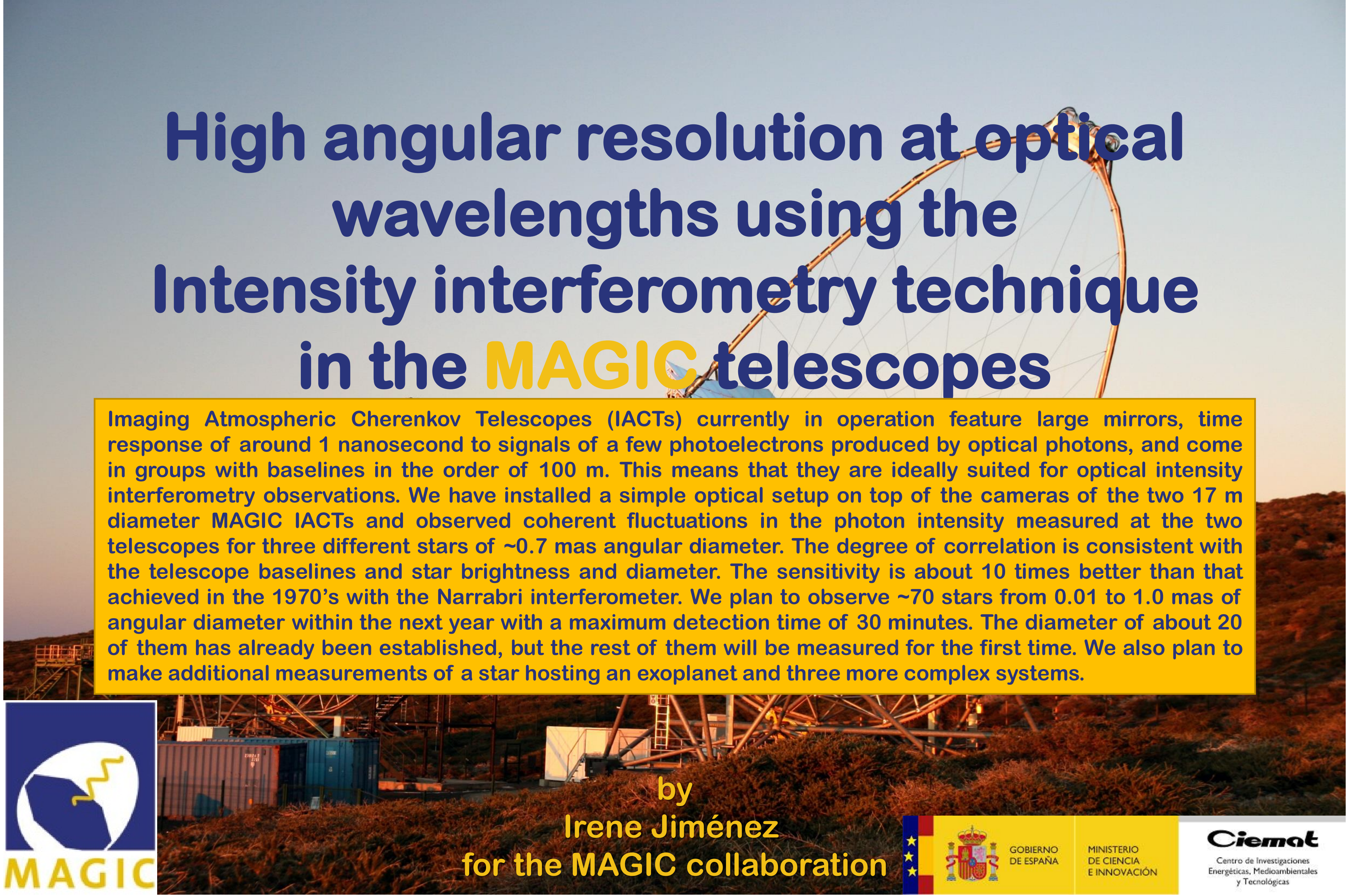

High angular resolution at optical wavelengths using the Intensity interferometry technique in the MAGIC telescopes

Imaging Atmospheric Cherenkov Telescopes (IACTs) currently in operation feature large mirrors, time response of around 1 nanosecond to signals of a few photoelectrons produced by optical photons, and come in groups with baselines in the order of 100 m. This means that they are ideally suited for optical intensity interferometry observations. We have installed a simple optical setup on top of the cameras of the two 17 m diameter MAGIC IACTs and observed coherent fluctuations in the photon intensity measured at the two telescopes for three different stars of ~0.7 mas angular diameter. The degree of correlation is consistent with the telescope baselines and star brightness and diameter. The sensitivity is about 10 times better than that achieved in the 1970's with the Narrabri interferometer. We plan to observe ~70 stars from 0.01 to 1.0 mas of angular diameter within the next year with a maximum detection time of 30 minutes. The diameter of about 20 of them has already been established, but the rest of them will be measured for the first time. We also plan to make additional measurements of a star hosting an exoplanet and three more complex systems.

MAGIC

by
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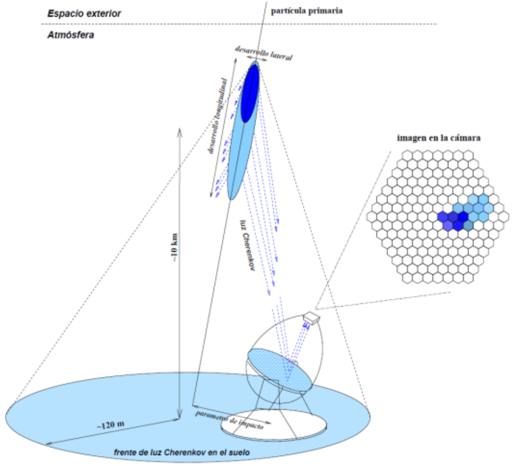
Context of the research

What is **MAGIC**?

- ‘**M**ajor **A**tmospheric **G**amma **I**maging **C**herenkov Telescopes’
- System of two Imaging Atmospheric Cherenkov Telescopes in Roque de los Muchachos (La Palma, Spain) sensitive to gamma rays above 50 GeV
- Diameter of each reflector: 17m

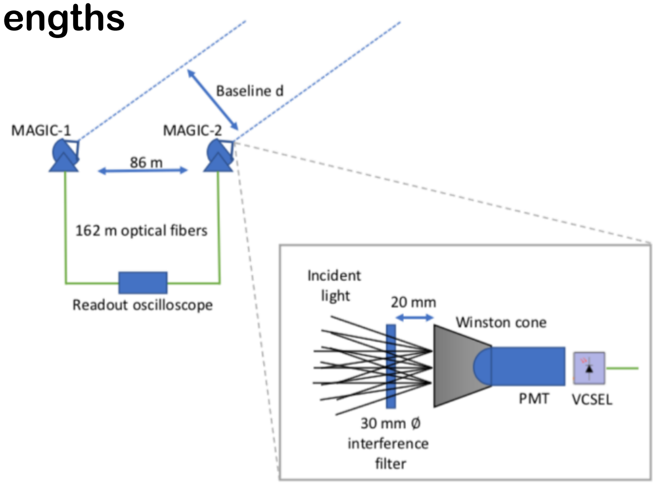
How does it work?

- Charged particles interact with our atmosphere, producing a series of cascades or ‘atmospheric showers’
- Some of these particles move faster than light in that medium, producing a very short flash (nanoseconds) of blue light
- This effect is known as ‘Cherenkov radiation’

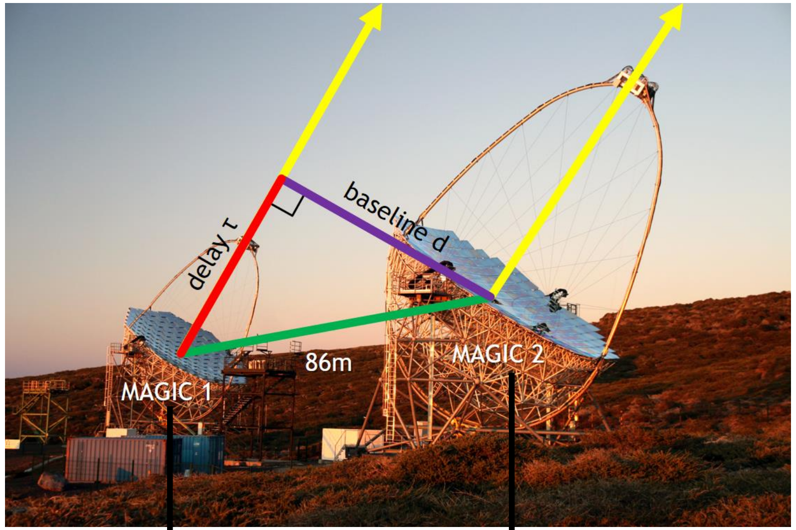


What is the Intensity interferometry technique?

- For the right telescope separation both starlight amplitude and intensity are correlated
- Conventional “phase/amplitude interferometry” looks for correlation in amplitude while we are measuring correlation in intensity
- The correlation of the starlight intensity fluctuations allows us to measure the spatial coherence or visibility $|V_{1,2}|^2$
- Measuring $|V_{1,2}|^2$ over a sufficient range of baselines allows us to construct an image of the source
- Most stars have angular diameters of less than 1 miliarcsecond (m.a.s.) and resolving them requires baselines of hundreds of meters at optical wavelengths



Description of the work/project/methodologies



162 m
optical fibers

Correlator

Pearson's correlation coefficient ρ

- Calibrator: star whose diameter has already been measured by other means.
- Candidate: star whose diameter we want to measure.

- Pearson's correlation coefficient ρ
- Delay τ

- Starlight statistical fluctuations (DC)
- PMT's gain G_i
- Estimated moonlight statistical fluctuations from model

- Delay-corrected ρ
- Normalized DC's corrected from Moon background DC_i/G_i

- Contrast of the signal:

$$c(d) = K\frac{\rho}{\sqrt{\frac{DC_1}{G_1}\frac{DC_2}{G_2}}}$$

- Baseline d
- Wavelength λ = 430 nm
- Calibrator star diameter θ

- Visibility:

$$|V_{12}(d)| = 2\frac{B_1(\pi \cdot d \cdot \theta/\lambda)}{\pi \cdot d \cdot \theta/\lambda}$$

$$\frac{c(d)}{c(0)} = |V_{12}(d)|^2$$

$$\frac{c(0)}{K}$$

Once we have this 'calibration factor' we can calculate the visibility for each candidate star and fit the resulting $|V_{12}(d)|^2$ to a certain diameter θ.

Results

The significances of the observed correlation signals are similar to the expected ones.

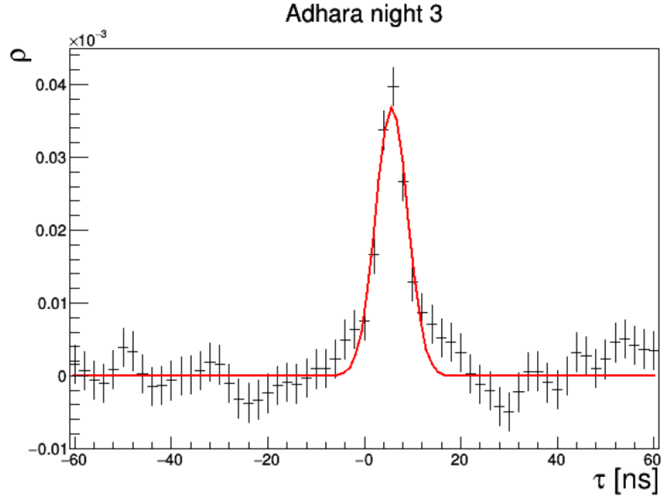
Three stars were observed within 5 nights: 2019/04/15-19:

- **Calibrator:** $\epsilon\ CMa$ **(Adhara)**
- **Candidates:** $\eta\ UMa$ **(Benetnasch) &** $\beta\ CMa$ **(Mirzam)**

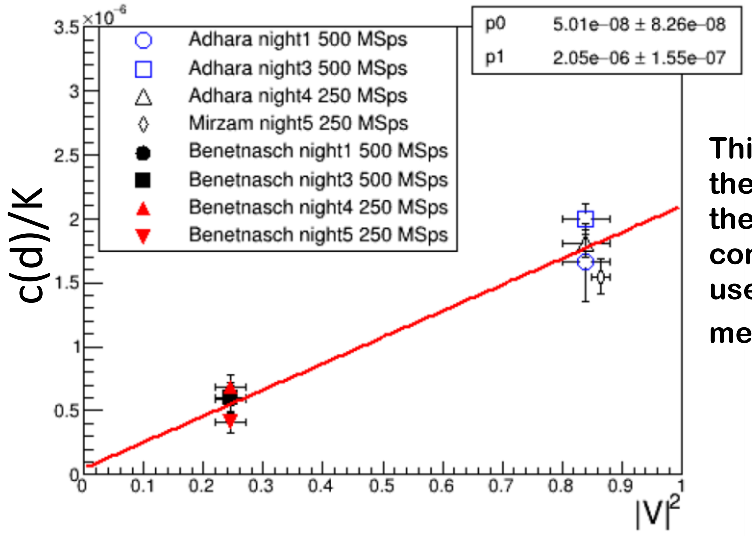
Star	Night	MSps	Runs	Eff. Time [sec]	Sigma
$\epsilon\ CMa$	1	500	100	200	5.3
$\epsilon\ CMa$	2	500			Bad weather
$\epsilon\ CMa$	3	500	300	600	15.4
$\epsilon\ CMa$	4	250	260	1040	12.6
$\eta\ UMa$	1	500	201	402	5.8
$\eta\ UMa$	2	500			Bad weather
$\eta\ UMa$	3	500	175	350	4.9
$\eta\ UMa$	4	250	190	760	7.3
$\eta\ UMa$	5	250	220	880	5.1
$\beta\ CMa$	5	250	268	1072	9.3

See paper: Acciari, V. A., et al. MNRAS 491.2 (2020) 1540. arXiv:1911.06029

Pearson's correlation factor v.s. delay:



Contrast v.s. visibility:



This plot shows that the observations of the 3 stars are consistent and can be used to calibrate the measurement of $|V_{1,2}|^2$.

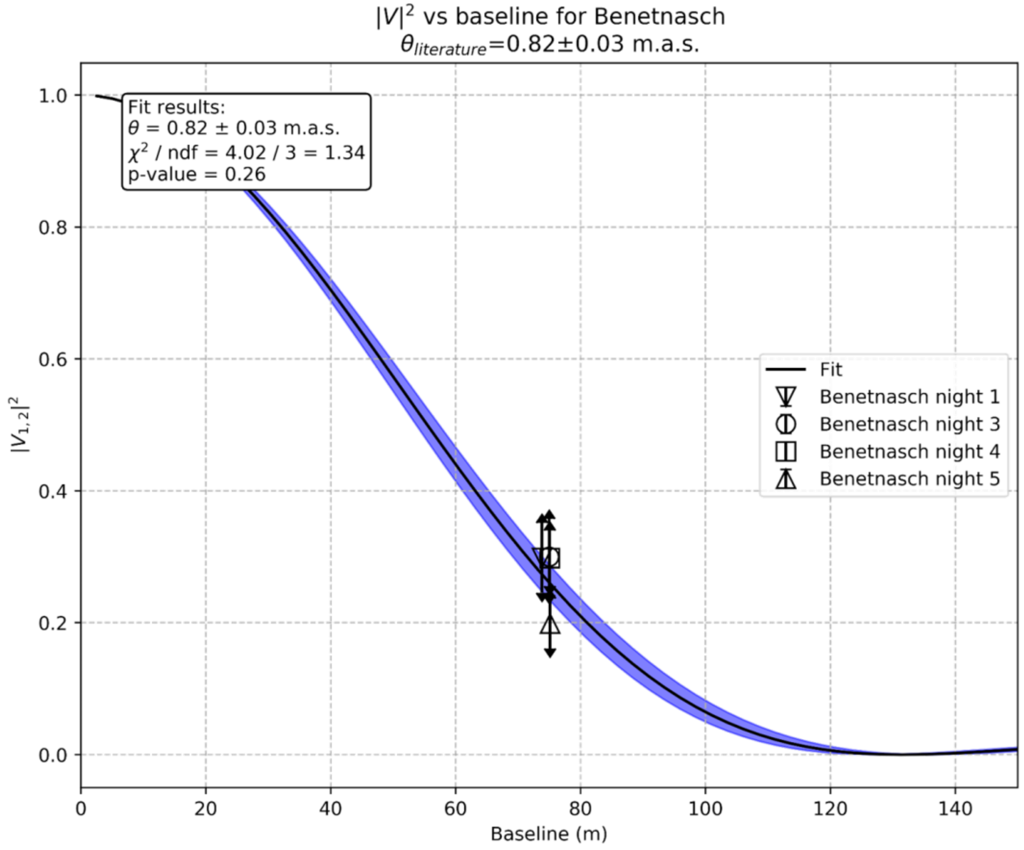
Results

Estimated sensitivity based on our observations:

Star magnitude in B	$\|V_{1,2}\|^2$	Time for 5σ detection
3	1 (unresolved)	4.5 min
	0.8	7 min
	0.3	50 min
4	1 (unresolved)	28 min
	0.8	44 min
	0.3	5.2 hours
5	1 (unresolved)	~3 hours
	0.8	4.7 hours
	0.3	52 hours

An example of how we measure the diameter of a star: we use $\epsilon\, CMa$ (Adhara) as a calibrator and fit $|V_{12}|^2$ measurements of $\eta\, UMa$ (Benetnasch) over several nights.

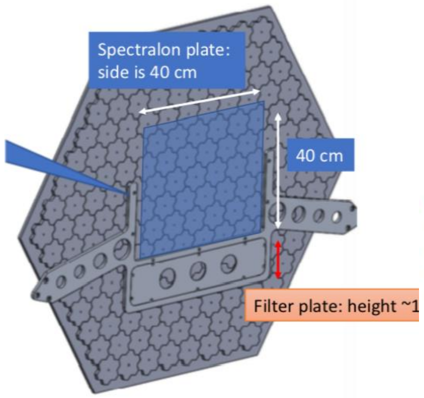
$\eta\, UMa$ (Benetnasch): diameter is consistent to the estimated value from the literature.
Literature: 0.82 ± 0.03 m.a.s.
Measured with I.I.: 0.82 ± 0.03 m.a.s.



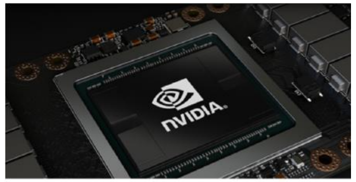
Impact and prospects for the future

Technical improvements:

- Installation of remotely deployable filter holder
- Eliminating deadtime with a new digitizer card
- Introducing real time processing with a new GPU



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



GPU NVIDA TESLA VT100

Candidates and calibrators catalog for future observations (hopefully starting this September):

- 361 stars:
    - 32 calibrators
    - 329 candidates

Main ID	$\theta_{Swihart}$[m.a.s.] (estimated)	θ_{JSDC}[m.a.s.] (estimated)	θ_{JMDC}[m.a.s.] (measured)	B[mag]	Type
* eps CMa	-	-	0.77±0.05	1.29	calibrator
* bet CMa	-	-	0.508±0.03	1.73	calibrator
* eps Ori	-	-	0.67±0.04	1.51	calibrator
* kap Ori	0.662±0.042	-	0.44±0.03	1.88	calibrator
* eta UMa	0.67±0.141	0.748321±0.091078	0.937±0.144	1.751	calibrator
* gam Ori	0.756±0.114	0.686141±0.070273	0.704±0.04	1.416	calibrator
* sig Sgr	-	0.678677±0.058212	-	1.916±0.005	candidate
* zet Pup	-	-	0.41±0.03	1.98	calibrator
* alf Gru	-	-	0.98±0.07	1.58	calibrator
* gam Cas	0.545±0.098	-	0.9	2.29	calibrator
* eta Cen	-	0.569879±0.059438	-	2.173	candidate
* zet Oph	0.319±0.055	-	0.5±0.05	2.58	calibrator
* eta CMa	-	0.815488±0.077849	0.72±0.06	2.367	calibrator
* ups Sco	-	0.483078±0.046765	-	2.521	candidate