

Intensity interferometry observations of stars with sub-100 ps photodetectors and individual mirror facets in MAGIC

Fernando Frías García-Lago (fernando.frias@iac.es)
for the MAGIC collaboration

HPDs team

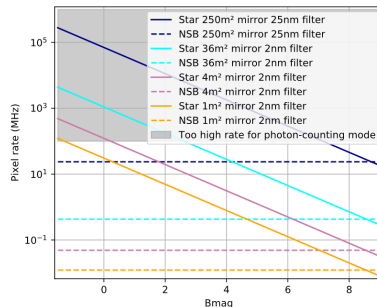
J. Cortina, T. Hassan, J. Bernete, M. Polo, C. Díaz, I. Brunelli, D. Cuenda, M. Molero

The optics of an IACT

IACTs were optimised for γ -ray astronomy.

Design choice	Price for SII
$f/D \approx 1\text{--}1.3$	Light arrives in a $\sim 25^\circ$ cone; interference filters shift and grow tails, so passbands stay at 10–20 nm
Large PSF $\sim 0.1^\circ$ due to large size of γ -ray shower	Large night sky background
Whole dish on one pixel	GHz rates on bright stars, so photon counting is impossible and we correlate waveforms
ns PMTs, 125 MHz readout	The electronic bandwidth caps the correlation S/N

None of these is fundamental. All four follow from pointing the whole dish at a single pixel.



Rate per pixel vs B magnitude.

From Cortina et al. 2025, PASP 137, 125004

2025 Workshop: the Butterfly's Eye Camera for SII

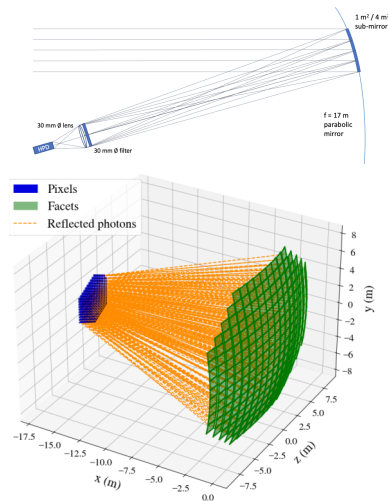
- Presented last year, inspired by:
 - QuantEye (arXiv:astro-ph/0511027)
 - I3T (MNRAS 505/2 (2021) 2328)
- Incidence angle drops below $2^\circ \Rightarrow \sim 1$ nm filters become usable
- Rate per pixel drops by orders of magnitude $\Rightarrow$ photon counting becomes possible
- Baselines of 1–17 m $\Rightarrow$ angular scales 2–40 mas, unreachable with two telescopes baselines

	sub-mirror	pixels	optical time spread
B1	1 m ²	250	<1 ps
B2	4 m ²	64	~ 80 ps
B3	36 m ²	7	~ 60 ps

Time spread of the configurations studied

Predicted sensitivity gain $\times 4\text{--}6$ (~ 2 magnitudes).

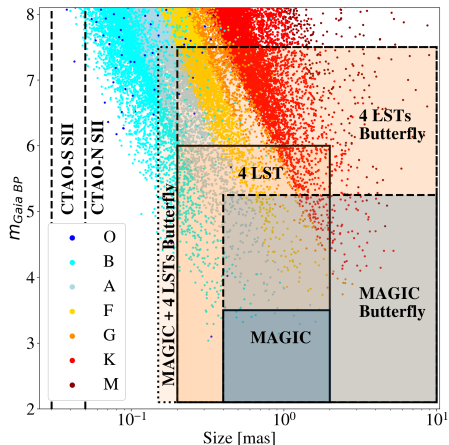
Now published: **PASP 137, 125004 (2025)**.



I3T concept applied on MAGIC-2.

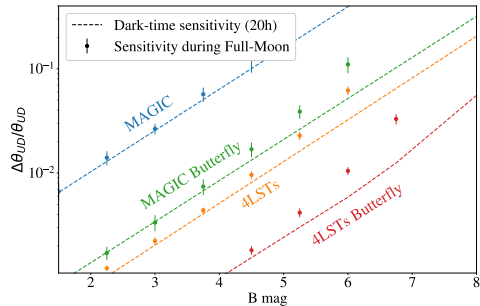
From Cortina et al. 2025.

2025 Workshop: the Butterfly's Eye Camera scientific impact



The limiting magnitude (corresponding to a 3% relative uncertainty over 20 h) and angular resolution is shown for different arrays of IACTs,

From Cortina et al. 2025.



Relative uncertainty of measured stellar diameters as a function of their B magnitude, considering the sensitivity boost achieved with the Butterfly camera.

From Cortina et al. 2025.

2026 Workshop: observational setup and first on-sky results

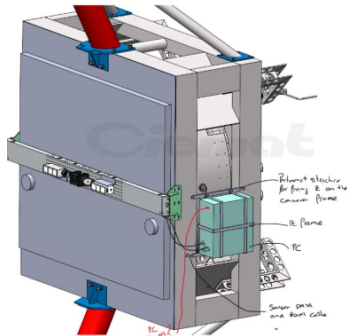
Laboratory

Two HPDs, different diaphragms, filters, a 50:50 beam-splitter and a correlator.



Hardware

A two-pixel module built at CIEMAT and mounted on the MAGIC-2 camera lid.



On-sky

Observational campaigns in La Palma with bright stars

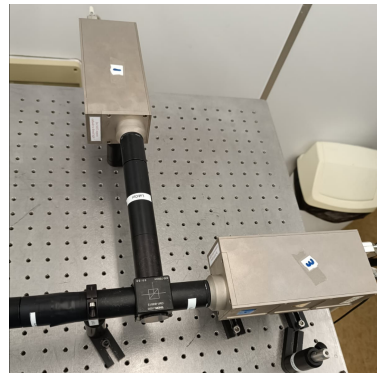


The concept requires ~ 1 nm filters *and* photodetectors with **TTS below 100 ps**. Neither had been demonstrated on an IACT.

Becker & Hickl HPM-100-06

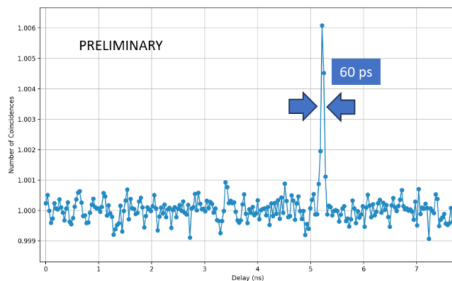
Sensitive	290-600 nm
Peak QE	28 % at 400 nm
Time Resolution TTS FWHM	<20 ps
Dark counts	100 to 400 s ⁻¹
Overload shutdown	> 15 MHz
Cathode Diameter	6 mm

Selection inspired by SII observations of *V. Leopold*, *S. Karl et al*, *arXiv:2408.08173*. Readout and correlator also provided by the same company: SPC-QC-104.



IAC optics laboratory detail: cube beamsplitter 50:50 and each arm feeds one bare HPD.

Correlation signal at the laboratory



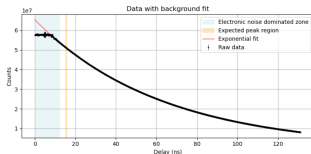
Configuration used in this measurement:

- Hg lamp, targeting 404,7 nm line
- Filters: Semrock LL01-407-25D centred at 407 nm with FWHM $\sim$ 2 nm *manually tilted* + Thorlabs FBH405-10 which transmits only in the range 400-410 nm.
- 50 μ m diaphragm that ensures $V^2 \sim 1$
- 1 h observation
- Background normalized with a previous measurement

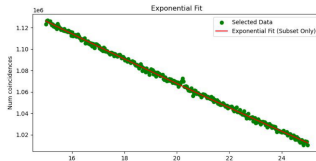
- As [Juan showed in 2024](#), laboratory characterization has been going on for several years already.
 - Each delay bin is 32 ps
- $\Rightarrow$ Correlation peak FWHM $\sim$ 60 ps
- Depending on the light source and setup, $g^{(2)} - 1$ ranges from
 - 2 nm filter and broadband LED $\Rightarrow$ 3 ‰
 - 0.37 nm filter and broadband LED $\Rightarrow$ 8‰
 - 2 nm filter and mercury lamp $\Rightarrow$ 8‰
- $\Rightarrow$ Requirements were satisfied enough to test them on the MAGIC-2 telescope.

Extracting a correlation

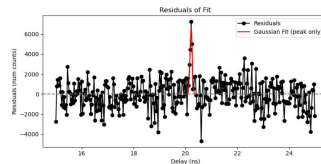
For short delays we suffer from correlated noise induced by the other photodetector and from deadtime so we work with delay > 15 ns. The following method has been used to extract correlation signals on-sky:



1. Raw coincidences vs delay



2. Exponential fit to the baseline



3. Gaussian fit to the residual peak

1. Near-exponential baseline (start-stop TCSPC statistics), the interval to the next photon goes as $Re^{-R\tau}$, a 100 ns decay constant at rate $R = 10$ MHz. Delay time of the peak depends on the longitude of the cable used.
2. Fit an exponential to the baseline away from the peak
3. Take residuals; fit a Gaussian to the peak $\Rightarrow$ number of excesses
 - RMS of the residuals away from the peak $\Rightarrow$ noise
 - Significance = excesses / RMS; $g^{(2)} - 1 = \text{excesses} / \text{baseline value at peak position}$

Summary of correlation values at the lab - March 2025

Diaphragm	Filter	Light Source	$g^{(2)} - 1$
50 μm	2 nm Semrock 407	HG lamp	8‰
50 μm	2 nm Semrock 407	Thorlabs LED	3‰
50 μm	0.37 nm Alluxa 400	Thorlabs LED	8‰

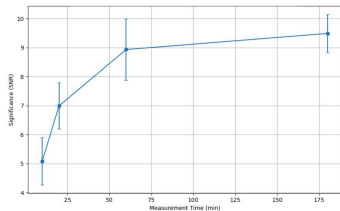
Summary of the results with some optical configurations used keeping the delay bin at 32 ps.

Thorlabs LED is the model M405L4 with peak wavelength 405 nm and FWHM $\sim$ 12 nm.

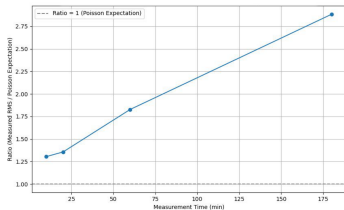
Laboratory characterization was advanced enough to test HPDs in La Palma:

- Understanding of how HPDs could be used to measure a HBT correlation signal
- Using the brightest stars on the sky we could try to replicate the results on the lab
- One important problem remained: understand origin of / model the **non-Poissonian correlated noise**

Non-Poissonian noise: observing longer does not help



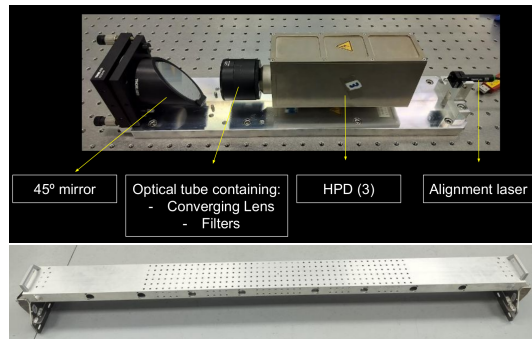
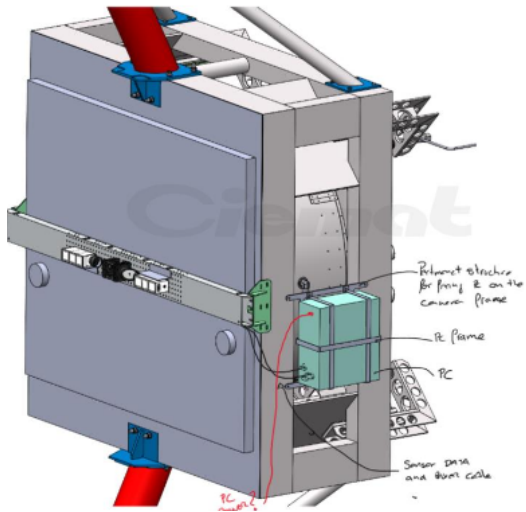
Significance vs measurement time for an excess of 7‰



Measured RMS / Poisson expectation

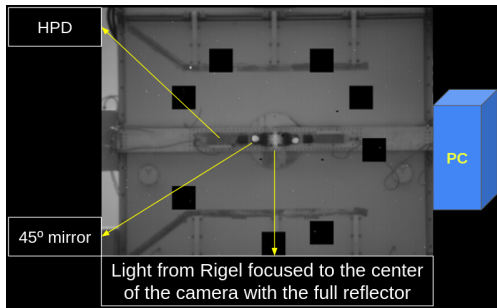
- Excesses grow linearly with T , as they should
- So does the RMS — which it should not
- The ratio climbs from 1.1 at 10 min to 2.9 at 3 h
- Significance saturates: $\sim 10\sigma$ for a 7‰ signal, $\sim 4\sigma$ for 3‰
- Different tests were carried out to try to identify some sources of this non-poissonian noise unsuccessfully so far.

HPD mechanics on the camera



Mechanical design: M. Polo, C. Díaz (CIEMAT)

Deployment on MAGIC-2

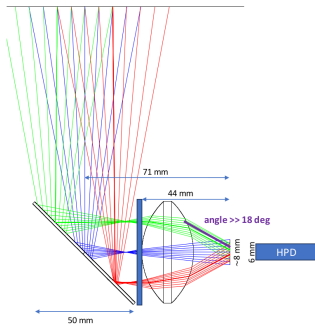


Both modules on the camera lid, seen by the Starguider camera. The DAQ PC is bolted to the camera frame.

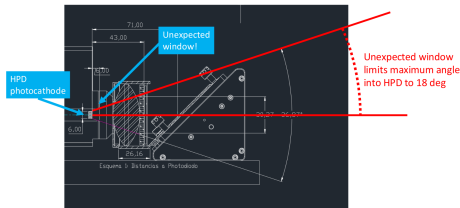
HPD-3 (left) mirror was pointing to facet (0, +2) and HPD-1 (right) was pointing to facet (0, -2). November 2025.

- It can be mounted and dismounted in around 20 minutes
- Mounted on the MAGIC-2 camera lid: we are ~ 30 cm away from the focal plane of the telescope.
- Operated from the MAGIC counting house connecting remotely to the DAQ PC attached to the camera frame.
- Campaigns run in moon breaks when γ -ray observations are not feasible.
- Whole setup is not very well protected from weather conditions. Low (~ 0 °C) temperature during winter campaigns.

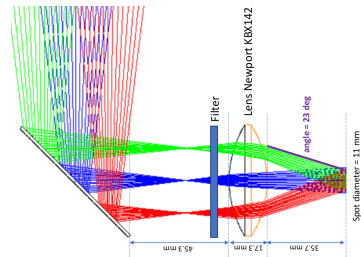
Angular geometry and optical configuration



Initial optical configuration



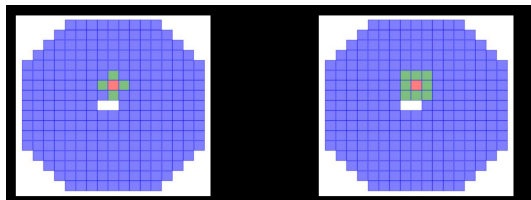
Detail of the HPD module angular geometry



One of the two new optical configurations considered. A second one uses a KBX139AR.14 Lens with $f/D = 0.7$.

Active Mirror Control and grouping of facets

- The MAGIC Active Mirror Control allows us to set the position of each facet of the reflector modifying three different coordinates (F, X, Y) with the goal of maximising the HPD rate by hand
- We also explored how the HPD rate changes if we try to focus more facets trying to include the closest ones to the central one.
- **Disadvantage:** when using more than one facet the rate increases, but correlation peak widens as it is the convolution from each individual peak slightly displaced in delay, we lose the sensitivity.



Facet groups used during November 2025 campaign. Central facet (0 +2) (red) was covered since it was used to align the setup. Left: 4 closest facets to (0 +2). Right: 8 closest ones.

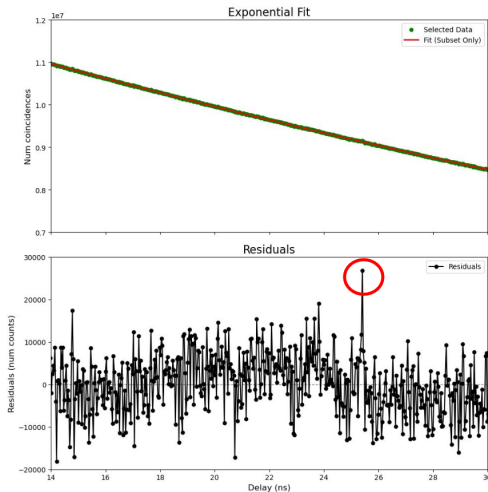
Star	B	ZD	4 facets	8 facets
Vega	0.03	43°	12 MHz	–
Capella	0.08	64°	6.2	10
Deneb	1.34	30°	4.3	6.3
Gam Cas	2.30	37°	2.9	3.8

NSB 0.2–1.1 MHz. We need $\gtrsim 10$ MHz per pixel with an individual panel, which means **Sirius and Vega**.

On-sky campaigns on MAGIC-2

Campaign	Goal	Outcome
Nov 2025	Test: one pixel module on the lid	AMC focusing procedure established
Dec 2025	Test: both modules on the lid	First correlation attempt unsuccessful
Mar 2026	Achieve detection	Sirius: first on-sky detection
Apr 2026	Test: optical configuration comparison	Lens and tube trade-offs measured
May 2026	Test: new hardware and acquisition mode	DAQ failures
Jun 2026	Detection with Vega, noise characterization	Vega excess
Aug 2026	Test: improve noise	Better understanding of the setup

First on-sky correlation: Sirius - March 2026

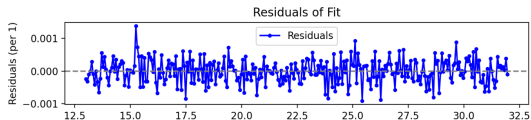


- One facet per HPD, adjacent; Semrock 407/2 nm; rates 8.5 and 15 MHz

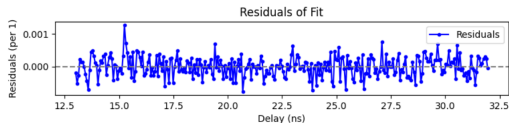
1 h on source	32 ps bins	64 ps bins
excess at	25.4 ns	25.4 ns
$g^{(2)} - 1$	3×10^{-3}	2×10^{-3}
Noise measured	8.0×10^{-4}	5.8×10^{-4}
Poissonian noise	3.3×10^{-4}	2.3×10^{-4}
SNR	3.8	3.4

Noise is expressed relative to the exponential background

- Rebinning to 64 ps costs 30% of the amplitude: the peak is narrower than 64 ps
- Non-Poissonian noise already dominates after one hour



407/2 nm, 2 h, rebinned to 64 ps, normalised with a background moon run taken in analogous conditions.



Combination of several runs with two filters, 5 h, rebinned to 64 ps, normalised with a background moon run taken in analogous conditions.

	bin	$g^{(2)} - 1$	SNR
Sirius, 1 h, 1 facet	32 ps	3×10^{-3}	3.8
Sirius, 1 h, 1 facet	64 ps	2×10^{-3}	3.4
Vega, 2 h, 2 facets	64 ps	1×10^{-3}	2.0
Vega, normalised	64 ps	1.4×10^{-3}	3.5

- Two facets per HPD, so four baselines contribute at once
- Lower $g^{(2)}$ than Sirius, as expected: the signal spreads over more delay bins
- More facets increase rate, but cost contrast

1. **The chain works end to end.** Narrow-band filtered light from individual MAGIC facets, photon counting at 10–15 MHz per pixel, correlation at the predicted delay when observing Sirius.
2. **Effective time resolution of a few tens of ps**, $\sim 90\times$ narrower than the MAGIC-SII correlation peak. The timing requirement, $\text{FWHM} \sim 60$ ps of the concept is met.
3. **We are currently limited by correlated, non-Poissonian noise** — not by photon statistics, not by the optics, not by the detectors themselves.
4. At this sensitivity we cannot yet measure $g^{(2)}$ against baseline, which is the actual goal and the reason a Butterfly camera would be worth building.

More signal

- **1 nm filter:** it doubles $g^{(2)}$ for the same non-poissonian noise.
- **Single-facet observations:** focus on this scenario, as some MAGIC panels have a better reflectivity, multi-facet observations dilute the signal too much.

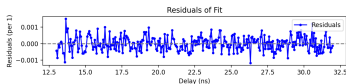
Less noise

- High-pass filtering of the correlation, as MAGIC-SII does for its own residual electronic noise
- A real background model: interleaved runs, offset dependence
- Gaussian fit over several bins instead of the peak value when working with correlations product of multi-facet observations.
- DAQ: absolute-timing mode, debug in the lab with a pulse generator rather than on the telescope

Next steps II

The LED artificial star

- Installed at the Roque, 930 m from MAGIC-2
- A source of known size, available all night, independent of weather and Moon
- Would give the zero-baseline correlation and let us study the noise floor under controlled conditions
- Needs a $\leq 100 \mu\text{m}$ diaphragm for adjacent facets to be coherent — that is the next test



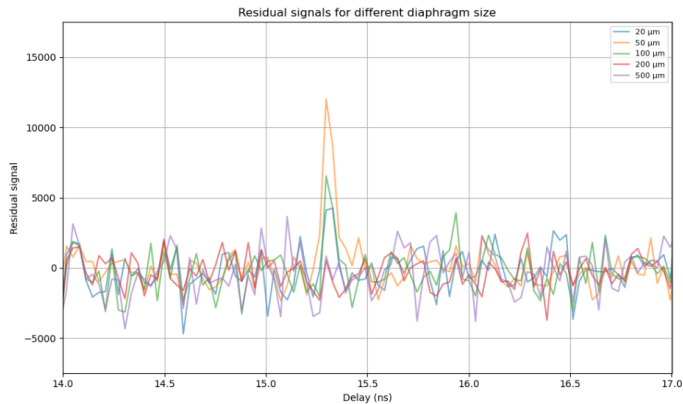
20 min observation pointing to the LED at 407 nm
with a $200 \mu\text{m}$ diaphragm: no signal yet



- Last year we proposed the Butterfly's Eye. This year we built a proof of concept: **two picosecond photon-counting pixels, each fed by a single 1 m^2 MAGIC facet.**
- Complete HBT validation in the laboratory — the signal follows the delay, follows the coherence region, and its amplitude is consistent across different source and filter combinations.
- Effective time resolution of a few tens of ps with off-the-shelf components, on a telescope built for gamma rays.
- First on-sky correlation excesses at the predicted delay with bright stars, Sirius and on Vega — preliminary, at $3\text{--}4\sigma$.
- The route to a real Butterfly camera now runs through the correlated-noise floor, while also improving our material, software and signal extraction.
- **We have demonstrated that IACTs are able to perform SII observations with $\sim 1\text{ nm}$ optical passband and sub-100 ps bandwidths.**

Backup

Backup: diaphragm study



Residuals after background subtraction showing how the correlation peak is lost as the diaphragm opens. Measurements performed in the optics laboratory with 30 minute runs using the HG lamp. Credit: Joanes Basurto.

Backup: signal-to-noise, and what the Butterfly changes

$$S/N = A \alpha q n |V(d)|^2 \sqrt{b_\nu} F^{-1} \sqrt{T/2} (1 + \beta)^{-1} \sigma$$

		MAGIC now	Butterfly
α	quantum efficiency	0.33	0.45
q	optical efficiency	0.304	0.304
b_ν	electronic bandwidth	125 MHz	2.3 GHz
F	excess noise factor	1.15	1.05
σ	spectral distribution	0.87	0.87
	filter passband	25 nm	0.5–2 nm
sensitivity gain		–	$\times 4\text{--}6$

- $S/N \propto \sqrt{b_\nu}$: bandwidth is the lever the HPDs pull, and 125 MHz $\rightarrow$ 2.3 GHz is $\times 4.3$ on its own
- $S/N \propto \sqrt{T}$ only while the noise is Poissonian, which for us it is not
- S/N does *not* depend on the width of the optical passband
- $S/N \propto A$, which tempts you to add facets — but extra facets add extra baselines and spread the signal
- N_{spectral} channels would improve S/N by $\sqrt{N_{\text{spectral}}}$: the collimated beam of a Butterfly pixel makes dichroics realistic

Backup: photodetector technologies

	TTS	sensitive area	DCR	operating T
IAC T PMTs (now)	~ 2 ns	cm	< 1 kHz	room
Fast PMTs	few 100 ps	cm	< 1 kHz	room
HPD	tens of ps	mm	< 1 kHz	room
MCP-PMT	tens of ps	cm	< 1 kHz	room
SiPM	degrades fast	cm	> 50 kHz mm $^{-2}$	$< -20^{\circ}\text{C}$
SPAD	< 15 ps	< 1 mm	> 50 kHz mm $^{-2}$	$< -20^{\circ}\text{C}$
SNSPD	< 15 ps	μm	very low	< 4 K

Backup: the correlator, and delay bookkeeping

The Becker & Hickl SPC card is a start-stop TCSPC device: a pulse on SYNC starts a clock, the next pulse on a signal channel stops it, and the interval goes into a histogram bin.

- Hence the decaying baseline: for a Poisson process at rate R the interval to the next photon is distributed as $Re^{-R\tau}$
- Hence the delay cables: they push the physics out to 15–25 ns, away from the dead-time region at short delays where the baseline is not clean
- Offset1-3 delays the signal channel and moves the peak *right*; the SYNC Offset moves it *left*

$$\tau_0 = \Delta\ell_{\text{cable}} + \text{Offset1-3} - \text{Offset}_{\text{SYNC}} + 0.16 \text{ ns}$$

- 1 m of coax $\approx 5 \text{ ns}$ (signal travels at $\sim 2/3 c$)
- Worked example, Sirius: 4 m extra on the signal channel gives 20 ns, plus Offset1-3 of 5.120 ns, gives **25.3 ns**

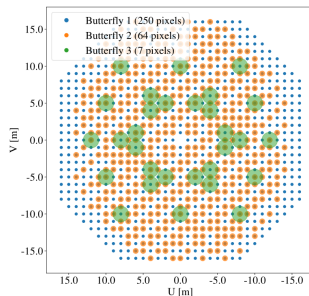
Backup: the three Butterfly configurations

	sub-mirror	pixels	camera R	spread
B1	1 m ²	250	25 cm	<1 ps
B2	4 m ²	64	25 cm	80 ps
B3	36 m ²	7	<10 cm	60 ps

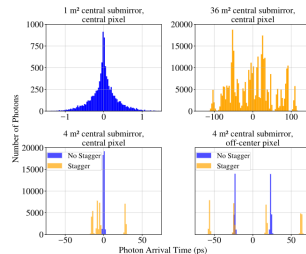
Our prototype is a **two-pixel B1**.

B2 is worse than B3 because the random stagger of the facets ($\sigma = 3.5$ mm) dominates the time spread as soon as a sub-mirror contains more than one facet.

B1 gives 229 pixel pairs at the shortest baselines — dense enough that one expects pseudo-images.

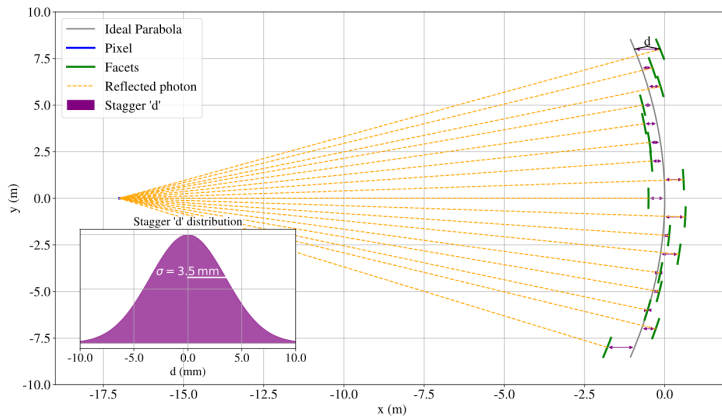


instantaneous UV coverage



simulated arrival times

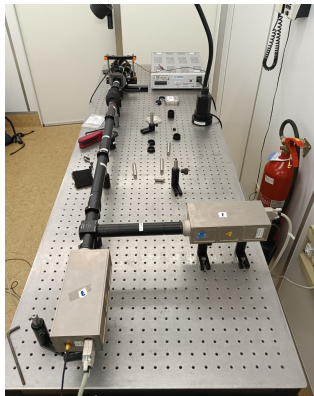
Backup: facet stagger, origin of the optical time spread



MAGIC-2 facets sit a few mm off the ideal paraboloid, Gaussian with $\sigma = 3.5$ mm. Irrelevant for gamma rays, dominant here.

MAGIC-1 is worse: its facets are installed in two layers 6 cm apart, which is why all this work is on MAGIC-2.

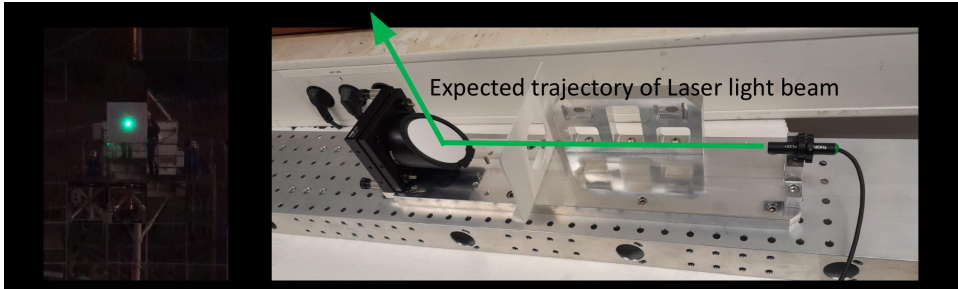
Backup: laboratory material



Along the rail, from the detector end

- Sources tried, in order: an Oriel 66001 Hg arc lamp on the 404.66 nm line, a Thorlabs M405L4 LED, and a 405 nm laser
- The Semrock 407/2 nm filter must be *tilted* to bring its passband onto the line
- Light-tightness was improved in stages: blankets, then foil over the beamsplitter, then the whole setup. Background went from 3.5×10^6 to $\sim 3 \times 10^3$ Hz

Backup: alignment on the telescope

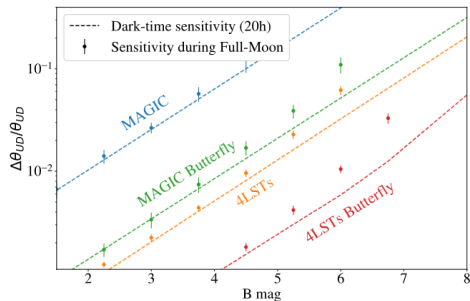


A green laser on the module bench is bright enough to be seen on the facet in daylight.

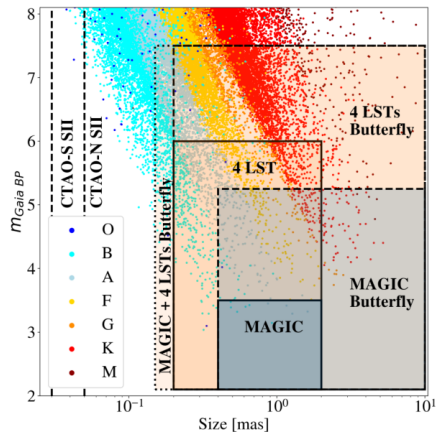
Backup: acquisition modes and the DAQ

- **FIFO** — card memory emptied to the PC every second. Every result in this talk was taken this way. Vulnerable to DMA transfer failures when the PC cannot keep up.
- **SINGLE** — data stay on the card until the run ends. More robust, but bins saturate at 65535 counts
- **Absolute timing** — every photon timestamped. The most flexible offline and the most demanding on disk throughput. Tested, never yet used for a result.

Backup: what the Butterfly camera would deliver



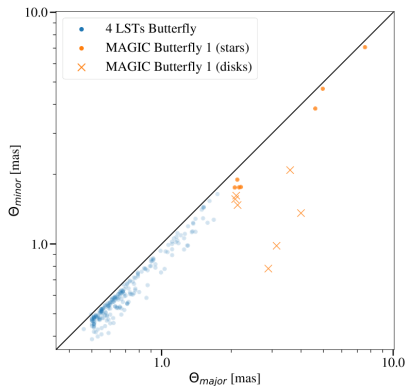
relative error on the diameter vs B magnitude



accessible stars: a $\times 9$ larger sample

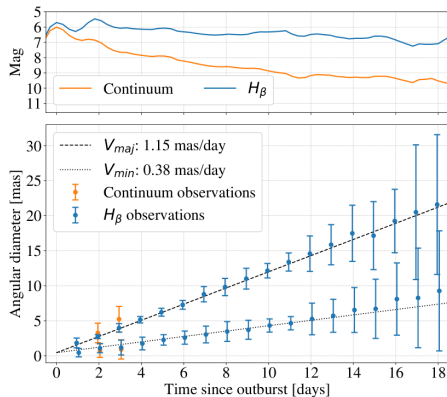
Cortina et al. 2025, PASP 137, 125004

Backup: science case I — fast rotators and decretion disks



Cortina et al. 2025, PASP 137, 125004, Fig. 10

- Oblateness gives the rotation rate, a parameter that affects stellar evolution perhaps as much as mass and metallicity
- Simulated as uniform ellipses using the oblateness and major diameter from van Belle (2012), random position angle
- 7 stars and 7 Be-star decretion disks are detectable by a *single* MAGIC Butterfly 1 in 2.5 h, to the 1% level on oblateness, diameter and position angle
- Three of them have never been studied at any wavelength
- With 4 LSTs and a Butterfly 3, the same result for a sample of 226 candidates
- A narrow H_{β} filter is what makes the disks accessible



Cortina et al. 2025, PASP 137, 125004, Fig. 11

Expanding ejecta reach

$$\Theta = 1.15 \text{ mas} \left(\frac{d}{1 \text{ kpc}} \right)^{-1} \left(\frac{v_{ej}}{1000 \text{ km s}^{-1}} \right) \left(\frac{t}{\text{days}} \right)$$

- Below 1 mas on the first night, then 2–40 mas over the following weeks — precisely the Butterfly's range
- Simulated: 1.5 kpc, peak $V = 6$, $v_{maj} = 1500$ and $v_{min} = 500 \text{ km s}^{-1}$, five hours per night
- Continuum gives $\sim 10\%$ on both expansion rates; H_β improves that to the 2% level
- One such nova per year on average, and the limitation is the magnitude, not the angular size