II observations with MAGIC & the CTAO-North LSTs

J. Cortina, A. Cifuentes & T. Hassan (CIEMAT, Madrid) for the LST and MAGIC colls.

STELLAR INTENSITY INTERFEROMETRY 2024 WORKSHOP

Outlook

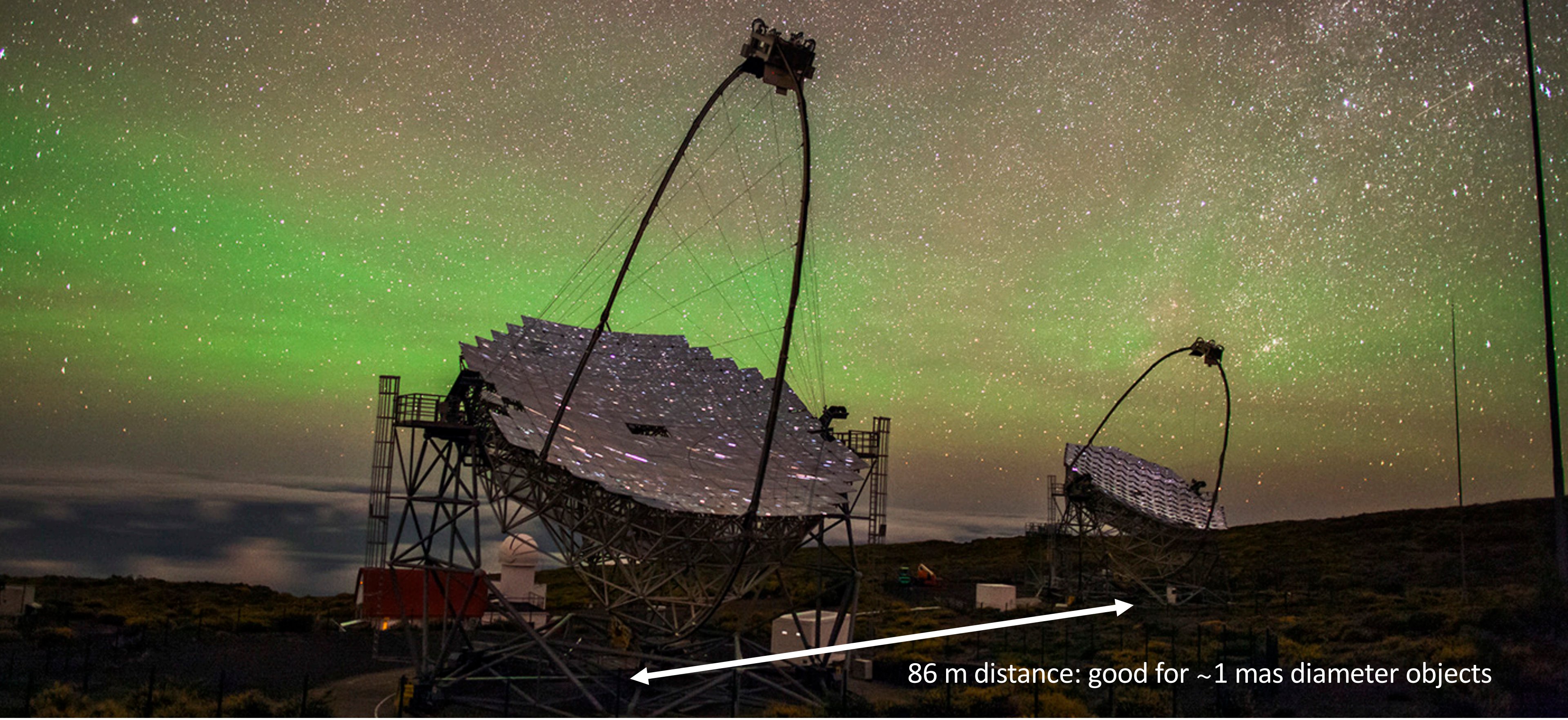
- Intensity Interferometry with MAGIC.
- Extension to CTAO LST.
- Further technical developments

The general idea

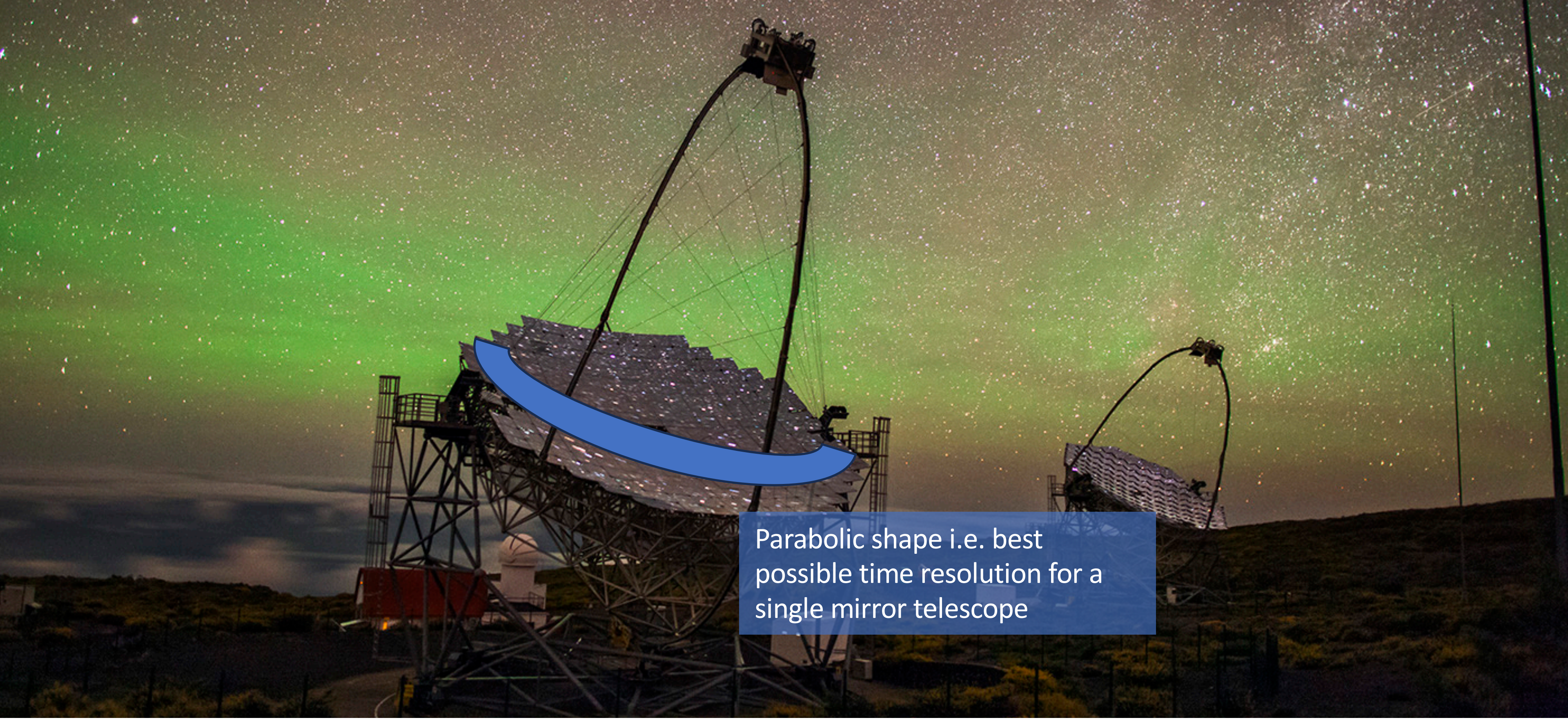
- IACTs are easy to use for **intensity interferometry:** they come in arrays and have large mirrors and fast time response.
- With MAGIC we started in 2019 (*MNRAS 491 (2020) 1540–1547*): we turned a γ-ray telescope into an interferometer with two filters and an oscilloscope.
- Our interferometer designs follow this philosophy:
  - **We don't interfere with γ-ray observations.**
  - **We can move from interferometry to γ-rays and back in <1 minute.**
  - **We re-use as much of the existing hardware as possible.**

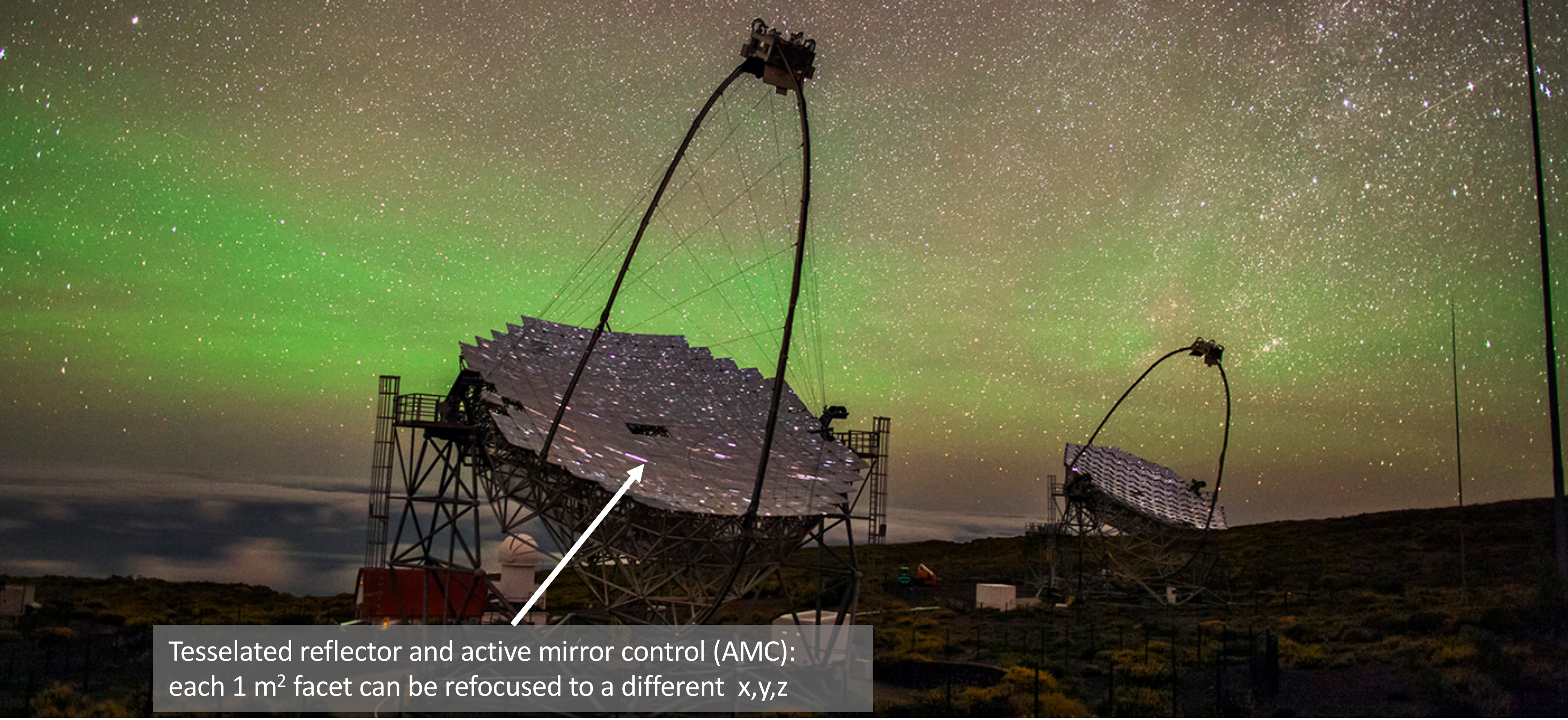
Intensity interferometry with MAGIC

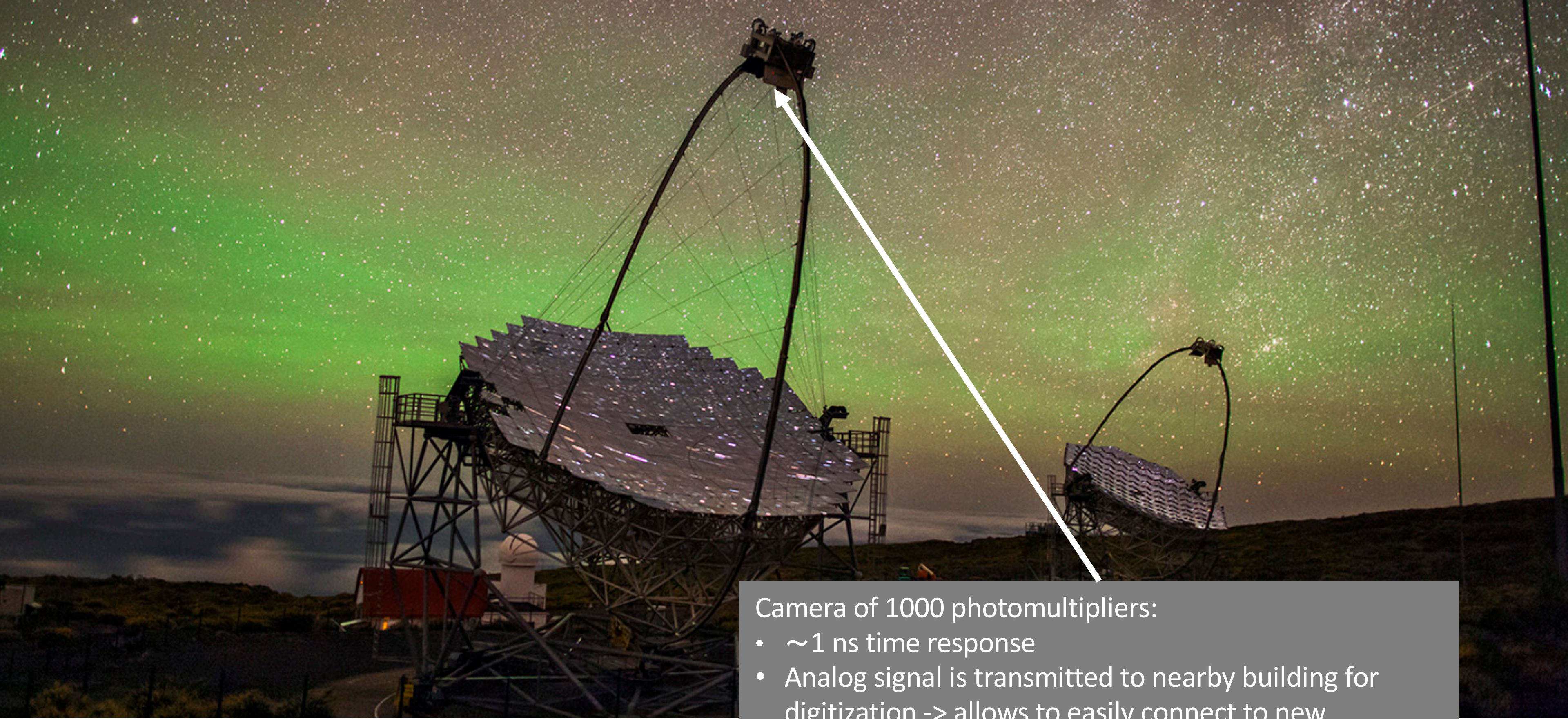
- Two 17 m diameter Imaging Atmospheric Cherenkov Telescopes (IACTs) for >50 GeV γ-ray observations *(MAGIC coll., 2016 Astroparticle Physics, 72, 61).*
- Operational since 2004 at the Roque de los Muchachos observatory on La Palma (Canary islands, Spain) .


86 m distance: good for ~1 mas diameter objects


17 m diameter: mirror area
larger than that of the largest
optical telescope


Parabolic shape i.e. best
possible time resolution for a
single mirror telescope

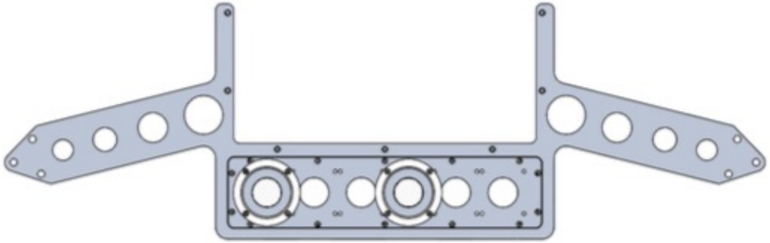

Tesselated reflector and active mirror control (AMC):
each 1 m² facet can be refocused to a different x,y,z

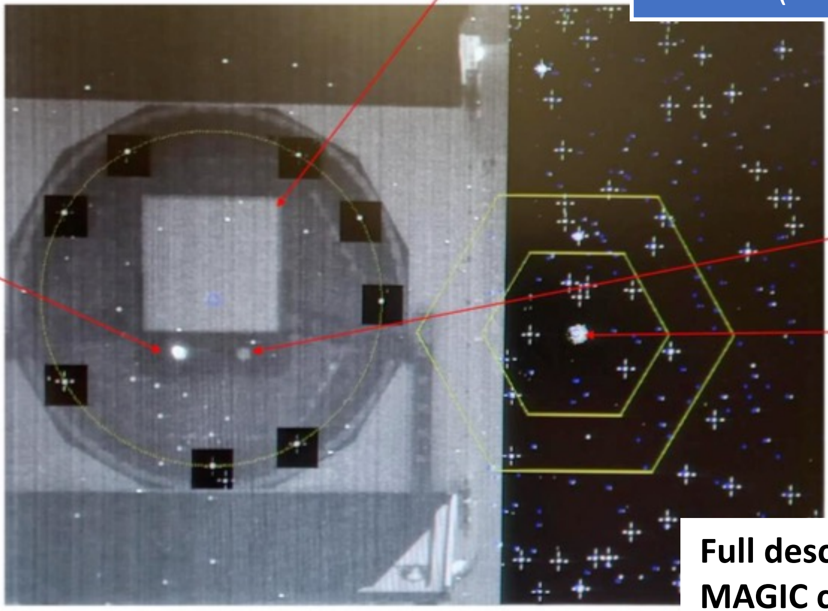


Camera of 1000 photomultipliers:
- ∼1 ns time response
- Analog signal is transmitted to nearby building for digitization -> allows to easily connect to new hardware
- Sensitive to near UV / blue wavelengths

MAGIC setup: mechanics and optics

Filters for both telescopes (Semrock centered at 425 nm, FWHM 26 nm) can now be automatically put in place along with the Spectralon target for SII observations without manual camera intervention





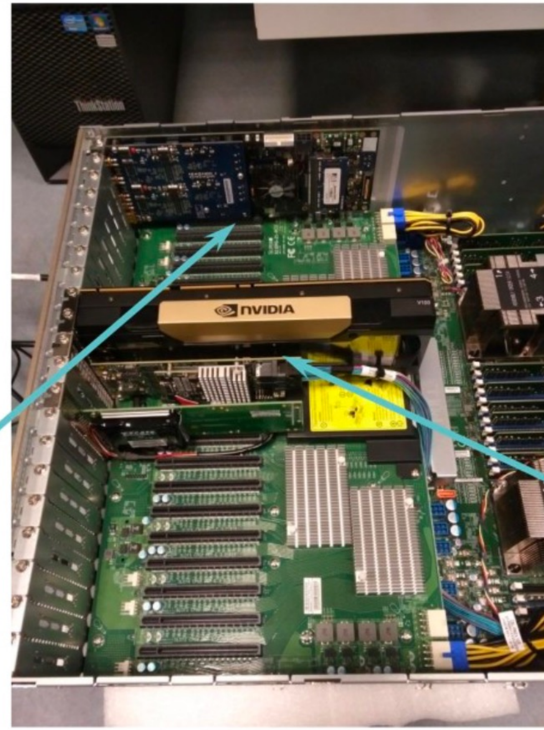
CIEMAT (C. Díaz, M. Polo)

Full description in MAGIC coll., MNRAS 11 March 2024

MAGIC setup: digitizer and correlator

Current SII Setup

- SUPERMICRO GPU SuperServer SYS- 6049GP-TRT
- NVIDIA® Tesla V100-32GB – PCIe GPU
- **2** Spectrum M4i.4450-x8 Digitizers
- **4** channels of 14 bit resolution @500MS/sec



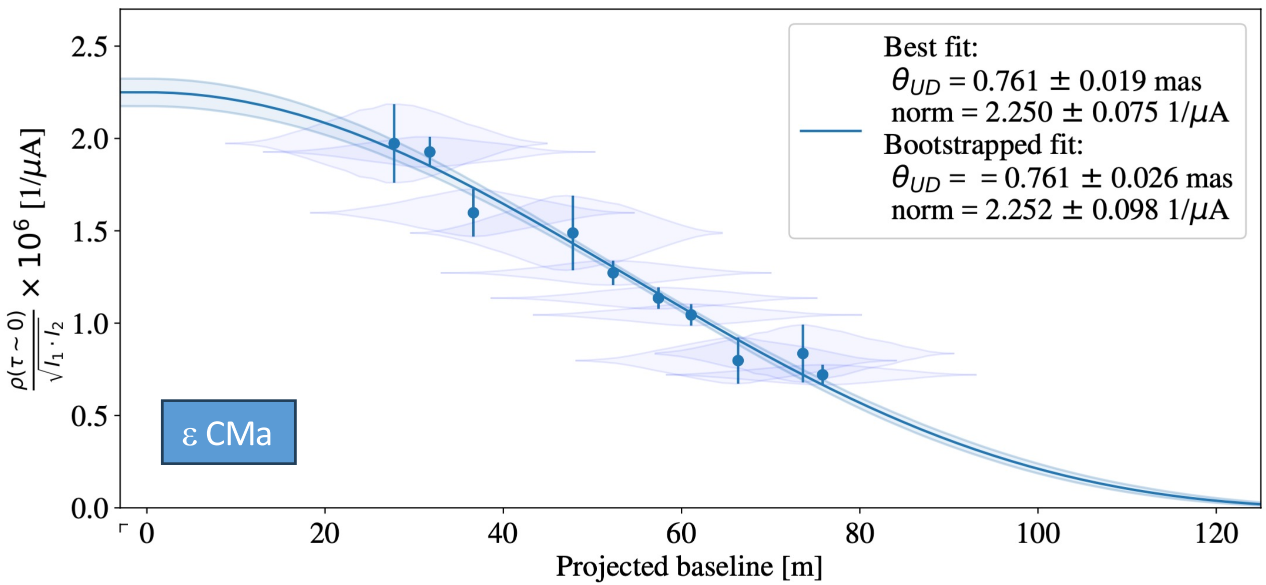
- Signals from 4 pixels sent to digitizers (labeled A, B, C and D)
- Raw data is never stored: directly sent to GPU and correlated
- Able to produce on-line correlation measurements
- Currently 6 Corr + 4 Autocorr

D. Fink
C. Delgado,
J. J. Rodriguez et al
(MPI, CIEMAT)

Full description in MAGIC coll., MNRAS 11 March 2024

First science results with MAGIC

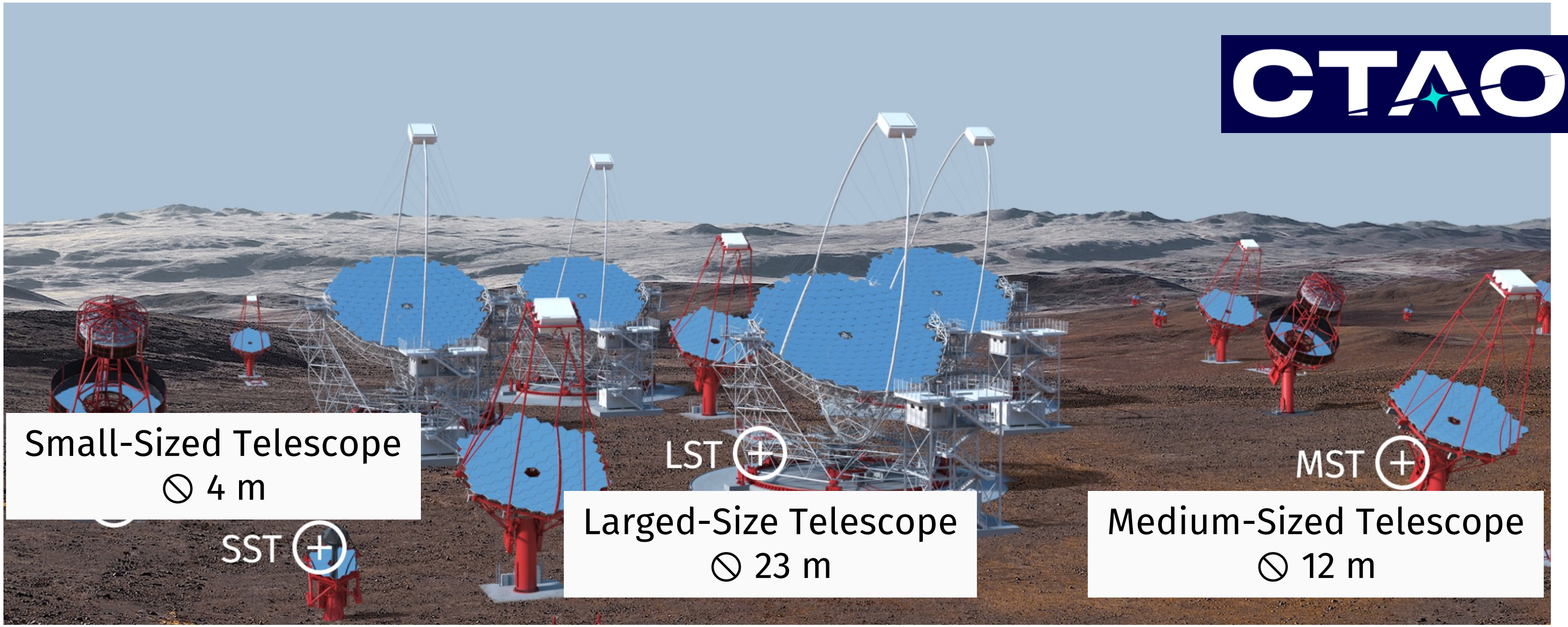
"Performance and first measurements of the MAGIC Stellar Intensity Interferometer", arXiv:2402.04755 and MNRAS 11 March 2024



Refer to Alejo's presentation for a full performance study

Extension to the LSTs

Cherenkov Telescope Array Observatory

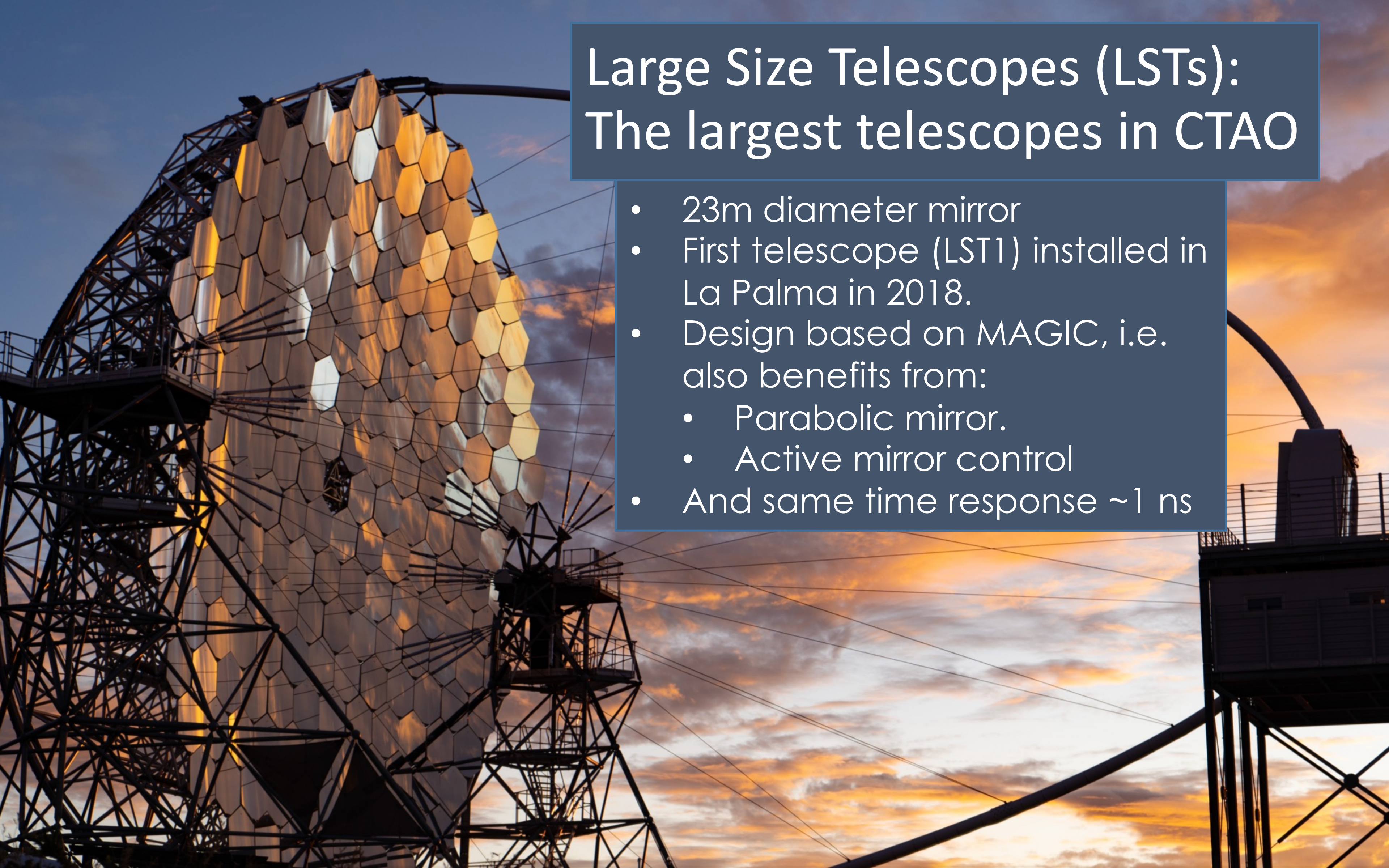


- 2 sites (La Palma in north & Paranal in the south) → full sky coverage
- 3 telescope size classes → wider energy coverage (~20 GeV – 100 TeV γ-rays)
- Tens of telescopes → Larger area i.e. higher sensitivity

We are designing instrumentation in a way that CTAO could consider to offer the stellar intensity interferometry capability in a close future.

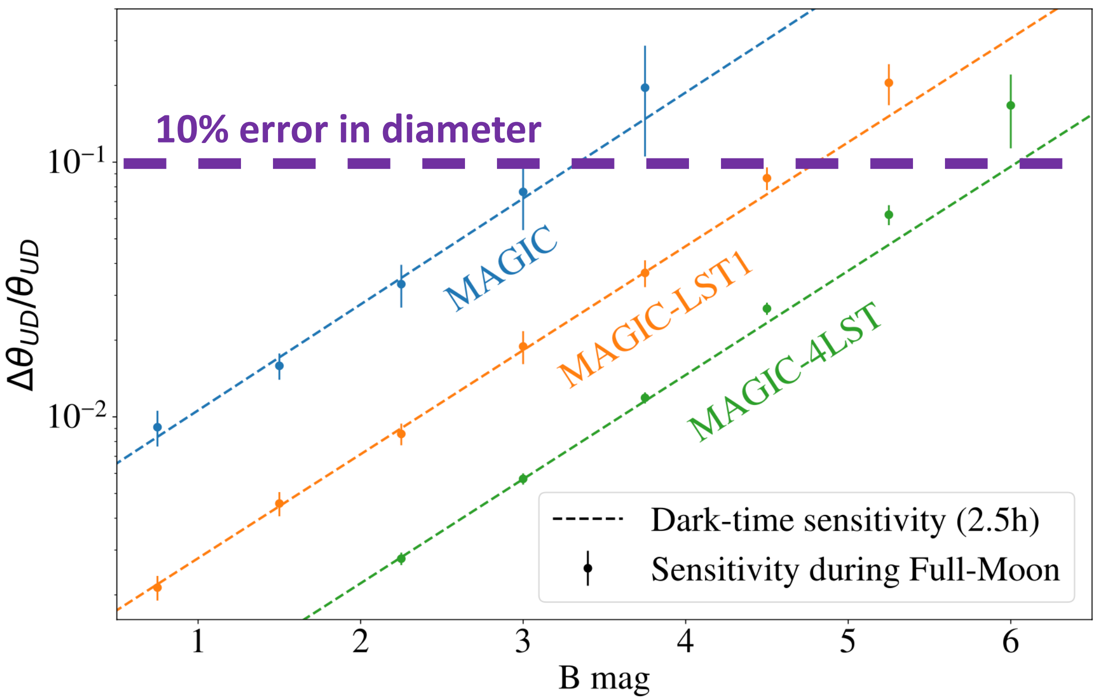
Large Size Telescopes (LSTs): The largest telescopes in CTAO

- 23m diameter mirror
- First telescope (LST1) installed in La Palma in 2018.
- Design based on MAGIC, i.e. also benefits from:
  - Parabolic mirror.
  - Active mirror control
- And same time response ~1 ns



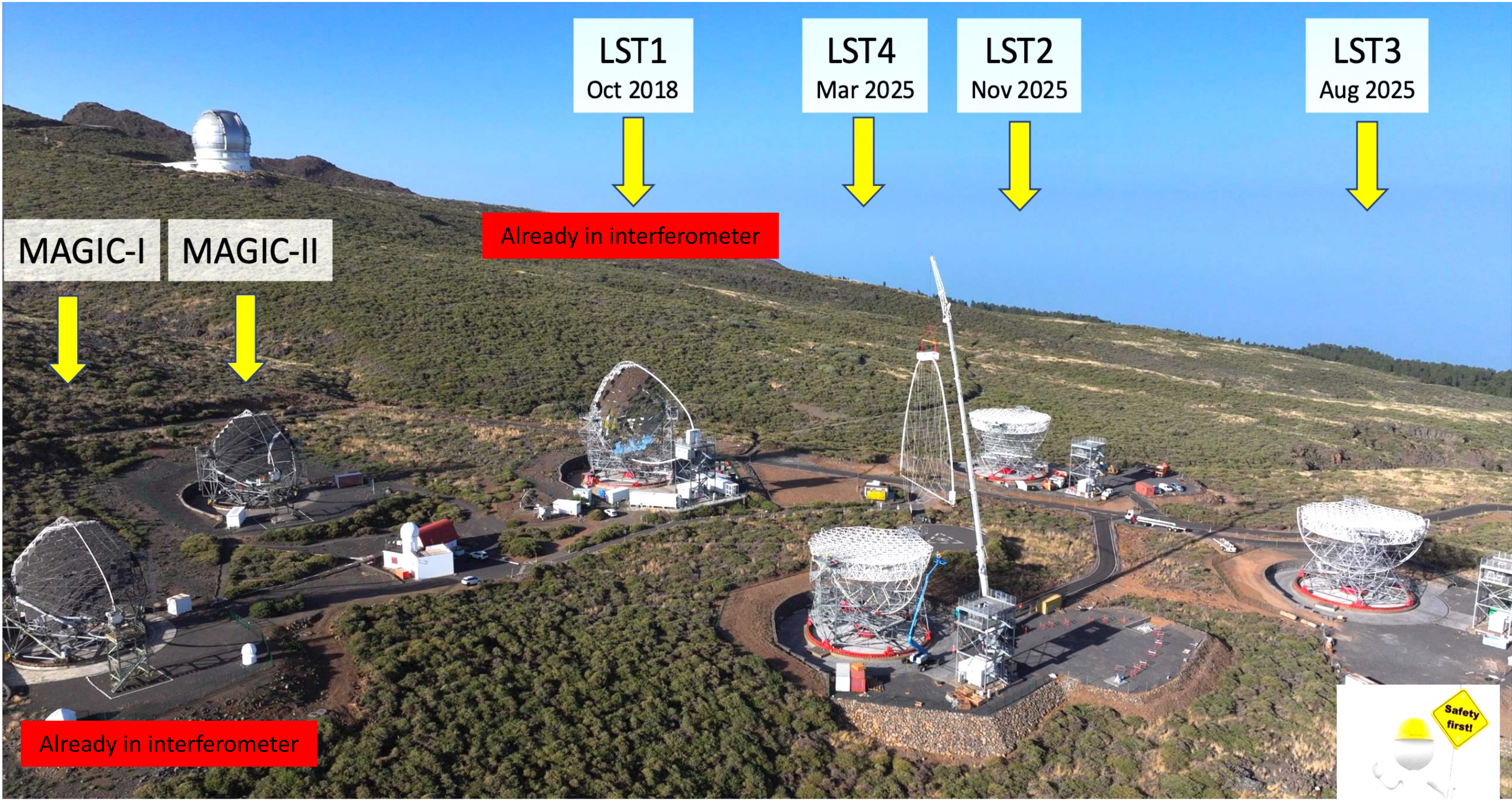
+CTA LSTs: Impact on sensitivity

MAGIC coll., MNRAS March 2024



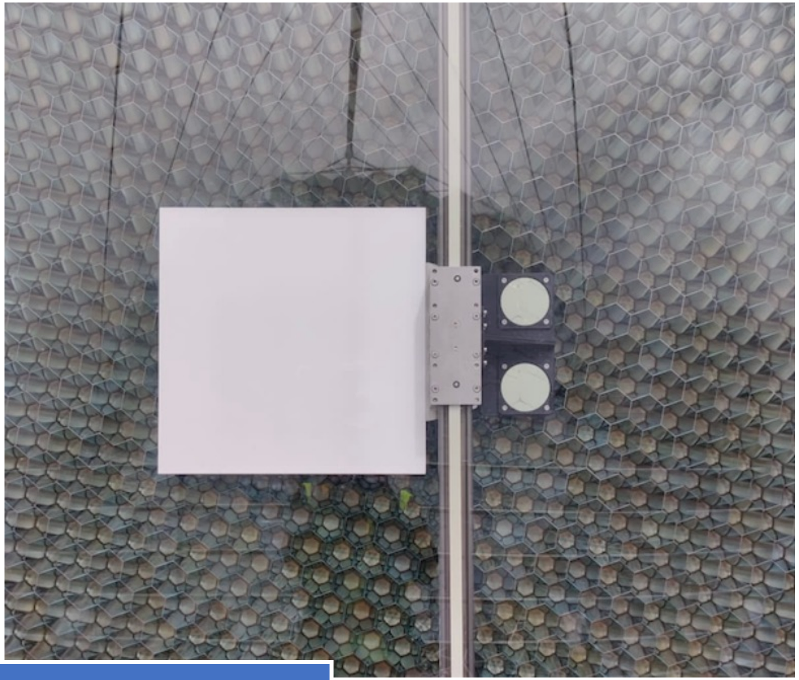
- We expect to increase sensitivity by a factor 10.
- Reach B=6^m for 10% error in diameter in 2 hours with 4 LSTs.
- T. Hassan (CIEMAT) has received an ERC Starting Grant to design and test interferometer for MAGIC+LSTs.

Ongoing deployment of the LSTs in La Palma



August 22nd, 2024

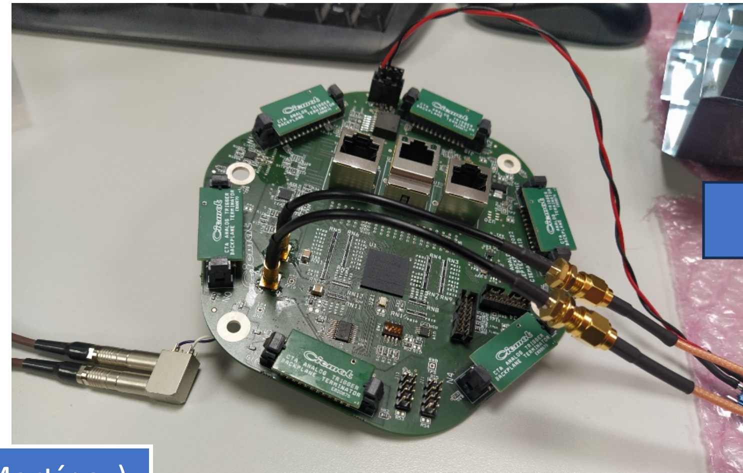
LST hardware modifications: filters



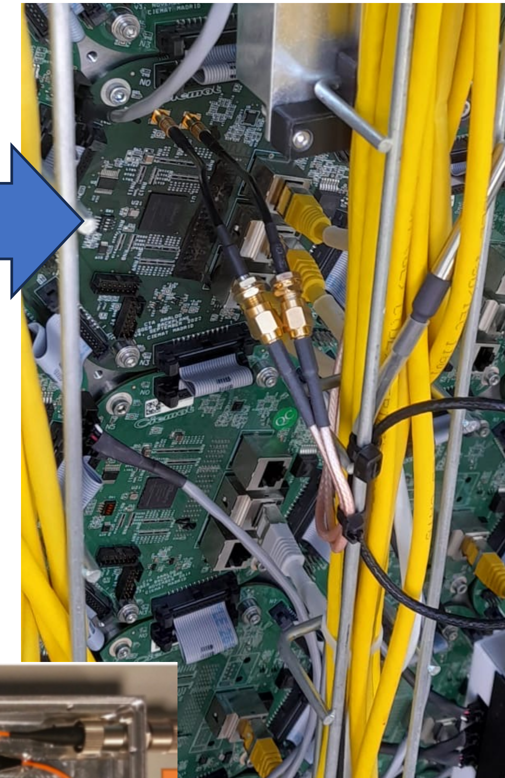
CIEMAT (C. Díaz, M. Polo)

- LST1 is equipped with a starguider screen that can be moved to any position in the camera front.
- We have modified the screen to add two 75 mm diameter filters (same Semrock model as in MAGIC).
- So far we are using one of the pixels (central one of the camera) as signal pixel and the second one to estimate the background.
- The same scheme can be extended to more pixels.

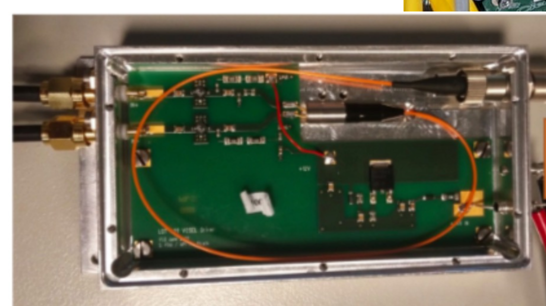
LST hardware modifications: signal transmission



CIEMAT (G. Martínez)



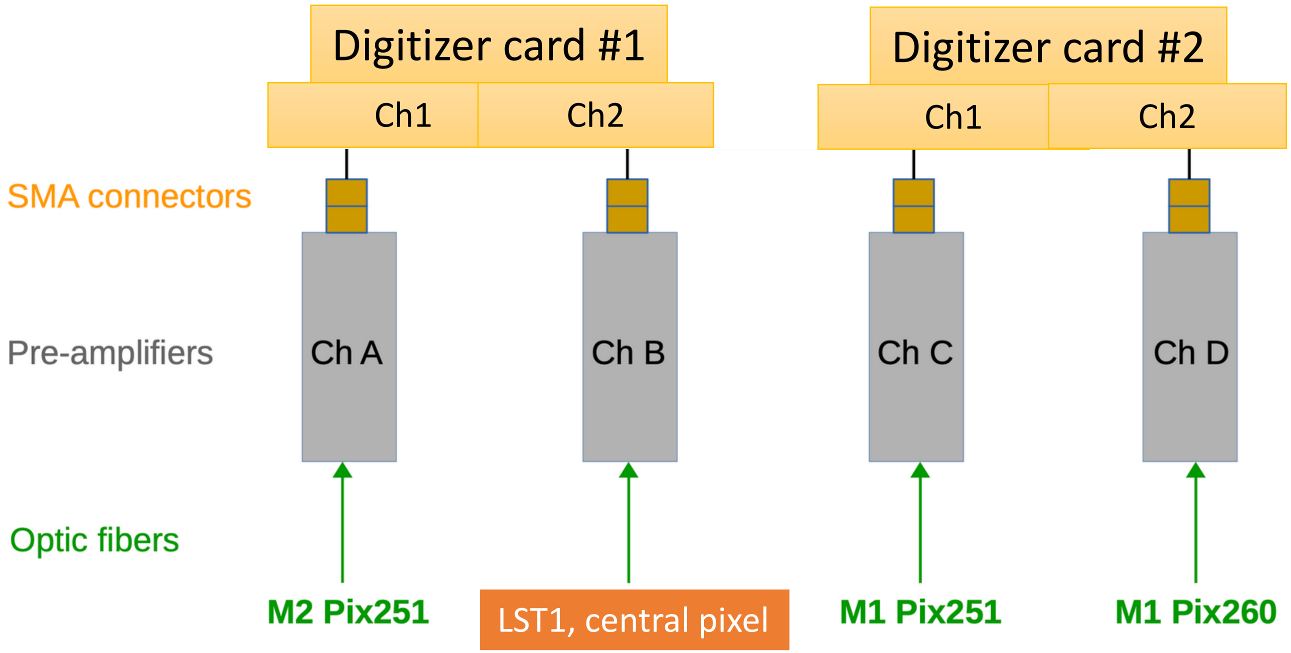
MPI Munich (D. Fink)



- One of the 7-pixel front-end trigger distribution boards was redesigned to extract a replica of a PMT analog signal.
- Optical transmitter "a la MAGIC" has been designed as small standalone box.
- Optical fiber routed to MAGIC counting house and connected to existing correlator.

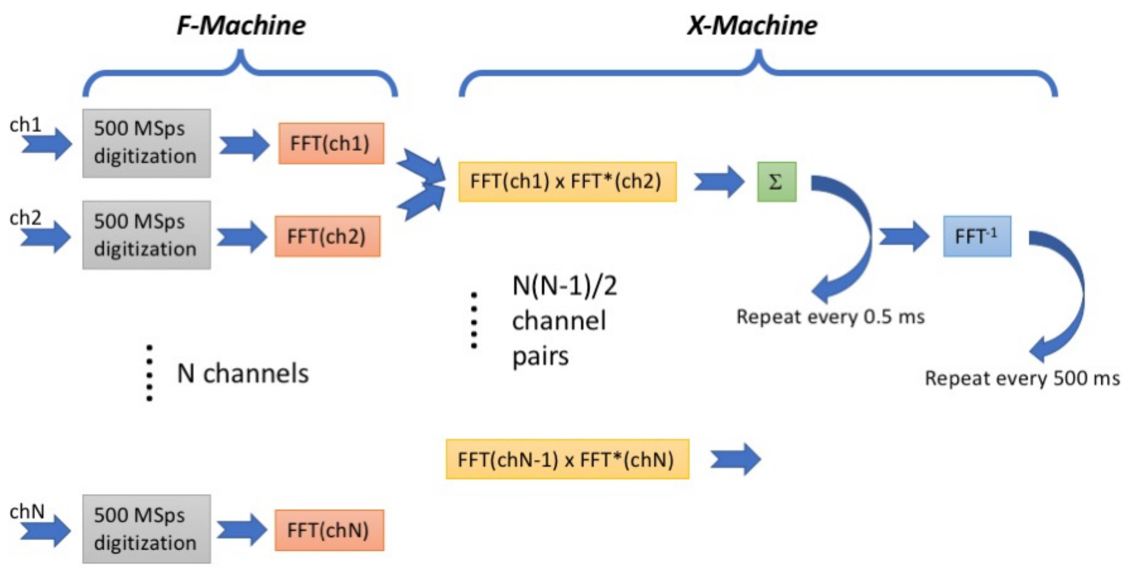
LST hardware modifications: correlator

We are re-using the same digitizers and correlator: we swapped one of the MAGIC pixels with the LST1 signal one.



Correlator upgrade for all MAGIC + 4 LSTs

- We need a significantly more powerful correlator to deal with 6 telescopes.
- We are playing several tricks in our new design. We are e.g. splitting the correlation calculation in an FFT and an inverse FFT, and performing them in different computers.

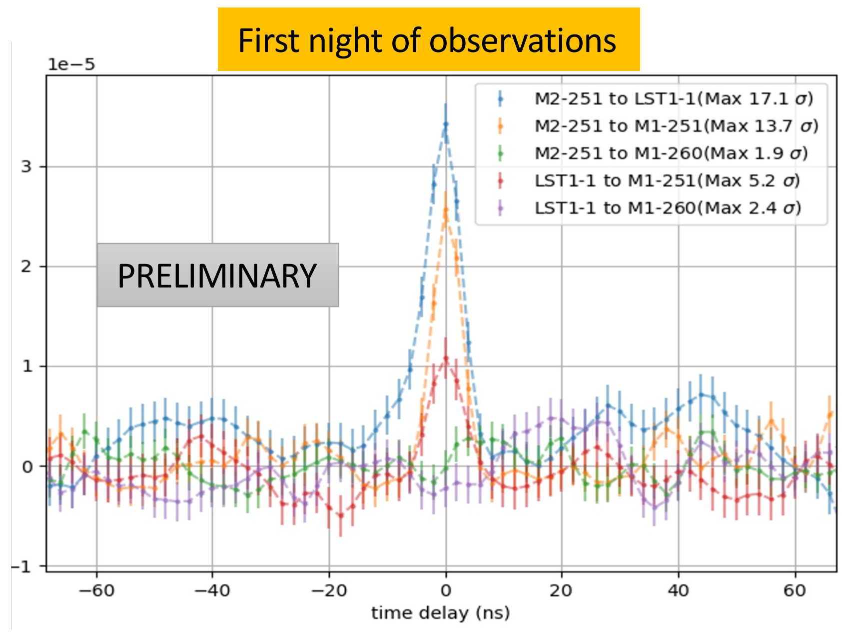


J. Cortina et al, SPIE 2022

- Most of the hardware is already delivered to La Palma for installation in MAGIC.

First MAGIC+LST1 observations

- So far a few tens of hours of common MAGIC+LST1 observations:
  - Calibration stars already detected with MAGIC (Mirzam, Adhara, kap Ori…)
  - Weaker and smaller stars, now within reach of MAGIC+LST1: $\theta<0.4$ mas
  - Fast rotators, especially with small diameter.
- See Alejo's presentation for first results.



NectarCAM: MSTs in the north

Slide shamelessly stolen from
J. Biteau, IJCLab / Univ. Paris Saclay
Please listen to his talk ☺

Routing of the signal *Julie, Alex, Oscar*

- from camera to telescope pedestal ✓

Definition and mounting of filters *Kevin*

- full compatibility with LST ✓

Anode signal → Optical fiber *Kale, François, David*

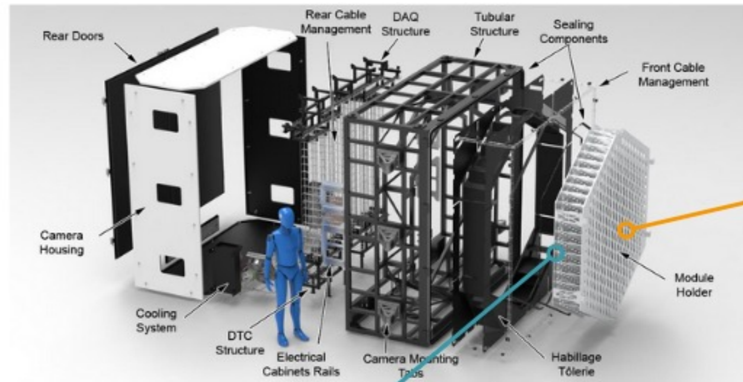
- signal conditioning ✓
- signal degradation to be measured

NectarCAM operation

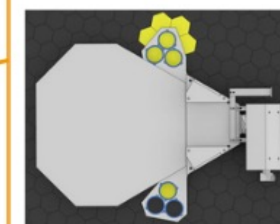
- sampling at ~Hz rate of ON/OFF pixel current
- definition of the observing mode

Prepare SII observations with NectarCAM

- end-to-end validation of signal transmission
- characterize NectarCAM performance for SII in Irfu dark room
- explore the science case to prepare 1st observations

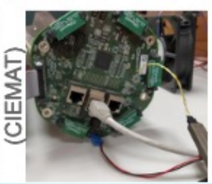


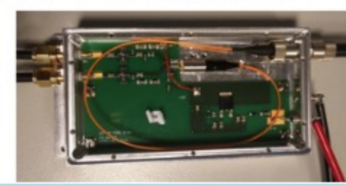
Movable filters
(two sets of ON/OFF)
Credits for NectarCAM
Kevin Pressard (IJCLab)



Amplification of anode current and optical transmission

Credits for LST1
Gustavo Martinez
(CIEMAT)



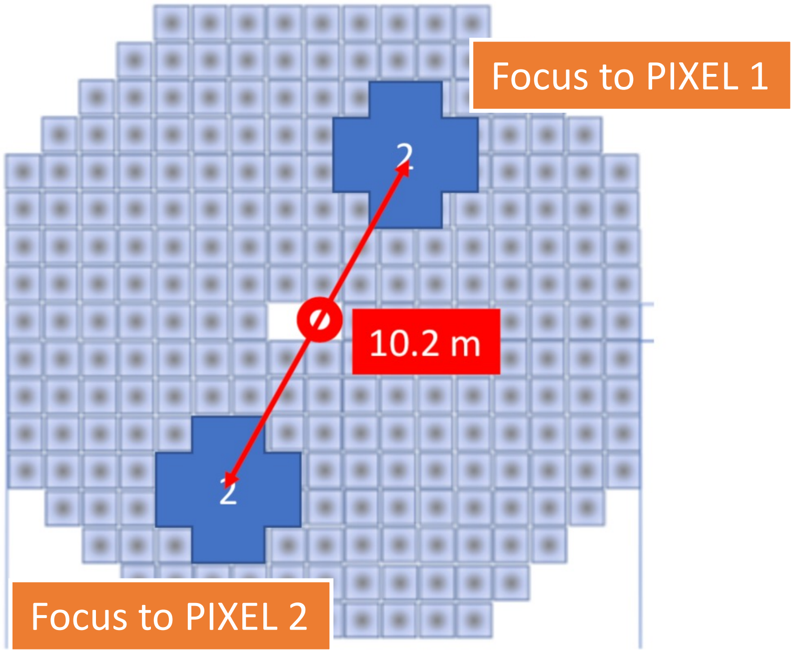


Credits for LST1
David Fink
(MPI Phys)

Further technical developments

“Intra-telescope” focusing

Both MAGIC and LST can focus each individual facet to an arbitrary point in the focal plane, i.e. to an arbitrary pixel.



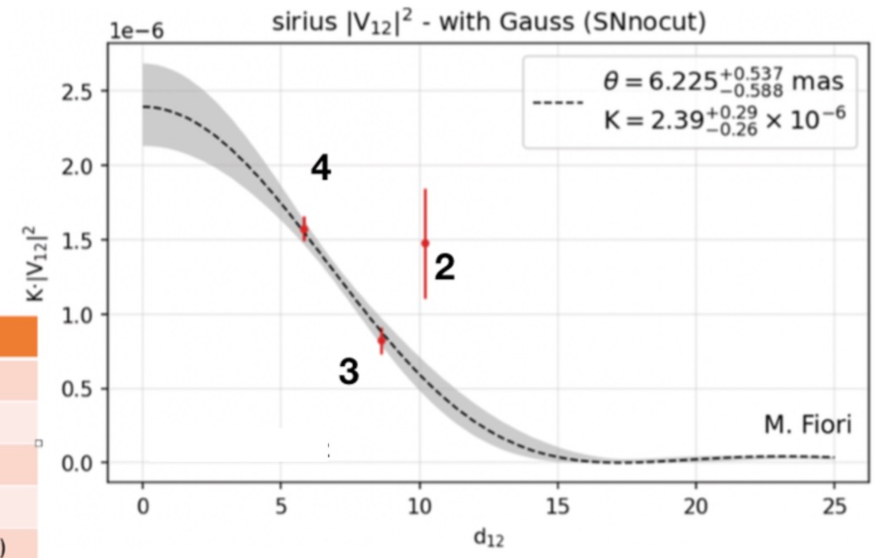
- This allows for instance to focus light from a section of the reflector (a few facets) to a pixel and a different section to a second one.
- In other words, we can correlate “sub-telescopes” with baselines smaller than the diameter of the telescope.
- This goes in the direction of the “I3T concept” introduced by Gori et al, MNRAS 505/2 (2021) 2328

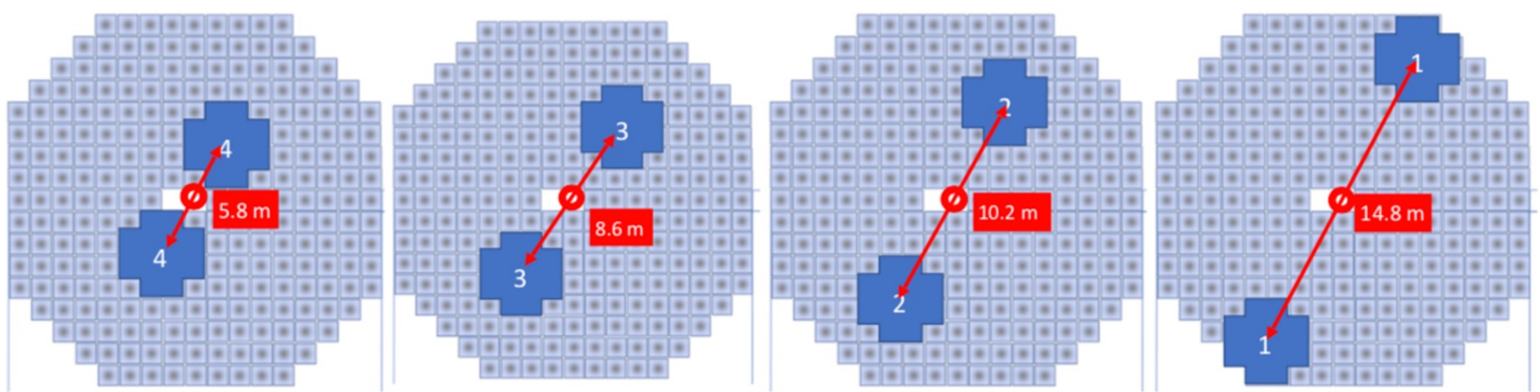
First tests on Sirius

- We observed each constellation for about 20 minutes at very high zenith angle up to 80 degrees

- Measurement: 6.23+-0.59 mas
  Literature: 6.05+-0.04 mas

arrangement	Baseline (m)	V^2	$T_{5\sigma}$(min)
	0	1	0.8
4	5.8	0.68	1.7
3	8.6	0.41	4.8
2	10.2	0.52	10.8
1	14.8	0.03	675 (~11 hours)



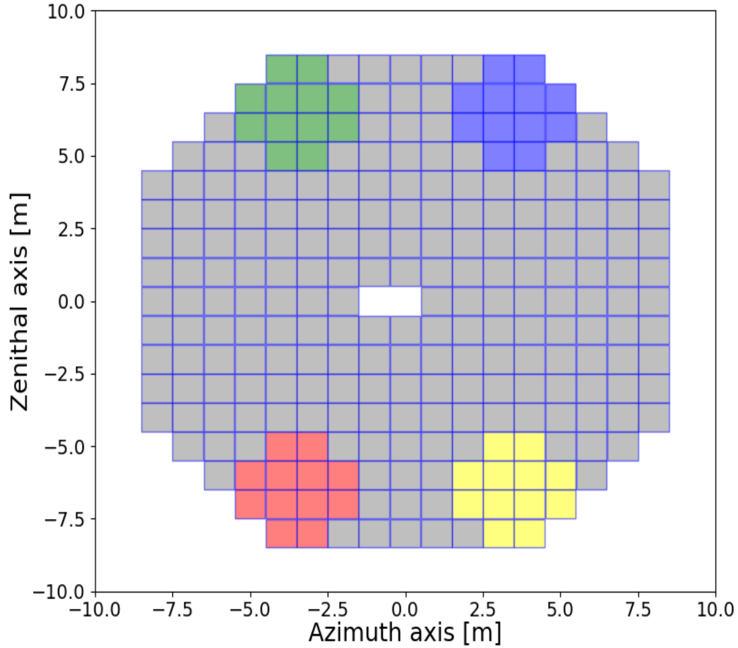


T. Hassan, Ohio meeting, 2023

Extension to more channels

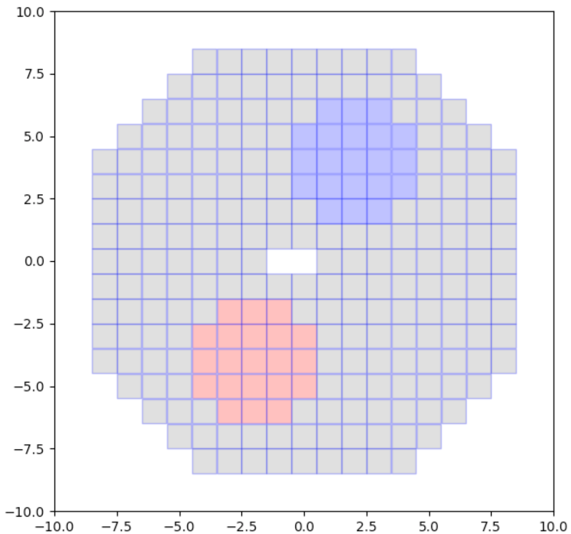
- After upgrading our correlator to four channels, we installed four filters in one of the MAGIC telescopes.
- This allows an even more dense sampling of V^2 in different orientations of the sky and and baselines (~5 m to ~14 m).

Example configuration with 12 m^2 sub-mirrors and 7 -- 14 m baselines

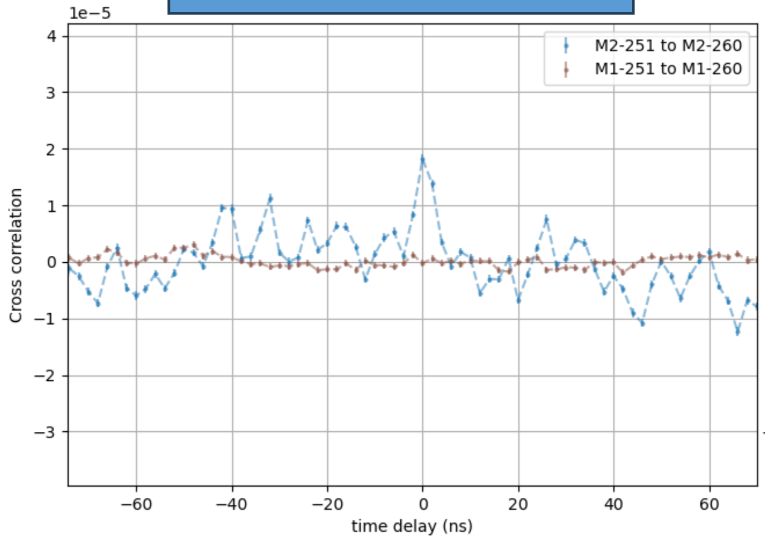


But strong correlated noise

- When correlating signals from the same camera, noise produced in the camera is common to both channels.
- For stars weaker than Sirius the star's signal quickly hits the level of the camera correlated noise.
- Even worse: the noise goes to high frequencies, thus "mimicking" the shape of the stellar signal.
- No luck so far in our efforts to remove the noise either in the hardware or in the analysis. Ideas are welcome ☺



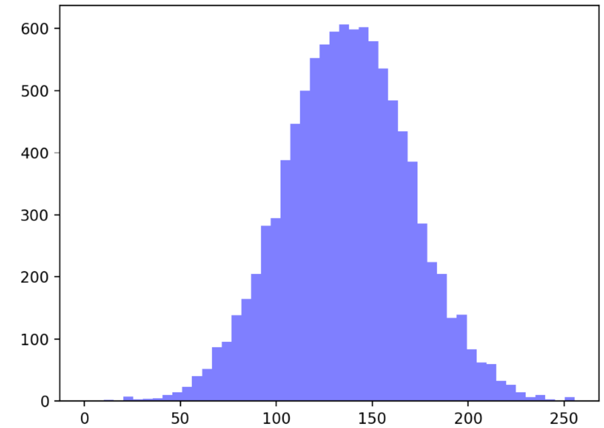
120 minute observation of Altair



Faster photodetectors

- Our interferometer would benefit from faster time resolution: SNR increases inversely to the square root.
- Photodetectors in IACTs have time resolutions ~1 ns because that's the characteristic time scales of γ-ray showers.
- The next limiting factor in an IACT is the reflector. For a parabolic reflector at the optical axis, the time spread is theoretically 0. But facets are not perfectly aligned in real IACTs. This easily introduces a time spread of FWHM ~ 60 ps in MAGIC (even more in the first telescope, which has two layers of facets at different heights).
- However, FWHM ~60 ps is still way smaller than the FWHM of our current photodetectors, which is ~2500 ps.

FULL REFLECTOR
RANDOM 5 mm FACET STAGGER



MAGIC, rough MC simulation of photon arrival time distribution in ps

What photodetectors?

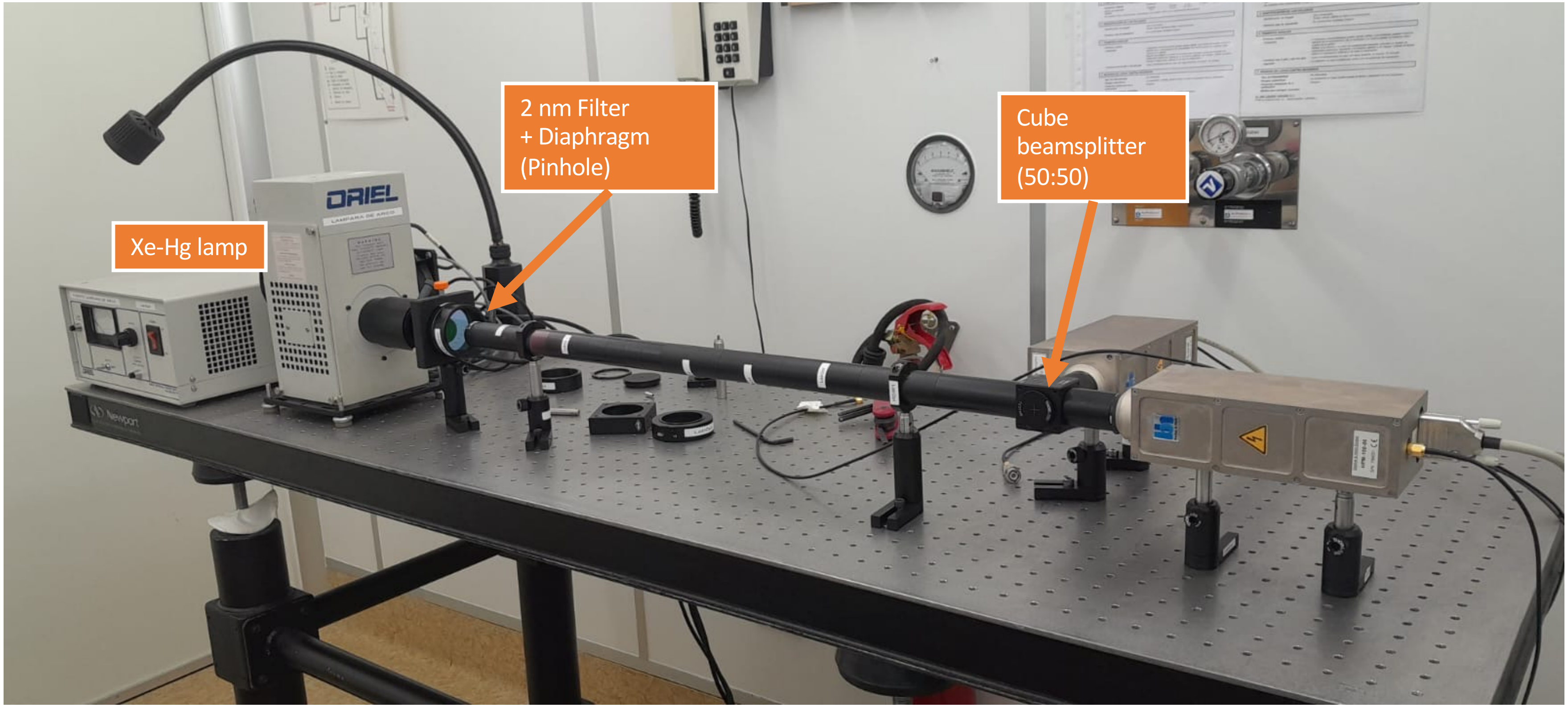
IACTs impose many constraints on possible photodetectors, especially large diameter IACTs like MAGIC or LST:

- The optical Point Spread Function has a size $\sim$3 cm and incident photon angle goes up to 25-30 deg, so even with high optical concentrations one needs photodetection areas of $\sim$1 cm .
- Devices should be sensitive to single phe.
- Dark counts must be smaller than the photon rate expected from the star.
- Afterpulses coming short after the photon should be avoided.
- Deadtime should be short ($\lesssim$10 ns).
- It's easier to work at ambient temperatures.
- Quantum efficiency should be acceptable, at least 20%.

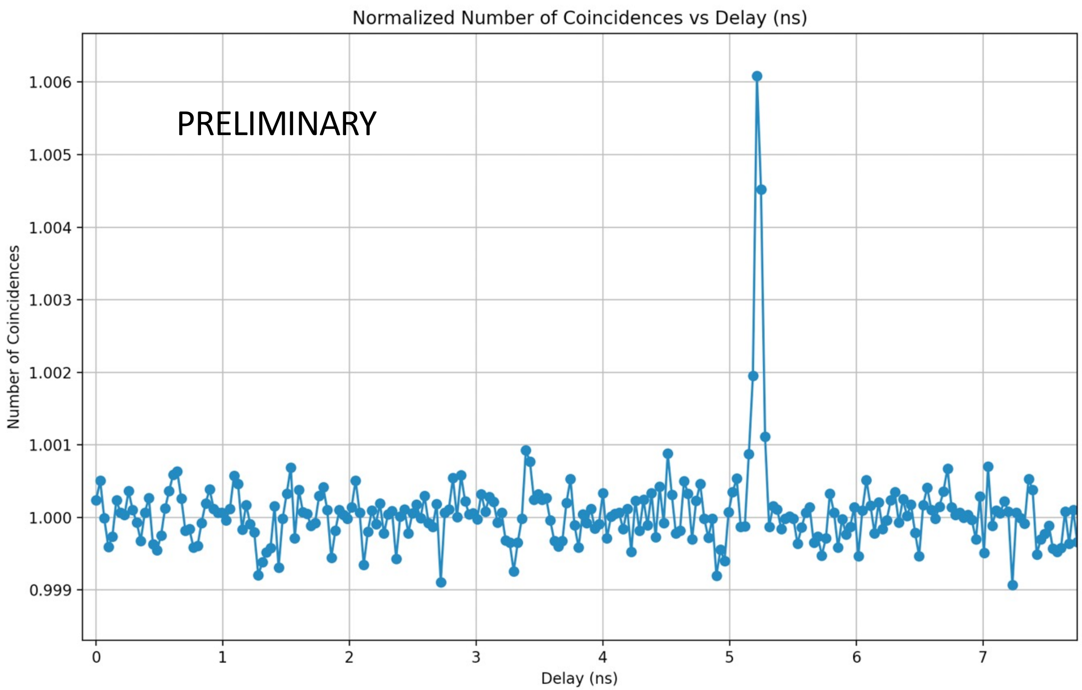
Lab tests of Hybrid Photodetectors

- Off-the-shelf product HPM-100-06 from company Becker & Hickl (specialized in single photon fast time applications). Selection inspired by SII observations of *V. Leopold, S. Karl et al, arXiv:2408.08173*.
- Based on Hamamatsu HPD. We had actually tested similar devices in the past in MAGIC.
- Sensitive at 220-650 nm, peak QE 28%, time resolution TTS FWHM<20 ps, photosensitive size 6 mm.
- Readout and correlator also provided by the same company: SPC-QC-104. Able to process 4 channels up to tens of MHz single phe rate.

Lab setup


Xe-Hg lamp
2 nm Filter
+ Diaphragm
(Pinhole)
Cube
beamsplitter
(50:50)
ORIEL

Preliminary results



- Each bin is 32 ps, so the peak has FWHM ~60 ps.
- Fraction of coherent events: observed 0.6% vs expected 0.9%
- Significance: observed 17σ vs expected 30σ.
- Still performing more sanity checks…
- But this device may satisfy our requirements, so we are considering to test them on the telescopes: it should be possible to focus a sub-mirror into an individual HPD.

Wrap-up

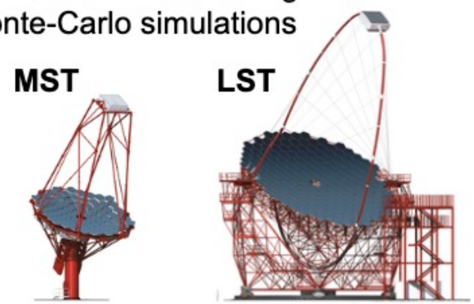
- MAGIC is already taking data as an intensity interferometer. First measurements have just been published.
- Hardware upgrade was minimal and allows swapping from γ-ray to interferometry in a trivial way.
- A similar upgrade has just been tested in LST-1. We are already taking data with MAGIC+LST-1
- We are implementing the same setup in the next three LSTs in the north. An upgrade of the correlator is also ongoing. The target installation date is end of 2025.
- We are evaluating several ways to improve our performance: by taking data with several sub-mirrors, by introducing faster photodetectors and even by combining both.

backup

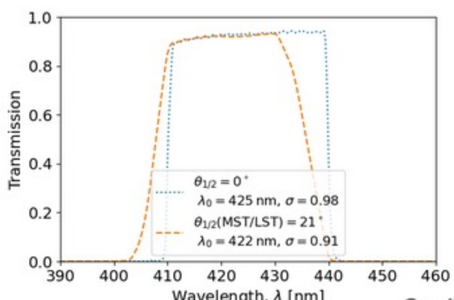
SII at CTA-North

Performance of CTA-N telescopes

→ Based here on Prod6 config. files for Monte-Carlo simulations



+ Semrock 425/26 nm filters (as in MAGIC SII paper)



Credits: Jonathan Biteau

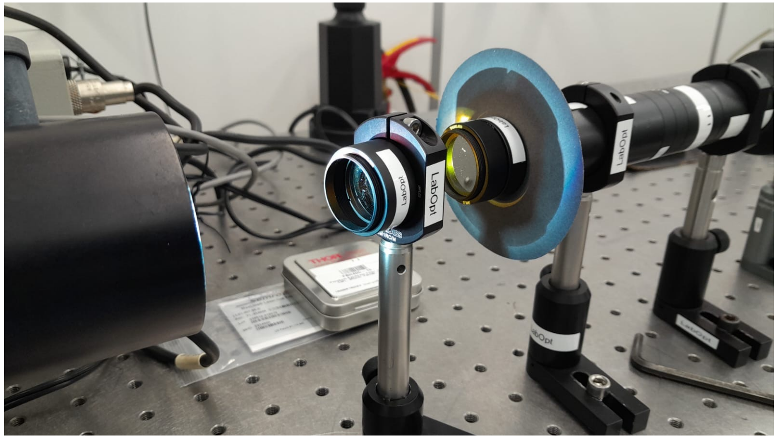
CTA-N	Large-Sized Telescope (LST)	Medium-Sized Telescope (MST)	
	Mechanics		
Number of telescopes	4	9	
Effective mirror area (including **shadowing**)	370 m²	88 m²	
Primary reflector diameter	23 m	11.5 m	
Focal length	28 m	16 m	
Optical design	Parabolic	Modified Davies-Cotton	
Arrival time standard deviation	-	0.7 ns	
Pixel size (imaging)	6 arcmin	10 arcmin	
95% containment diameter of point spread function In the filter plane at zenith	56 mm	33 mm	
Pointing precision	< 14 arcsec	< 7 arcsec	
	Optics		
Cone half angle	22 deg	20 deg	
Optical efficiency at 420 nm, incl. mirror reflectivity, ~~shadowing~~, entrance window, filters, light cones	0.64	0.73	
Normalized spectral distribution with a 420 nm filter, for a 21 deg cone	0.91		Ref.
	Photodetection		
PMT excess noise factor	1.21		Ref.
PMT quantum efficiency at 420 nm	39%		Ref.
PMT transit time standard deviation at 1 p.e.	1.5 ns		Ref.
	Bandwidth		
Maximum electronic bandwidth	650 MHz	600 MHz	

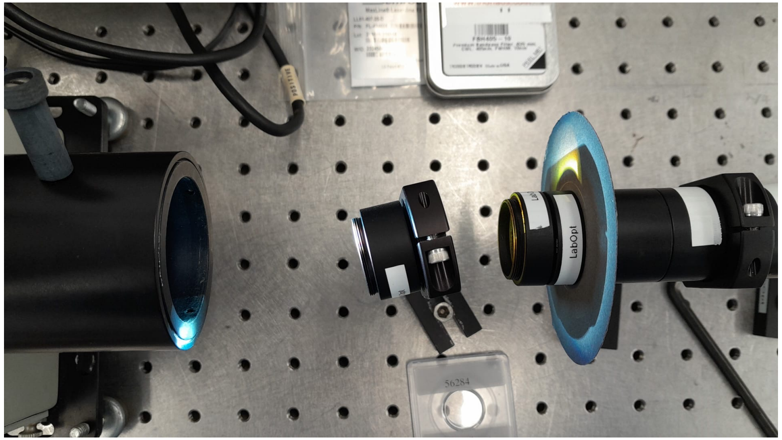
Ref. Prod 6 + MST-STR TDR

3

Filters

- Since the Hg line is at λ = 404.6563 nm, we use a filter Semrock LL01-407-25D, centered at 407 nm with FWHM~2 nm but we tilt it: that shifts the transmission curve to shorter λ. We change the tilting angle slowly by hand until we get the highest possible rate (~20 deg).
- The Semrock filter has high transmission for λ >500 nm so we add a second filter: Thorlabs FBH405-10, which transmits only in the range 400-410 nm.





- We use a set of Edmund Optics pinholes with diameters 20, 50, 100, 200 and 500 μm.
- The distance between the pinhole and the photodetectors is 1 m.
- For λ=405 nm

Pinhole diameter (μm)	First zero of correlation function (mm)
20	24
50	9.5
100	4.75
200	2.37

- The HPD photocathode has a diameter of 6 mm and the center of the photocathodes are aligned to $\sim$1 mm.
- So we need a pinhole diameter of 50 μm or less to be at $V^2\sim1$.

Ongoing deployment of the LSTs in La Palma