Observation of star deformation using intensity interferometry

IMPRS Recruitment Workshop

Álvaro García Lozano

17 March 2025

Not phase, but intensity interferometry

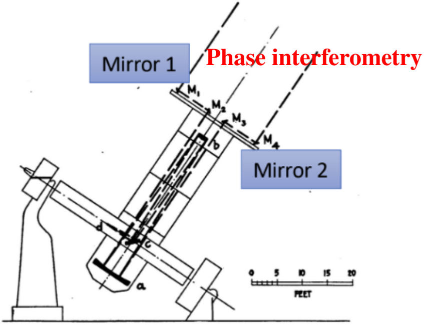


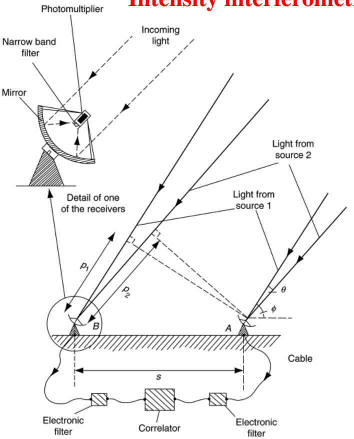
FIG. 1

Michelson Stellar Interferometer

↓

The light is made to physically interfere.

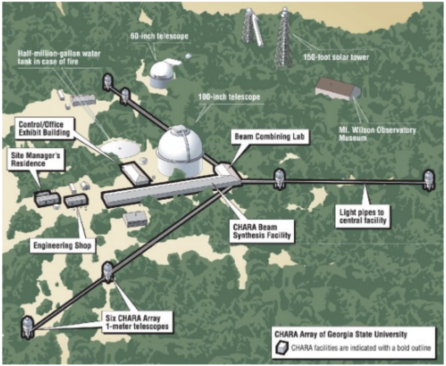
Intensity interferometry



We measure the time correlation of detected photons (intensity) inside a coherence region d$\sim \lambda$R/D

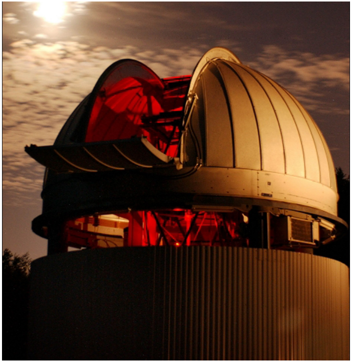
Phase interferometry in the visible regime

More accurate optics, including active optics, lasers, precision mechanics, faster electronics, more efficient photodetectors....



CHARA in Mt. Wilson: 6x 1 m telescopes, connected to correlator. Baseline <331 m. 200 μas resolution in visible (V,R) for V<10^{m}.

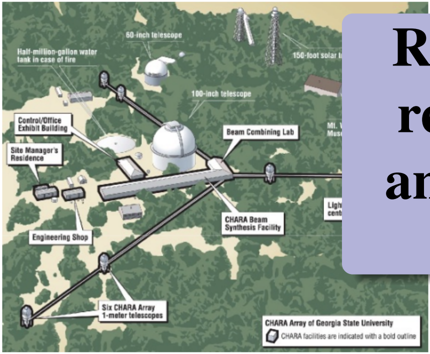
CHARA ('Center for High Angular Resolution Astronomy')



Slide from Juan Cortina (IAC & CIEMAT)

Phase interferometry in the visible regime

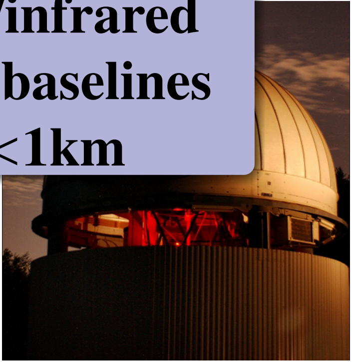
More accurate optics, including active optics, lasers, precision mechanics, faster electronics, more efficient photodetectors….



CHARA in Mt. Wilson: 6x 1 m telescopes, connected to correlator. Baseline <331 m.
200 μas resolution in visible (V,R) for V<10^{m}.

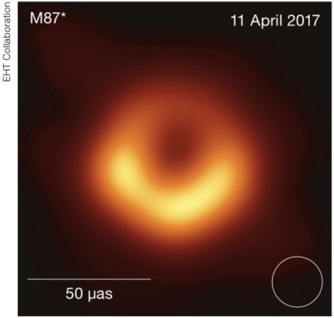
Restricted to red/infrared and baselines <1km

Angular



Slide from Juan Cortina (IAC & CIEMAT)

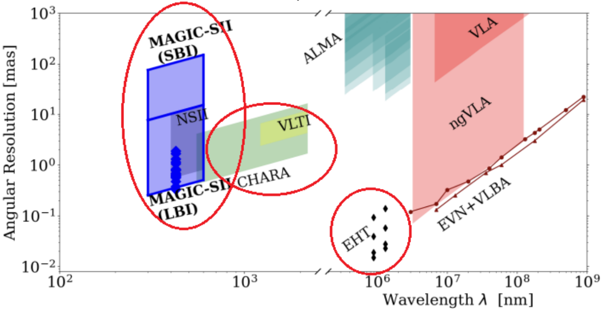
Current scenario



Imaging of area surrounding the supermassive black hole in M87

Intensity interferometry allows us to achieve better angular resolution!

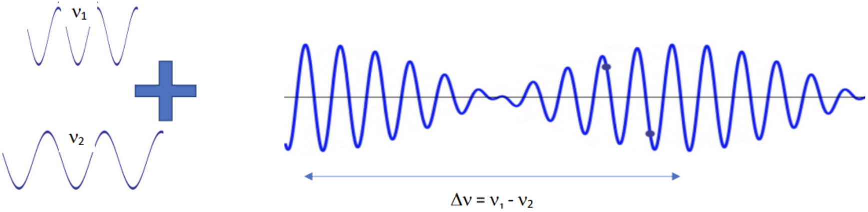
↑



MAGIC+LST-1 has achieved better angular resolution than CHARA (MNRAS 529, 4387–4404 (2024)) and is only about 50 times worse than the highest angular resolution instrument, the EHT, which utilizes telescopes across the globe.

Intensity Interferometry: Beats

- Consider two waves of frequencies ν_1 and ν_2
- Amplitude of sum has characteristic frequency $\Delta\nu = \nu_1 - \nu_2 < \nu_1$, smaller than original frequencies!



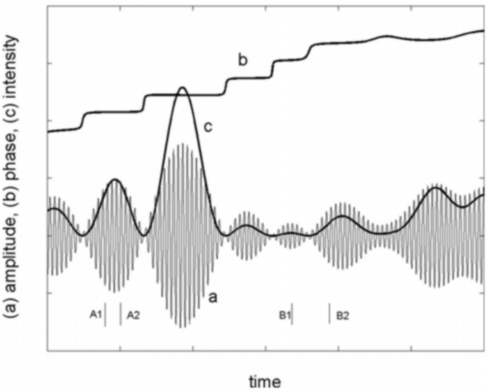
These are called “beats” in music

Slide from Juan Cortina (IAC & CIEMAT)

Intensity Interferometry: Intensity Time Modulation

Simulation of:

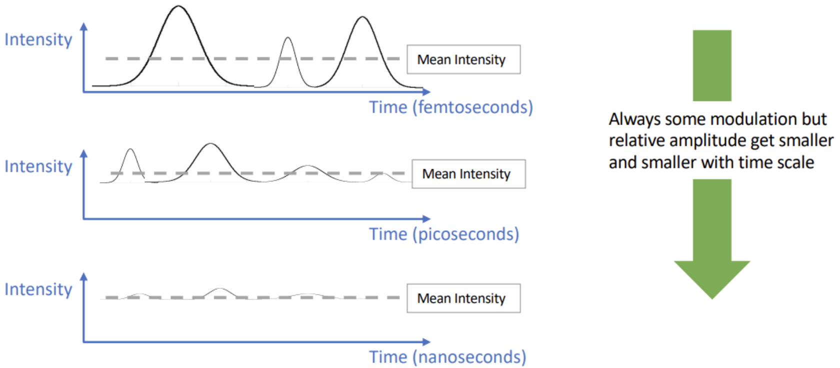
- Many sinusoidal components
- unit amplitude
- Randomly chosen frequencies within a band $\nu_0 \pm 0.05 \cdot \nu_0$



One can see many different time scales: from $1/\nu_0$ to the longest for the two components that happen to be closest in frequency, $1 / (\nu_i - \nu_j)$
For a continuum in $\nu_0 \pm \Delta\nu_0$ there is always some degree of modulation for **any** time scale

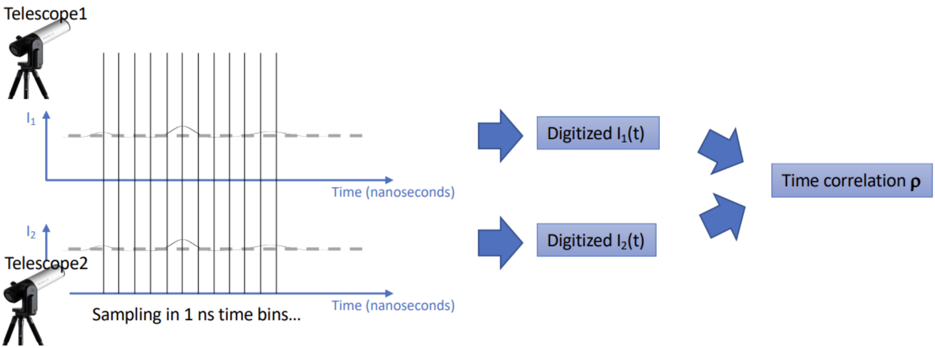
Slide from Juan Cortina (IAC & CIEMAT)

Intensity Interferometry: Modulation at any time scale



Slide from Juan Cortina (IAC & CIEMAT)

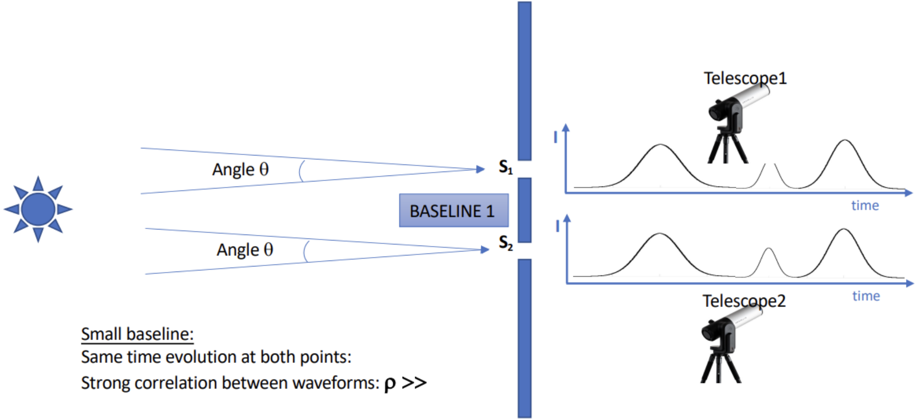
Intensity modulation even for long time scales



- There is some intensity modulation even at ns time scales: similar to radio, we can digitize the signal.
- Allows to increase baseline indefinitely: 100 m, 1 km, 10 km....

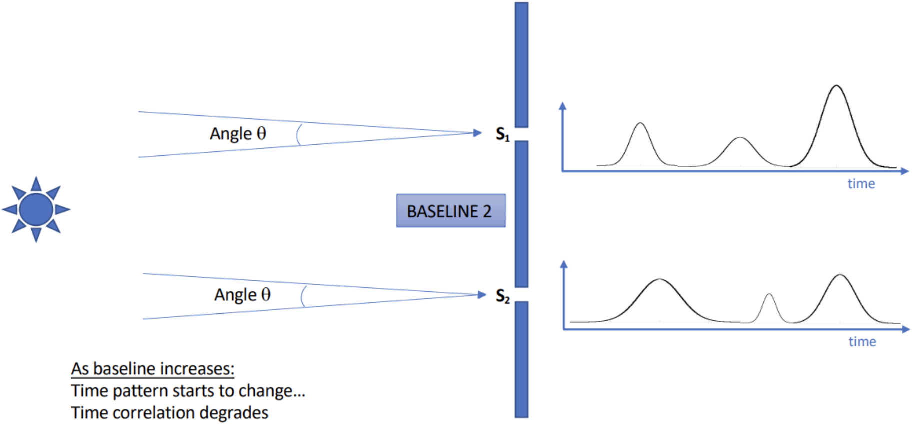
Slide from Juan Cortina (IAC & CIEMAT)

How does time pattern evolve with baseline?



Slide from Juan Cortina (IAC & CIEMAT)

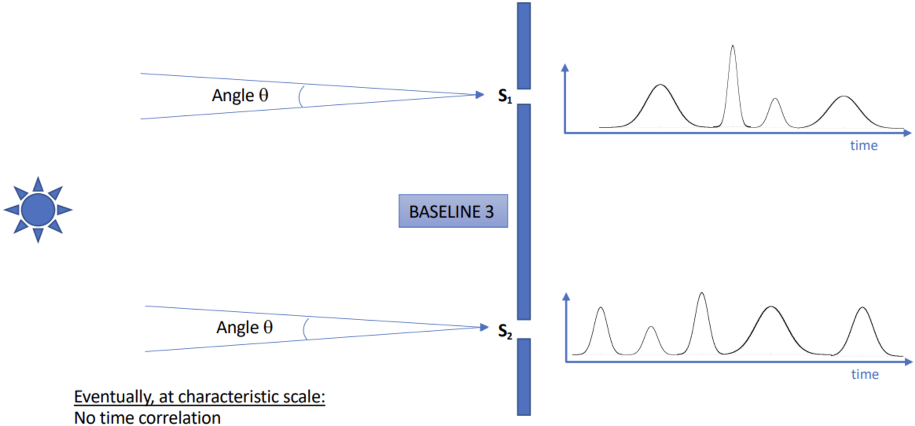
How does time pattern evolve with baseline?



As baseline increases:
Time pattern starts to change...
Time correlation degrades

Slide from Juan Cortina (IAC & CIEMAT)

How does time pattern evolve with baseline?

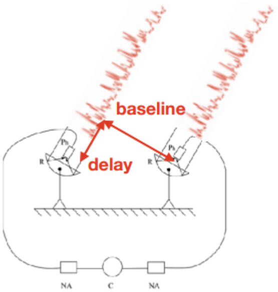


Eventually, at characteristic scale:
No time correlation

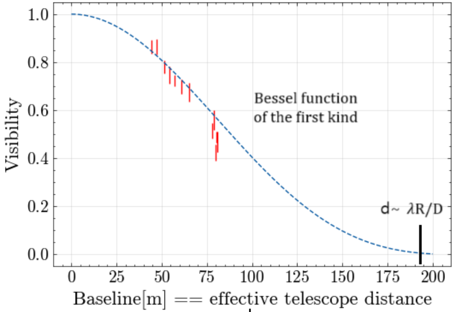
Slide from Juan Cortina (IAC & CIEMAT)

Intensity Interferometry with Cherenkov Telescopes

- Large mirrors + fast photo-sensors + single photon resolution - **They are suitable to perform intensity interferometry.**
- Within the coherence region (d~ λR/D) on ground **we can observe time coincident photons due to coherent intensity fluctuations in time.**



We measure the time correlation of intensity



The observed coherent interference pattern on the ground is described by the visibility

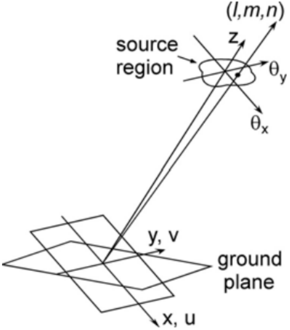
$$|V_{12}|^2 = K \cdot \frac{\rho(\tau)\sqrt{G_1 G_2}}{\sqrt{DC_1 DC_2}}$$

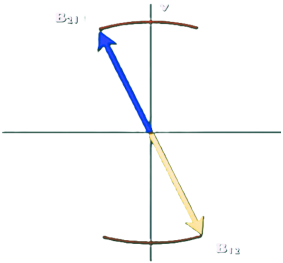
The visibility is the probability of detecting photon coincidences in two telescopes separated by a certain delay.

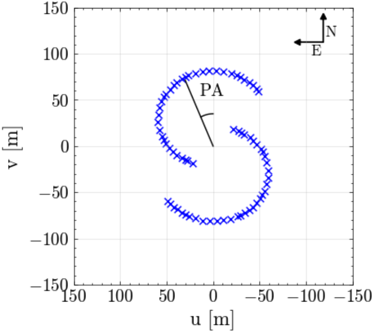
The intensity interferometry technique

UV plane

The UV plane is the **projection of the baseline** d (distance between telescopes) **on the plane perpendicular to the direction of the object.** With our measurements from two telescopes, **we scan the UV plane.**

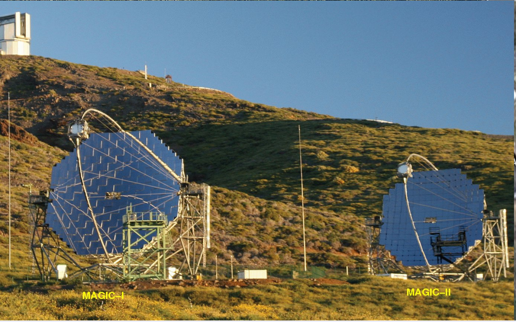


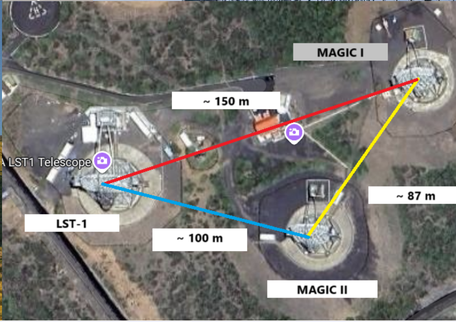




(Labeyrie, A., Lipson, S., Nisenson, P. 2006, in An introduction to optical stellar interferometry (Cambridge University Press))

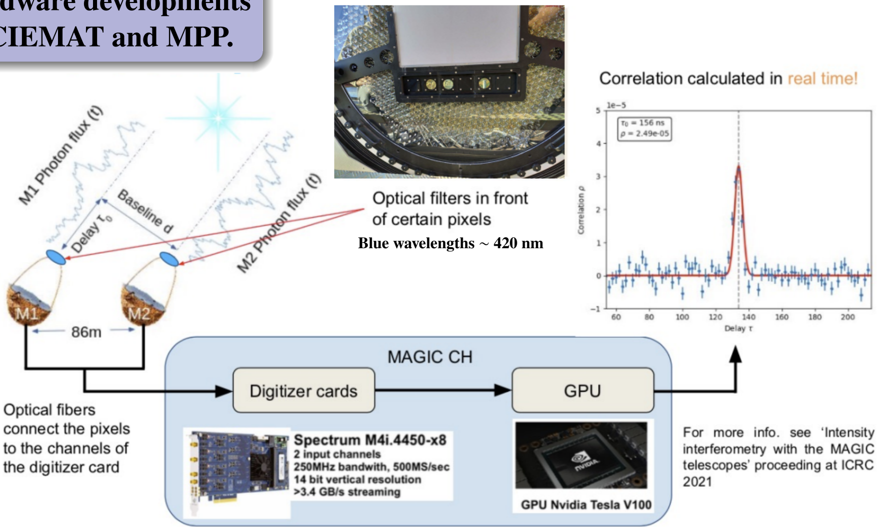
The MAGIC+LST-1 Stellar Intensity Interferometer





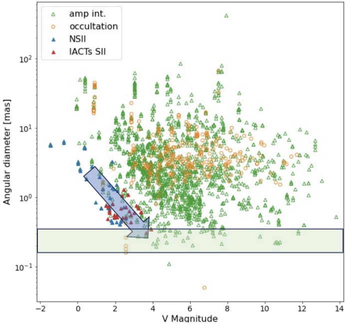
Setup

Hardware developments by CIEMAT and MPP.



Slide from Juan Cortina (IAC & CIEMAT)

Future (and current) science

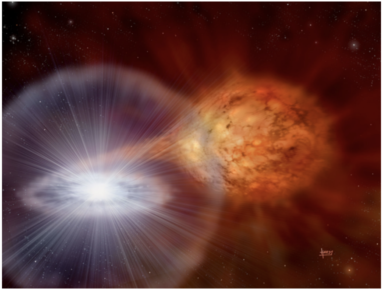


Credit: A. Cifuentes (CIEMAT), based on CHARA, JMDC catalogs

Weaker
... and smaller stars

↓

More stellar diameter measurements



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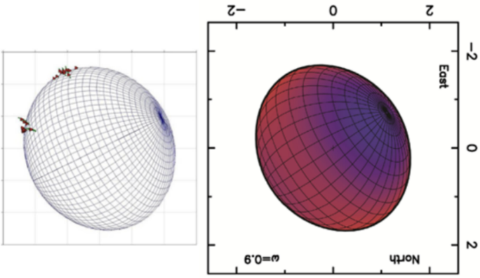
Measurements of the speed of a novae expanding shell

Distortions due to interacting binaries

My contribution: Fast rotators

Fast rotators are stars that **spin so rapidly** that they **suffer a broadening** perpendicular to the axis of rotation.

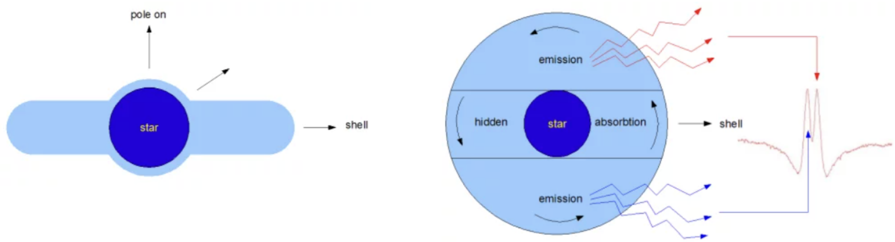
Fast rotators are Be stars, crucial for high-energy astrophysics and gamma rays. Optical interferometry using Cherenkov telescopes, and high-energy astronomy have clear synergies.



Altair (van Belle+ 2001, Peterson+ 2006, Monnier+ 2007*)

Fast rotators

CHARA (phase interferometry) restricted to the infrared is **only sensitive to the circumstellar disk**, while **MAGIC+LST-1 SII** in the visible regime is **sensitive to the actual shape of the star.**

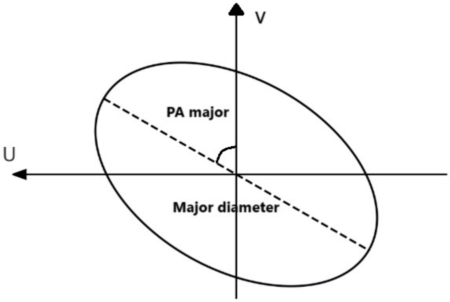


Model of a typical Be star (Kogure & Hirata, 1982)

Fast rotators

I am using for the first time the MAGIC+LST-1 Stellar Intensity Interferometry to constrain crucial parameters in fast rotators, namely, **Gamma Cassiopeiae, Delta Persei and Zeta Ophiuchi.**

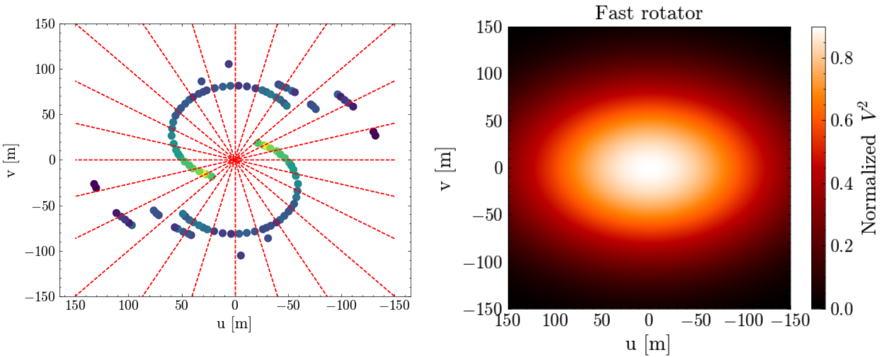
I aim to determine the major diameter of the star (θ_{major}), the position angle of the major diameter (PA_{major}) and the diameter ratio ($\theta_{\text{minor}}/\theta_{\text{major}}$).



My results

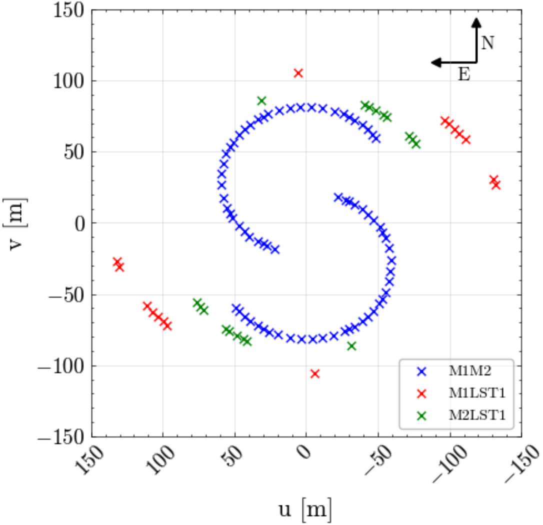
I use a **double approach** to perform the analysis:

1. **One-dimensional analysis**: To cross-check our measurements. Data is binned into variable position angles in the UV plane.
2. **Two-dimensional analysis:** Standard procedure in phase interferometry. Ellipse fitting in the UV plane.

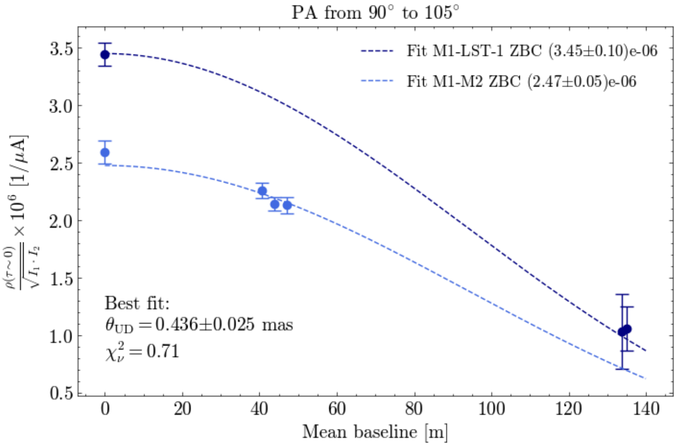


Gamma Cassiopeiae

2024 Gamma Cassiopeiae dataset

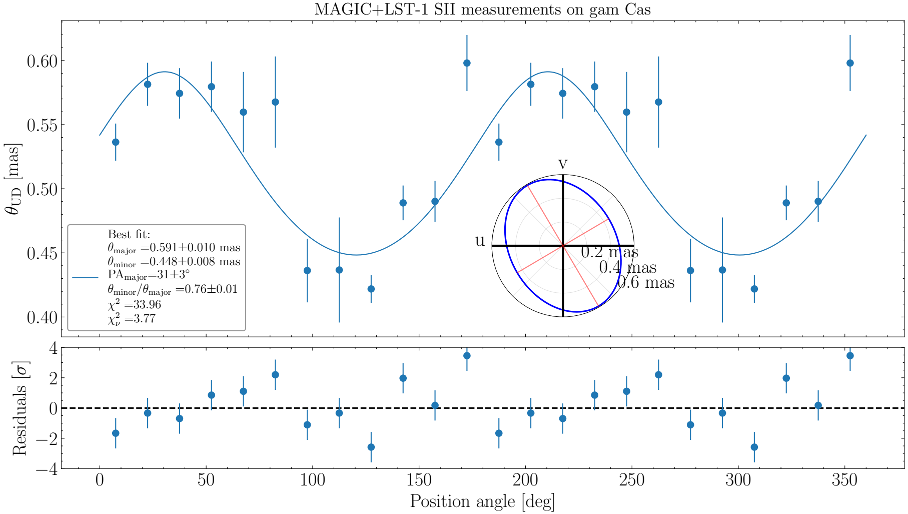


Gamma Cassiopeiae

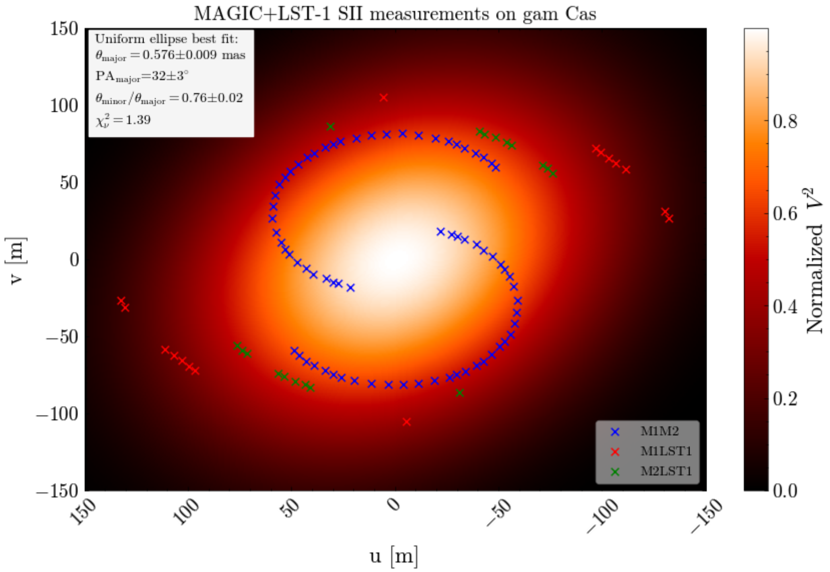


$$|V(d)| = 2 \cdot \frac{J_1(\pi \cdot d \cdot \theta_{\mathrm{UD}}/\lambda)}{\pi \cdot d \cdot \theta_{\mathrm{UD}}/\lambda}$$

$$\theta(PA) = \frac{1}{\sqrt{\left(cos\left(\frac{PA - PA_{\mathrm{major}}}{\theta_{\mathrm{minor}}}\right)^2 + sin\left(\frac{PA - PA_{\mathrm{major}}}{\theta_{\mathrm{major}}}\right)^2\right)}}$$

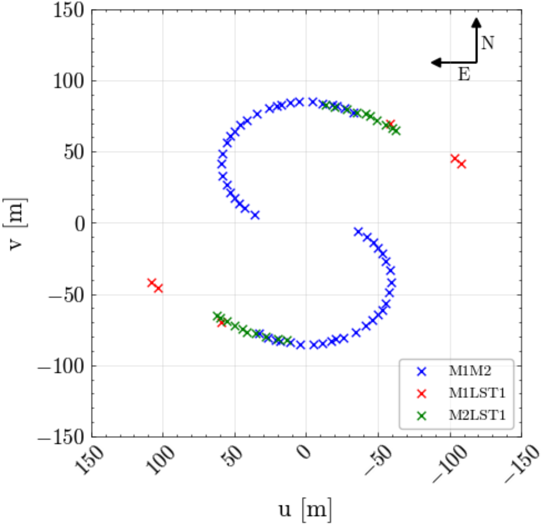


$$|V(r)| = \frac{J_1\,(2\pi \cdot a \cdot r)}{\pi \cdot a \cdot r}$$

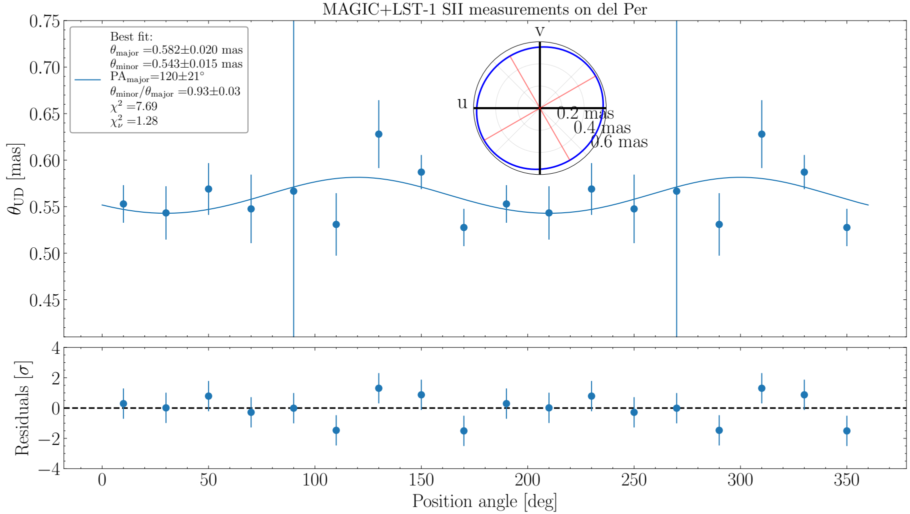


Delta Persei

2024 Delta Persei dataset



$$\theta(PA) = \frac{1}{\sqrt{\left(cos\left(\frac{PA-PA_{\mathrm{major}}}{\theta_{\mathrm{minor}}}\right)^2 + sin\left(\frac{PA-PA_{\mathrm{major}}}{\theta_{\mathrm{major}}}\right)^2\right)}}$$



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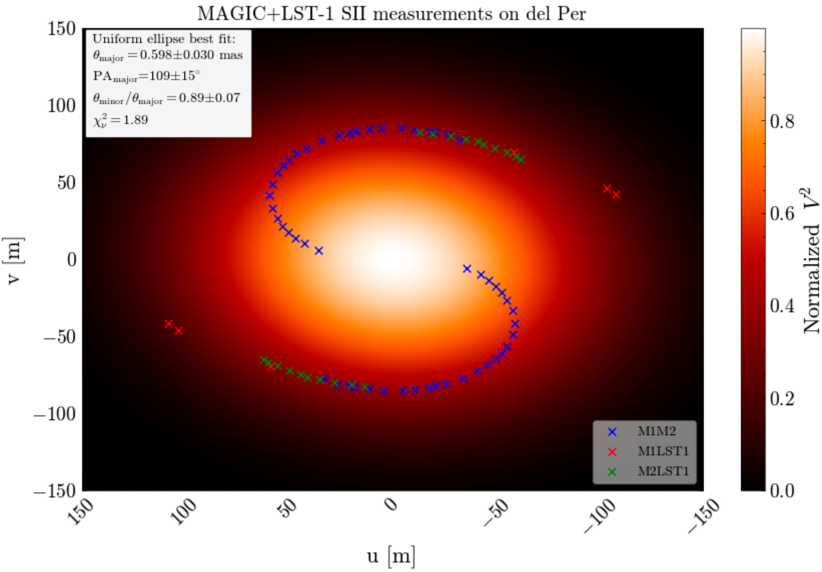
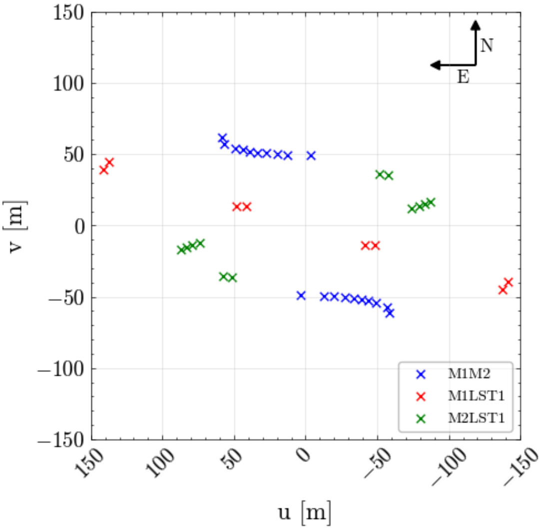
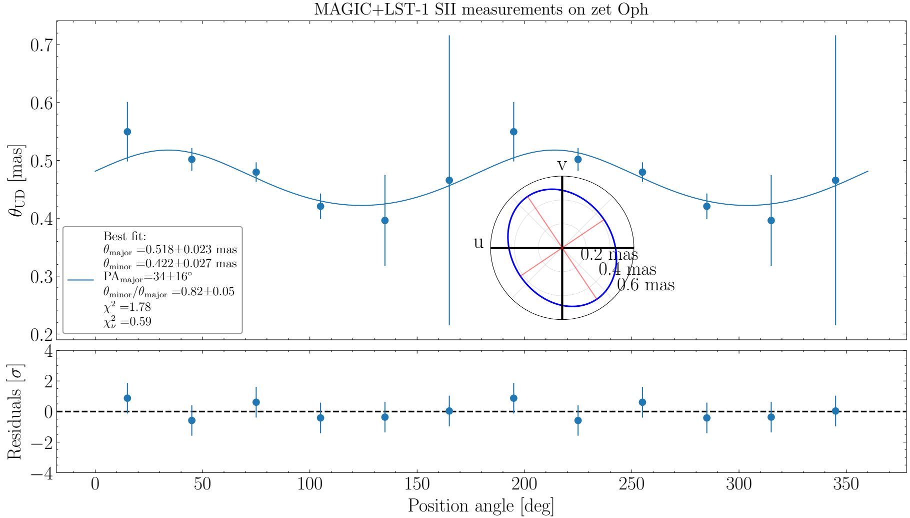


Zeta Ophiuchi

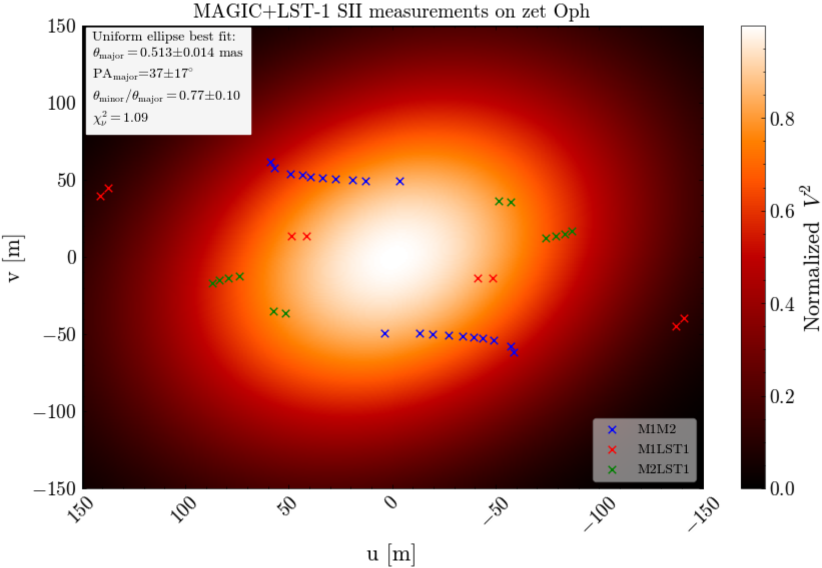
2024 Zeta Ophiuchi dataset



$$\theta(PA) = \frac{1}{\sqrt{\left(cos\left(\frac{PA-PA_{\mathrm{major}}}{\theta_{\mathrm{minor}}}\right)^2 + sin\left(\frac{PA-PA_{\mathrm{major}}}{\theta_{\mathrm{major}}}\right)^2\right)}}$$



$$|V(r)| = \frac{J_1(2\pi \cdot a \cdot r)}{\pi \cdot a \cdot r}$$



Results

Gamma Cassiopeiae

	One dimensional	Two dimensional
θ_{major} [mas]	0.591 ± 0.010	0.576 ± 0.009
PA_{major} [deg]	31 ± 3	32 ± 3
$\theta_{\text{minor}}/\theta_{\text{major}}$	0.76 ± 0.01	0.76 ± 0.02

Delta Persei

	One dimensional	Two dimensional
θ_{major} [mas]	0.582 ± 0.020	0.598 ± 0.030
PA_{major} [deg]	120 ± 21	109 ± 15
$\theta_{\text{minor}}/\theta_{\text{major}}$	0.93 ± 0.03	0.89 ± 0.07

Zeta Ophiuchi

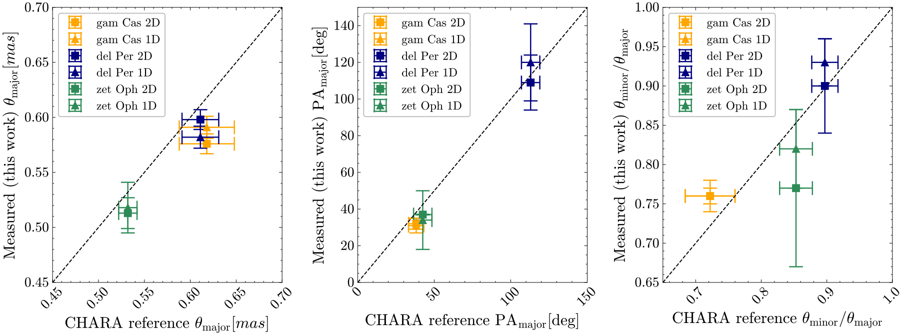
	One dimensional	Two dimensional
θ_{major} [mas]	0.518 ± 0.023	0.513 ± 0.014
PA_{major} [deg]	34 ± 16	37 ± 17
$\theta_{\text{minor}}/\theta_{\text{major}}$	0.82 ± 0.05	0.77 ± 0.10

Significance of results

In the **worst-case scenario and only using data from 2024** (we have also data from 2021-2023 using only MAGIC):

- I found an **indication of the oblateness of Gamma Cassiopeiae with a significance of 3.3σ**
- Some **more measurements with the LST-1** still need to be done **to confirm the oblateness for Delta Persei and Zeta Ophiuchi** ($< 2\sigma$)

Results comparison



My work

I have presented **for the first time measurements on several fast rotators using the MAGIC+LST- 1 Stellar Intensity Interferometer** in blue wavelengths. These are also **the first results ever published. Adding LST-1 to the interferometer is a real breakthrough**: it allows to dramatically improve sensitivity, enhance the UV coverage of the array and lower the uncertainty on measured diameters. The upcoming **LST2-4 telescopes will help exponentially enhance the interferometer**.

THANK YOU FOR THE ATTENTION

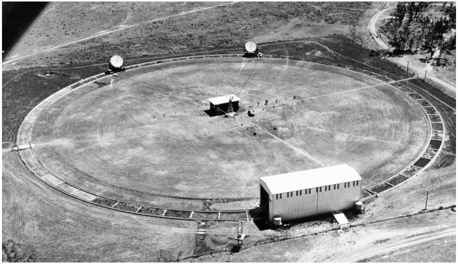
BACKUP

Objectives

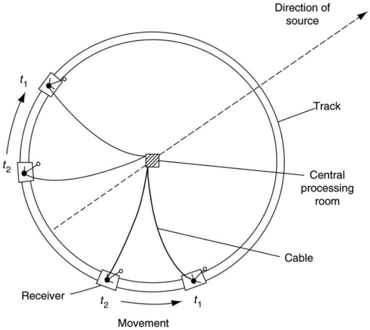
The objective of this thesis is **to constrain the diameter ratio in fast rotators** with high accuracy using for the first time data from **MAGIC+LST-1 Stellar Intensity Interferometer.**

Historical introduction

Hanbury-Brown and Twiss interferometer



Narrabri Observatory in Australia



Schematic layout of the intensity interferometer at Narrabri

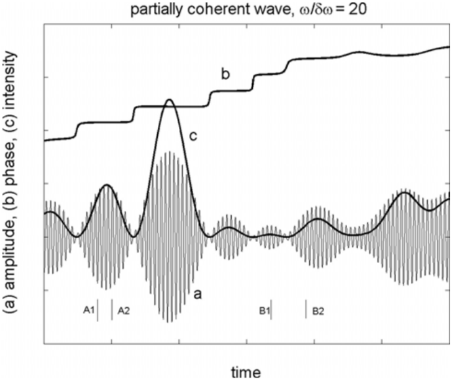
- At the time, Narrabri was a real success: measured for the first time the diameter of 32 stars (HB, Davis, Allen, MNRAS. **167**-1 (1974) 121-136)
- However **the instrument was only sensitive to stars brighter than 2.5m.** They quickly ran out of targets....

The intensity interferometry technique

- **Intensity interferometry** is most clearly understood by looking at a typical waveform of light emitted by a **quasi-monochromatic source**.

- Classical interpretation:

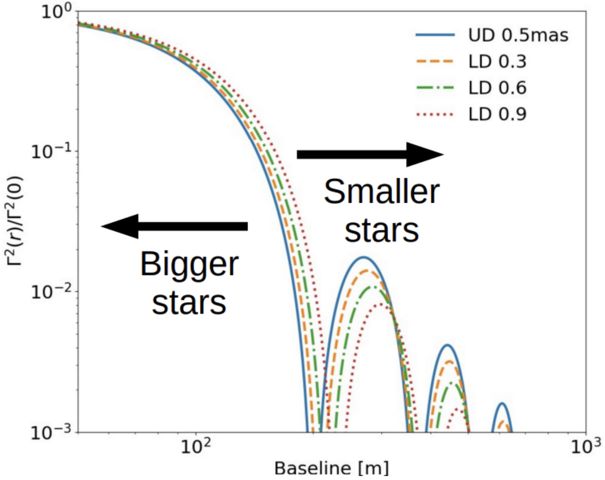
1. Quasi-monochromatic source ($\delta\omega/\omega_0 \ll 1$) of **many sinusoidal components.**
2. Randomly chosen frequencies ω within a band $\omega_0 \pm \delta\omega$
3. The coherence time τ_c, this is the time during which the phase is more or less stable, i.e., **coherence is expected**



(Labeyrie, A., Lipson, S., Nisenson, P. 2006)

- Points A1 & A2 ($\tau \ll \tau_c$): Strong correlation
- Points B1 & B2 ($\tau \gg \tau_c$): Lesser correlation

Visibility

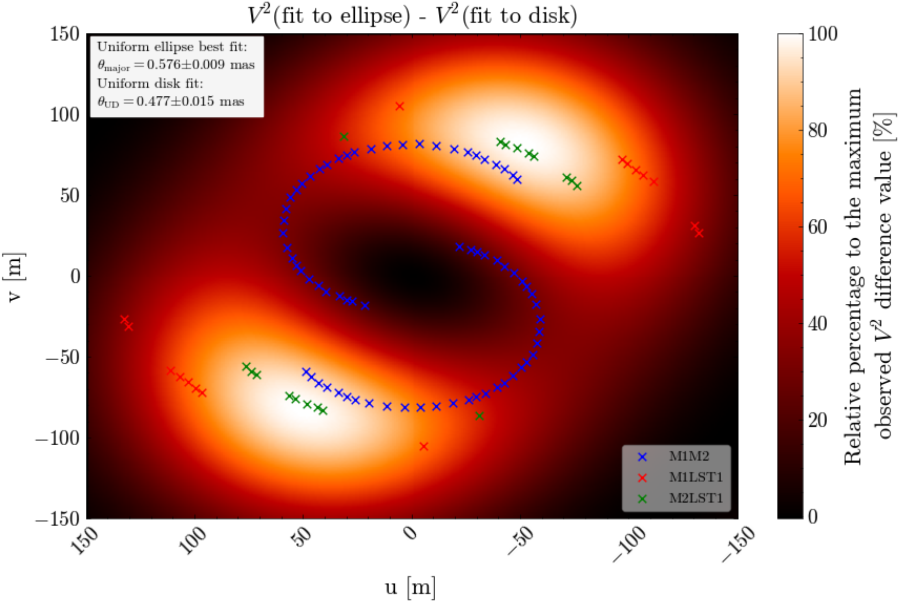


10^0
10^{-1}
10^{-2}
10^{-3}
$\Gamma^2(r)/\Gamma^2(0)$
10^2
10^3
Baseline [m]
UD 0.5mas
LD 0.3
LD 0.6
LD 0.9
Smaller stars
Bigger stars

ZBC values

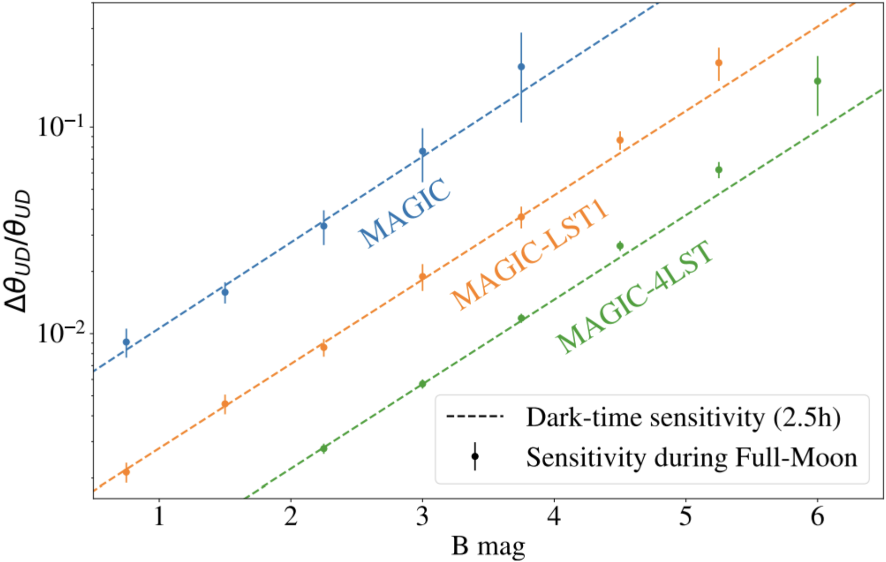
Correlation channel (Telescope pair)	Zero baseline correlation ($\times 10^{-6}$ [1/μA])
M1-251/M2-251	2.59 ± 0.05
M1-251/LST1-1	3.44 ± 0.14
M2-251/LST1-1	3.68 ± 0.09

LST-1



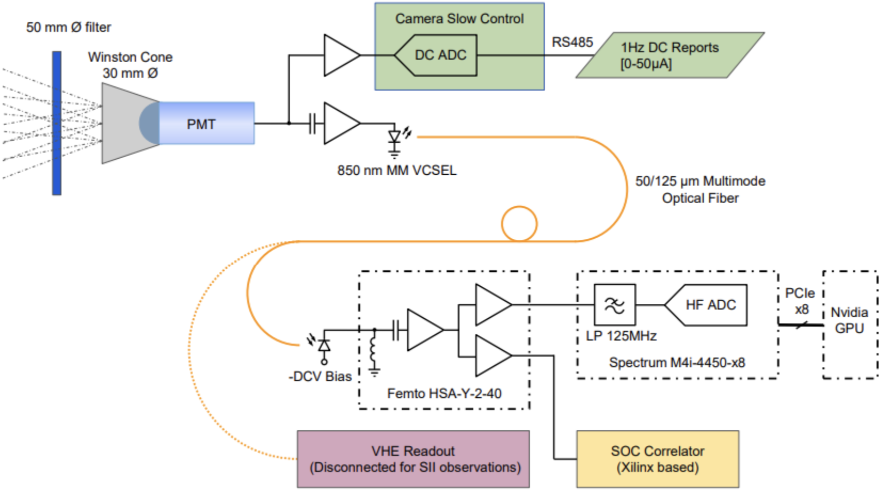
V^2(fit to ellipse) - V^2(fit to disk)
Uniform ellipse best fit:
$\theta_{major} = 0.576 \pm 0.009$ mas
Uniform disk fit:
$\theta_{UD} = 0.477 \pm 0.015$ mas
M1M2
M1LST1
M2LST1
v [m]
u [m]
150
100
50
0
−50
−100
−150
Relative percentage to the maximum observed V^2 difference value [%]

Future plans



(Proc. SPIE 12183, Optical and Infrared Interferometry and Imaging VIII, 121830C (26 August 2022))

The MAGIC+LST-1 Stellar Intensity Interferometer

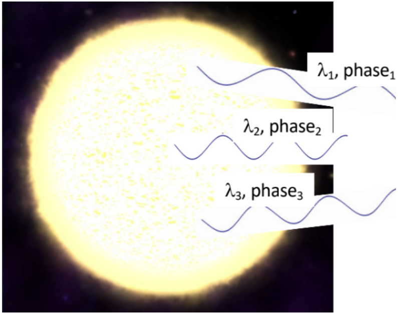


(Abe, S., Abhir, J., Acciari, V. A., et al. 2024, MNRAS **529**, 4387–4404 (2024))

The intensity interferometry technique

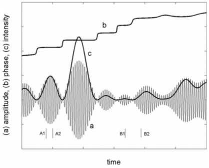
The intensity interferometry technique is based on the **measurement of the time correlation of photons** detected at telescopes distant by hundreds of meters with the goal of measuring the 2nd order of coherence of light (that of intensity, not of phase).

We look for some **tiny intensity fluctuations** between signals, i.e., some degree of modulation:



Simulation of:

- Many sinusoidal components
- unit amplitude
- Randomly chosen frequencies within a band $\nu_0 \pm 0.05 \cdot \nu_0$



One can see many different time scales: from $1/\nu_0$ to the longest for the two components that happen to be closest in frequency, $1 / (\nu_i - \nu_j)$
For a continuum in $\nu_0 \pm \Delta\nu_0$ there is always some degree of modulation for **any** time scale

Credit: Juan Cortina (IAC & CIEMAT)

The intensity interferometry technique

Van Cittert-Zernike theorem

When observing a thermal (non-coherent) light source through a narrow spectral band, the coherence of light measured between two points is proportional to the **Fourier transform of the intensity pattern of the source** at the distance between two points in units of wavelength. In the case of non-polarized light this relationship follows the equation:

$$g^{(2)}_{1,2} = \frac{\langle I_1(t) \cdot I_2(t+\tau)\rangle_{\mathrm{t}}}{\langle I_1(t)\rangle \cdot \langle I_2(t+\tau)\rangle_{\mathrm{t}}} = 1 + \frac{\Delta f}{\Delta \nu} \cdot \left|V_{1,2}(\tau)\right|^2 \qquad (1)$$

where $g^{(2)}_{1,2}$ is the **second-order intensity correlation** and $V_{1,2}(\tau)$ is the Fourier transform of the source intensity pattern and is also called **visibility.**

The intensity interferometry technique

Normalized contrast of the visibility pattern:

$$c(d) = g^{(2)}_{1,2} - 1 = \frac{\Delta f}{\Delta v} \cdot \left|V_{1,2}(d)\right|^2 \rightarrow \frac{c(d)}{c(0)} = \left|V_{1,2}(d)\right|^2 \qquad (2)$$

where c(0) is a normalization correlation factor called **zero-baseline correlation (ZBC).**

The intensity interferometry technique

Intensity interferometry allows the **determination of amplitude** of the squared visibility for a stellar object, **but not of its phase**.

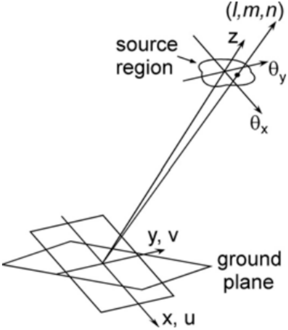
- The modulus of the visibility can take different forms depending on the brightness distribution of the source:

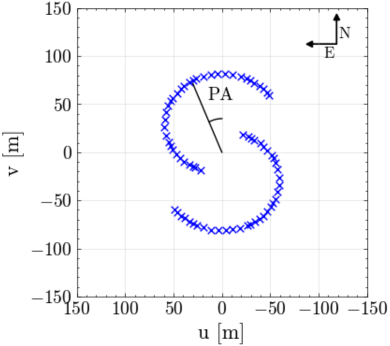
$$|V(d)| = 2 \cdot \frac{J_1\left(\pi \cdot d \cdot \theta_{\mathrm{UD}}/\lambda\right)}{\pi \cdot d \cdot \theta_{\mathrm{UD}}/\lambda} \tag{3}$$

$$|V(r)| = \frac{J_1\left(2\pi \cdot a \cdot r\right)}{\pi \cdot a \cdot r} \tag{4}$$

The intensity interferometry technique

Depending on the arrangement of the telescopes with respect to the source, it will be observed at different angles to the the stellar projection on the sky, or as it is known in interferometry **position angles (PA)**.



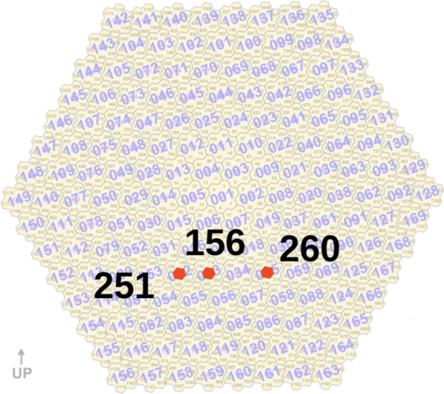


(Labeyrie, A., Lipson, S., Nisenson, P. 2006, in An introduction to optical stellar interferometry (Cambridge University Press))

The MAGIC+LST-1 Stellar Intensity Interferometer

Credit: Juan Cortina (IAC & CIEMAT)

Credit: Irene Jiménez Martínez (MPP)



Observables and data acquisition

The digitized signal is later processed by the GPU-correlator which computes the **Pearson's correlation factor** as:

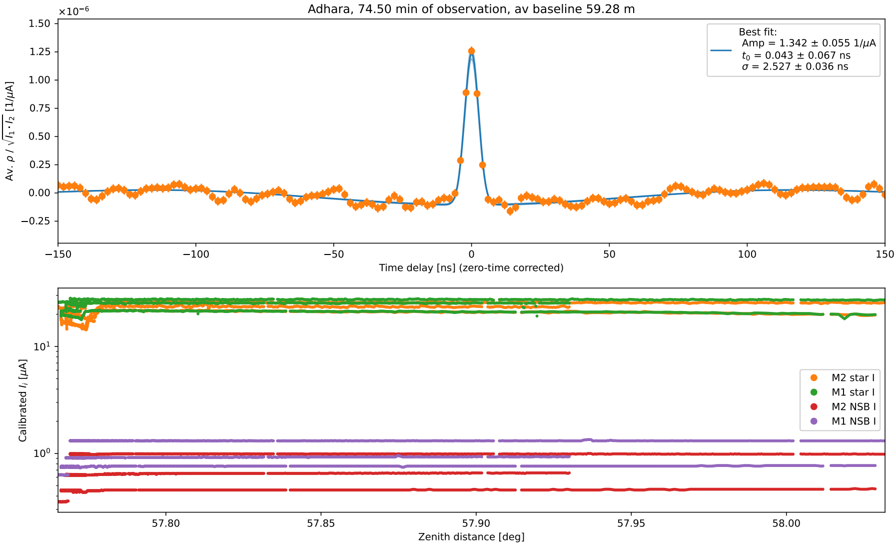
$$\rho(\tau) = \frac{\langle (I_1(t) - \langle I_1 \rangle) \cdot (I_2(t+\tau) - \langle I_2 \rangle) \rangle}{\sqrt{\left\langle (I_1(t) - \langle I_1 \rangle)^2 \right\rangle} \sqrt{\left\langle (I_2(t+\tau) - \langle I_2 \rangle)^2 \right\rangle}} \tag{5}$$

Observables and data acquisition

The **contrast c**, which is **proportional to the squared visibility**, is defined:

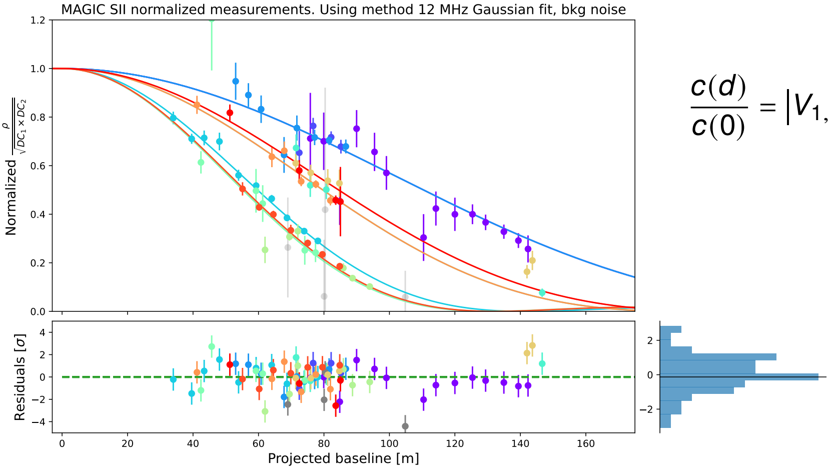
$$V^2 \propto c = \frac{\langle (I_1(t) - \langle I_1 \rangle) \cdot (I_2(t+\tau) - \langle I_2 \rangle) \rangle}{\langle I_1(t) \rangle \cdot \langle I_2(t+\tau) \rangle_{\mathrm{t}}} = K \cdot \frac{\rho(\tau_0)\beta\sqrt{G_1 G_2}}{\sqrt{DC_{1,\mathrm{Star}} DC_{2,\mathrm{Star}}}} \quad (6)$$

where K is a **constant**, ρ is the **Pearson's correlation factor** at the delay τ_0 where the signal is expected, G_{i} are the **gains of the PMTs**, $DC_{\mathrm{i,Star}}$ are the **DCs of the pixels** for which the starlight has been focused into and β is the **ratio between the light coming from the night-sky background (NSB) and the star.**



Adhara, 74.50 min of observation, av baseline 59.28 m
Best fit:
Amp = 1.342 ± 0.055 1/μA
t_0 = 0.043 ± 0.067 ns
σ = 2.527 ± 0.036 ns
Av. ρ / $\sqrt{I_1 \cdot I_2}$ [1/μA]
Time delay [ns] (zero-time corrected)
Calibrated I_i [μA]
M2 star I
M1 star I
M2 NSB I
M1 NSB I
Zenith distance [deg]

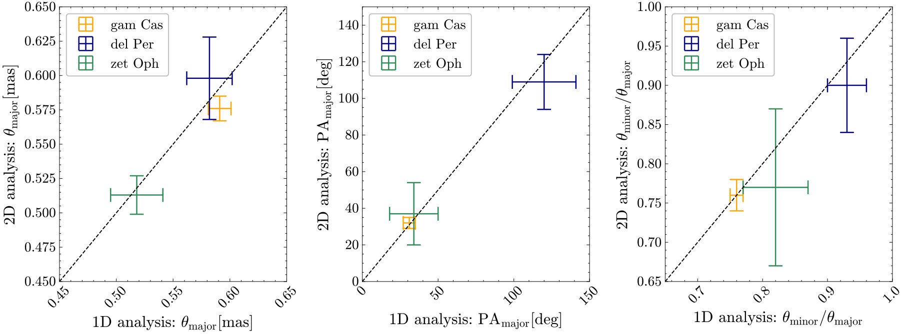
Zero baseline correlation determination



$$\frac{c(d)}{c(0)} = \left|V_{1,2}(d)\right|^2$$

Using calibrator stars

Results


gam Cas
del Per
zet Oph
0.650
0.625
0.600
0.575
0.550
0.525
0.500
0.475
0.450
0.45
0.50
0.55
0.60
0.65
2D analysis: θ_{major} [mas]
1D analysis: θ_{major} [mas]
140
120
100
80
60
40
20
0
50
150
2D analysis: $\mathrm{PA}_{\mathrm{major}}$ [deg]
1D analysis: $\mathrm{PA}_{\mathrm{major}}$ [deg]
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.7
0.8
0.9
1.0
2D analysis: $\theta_{\mathrm{minor}}/\theta_{\mathrm{major}}$
1D analysis: $\theta_{\mathrm{minor}}/\theta_{\mathrm{major}}$

What's limiting us?

Angular resolution ∝ 1 / Baseline

$$\text{Sensitivity} \propto S_{mirror} \cdot QE_{pixel} \cdot F_{pixel}^{-1} \cdot N_{telescopes} \cdot \sqrt{\text{Bandwidth}} \cdot \sqrt{N_{spectral\_channels}}$$

Mirror area

Quantum efficiency of photodetector

Number of telescopes

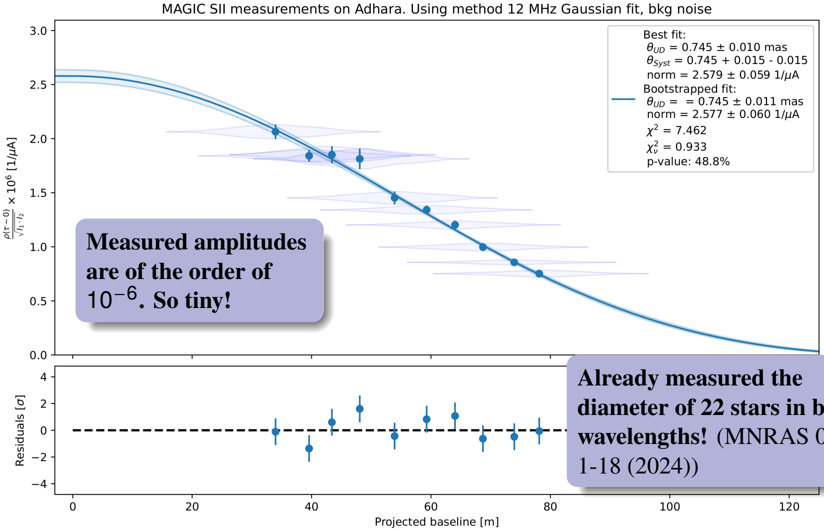
1/ sqrt(Photodetector Time resolution)

sqrt (Num spectral channels)

Amazing feature of intensity interferometry: one can split light in more and more narrower spectral channels and sensitivity is the same for each spectral channel

Slide from Juan Cortina (IAC & CIEMAT)

MAGIC+LST-1 Science Results



Measured amplitudes are of the order of 10^{-6}. So tiny!

Already measured the diameter of 22 stars in blue wavelengths! (MNRAS 000, 1-18 (2024))

Fast rotators

Establishing a link between fast rotators and cosmic-ray accelerators is essential. Many gamma-ray binaries host fast rotators, whose deformations will help us better understand stellar winds, accretion disks, and particle acceleration mechanisms.