Simulations and analysis of ASTRI Stellar Intensity Interferometry Instrument data

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Outline

- Introduction to Stellar Intensity Interferometry (SII)
- ASTRI SII Instrument (SI^3)
- Simulations: $g^{(2)}$ and time series
- Computational Time Estimation
- Conclusions

Stellar Intensity Interferometry (SII)

Mini-Array

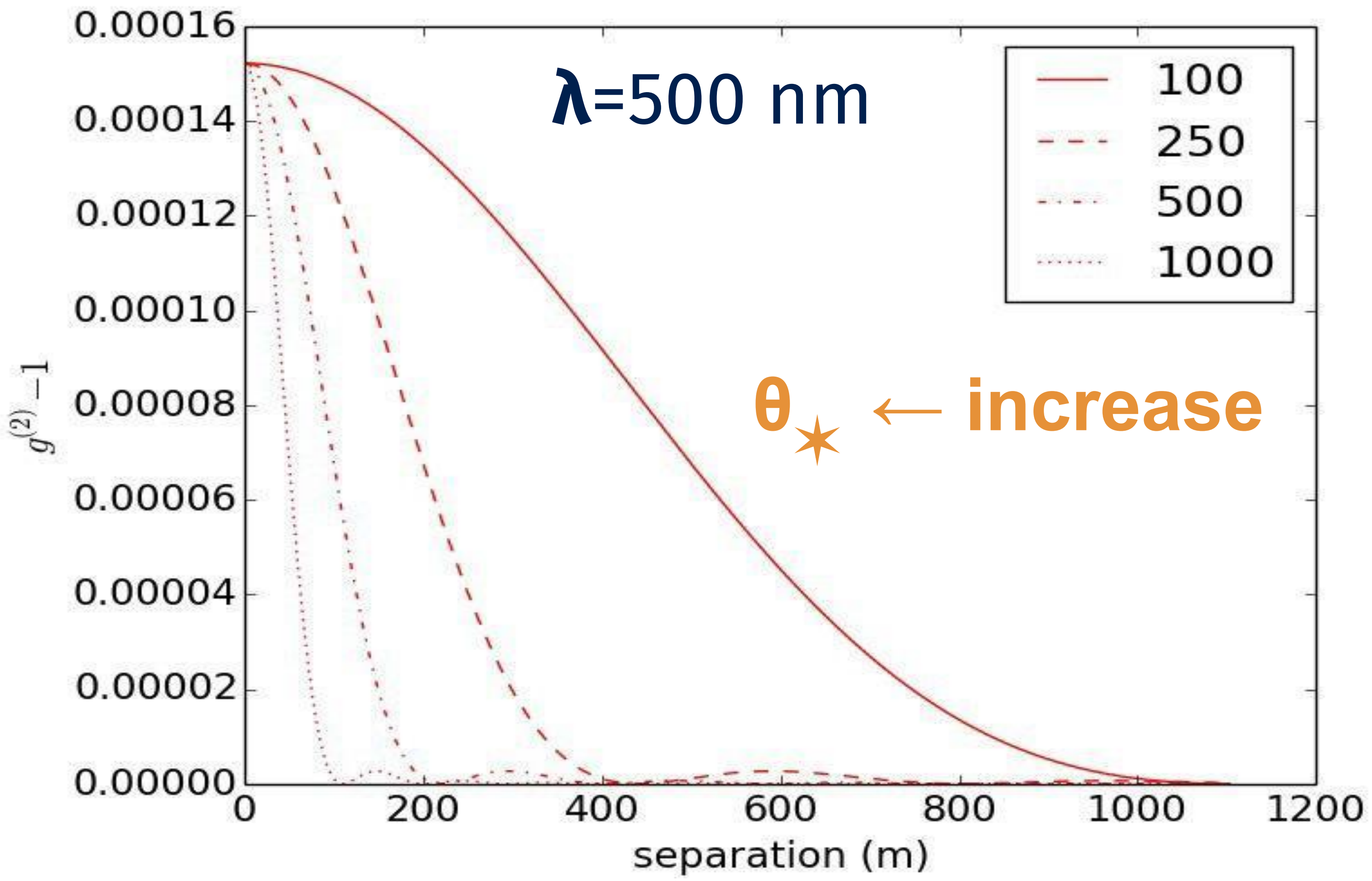
SII consists in a measurement of the **spatial correlation of the intensities of the light from a star with two telescopes** at distance **d** (Hanbury Brown & Twiss 1957, 1958).

Photon counting SII

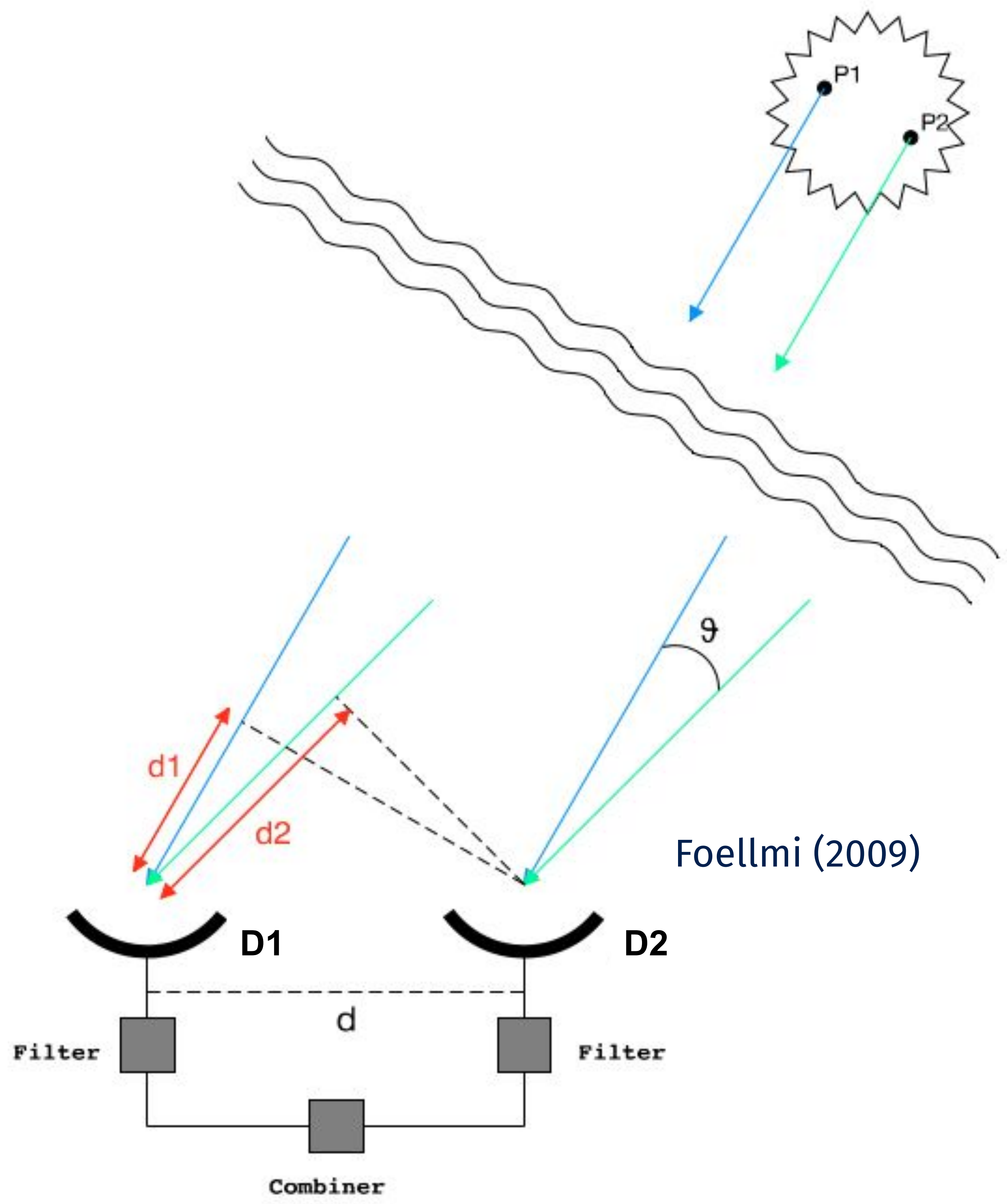
Counting coincidences in photon arrival times measured at 2 telescopes and exploits entirely the quantum properties of the light emitted from a star.

$$g^{(2)}(\tau, d) = \frac{N_{XY} N}{N_X N_Y}$$

N_X, N_Y = # photons detected at telescopes X and Y in time T
N_{XY} = # simultaneous detection in bin *dt*
N = # intervals (T/*dt*)



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

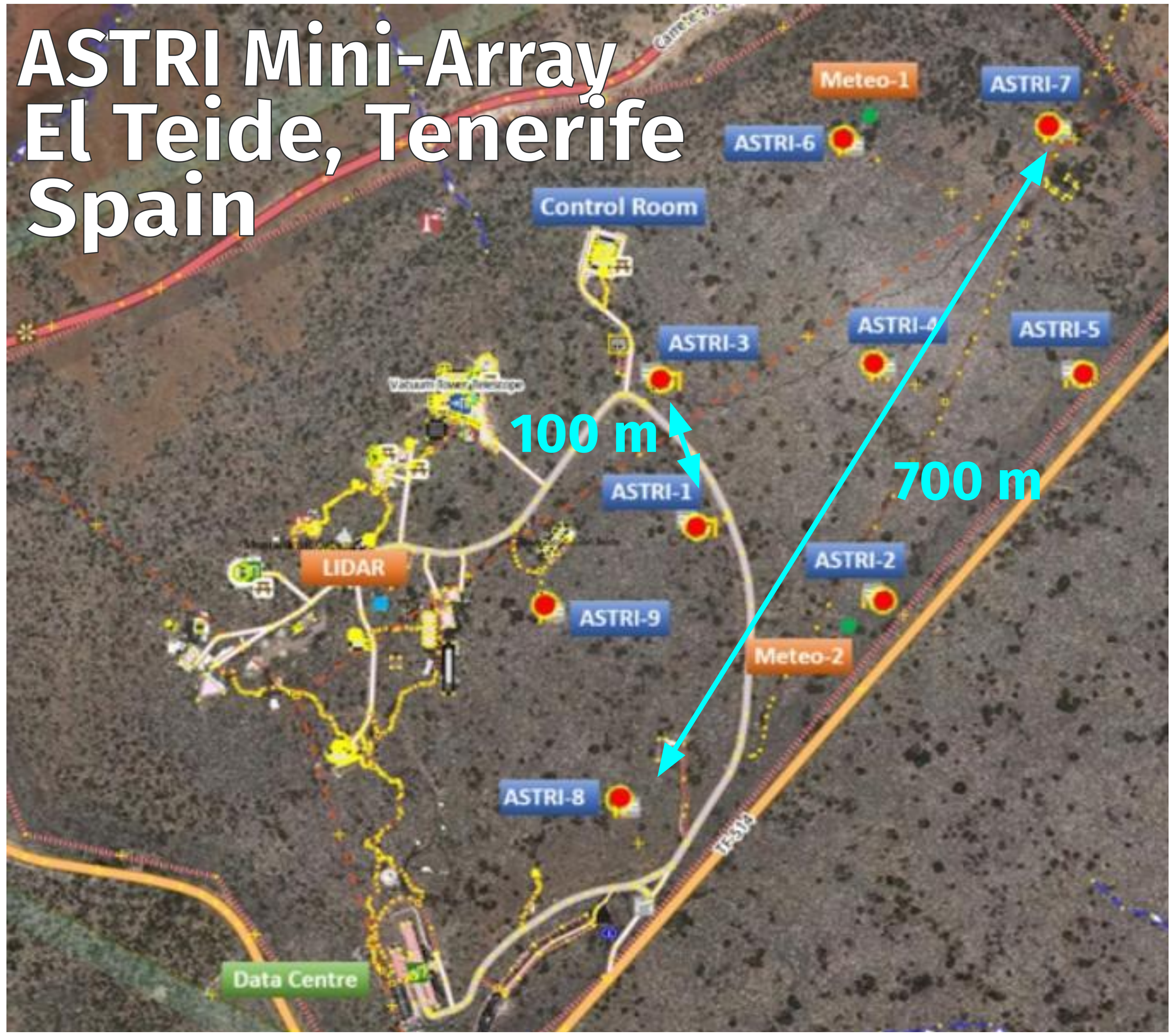


Foellmi (2009)

ASTRI SII Instrument (SI^3)

ASTRI Mini-Array

The **ASTRI Mini-Array**: International collaboration, led by the Italian National Institute for Astrophysics (INAF).
An array of 9 Imaging Atmospheric Cherenkov Telescopes to
- study gamma-ray sources at very high energy (TeV)
- perform **optical stellar intensity interferometry observations**

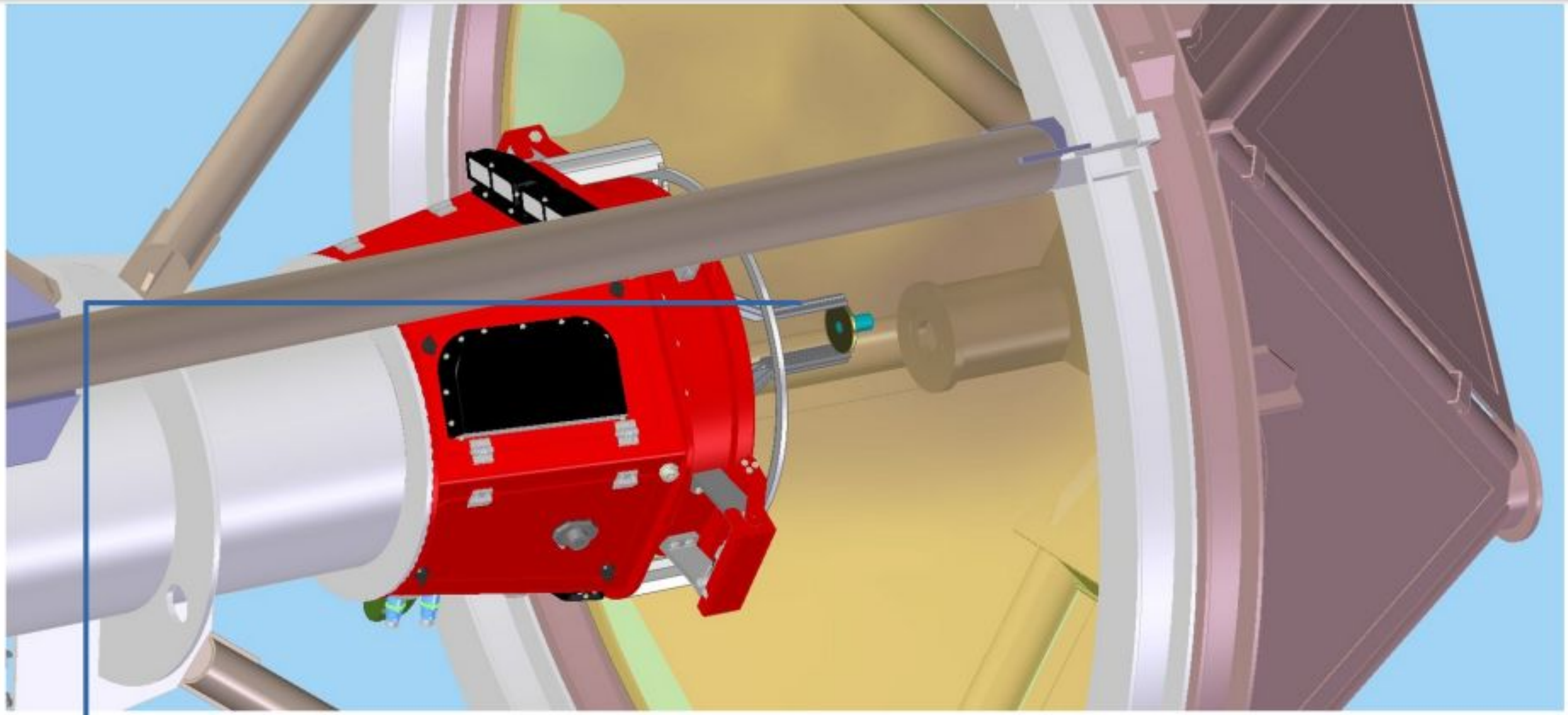


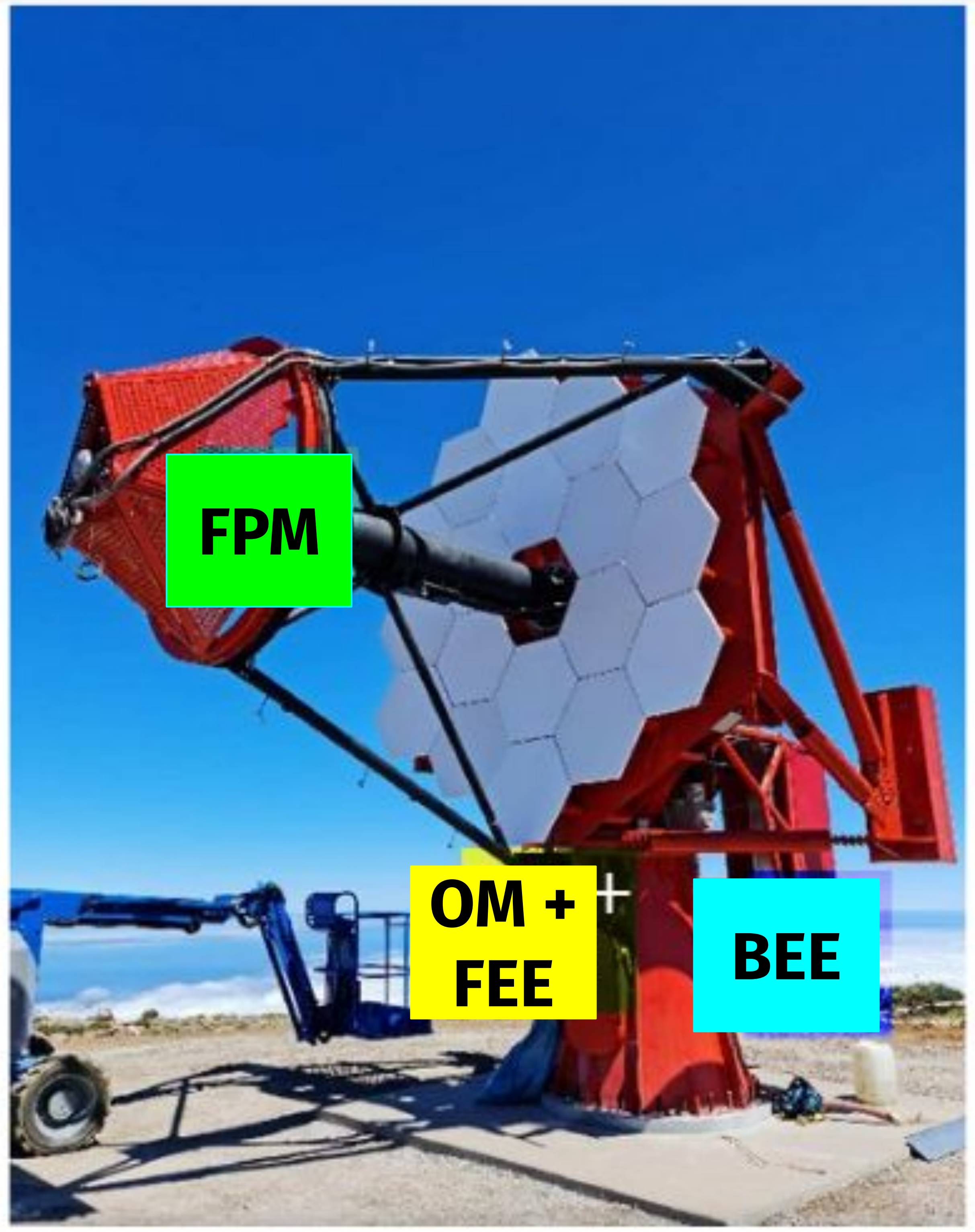
Stellar Intensity Interferometry with ASTRI

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

Ultimate goal: using the long multiple baseline (36) of all 9 telescopes to do image reconstruction with resolution of ~ 100 μas.
Baseline = 100-700 m.
SI^3 ⇒ narrow optical band (1-8 nm: length of the filter) [centered at 420-500 nm].

SI³ Version 2
Instrument Design





FPM

Focal Plane Module (placed on top of the camera)

Focussing optics + optical fiber bundle + field camera

OM + FEE

Optical Module

Injecting light on detectors

Front End Electronics

Detectors + signal conditioning + power distribution + control

BEE

Back End Electronics

Data acquisition

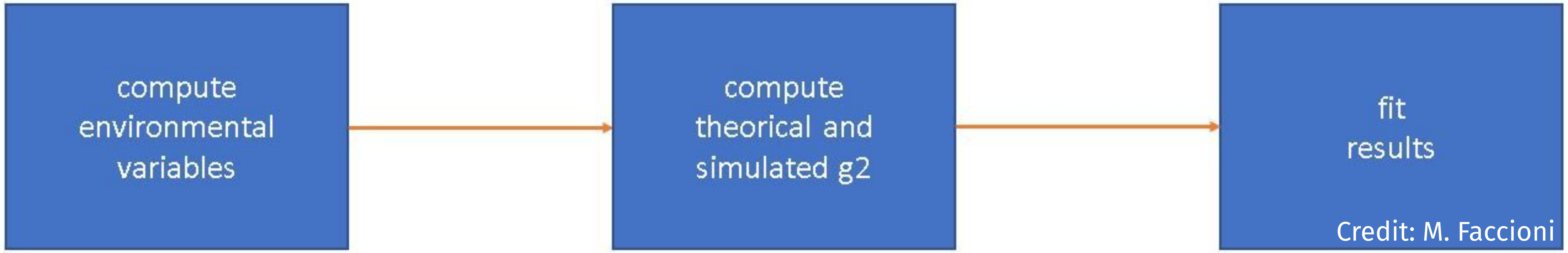
Zampieri et al. (2024)

Simulation Software

Dedicated **Python** software, designed to be **modular** and **easily extendable** by integrating new functionalities.

We can simulate the entire observation process, starting from the acquisition of the data up to post-processing, taking into account:

- Technical specifications of the array
- Properties of the targets
- Sources of noise



Credit: M. Faccioni

A specific module for the simulation of the **time-of-arrival (ToA)** of photons is also included, which was included for testing the **acceleration of the algorithm for the calculation of $g^{(2)}$** (Zampieri et al. 2021, Spolon et al. 2024) and to simulate any possible systematics in the system.

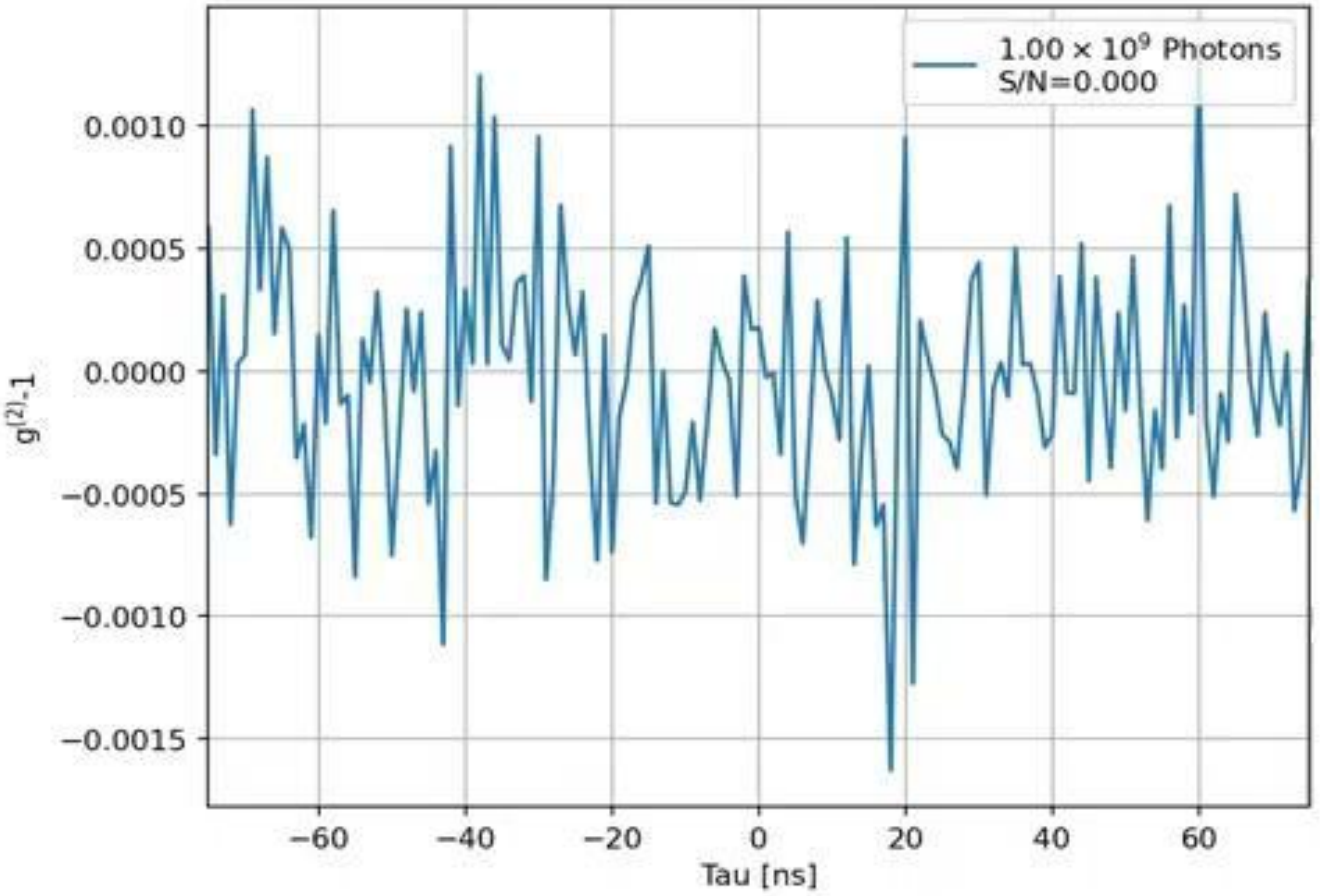
Simulations of time series
Example

Mini-Array

The plot shows the simulation of the calibrated temporal correlation at zero baseline <$g^{(2)}$ (τ, 0) > in the interval of delays τ = [−90, 90] ns.

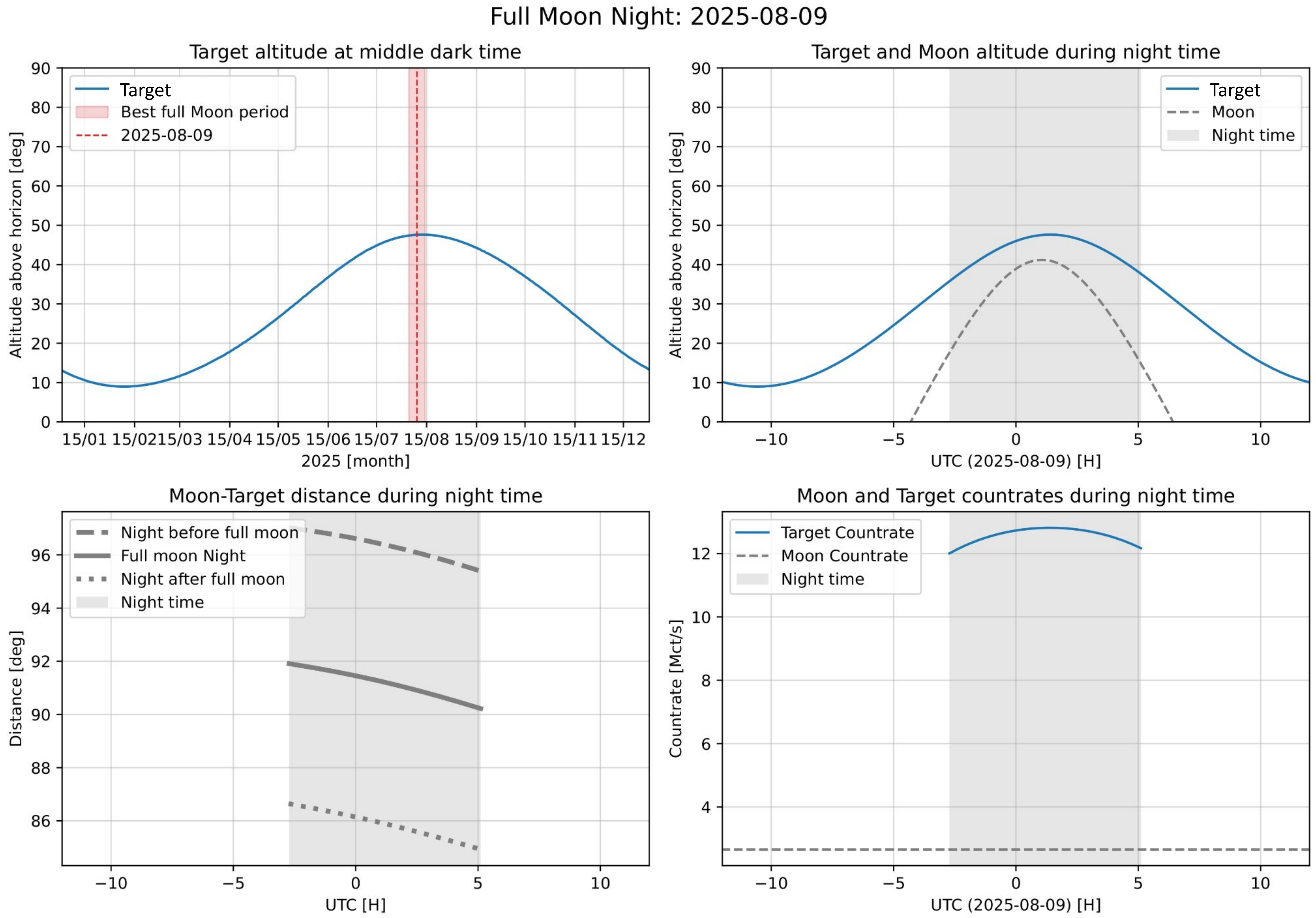
The video allows us to see how, **as the total number of simulated photons per channel increases**, the **correlation peak emerges more and more clearly from the noise**.

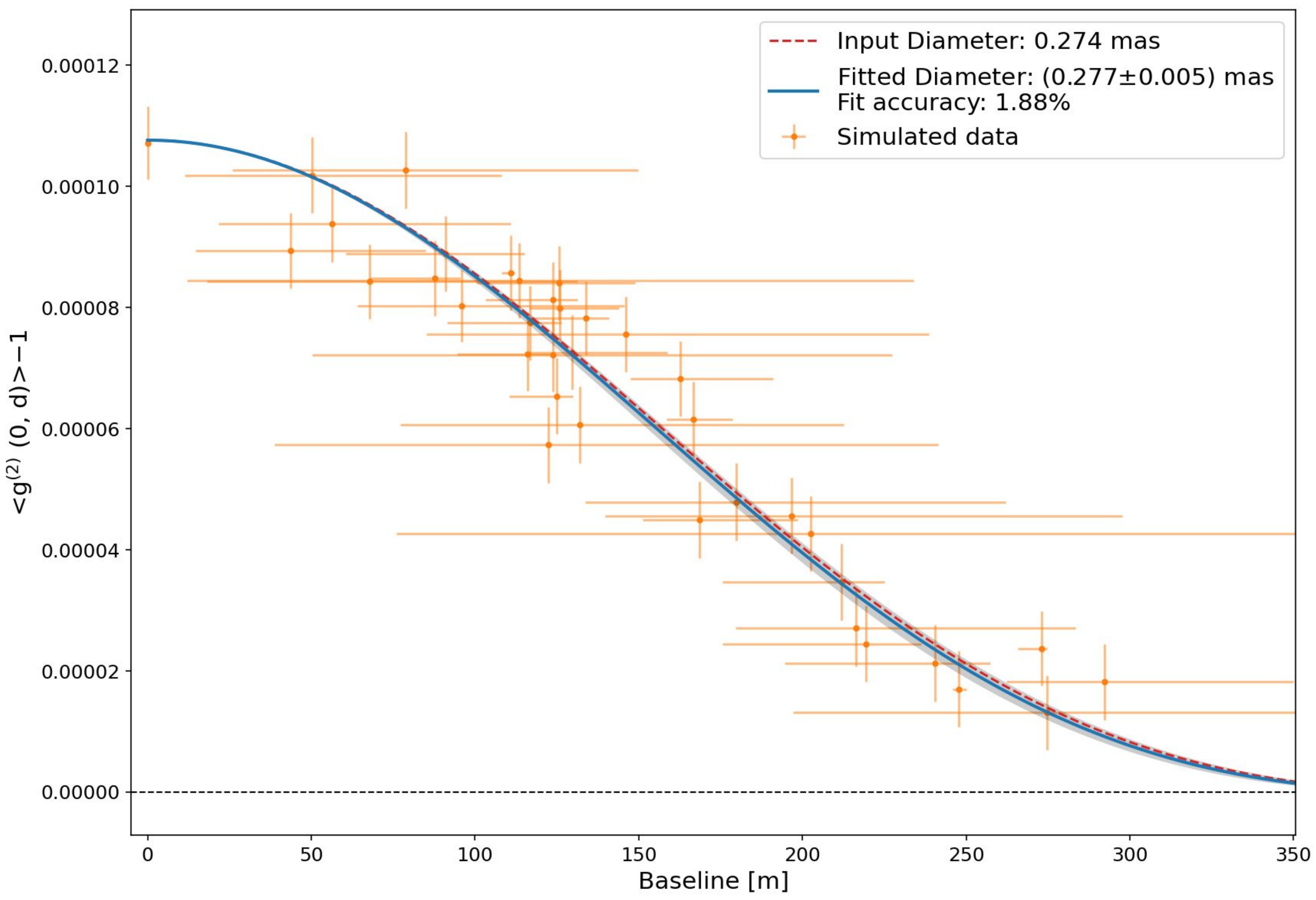
The simulation corresponds to an observation with a total acquisition time of ~300 min, considering a B-type star (V=2) and a filter with a bandwidth of 1 nm at 440 nm (total expected count rate ~20 Mcount/s).



Simulations
Illustrative result

Simulated measurements of $g^{(2)}$ with the 9 ASTRI Mini-array telescopes. The target is a **B0-type star** with magnitude **V = 3.2** and input angular diameter **θ = 0.274 mas**. The total **observing time is ~ 20 hours**. The data are fitted with a Uniform Disk brightness distribution, that returns a fitted diameter **θ_{UD} = 0.277 ± 0.005 mas (~2% accuracy)**.





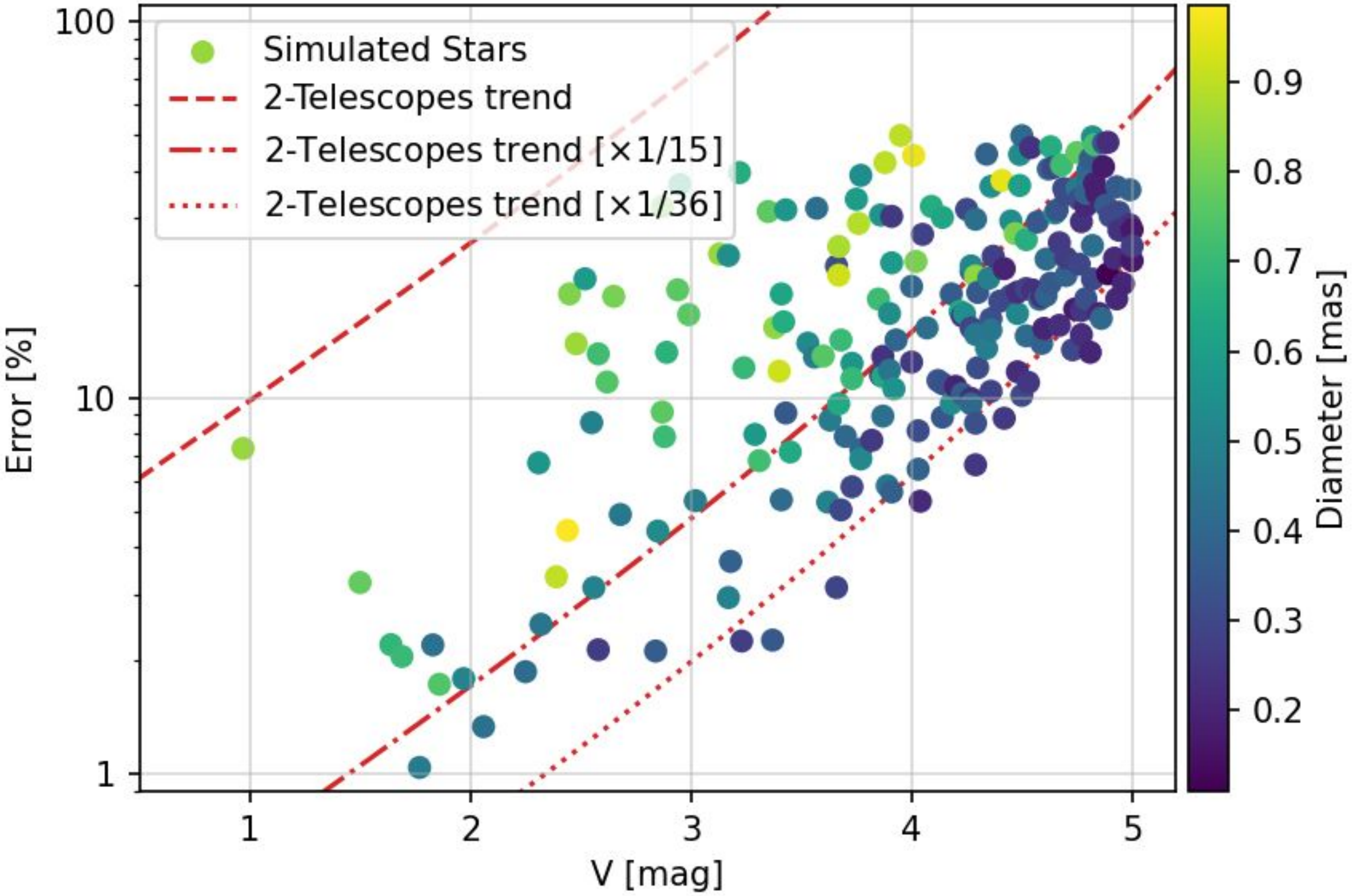
Simulations
Targets selection

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.



Computational Time Estimation

Mini-Array

Computational Time to analyze SII data

To analyze 1 hr of data

(36 baseline):

10^4 hr (CPU time) → 10^4/2000 core = 5 hr

→ 5*24 hr (real data) = 5 days

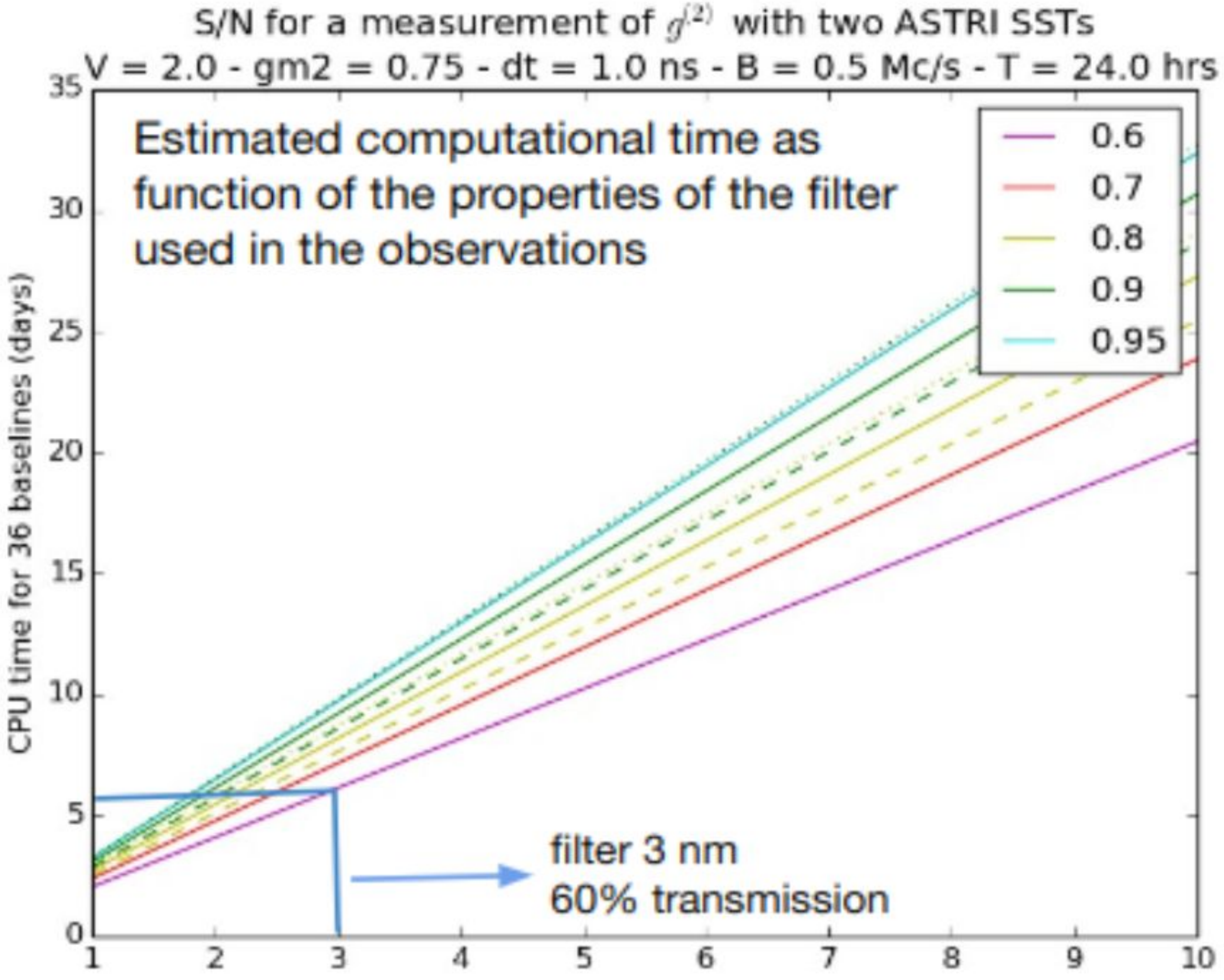


Fig. 3:

Resources Request

Parallelize and accelerate algorithms with CUDA.

Start from **multiples CPUs** (2000 CPU cores: 1 hr data)

→ code optimized (100 hr of data)

→ **GPUs** (to accelerate the computing time: 20x).

4 Leonardo Booster GPUs (1 hr data in 1 hr).

Computational Time Estimation
Test

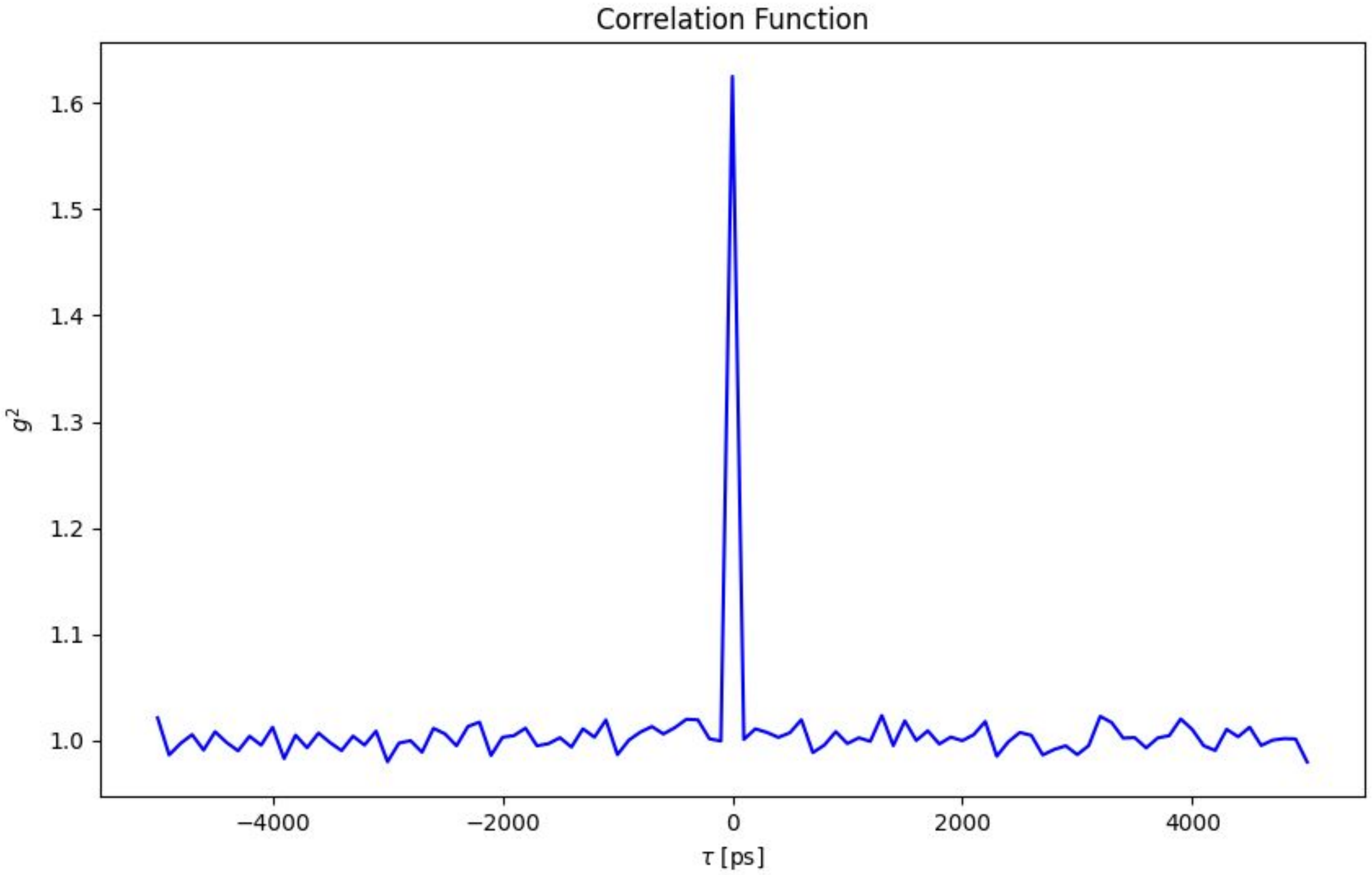
Mini-Array

Work on: simulated signal with an extremely high correlation peak.

Considering the two simulated time series ~ 10 millions of events.
dts =100 pcs

Execution time: from ~ 40 min. →
~ 2-3 sec !! [ex: parallelization, @jit]

With GPUs → an improvement of the execution time.



Conclusions

Mini-Array

- ➔ 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**.

- ➔ Produced **detailed simulations** starting from the acquisition of the data up to post-processing. Stars with angular diameters of less than 500-600 μ-as up to about magnitude 4.5 will be observable. Thanks to the 36 simultaneous baselines, **accurate (up to ~1%) angular measurements** can be obtained **with 10-30 hours of observations.**

- ➔ The **simultaneous measurements** provided by all the **36 baselines** allow us to **increase** the achievable **accuracy by a factor ~15 compared** to a 2 telescope system. Considering only **sources** with angular diameters **< 0.4 mas**, **improvement** roughly **proportional to the number of baselines**. This accuracy can rival with that obtained with other arrays of Cherenkov telescopes, despite the smaller collecting area of a single ASTRI telescope.

- ➔ Computational **Time Estimation** for SI³ data: Work In Progres!

Thank you for your attention!

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SI^3

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Backup Slides

Pros and cons of SII

Pros

- → Insensitive to phase errors in the optical light path (1 ns ~ 30 cm). Immune to atmospheric turbulence or (small) optical imperfections
- → Very long baselines
- → Possible to observe at short optical wavelengths

Cons

- → Very good photon statistics needed
- → Lost the information on phase