Interferometria di Intensita` con il Mini-Array ASTRI
Intensity Interferometry with the ASTRI Mini-Array (ASTRI-SII)

Luca Zampieri

For the ASTRI Mini-Array SI^3 Work Package

Audizioni INAF RSN2 - May 20, 2021

'Figlia' della scheda PROGRESS

Outline

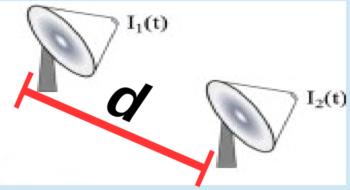
- Science: Potential goals
- ASTRI SI^3: Design, product breakdown structure, team
- ASTRI SII: Program, leadership, funds, critical aspects

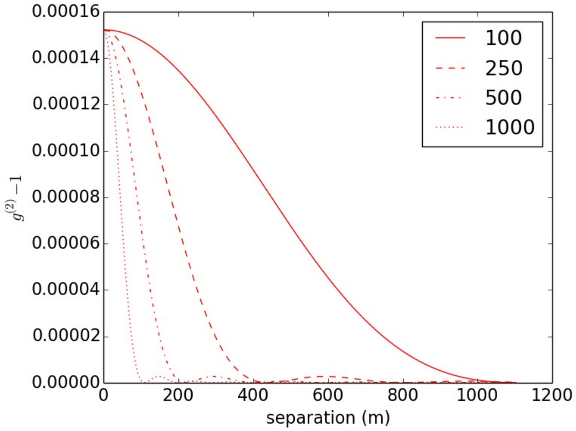
Stellar Intensity Interferometry with the ASTRI Mini-Array

Intensity Interferometry

Technique based on the measurement of the 2nd order spatial correlation of the radiation intensities of a star measured at two telescopes

The main observable is the *(discrete) degree of coherence*





$$|\gamma|^2 = \frac{\langle \Delta I_1 \Delta I_2 \rangle}{\langle I_1 \rangle \langle I_2 \rangle}$$

Degree of coherence of a source with angular size **θ** (in μarcsec) as a function of the telescope separation **d**

Stellar Intensity Interferometry (SII) with ASTRI

The ASTRI Mini-array provides a suitable infrastructure for performing SII measurements

Main goal: Achieving optical imaging with resolution of **~100 microarcseconds** using the **long multiple baselines (36)** of the 9 ASTRI SSTs

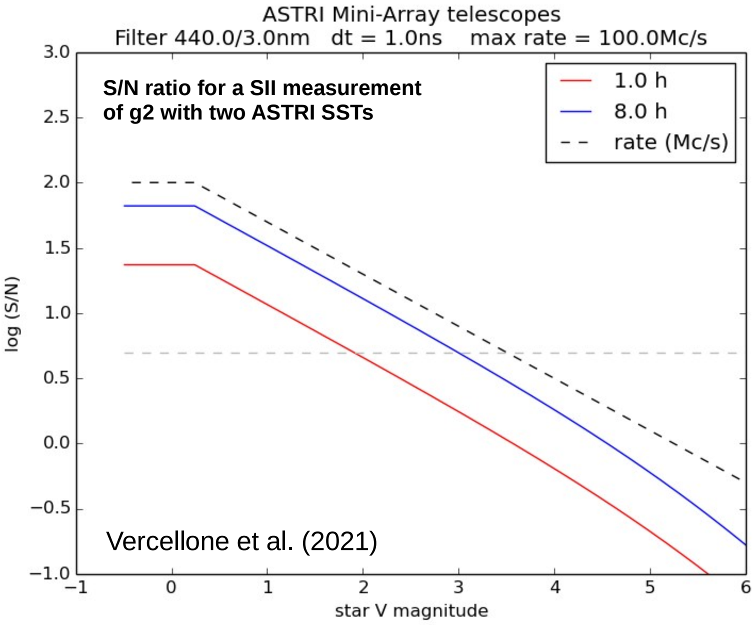
Stellar Intensity Interferometry with the ASTRI Mini-Array

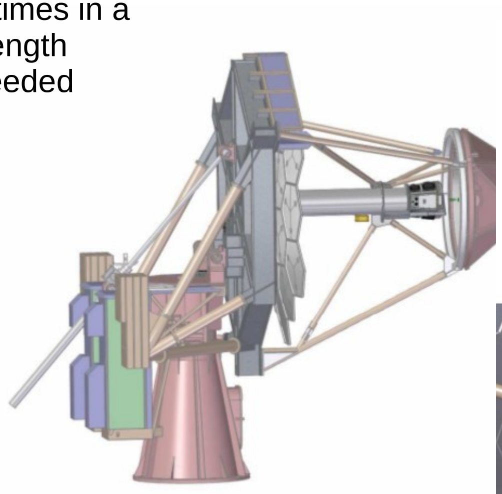
The ASTRI Stellar Intensity Interferometry Instrument (SI[3]) is conceived to *measure the 2nd order discrete degree of spatial and temporal coherence (g2) of a star*

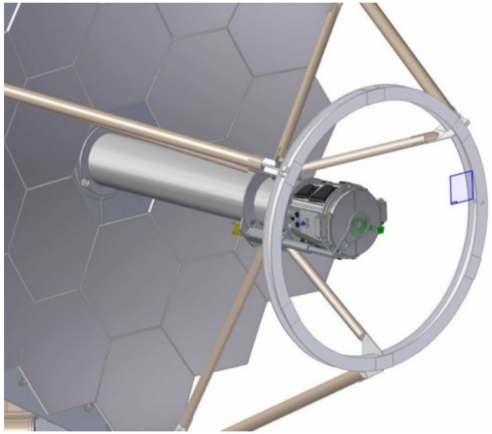
Photon counting approach, performing the correlation off-line

To this end, accurate measurements (**~1 ns**) of single photon arrival times in a narrow optical wavelength range (**~5 nm**) are needed

ASTRI Stellar Intensity Interferometry Instrument







Stars with magnitude V < 3 are observable with the ASTRI SSTs in < 24 hours with a S/N > 5

Stellar Intensity Interferometry:
The pilot SII Aqueye+Iqueye experiment in Asiago

In Press

Monthly Notices of the Royal Astronomical Society

Preprint 10 May 2021 Compiled using MNRAS LATEX style file v3.0

Stellar intensity interferometry of Vega in photon counting mode

Luca Zampieri[1★], Giampiero Naletto[2,1], Aleksandr Burtovoi[3,1], Michele Fiori[2,1] and Cesare Barbieri[2,1]

[1] *INAF - Astronomical Observatory of Padova, Vicolo dell'Osservatorio 5, 35122, Padova, Italy*
[2] *Department of Physics and Astronomy, University of Padova, Via F. Marzolo 8, 35131, Padova, Italy*
[3] *Centre of Studies and Activities for Space (CISAS) "G. Colombo", University of Padova, Via Venezia 15, 35131 Padova, Italy*

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

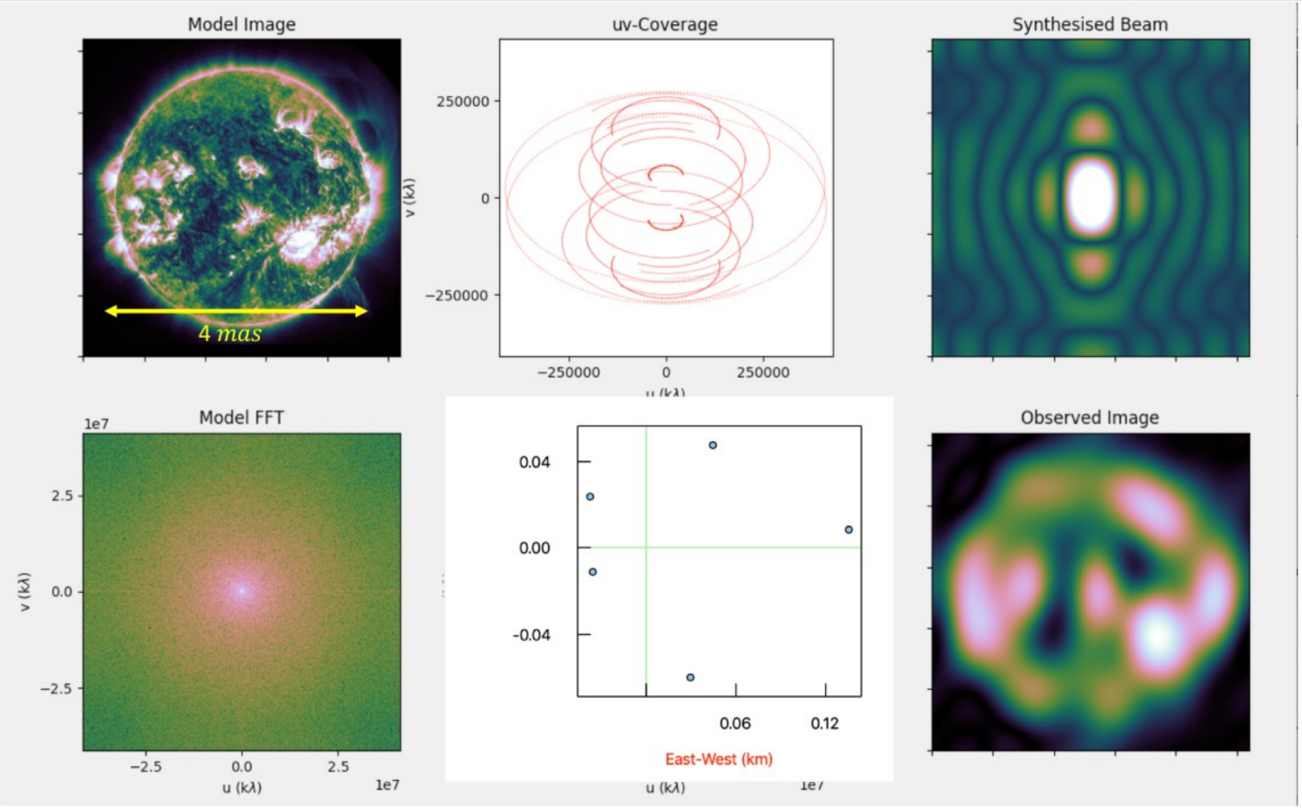
Stellar Intensity Interferometry is a technique based on the measurement of the second order spatial correlation of the light emitted from a star. The physical information provided by these measurements is the angular size and structure of the emitting source. A worldwide effort is presently under way to implement stellar intensity interferometry on telescopes separated by long baselines and on future arrays of Cherenkov telescopes. We describe an experiment of this type, realized at the Asiago Observatory (Italy), in which we performed for the first time measurements of the correlation counting photon coincidences in post-processing by means of a single photon software correlator and exploiting entirely the quantum properties of the light emitted from a star. We successfully detected the temporal correlation of Vega at zero baseline and performed a measurement of the correlation on a projected baseline of ~2 km. The average discrete degree of coherence at zero baseline for Vega is $< g^{(2)} > = 1.0034 \pm 0.0008$, providing a detection with a signal-to-noise ratio $S/N \gtrsim 4$. No correlation is detected over the km baseline. The measurements are consistent with the expected degree of spatial coherence for a source with the 3.3 mas angular diameter of Vega. The experience gained with the Asiago experiment will serve for future implementations of stellar intensity interferometry on long-baseline arrays of Cherenkov telescopes.

Key words: stars: individual: α Lyr (Vega) – instrumentation: interferometers – techniques: interferometric - software: data analysis

Photon counting SII successfully experimented with Aqueye+ and IFI+Iqueye in Asiago

It is part of the activities in Fast Photon Counting Optical Astronomy reported in 'scheda FPC-OA' (RSN4)

Stellar Intensity Interferometry: image reconstruction



VERITAS SII

D. Kieda et al. (2019)

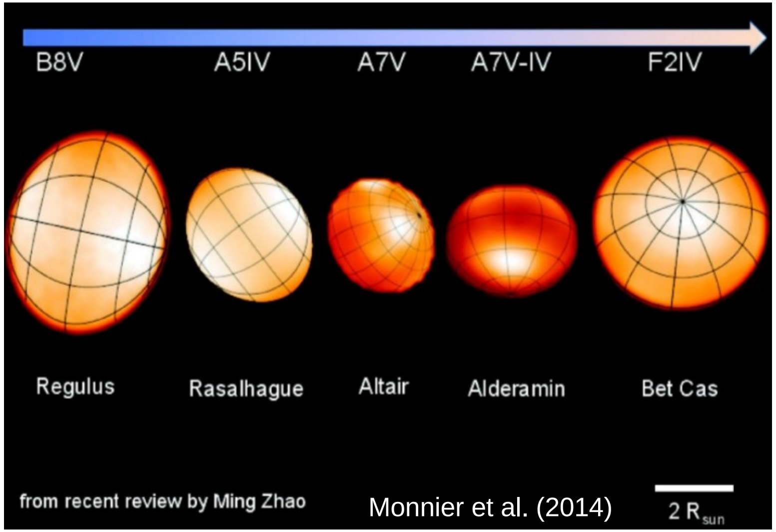
Simulated 8 hours SII Observation

4 VERITAS Telescopes + pSCT

420 nm

Only includes FFT Sampling effects

Stellar Intensity Interferometry with the ASTRI Mini-Array: Imaging rapid rotators



The ability to image the surface is the superior method to unambiguously measure the shape of a star

The more baselines used, the more model independent an image will be (CHARA has 6 telescopes, ASTRI MA has 9 tel.)

CHARA observations show that no rapid rotators have temperature contrasts as high as expected, inconsistent with any von Zeipel-like gravity darkening prescription assuming uniform rotation

Unexpected fast rotation of evolved sub-giants (Che et al. 2011)

Importance for stellar evolution:
- independent measurement of the star rotational speed
- revealing differential rotation (and meridional circulation)
- properly placing rapid rotators on the HR diagram
- understanding core-envelope coupling

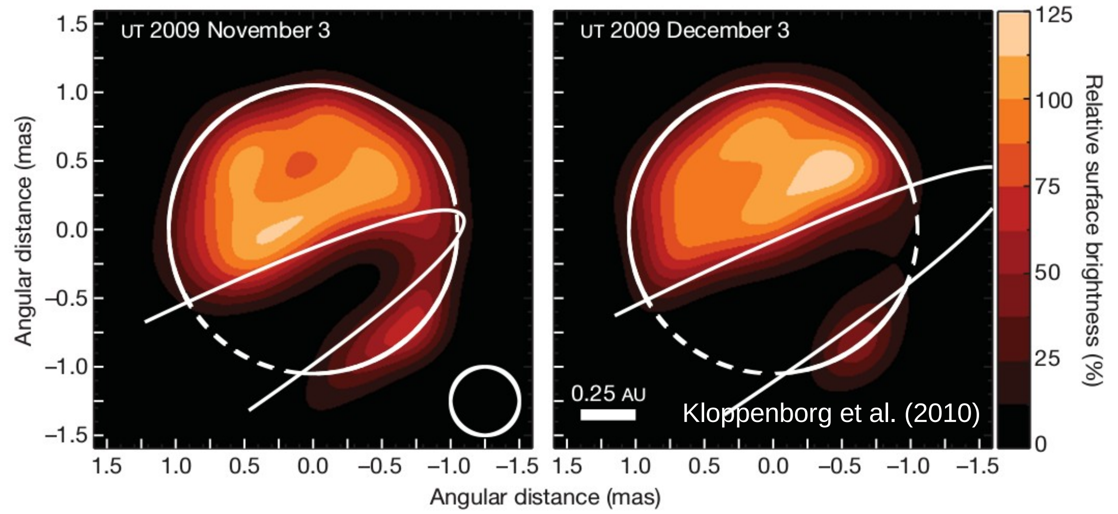
ASTRI SI^3 can measure the oblateness of many A-type and B-type stars in visible light, extending the sample collected with CHARA

Stellar Intensity Interferometry with the ASTRI Mini-Array: Imaging circumstellar features with the highest angular resolution

CHARA/MIRC IR (H band) synthetized images of eps Aur (A9I)

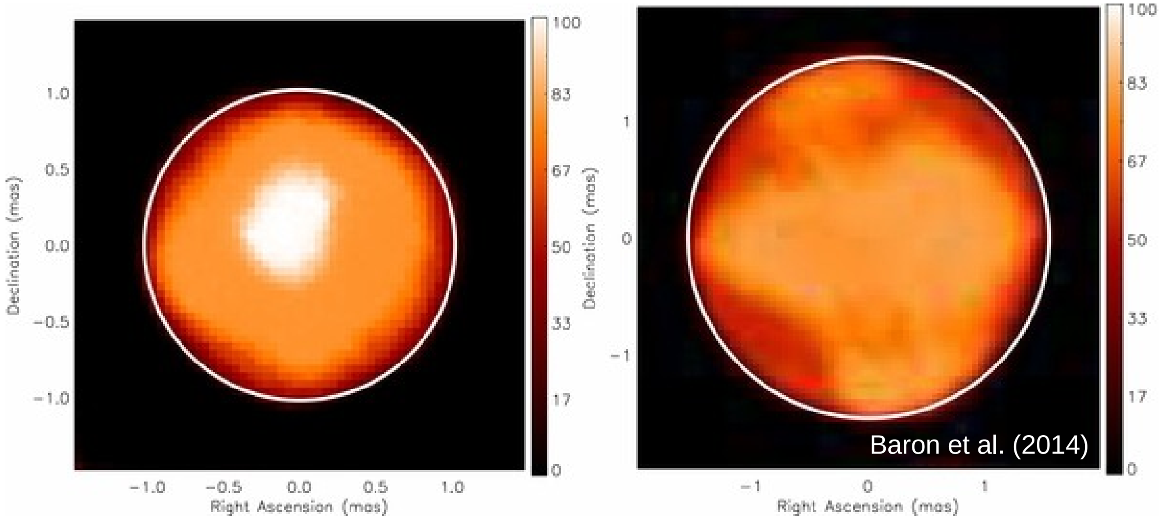
The image shows a long partial eclipse of the star eps Aur produced by an absorber with a disc-like geometry

Implications for binary evolution: the 18-month long eclipse of the star known since nearly 200 years is produced by a disc orbiting the companion



ASTRI SI^3 can observe systems of this type with unprecedented angular resolution. Imaging them can reveal details of the disc structure, density gradients, and scale height, and show how they evolve and dynamically interact

Stellar Intensity Interferometry with the ASTRI Mini-Array: Imaging bright spots with the highest angular resolution



CHARA/MIRC IR (H band) image of **RS Per (M3.5Iab) and T Per (M2Iab)**

A visible light image of **Betelgeuse (M2Iab)**, taken with VLTI/SPHERE on 2019 Dec 26 (Montargès et al. 2020), revealed a substantial dimming in the southern hemisphere (Dupree et al. 2020)

Bright spots and dimmer areas are present and are caused by temperature variations

Importance for stellar evolution:
They provide evidence of large convective cells/motions on the stellar surface

ASTRI SI^3 can resolve bright spots on smaller stars, pushing the limits of the present capabilities of interferometry (see e. g. Roettenbacher et al. 2018)

Stellar Intensity Interferometry with the ASTRI Mini-Array: Imaging dark spots with the highest angular resolution

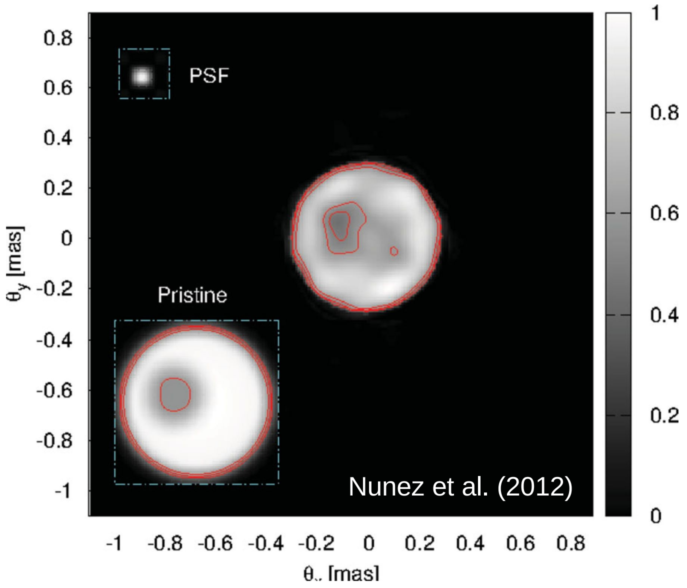
Star spots in A-type and F-type stars

Hot stars lack outer convective envelopes and are not expected to support sunspots and magnetic activity

But flaring activity was discovered with Kepler in numerous A-type stars (Balona 2013, 2014, 2017; Van Doorsselaere et al. 2017), indicating the possibility of the existence of magnetic reconnection processes, hot coronae, and star spots (from II with CTA white book)

Assessing whether star spot coverage correlates with rotational periods and stellar age in M-F type stars can test the association of star spots with magnetic fields (Nichols-Fleming and Blackman 2020)

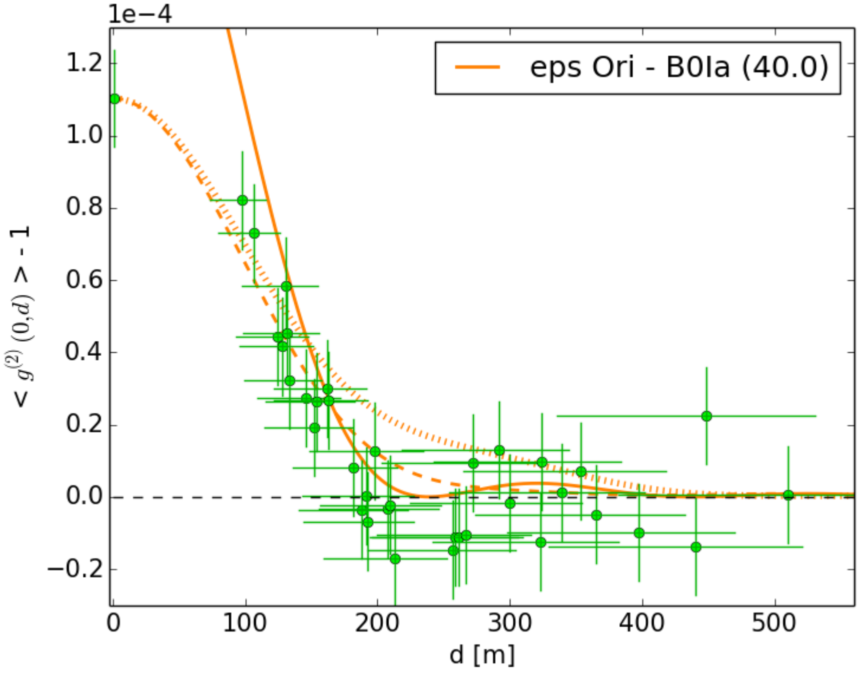
Importance for stellar evolution and exoplanets:
- poorly understood, unanticipated magnetic phenomena in hot stars
- magnetic activity of the host star has an impact on the habitability of orbiting exoplanets



ASTRI SI^3 can detect dark spots in many A-type and a few F-type stars. Its unique high resolution imaging ability provides an important tool for such an exploration

Stellar Intensity Interferometry with the ASTRI Mini-Array: Star spots with the highest angular resolution

Finding evidence of varying brightness distributions in B-through-F-type stars



eps Ori: B-type supergiant (V=1.7) with an estimated angular diameter of 460 microarcseconds

Three different surface brightness distributions:

- a **uniform brightness disc** of 460 microarcseconds (solid)
- a **dark spot** with a radius 68% that of the star and with a temperature 5% lower, superimposed on a uniform stellar disc (dashed)
- a **bright spot** with a radius 46% that of the star and with a temperature 40% higher, superimposed on a uniform stellar disc (dotted)

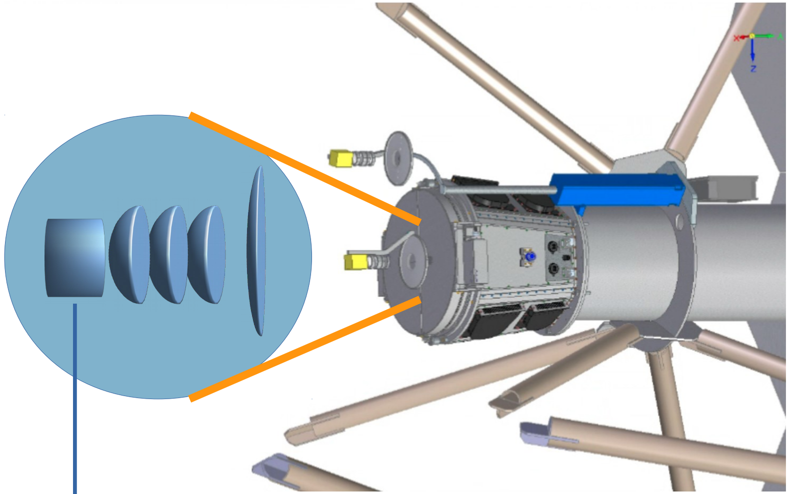
Simulated data (5 hours) derived from the dark-spot case (chi2 = 0.8 for 35 d.o.f.)

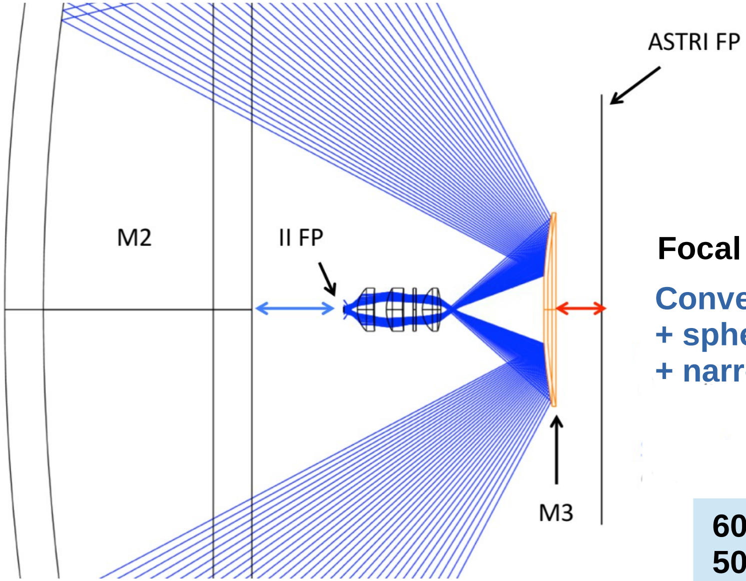
Other surface distrib. inconsistent with simulated data

Thanks to the long baselines and the zero baseline measurements, we would be able to clearly identify surface features and measure their size

ASTRI Mini-Array

ASTRI SI^3: The Instrument





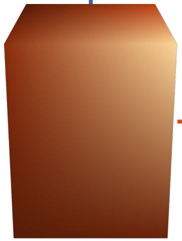
Focal Plane Optics

Convex spherical mirror
+ spherical lenses
+ narrow-band filters

60 Mcounts/s max rate
500 MB/s max data rate
~ 100 ps time res.
< 10 ns double hit res.

Focal Plane Module
(Optics + Detector +
PRE-Front End Electronics)

Placed on top of
the camera
with a positioning arm



Front End Electronics

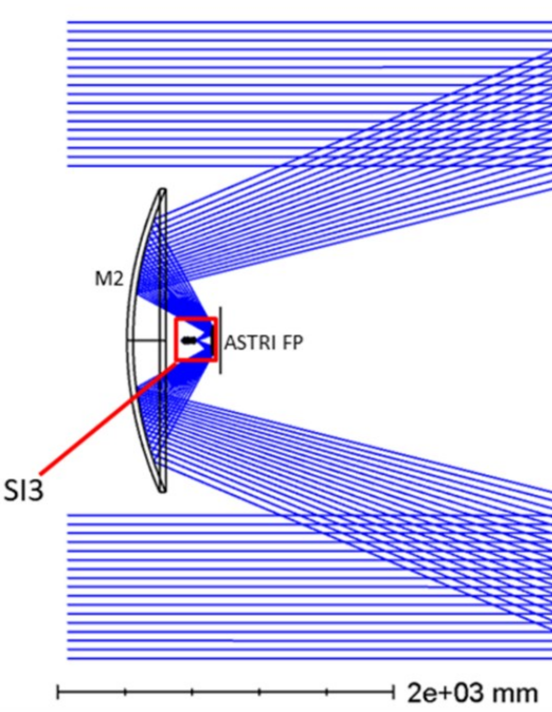
Signal conditioning + power
distribution + control

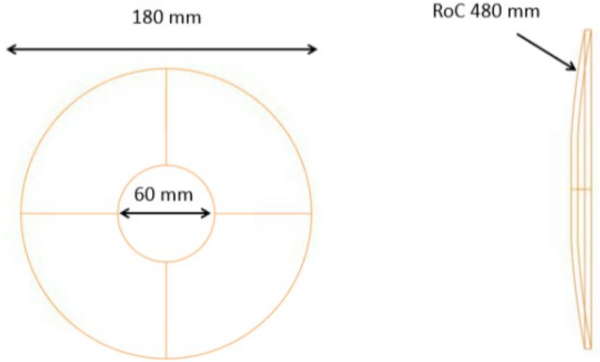
Back End Electronics

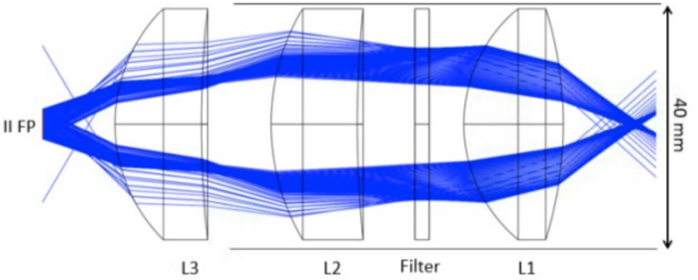
Data acquisition

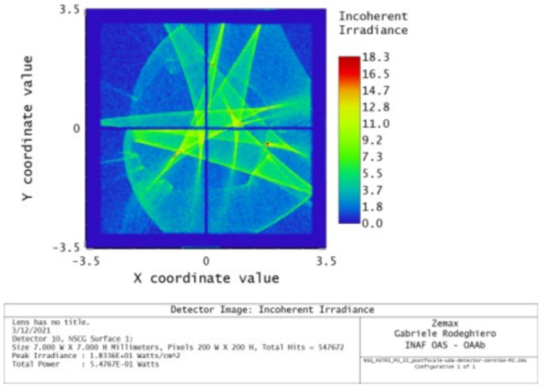
ASTRI SI^3: Focal Plane Optics

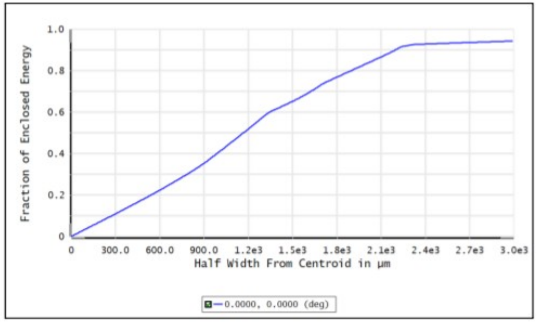
- **Convex spherical mirror (M3) + 3 spherical lenses**
- **Narrow-band filters**:
  CW: 440-500 nm – FWHM: 3-8 nm
- **Deployment and stability tolerances:**
  +/- 1 mm in x, y, z
  +/- 0.07 deg tilt x and y





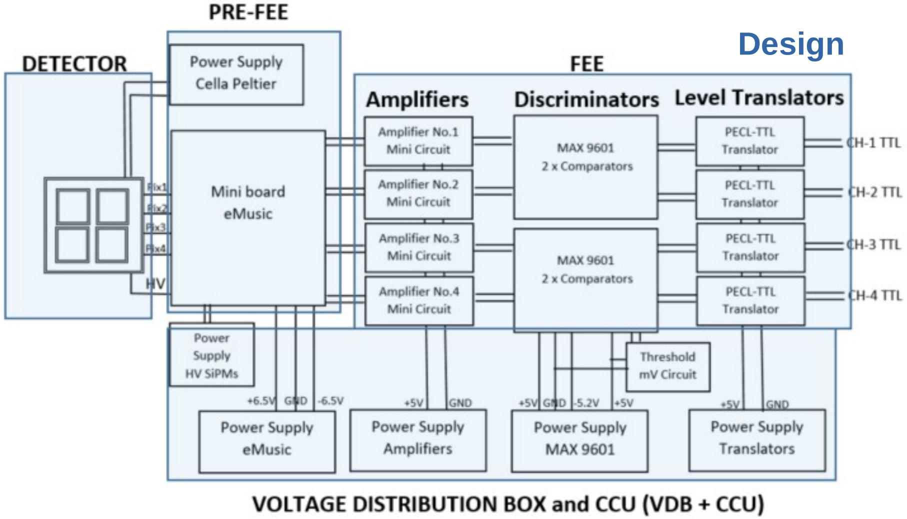


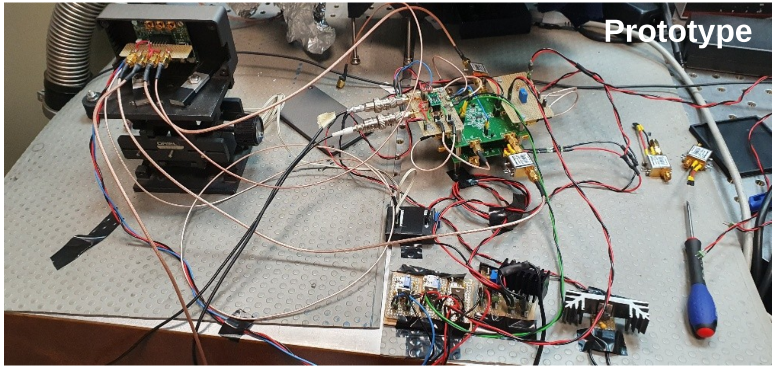




ASTRI SI^3: Front End Electronics

Design





Test: dark

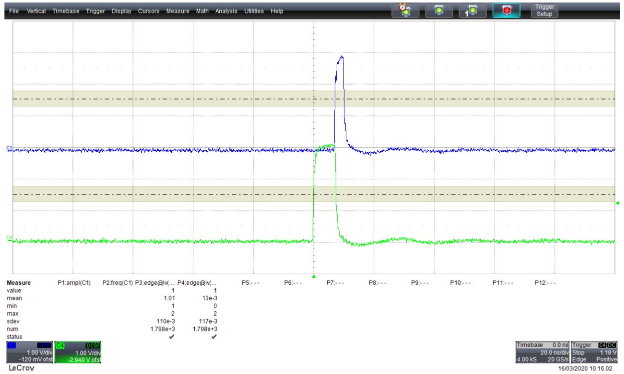
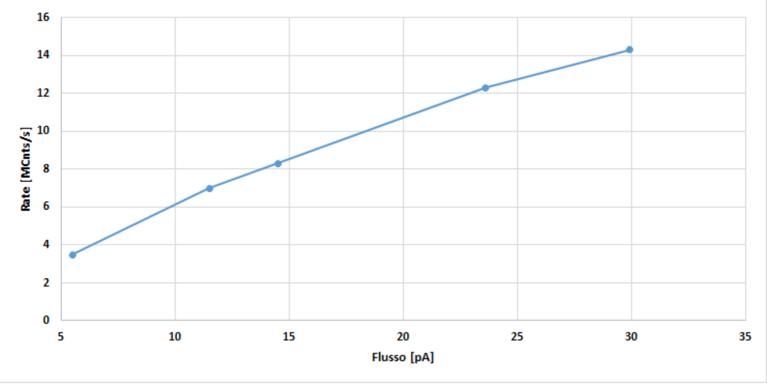


Figura 37. *Segnali digitali all'uscita del comparatore per i due canali con relativa durata. Base tempi 20 ns/div*

Double pulse resolution ~10 ns per channel and < 10 ns between different channels

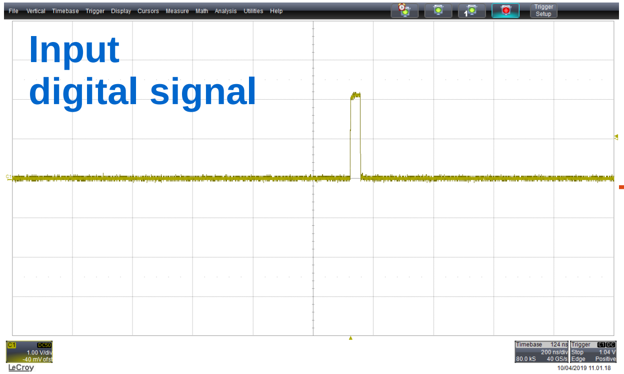
Test: illuminated



Almost linear response up to ~60 Mcounts/s (4 channels)

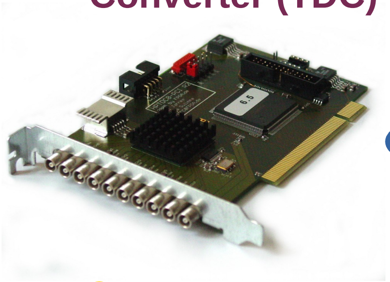
ASTRI SI^3: Back End Electronics

Input digital signal



x4

Time-to-Digital Converter (TDC)



60 Mcounts/s max rate
500 MB/s max data rate
~ 100 ps time res.
< 10 ns double hit res.
< 50 ps jitter

Industrial PC (IPC)

To storage

~ 4 Gb/s

PPS signal
Clock reference signal

Time Distribution Unit (TDU)

ASTRI SI^3: Product Breadown Structure

ASTRI Mini-Array

ASTRI WP SI^3 - PBS

Positioning Sub-system	Optics Sub-system	Detector Sub-system	PRE-FEE +FEE Sub-system	VDB+CCU Sub-system	BEE Sub-system	Acquisition and control Sub-system	Science data processing Sub-system	AIV
Mechanical support arm Arm motorization and power supply Arm control software Cable harness	Module with focal plane optics FPO box	Detector and thermo-electric cooling sys. Detector+ PRE-FEE box	Module for readout (PRE-FEE) Module for signal condition. FEE+VDB +CCU box	Module for voltage distribution Module for controlling the detectors and FEE	BEE Acquisition system: - IPC - TDC - TDU BEE Acq. Software	Local Acq/Control system: IPC Local Acq/Control software PRE-FEE/ FEE/ VDB+CCU control/monitoring soft.	Reduction/ analysis soft. Soft. for data simulations	Equipment for tests

ASTRI SI^3: Team

ASTRI SI^3 – Organization Chart

Positioning Sub-system (C. Gargano)	Optics Sub-system (G. Rodeghiero)	Detector Sub-system (G. Bonanno)	PRE-FEE +FEE Sub-system (G. Bonanno)	VDB+CCU Sub-system (G. Bonanno)	BEE Sub-system (L. Zampieri)	Acquisition and control Sub-system (L. Zampieri)	Science data processing Sub-system (L. Zampieri)	AIV (L. Zampieri)
C. Gargano	G. Naletto	G. Bonanno	G. Bonanno	G. Bonanno	G. Naletto	P. Bruno	M. Fiori	M. Fiori
L. Lessio	C. Pernechele	G. Romeo	P. Bruno	L. Paoletti	L. Zampieri	M. Fiori	L. Zampieri	L. Zampieri
	G. Rodeghiero		A. Grillo	G. Romeo		G. Naletto		
			G. Romeo			L. Zampieri		
			M. Timpanaro			+ members of the ASTRI Mini-array soft./hard. team		

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

- Work Package within the framework of the ASTRI project (ASTRI Project Office directly involved)
- All technological areas (optics, electronics, mechanics) well covered at present
- Main INAF Institutes involved: OA Padova (0.65 FTE), OA Catania (1.1 FTE), IASF Palermo (0.2 FTE), OAS Bologna (0.1 FTE)
- Close collaboration with Univ. Padova (0.3 FTE), INFN Roma Tor Vergata and other national and international Institutes/working groups (e.g. MAGIC, VERITAS, CTA)

SII with the ASTRI Mini-Array: Schedule of next activities

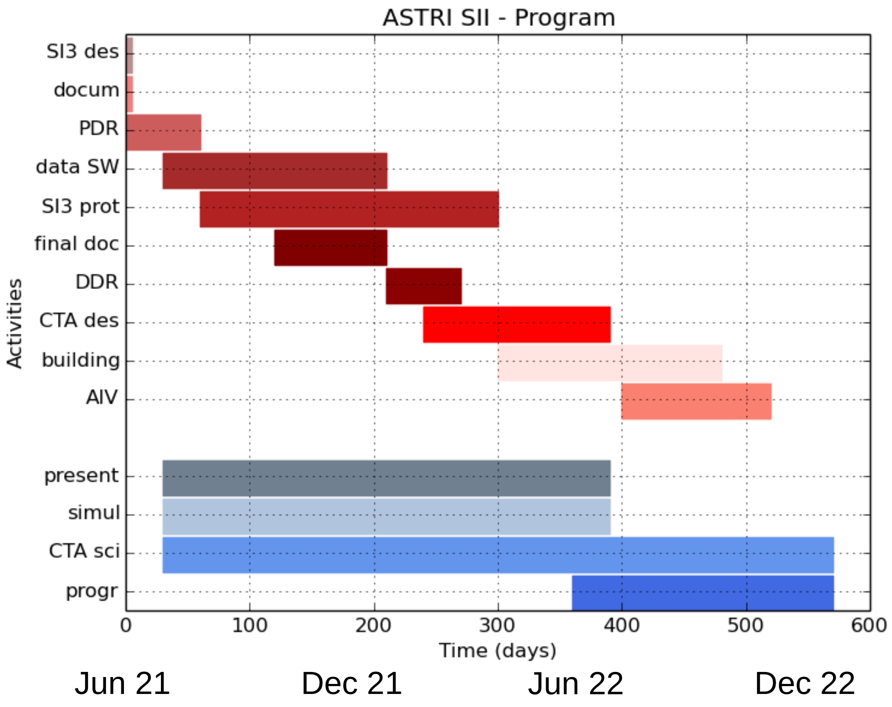
Program RSN2, project/laboratory RSN5 and RSN4 – Framework: 2021-2023

ASTRI SI^3

* Critical assessment of the design
* Documents for Preliminary Design Review:
  - **Science Requirements document (ASTRI-INAF-SCI-7400-001)**
  - **Concept Design document (ASTRI-DES-7400-001)**
  - **System Requirements document (ASTRI-INAF-SPE-7400-002)**
* Preliminary Design Review
* Science data processing software/activities (dedicated pipelines)
* Starting realization prototype, and testing it (Serra La Nave, Asiago)
* Completing documentation
* Detailed Design Review
* Contributing to the design of an SII instrument for CTA
* Building the instruments
* AIV (El Teide)

Science

* Presentation of the instrument to a wider Community
* Science data simulation
* Contributing to the CTA SII science
* Selection scientific cases, programs and targets



SII with the ASTRI Mini-Array: Leadership, Funds, Critical aspects

With the implementation of the ASTRI SI3 project **INAF is at the forefront in this area** and is laying the foundations to become a world-leading Institute for the technological and scientific development of stellar intensity interferometry

PI and some Co-Is are members of the MAGIC and CTA SII Working Groups
One of us is currently involved in the analysis of the MAGIC SII data

The capabilities of the ASTRI MA will only be overcome with the full implementation of CTA

Tabella fondi:

#	Provenienza	Certi 2021 (k€)	Certi 22 (k€)	Certi 23 (k€)	Presun. 2021 (k€)	Presun. 22 (k€)	Presun. 23 (k€)	Totale Certi (k€)	Totale Presunti (k€)
1	Fondi INAF "Astronomia Industriale"	40	60	112	0	0	0	212	0

SII with the ASTRI Mini-Array: Leadership, Funds, Critical aspects

Main critical aspect, future lack of manpower in two crucial areas

(A) Front-end electronics development and testing

Entirely managed by the detectors and electronics laboratory team of the Catania Observatory. There is a real risk that, in the near future, the team no longer has the human resources necessary to carry out this activity. There is already a person in the team with the necessary skills to do this, but his position is temporary. However, this person has the necessary requisites to be able to access the second phase of the 'stabilization process', a solution that would represent an excellent opportunity to cover the needs of this project.

(B) Development of the simulation software and of the data reduction / analysis pipelines (science data processing), and activities planned for the AIV phase

Temporarily assigned to the PI of the project and to an INAF associate with a fixed term expiring at the beginning of the 2022. The human resources for this activity can only be found to a small extent within INAF and there is therefore the need to acquire a dedicated position. The complexity of the system and the level of competence require a person with a qualification at the level of TD researcher.