First observations of CTA-LST1 and MAGIC as an optical interferometer

Juan Cortina & Tarek Hassan (CIEMAT) for the LST and MAGIC collaborations

Bologna, 15-18 April 2024

2nd Edition
CTAO Science Symposium

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

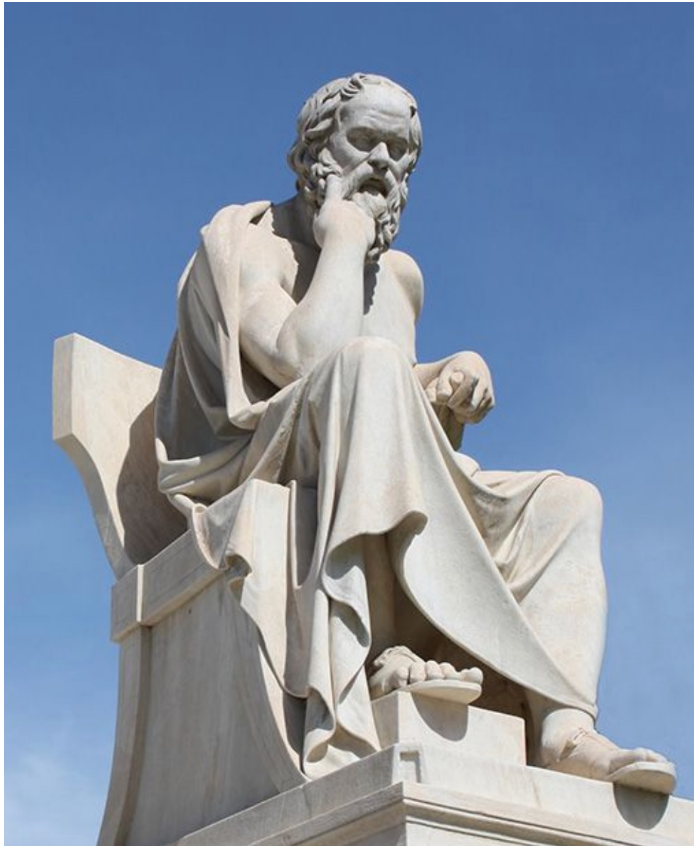
Outlook

- Intensity Interferometry with MAGIC.
- Extension to LST.
- Science with the interferometer.
- And so?

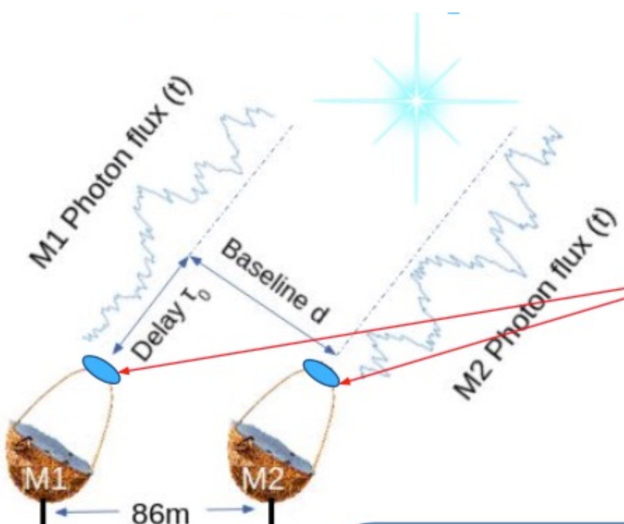
Intensity interferometry with MAGIC

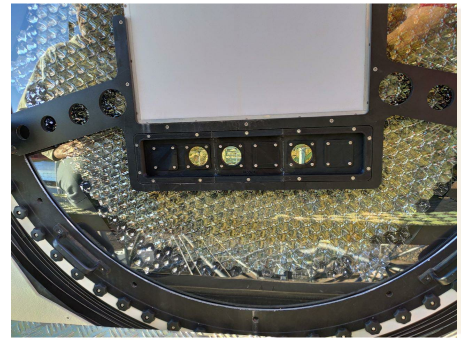
Philosophy

- 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*) with two filters and an oscilloscope.
- Our interferometer designs always follow <u>this philosophy</u>:
  - **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.**



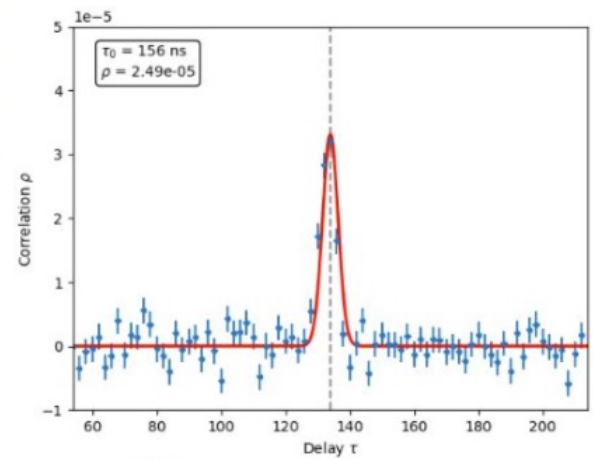
MAGIC interferometry setup (2020-)





Optical filters in front of certain pixels

Correlation calculated in real time!



Optical fibers connect the pixels to the channels of the digitizer card

MAGIC CH

Digitizer cards → GPU

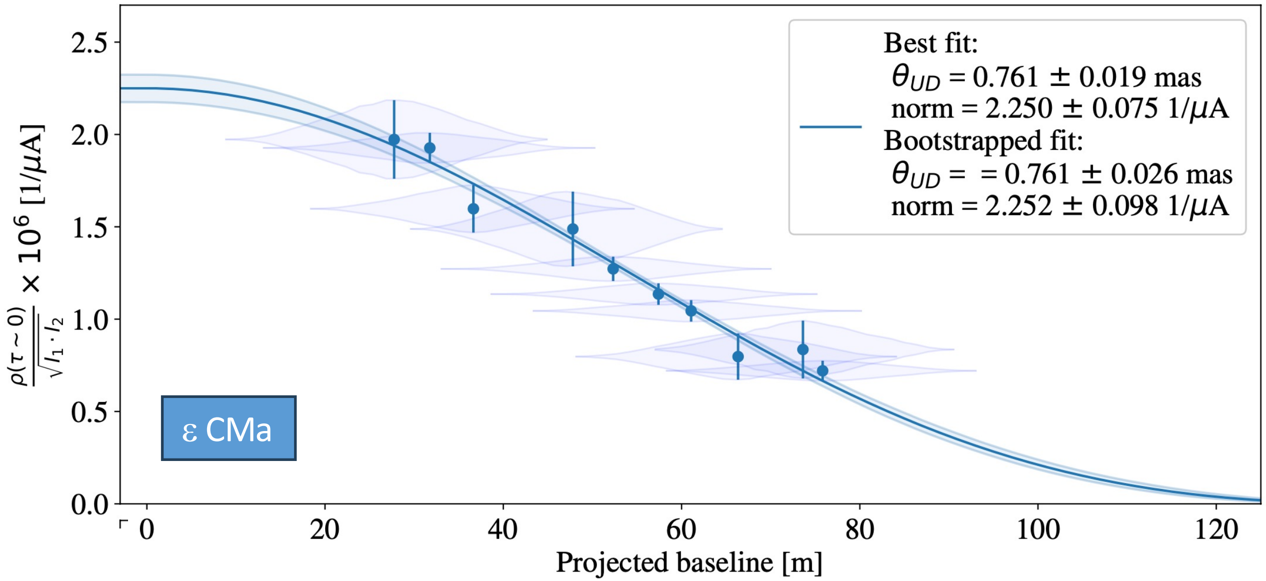
Spectrum M4i.4450-x8
2 input channels
250MHz bandwith, 500MS/sec
14 bit vertical resolution
>3.4 GB/s streaming

GPU Nvidia Tesla V100

For more info. see 'Intensity interferometry with the MAGIC telescopes' proceeding at ICRC 2021

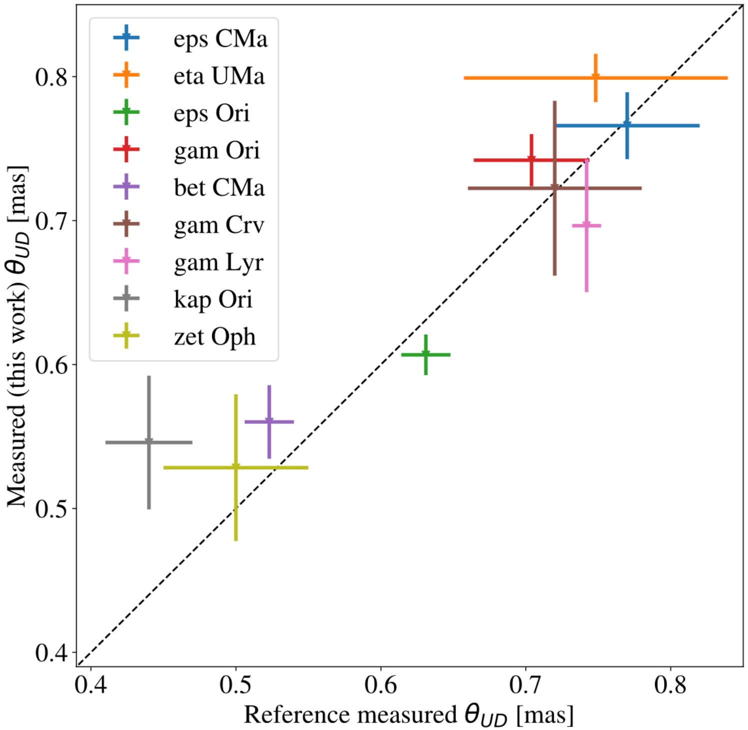
First science results with MAGIC (2023)

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

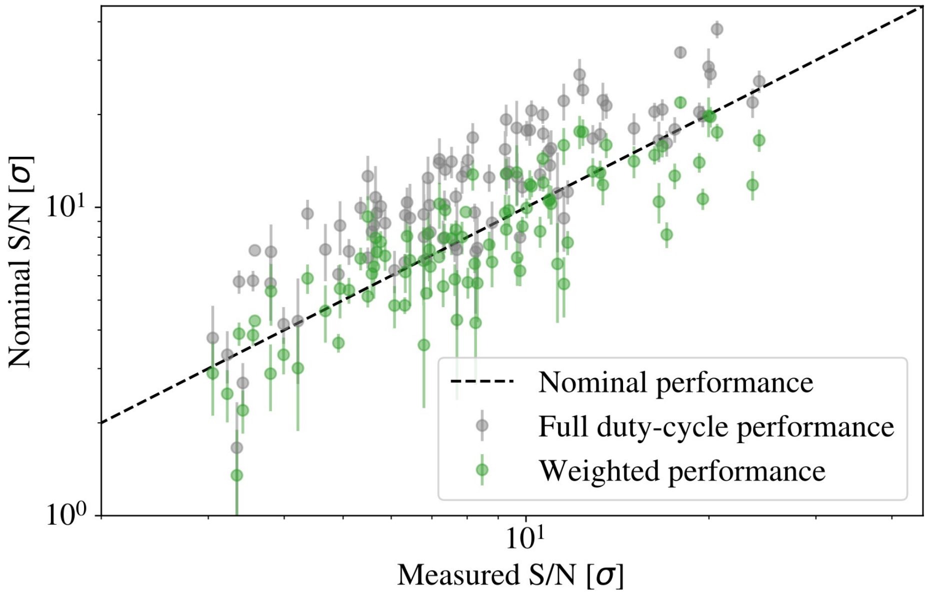


Performance of MAGIC interferometer

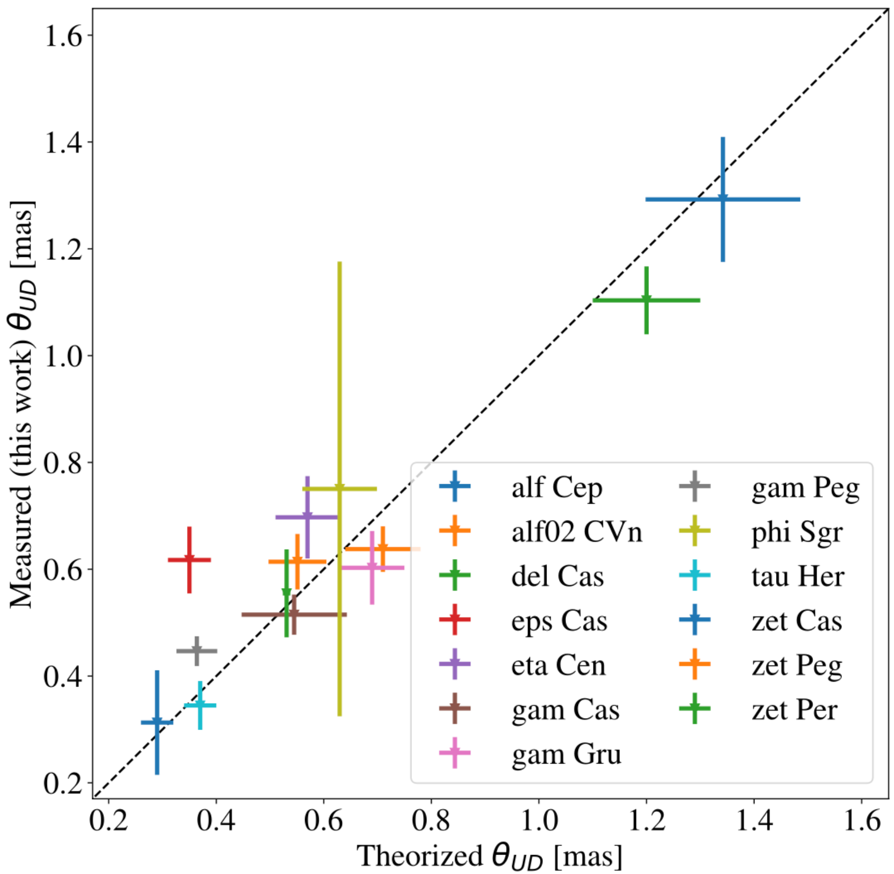
Calibrator stars: crosscheck with previous measurements



Expected vs measured S/N



New stellar diameter measurements

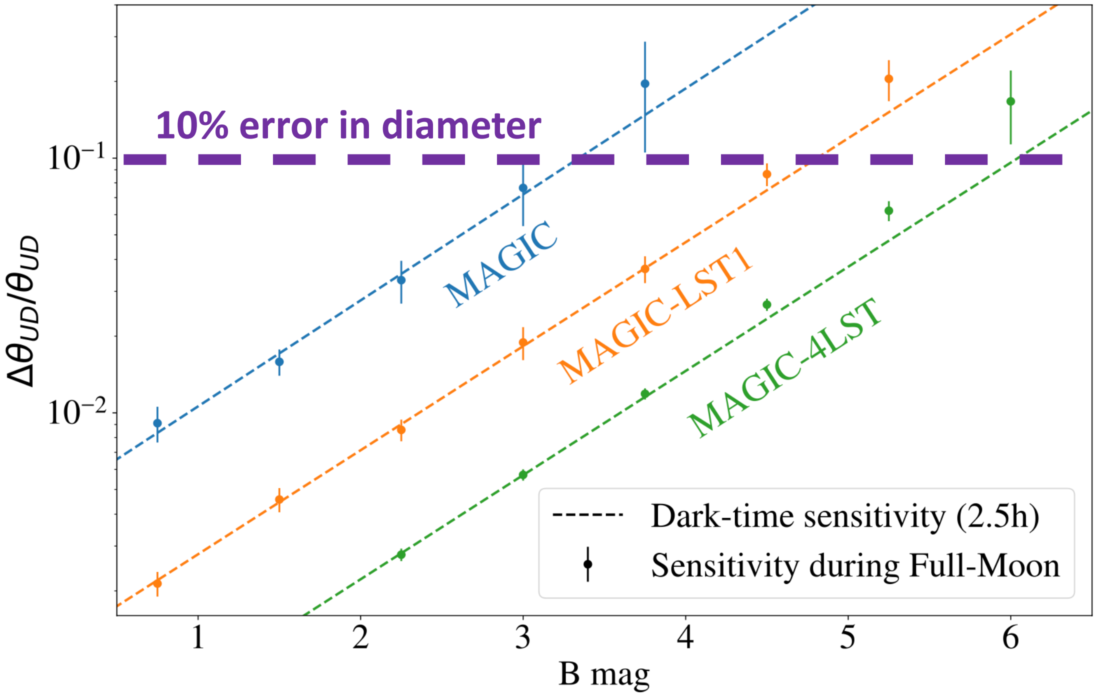


New diameter measurements, compared to <u>models</u>

Extension to the LSTs

+CTA LSTs: Impact on sensitivity

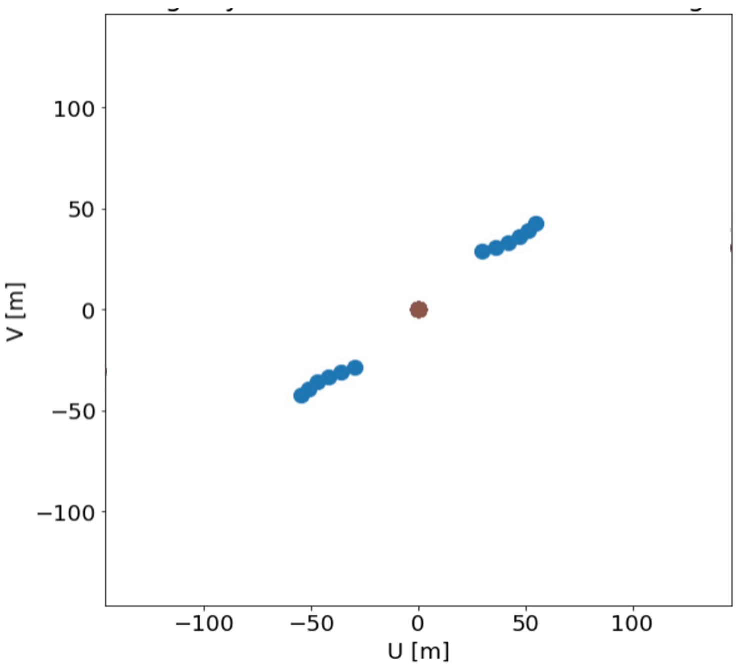
MAGIC coll., MNRAS March 2024



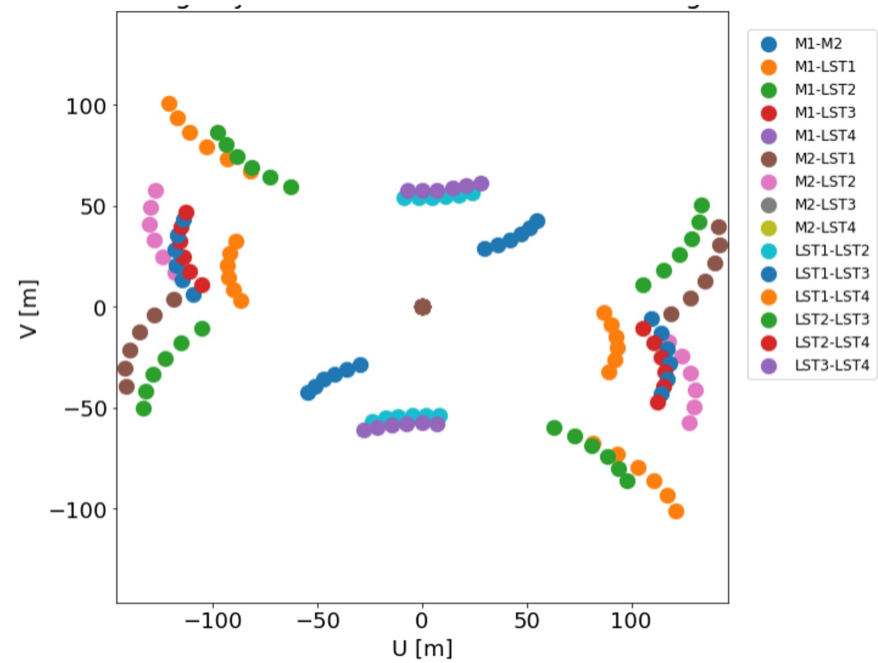
- We expect to increase sensitivity by a factor 10.
- Reach $B=6^m$ for 10% error in diameter in 2 hours with 4 LSTs.
- T. Hassan (CIEMAT) has received an ERC Starting Grant to design and test interferometer for MAGIC+LSTs.

+CTA LSTs: Impact on spatial reconstruction

MAGIC only

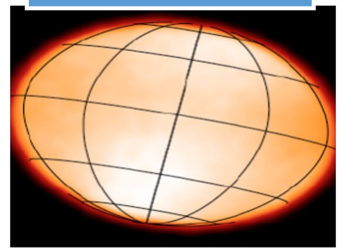


MAGIC + 4LSTs

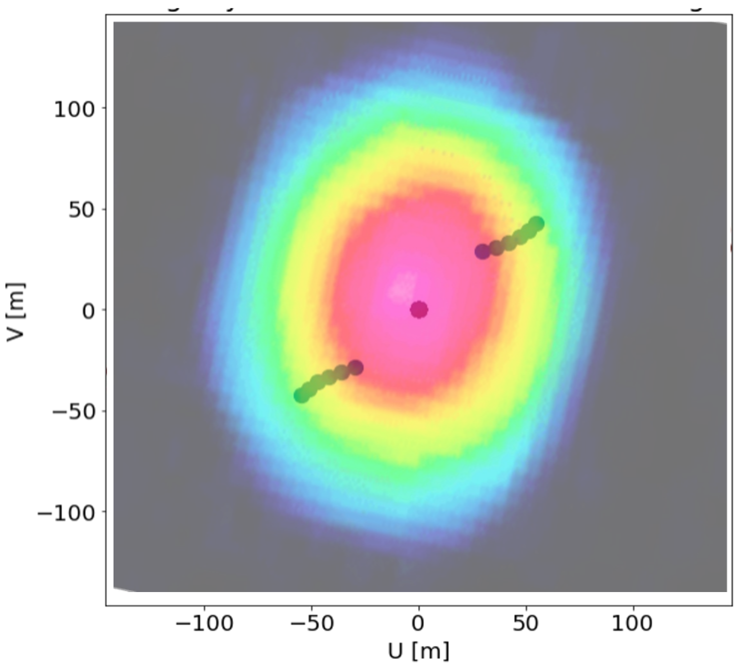


+CTA LSTs: Impact on spatial reconstruction

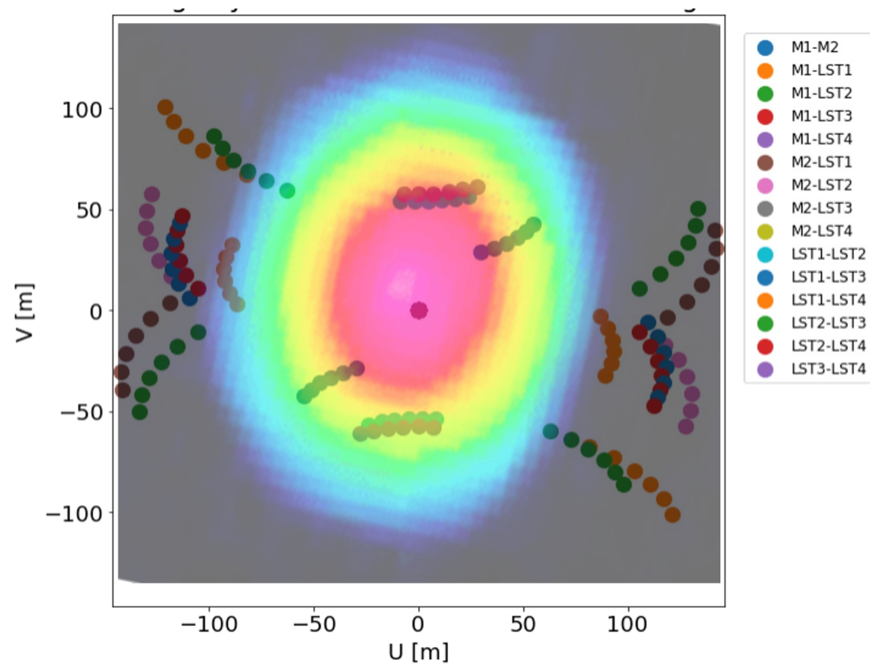
Fast rotating star



MAGIC only



MAGIC + 4LSTs



Hardware add-ons to LST

Few “innocuous” modifications:

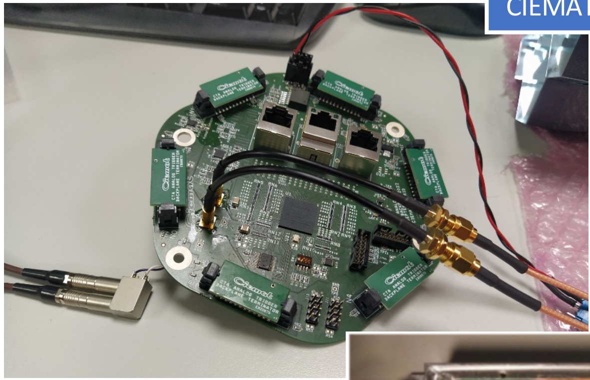
- Two filters mounted on existing star imaging target.
- One of the front-end boards redesigned to extract a replica of a PMT analog signal.
- Optical transmitter “a la MAGIC” added as small standalone box.
- Optical fiber routed to MAGIC counting house and connected to existing correlator.

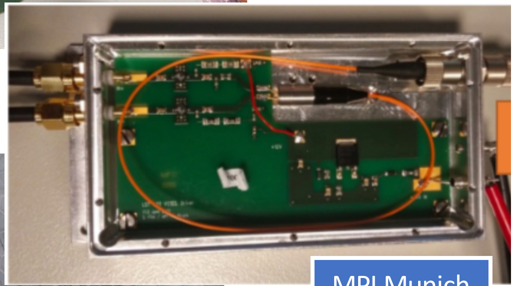
Already implemented in LST 1 in La Palma.

Easy to extend to LST 2-4. The correlator can be also upgraded.

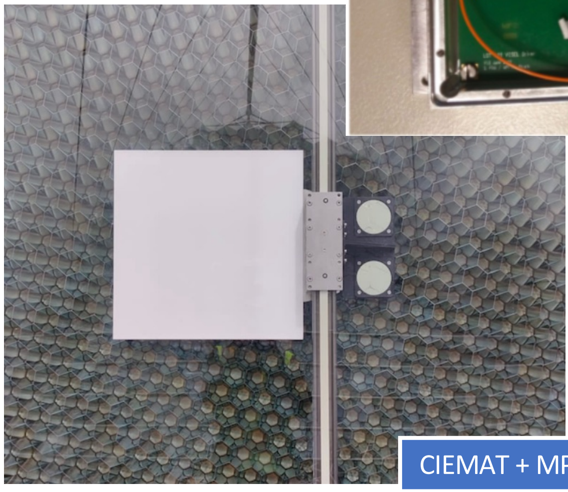
No impact on regular data taking but allows new science!

CIEMAT





MPI Munich

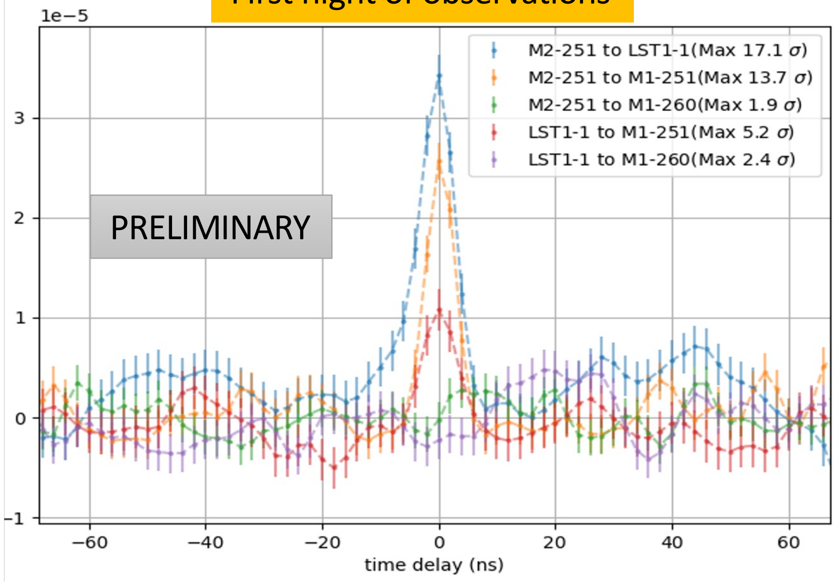


CIEMAT + MPI

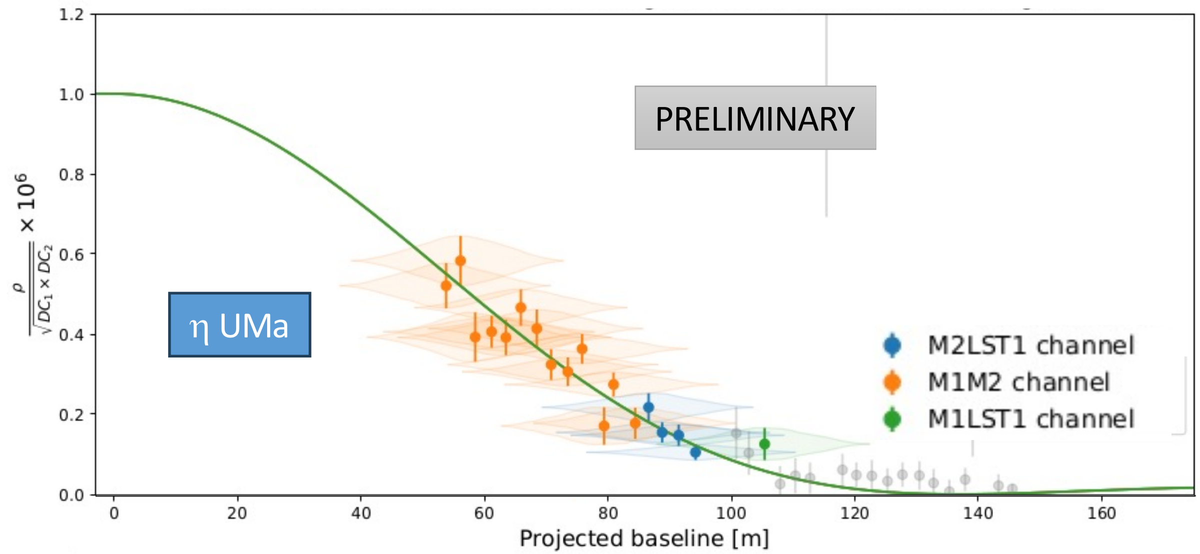
First MAGIC+LST1 observations

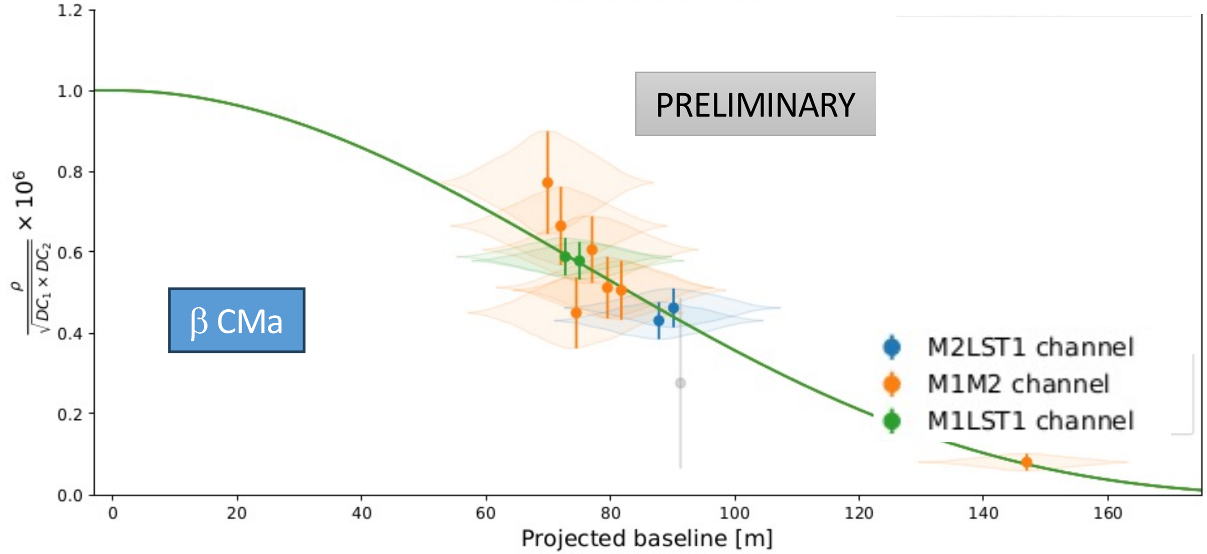
- So far only 25 hours of common MAGIC+LST1 observations:
    - Calibration stars already detected with MAGIC (Mirzam, Adhara, kap Ori…)
    - Weaker and smaller stars, now within reach of MAGIC+LST1: θ<0.4 mas
    - Fast rotators, especially with small diameter.
- Detections are very clear. Sensitivity roughly matching expectations.

First night of observations



- Observations of two calibration stars.
- Preliminary zero baseline calibration based on a 3rd star with high statistics.
- All three pairs are consistent and the improvement is clear:
  - ✓ Much broader coverage in baseline.
  - ✓ Higher statistics -> smaller errors.





NectarCAM: MSTs in the north

Slide shamelessly stolen from
J. Biteau, IJCLab / Univ. Paris Saclay

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*

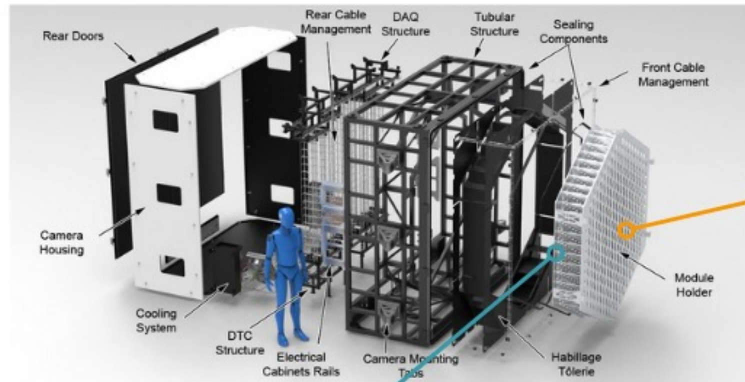
- signal conditioning ✓
- signal degradation to be measured

NectarCAM operation

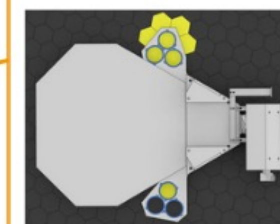
- sampling at ~Hz rate of ON/OFF pixel current
- definition of the observing mode

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

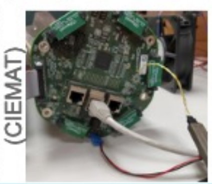


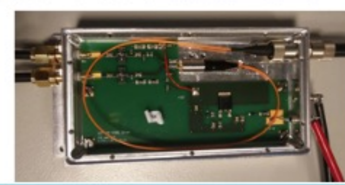
Movable filters
(two sets of ON/OFF)
Credits for NectarCAM
Kevin Pressard (IJCLab)



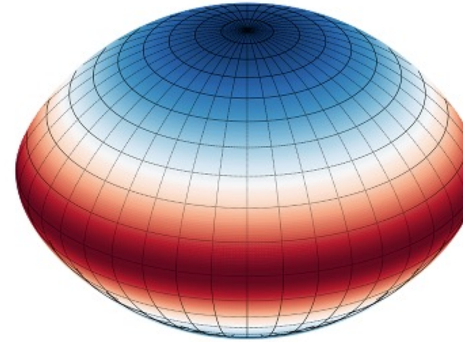
Amplification of anode current and optical transmission

Credits for LST1
Gustavo Martinez
(CIEMAT)



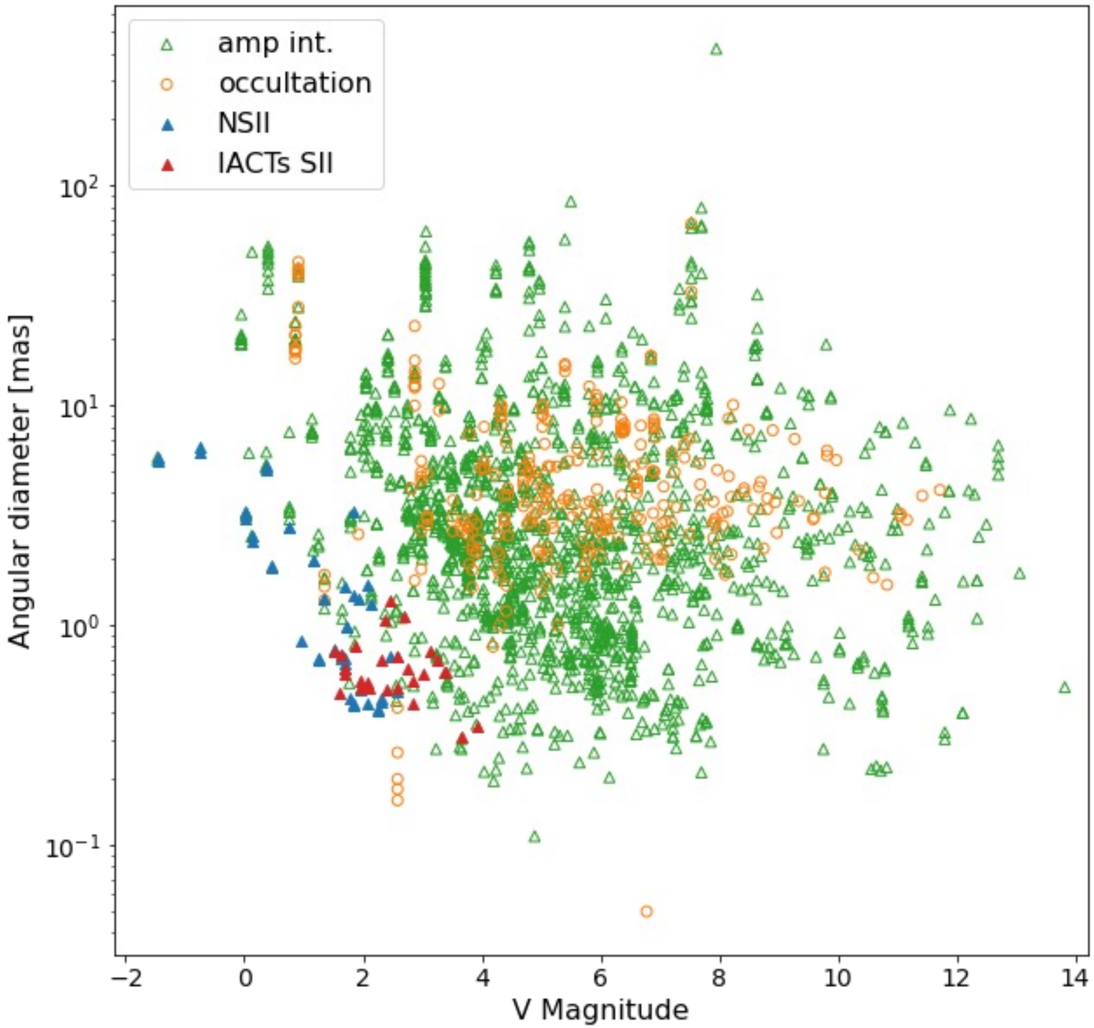


Credits for LST1
David Fink
(MPI Phys)



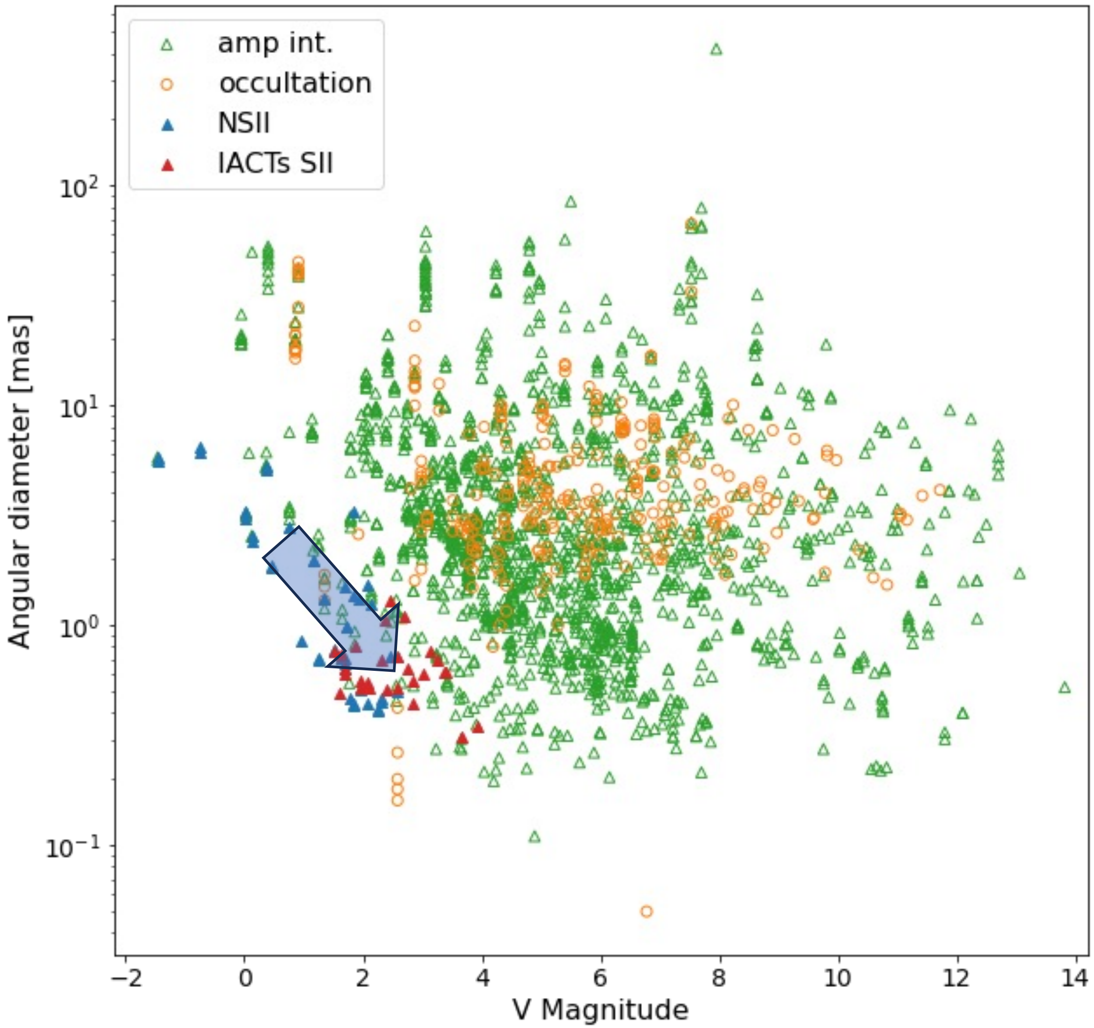
Science

Stellar diameters



Credit: A. Cifuentes (CIEMAT), based on CHARA (von Braun & Boyajian 2017, in Extrasolar Planets and Their Host Stars, Springer) and JMDC catalogs (Vizier, 2016yCat.2345....0D)

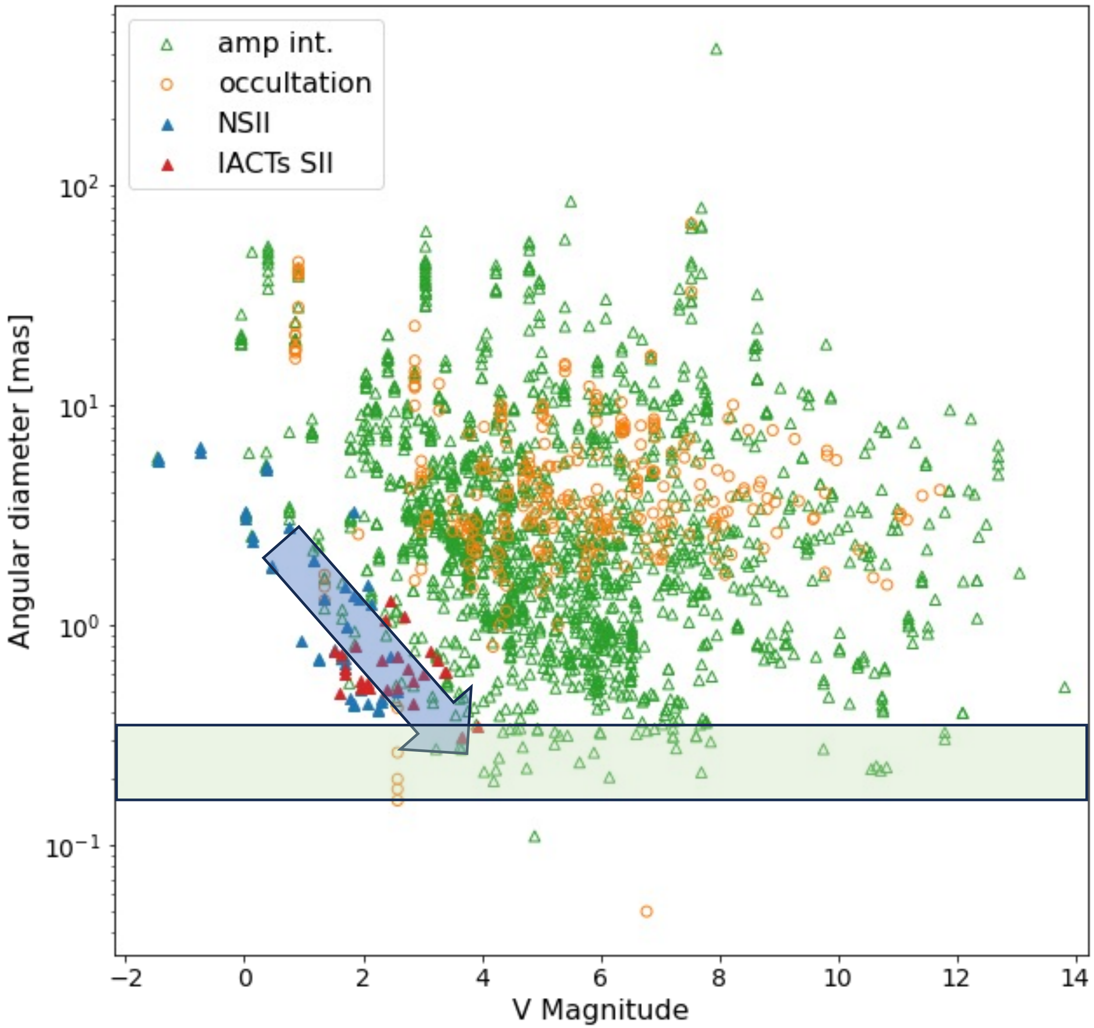
Stellar diameters



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

Weaker…

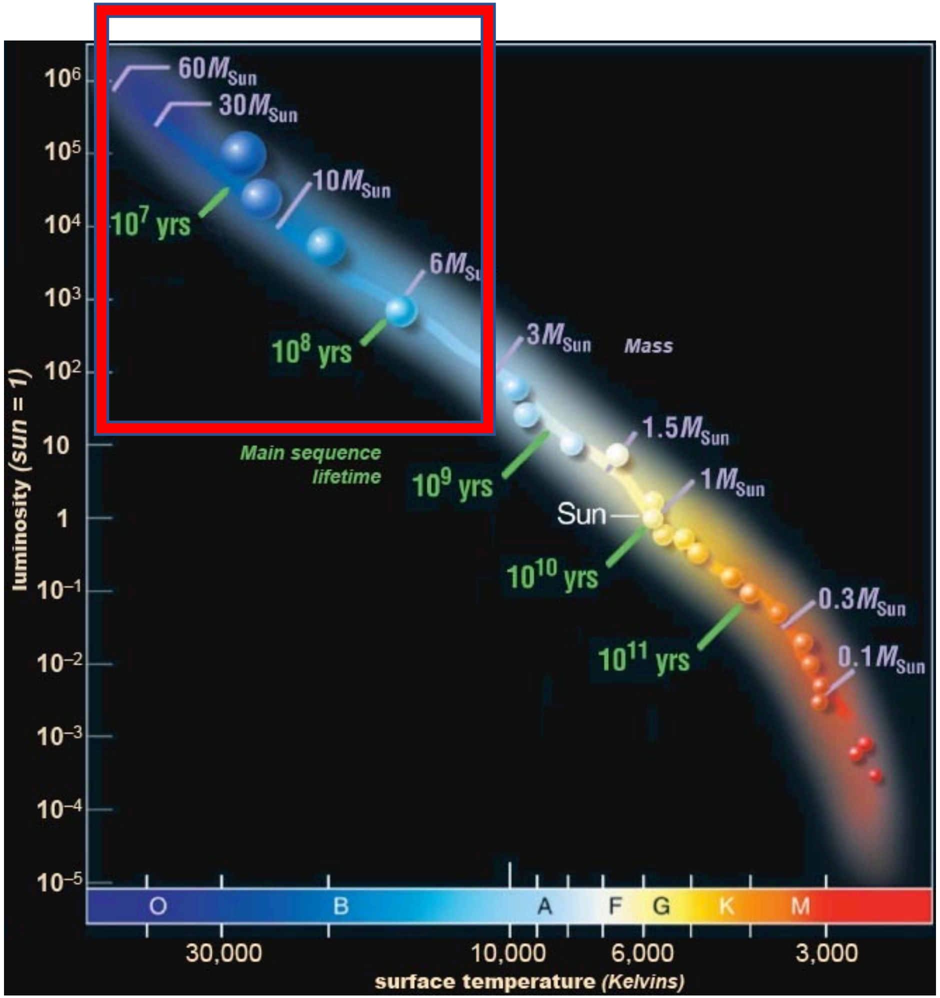
Stellar diameters



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

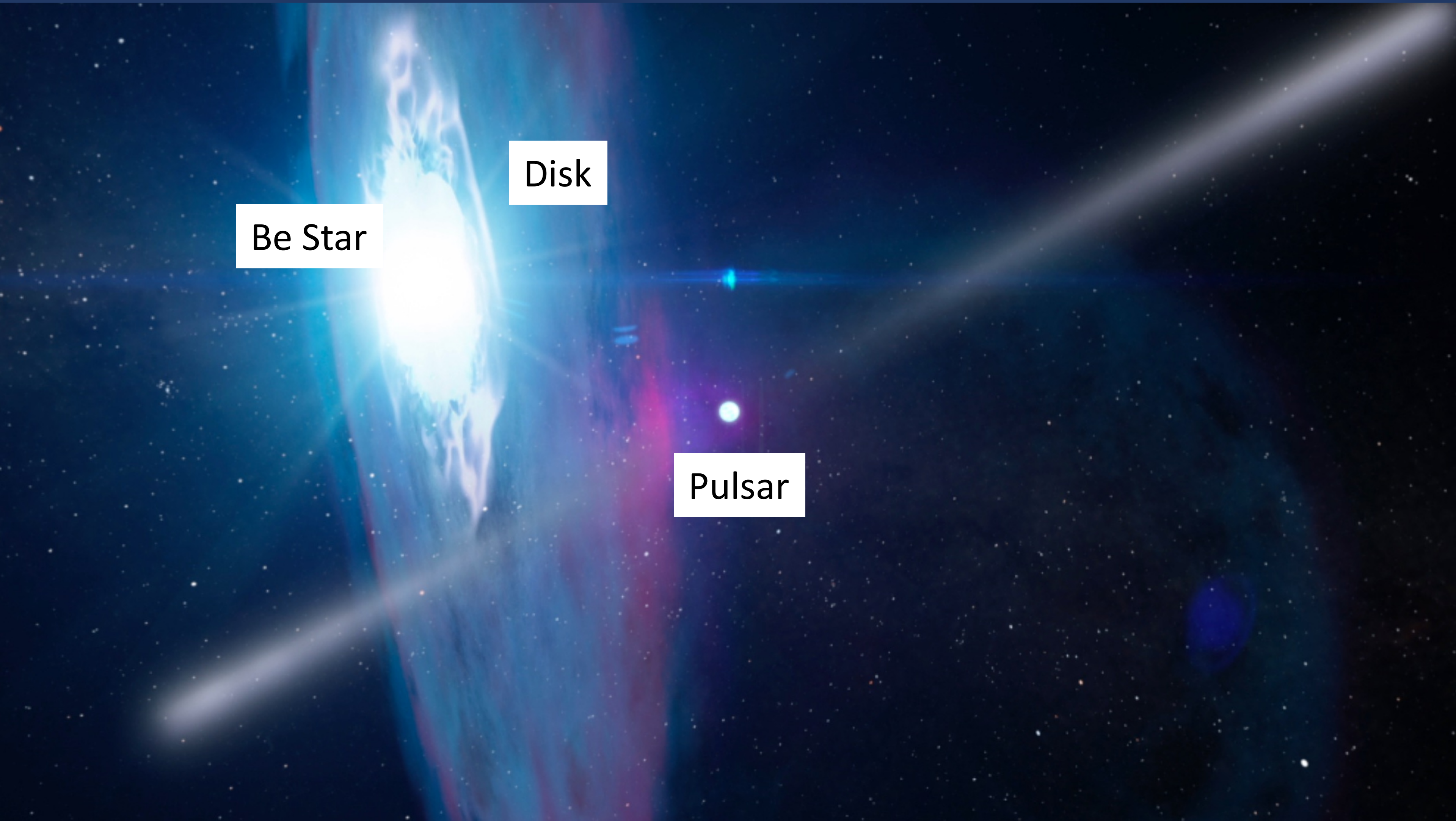
Weaker
… and smaller stars

Focus on massive stars



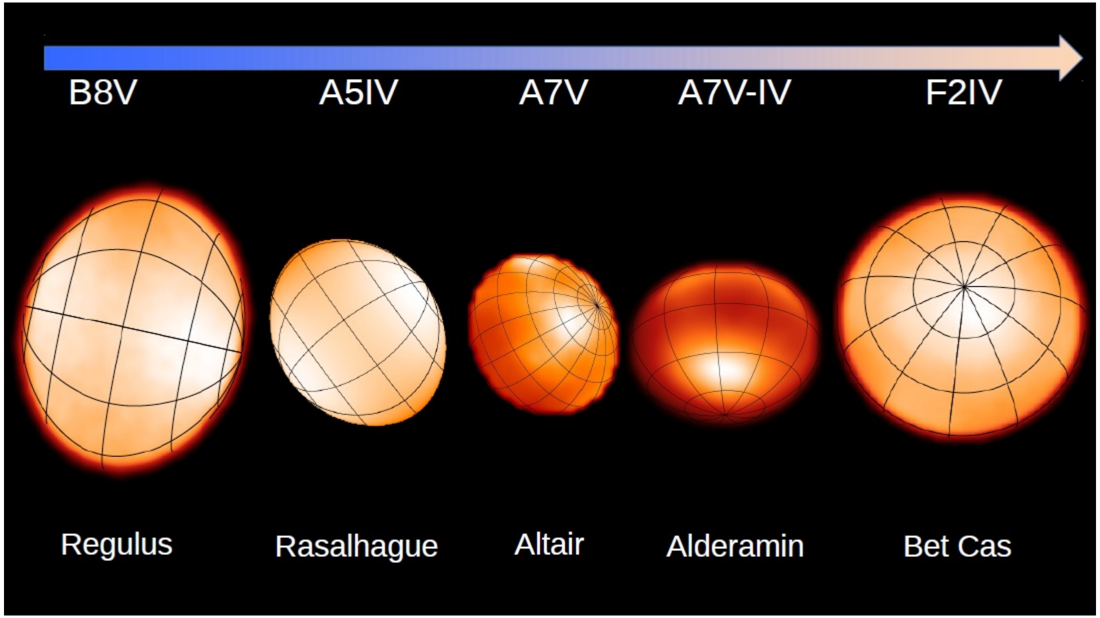
- Standard amplitude interferometers have troubles to go to blue and near UV. For us it's straightforward.
- This means that we are especially sensitive to O and B types: massive stars.
- Massive stars are experiencing a “revival” these days... They are the black hole progenitors. Do we understand their masses? E.g. the role of winds?

Be stars and pulsar = VHE γ-rays



Fast rotators

Stars are not spherical cows…

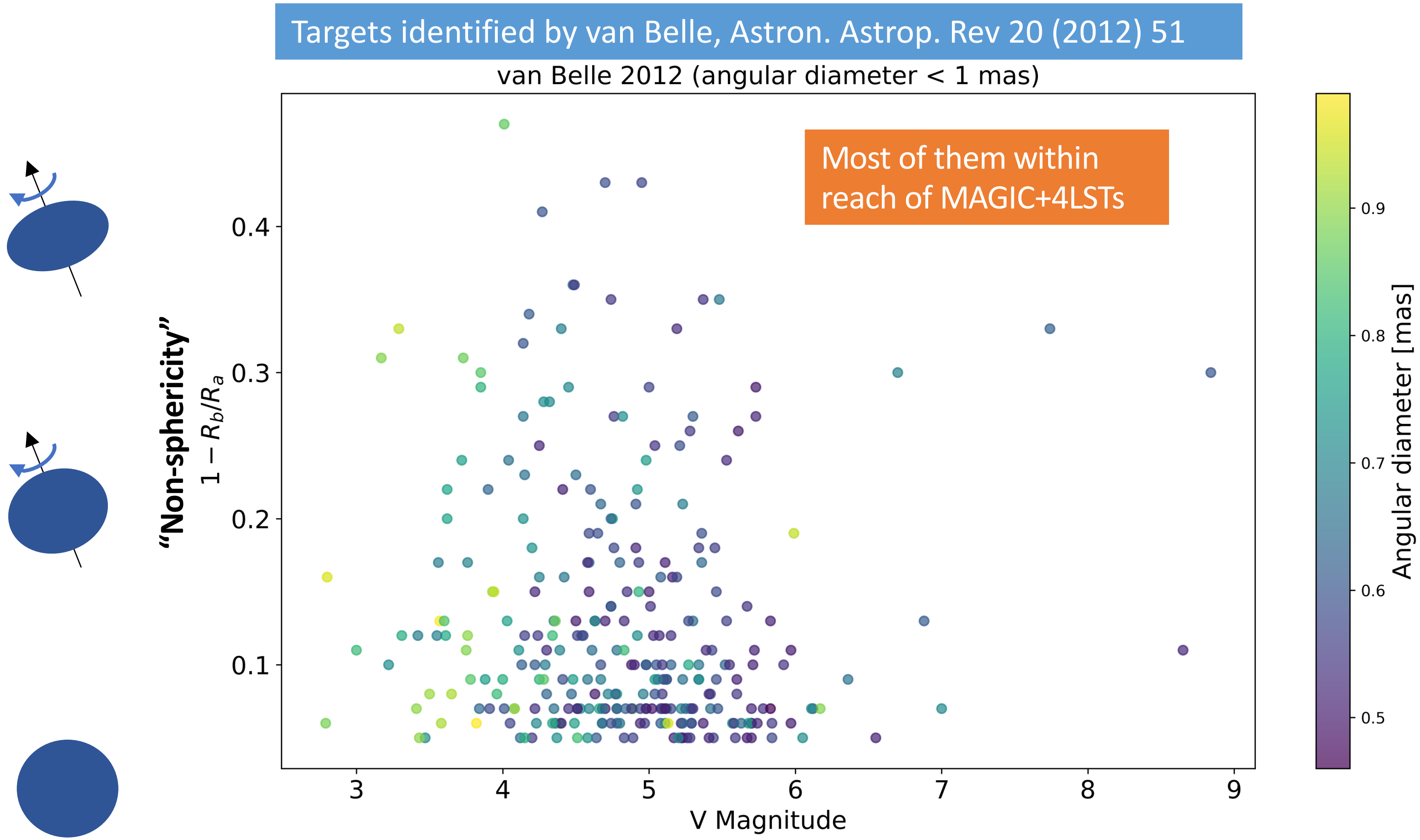


Credit: CHARA phase interferometer

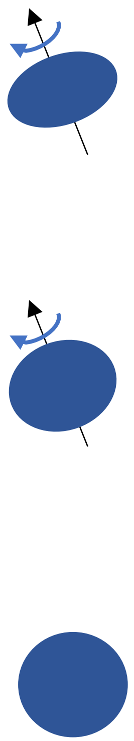
Shape of star <u>has</u> implications:

- Revise temperature and metallicity (gradients).
- Impact on convection.
- Asteroseismology.
- Understand wind injection…

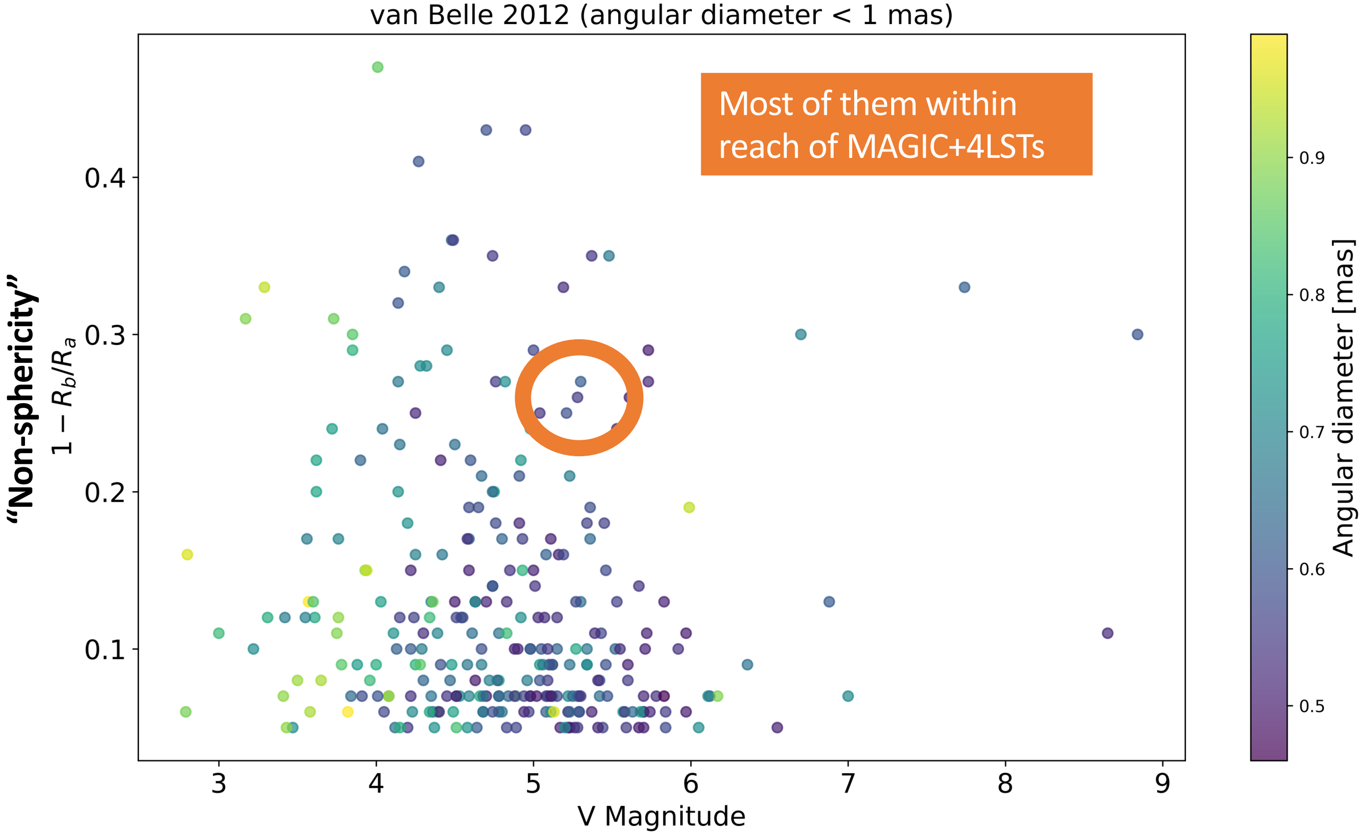
How many fast rotators?



How many fast rotators?

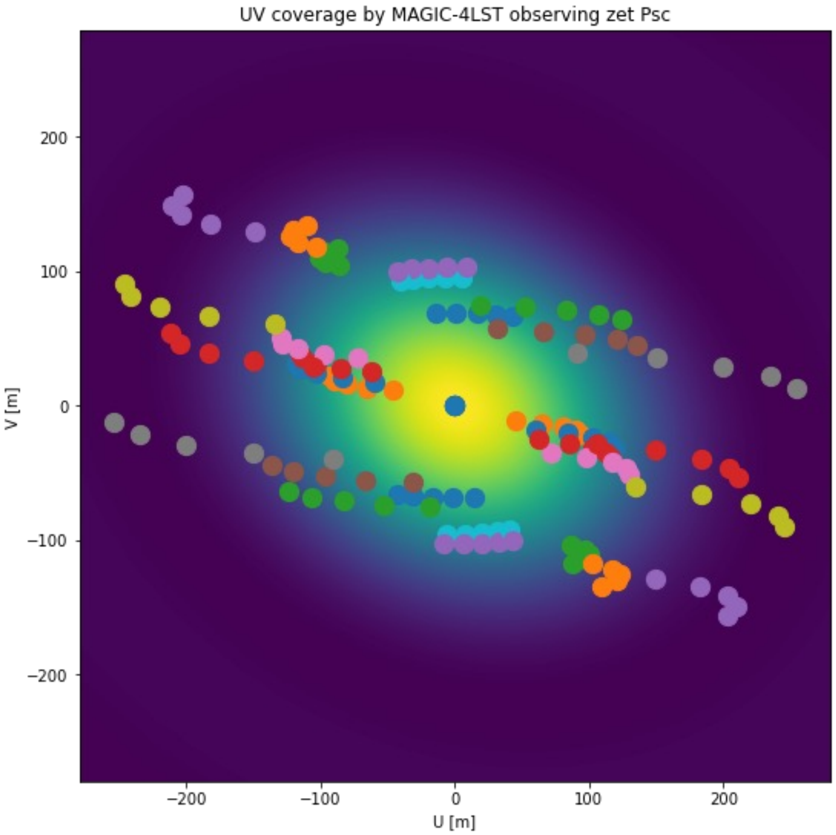


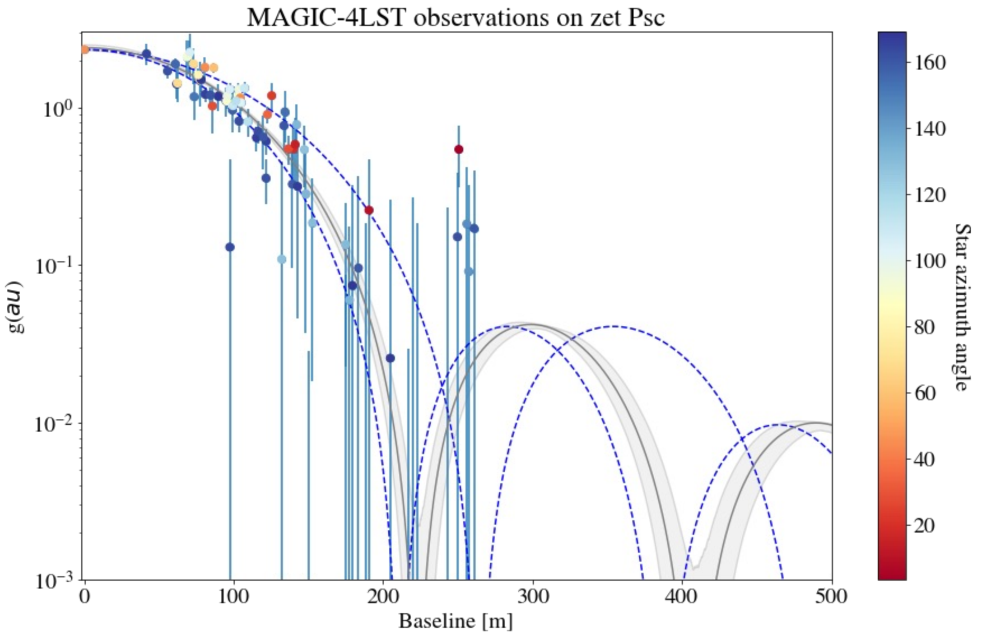
Targets identified by van Belle, Astron. Astrop. Rev 20 (2012) 51



Fast rotator observability

Zet Psc A, B=5.5, oblateness 0.25, θ=0.5 mas

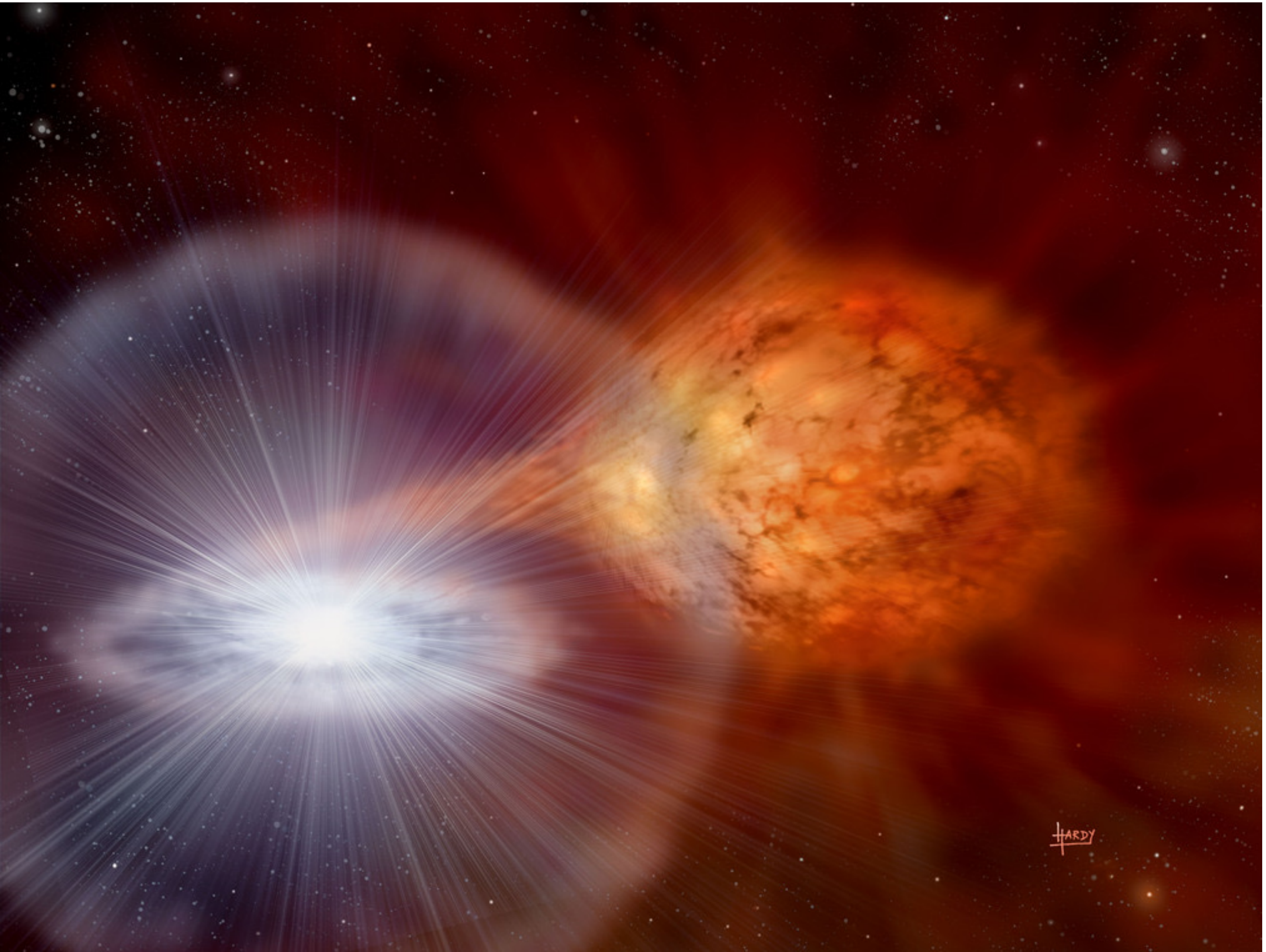




5 observations x 1 hour:

- Error in mean diameter ∼2%
- Error in orientation ∼5 deg
- Error in “non-sphericity ratio” ∼5%

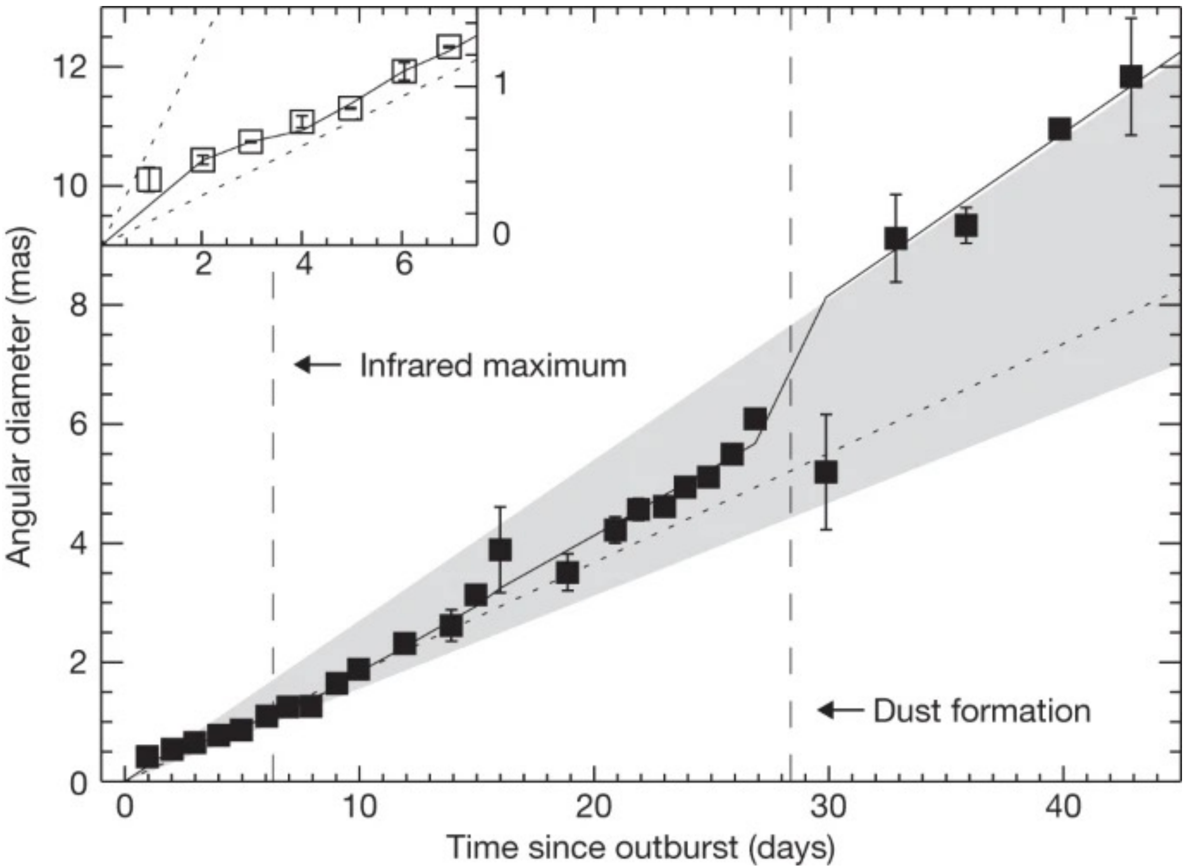
Newest type of VHE source: **novae**



<u>Recurrent nova RS Oph detected at VHE:</u>

- H.E.S.S., Science, 376-6588 (2022) 77
- MAGIC, Nat. Astr. 6 (2022) 689
- LST-1 (under internal review)

Novae: speed of expanding shell

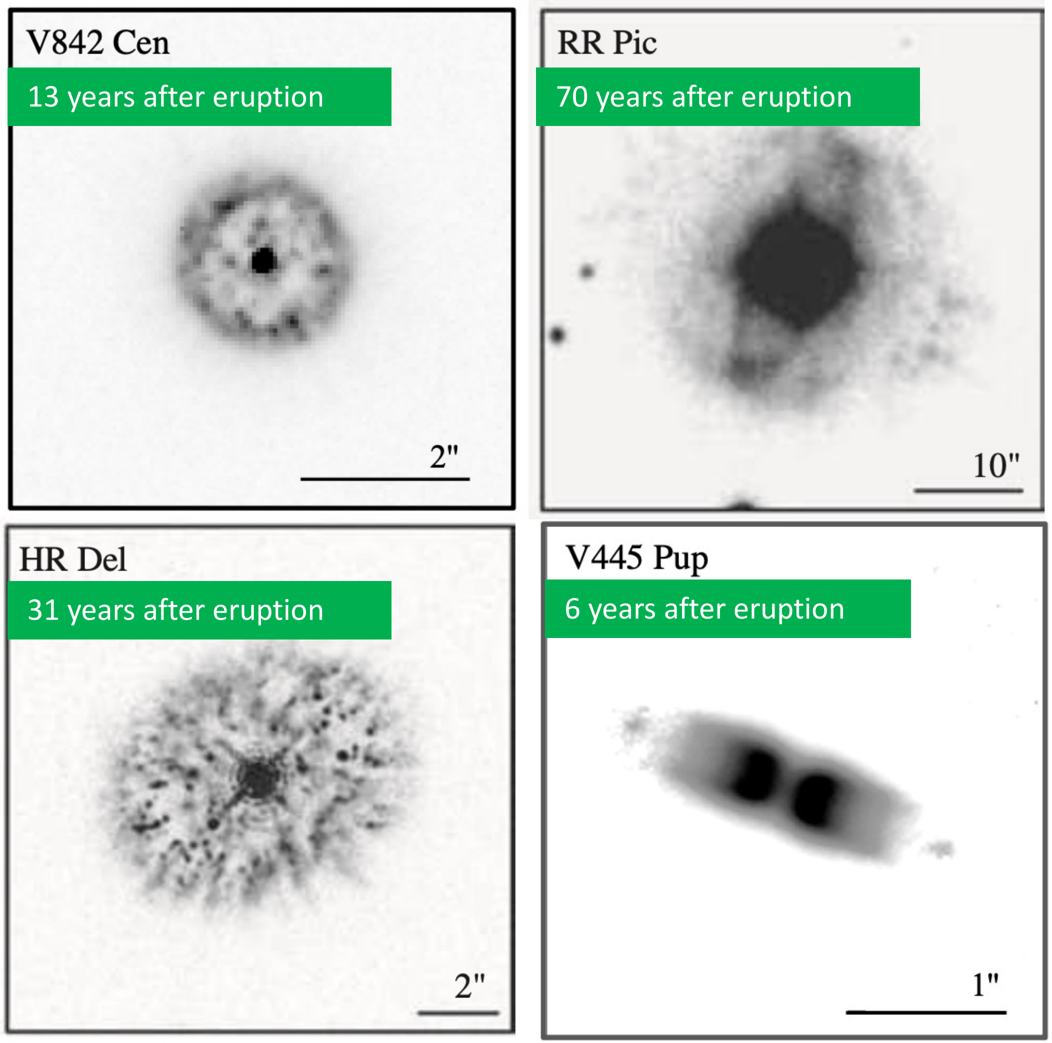


Expansion speed: 0.14 mas/day
Distance: 4.5 ± 0.6 kpc
Peak at $V=4.3^m$

The expanding fireball of Nova Delphini 2013, *G. H. Schaefer et al, Nature* ***515****, 234–236 (2014)*

Novae: anisotropy of expanding shell

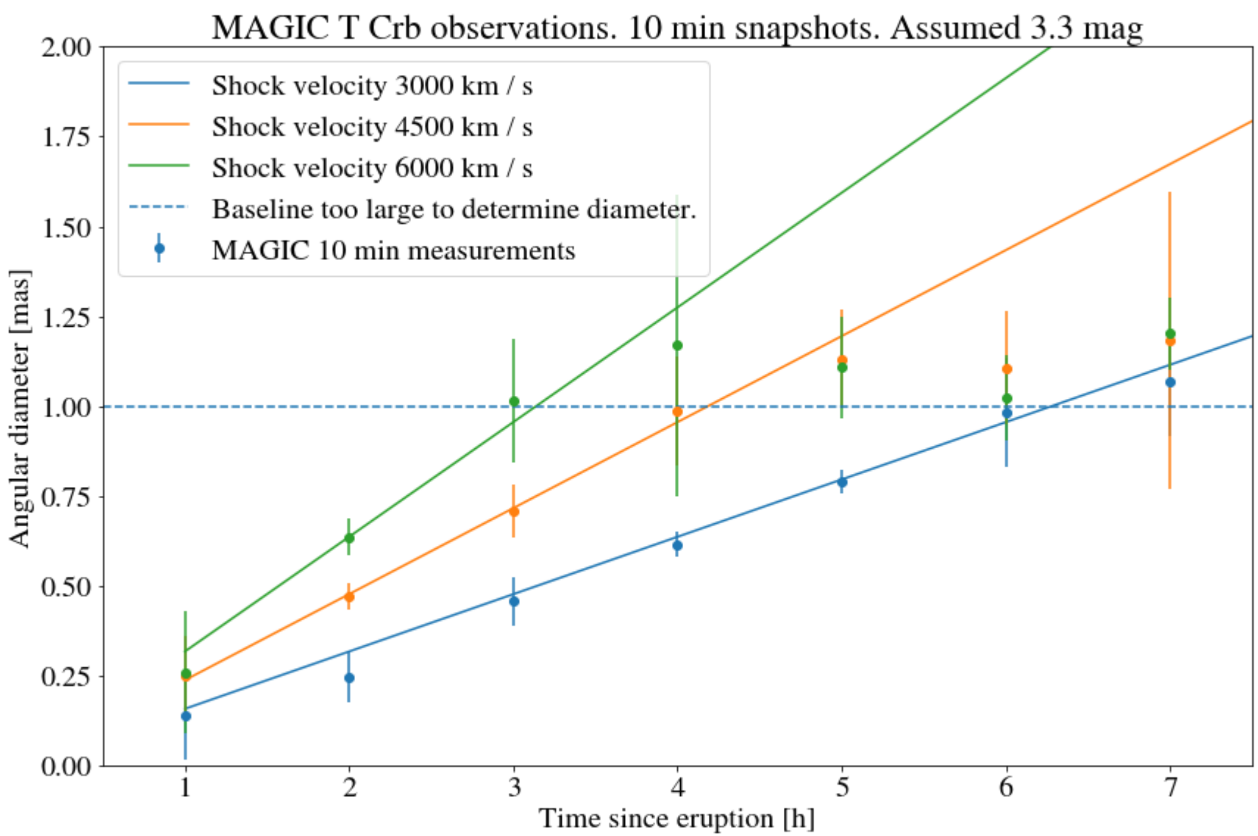
Nova remnant images in visible range **years** after nova explosion



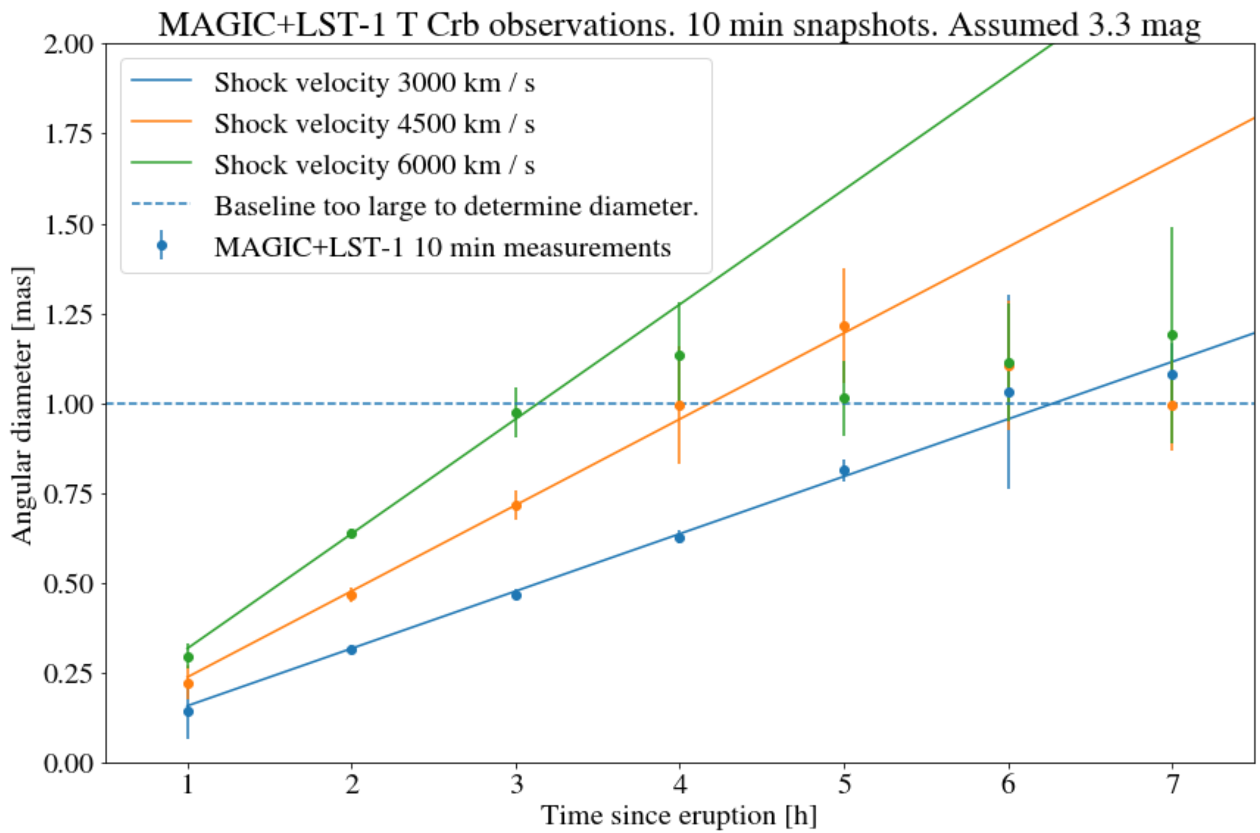
Chomiuk et al., arXiv:2011.08751

Also bipolar ejection in RS Oph

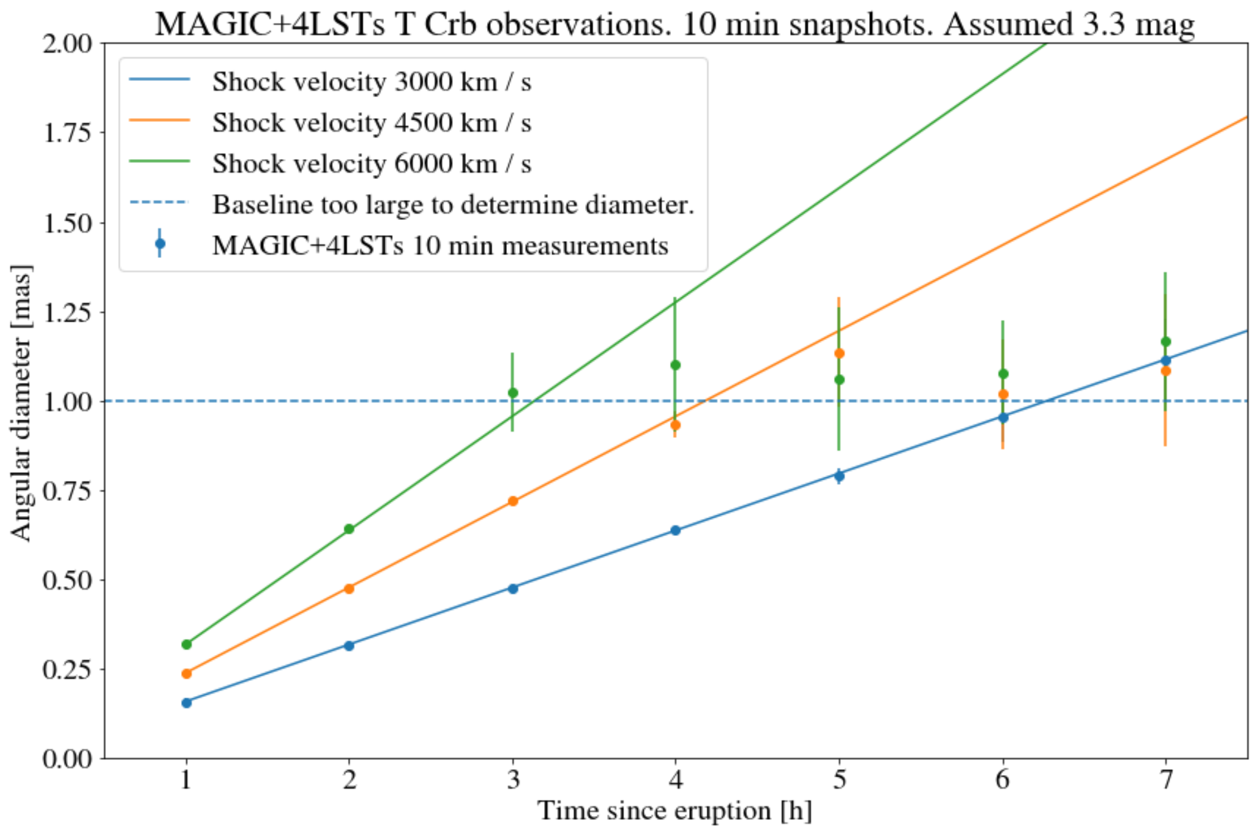
Prospects for upcoming nova T CrB



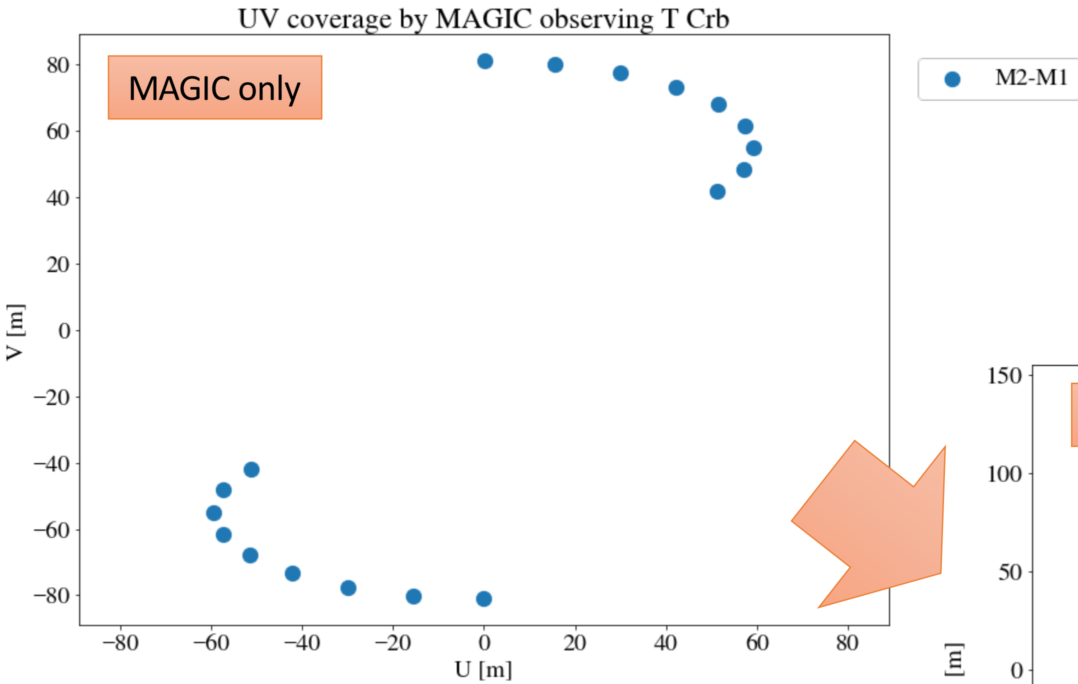
Prospects for upcoming nova T CrB

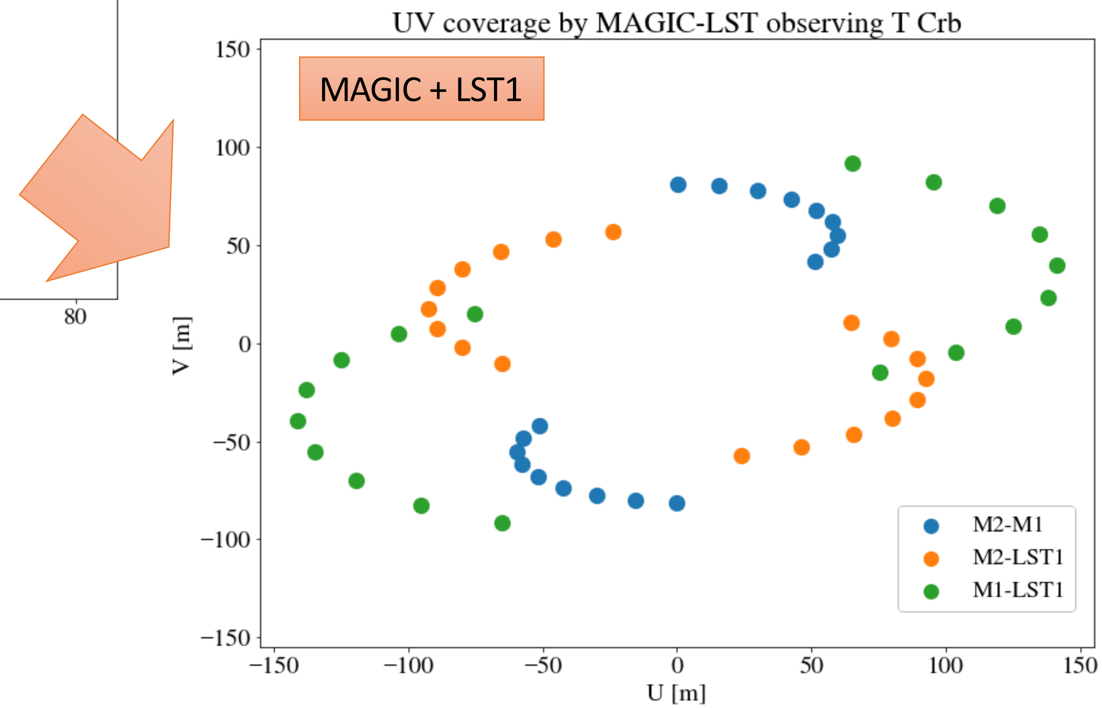


Prospects for upcoming nova T CrB



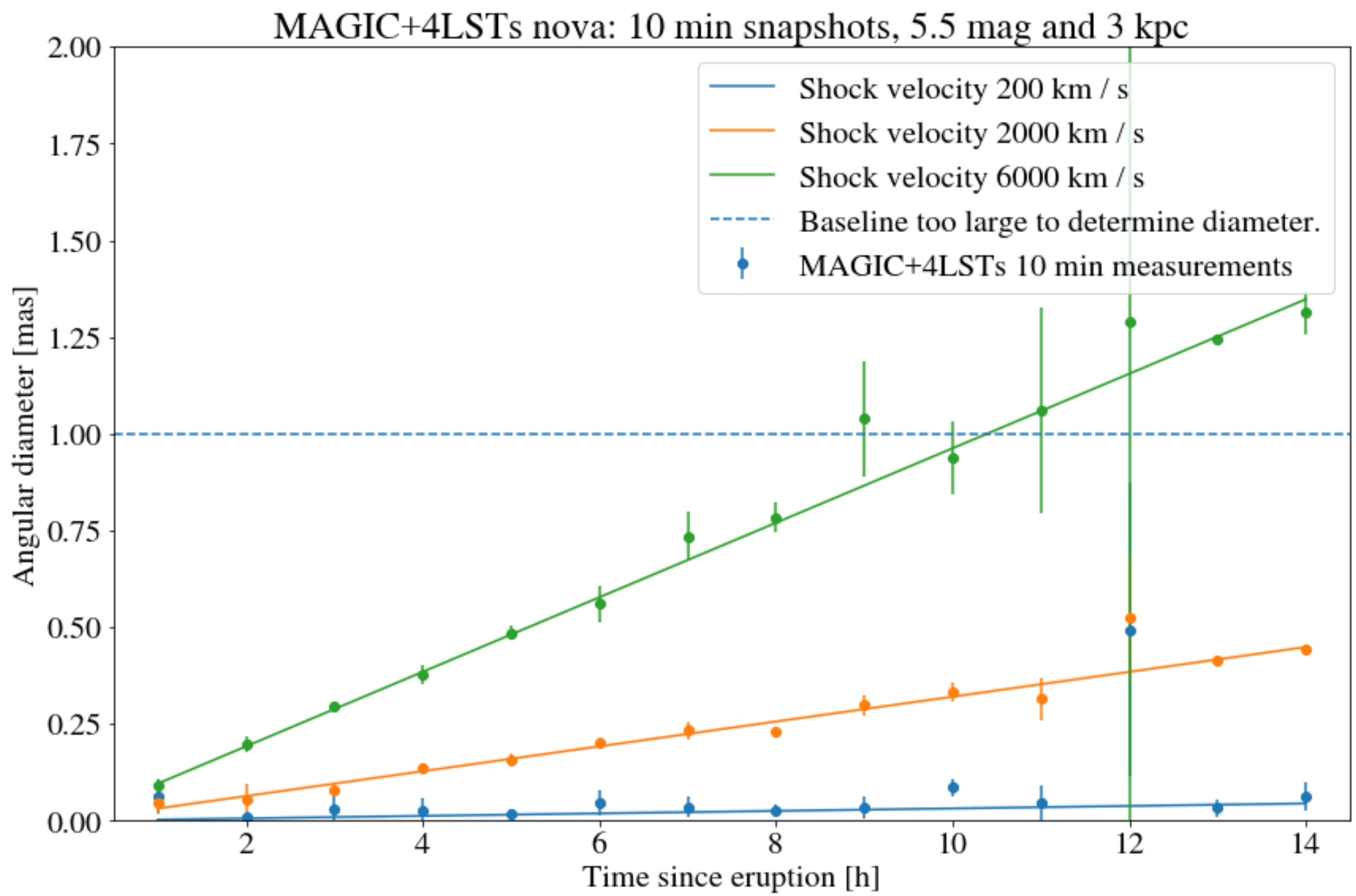
Prospects for upcoming nova T CrB





Prospects for weaker novas

A weaker nova, happening once every ~2 years in the northern sky.



And so?

- MAGIC is already taking data as an intensity interferometer. First measurements 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 and can be readily extended to all LSTs. We are starting test observations with MAGIC+LST-1
- The same scheme is being tested for NectarCam.
- The sensitivity should get a boost of a factor 10 only with the 4 LSTs, opening up the study of many new scientific cases.
- CTAO may easily be offered in this observation mode….

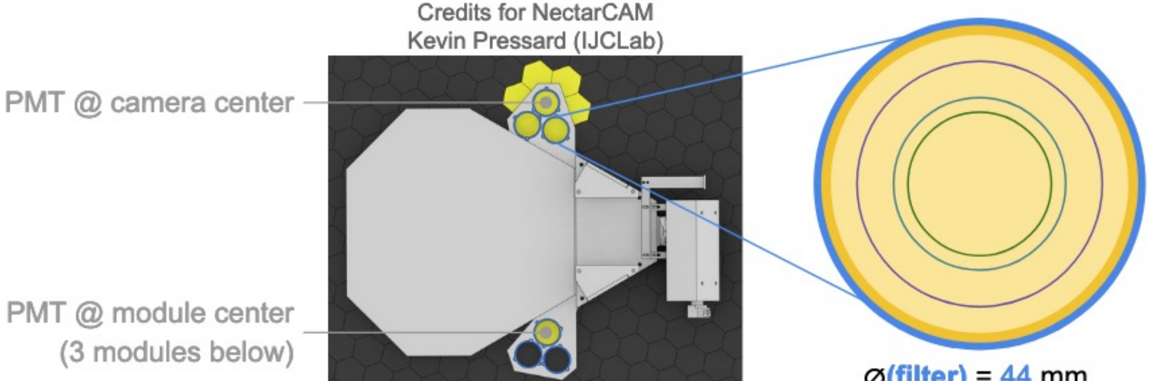
backup

Narrow-band filters for MSTs

Same concept as in LST-1 and MAGIC

MST/NectarCAM camera

Credits for NectarCAM
Kevin Pressard (IJCLab)



Movable filters

1 ON + 5 OFF

or 2 × (1 ON + 2 OFF)

Ø(filter) = 44 mm

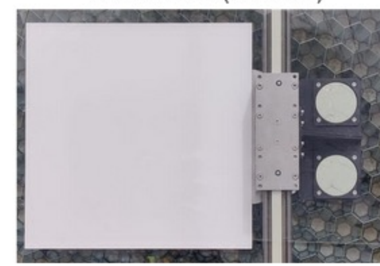
Ø(filter-mount) = 42 mm

Ø(usable area) = 39 mm

$\varnothing_{PSF}$(95, 80, 68 %) = 33, 23, 19 mm

LST camera

Credits for LST1
Carlos Diaz (CIEMAT)

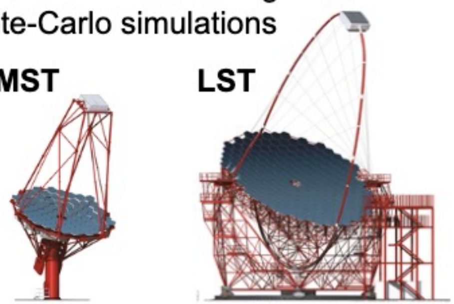


Semrock filters 425/26 nm, withØ = 44 mm for NectarCAM vs Ø = 75 mm for LSTs

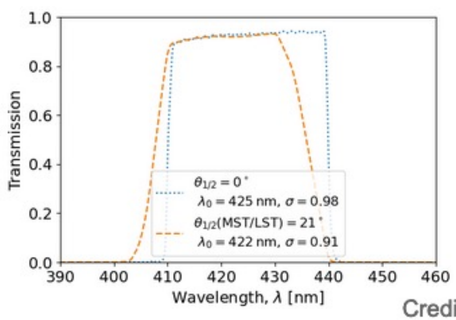
SII at CTA-North

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)



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	

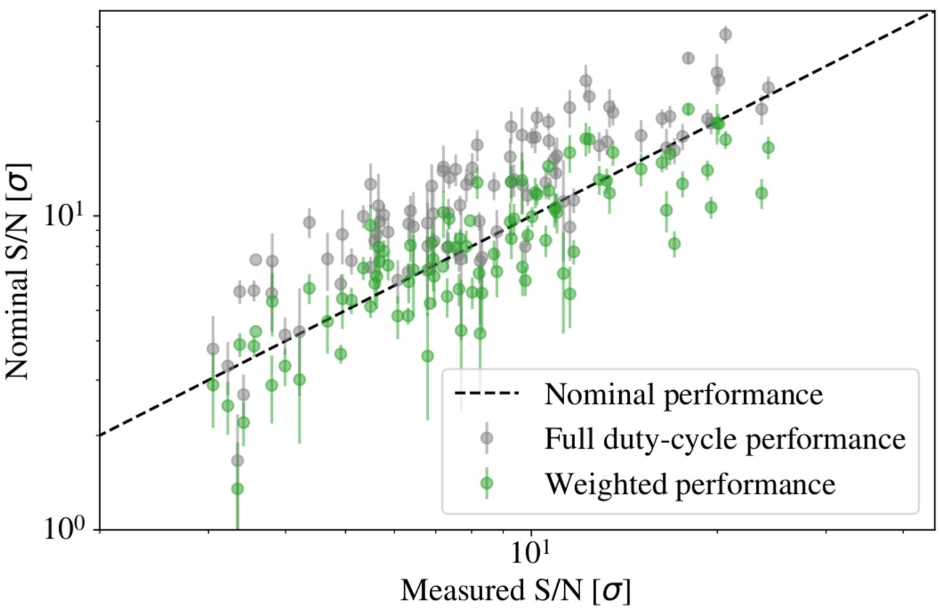
Ref. Prod 6 + MST-STR TDR

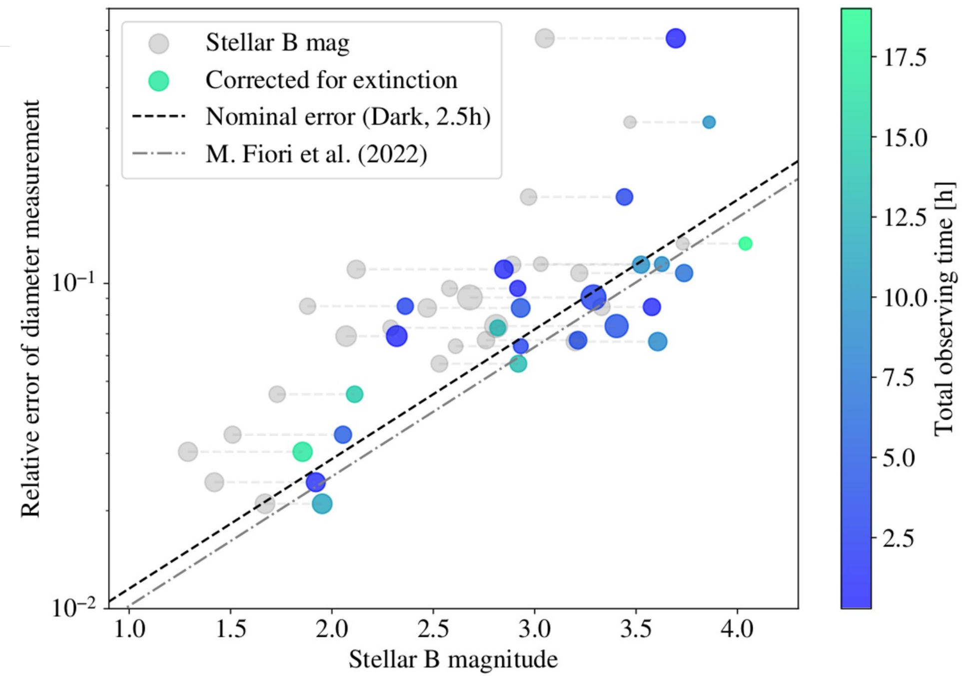
Credits: Jonathan Biteau

3

MAGIC SII – Performance paper – Results

- Signal to noise matches expectations:





MAGIC SII – Performance paper – Results

- Systematics associated with the "AC-coupled method" do not dominate:

Systematic effect	Uncertainty
Electronic bandwidth	0.5%
Optical bandwidth	$< 1\%$
Gain evolution of DC ADC branch	
- Seasonal temperature	Negligible
- Gain drift after DC jump	1%
- Long-term degradation	0.8%
- Deviations from linearity	Negligible
Residual electronic noise	Negligible
I_i(NSB) substraction	1.5/3% ($B_{mag} > 3.5$)

- Properly evaluating the background flux is currently the limiting systematic we identified

- This table does not include source-related systematics (multiple sources in FoV, etc…)

- These systematics may prevent detections in the $V^2 < 0.1$ range. **They are important!!**

LST 1-4 a week ago

CTAO-North in 2026