov telescopes)**: **Digital SII**, **off-line correlation**, **frequency domain**
- **VERITAS (Cherenkov telescopes)**: **Digital SII**, **off-line correlation**, **time domain**
- **I2C (Optical telescopes)**: **Photon-counting SII**, **on-line correlation**, **time domain**
- **ASTRI Mini-array (Cherenkov telescopes)**: **Photon-counting SII**, **off-line correlation**, **time domain**

ASTRI SII Instrument (SI^3)

Mini-Array

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**

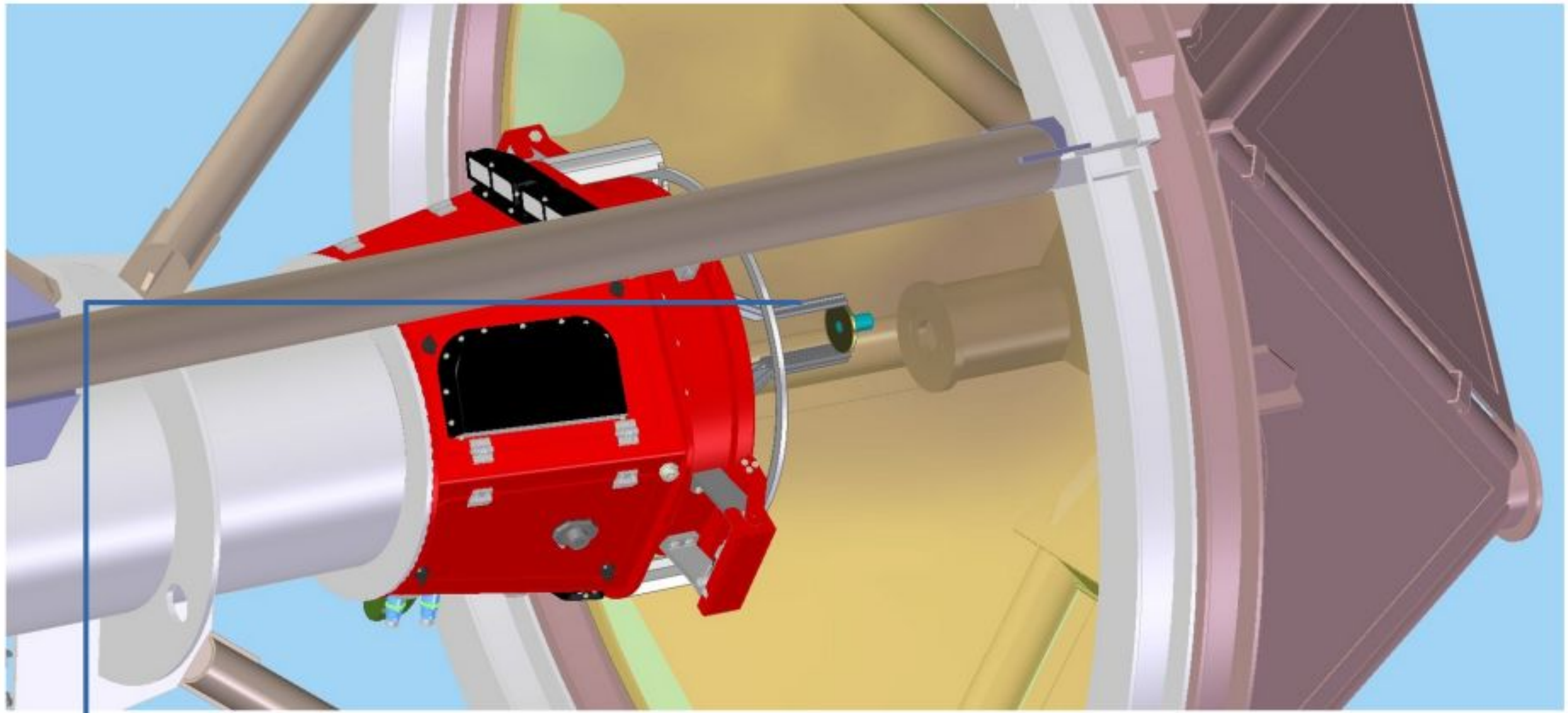


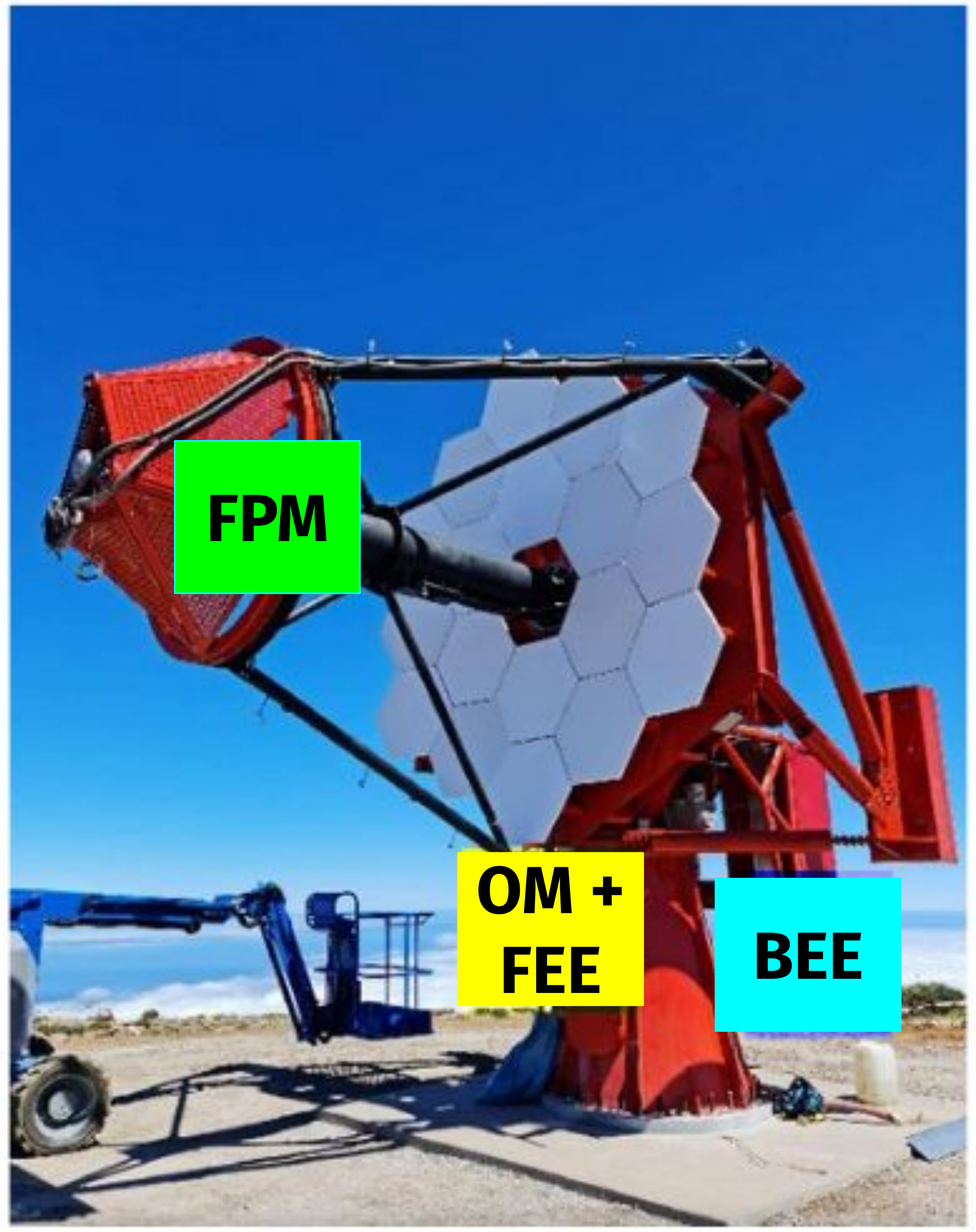
Stellar Intensity Interferometry with ASTRI

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

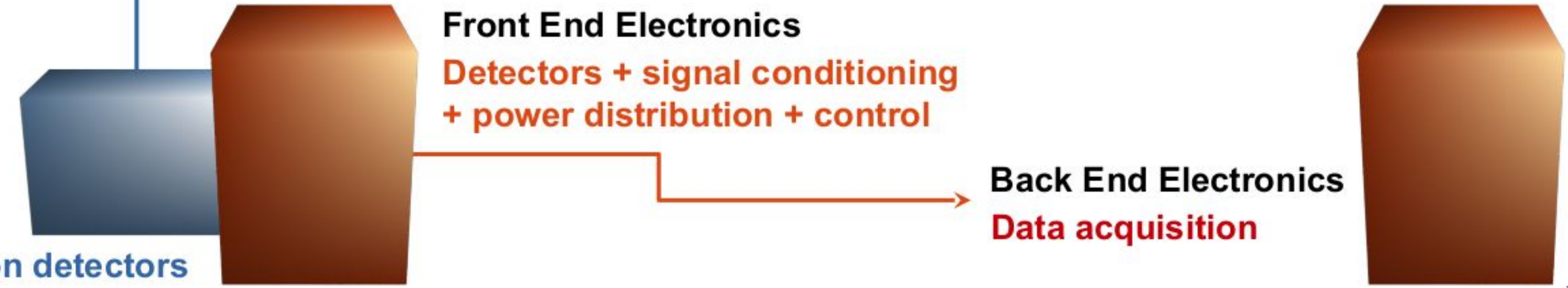
Ultimate goal: using the **long (up to ~700 m) multiple baselines (36)** of all 9 ASTRI Mini-Array telescopes to do image reconstruction with resolution of **~100 microarcseconds**

SI³ Version 2
Instrument Design





Focal Plane Module (placed on top of the camera)
Focussing optics + optical fiber bundle + field camera



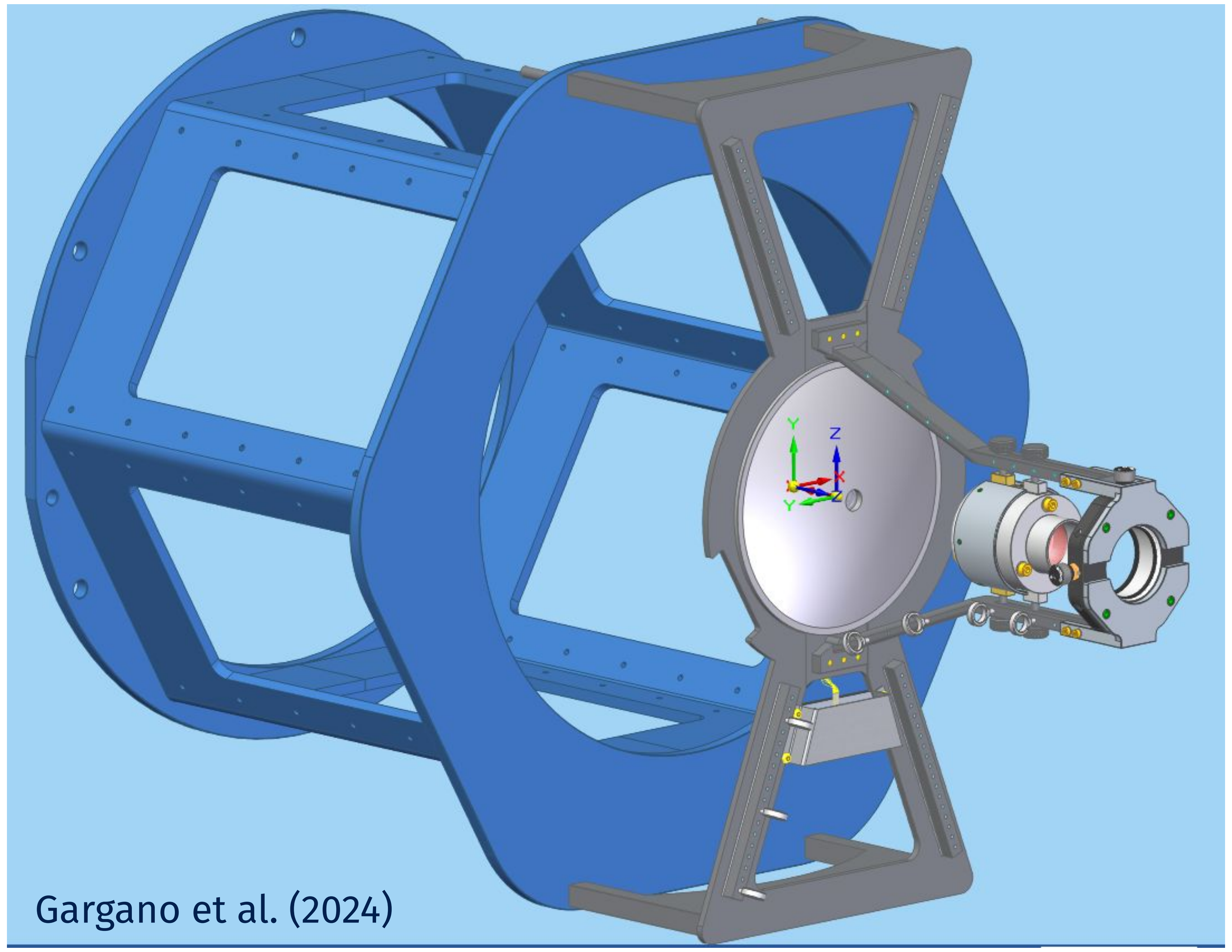
Front End Electronics
Detectors + signal conditioning + power distribution + control

Back End Electronics
Data acquisition

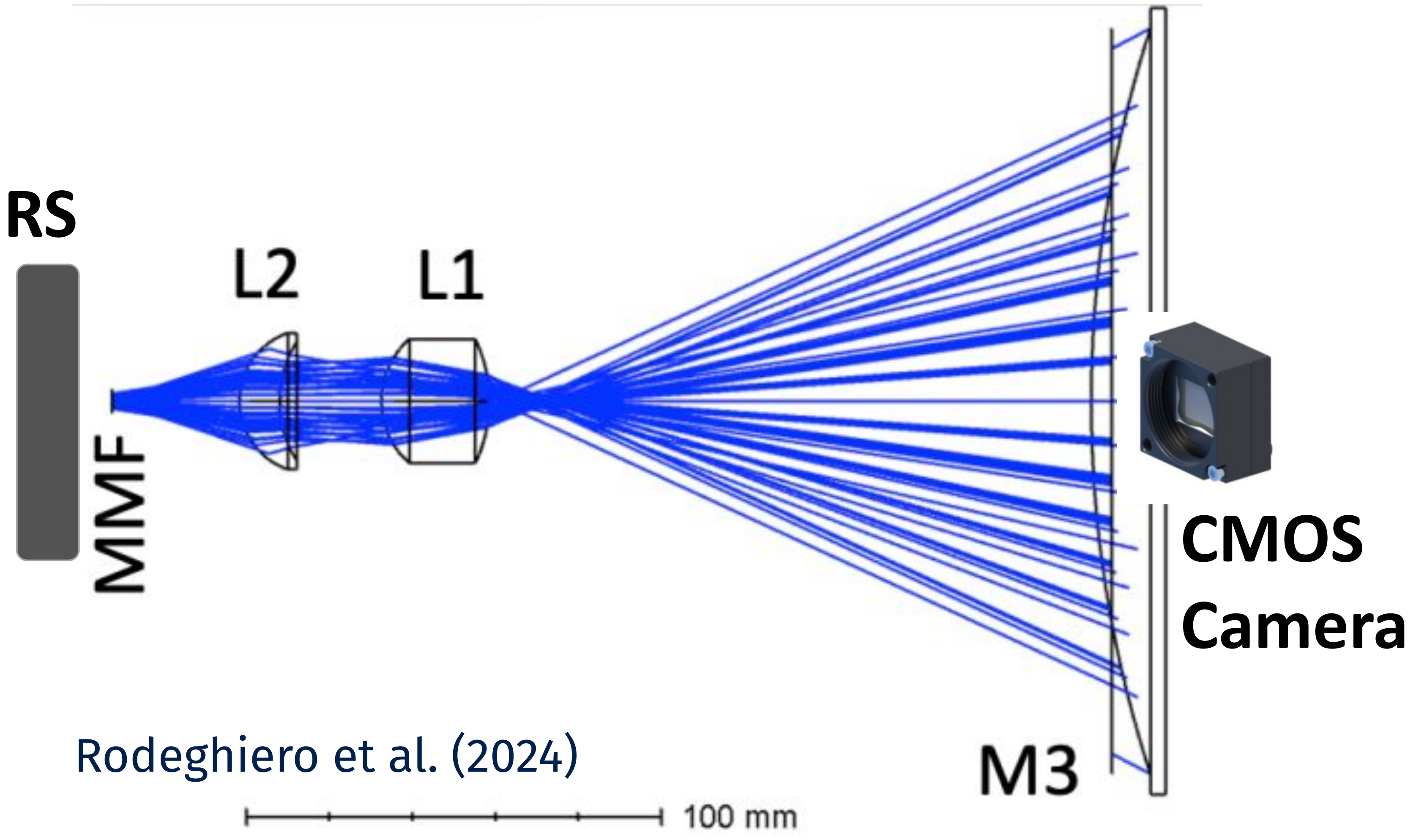
Optical Module
Injecting light on detectors

Zampieri et al. (2024)

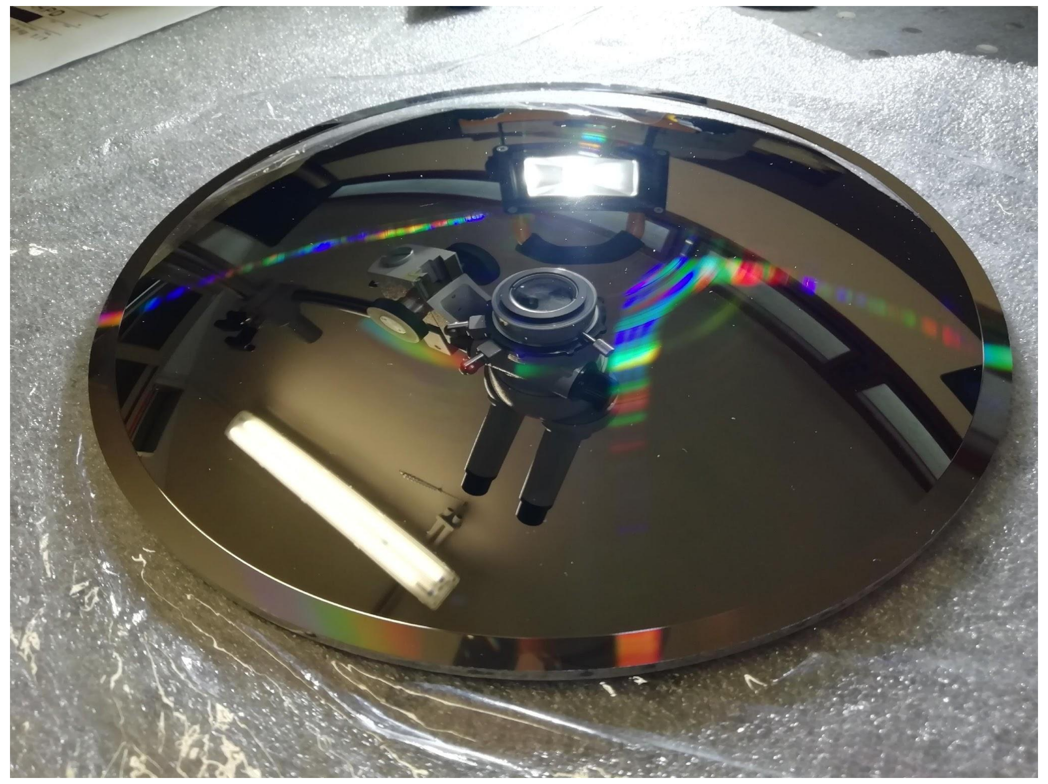
SI^3 Version 2
FPM: Focal Plane Module



Gargano et al. (2024)



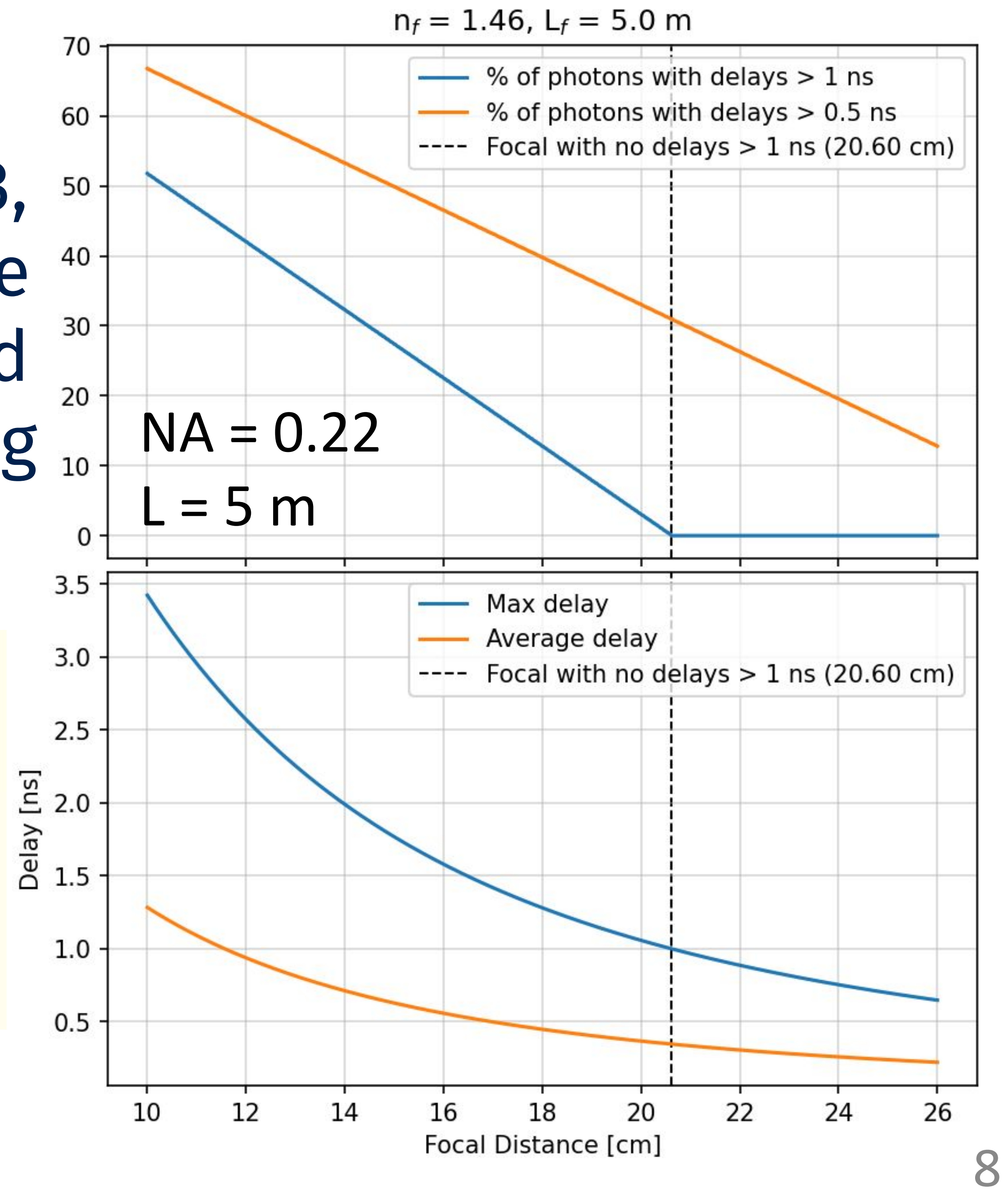
Rodeghiero et al. (2024)

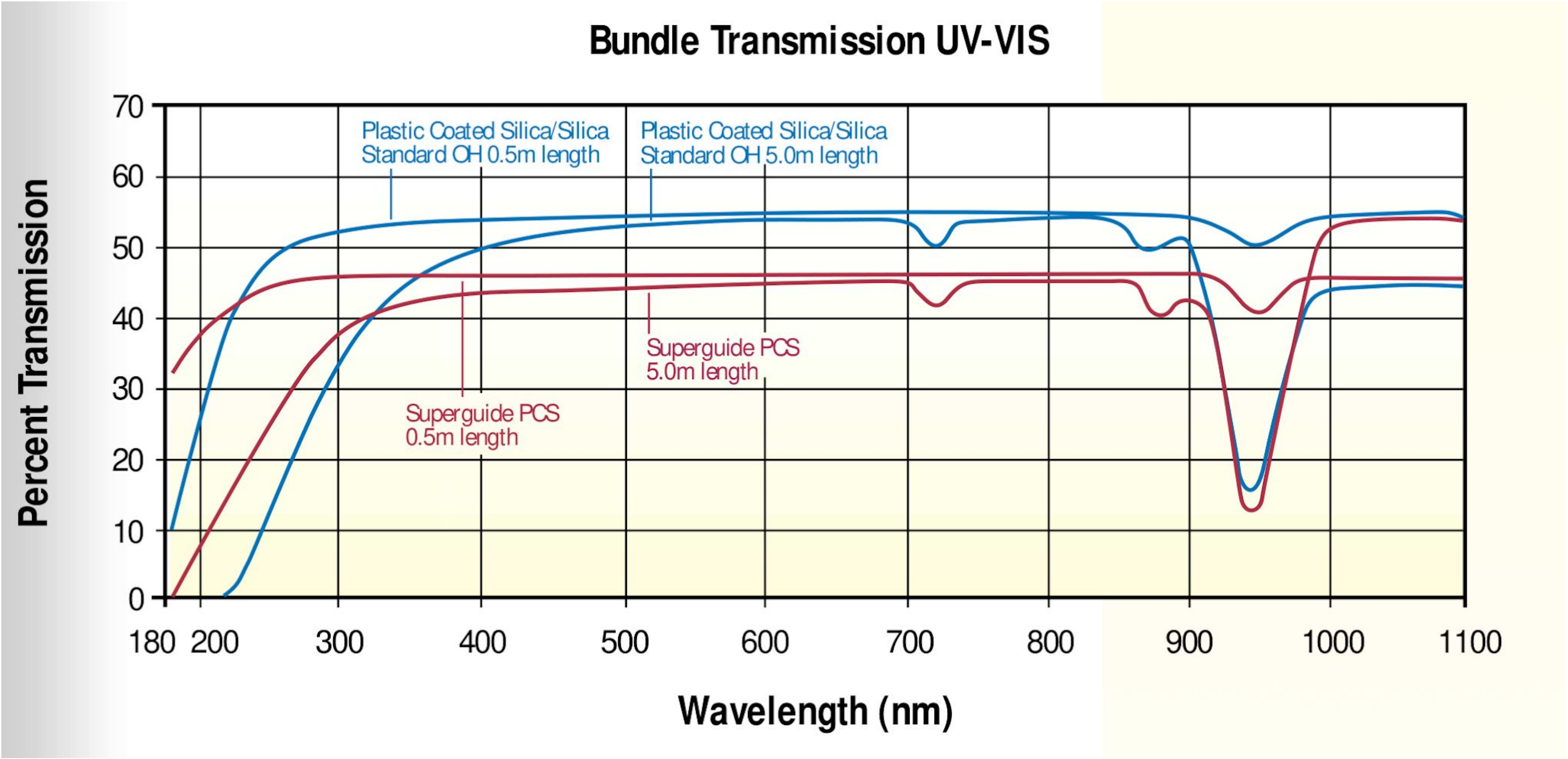


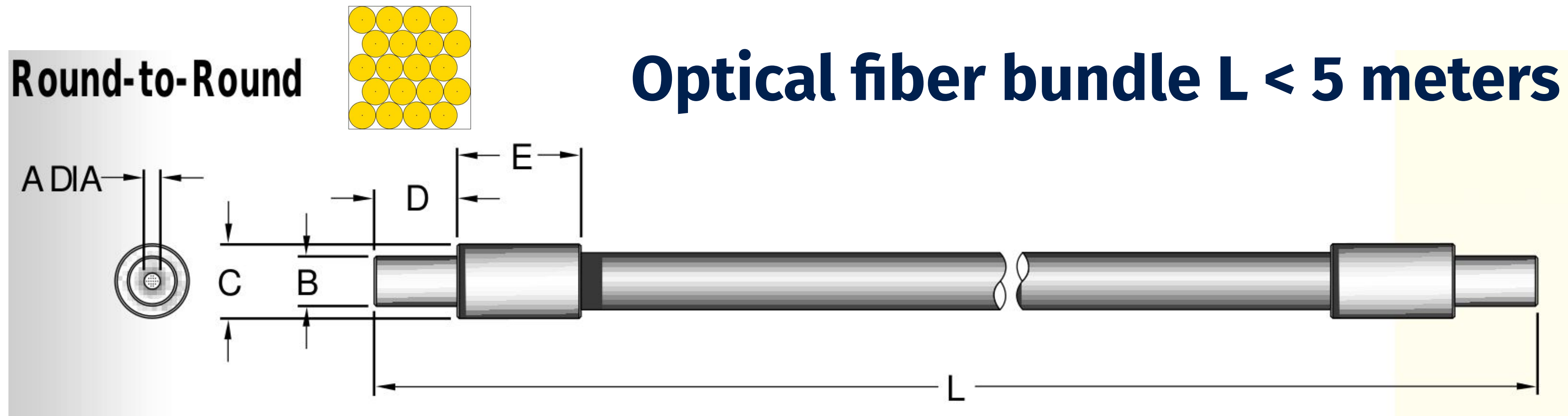
M3 Aluminum mirror

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





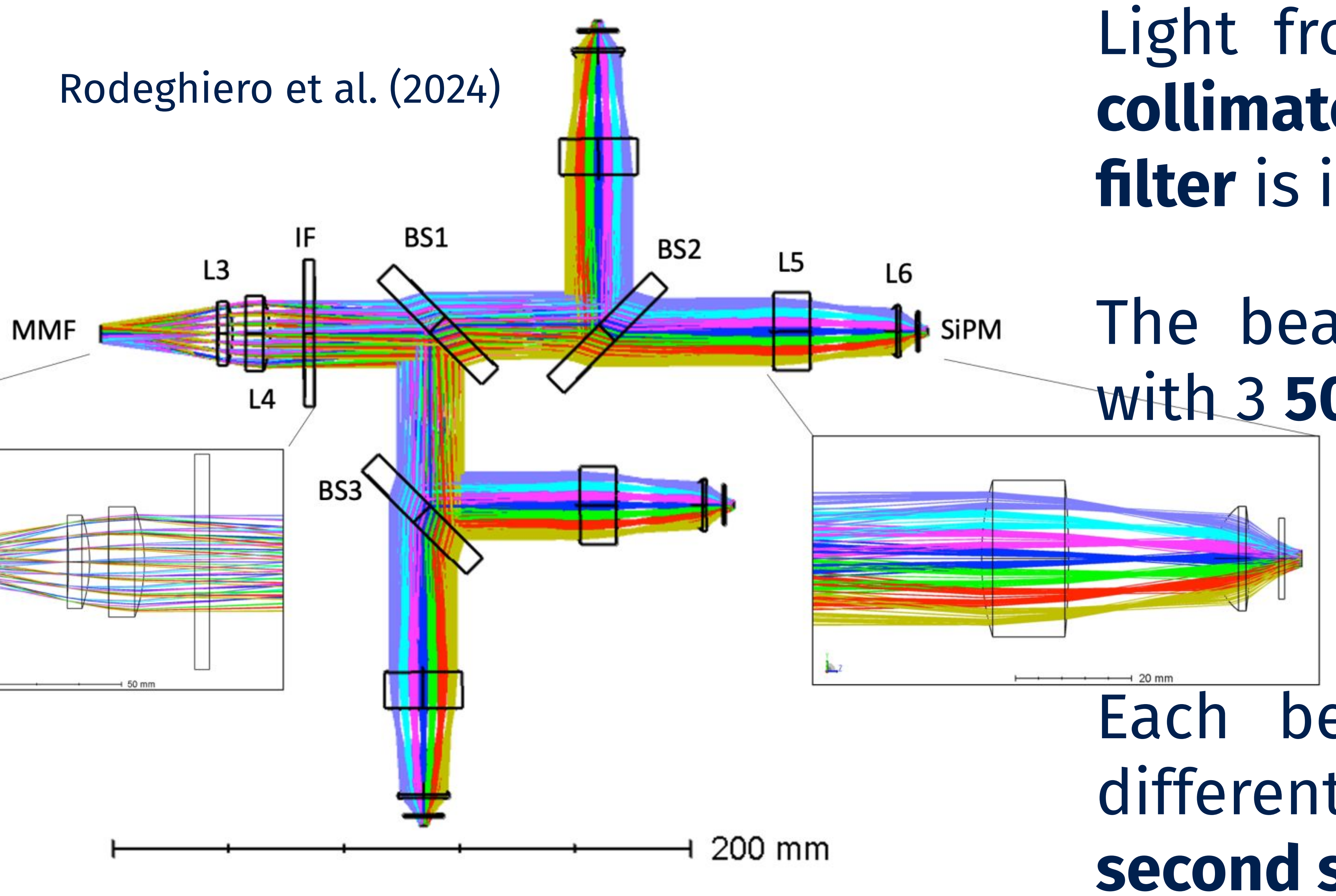


Optical fiber bundle L < 5 meters

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

SI^3 Version 2
OM+FEE: Optical Module with detectors and Front End Electronics

Rodeghiero et al. (2024)

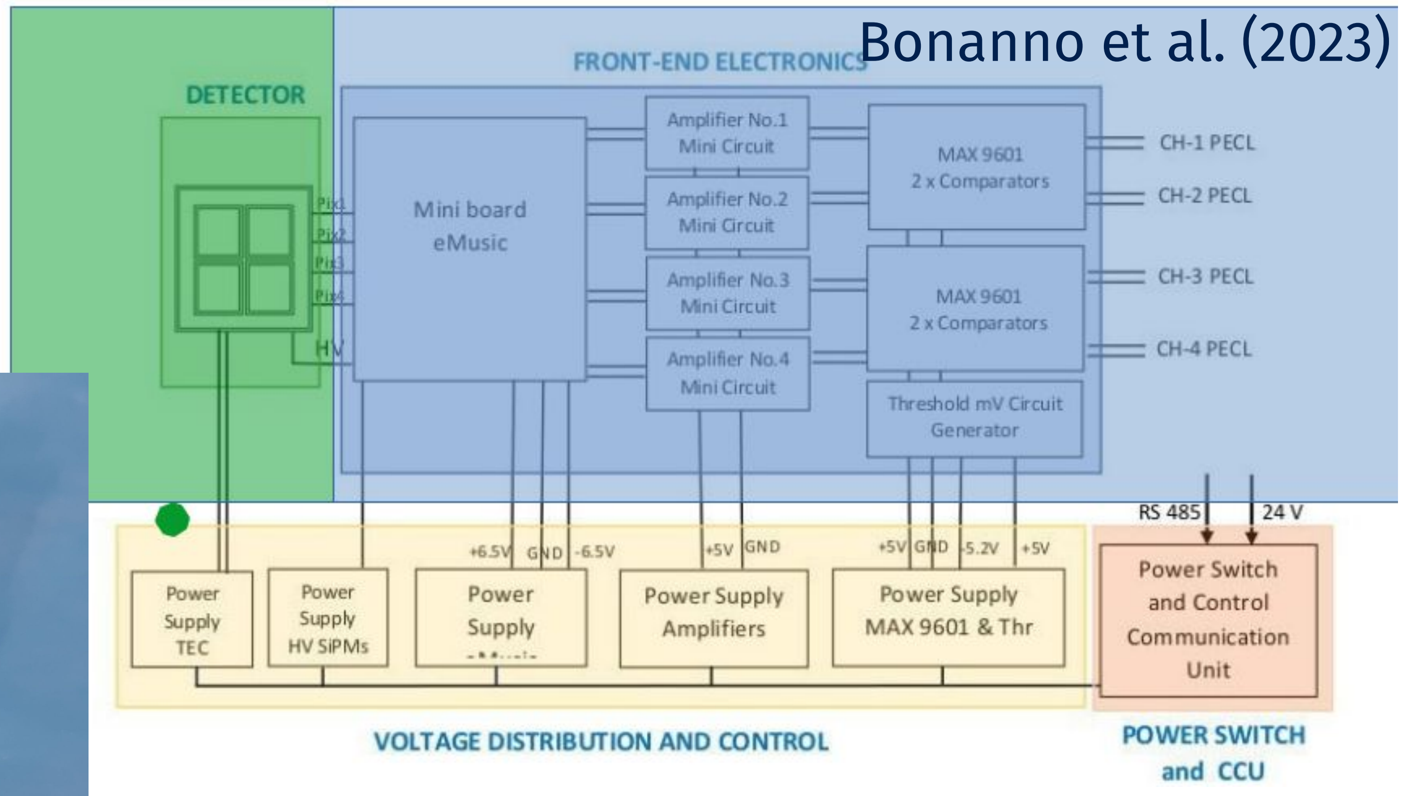


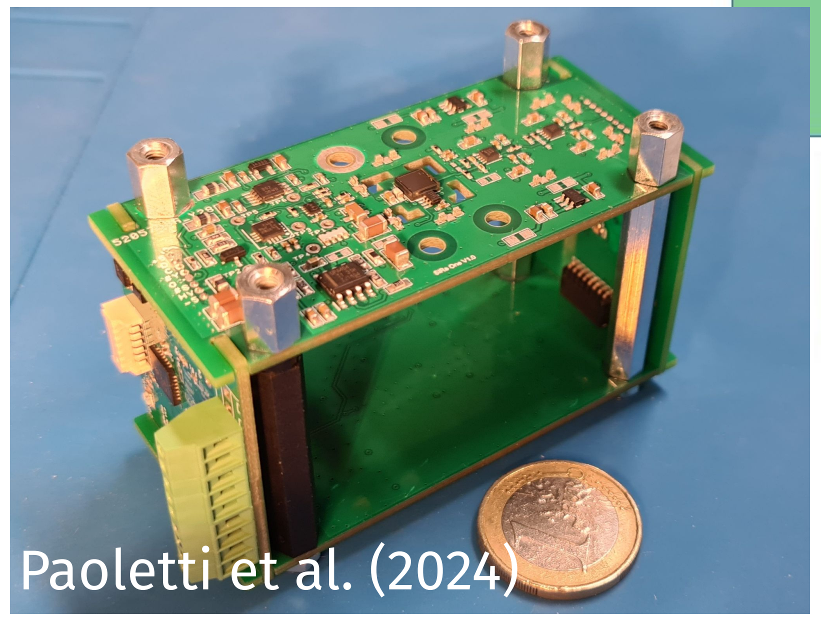
Light from the optical fiber is **collimated** and a **narrow band filter** is inserted (1-8 nm)

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**

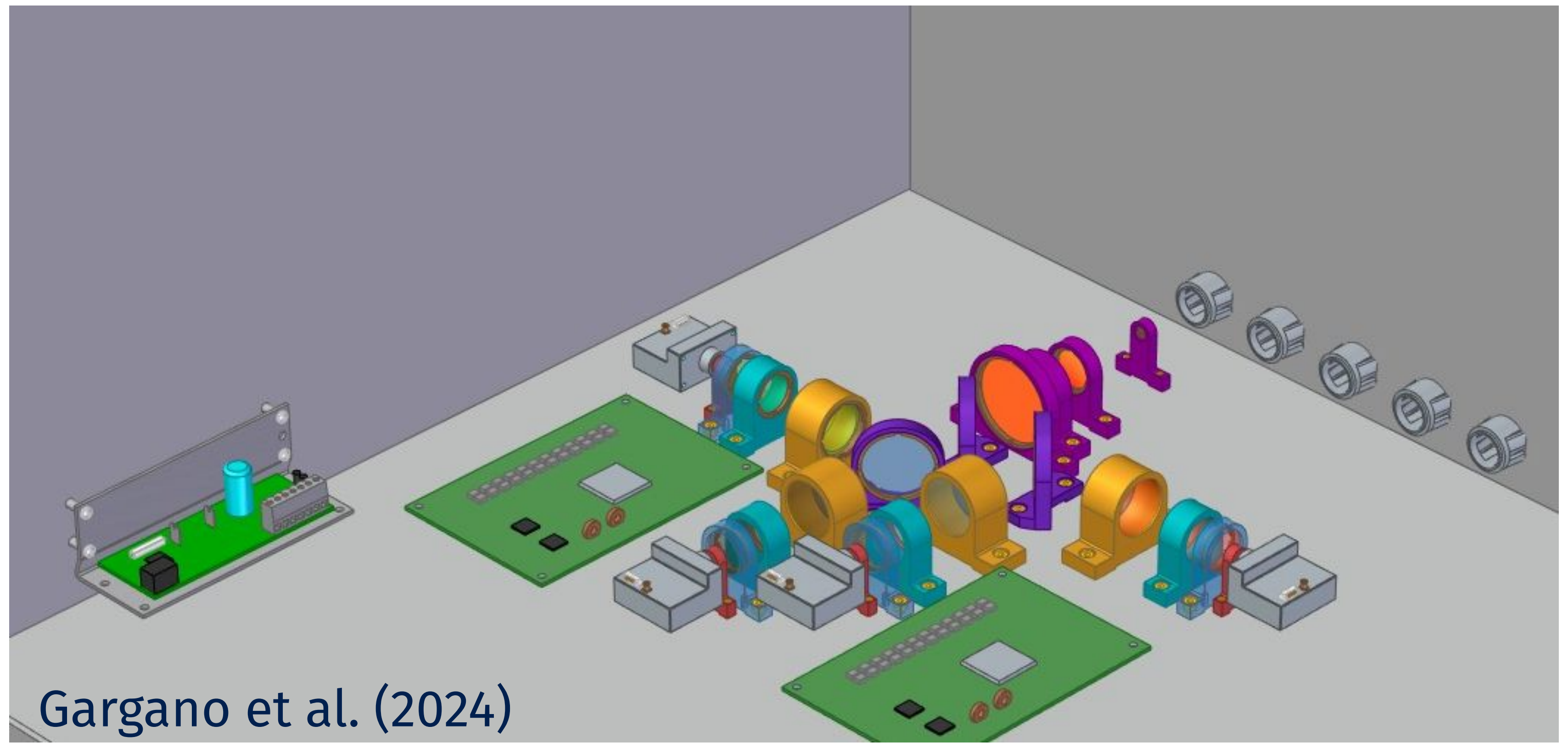
Custom SiPM Detector





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

Under development

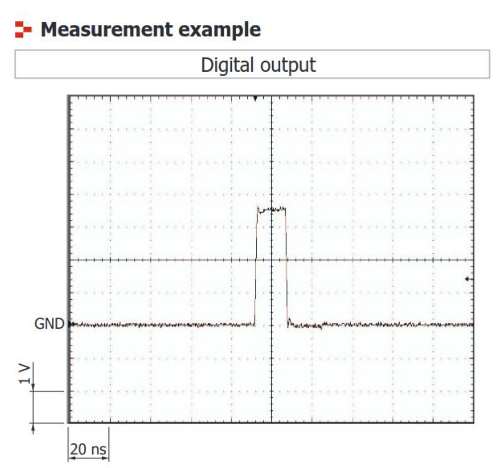


Commercial SiPM Detector

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

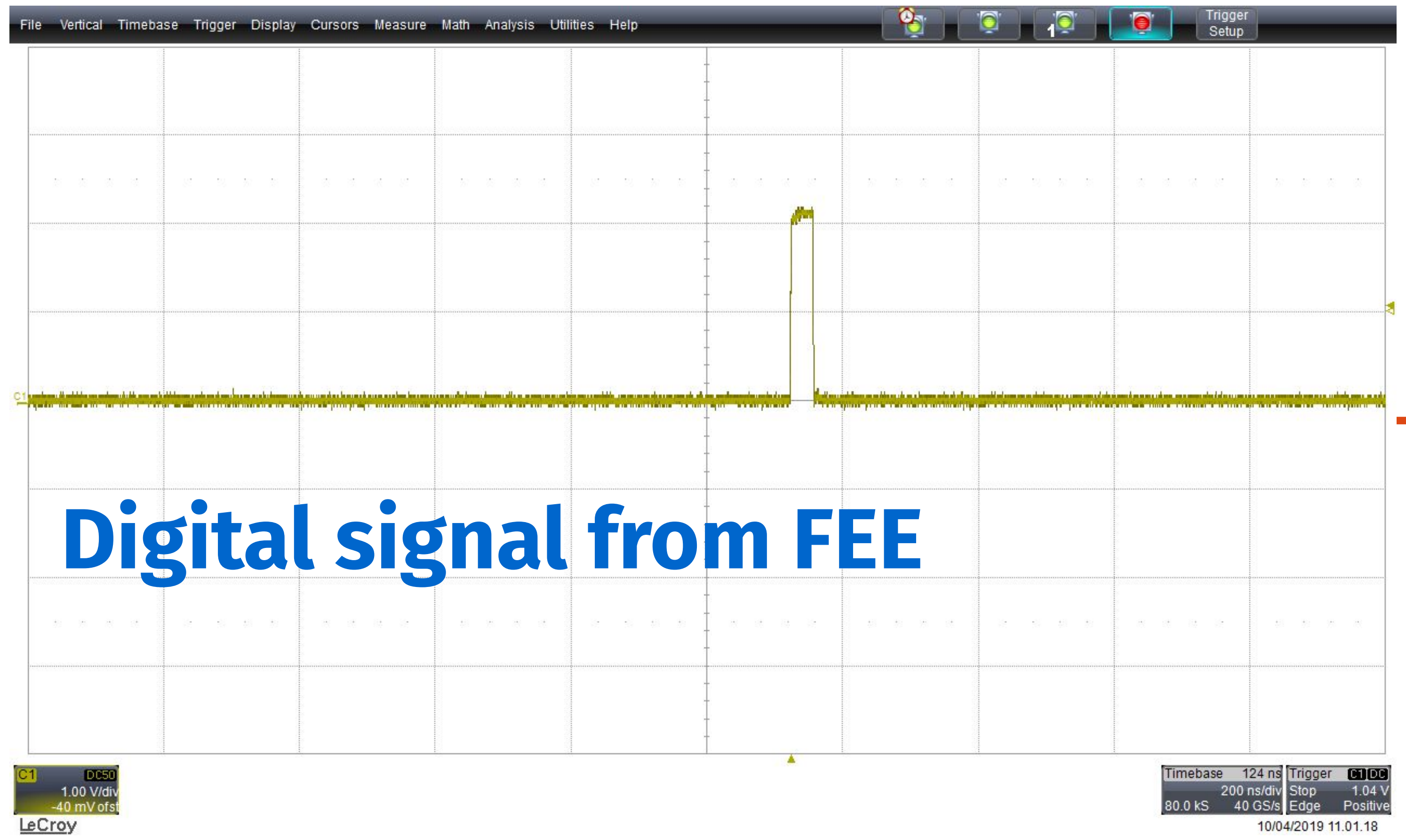
Max rate: ~17 Mct/s
Linearity preserved up to ~10 Mct/s
Jitter ~500 ps

For prototype phase

SI^3 Version 2

BEE: Back End Electronics

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

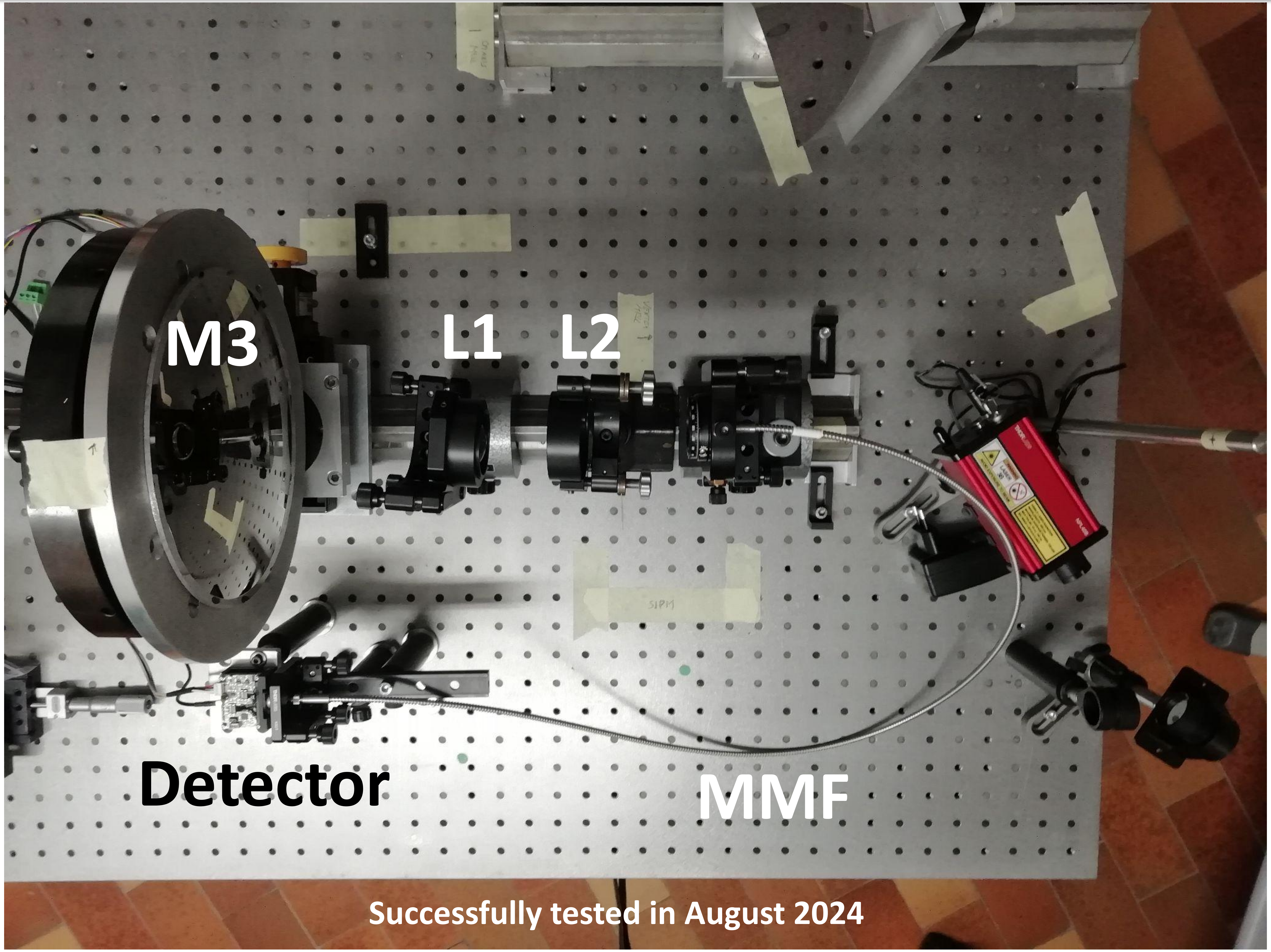
Workstation
Super Tower 732D3-903B
Supermicro

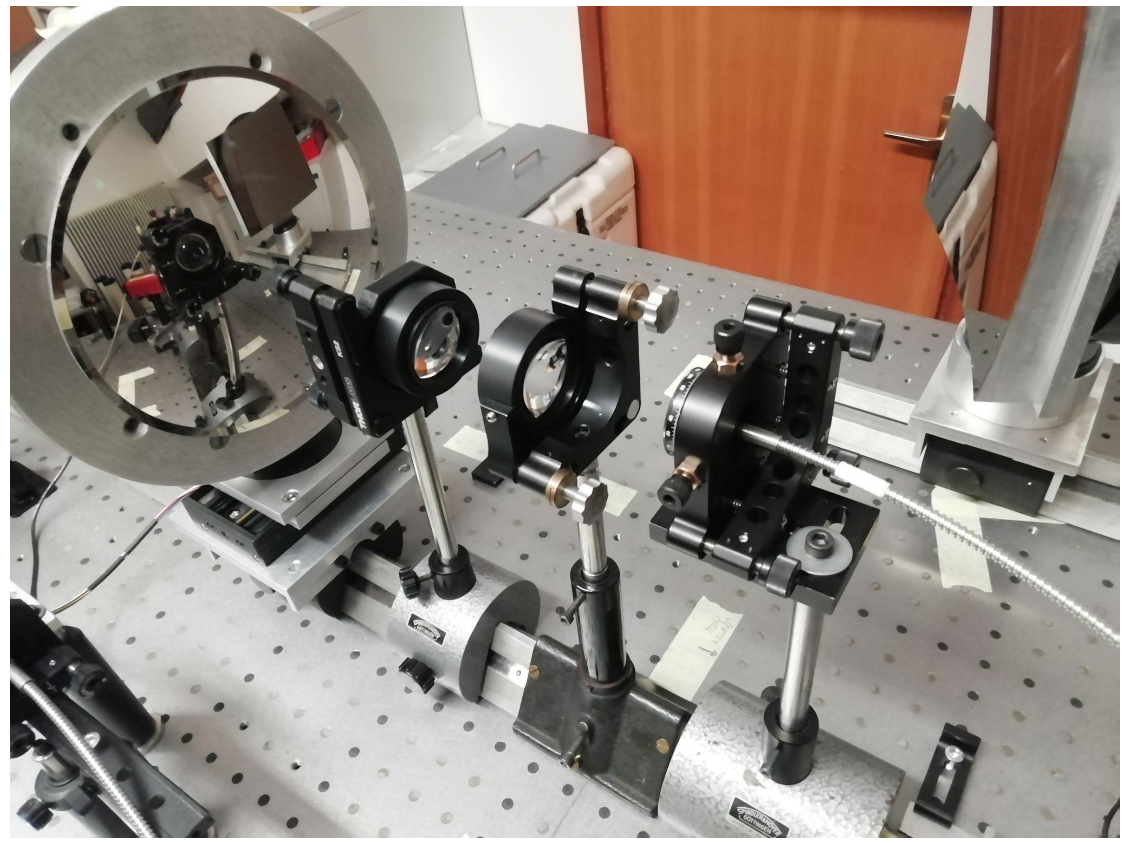
Time Distribution Unit (TDU)
White Rabbit system

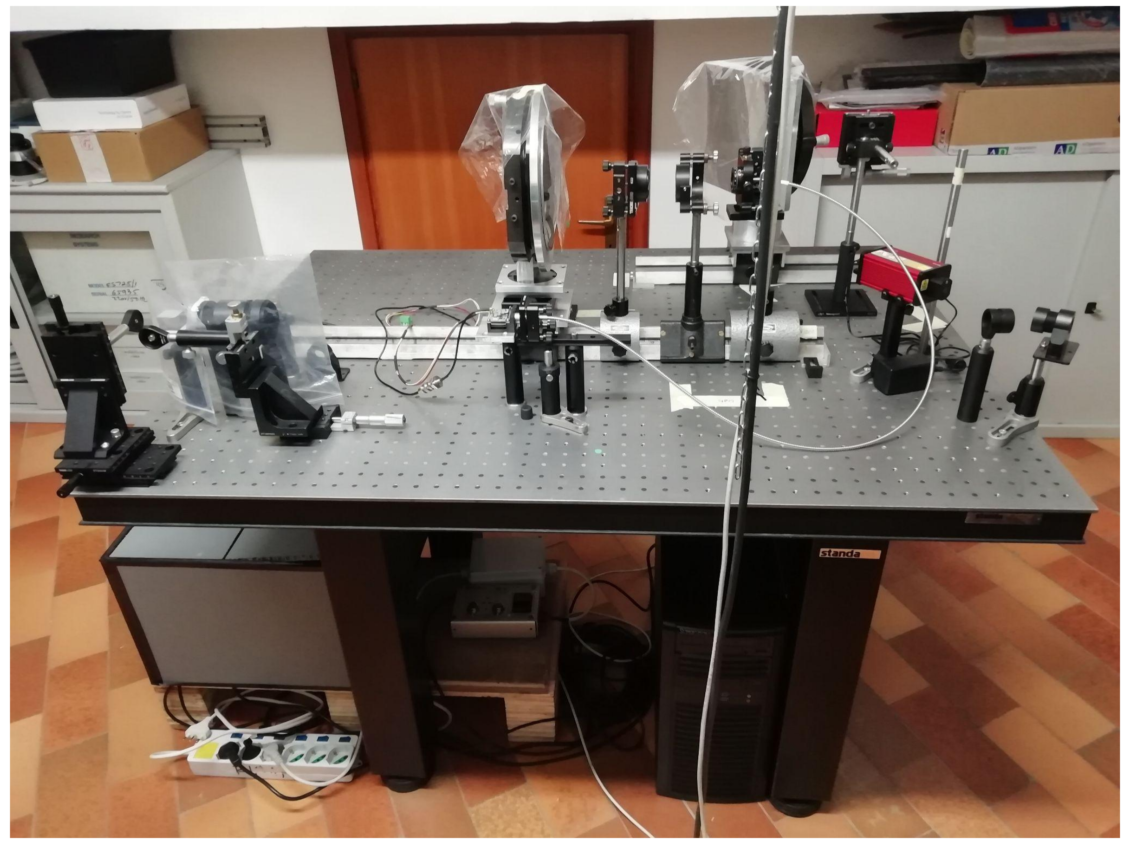
PPS signal + Clock reference signal

To Array Data Acquisition System
1.12 Gb/s max rate

AIV FPM
FPM Laboratory Prototype







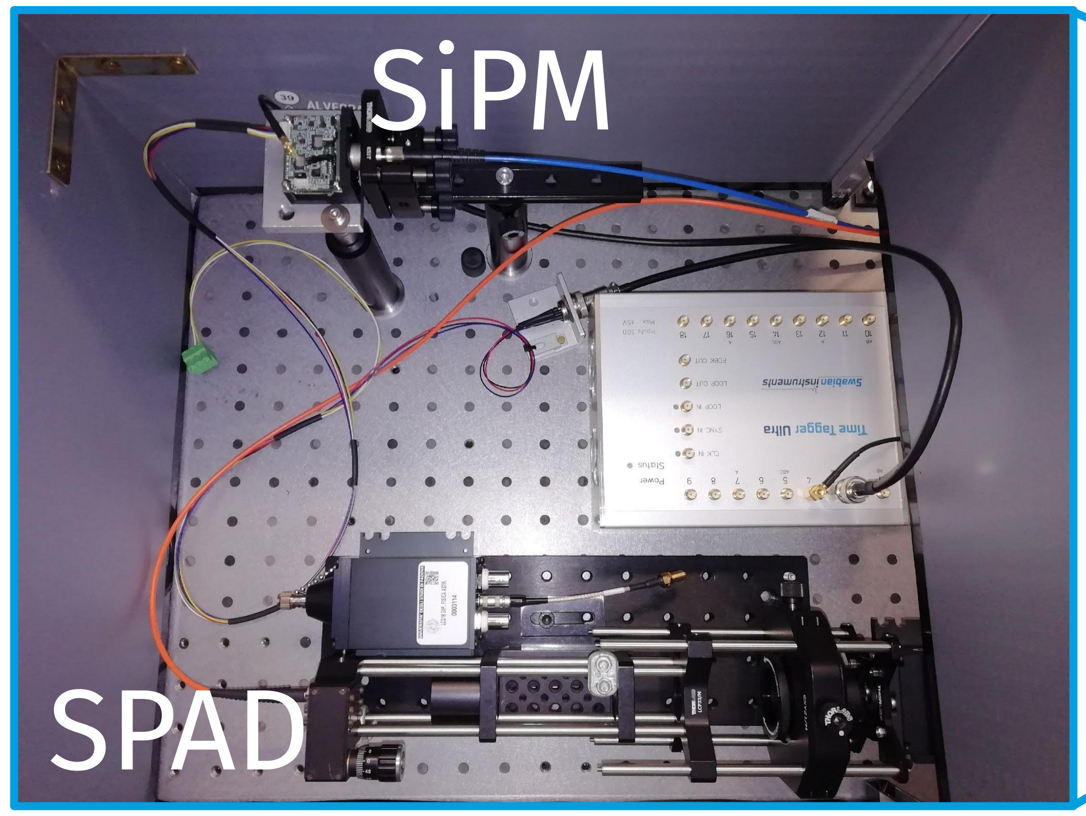
Laboratory located at mount Ekar (Asiago) in the 1.8m Copernicus telescope building

Zampieri et al. (2024)

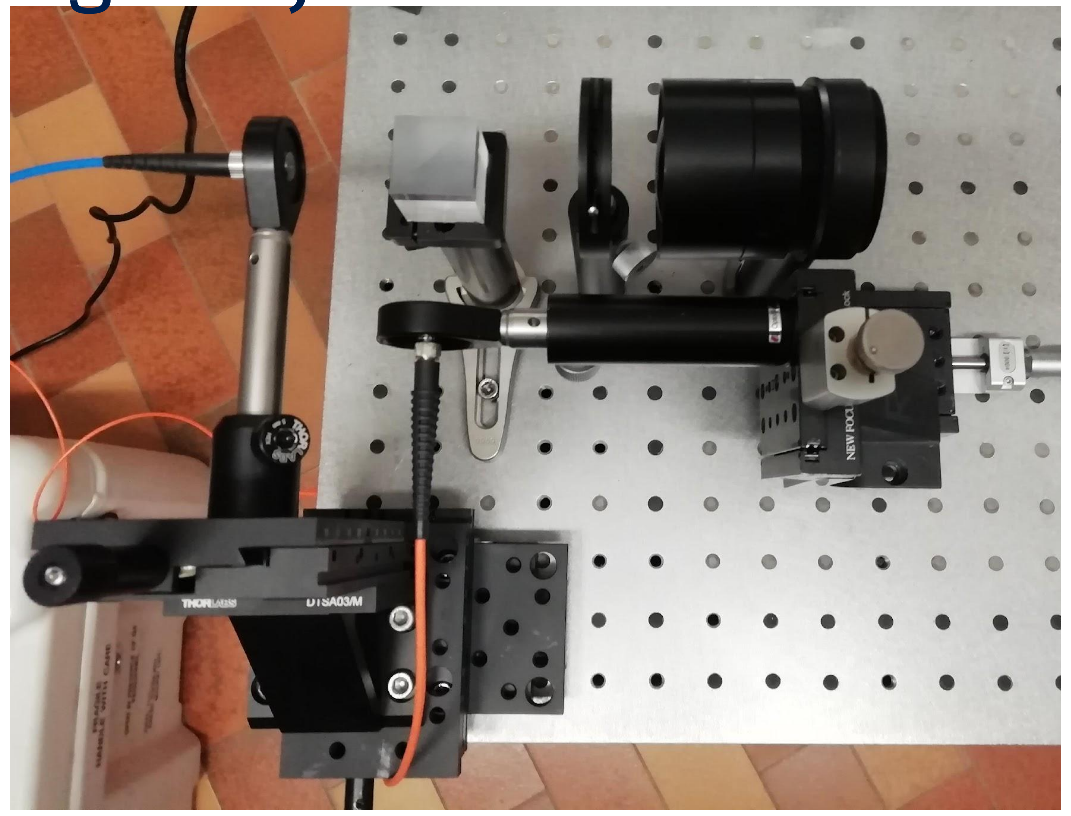
AIV Commercial Detector and Acquisition System
Laboratory Setup for correlation measurements

Mini-Array

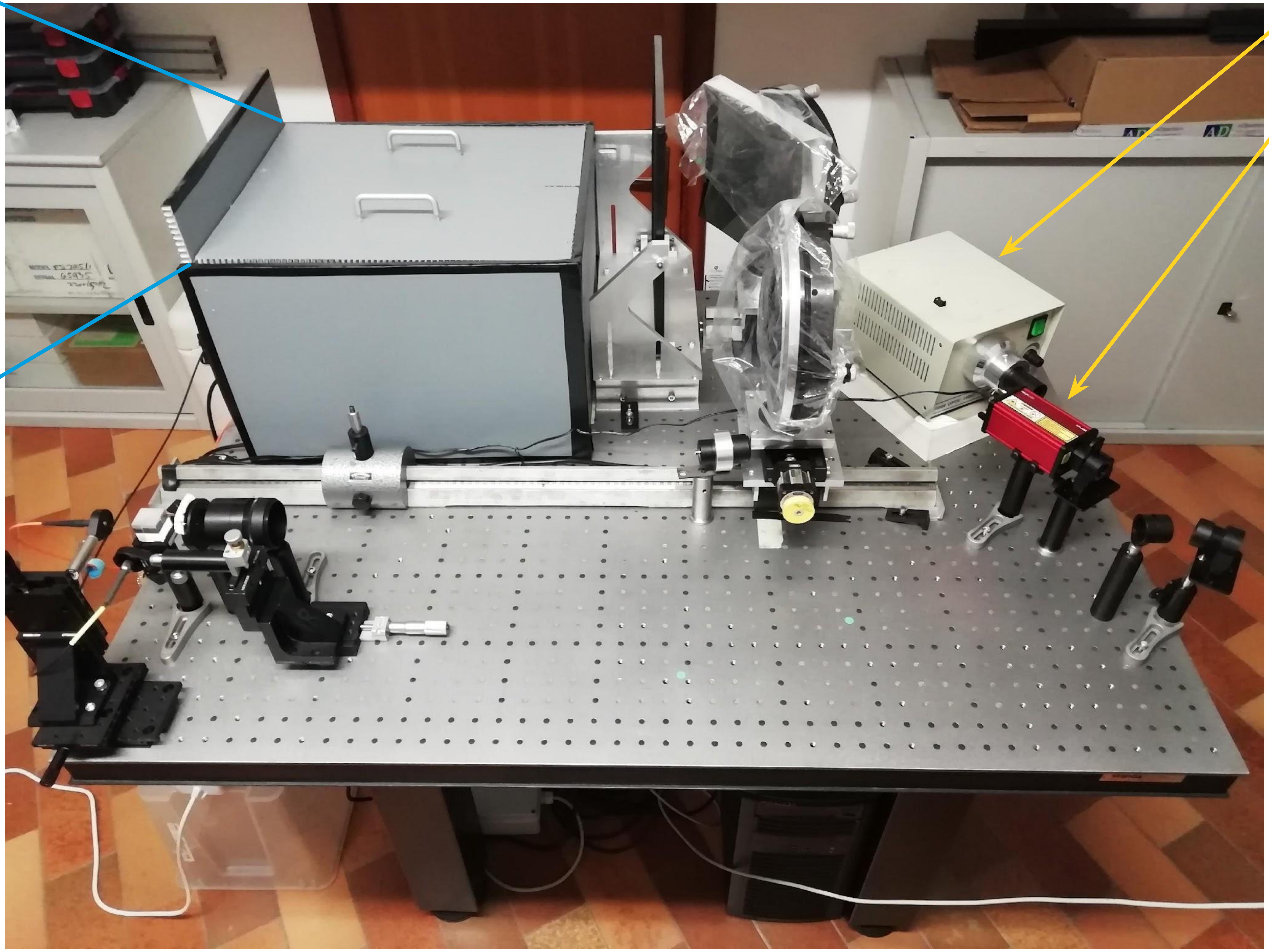
Assembly-Integration-Verification (AIV) of the commercial SiPM module and the acquisition system in the **ASTRI-AQUEYE laboratory In Asiago (Italy)**.



Light injection Module



Zampieri et al. (2024)



Thermal lamp

Nanosecond pulsed laser
1 to 10 MHz repetition rate, ~6ns pulse duration, λ=450nm

Reflecting mirror

Pinhole ~ 100 µm

Focusing lens + Baffle
at 950 mm from pinhole

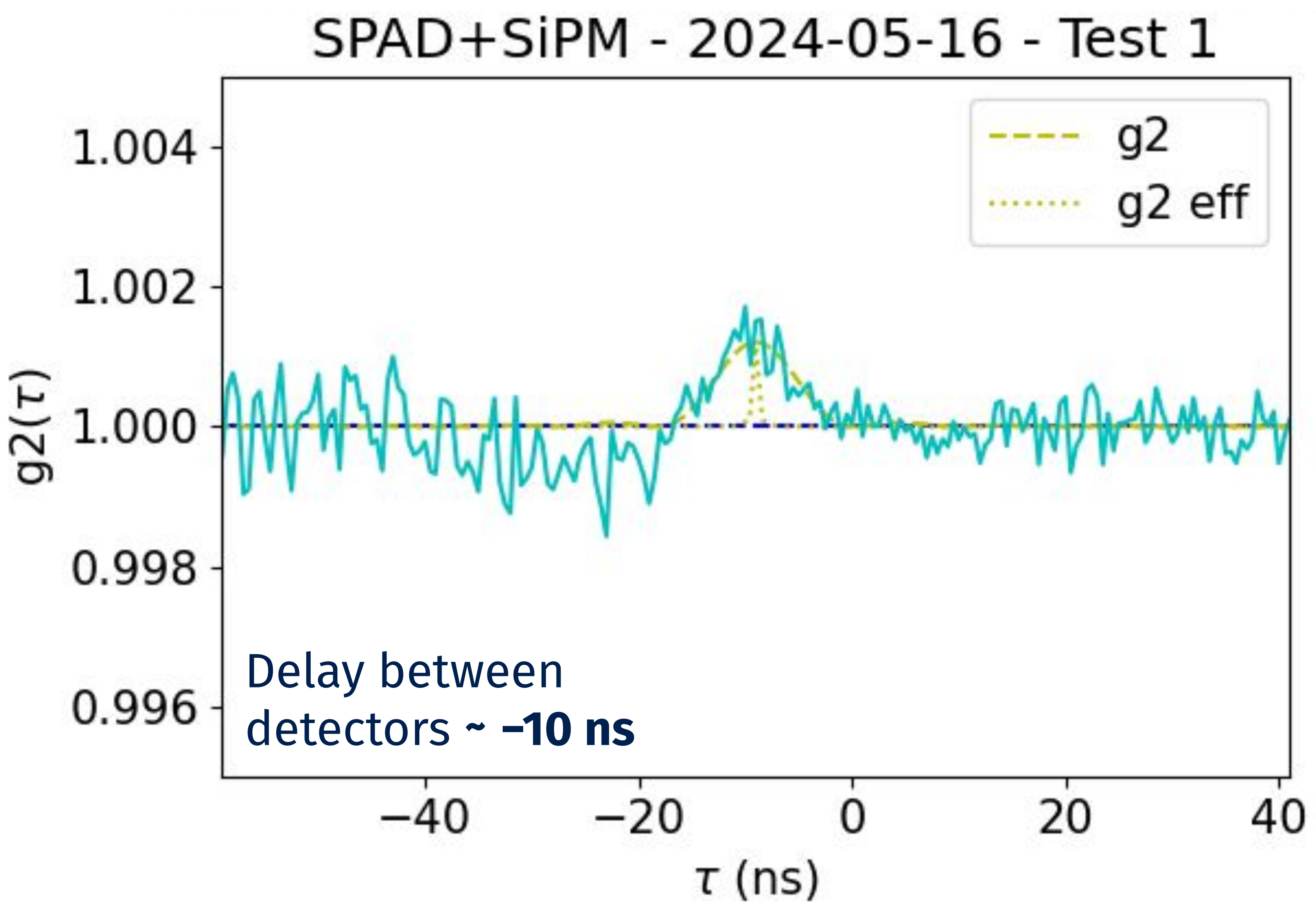
50-50 cube beam splitter

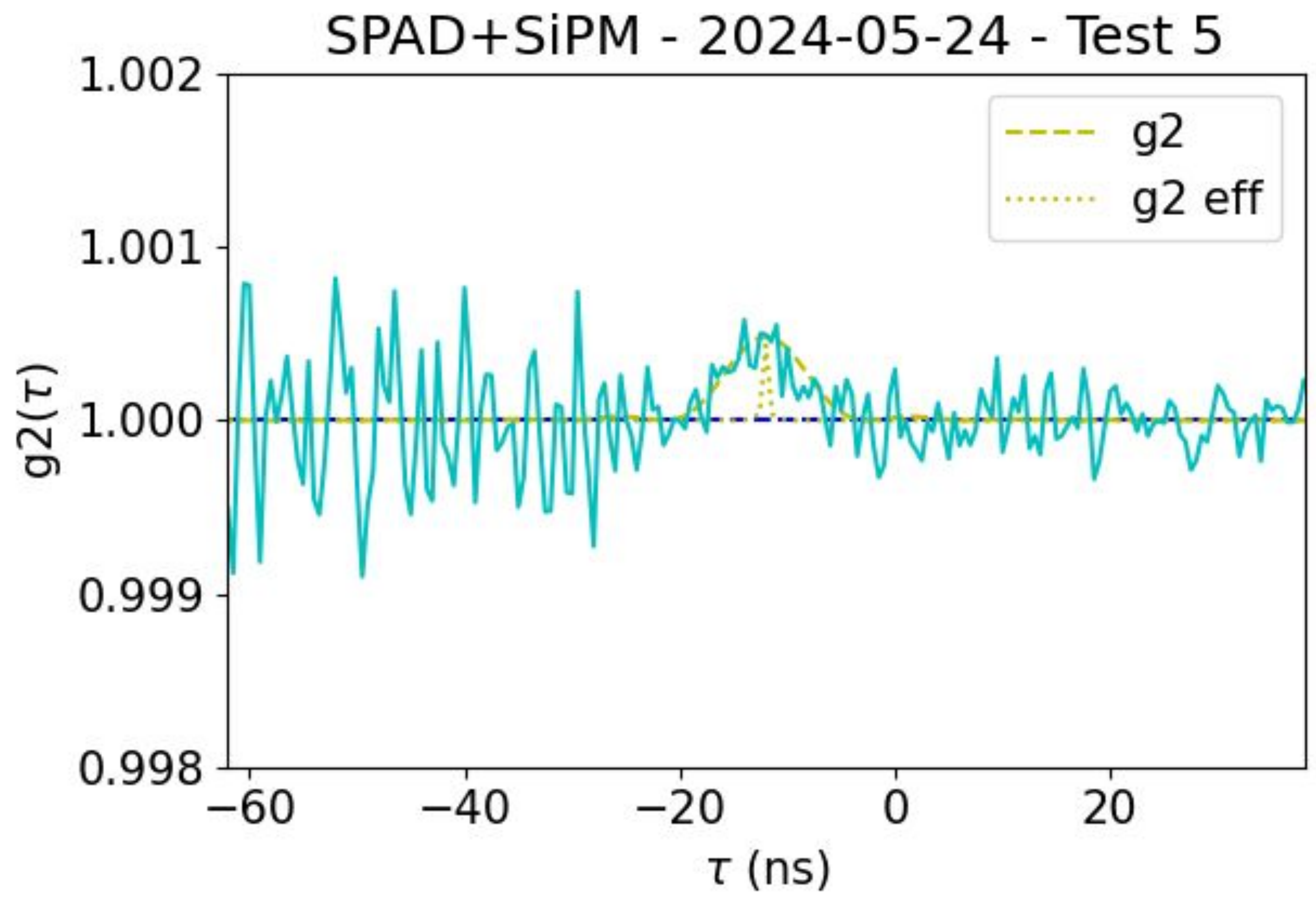
Optical fibers on the two arms feeding a SiPM and a SPAD detector

AIV Commercial Detector and Acquisition System
Correlation Measurements

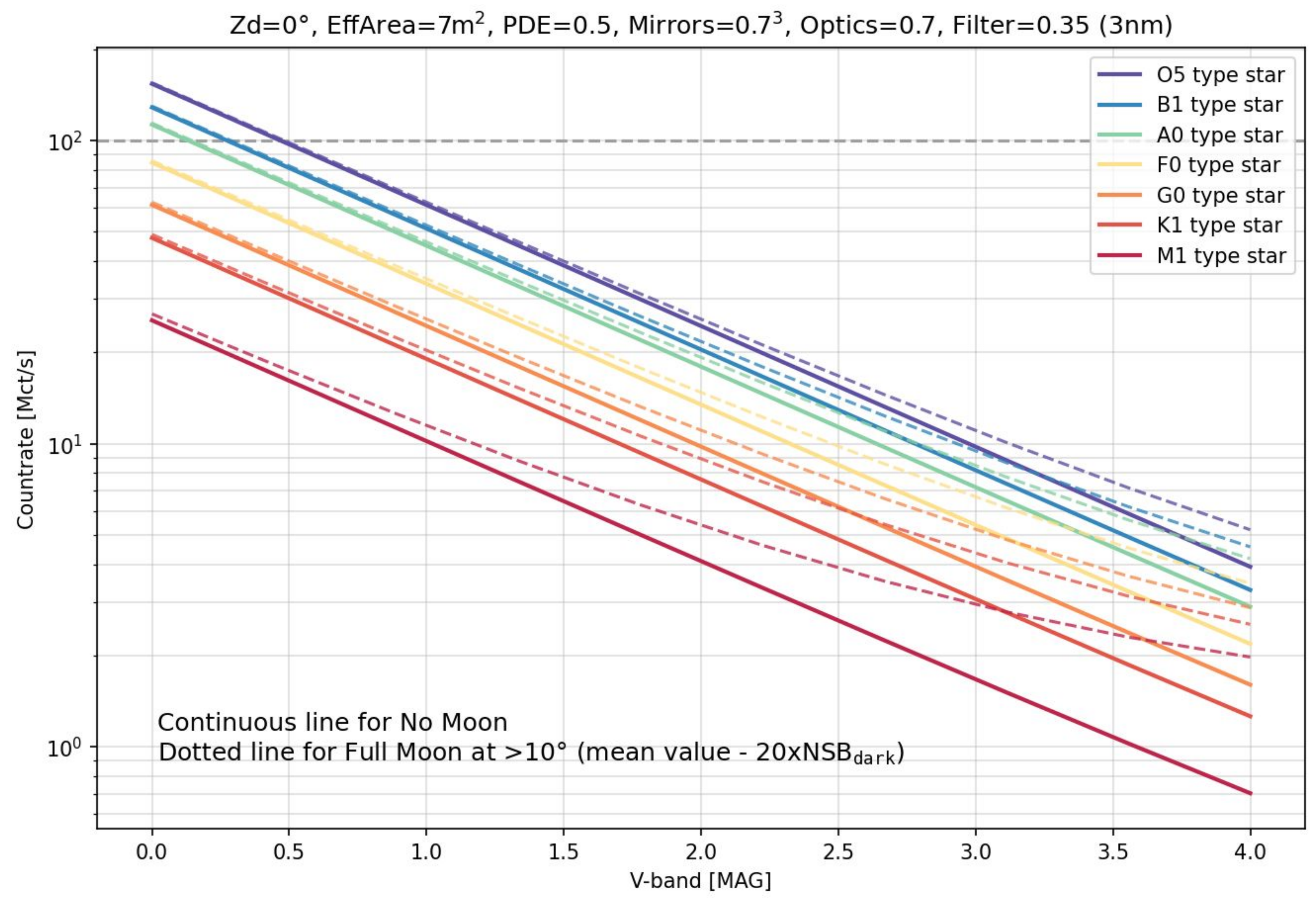
We simulated a thermal source with a superimposed 'coherent' signal by means of a **pinhole illuminated** with a **thermal lamp and nanosecond pulsed laser**

Zero baseline measurement obtained with a 50-50% beamsplitter feeding a SiPM and a SPAD detector (TTL output signals)





	$g^{(2)}$	Exp. s	S/N	Δλ nm	Ctrate Mct/s	Mag
Test 1	1.0012	300	~4	0.75	23.6	0.7
Test 5	1.00043	5400	~4	2.00	13.6	2.4



Electronic noise subtracted using a **"White Light" acquisition** (acquisition without the "coherent" pulsed signal). **Origin of noise still under investigation**

Residuals (systematics) in excess of the Poisson noise remains for negative delays with a root-mean-square (rms) variability at the level of ~ 10^{-4}

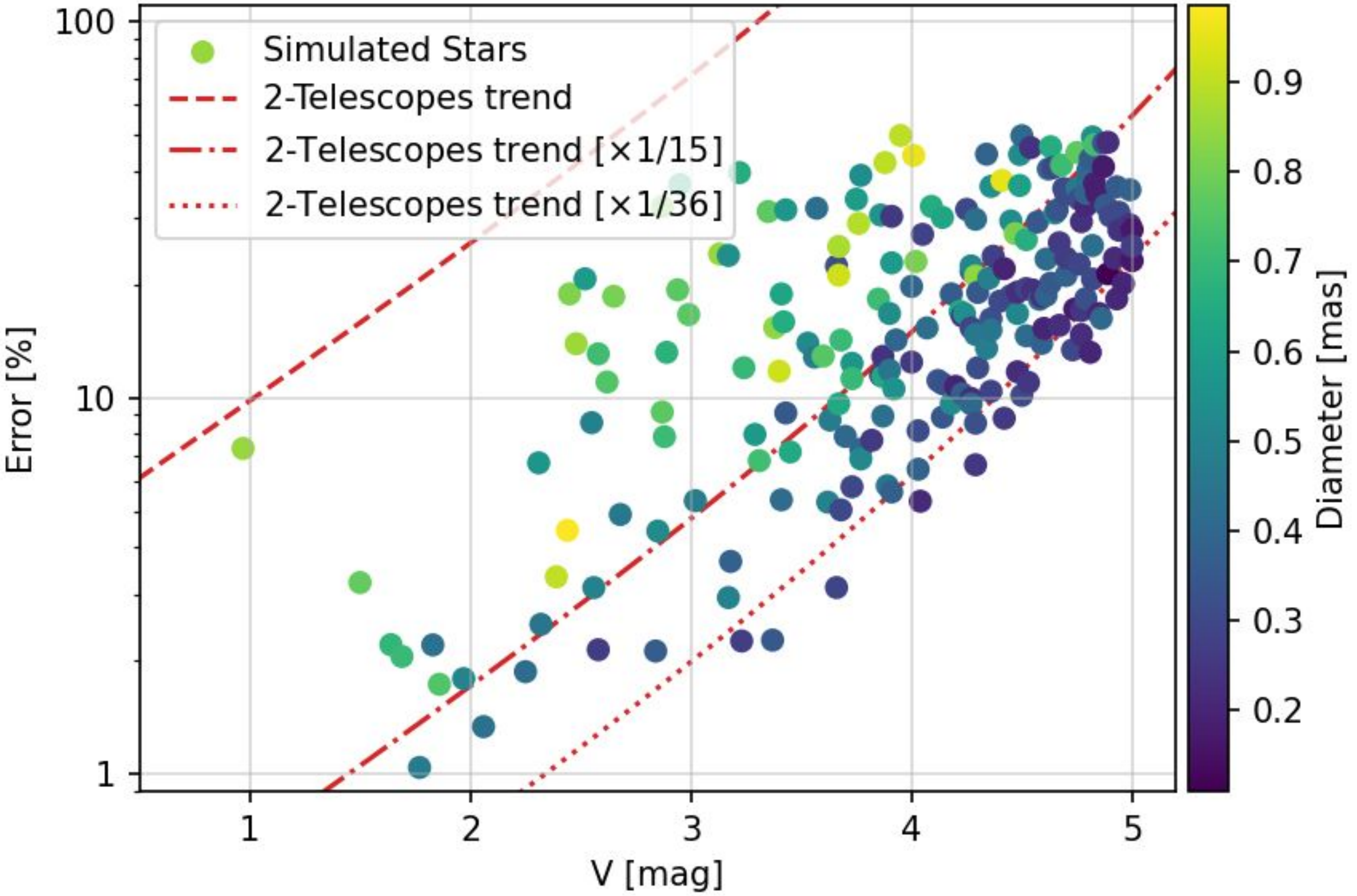
Simulations
Targets selection

Catalogue of stars with magnitude V ≤ 5 with known or estimated angular diameters **visible from El Teide**.

From simulations (**20-30 hours** observations):

- **> 50 stars** that have an **error** bar **below ~ 10%**
- **10 stars** have magnitude **V > 4** and **error** bar **below ~ 10%**
- Achievable **accuracy increased** by a factor **~15** compared to a 2 telescope system
- Achievable **accuracy increased** by a factor **proportional to the number of baselines (36)** for stars with **angular diameters < 0.4 mas**

Error on the stellar diameters obtained from fits of the simulated measurements of $g^{(2)}$ with SI3 on the ASTRI Mini-Array as a function of V band magnitude.

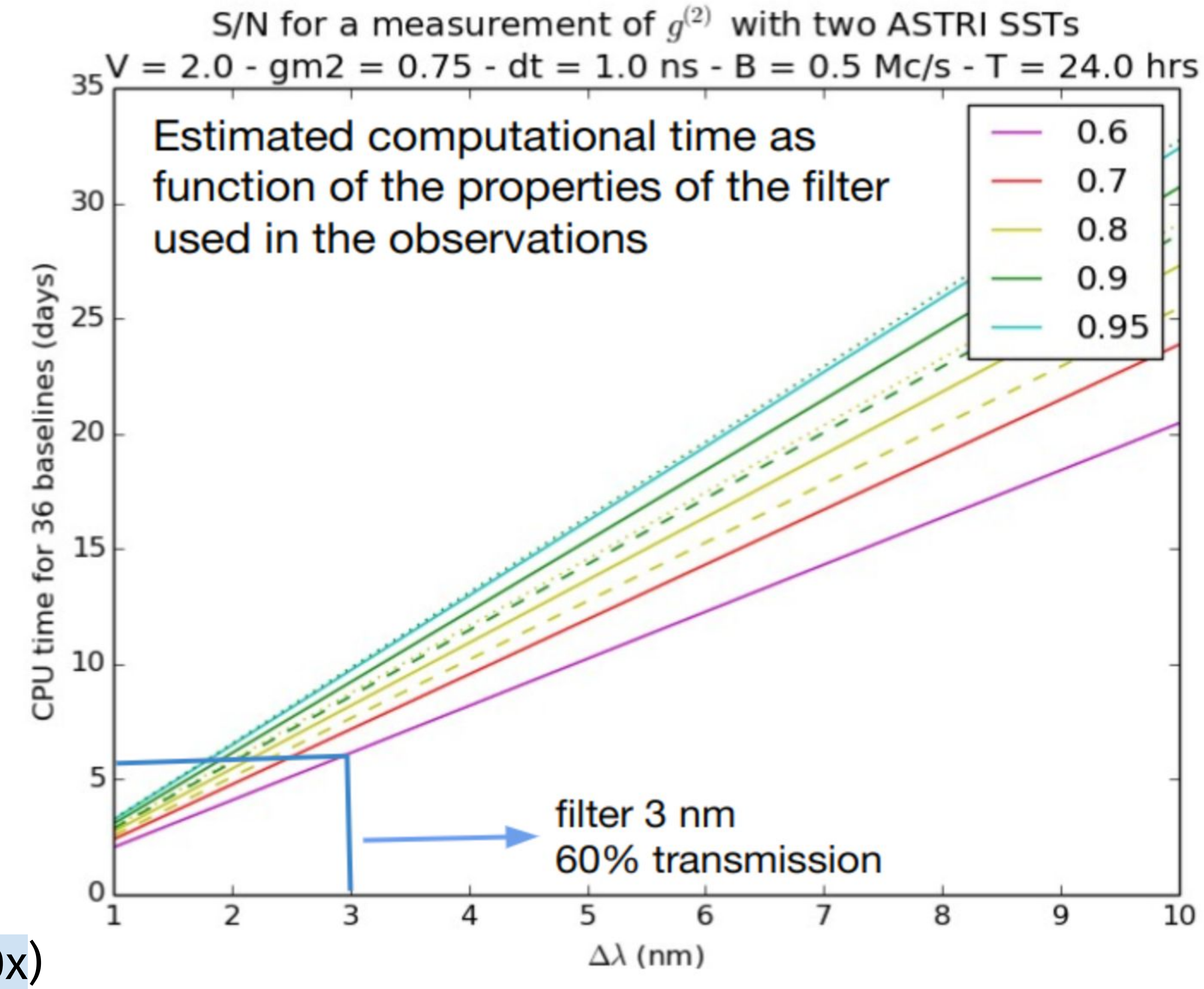


Data Processing
Computational time

Computational time to analyze PC-SII data

To analyze 1 hr of data on 36 baselines
(extrapolated from Aqueye+Iqueye PC-SII experiment; Zampieri et al. 2021)

10^4 hr (CPU time) → 10^4/2000 core = 5 hr
→ 5×24 hr (real data) = 5 days



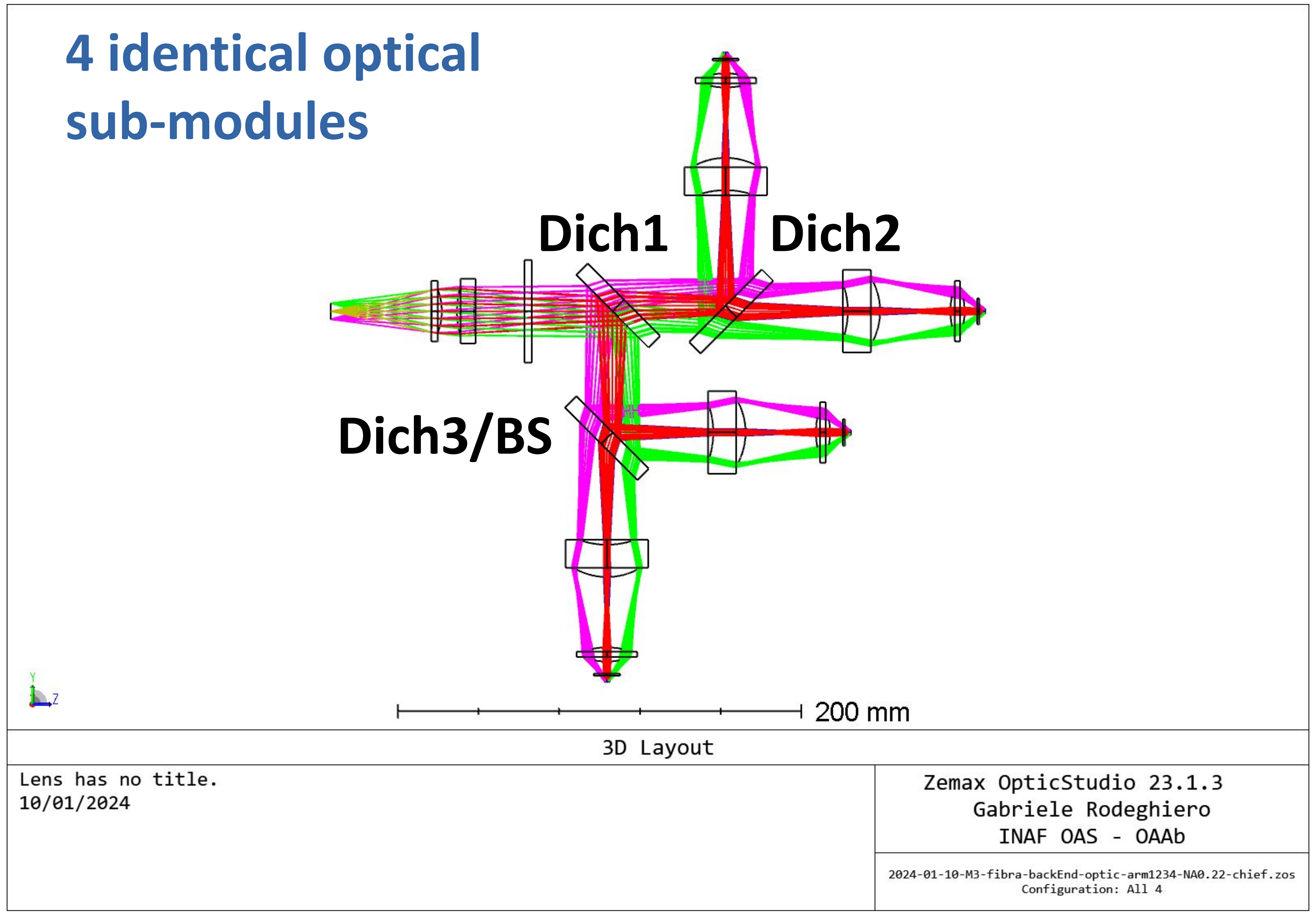
Parallelizing and accelerating the algorithm

Starting from 1 CPU core (1 hr data: 10^4 hr CPU time)
→ code optimized and parallelized **(48 CPUs): 12.5 hr**
→ code optimized and parallelized **(2000 cores): 0.3 hr**
→ **GPUs** (accelerating with Compute Unified Device Architecture: 20x)
Requested HPC time (4 Leonardo Booster GPUs; 3×10^5 hrs allocated)

SI^3 Version 3
Potential future upgrades

Custom SiPM-based detectors and FEE
- Will reach higher maximum rate better preserving linearity

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



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*

CTAO

Two sites: North and South to cover the whole sky

3 different telescope sizes (LST, MST, SST)

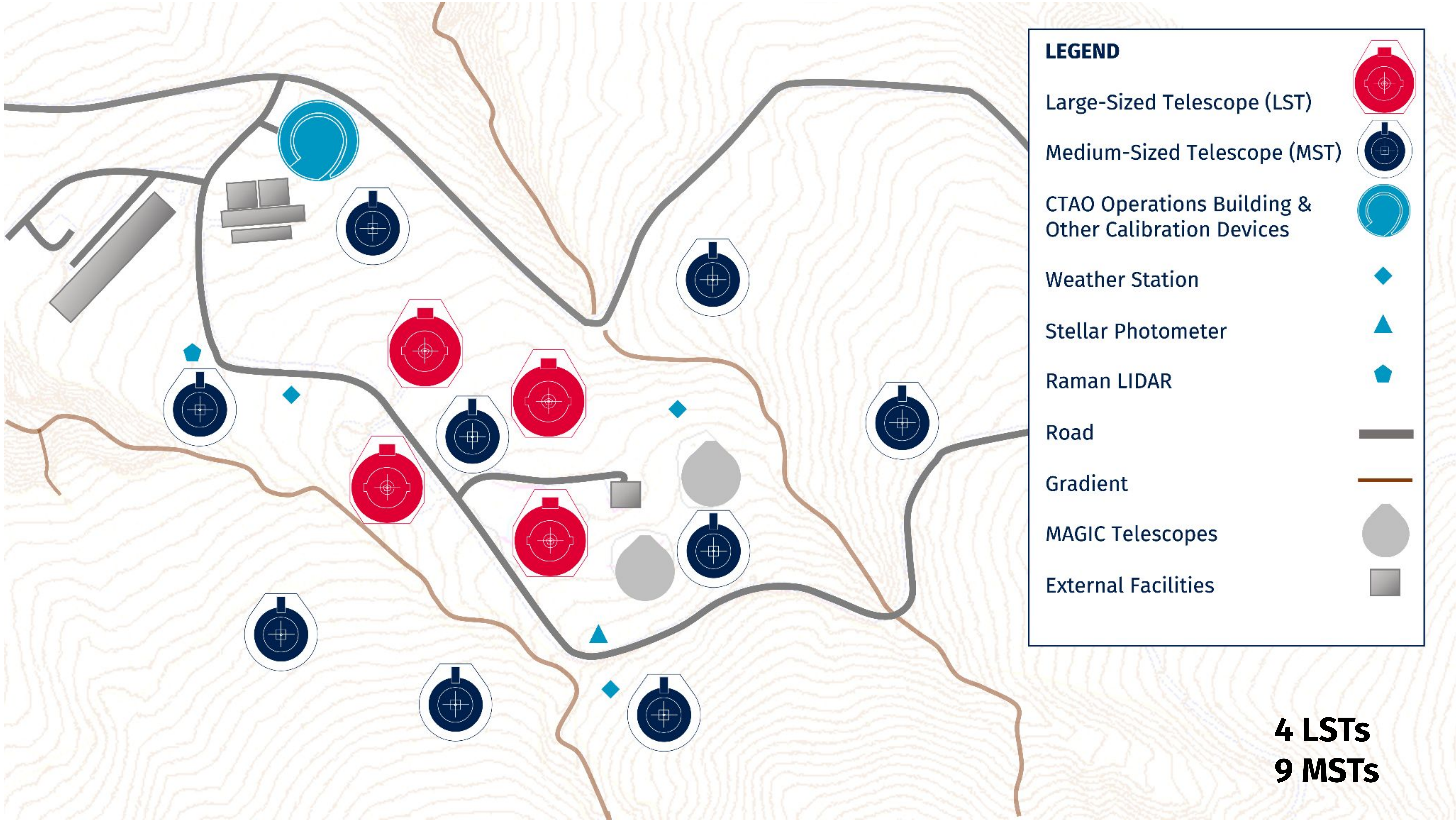
13 telescopes in the North (only LSTs and MSTs)

>50 telescopes in the South

km^2 effective area

CTA-North

Located on the island of **La Palma** in the **Canary Islands (Spain)** at the Instituto de Astrofísica de Canarias’ (IAC’s) **Observatorio del Roque de los Muchachos (ORM)** at 2200 metres

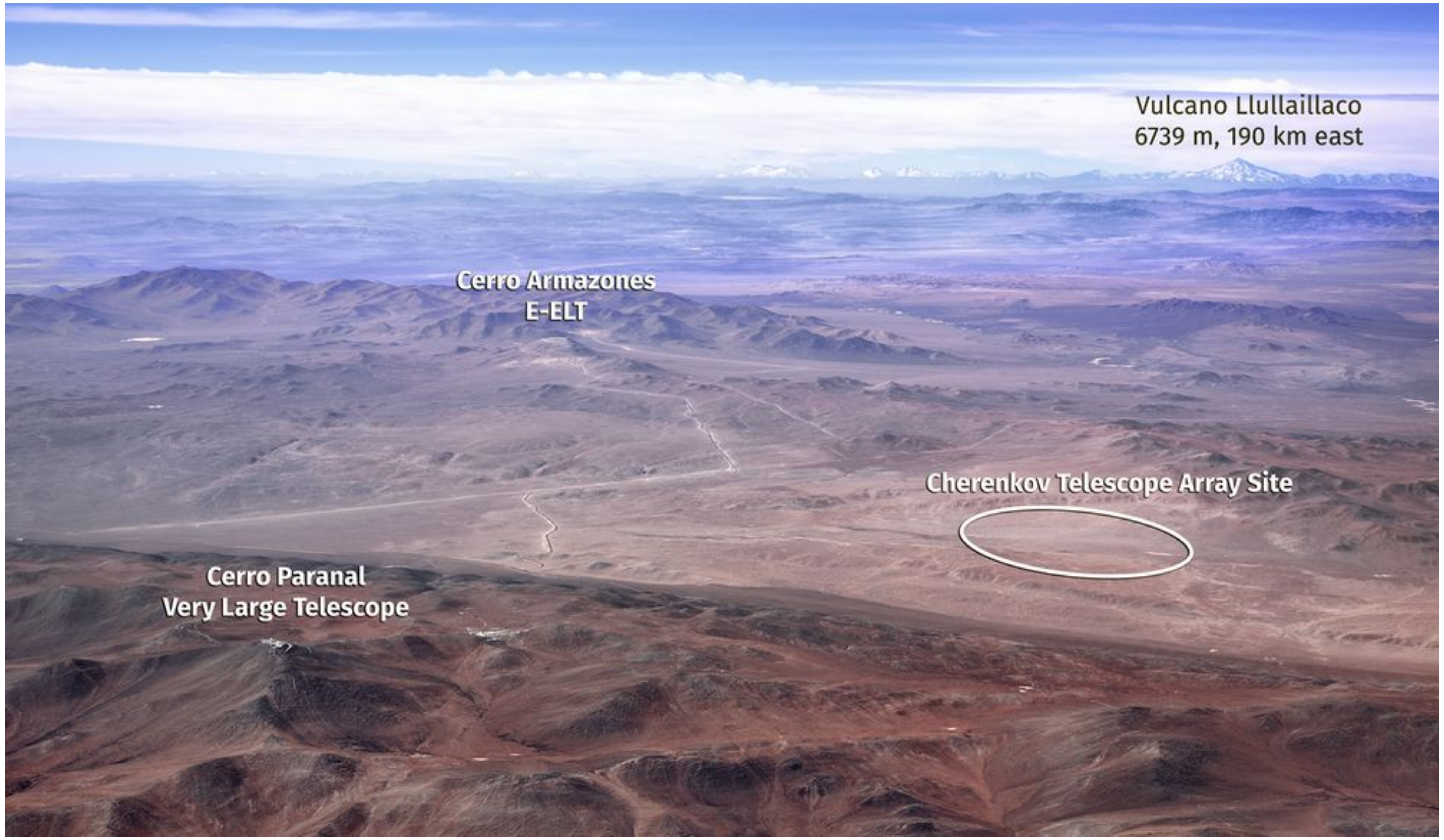


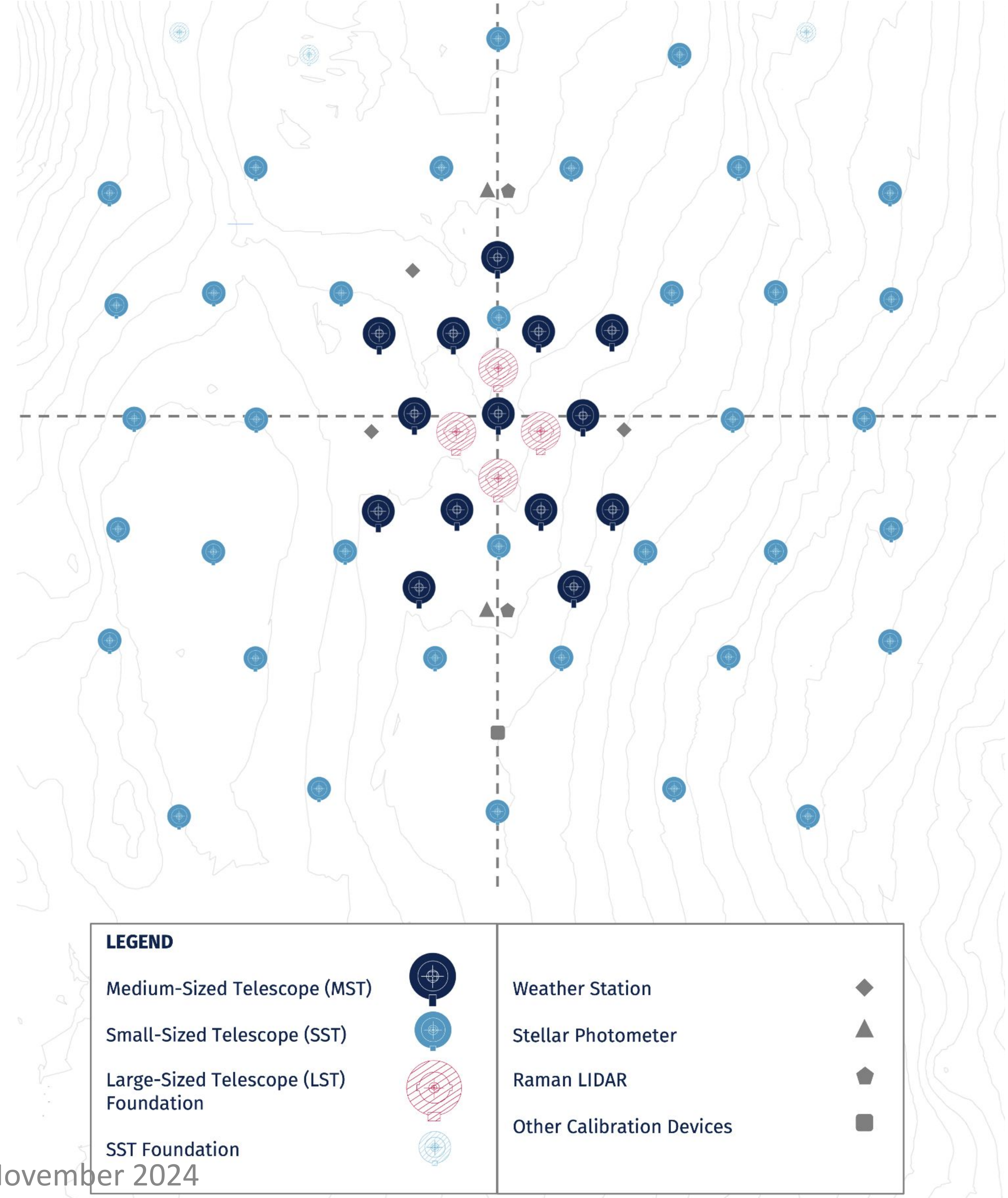
4 LSTs
9 MSTs

CTA-South

Located less than 10 km southeast of the European Southern Observatory's (ESO's) existing **Paranal Observatory** in the **Atacama Desert in Chile.**

(4 LSTs)
14 MSTs
37 SSTs





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: Luca Zampieri
  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, WPCF 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 Potential SII Science

'Disclaimer': *At present we cannot say that CTAO will operate as a SII facility*
We are designing instrumentation in a way that CTAO could consider to offer the SII capability in a close future

- ➔ **CTAO SII Science Working Group**: open discussion 'forum' on SII science and potential SII implementations on CTA.
- ➔ Drafting a White Paper on SII science cases with CTAO and potential SII implementation modes on CTAO

Unique capabilities of CTAO in terms of **angular resolution and number of available telescope pairs (baselines)**

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

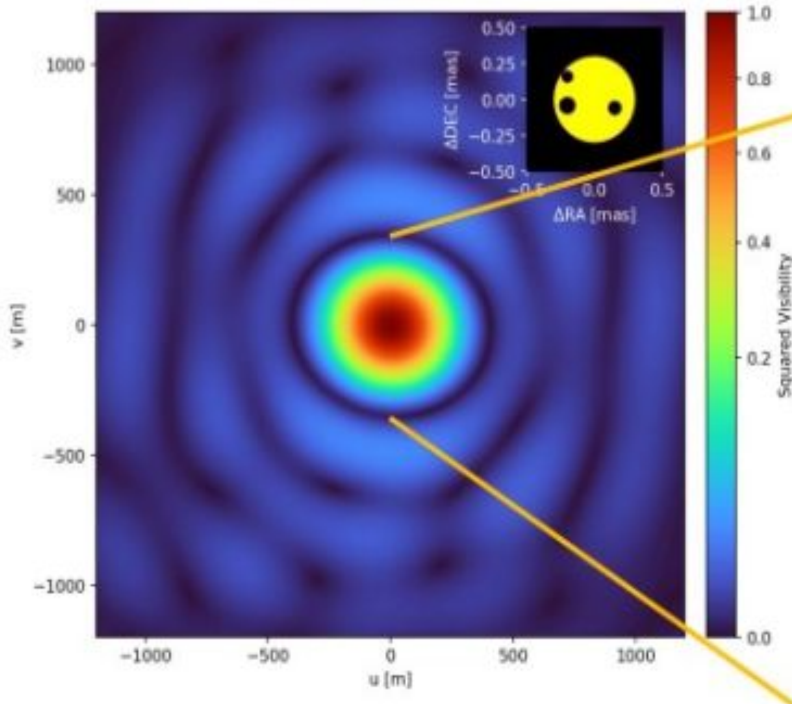
CTAO

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**

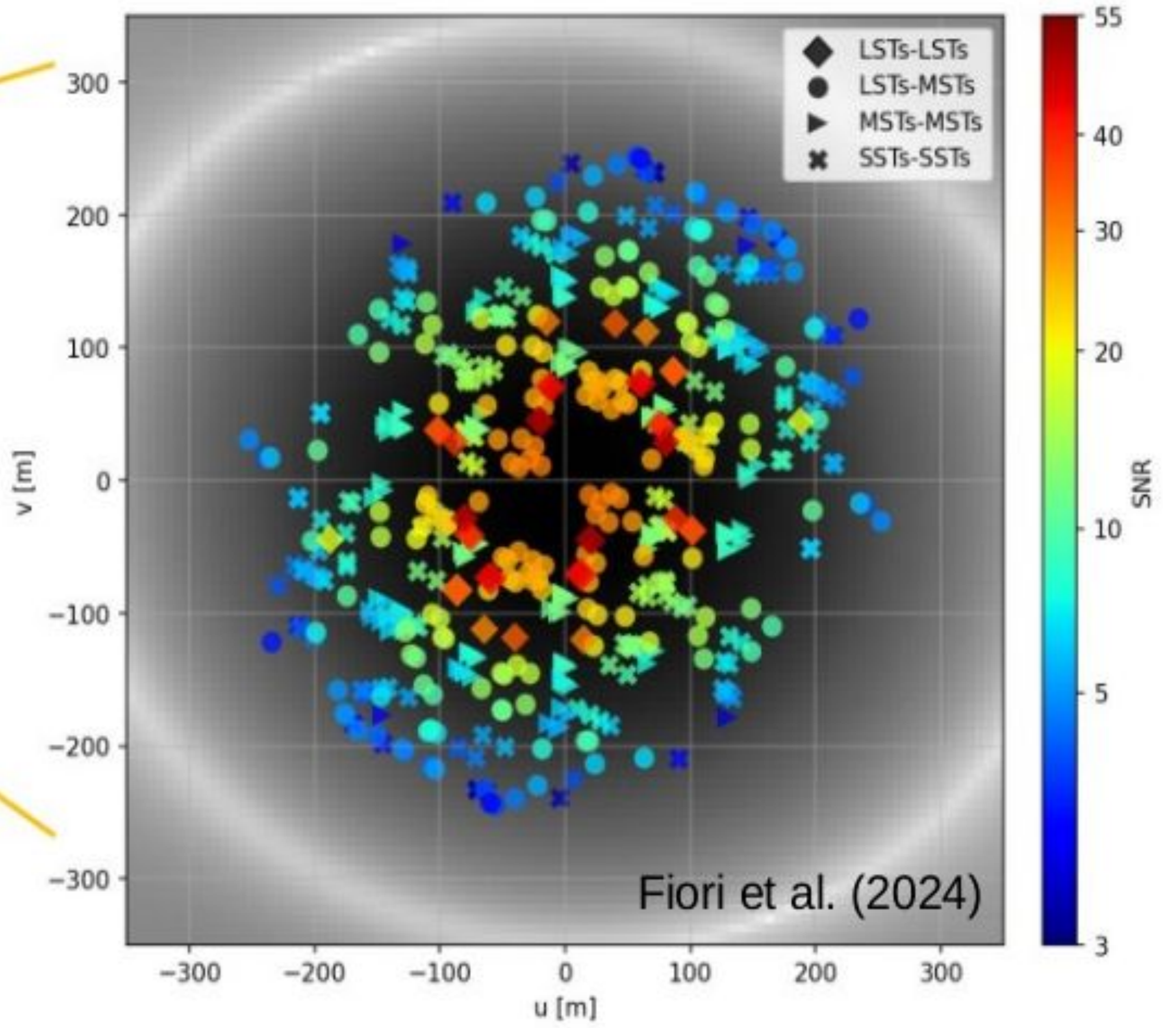
Solar-type stars are crucial for understanding the properties of the Sun in relation to other stars and for exploring the habitability conditions of exo-planets around stars similar to the Sun (e.g. Soderblom and King 1998; Charbonneau 2014; Ragulskaya 2018)

~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

CTAO Potential SII Implementations

CTAO Symposium 2024

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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

LSTs implementation under test with MAGIC+LST-1 (Digital)

MSTs implementation at the 'design/implementation' phase (Digital)

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

Implementation at the prototype phase on the ASTRI Mini-Array telescopes (Photon Counting), similar to the **SSTs**

Conclusions

- Working at prototype **implementation of PC-SII** on the ASTRI Mini-Array telescopes, similar to the SSTs of CTAO
- **The ASTRI Mini-Array** 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
- **SI^3** designed to implement **PC-SII** on the ASTRI Mini-Array and perform accurate **measurements of single photon arrival times (1 ns) in a narrow optical bandwidth (1-8 nm)**
- **Laboratory Prototype** completed; **Data Processing accelerated by a factor 16.5** (code optimized and parallelized on 48 CPUs)
- Potential future upgrades: **Channel Multiplexing**
- We are designing instrumentation in a way that CTAO could consider to offer the SII capability in a close future

ASTRI SI^3 Team

SI^3 – 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

ASTRI SI^3

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.

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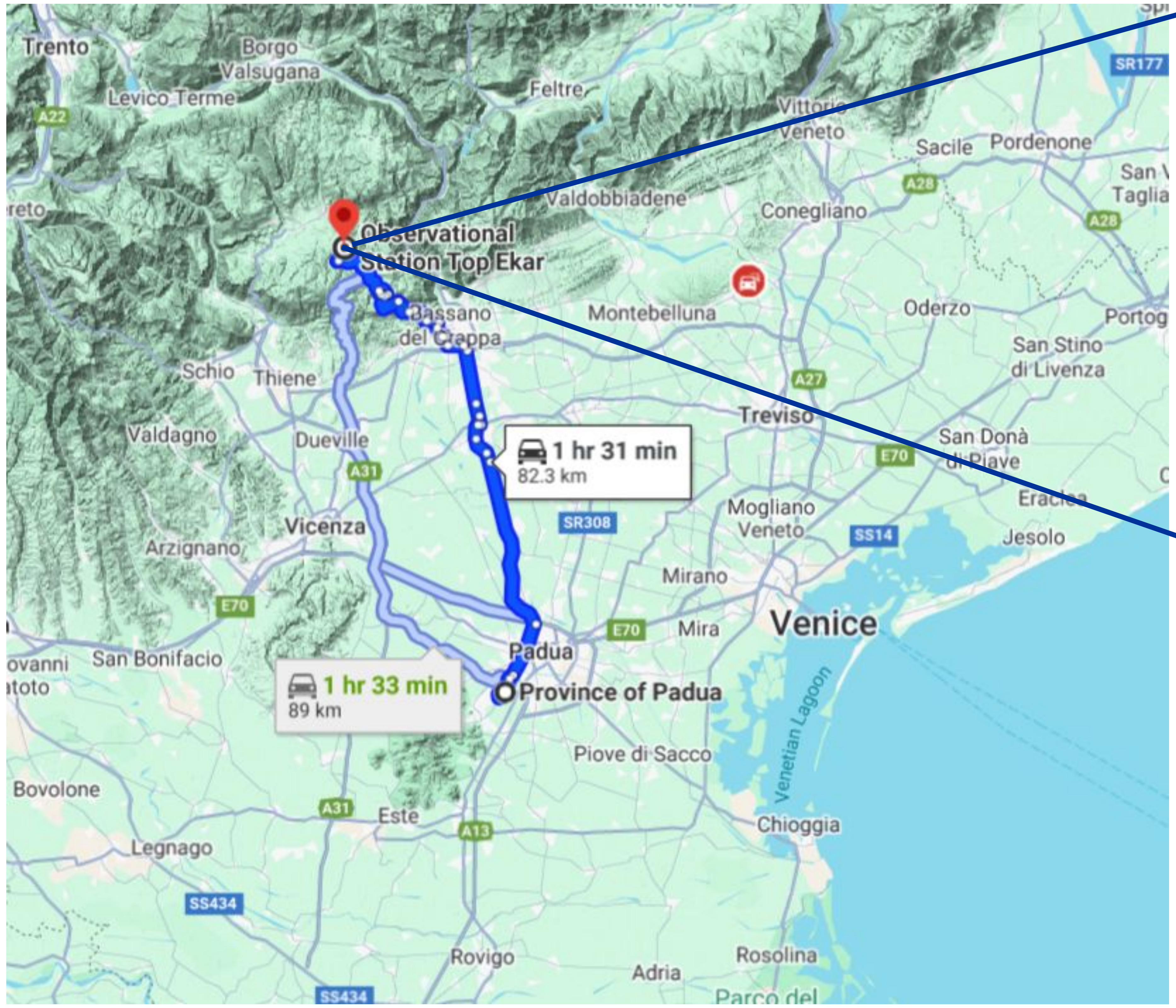
Backup slides

AIV
ASTRI/AQUEYE Laboratory



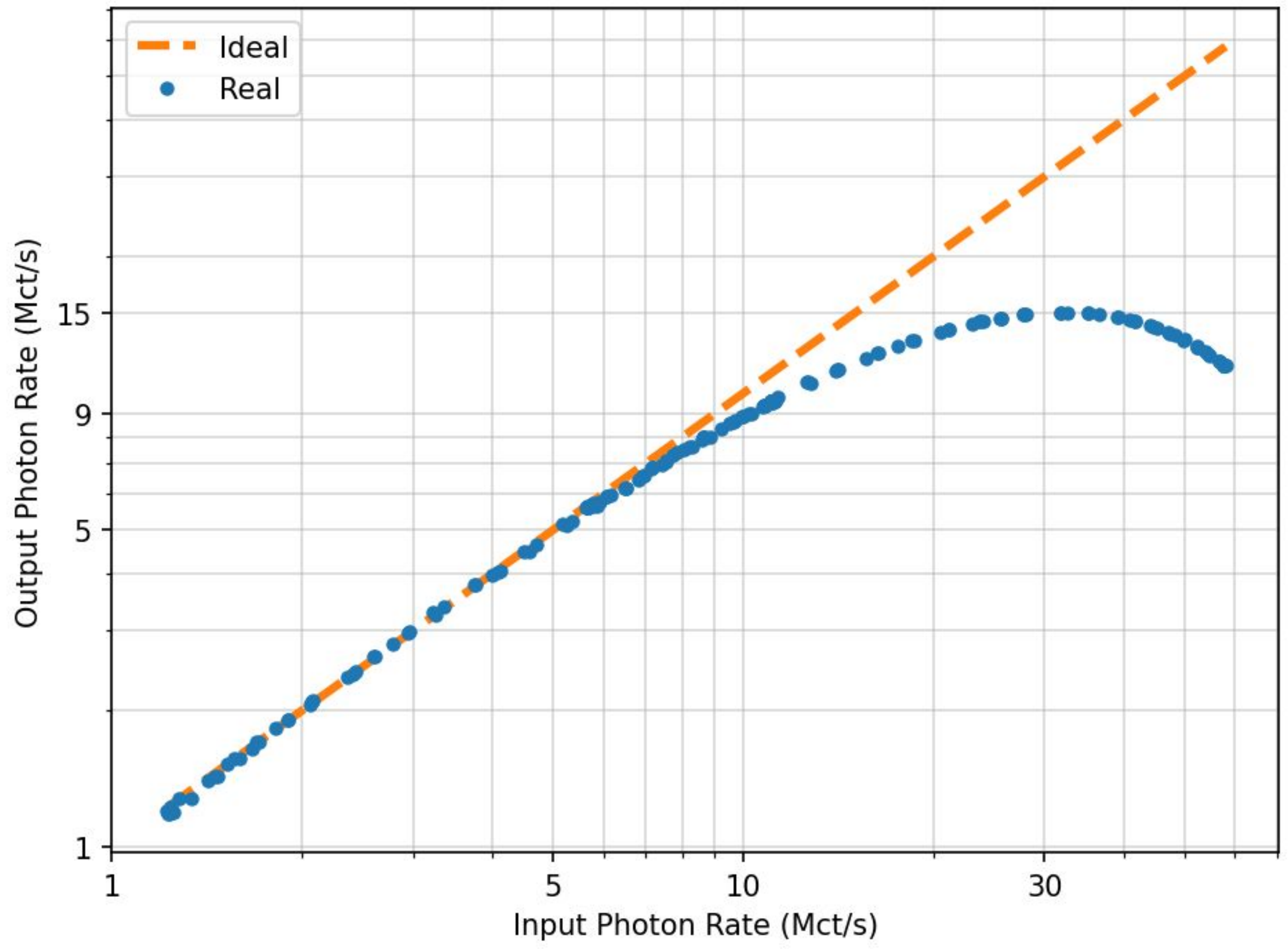
Laboratory located at Cima Ekar (Asiago) in the Copernico telescope building.

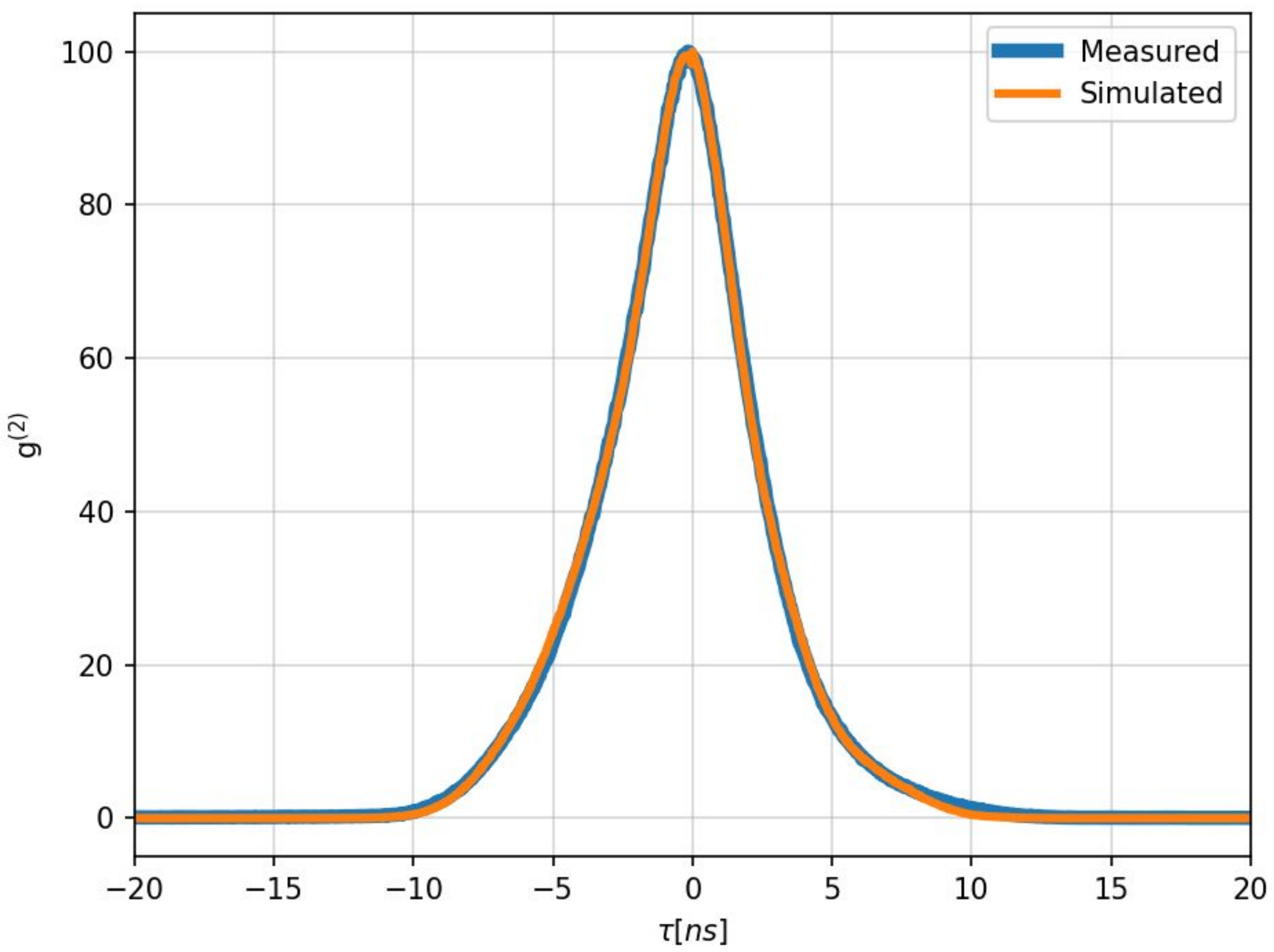
Intensive testing campaign started in 2023. From January 2024 almost every Thursday was dedicated to test

AIV Commercial Detector
Linearity curve and Jitter

SiPM powered with a **linear stabilized power supply**
[Bel Power AC/DC converter +/- 5V, 15W]

Power cable: **10 m long**
Data cable: **5 m long RG174 coaxial cable**
Booting phase: **~40 seconds**, both status output connectors switch to the 'high' state and the MPPC is active





Linearity: till **~ 10-12 Mct/s**

Max output rate: **~ 15 Mct/s**

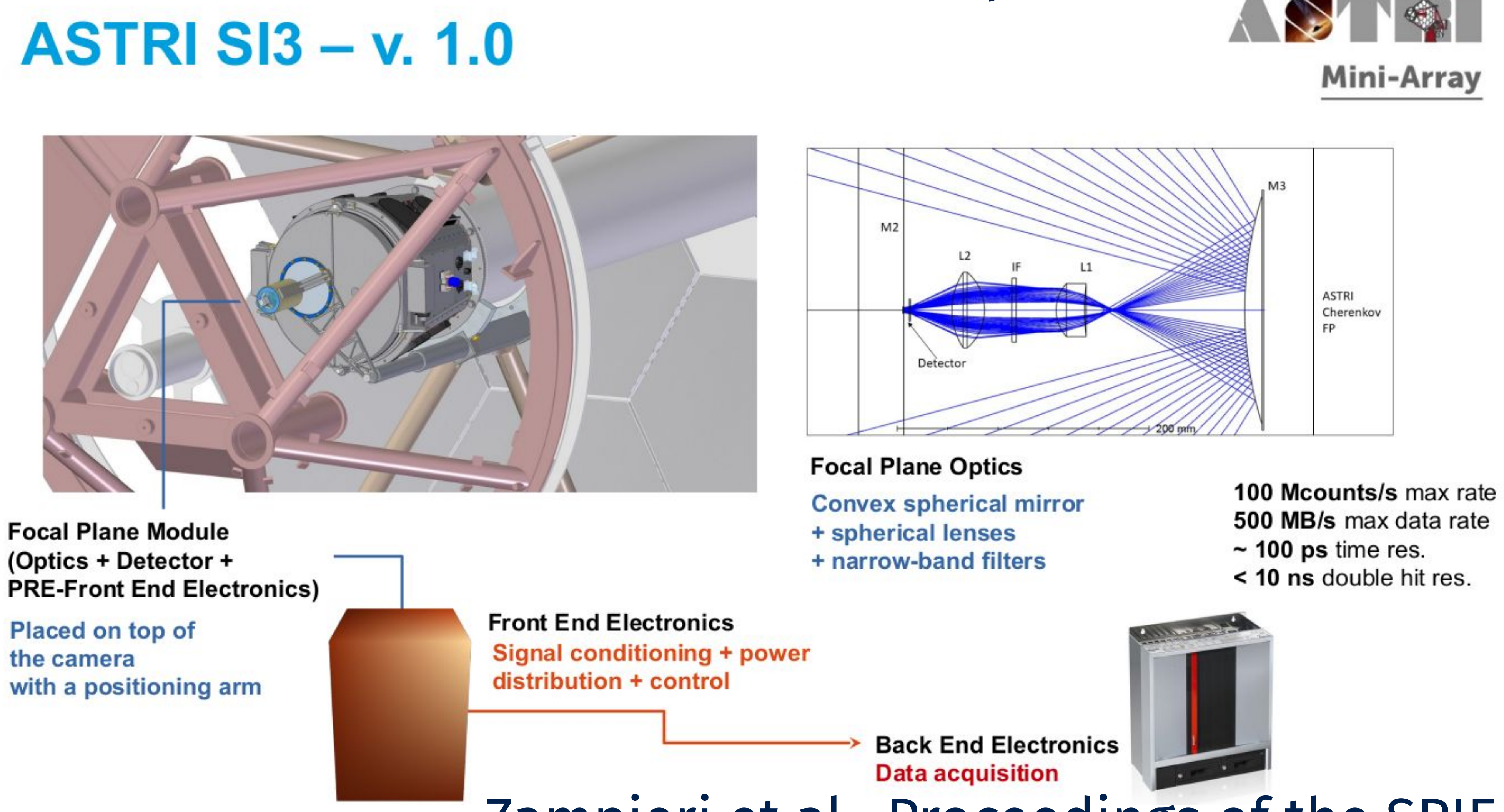
Dark rate: **~ 40 kct/s**

Jitter SiPM: **~ 600 ps** (a factor ~2 higher than that of a SPAD)

Total jitter: **~ 750 ps**

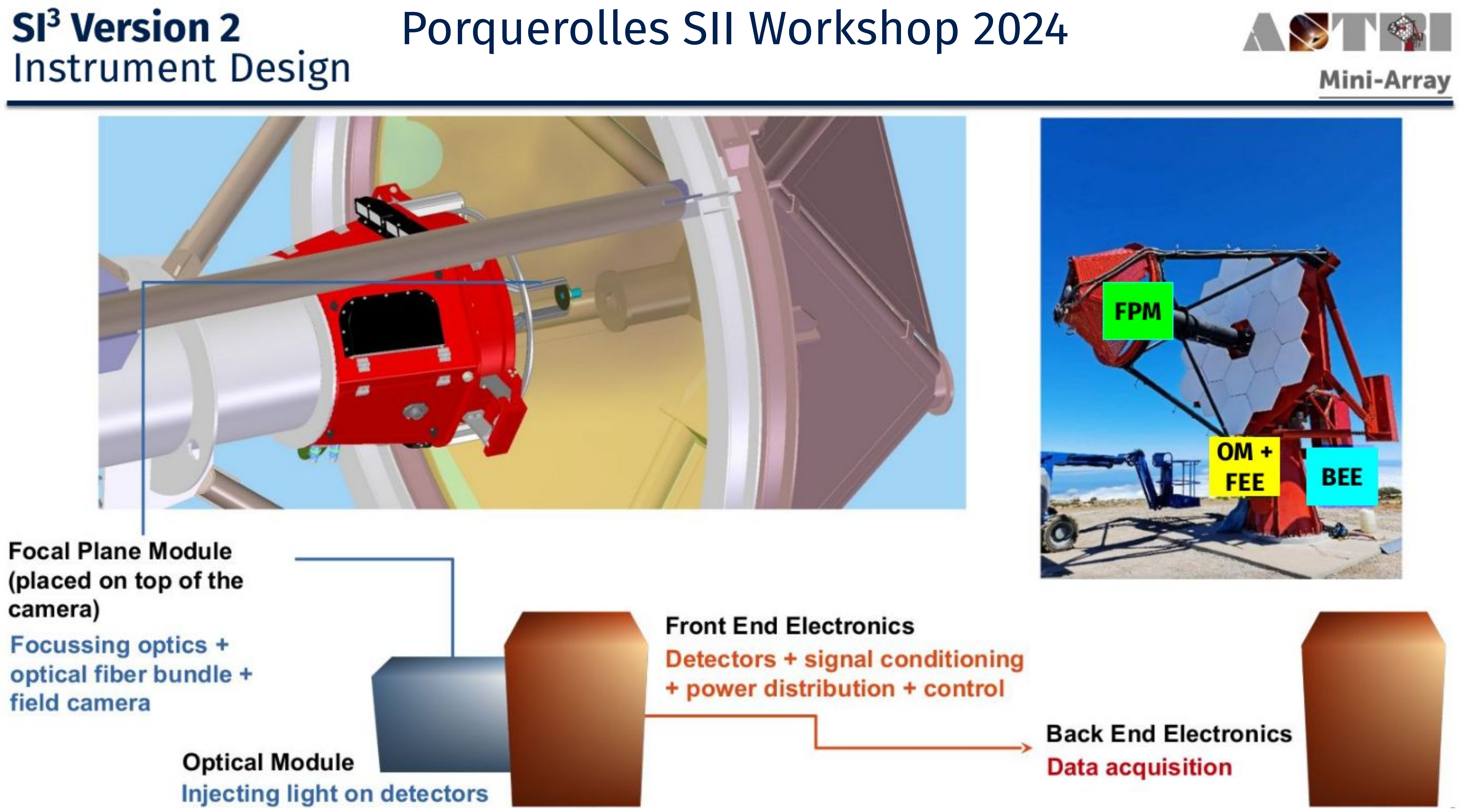
SI^3 Version 1 vs 2
Rationale and advantages

Columbus SII Workshop 2023



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

Porquerolles SII Workshop 2024



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

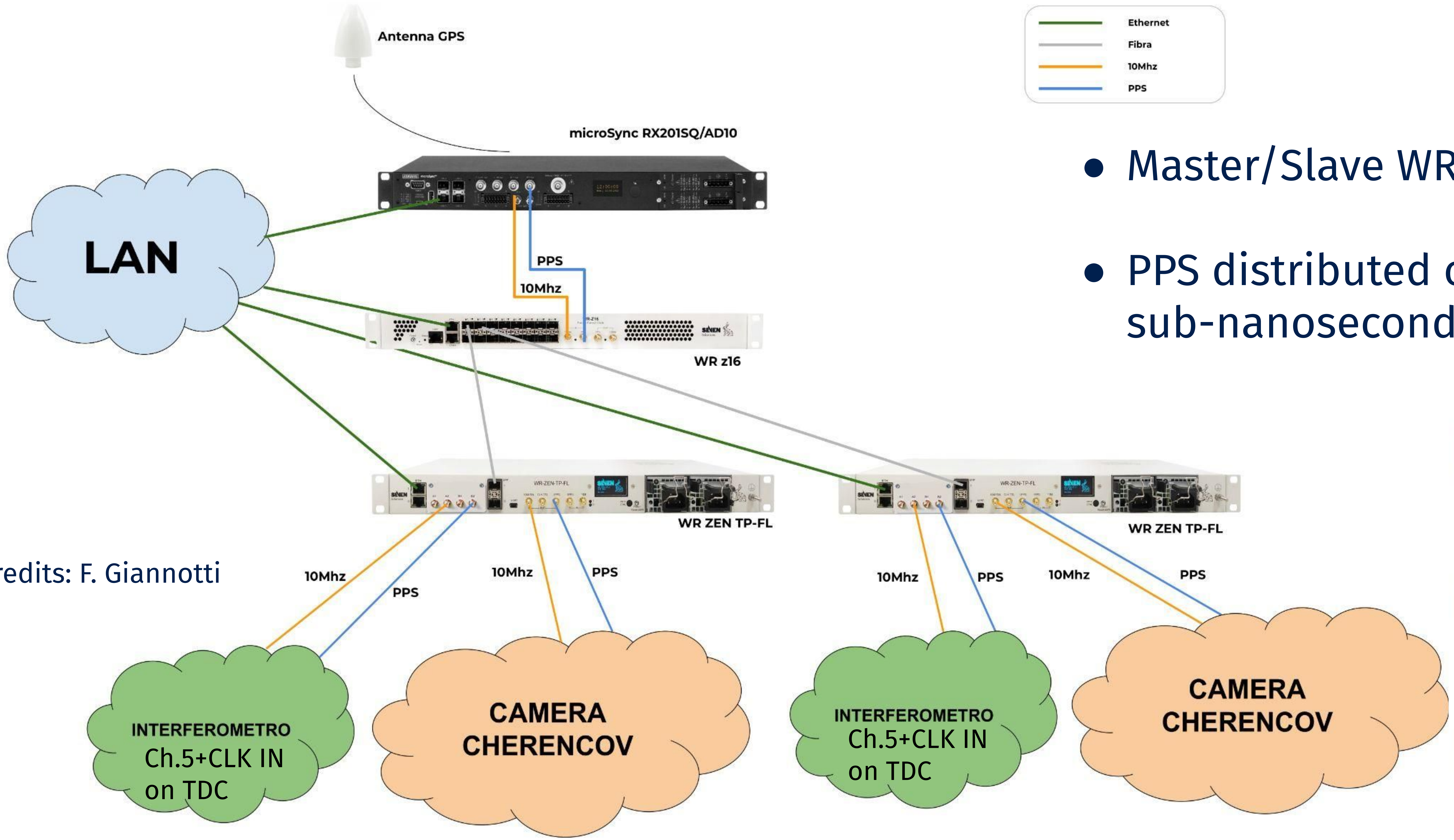
Pros

- 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

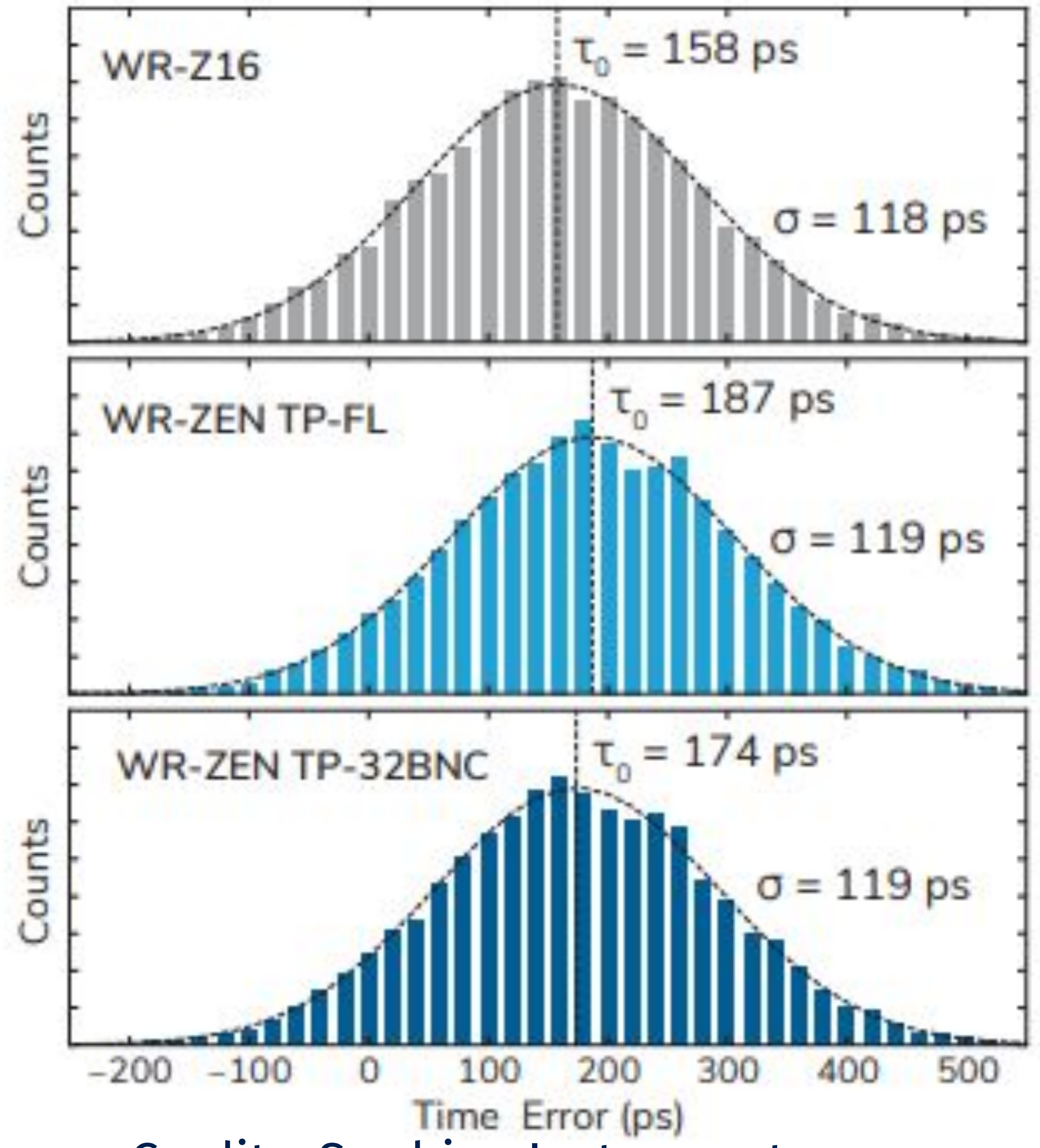
- Adding multimode optical fiber bundle - *Issue*: slight decrease of overall optical efficiency

TDU
ASTRI Mini-Array time synchronization system



Credits: F. Giannotti

- Master/Slave WR configuration
- PPS distributed over the network with sub-nanosecond timing accuracy

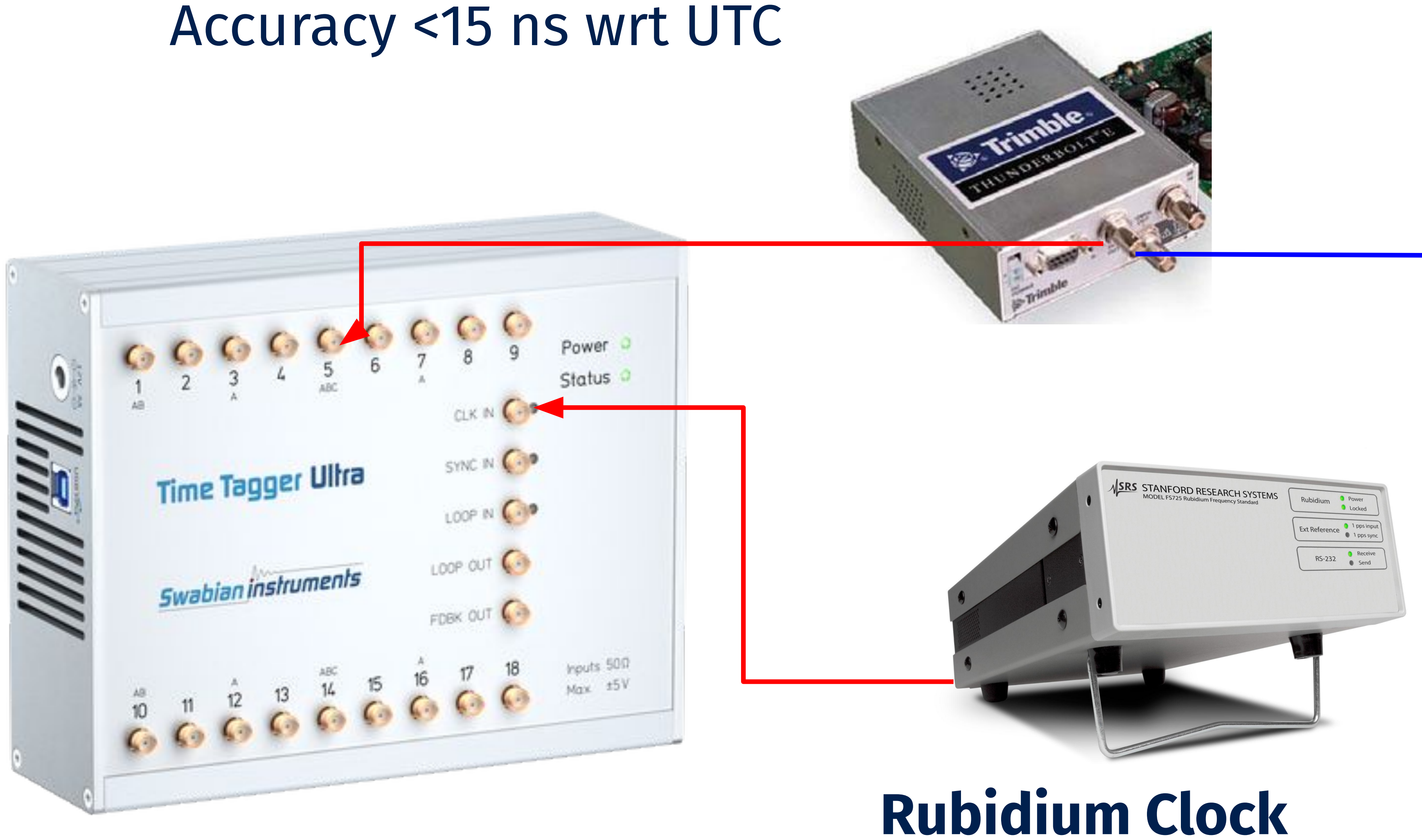


Credits: Swabian Instrument

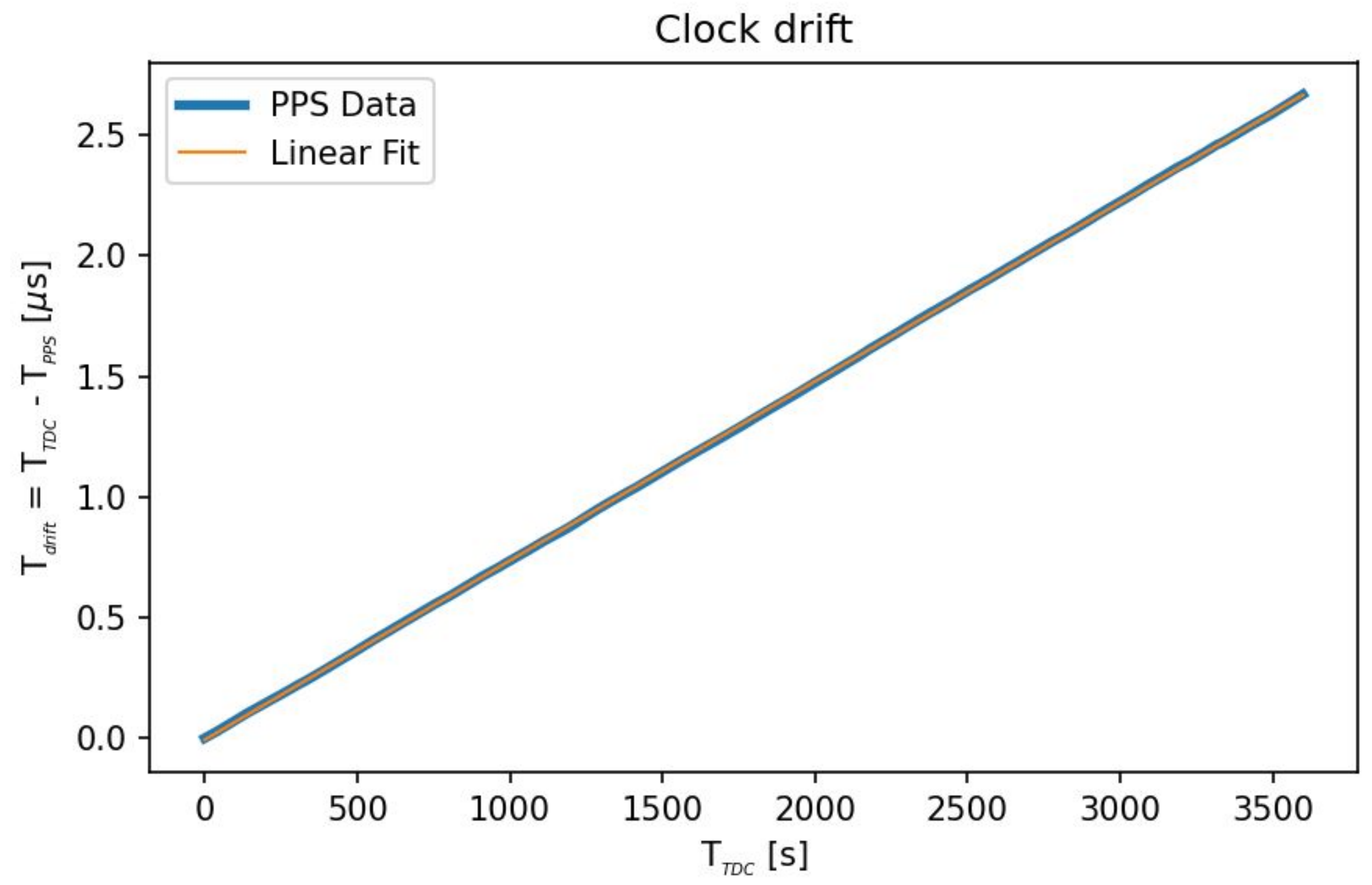
TDU
Time reconstruction algorithm

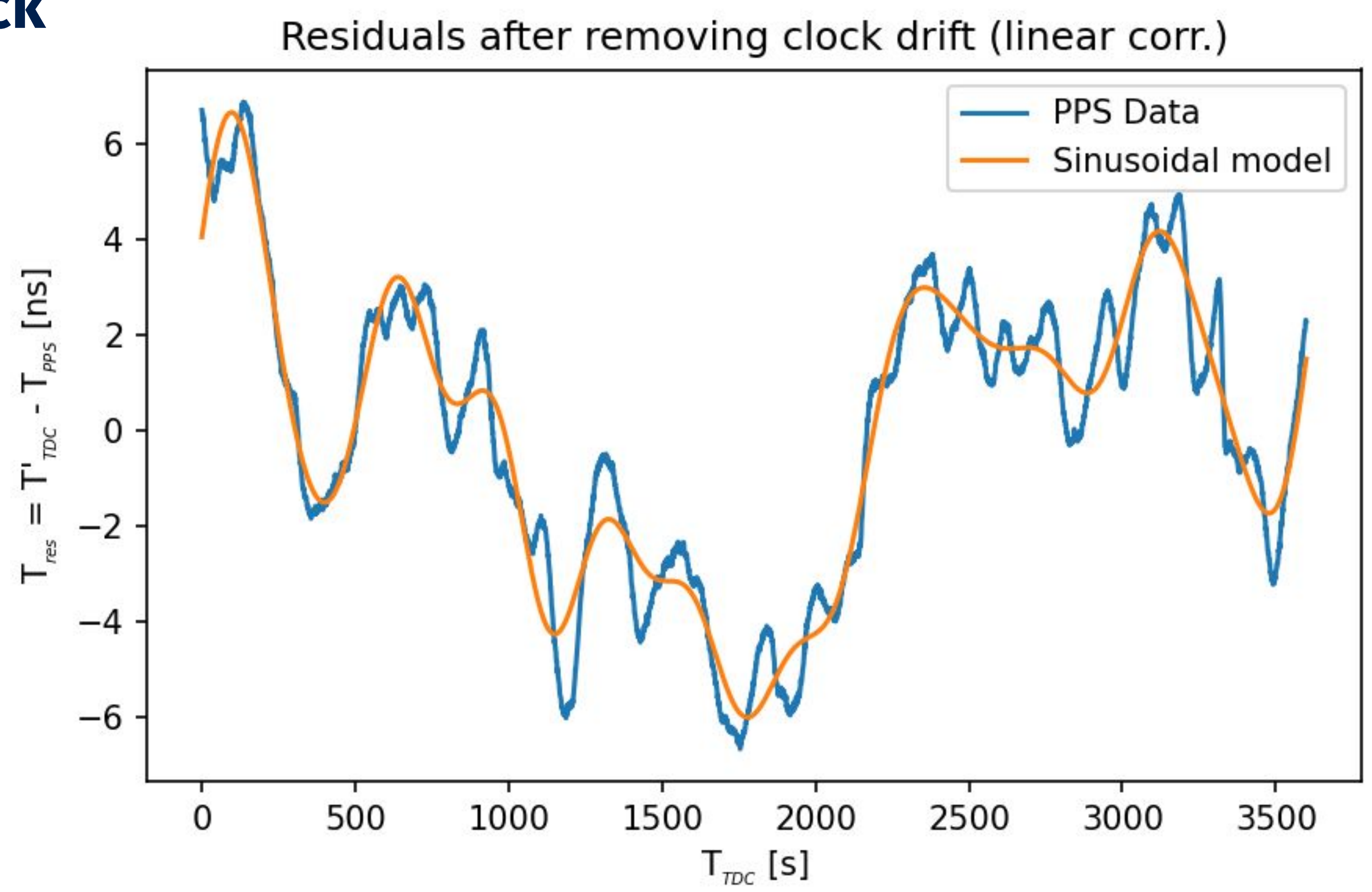
Thunderbolt E GPS (PPS Generator)
Accuracy <15 ns wrt UTC

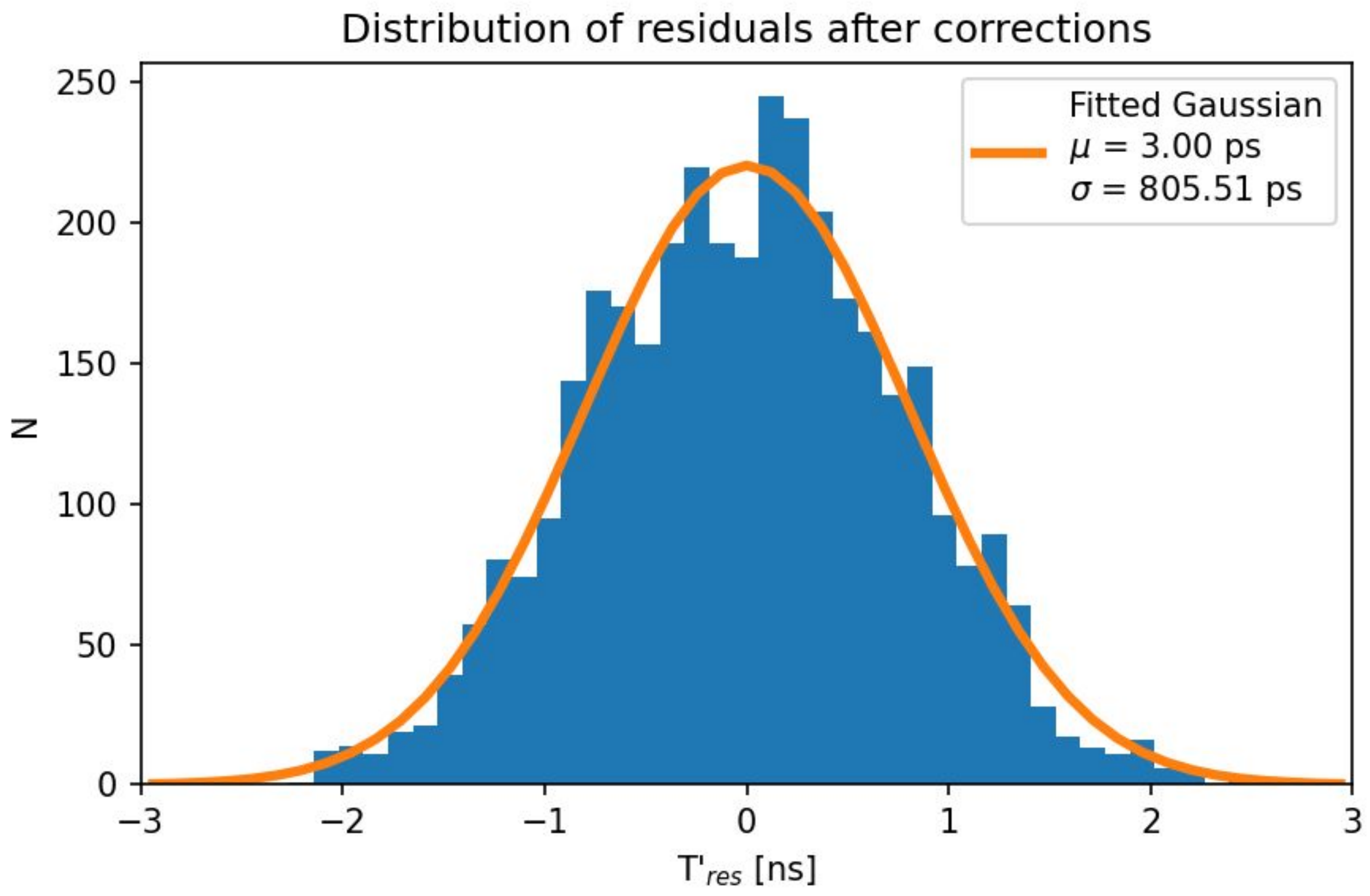
GPS antenna



Rubidium Clock
10 MHz signal







Preliminary test using a low-accuracy PPS generator + 10 MHz signal we could correct the drift of the internal clock of the TDC up to an accuracy <1 ns wrt to UTC.