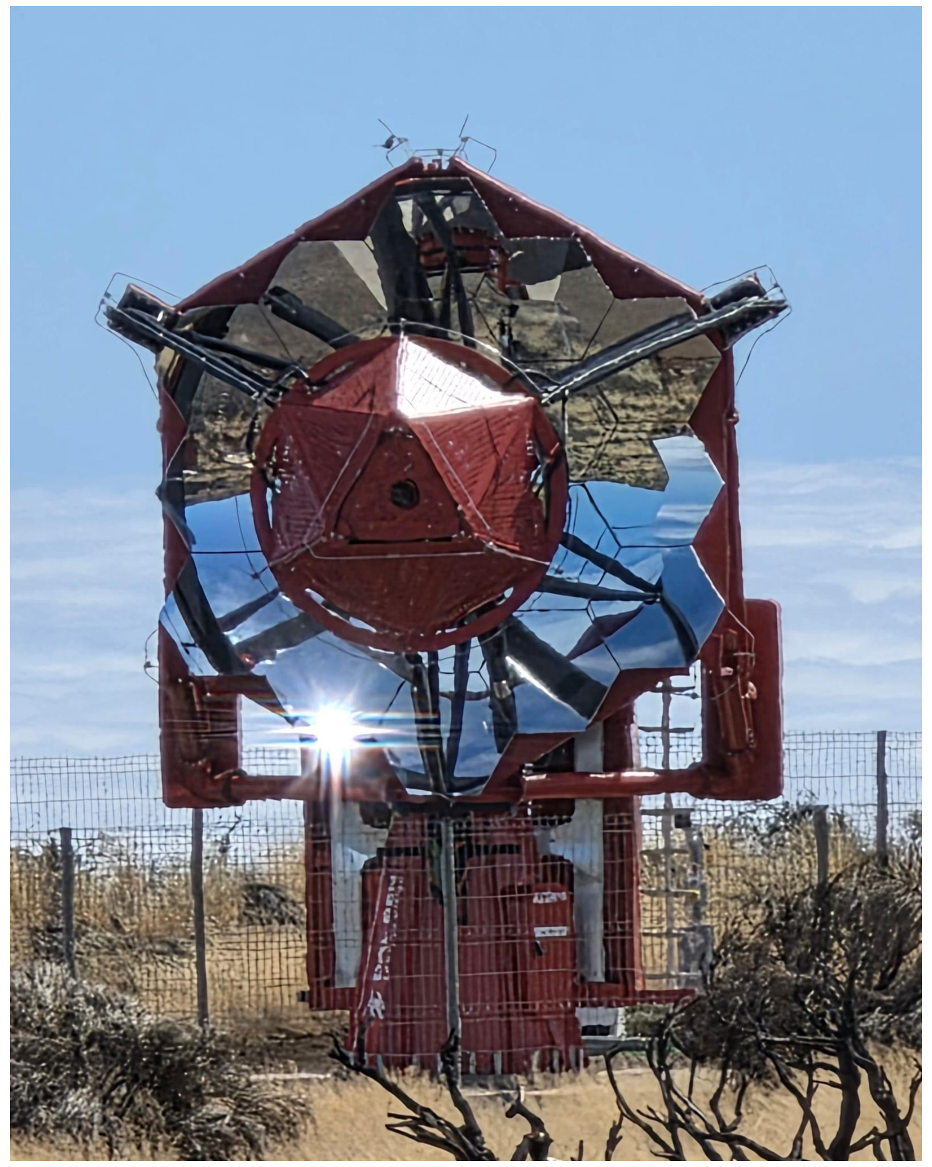
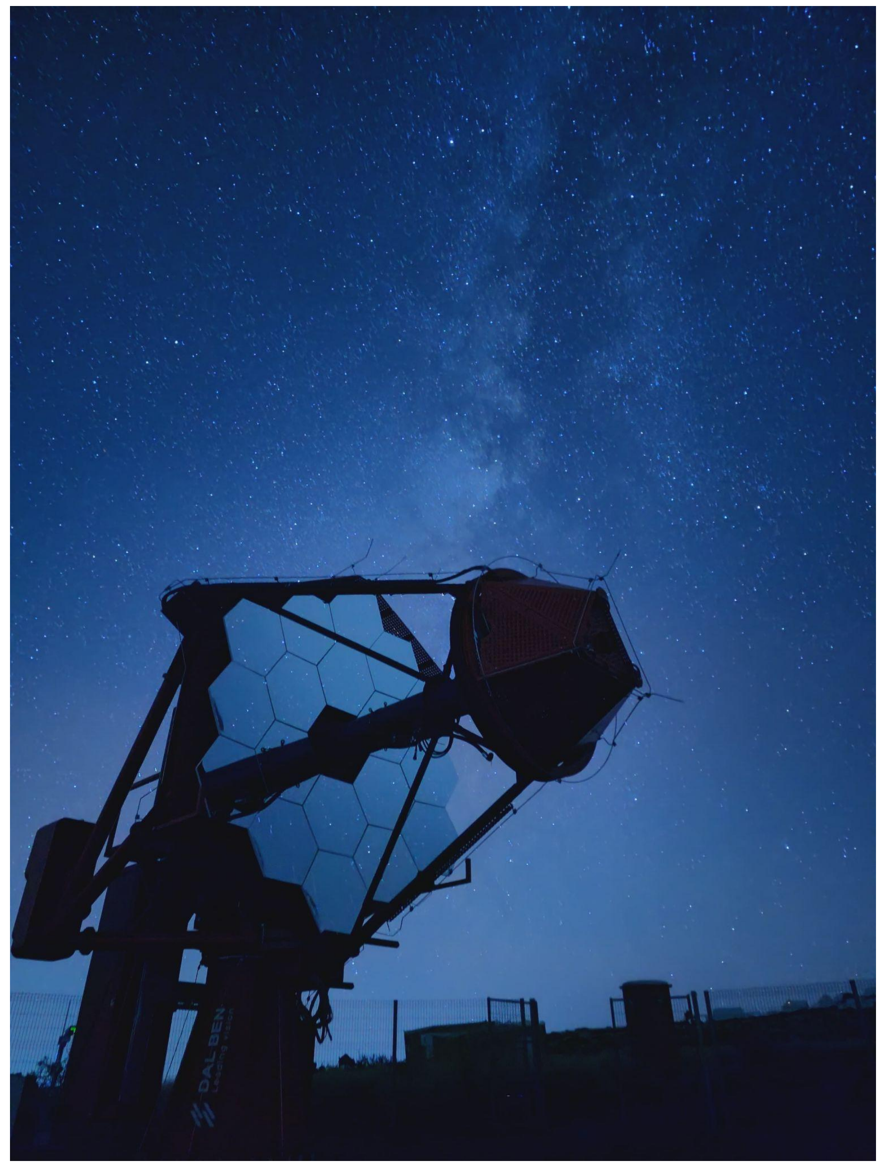
Stellar Intensity Interferometry: Past, Present, and Future Prospects with Imaging Air Cherenkov Telescopes

Luca Zampieri (*INAF-Astronomical Observatory of Padova*)

for the ASTRI-SI3 team and the ASTRI Project

From 9 to 40: the SST Telescopes and Gamma-Ray Science with ASTRI and CTAO - July 23, 2026





Stellar Intensity Interferometry: Past, Present, and Future Prospects with Imaging Air Cherenkov Telescopes

From 9 to … **23, 2026**

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LO STUDIO È STATO PUBBLICATO SU NATURE ASTRONOMY

La ribalta dell'interferometria a intensità stellare

Gli scienziati della collaborazione Veritas hanno misurato i diametri angolari di Beta Canis Majoris e Epsilon Orionis usando – per la prima volta dopo 50 anni dalla prima implementazione – l'interferometria a intensità stellare e dimostrando il miglioramento della sensibilità della tecnica e la sua scalabilità. Con il commento di Giovanni Pareschi dell'Inaf, principal investigator del progetto Astri

Maura Sandri 22/07/2020

Gli scienziati della collaborazione Veritas (*Very Energetic Radiation Imaging Telescope Array System*) – del Center for Astrophysics – Harvard & Smithsonian e dell'Università dello Utah – hanno misurato i diametri angolari di

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Outline

- ➔ Stellar Intensity Interferometry (SII) and the Narrabri Interferometer
- ➔ Intensity correlation and photon counting SII
- ➔ SII on Cherenkov Telescopes: past and present
- ➔ Future Prospects

Stellar Intensity Interferometry (SII)

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

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

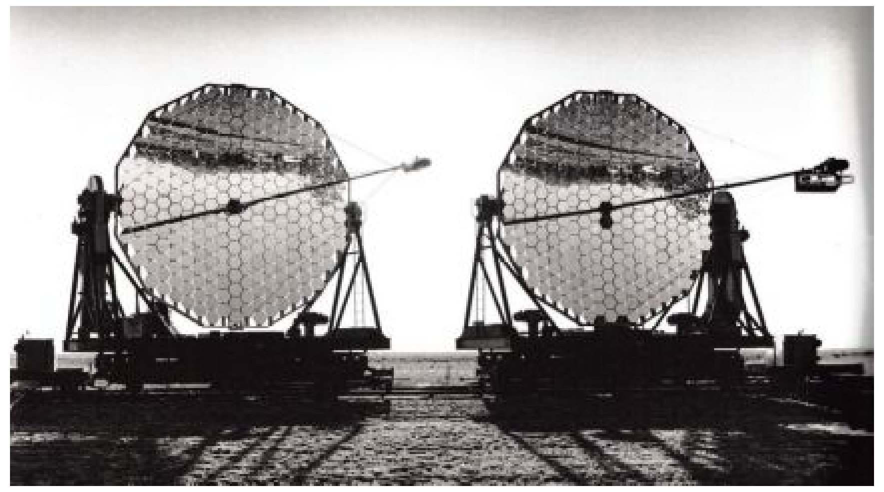
$$< I_1 I_2 > = \lim (1/2T) \int I_1(t) I_2(t-\tau) dt$$

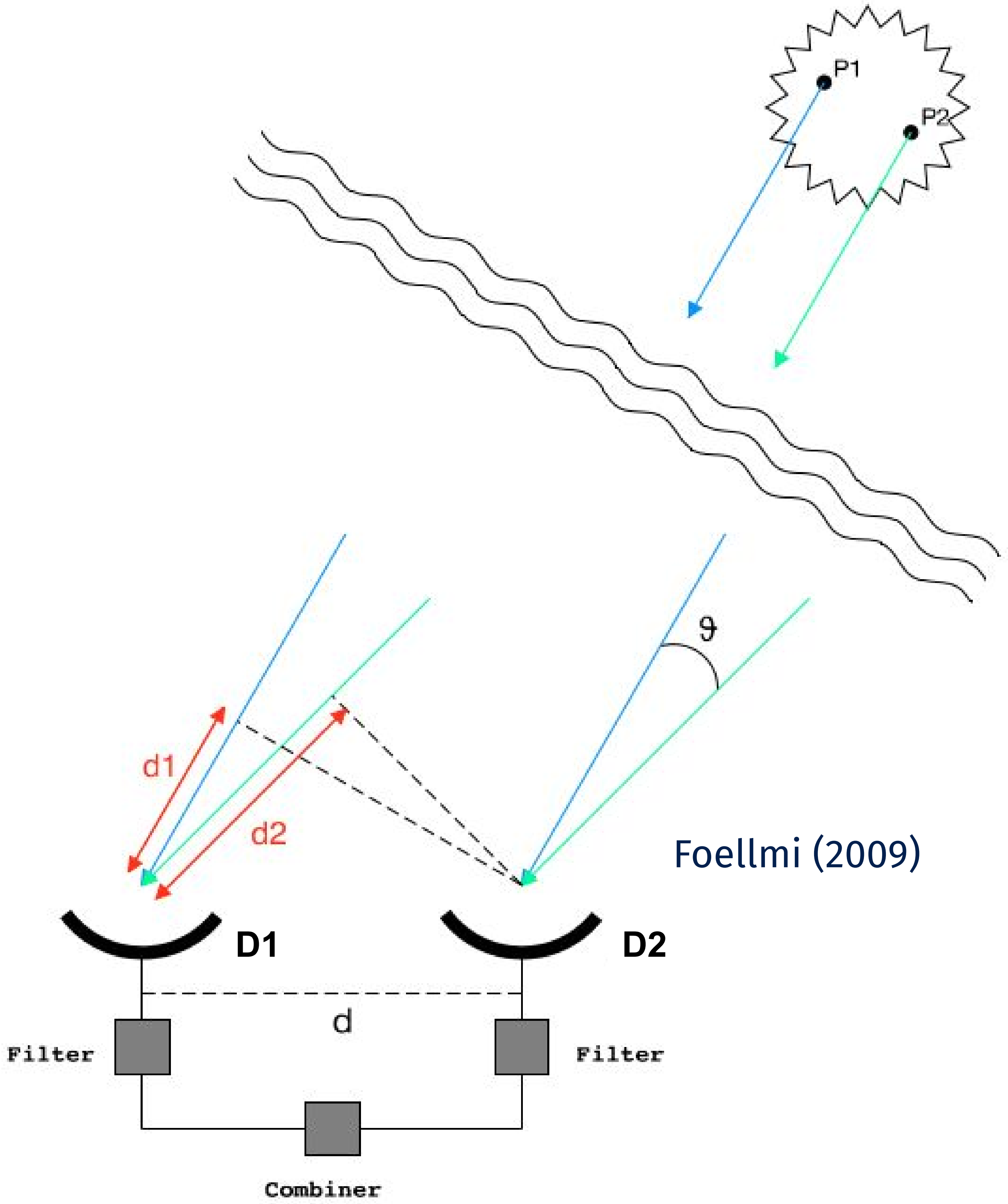
Under quite general assumptions, **for thermal (chaotic) light**:

$$< I_1 I_2 > - < I_1 >< I_2 > = \frac{1}{2} |\Gamma(u,v)|^2$$

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

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





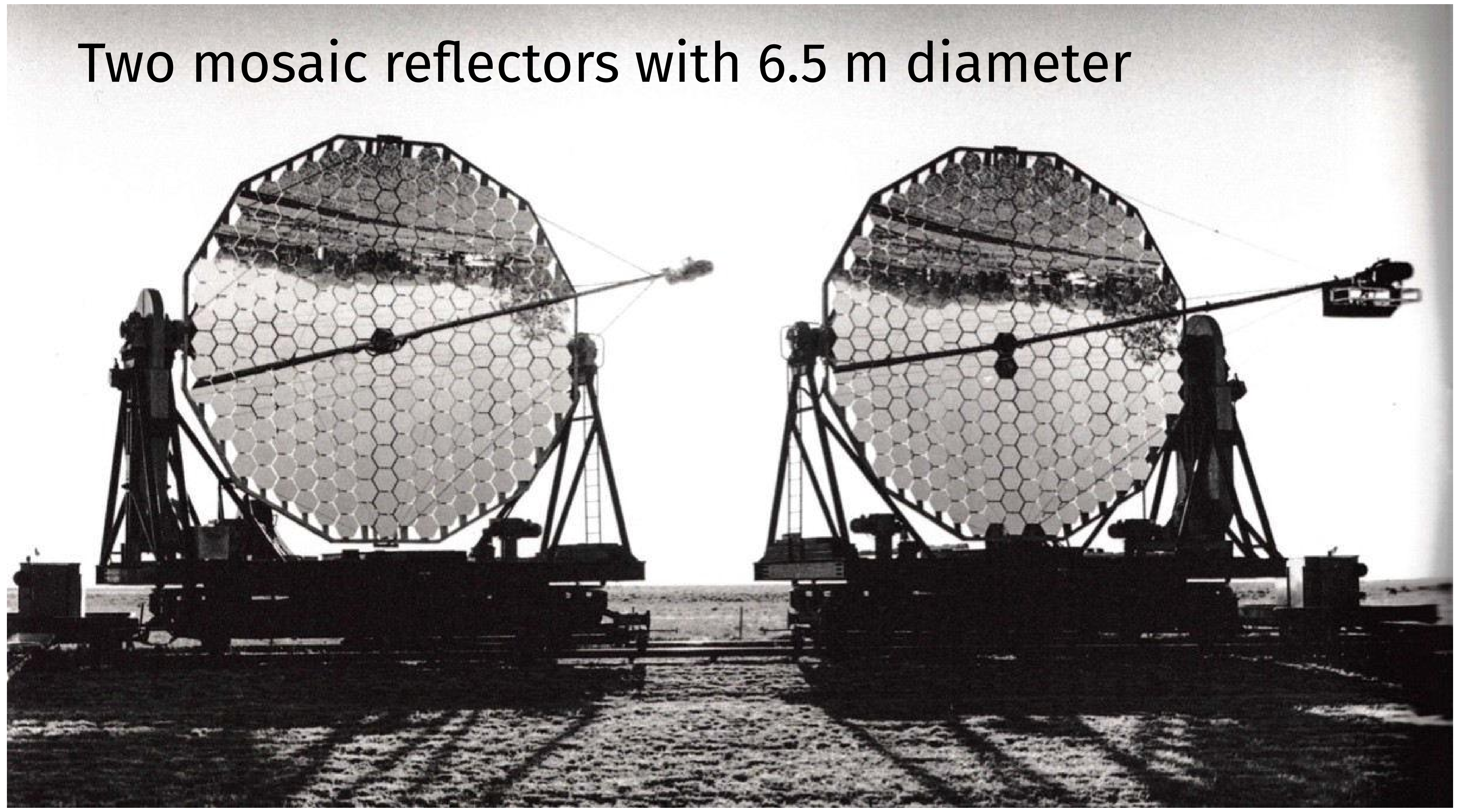
Foellmi (2009)

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

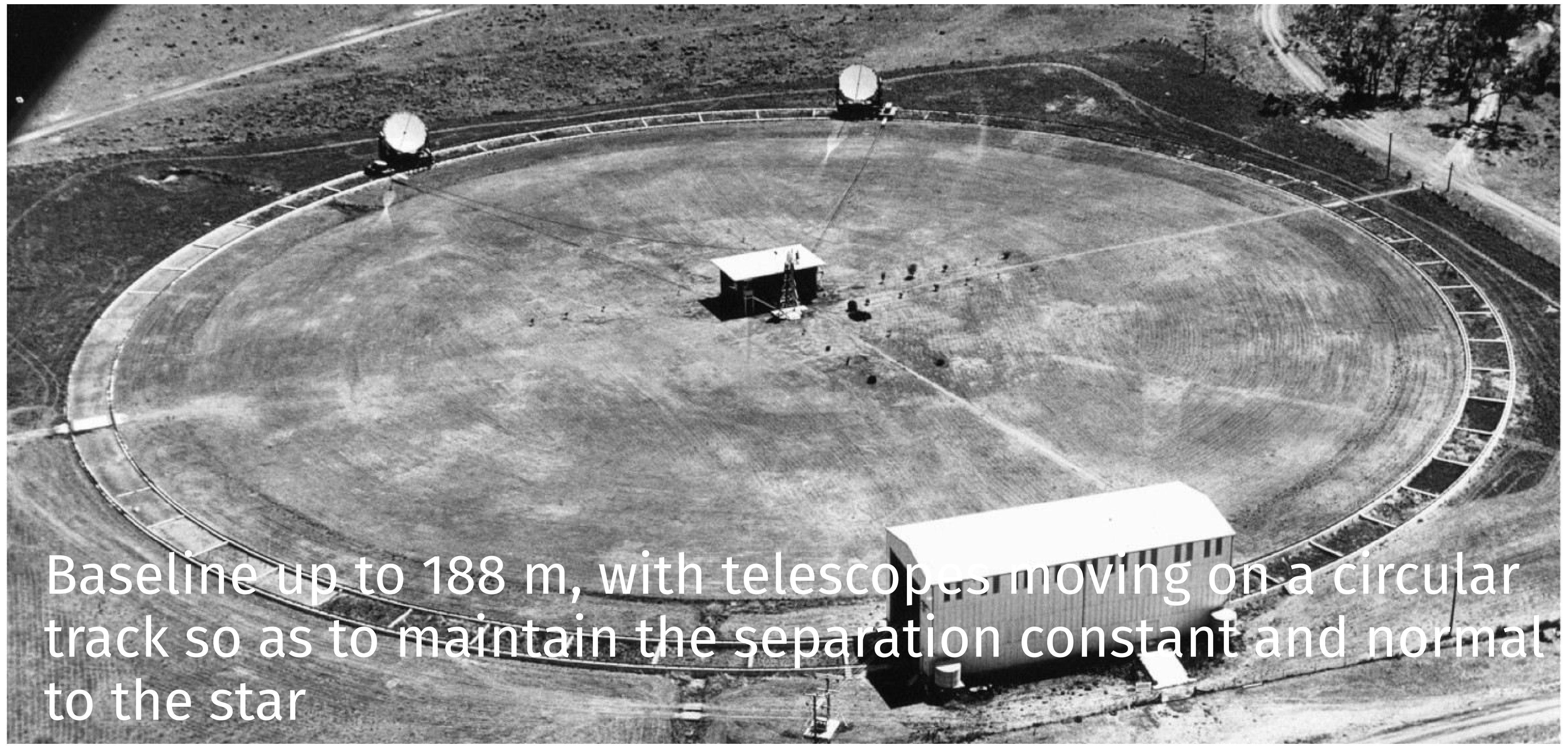
From 1963 through 1974 direct interferometric **measurements of the diameters of 32 single stars** of O-F spectral type (Hanbury Brown et al. 1974)

The Narrabri Stellar Intensity Interferometer

The **first Intensity Interferometer** for the measurement of the spatial correlation of the intensities of a star was built by **Hanbury Brown & Twiss** in Narrabri, Australia (Hanbury Brown 1956; Hanbury Brown & Twiss 1957, 1958)



Two mosaic reflectors with 6.5 m diameter



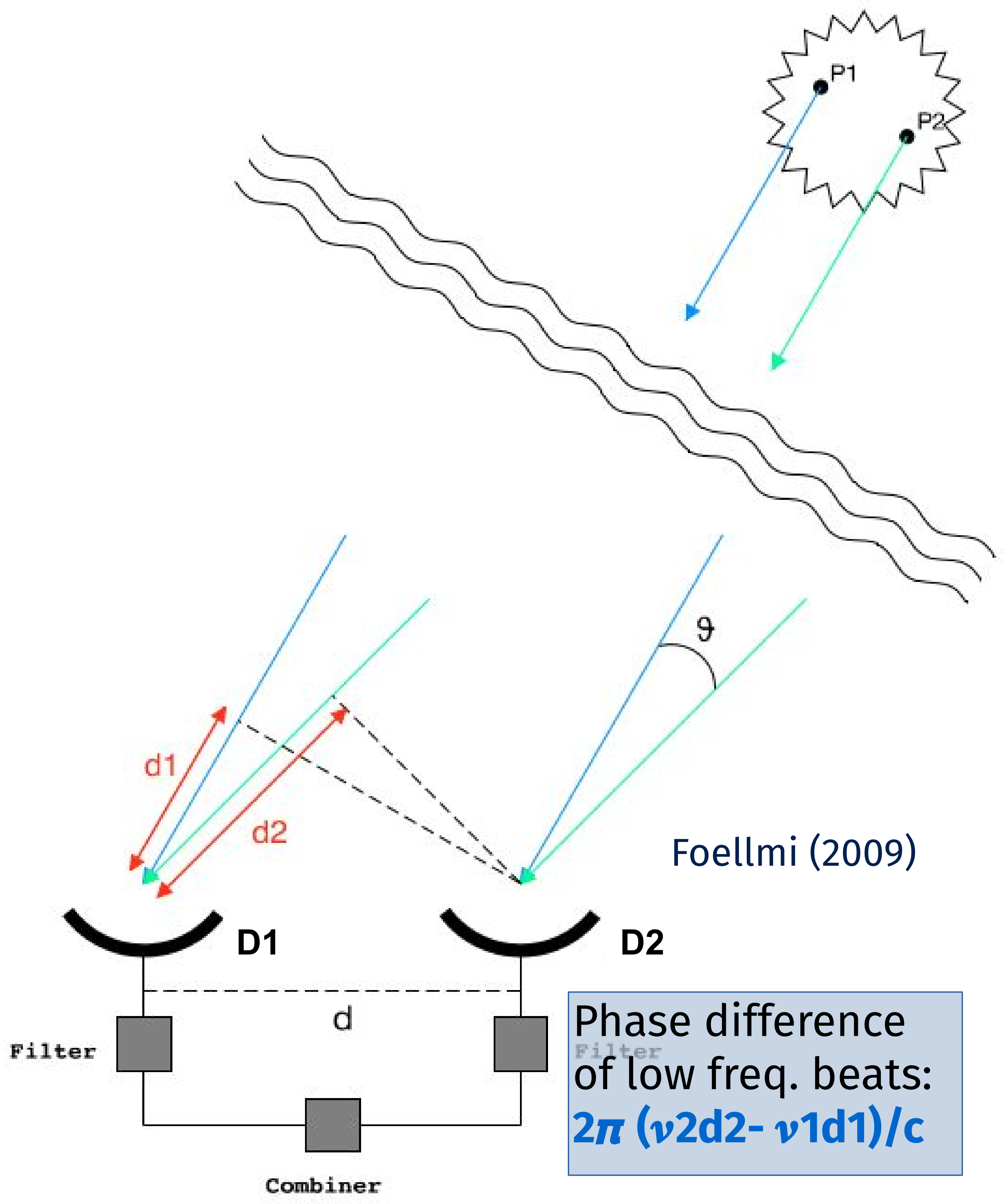
Baseline up to 188 m, with telescopes moving on a circular track so as to maintain the separation constant and normal to the star

From 1963 through 1974 direct interferometric **measurements of the diameters of 32 single stars** of O-F spectral type (Hanbury Brown et al. 1974; Hanbury Brown 1974)

Then, overshadowed by developments in Michelson interferometry...

Explaining SII

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: $2\pi(\nu_2 d_2 - \nu_1 d_1)/c$

Photon Counting Stellar Intensity Interferometry (PC-SII)

Mini-Array

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

Photon counting SII

With detectors **measuring single photon streams**, the correlation can be expressed through the normalized **2nd order correlation function $g^{(2)}$** (Glauber 1963):

$$g^{(2)} = < I_1 I_2 >/[<I_1><I_2>]$$

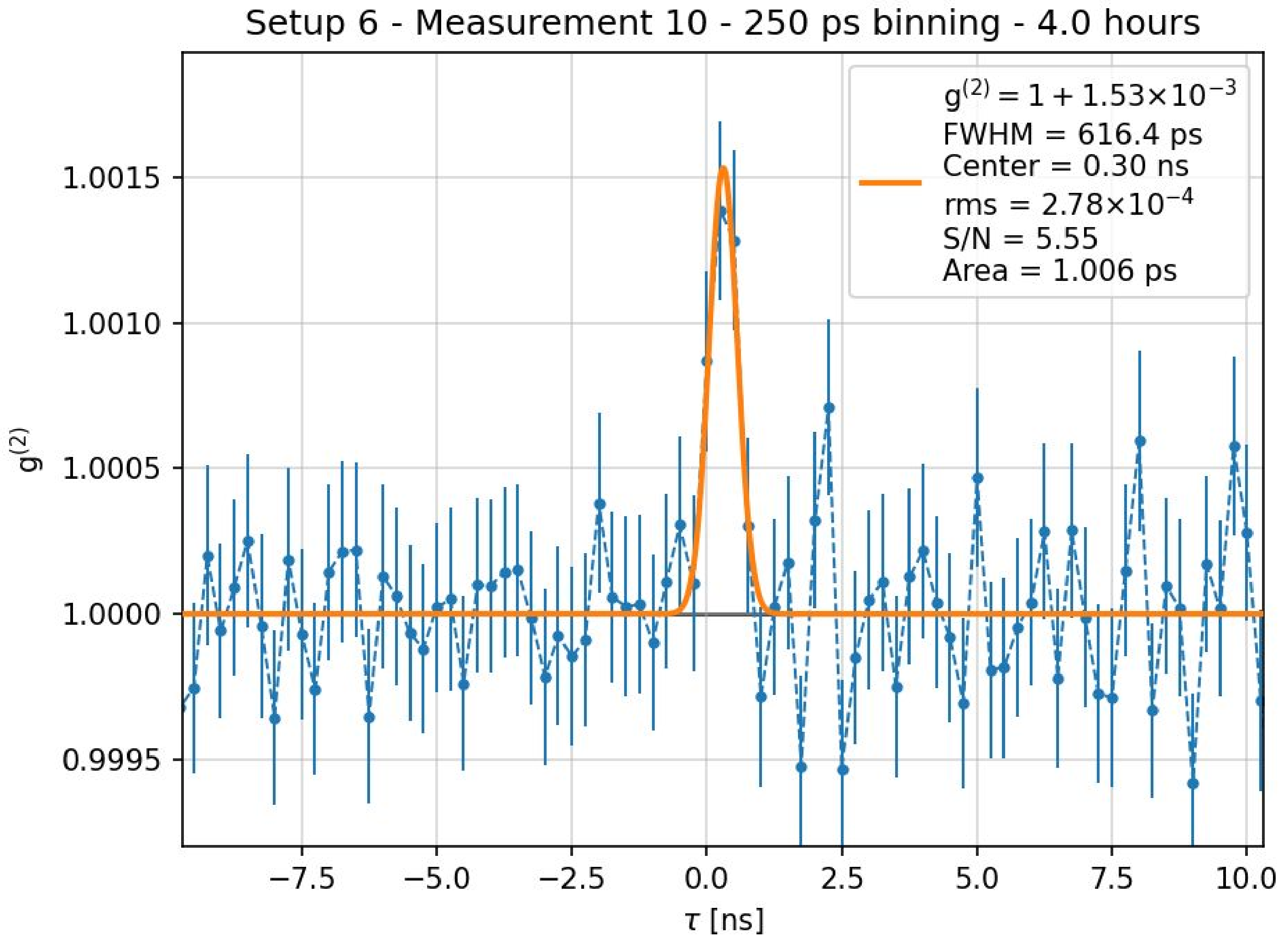
Averaging photon streams in **short time bins dx (detector resolution):**

$$(1/dx) \int g^{(2)}(\tau') d\tau' = N_{12} N/(N_1 N_2)$$

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

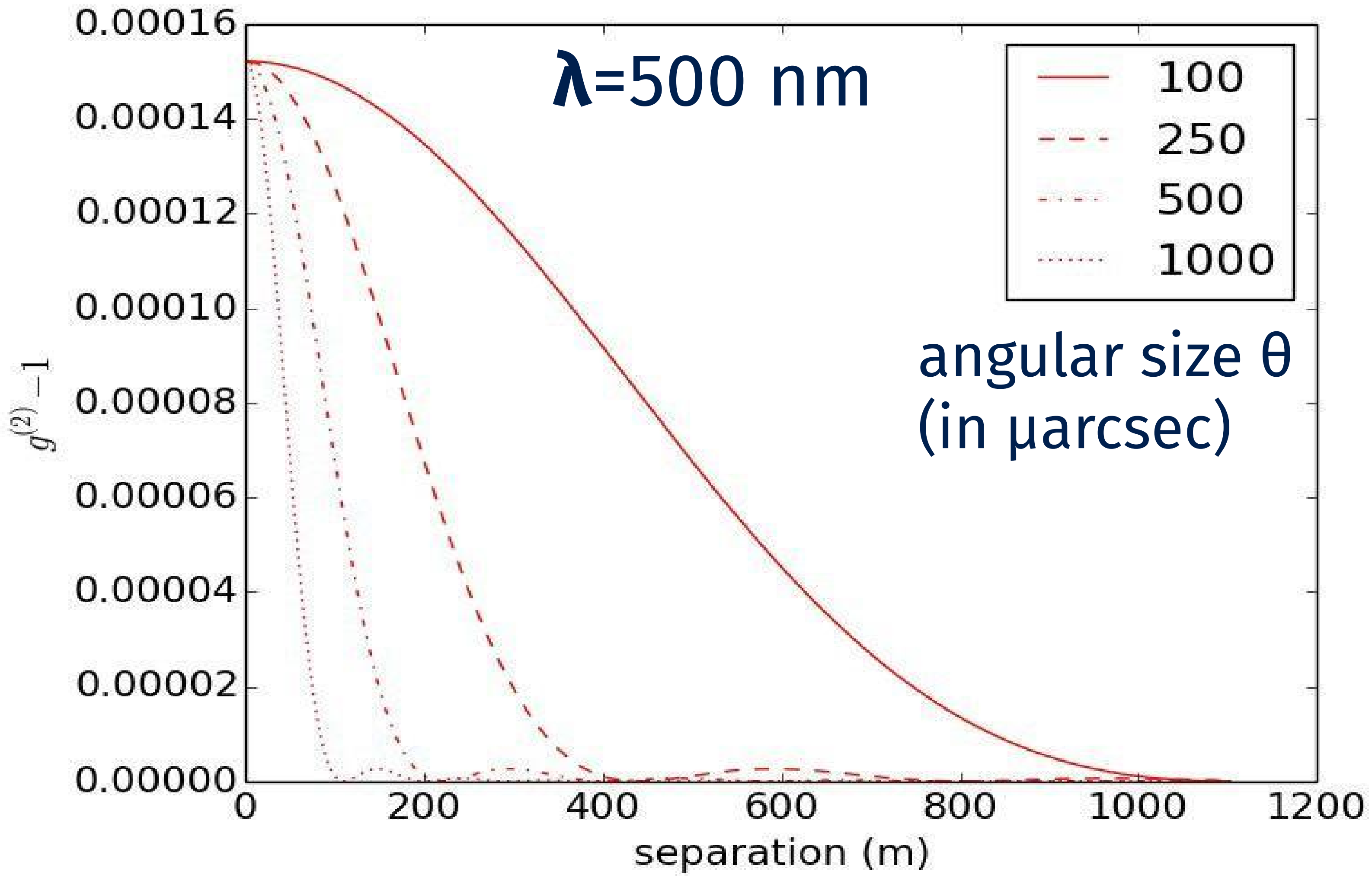
N_{12} = number of simultaneous detections in **dx** (random + quantum excess)

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



As for amplitude interferometry, in the far field **$g^{(2)}$ - 1** is the Fourier transform of the source intensity distribution

To resolve stars with size < sub-mas, 100-1000 m baselines are needed



Availability of a large number of very long (100-1000 m) baselines provided by arrays of Cherenkov Telescopes, and the fact that there is no need to combine light with fraction of a wavelength accuracy led to **renewed interest for SII** (LeBohec & Holder 2005; Dravins et al. 2012, 2013)

SII on Cherenkov Telescopes
Incredible progress made in last years

Renewed interest for SII with arrays of Imaging Atmopsheric Cherenkov Telescopes (IACTs)

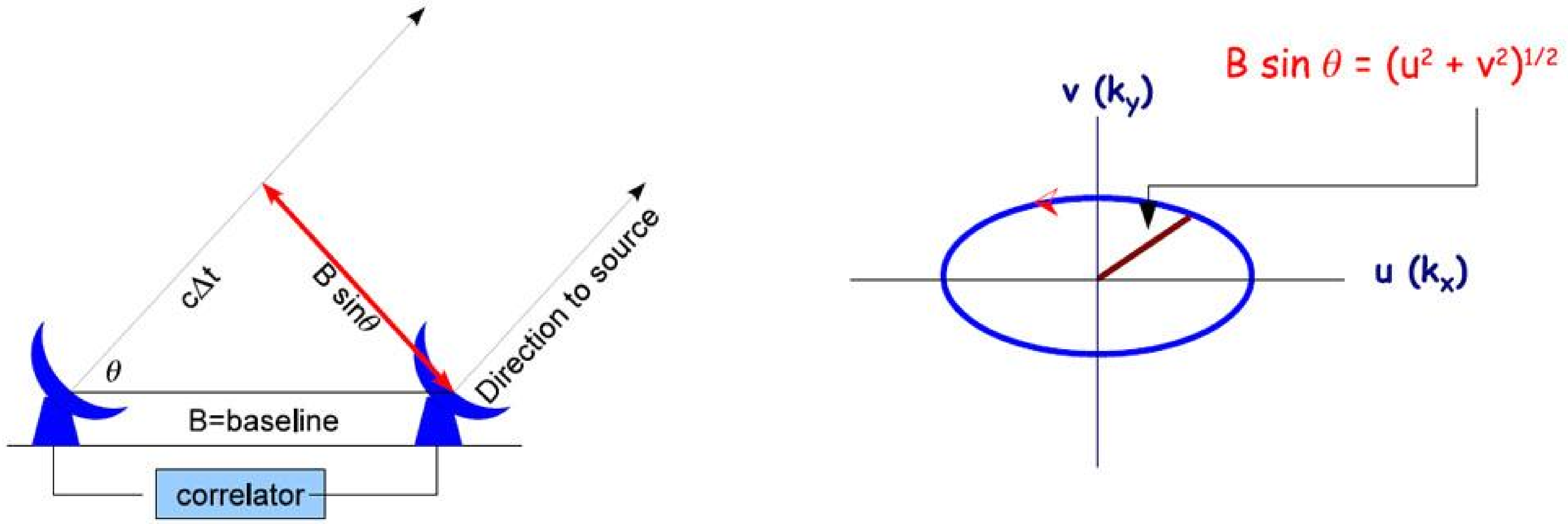
(LeBohec & Holder 2005; Dravins et al. 2012, 2013):

- Possibility of **sub-milliarcsec resolution with ~km baselines** (especially at short/blue wavelengths)
- **Significant number of baselines** available (dense coverage of the u-v plane)
- **Very large collecting area** and photon flux
- **No need** to combine light directly with a **fraction of the wavelength accuracy**
- Technological improvements in detector technology and acquisition electronics (**~ns time resolution**)
- Insensitivity to atmospheric seeing

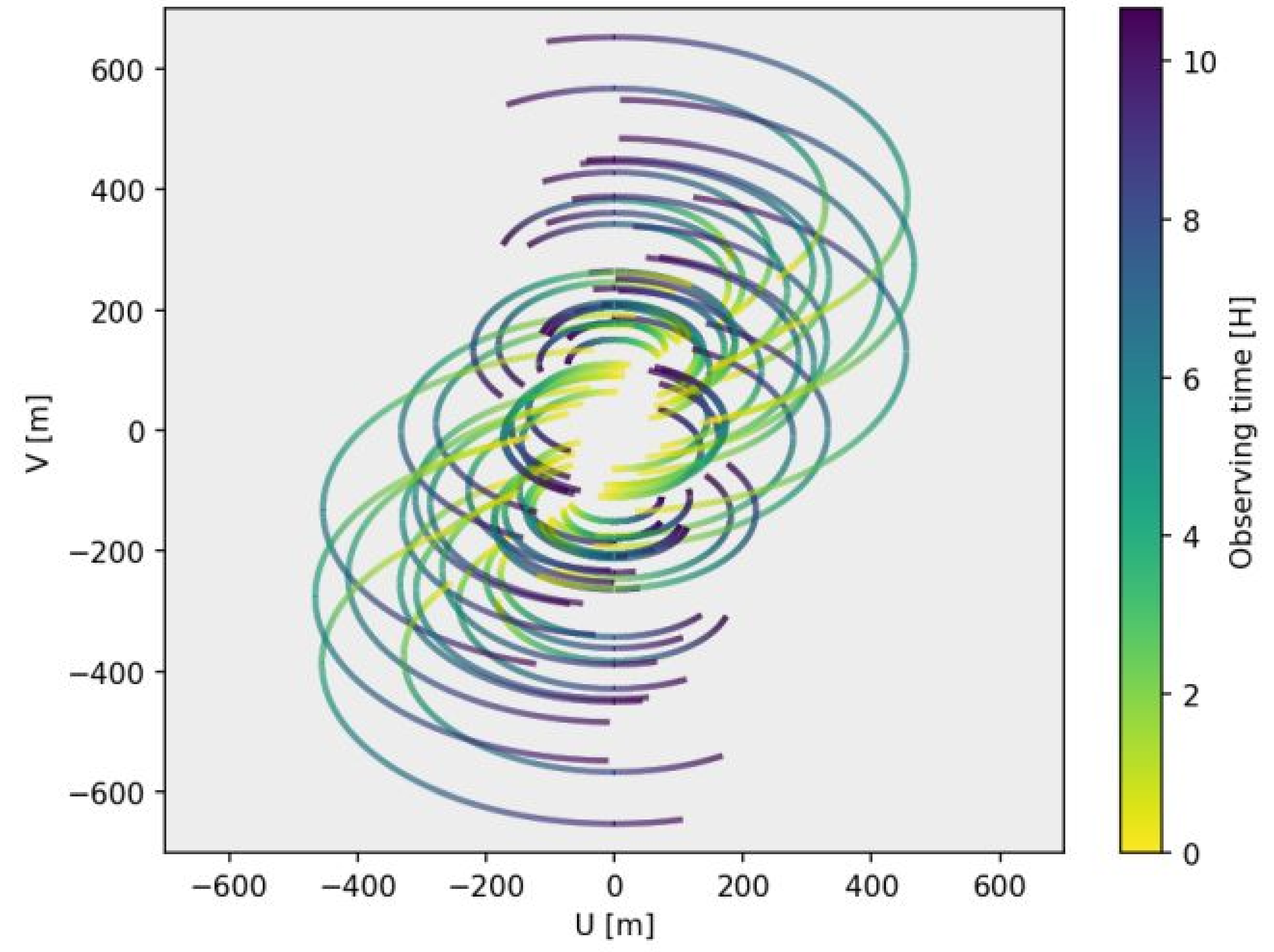
All major IACTs have implemented or are implementing SII and the rate of progress is impressive

Acciari et al. 2020; Abeysekara et al. 2020; Zmija et al. 2022, 2024; Abe et al. 2024; Acharyya et al. 2024; Archer et al. 2025; Vogel et al. 2025; Jiménez Martínez et al. 2025; Zampieri et al. 2026

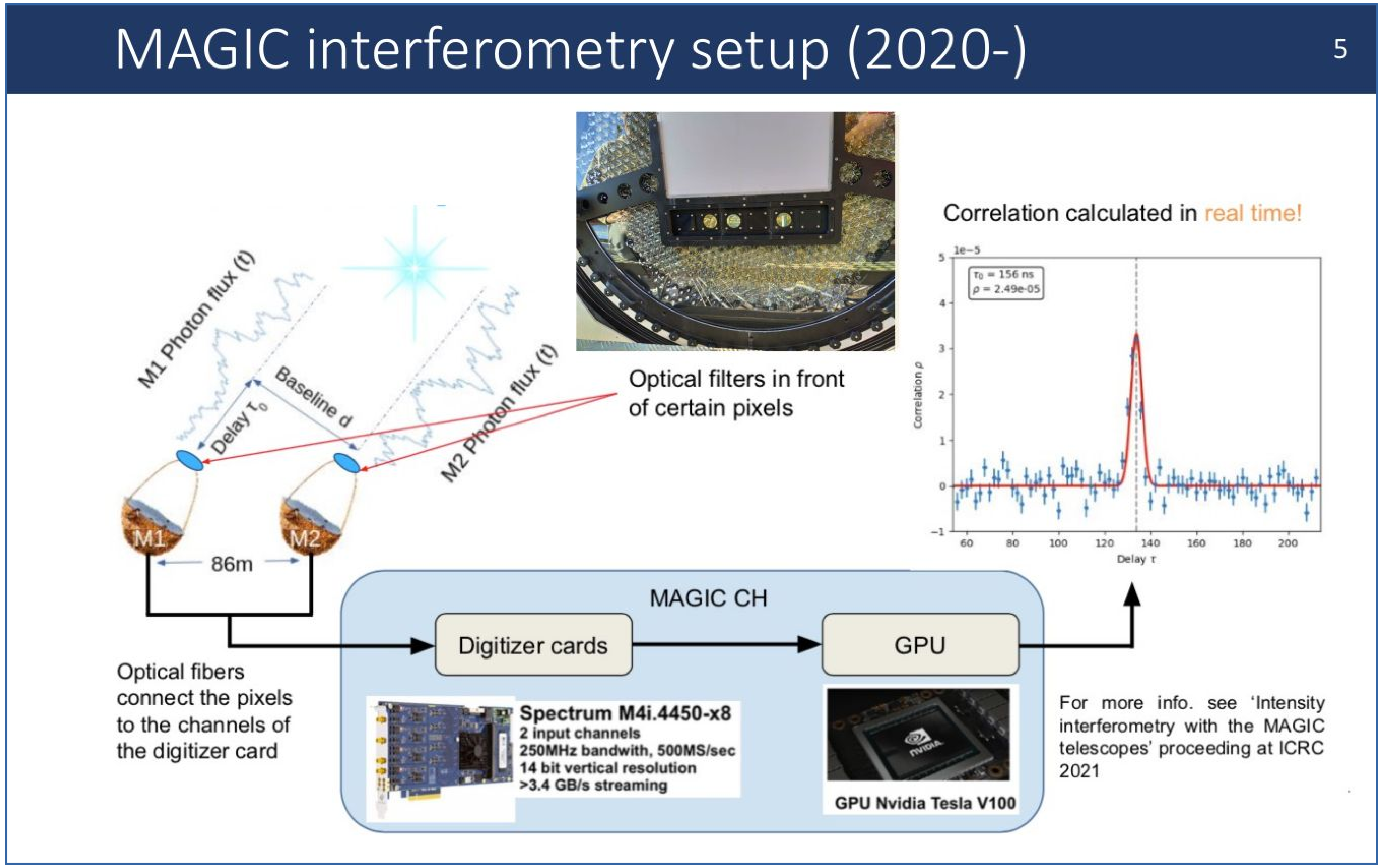
Interferometric u-v plane



ASTRI u-v plane 1 night coverage



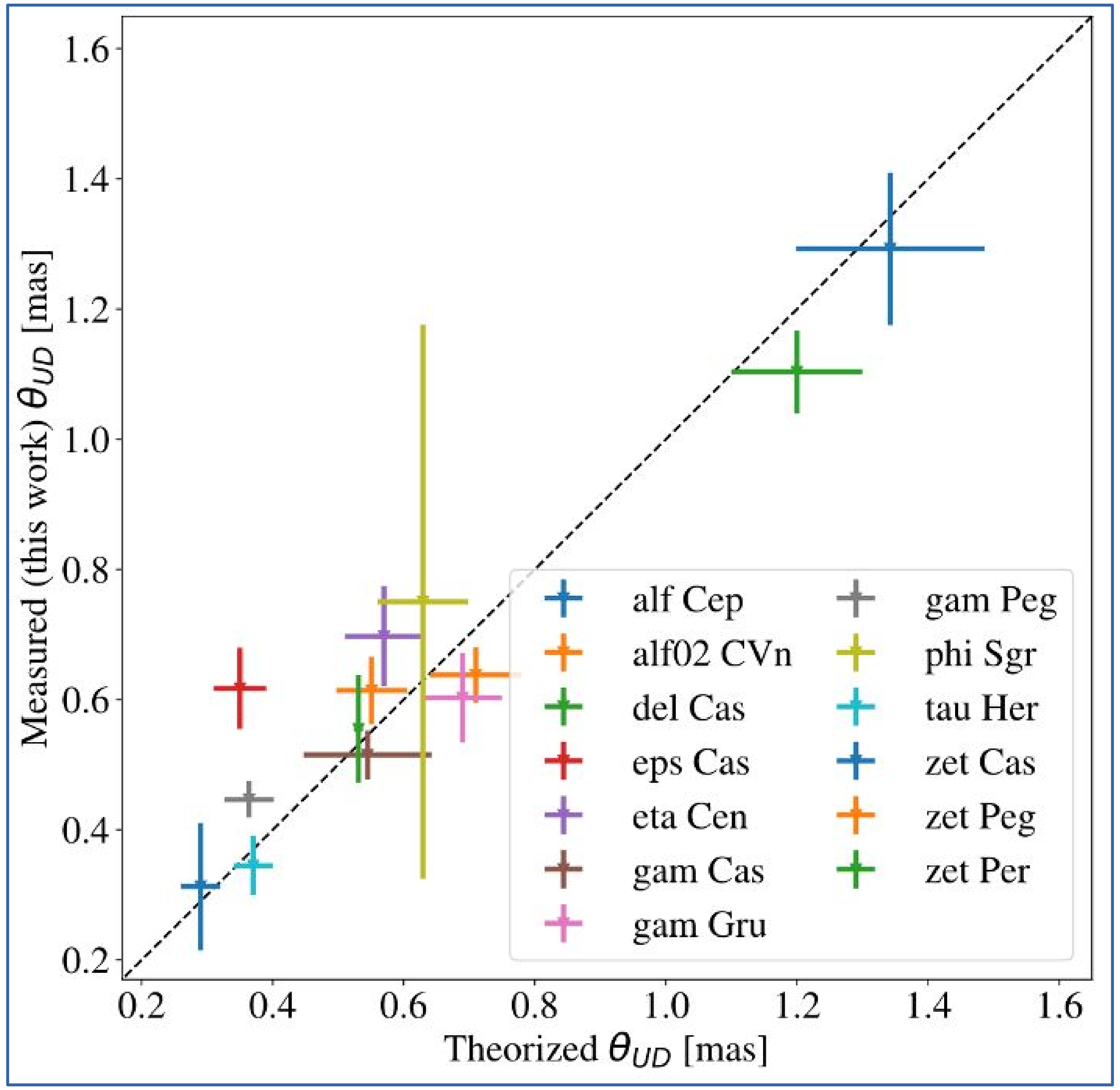
MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov) Telescopes



Credit: J. Cortina

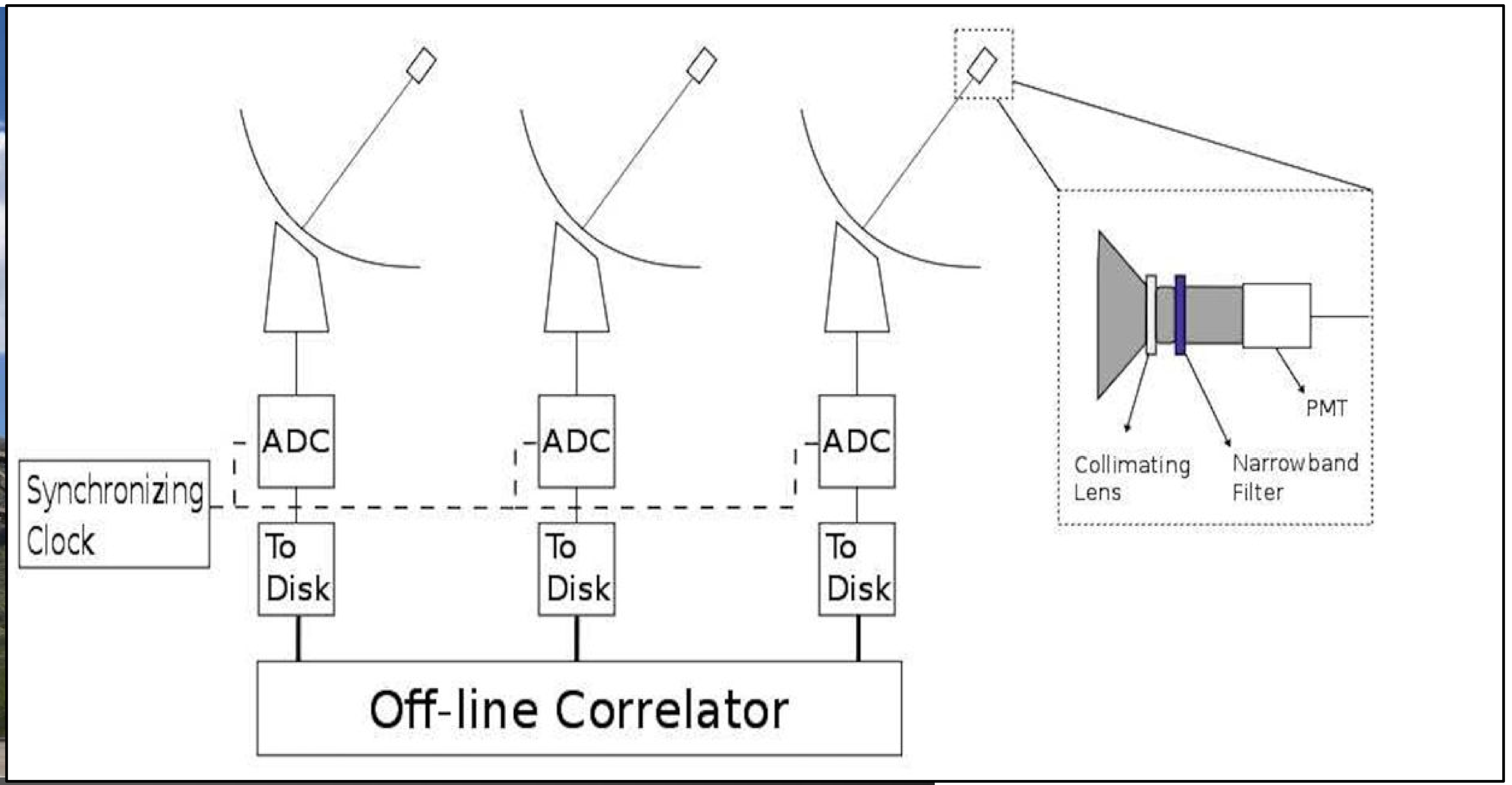
MAGIC successfully implemented SII and tested it (Acciari et al. 2020)

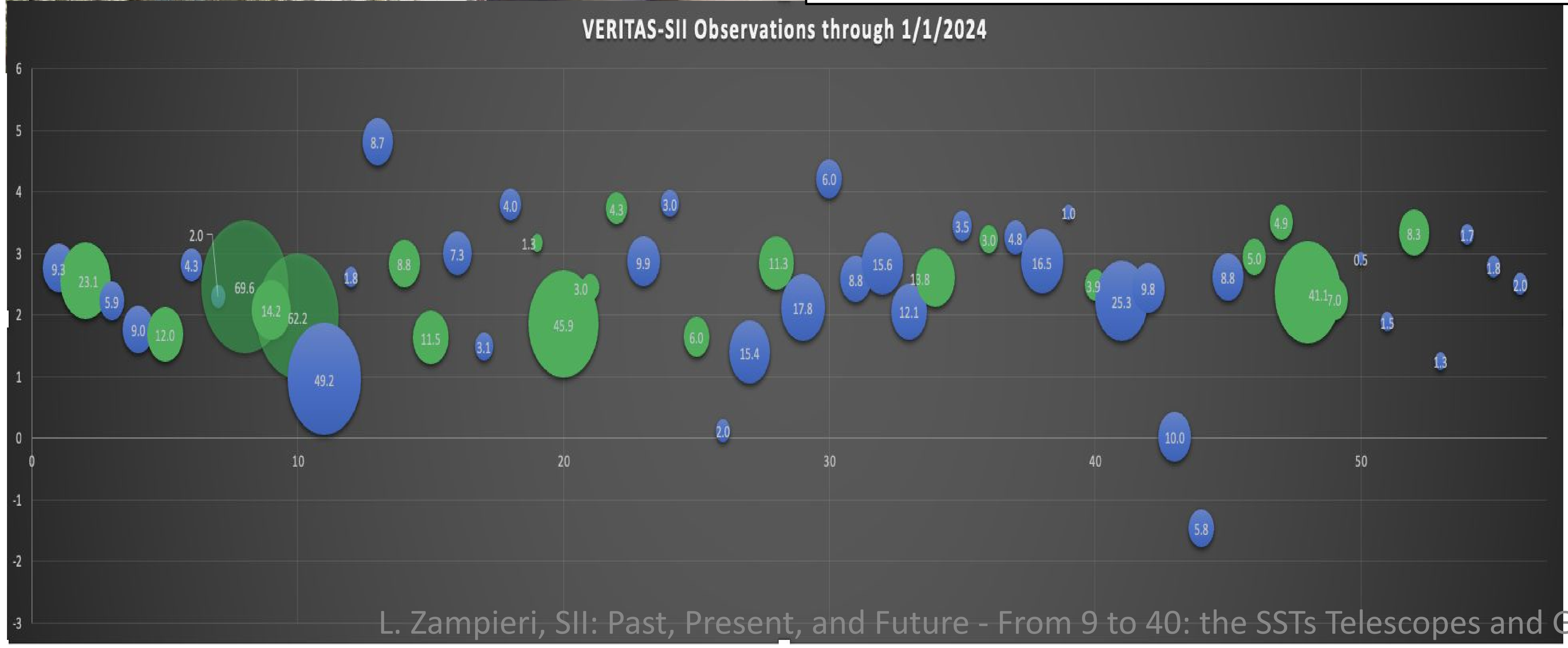
First science results with full instrument recently published in Abe et al. (2024)



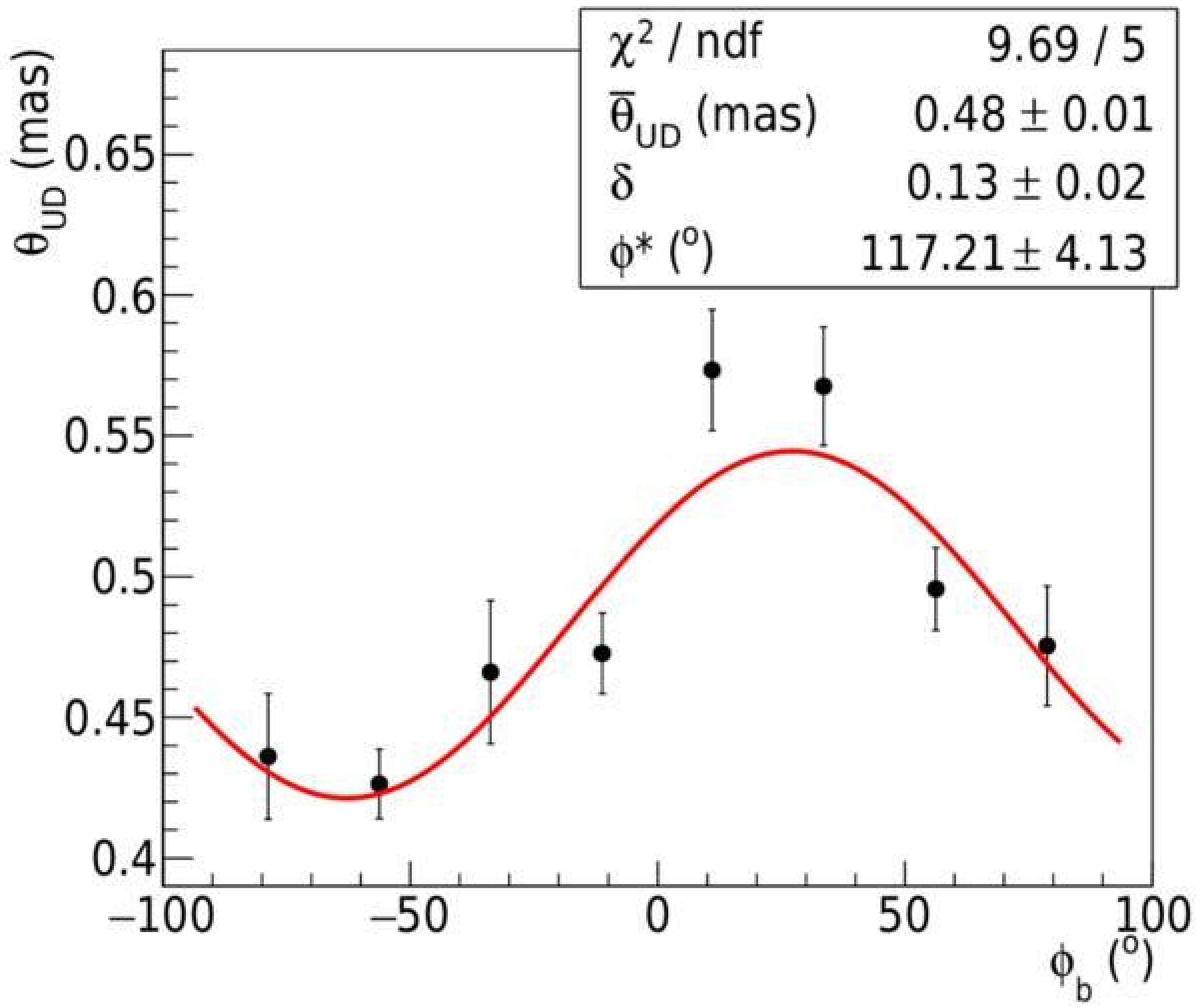
VERITAS (Very Energetic Radiation Imaging Telescope Array System)

VERITAS successfully implemented SII (Abeysekara et al. 2020) obtaining new results (Acharyya et. al 2024)



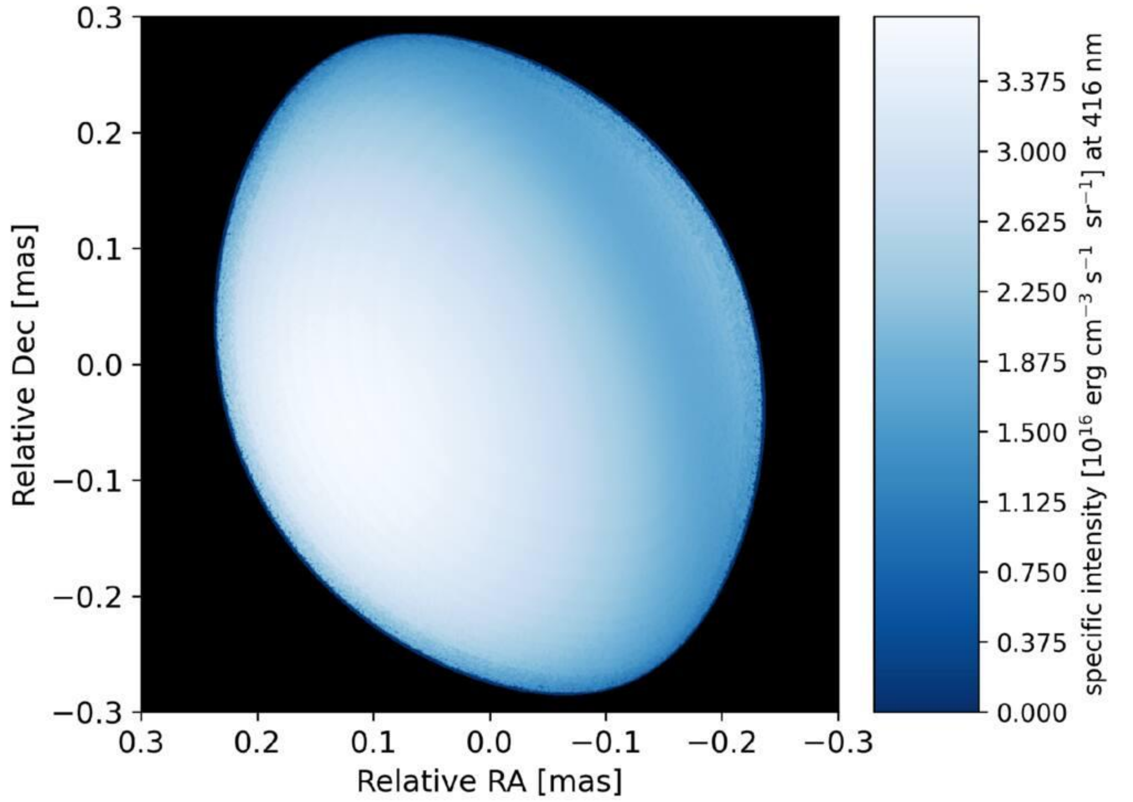


Gamma Cassiopeiae
(Archer et al. 2025)



Uniform-disk fit of g2 versus baseline in different angular slices on the u–v plane

First measurement of the **oblateness of the photosphere of a fast rotator** with SII



H.E.S.S. (High Energy Stereoscopic System)

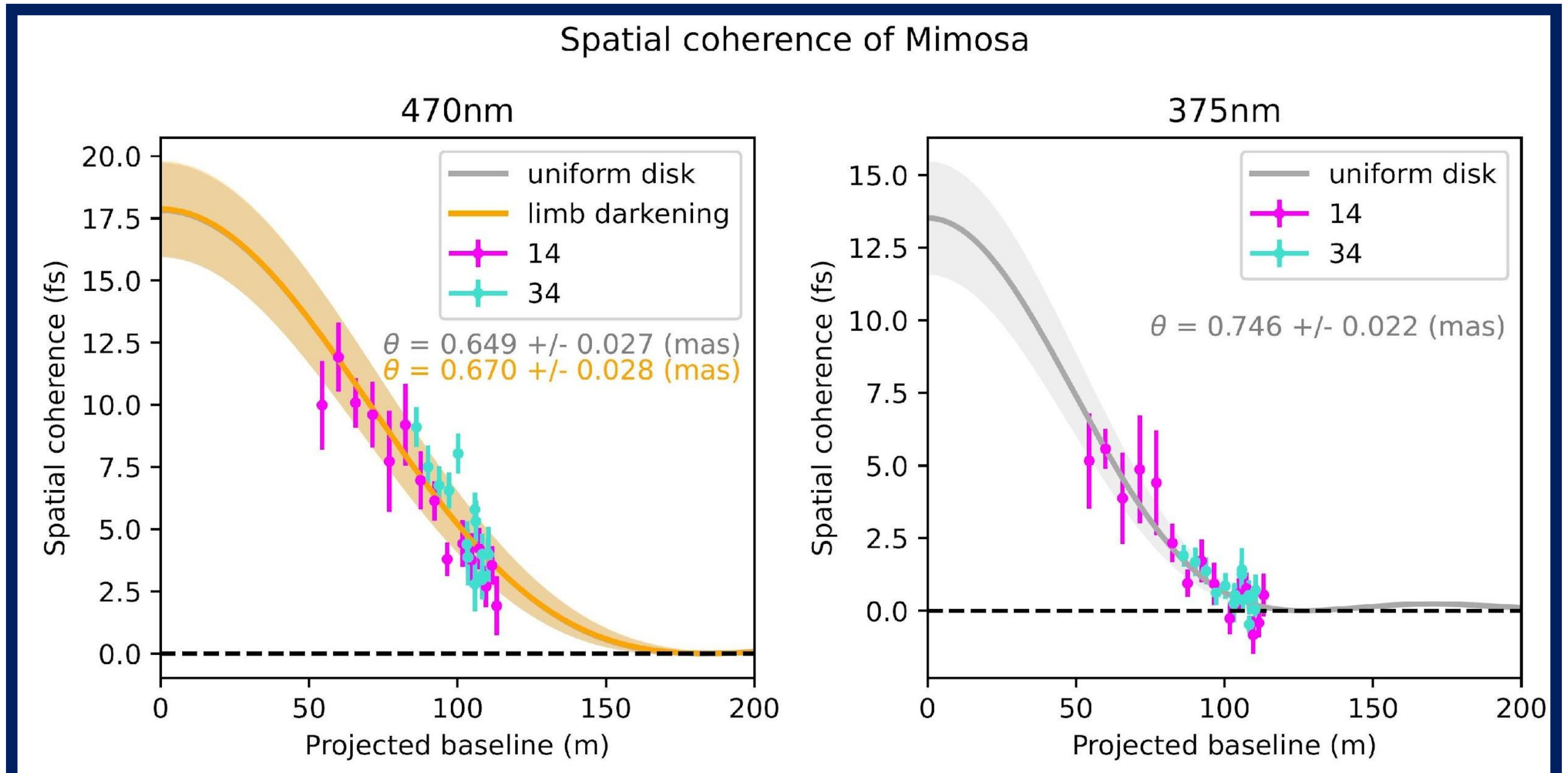
Motorized external setup is mounted to the lid of the Cherenkov camera

- Correct for telescope mispointing
- Toggle between gamma-ray and SII within minutes

2023: simultaneous two-color measurements

5 measurements of stellar diameters (Zmija et al. 2024; Vogel et al. 2025)

Source	Mimosa (Beta Crux)
Magnitude (mag)	1.2
HBT diameter (mas)	0.702 +/- 0.022
HBT Time (h)	178.7
HESS Time (h)	6.5



700 m

ASTRI (Astrofisica con Specchi a Tecnologia Replicante Italiana) Mini-Array

Mini-Array

The **ASTRI Mini-Array** is under completion at El Teide (Scuderi et al. 2022, 2026; all 9 telescopes are on site) and provides a suitable infrastructure for performing **SII observations on many (up to 36), long (up to ~700 m) baselines**

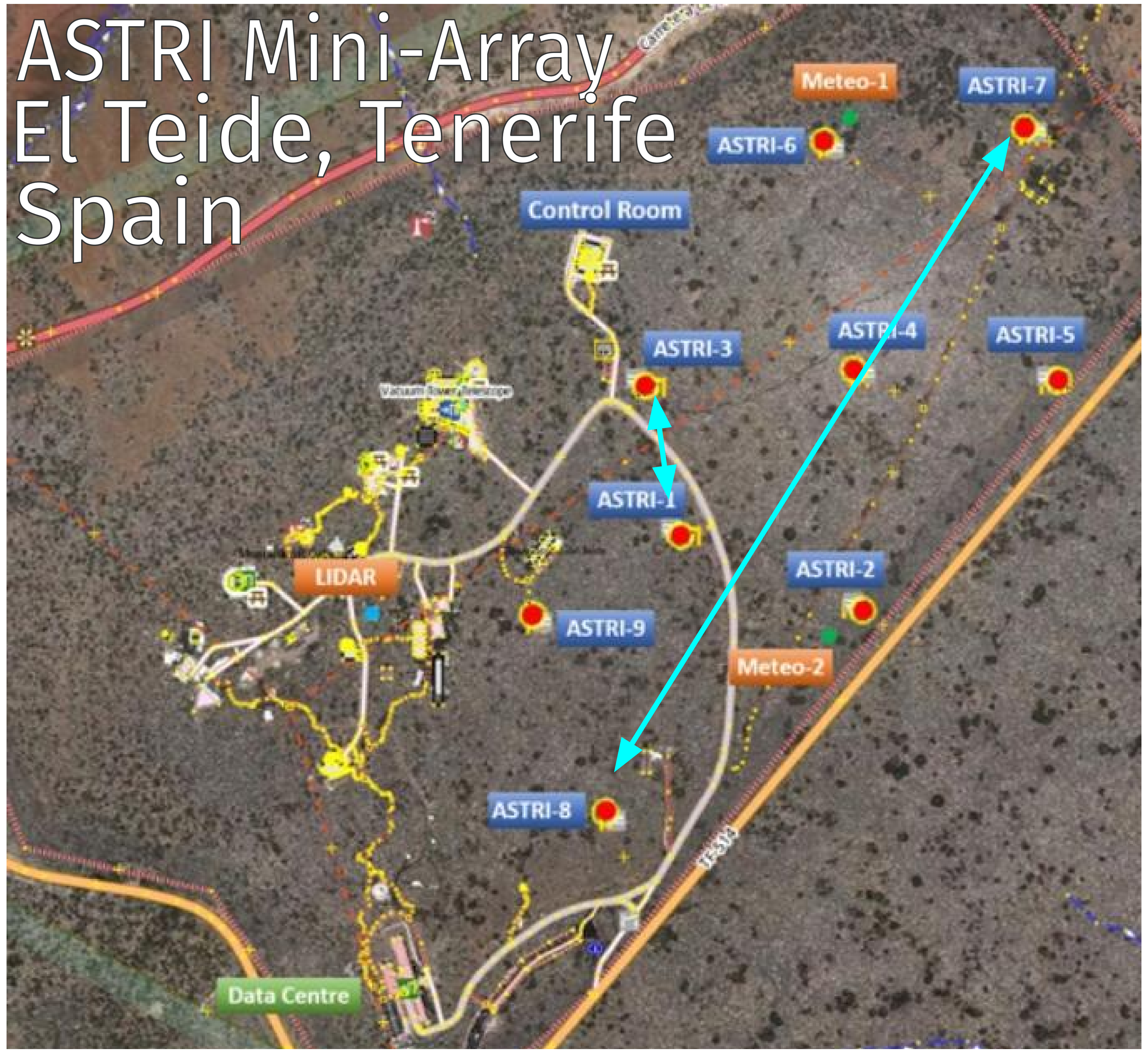
Telescopes are being equipped with the **Stellar Intensity Interferometry Instrument (SI3)** (Zampieri et al. 2022, 2024, 2026)

3 units successfully integrated between Nov 2025 and Apr 2026 (see **Michele's talk**)

SI3 is made of 3 modules:

- **Focal Plane Module**
- **Otical Module +Front End Electronics**
- **Back End Electronics**

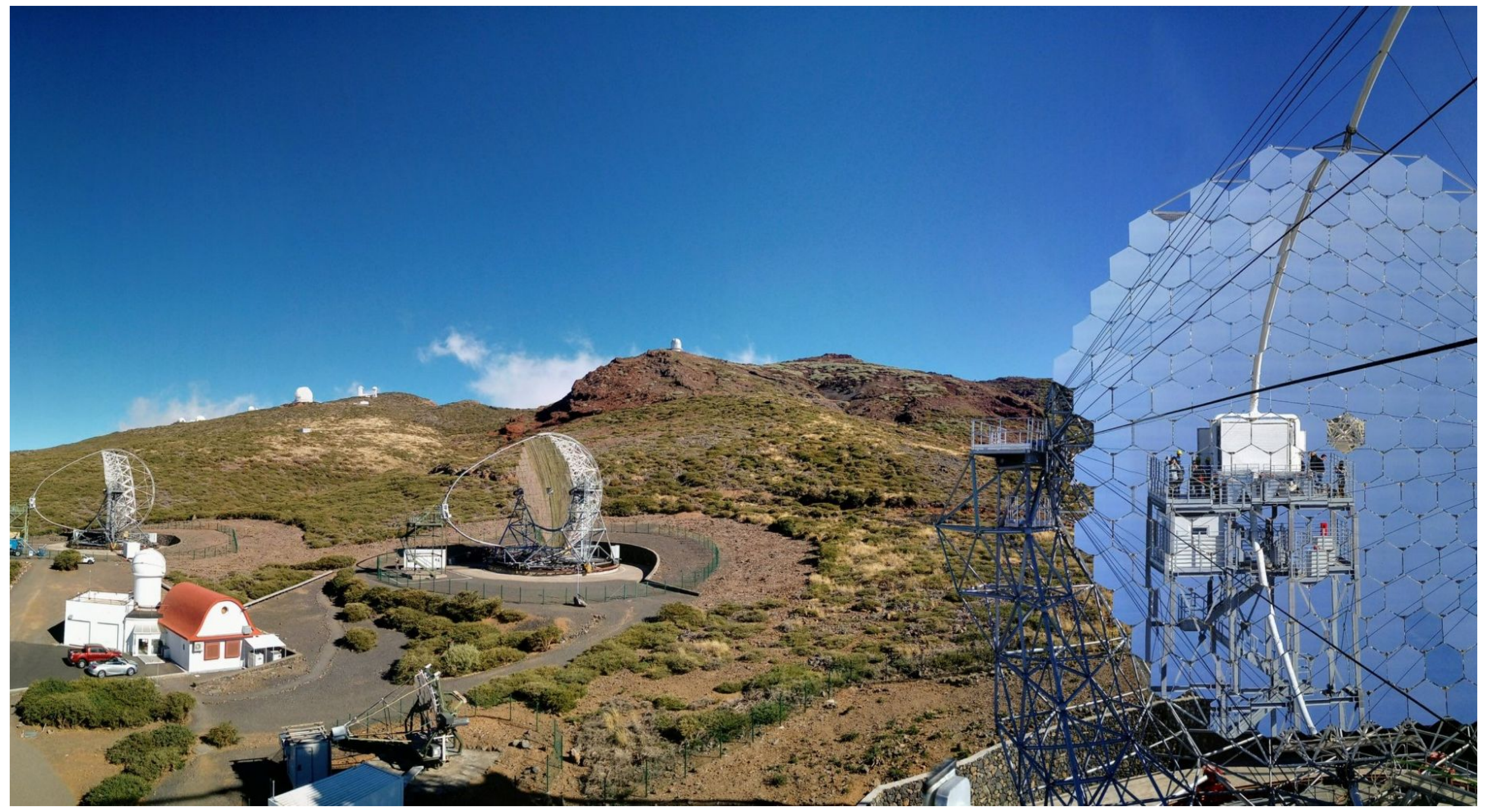
Goal: designed to implement **very narrow-band, sub-ns, PC-SII**

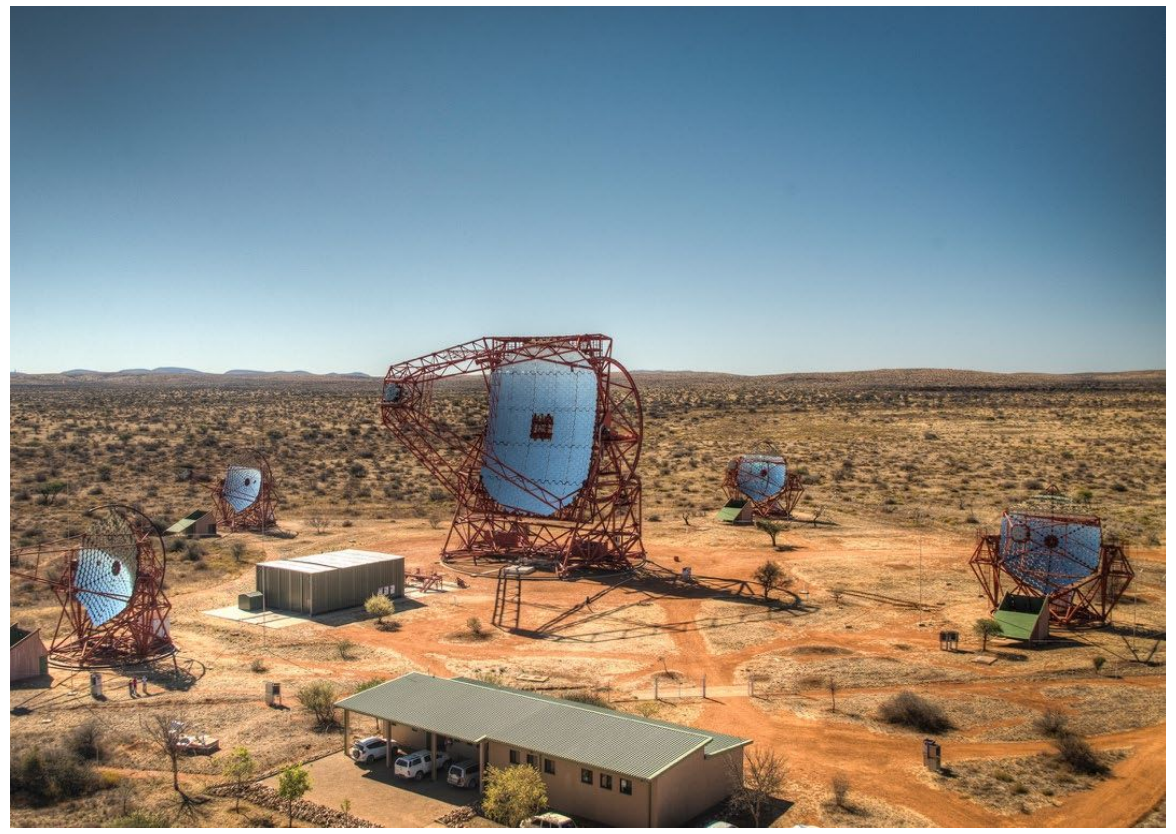


The **ASTRI Mini-Array** is an International collaboration, led by the Italian National Institute for Astrophysics (INAF), that is constructing and operating an array of nine Imaging Atmospheric Cherenkov Telescopes to study gamma-ray sources at very high energy (TeV) and **perform optical stellar intensity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

SII on Cherenkov Telescopes
Current implementation modes

MAGIC	Intensity corr.	on-line	freq. domain	no opt. module	PMT-res.	Well experimented
HESS	Intensity corr.	off-line	freq. domain	with opt. module	PMT-res.	
VERITAS	Intensity corr.	off-line	time/freq. dom.	with opt. module	PMT-res.	
ASTRI	Photon-coinc.	off-line	time domain	with opt. module	sub-ns res.	Implement.





Future improvements will be in the direction of optical telescopes, allowing for potential synergies with them

Optical telescopes (e.g. I2C): Photon-coinc., on-line, time domain, with opt. module, sub-ns res.

SII: Science Cases

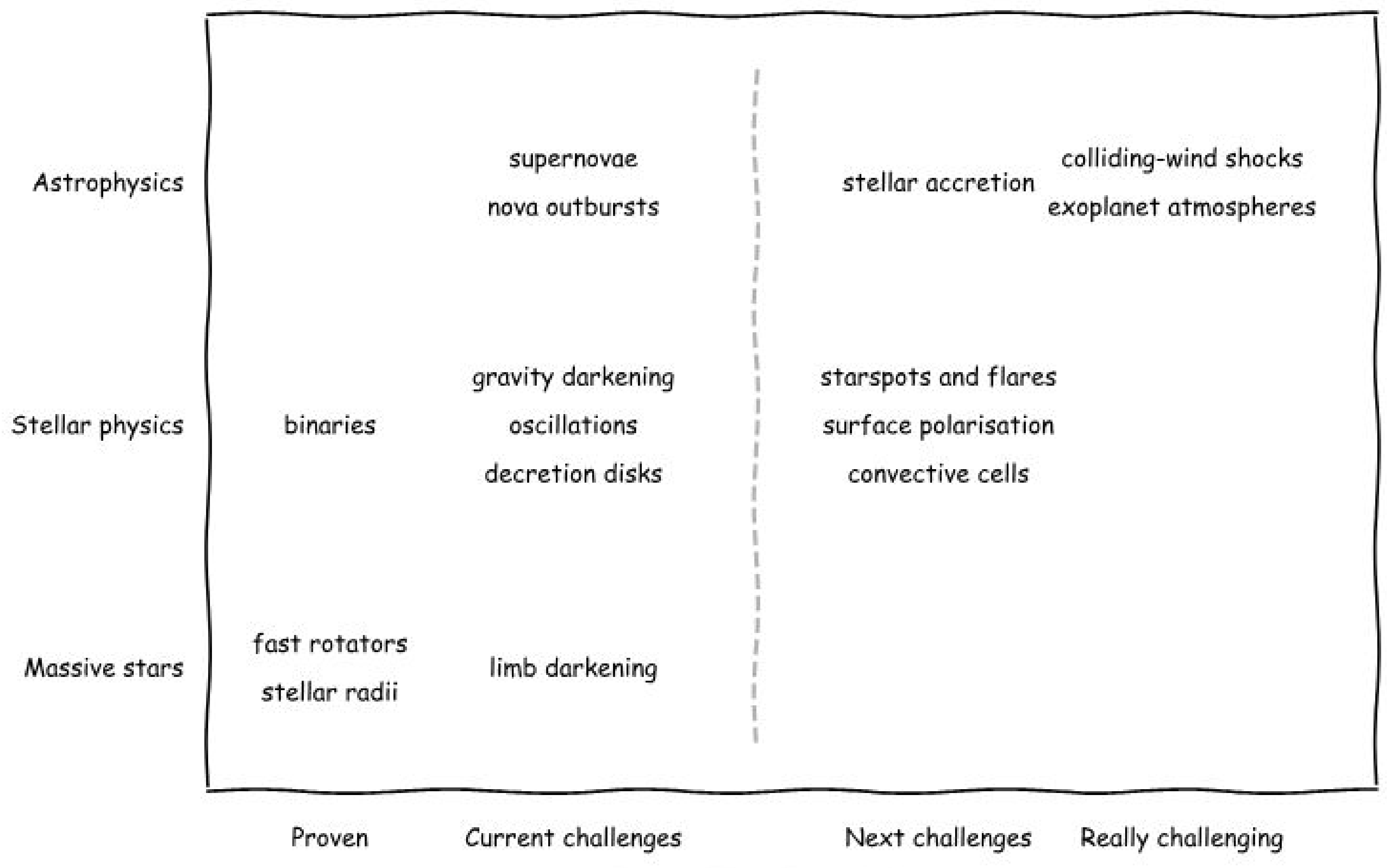
Measurement of stellar radii has an **all-pervasive impact on stellar astrophysics**

SII radii provide tests and/or constraints on stellar structure models and, combined with other (e.g spectroscopic) data, they lead to age and/or distance determinations

- **VERITAS**: a catalog of stellar radii is in preparation (Kieda et al. 2026)
- **MAGIC**: 22 stellar diameters, 13 with no prior measurements (Abe et al. 2024)
- **H.E.S.S.**: five stellar diameters of stars in the Southern sky in two bands simultaneously (Zmija et al. 2024)

Event Horizon Telescope-like angular resolution ($\lesssim$ 100 μarcsec) for stars

Going beyond stellar radii…

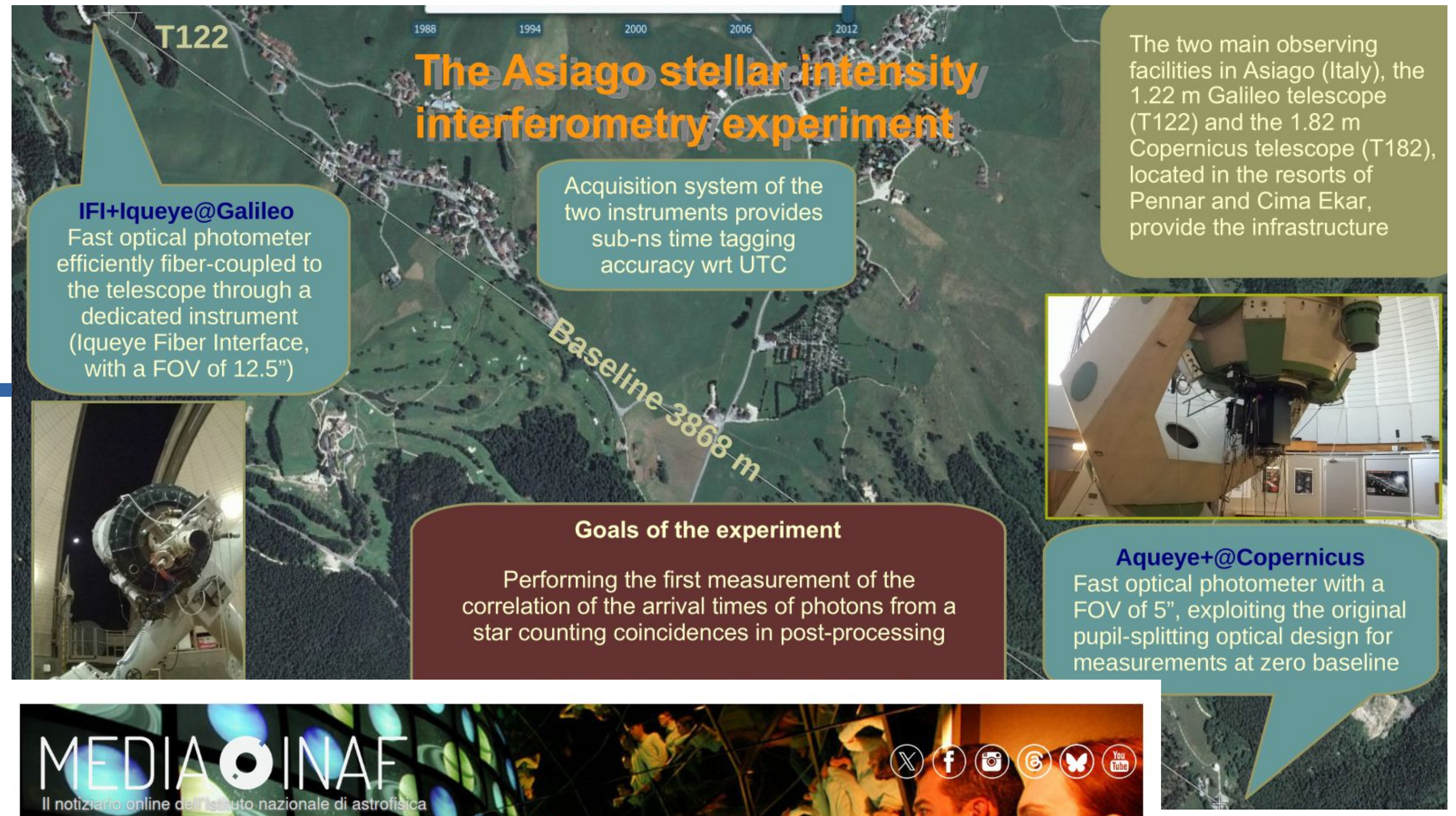


Credit: P. Saha
SII with CTAO, White Paper, 2026

SII on optical telescopes

Advanced SII instruments/implementations on optical-quality telescopes:

- Copernicus and Galileo telescopes at the **Asiago Observatory**, equipped with Aqueye+ and IFI+Iqueye (Zampieri et al. 2016, 2021)
- Telescopes of the C2PU at the **Observatoire de la Côte d'Azur** in Calern, near Nice (Guerin et al. 2017, 2018)
- Two/three mobile telescopes at **Southern Connecticut State University**, New Haven (Horch et al. 2022)
- Single 50 cm diameter telescope at the **University of Erlangen-Nürnberg**, Bamberg (Karl et al. 2024)

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I RISULTATI SU MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY

Contare i fotoni per "zoomare" sulle stelle

Un gruppo di ricercatori dell'Istituto nazionale di astrofisica e dell'Università di Padova ha dimostrato la fattibilità di un metodo per lo studio di stelle brillanti contando uno ad uno i fotoni provenienti dalla stella Vega con i due telescopi da 1,8 e 1,2 metri dell'Osservatorio di Asiago. Questa tecnica potrà essere utilizzata in futuro da osservatori come Astri Mini-Array per catturare dettagli sulle superfici stellari con risoluzione mai raggiunta in banda ottica

Ufficio stampa Inaf 16/07/2021

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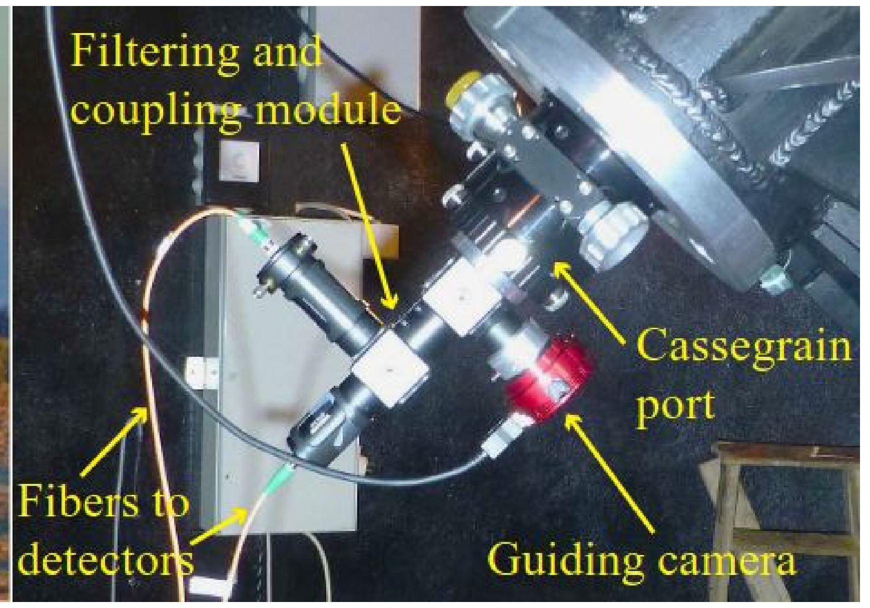
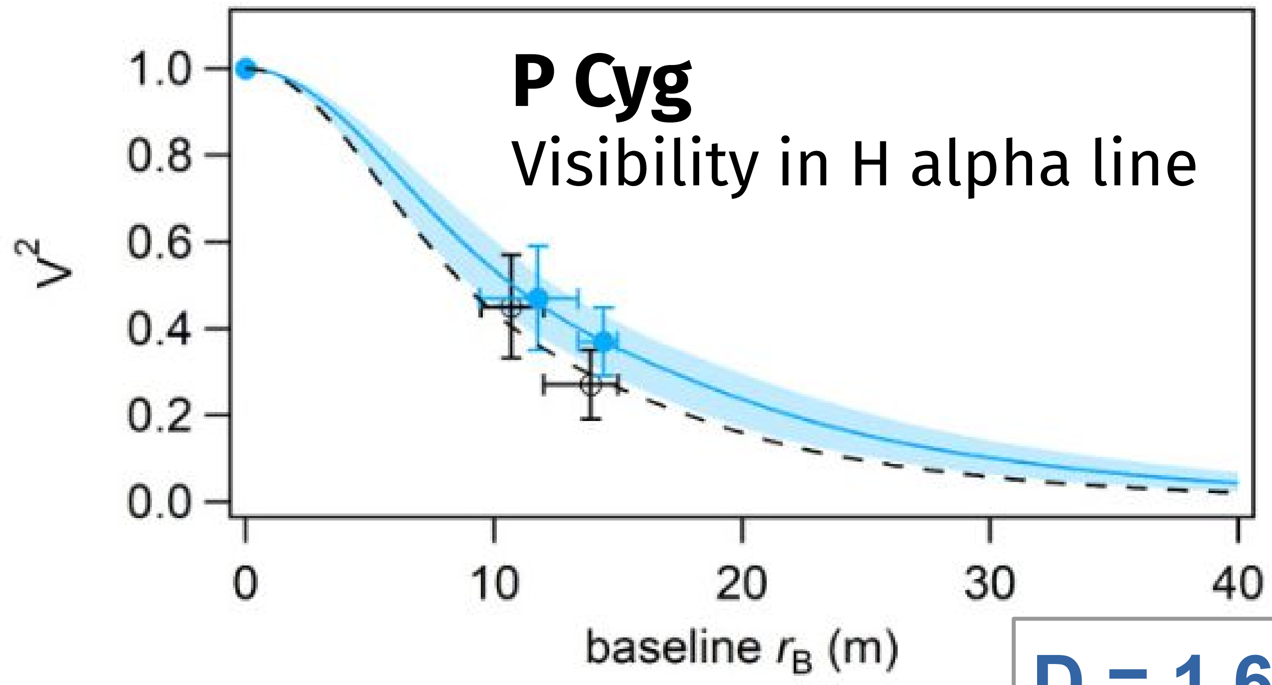
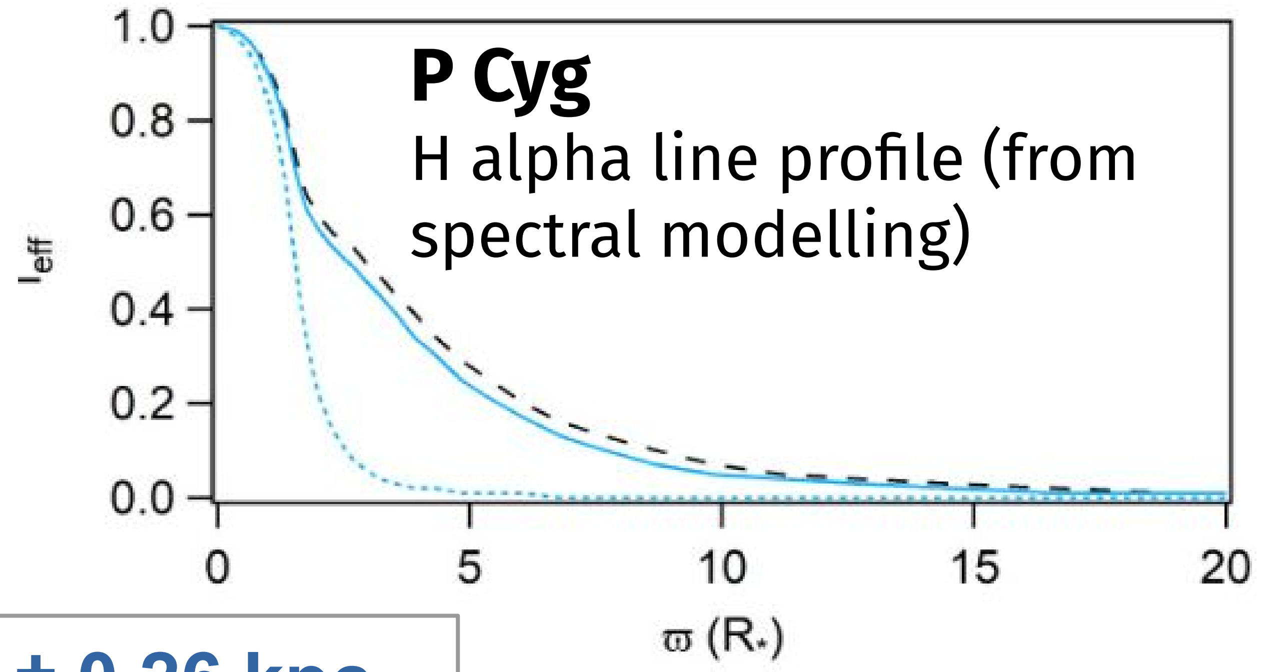


New measurements of **stellar radii** (Vega, Rigel, P Cyg) and **distances** (Rivet et al. 2020; de Almeida et al. 2022; Matthews et al. 2023)

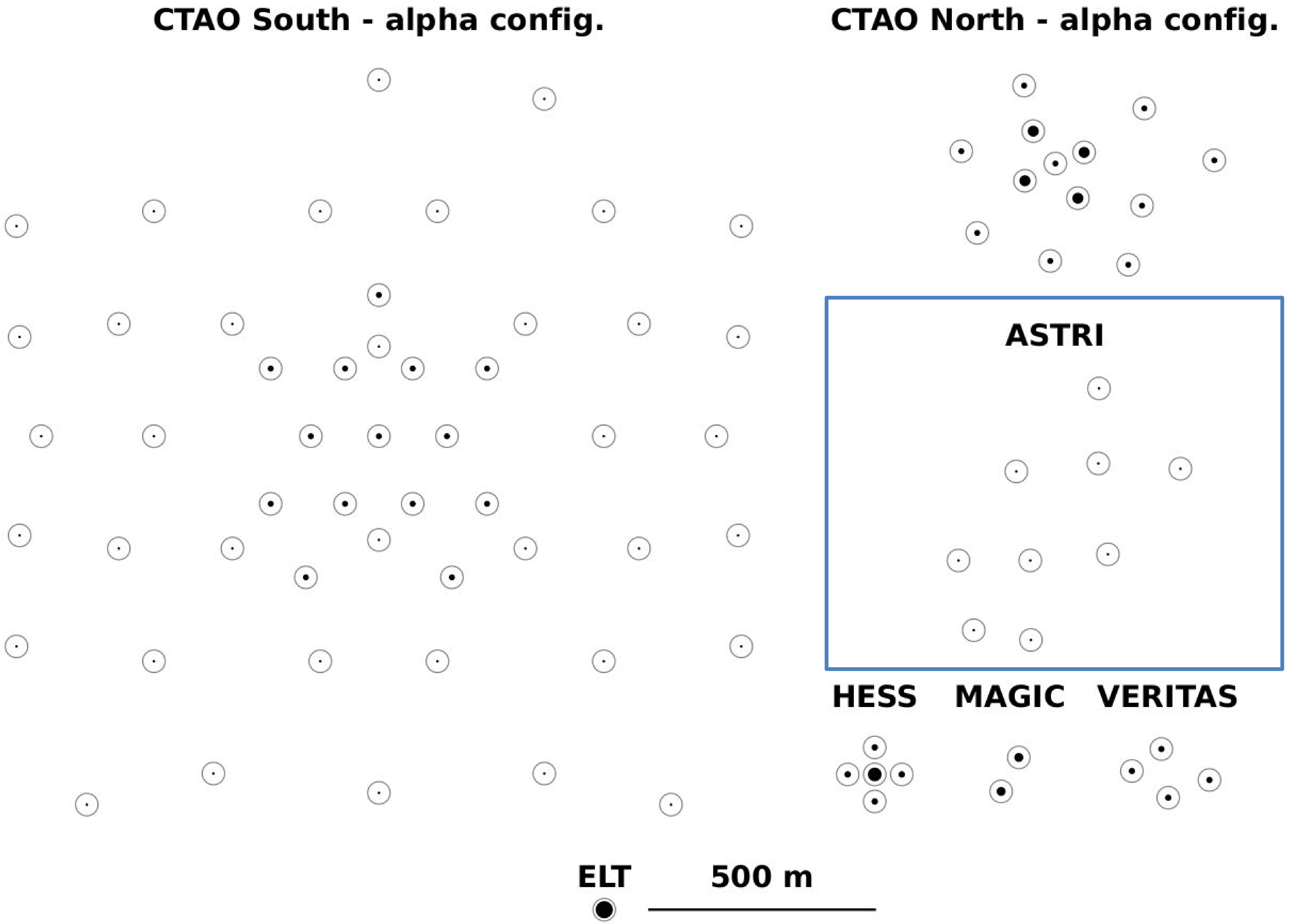




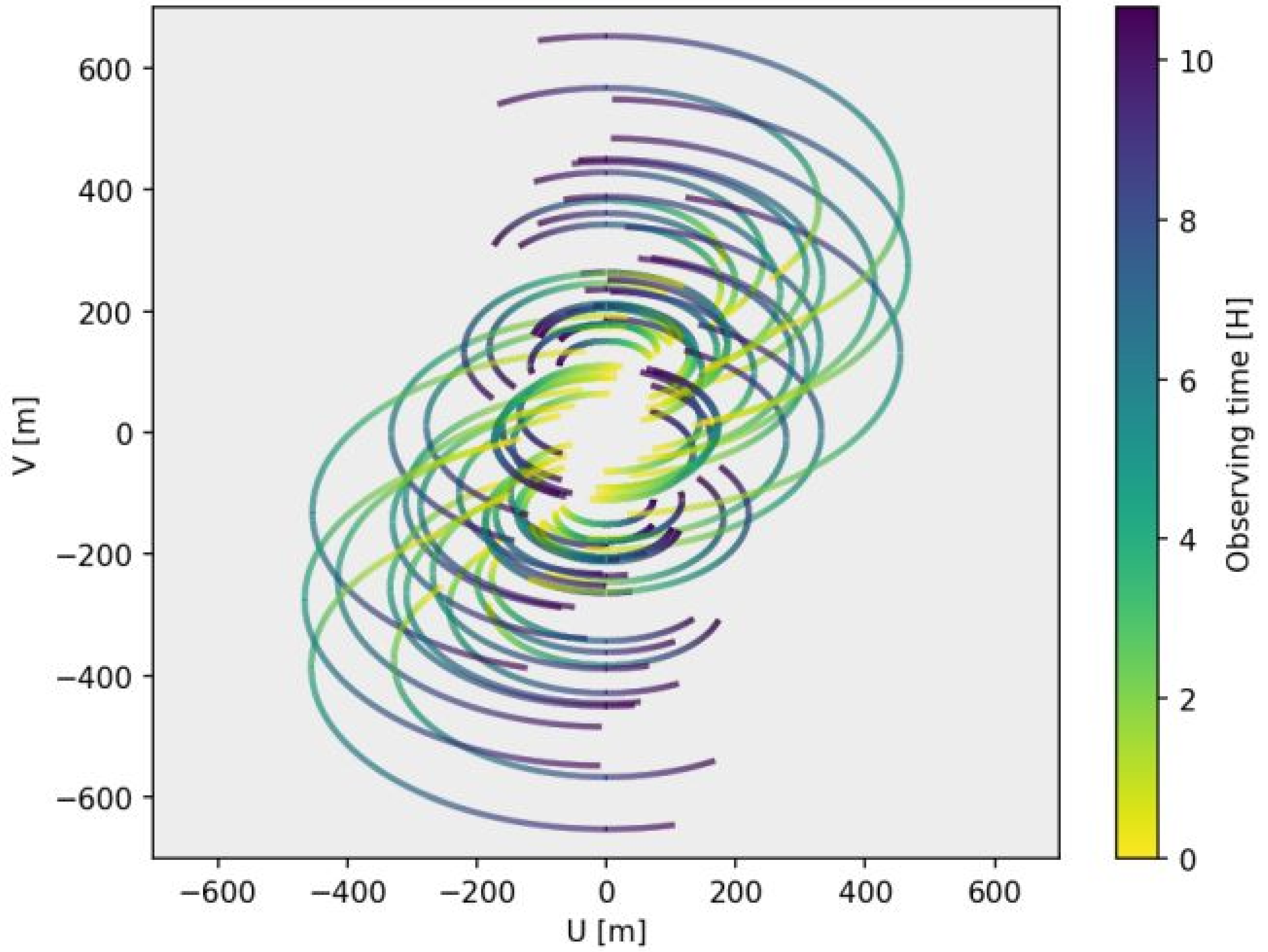
D = 1.67 ± 0.26 kpc

SII on Cherenkov Telescopes: Future Prospects
Increasing angular resolution and U-V coverage

Mini-Array



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

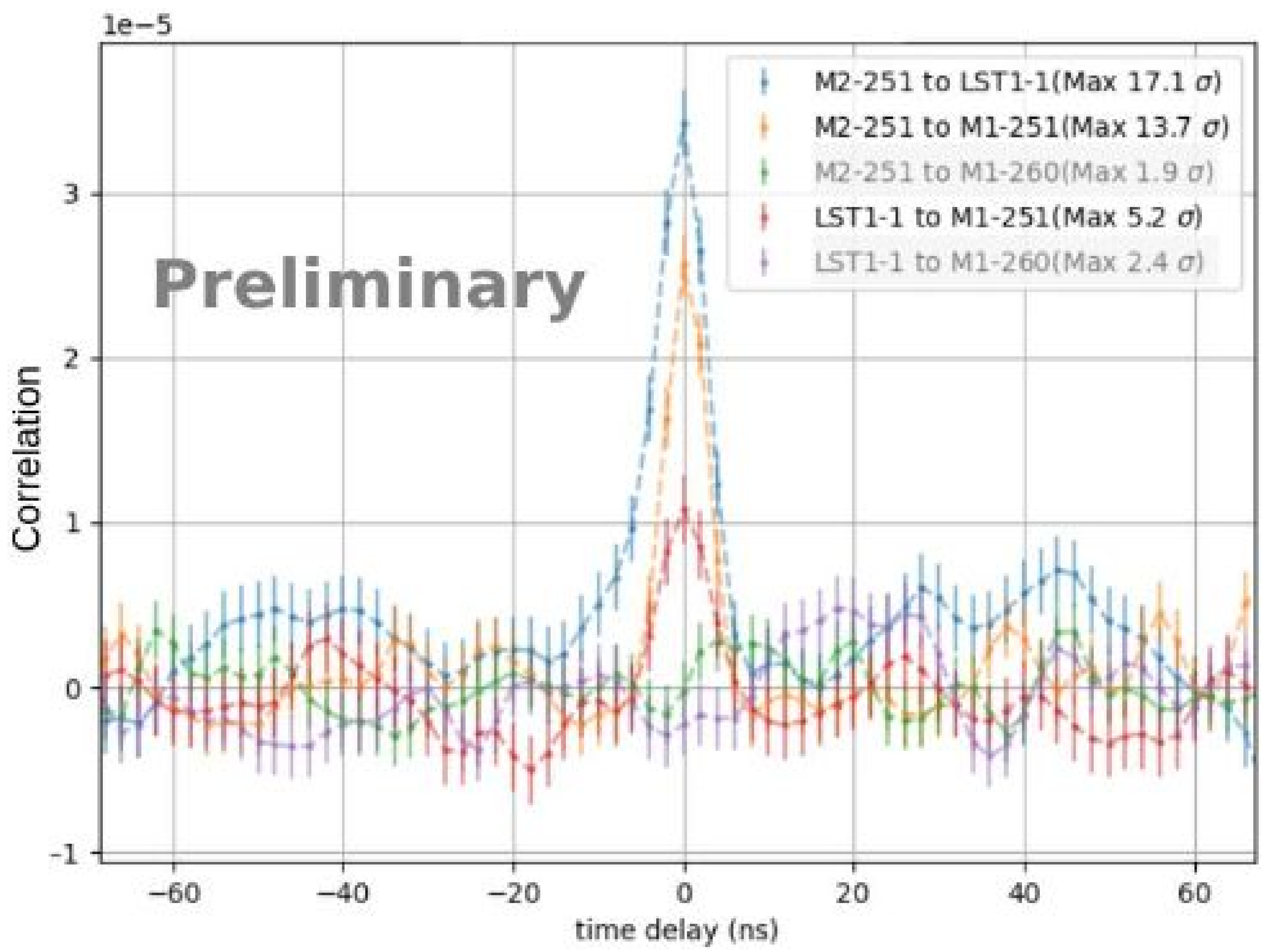


Angular resolution ~< 100 microarcsec

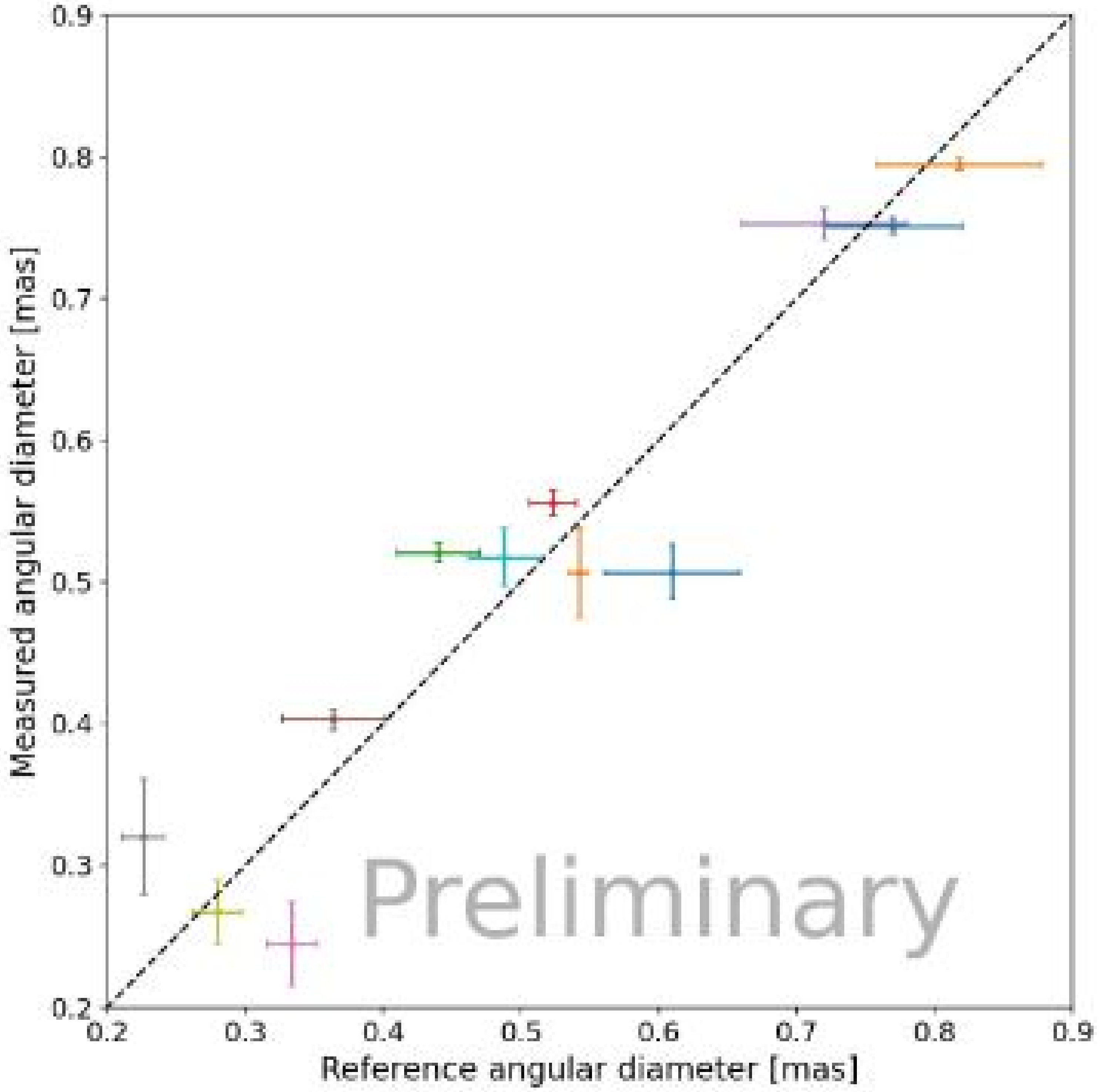
36 different baselines with dense coverage

SII on Cherenkov Telescopes: Future Prospects MAGIC + LST1

In 2024, the **first LST of CTAO was added to the MAGIC telescopes** with a similar setup (Jiménez Martínez et al. 2025)

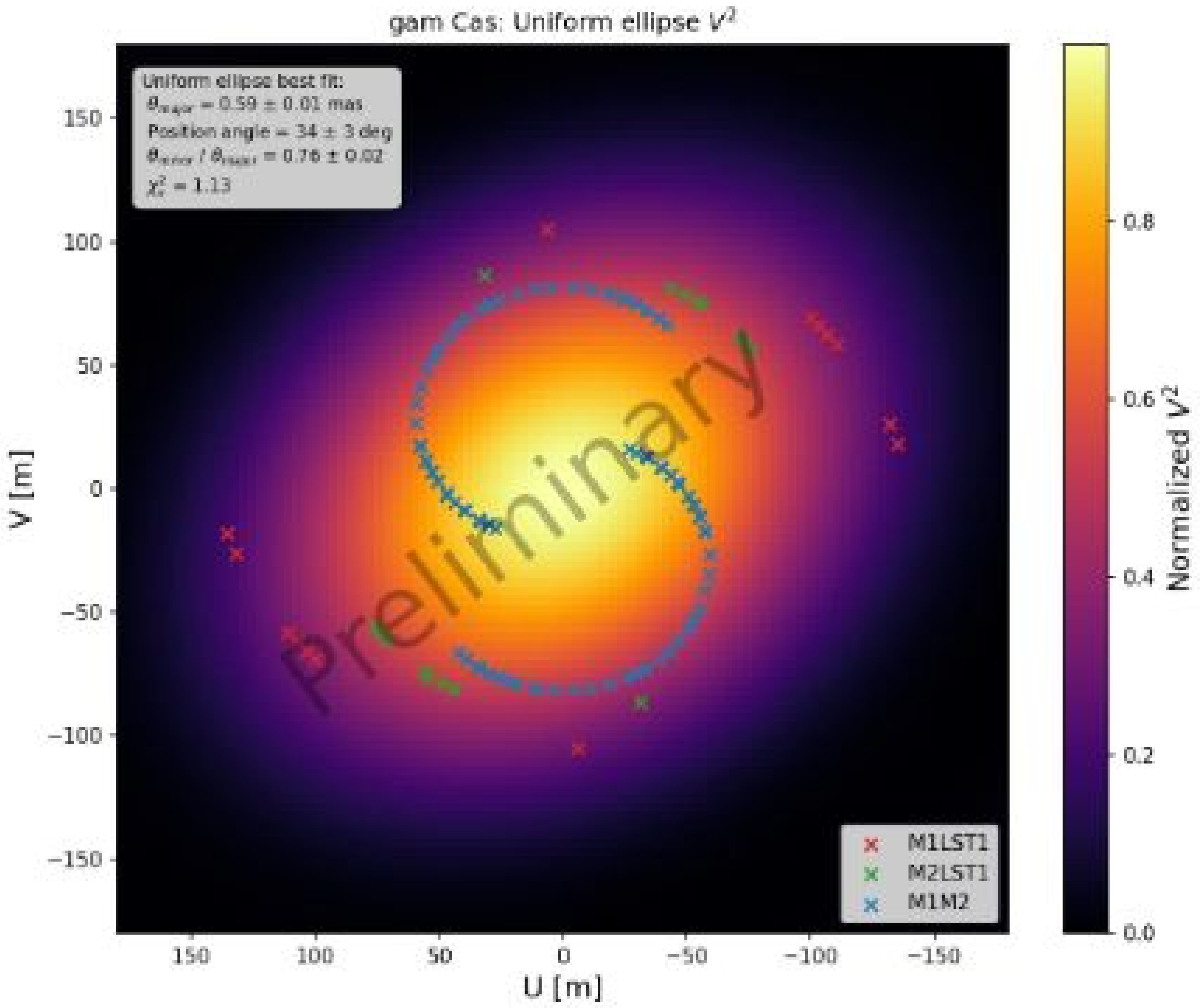


Correlation from all 3 baseline combinations successfully detected



Calibrator stars from MAGIC SII and CHARA compared with new measurements with the MAGIC+LST-1 SII

Jiménez Martínez et al. (2025)



Measurement of the oblateness of the photopshere of **Gamma Cas**

Preliminary result in agreement with the literature and the VERITAS SII measurement

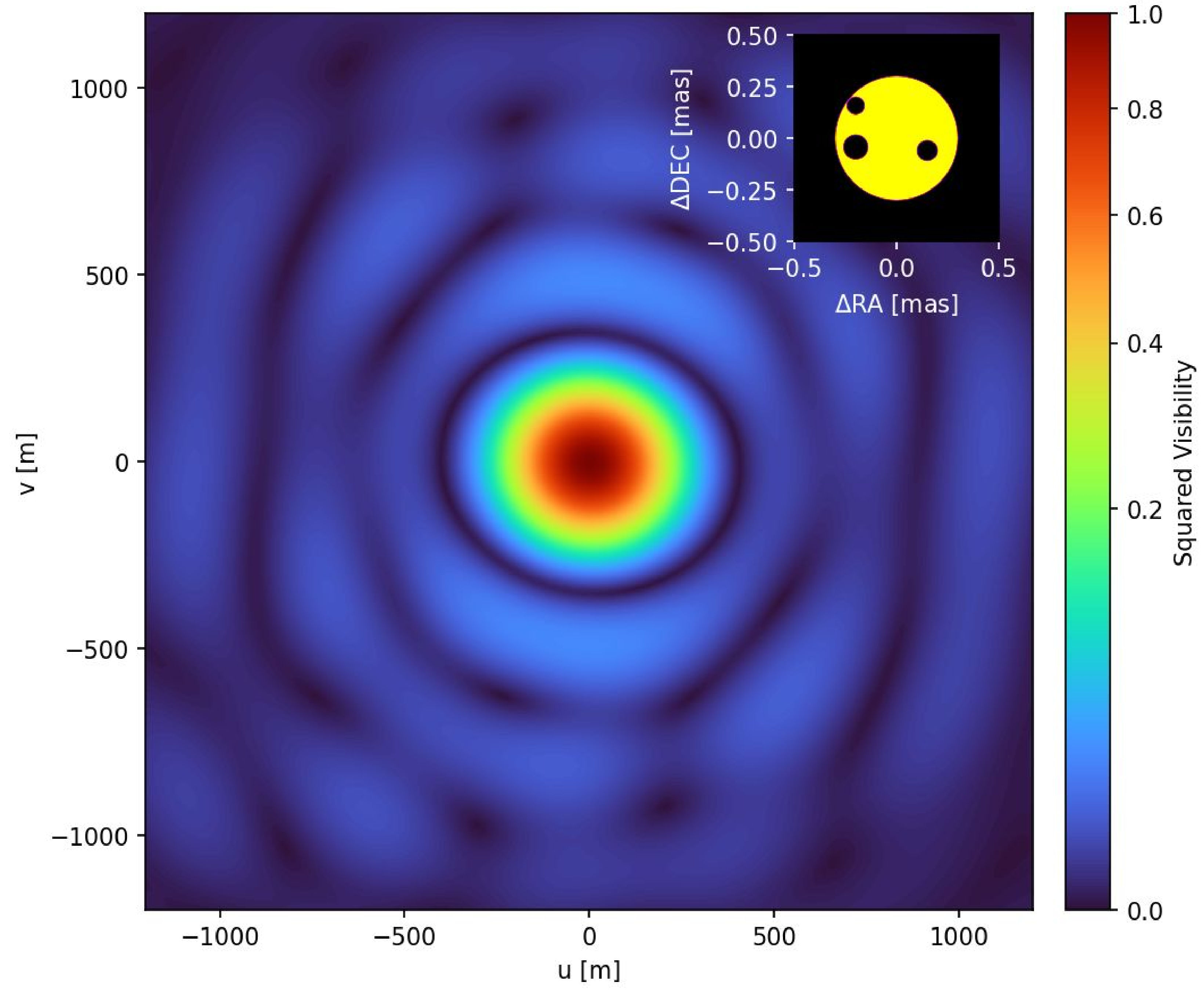
SII on Cherenkov Telescopes: Future Prospects
Starspots on solar-type stars

Mini-Array

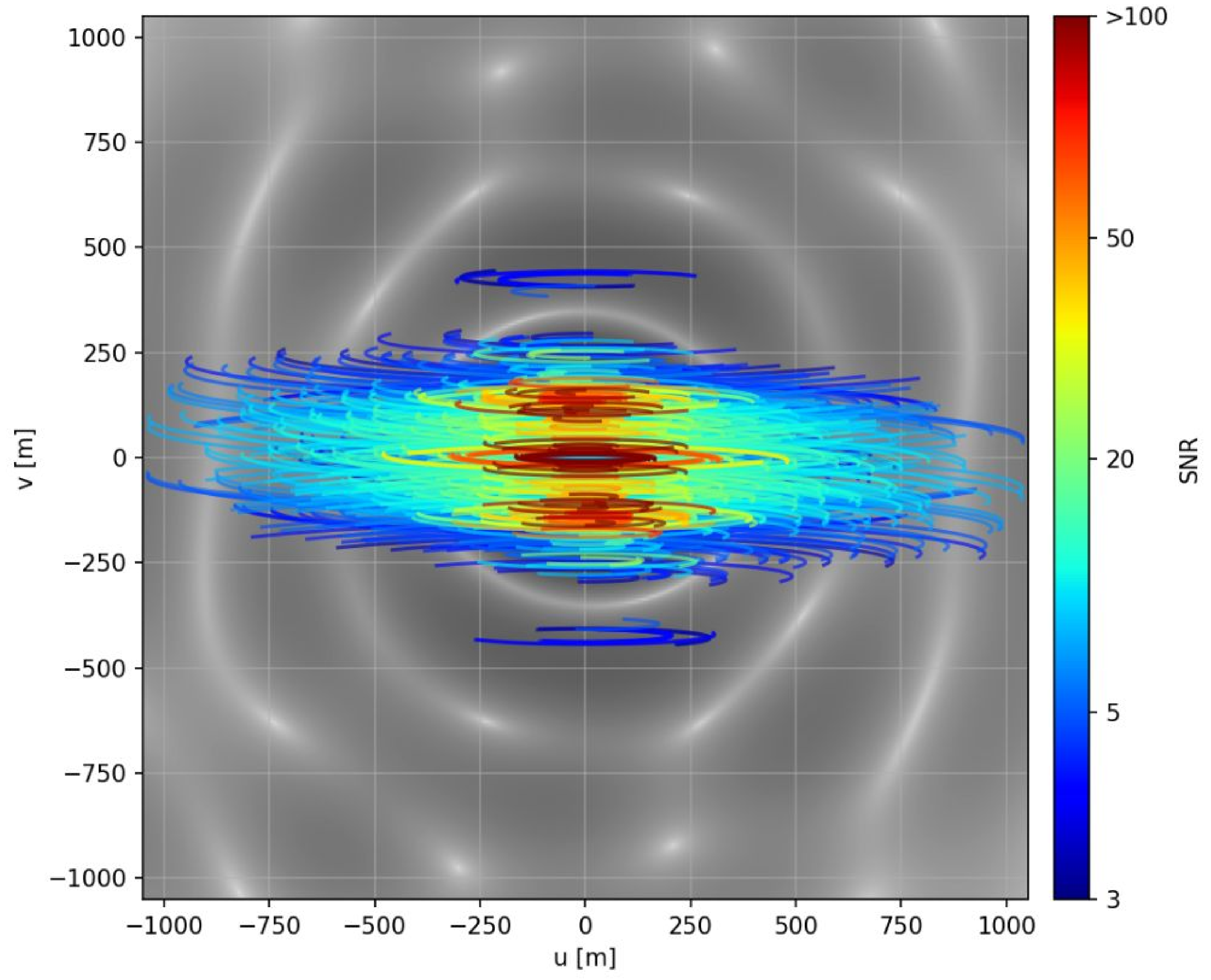
Solar-type stars are crucial for understanding the properties of the Sun in relation to other stars and for exploring the habitability conditions of exo-planets around stars similar to the Sun (e.g. Soderblom and King 1998; Charbonneau 2014; Ragulskaya 2018)

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

SII with CTAO White Consortium Paper in preparation



Simulated coherence on (U,V) plane of **F/G-type star with ~100 micro-arcsec spots**



Several telescope pairs at CTAO-South give measurements with S/N > 5 in 10 hours

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

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

Image credit: M. Fiori
SII with CTAO, White Paper, 2026

SII on Cherenkov Telescopes: Future Prospects
Improving time resolution and sensitivity

Mini-Array

S/N ratio in Photon Counting SII

(Guerin et al. 2025; Zampieri et al. 2026)

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

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

Reduce the time resolution

Achieving **sub-ns** sampling (compared to the > 2 ns resolution of Photo-Multipliers currently adopted)

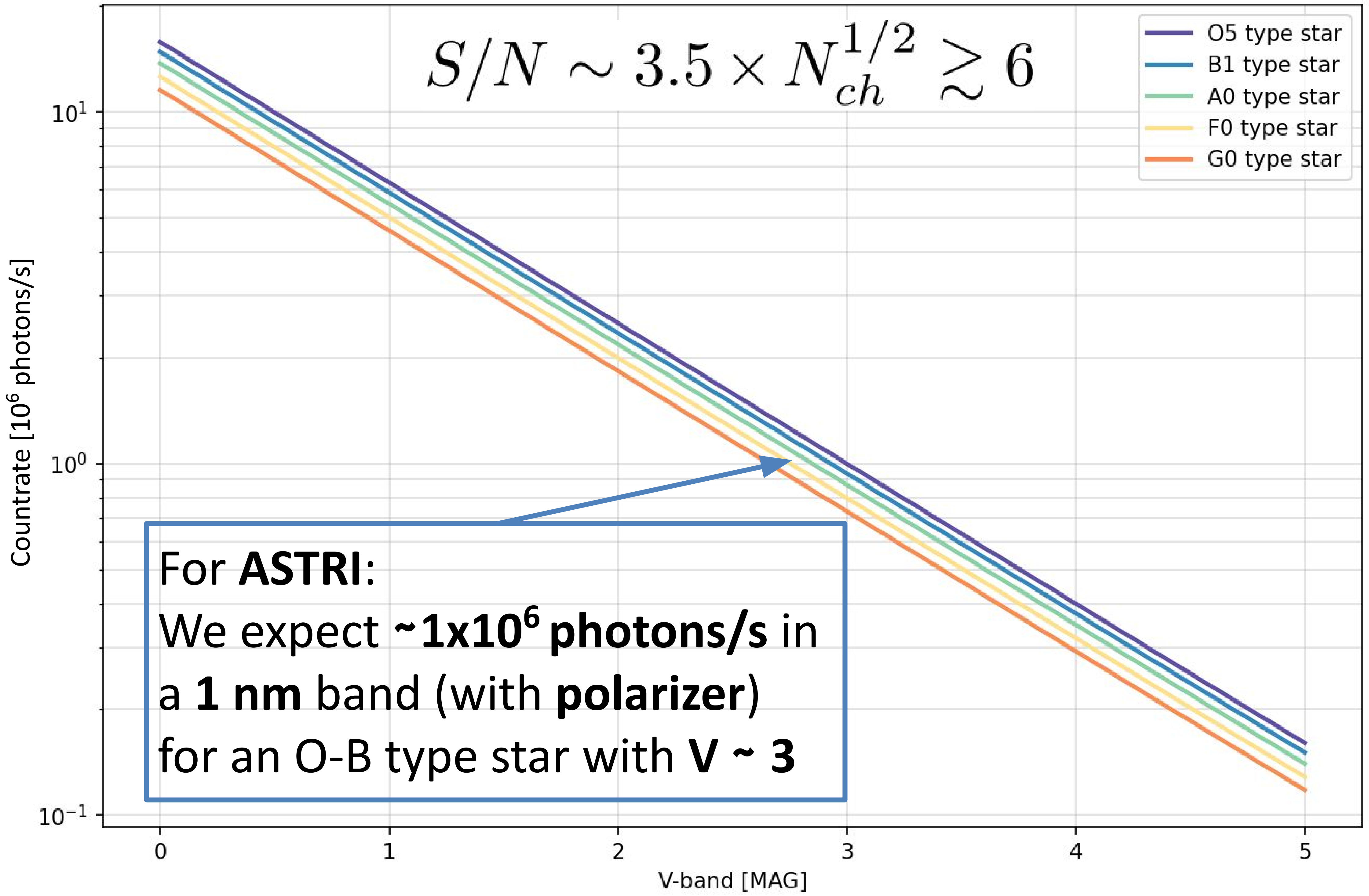
Squeeze the spectral band

Operating in *photon-count. Mode*

Attaining *'spectral' SII capabilities*

Increase the number of spectral channels

Combining measurements from several **very narrow spectral channels**



ASTRI SI3 is designed to perform photon-counting **sub-ns, very narrow band (1-3 nm), multichannel (3 to 16)** SII

SII on Cherenkov Telescopes: Future Prospects
Improving time resolution and sensitivity

SII with CTAO White Consortium Paper in preparation

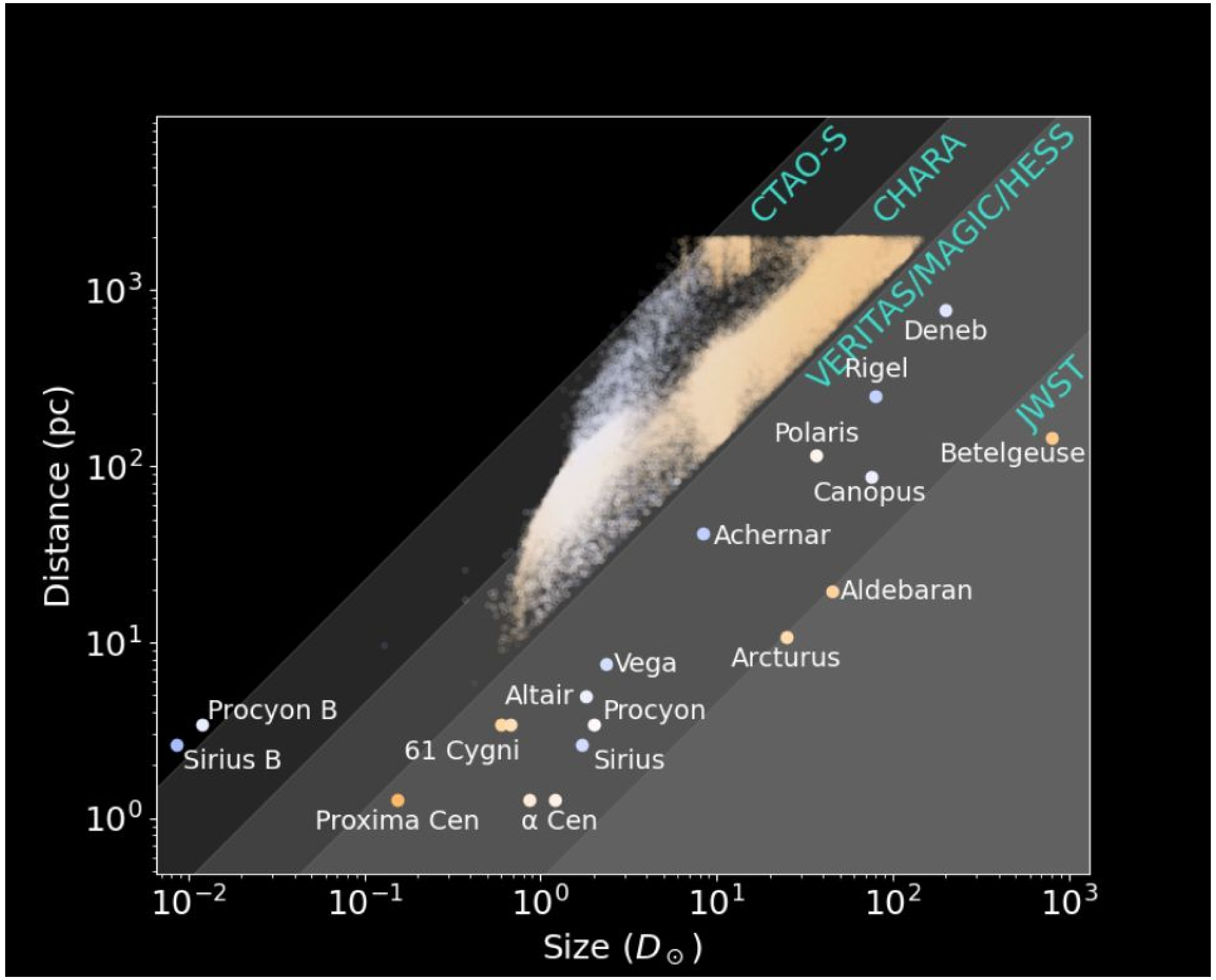


Image credit: P. Saha
SII with CTAO, White Paper, 2026

- Proposal for a new generation of SII instruments on CTAO with:

  < 500 ps time resolution
  1 nm bandpass
  10 channels

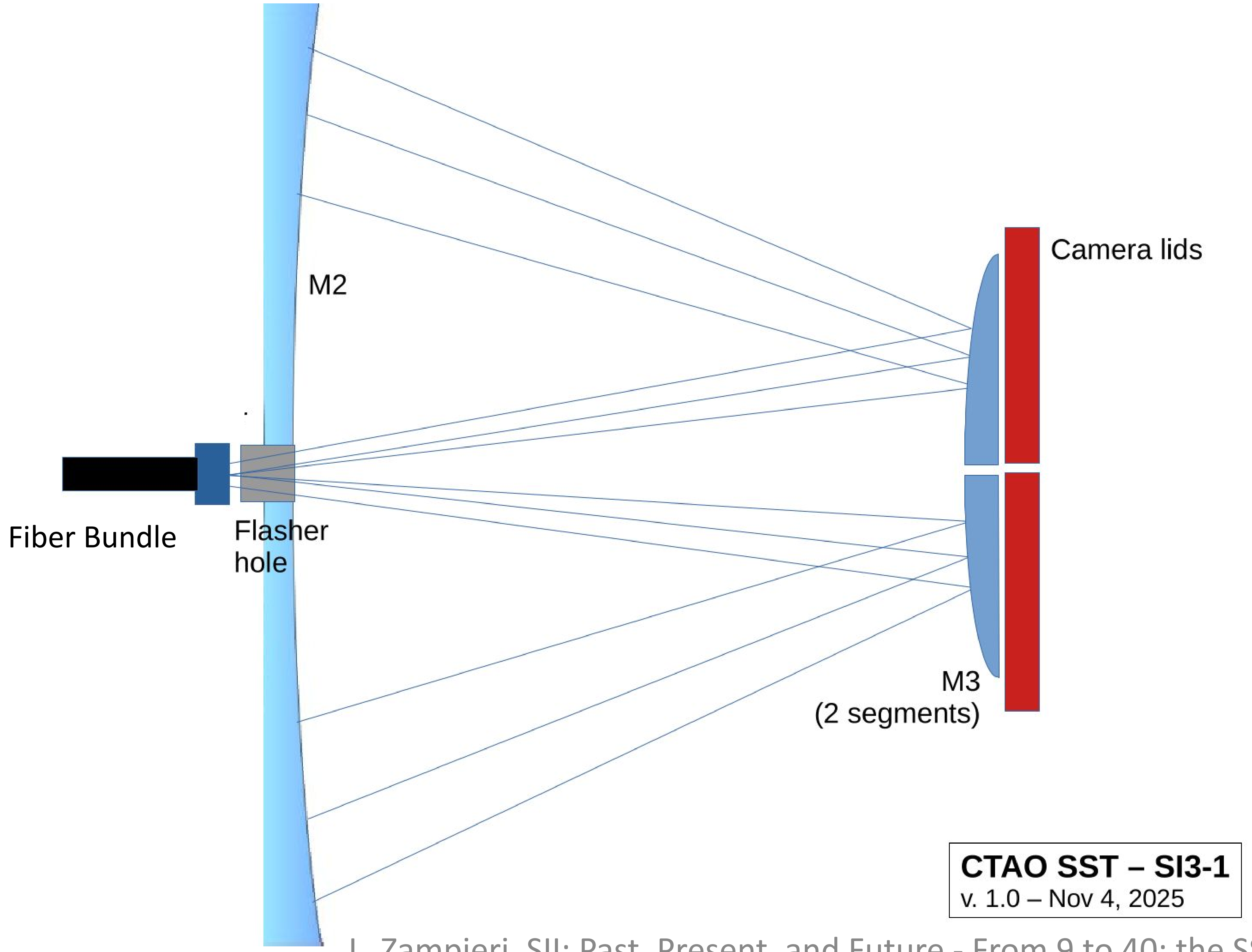
- It will boost the limiting magnitude to ~7.5 mag, and more than 10000 targets of all spectral types (including bluer and smaller stars) will be detectable

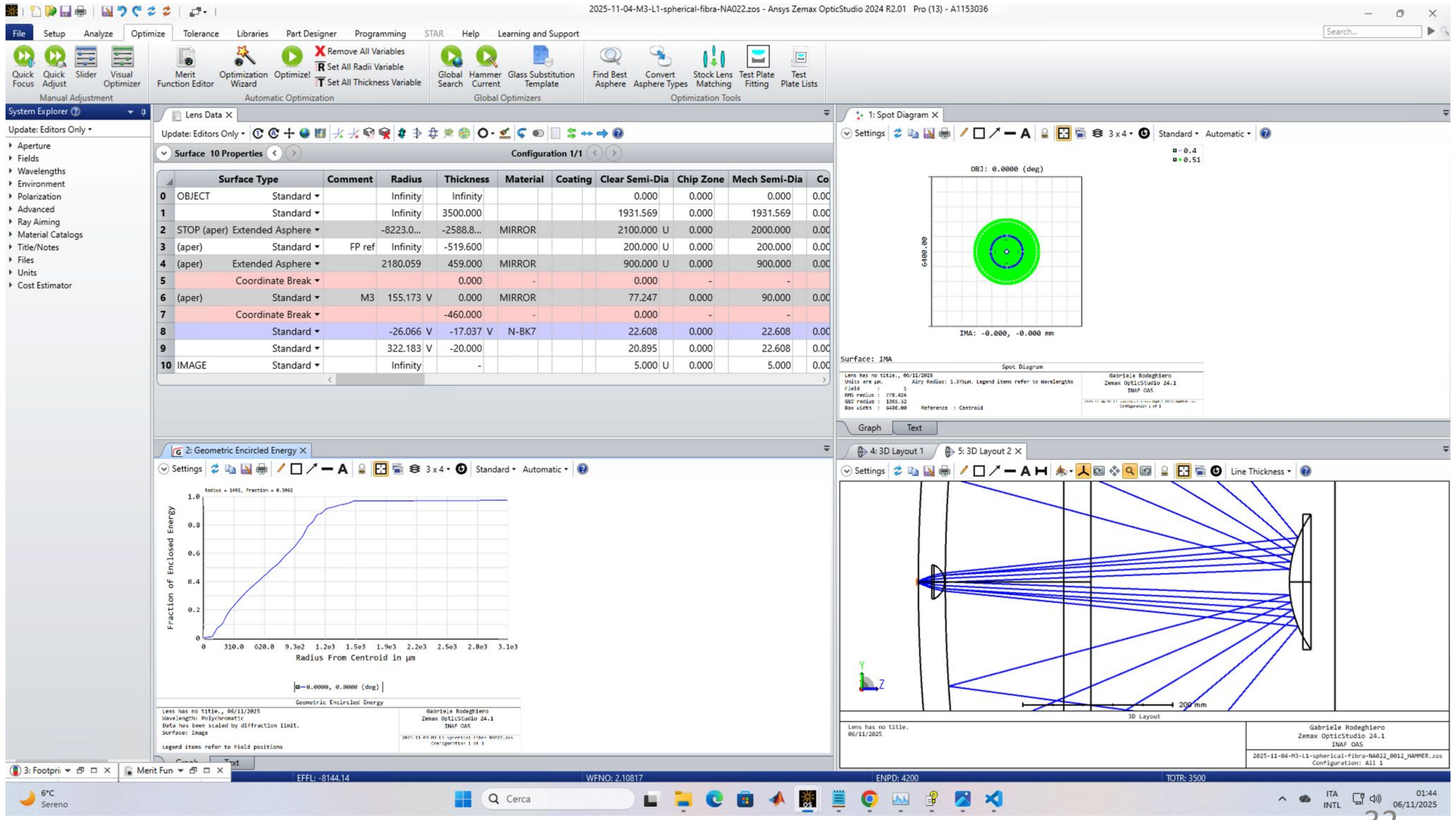
- Relativity uncertainty in radius measurements will also significantly decrease with the number of telescopes/baselines

SII on Cherenkov Telescopes: Future Prospects
Concept for a SST-SII instrument (building on ASTRI SI^3)

SSTs provide the longest and largest number of baselines for CTAO SII

- ➔ 3 separate modules on the telescope: Focal Plane Module (see Figure), Optical Module (1 nm bandpass, 10 channels), Back End Electronics (for time tagging)
- ➔ SiPM detectors in Optical Module (< 500 ps time resolution)
- ➔ Analog output split in two signals: one sent to central correlator, one to the Back End Electronics





SII: Future Prospects
Beyond ASTRI and CTAO

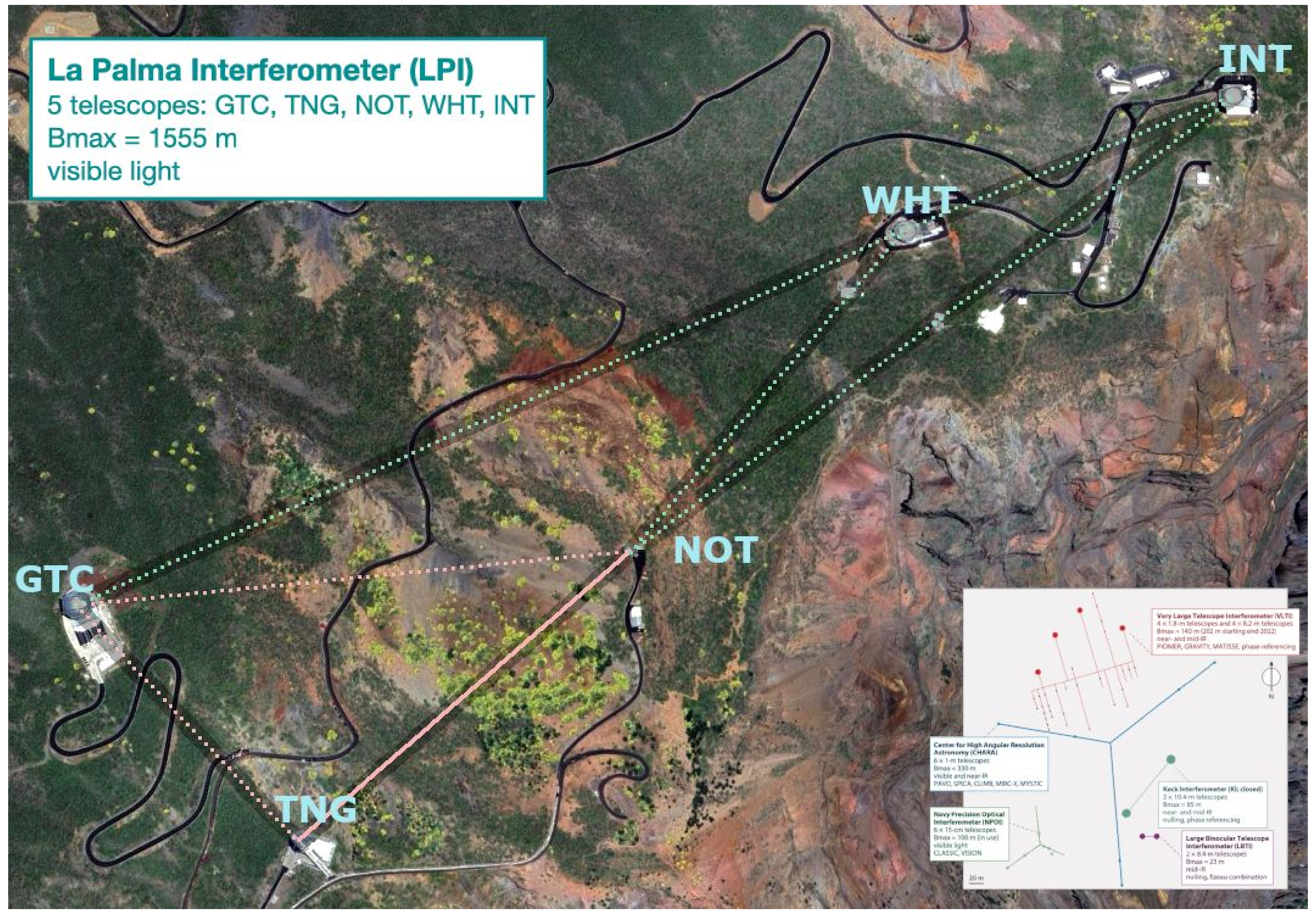
- **QUASAR** (Walter et al. 2025)
  Extremely large telescopes, 10ps resolution single photon detectors bring the key improvements to reach, in the optical, angular resolutions better than achieved in the radio by the Event Horizon Telescope and to obtain the first images of accretion disks around galactic compact objects, active galactic nuclei and quasars

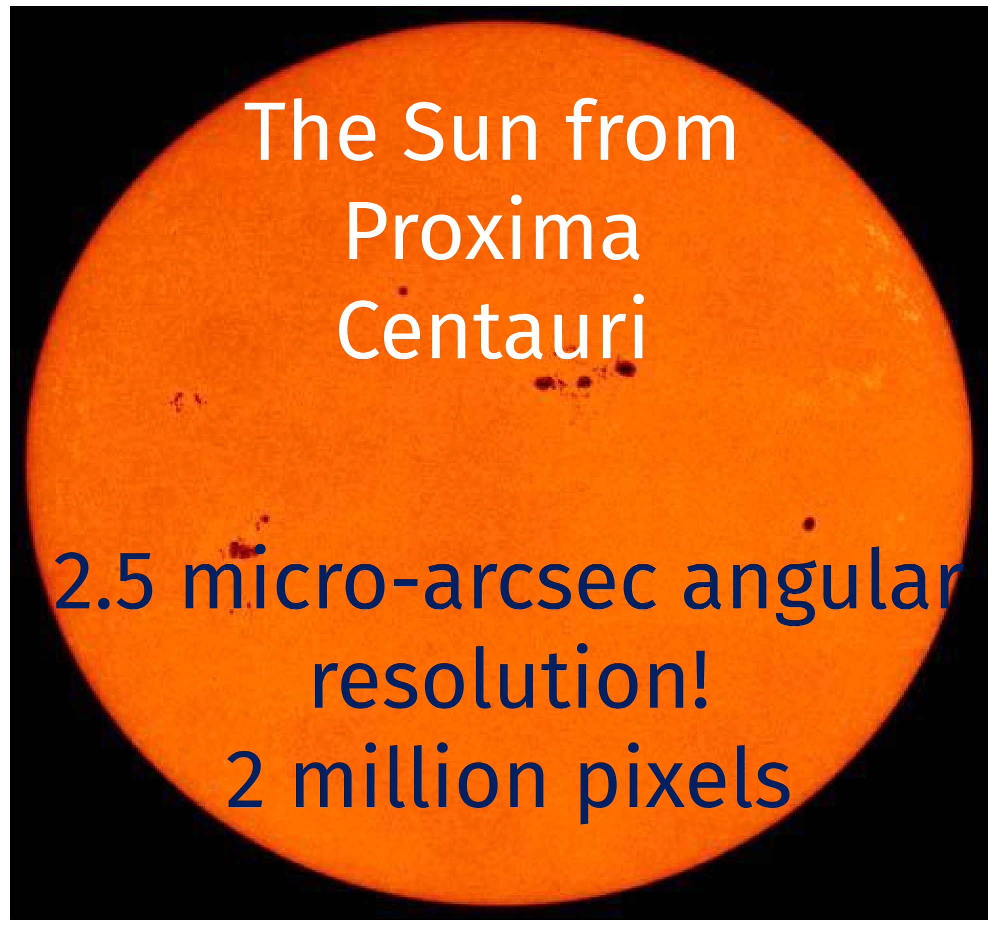
- **I2C Consortium** (Guerin et al. 2025)
  Second-generation instrument working with 16 wavelength channels around 420 nm using large-area single-photon detectors, with the goal of resolving Sirius B, the brightest white dwarf, using two large telescopes separated by more than 600 m in Hawaii

- **La Palma Quantum Interferometer** (Prada et al. 2026)
  Correlations between optical telescopes at the Roque de los Muchachos Observatory (NOT, TNG, GTC, WHT, and INT), with baselines between ~500 m and 1.5 km, a new generation of single-photon detectors and picosecond timing and synchronization

- **Sephira** (Ironi et al. 2026): Stellar intensity interferometry with the MAST Array Telescopes
  Modular, cost-effective interferometric array based on portable small telescopes with modern SPAD arrays and spectral multiplexing

- A purpose-built observatory for SII (Stellar Intensity Interferometry Telescope ARray, **SIITAR**; Carlile, Dravins & Thorsbro 2024), inspired by the Deep Synoptic Array (Hallinan et al. 2024), with 2048 telescopes in a 16 km x 18 km area





ASTRI SI3
Conclusions

Mini-Array

➔ Starting from the 20' **renewed interest for SII**, in particular with (but not limited to) arrays of IACTs

➔ Driven by availability of **km-scale baselines**, a **large number of telescopes**, and parallel technological improvements in detector technology and acquisition electronics (**10-100 ps time resolution**)

➔ Incredible progress made in recent years with with measurements going beyond stellar radii**:**

 * First measurement of the **oblateness of the photosphere of a fast rotator** with SII

➔ Breadth of **science cases significant**, with **impact beyond stellar astrophysics**

➔ Future Prospects for SII on Cherenkov Telescopes with the potential of achieving an **angular resolution < 100 μarcsec in the visible band,** a **dense coverage of the u-v plane,** and **improved sensitivity**

Looking forward to SII on ASTRI, CTAO and beyond…!

ASTRI SI^3

Mini-Array

SI^3

Cherenkov Telescope Array Plus

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