Cherenkov Telescope Array Observatory @IJCLab/A2C/APHE

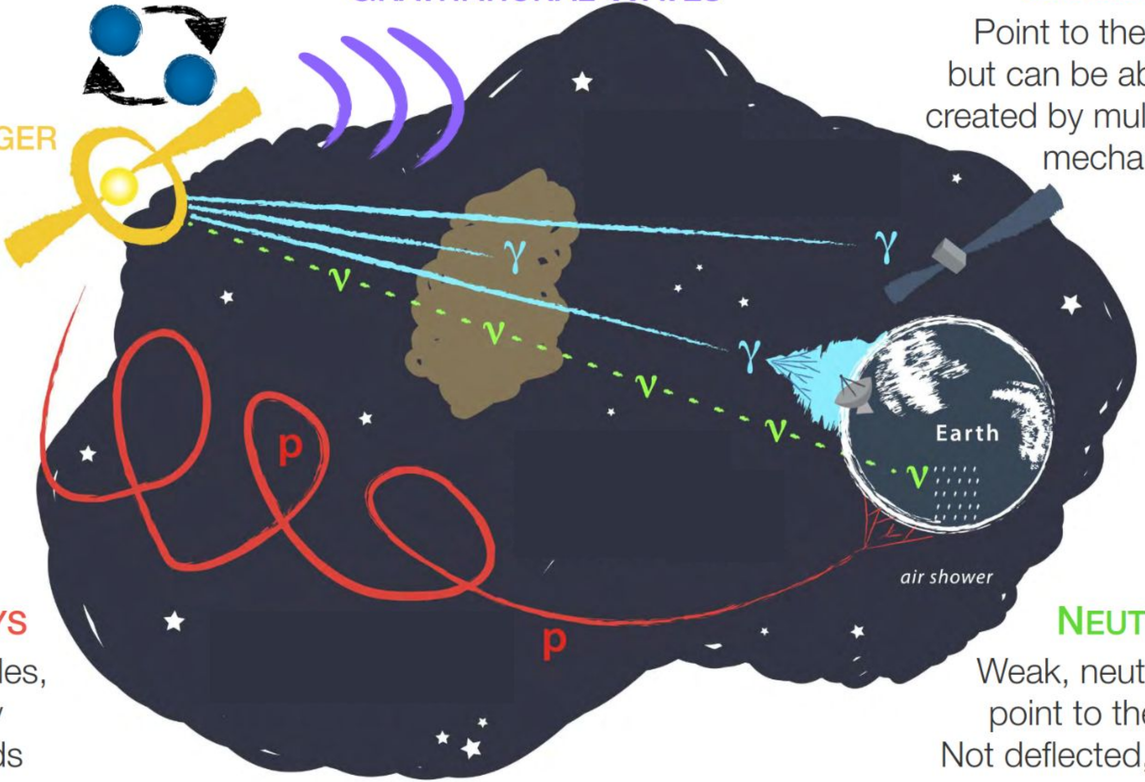
From the camera of a telescope to the observations of stars

Quentin Luce

Multi-messenger astrophysics

GRAVITATIONAL WAVES

MULTI-MESSENGER SOURCE



GAMMA RAYS

Point to their sources, but can be absorbed and created by multiple emission mechanisms

COSMIC RAYS

Charged particles, deflected by magnetic fields

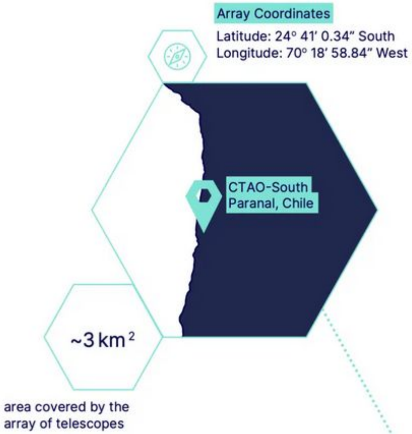
NEUTRINOS

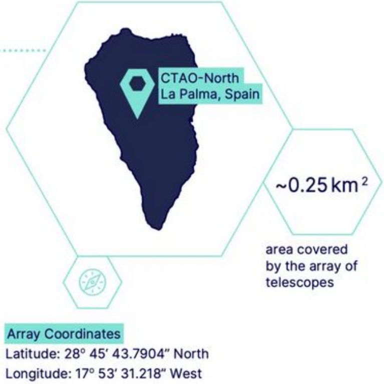
Weak, neutral particles, point to their sources, Not deflected, not absorbed

Cherenkov Telescope Array Observatory

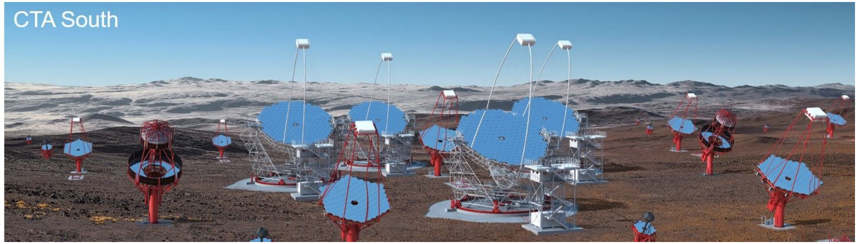
CTAO

4 LSTs + 9 MSTs
20 GeV < E < 5 TeV

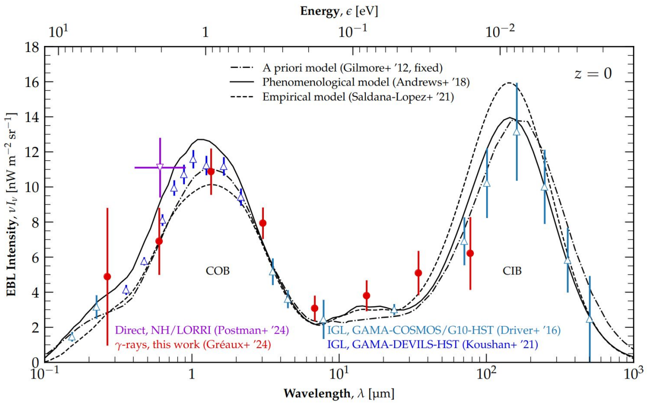




14 MSTs + 37 SSTs
150 GeV < E < 300 TeV



Extragalactic Background Light, SuperNova Remnants, Alerts, etc.

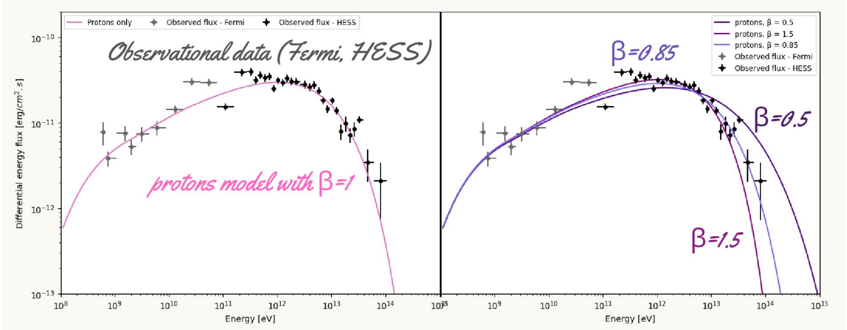


Gamma-ray cosmology — Conclusions from three decades of extragalactic gamma-ray astronomy and perspectives for CTAO

Thesis of Lucas Greaux

4D mapping of blazars: from optical to γ-ray emission

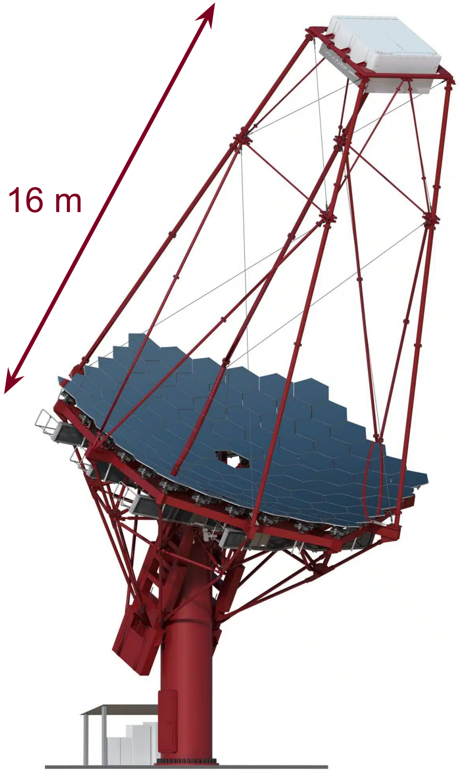
Thesis of Julian Hamo



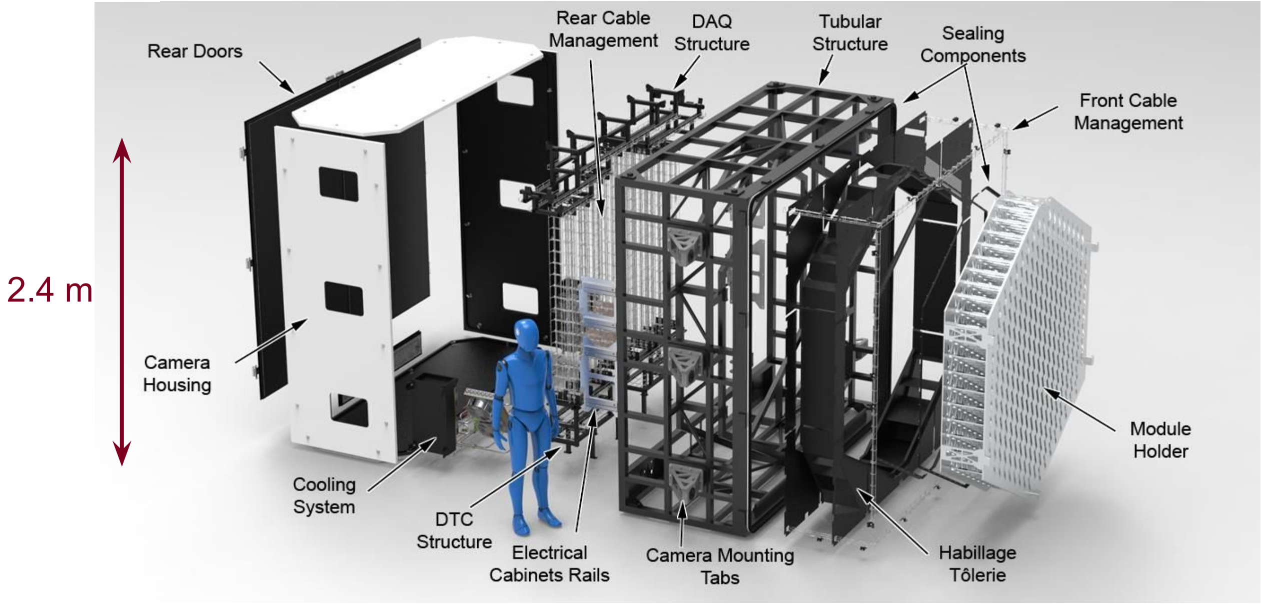
High-energy gamma observation by CTA: origin of the Pevatrons, and development and analysis of the NectarCAM calibration

Thesis of Coline Dubos

Medium Size Telescope (MST)

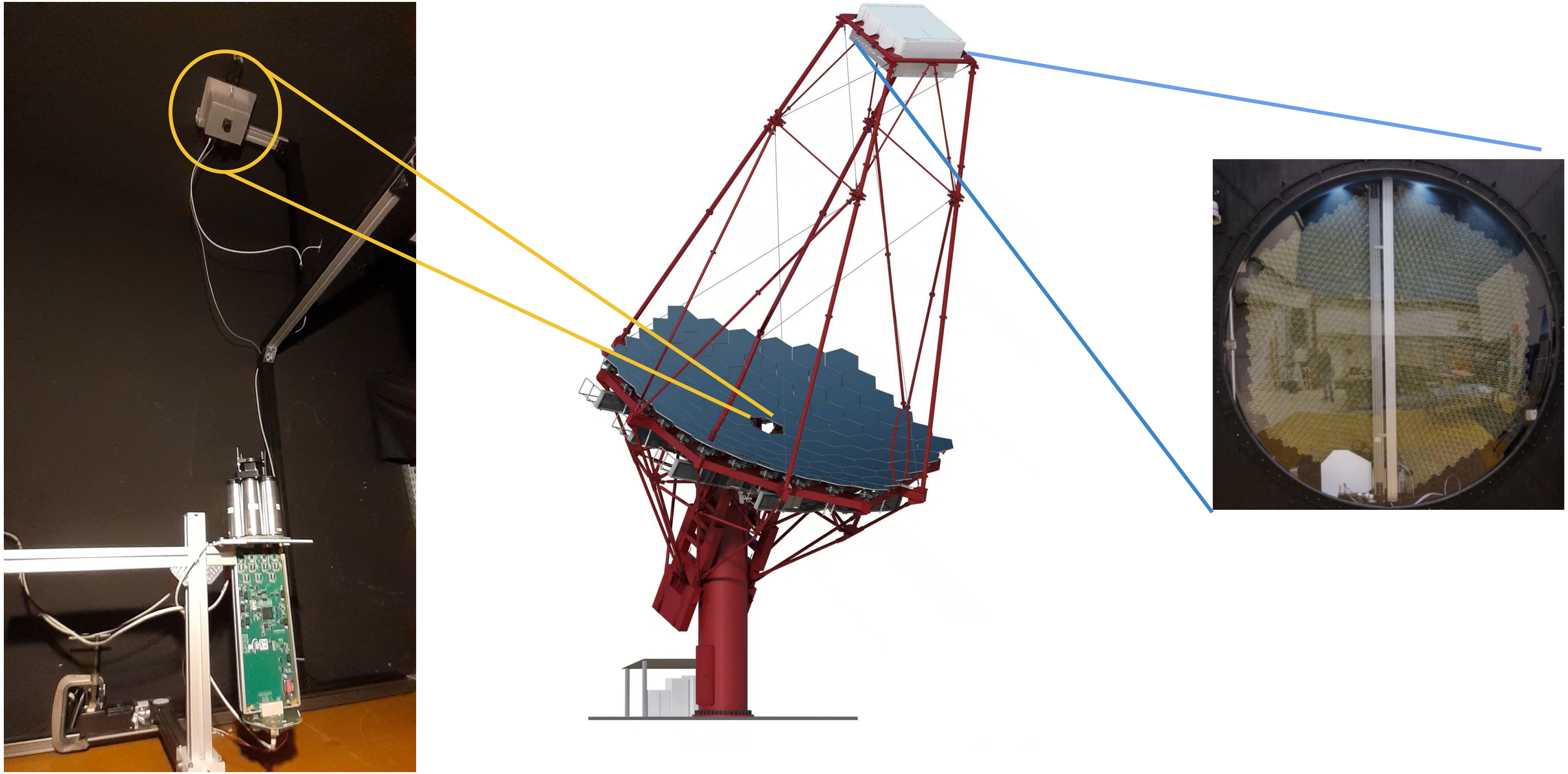


NectarCAM



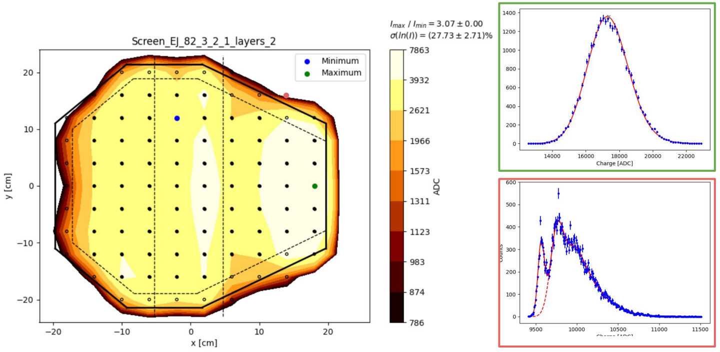
= **1855 photo-multiplier tubes**, with a field of view of 0.18° each, for a **total field of view of 8°**

Calibration devices of NectarCAM



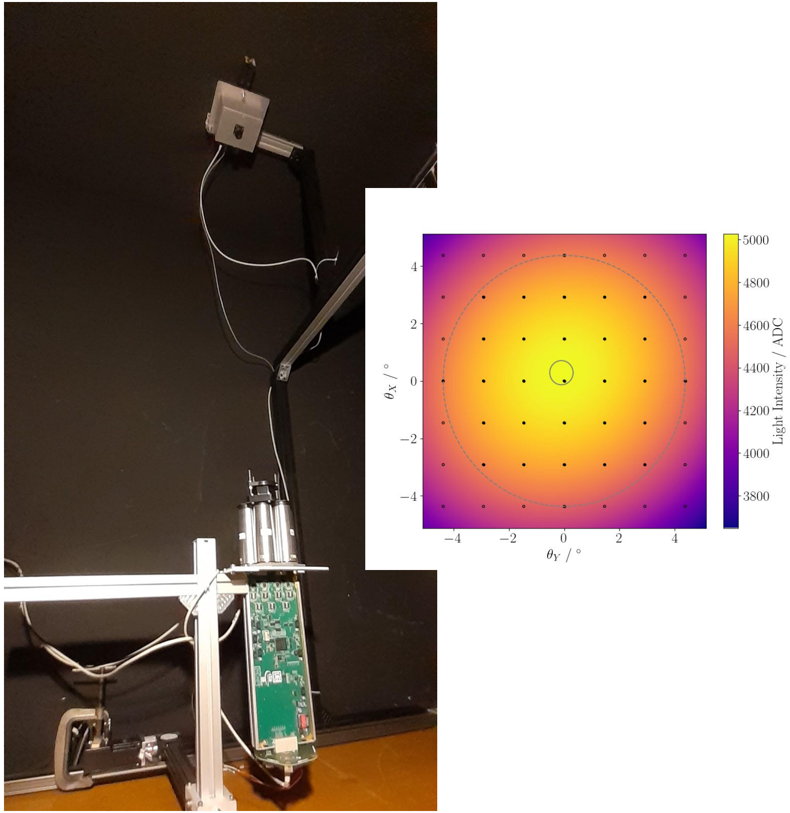
Calibration devices of NectarCAM

Critical design & manufacturing review
→ produced and characterized for 9 cameras (+ spares)



Credits: Coline Dubos

Critical design & manufacturing review
→ production and characterization in **progress**

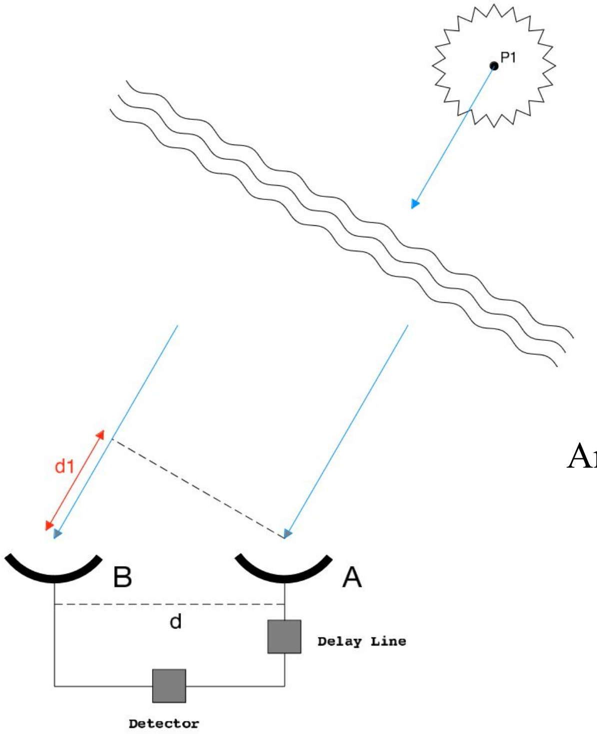


*Thanks to great IJCLab **R&D team**,*
*as well as **Barbara Biasuzzi**'s postdoc, **Pooja Sharma**'s thesis, **Sonal Patel**'s postdoc, **Coline Dubos**'s thesis*

From the camera of a telescope to the **observations of stars**

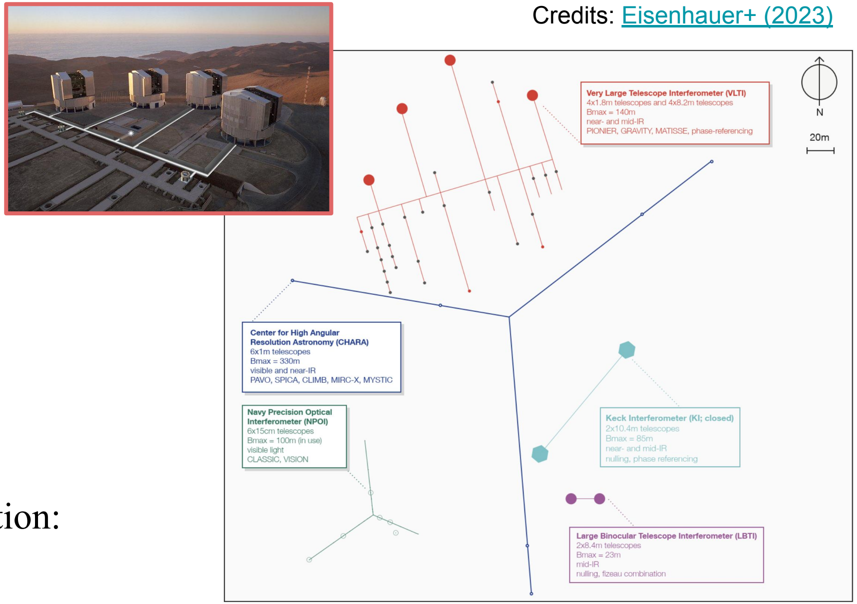
Phase Interferometry vs Intensity Interferometry

Michelson interferometer



Credits: Foellmi (2009)

Credits: Eisenhauer+ (2023)



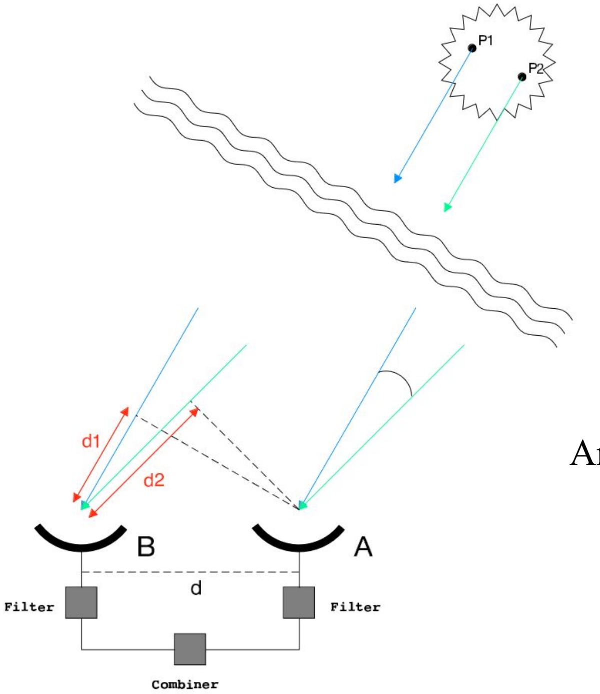
Angular resolution:

$$\Delta\theta \propto \frac{\lambda}{d}$$

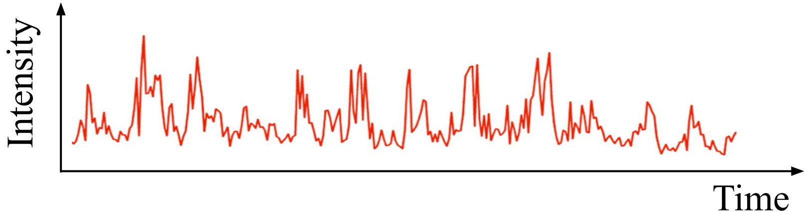
- Cannot be digitized at each telescope
- Need a stability of the optical delay line and of the atmosphere turbulences
- Large baselines (~hundreds of meters)
- Excellent signal to noise ratio

Phase Interferometry vs Intensity Interferometry

Intensity interferometer

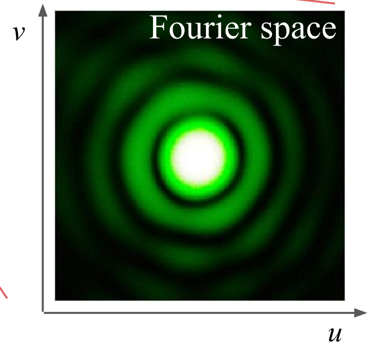


Correlation of the signals of the telescopes:



Correlation of the signals of the telescopes:

$$\frac{\langle I_A I_B \rangle}{\langle I_A \rangle \langle I_B \rangle} \propto g^{(2)}(u, v, t) \propto |V|^2$$



Angular resolution:

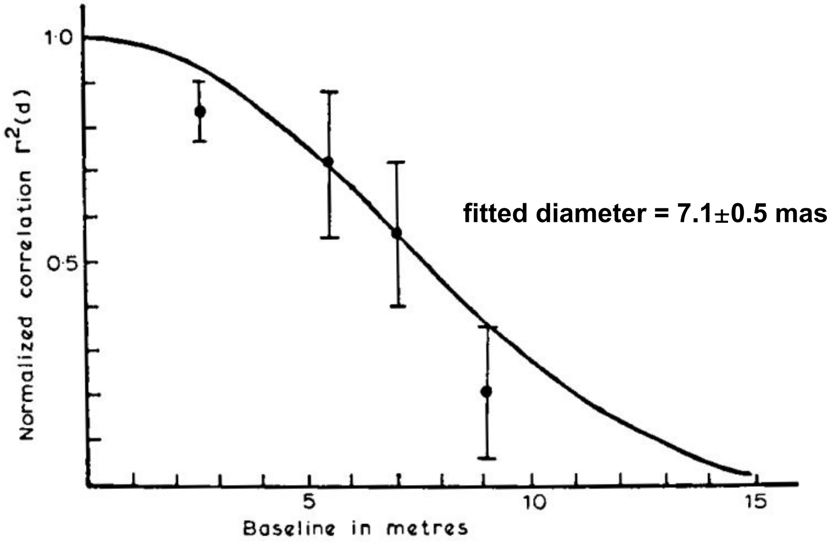
$$\Delta\theta \propto \frac{\lambda}{d}$$

- Can be digitized at each telescope
- Very very large baselines (> kms)
- Efficient at short wavelength (blue, UV)
- Insensitive to the atmosphere turbulences
- **Poor signal to noise ratio…**

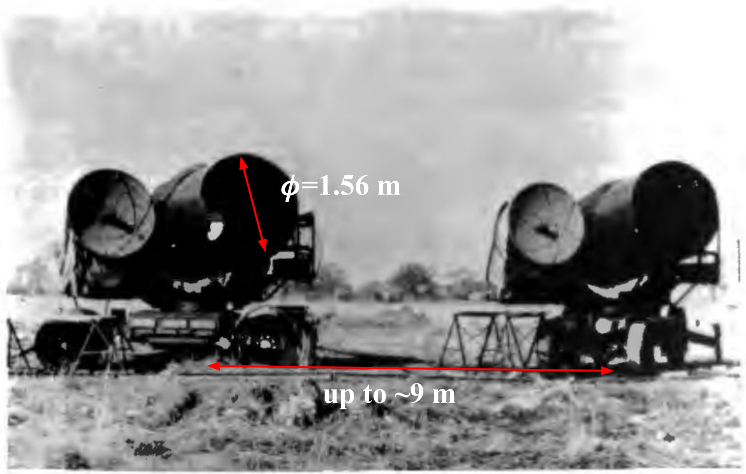
Credits: Foellmi (2009)

Validity of the concept: 1956

Measurements of Sirius A



First Stellar Intensity Interferometer
@Jodrell Bank (University of Manchester)



Credits: Hanbury-Brown and Twiss, Nature (1956)

Narrabri Stellar Intensity Interferometry (NSII)

Initiated by Hanbury-Brown & Twiss

Development of the Narrabri Stellar Intensity Interferometer (in Australia)

Distance d = 10-200m between the two telescopes (6.5m diameter)

Single PMT with 20% Q.E. at λ = 440 nm on each telescope, $I_{anode} \sim 100\ \mu A$

Measurement of the angular diameter of 32 stars (1963-1974)

Time correlation of 2 PMTs ↔ constructive interference of 2 photons pathways

Signal to noise ratio

$$S/N \propto A \cdot \alpha(\lambda_0) \cdot q(\lambda_0) \cdot n(\lambda_0) \cdot |V|^2(\lambda_0, d) \cdot \sqrt{b_\nu} \cdot F^{-1} \cdot \sqrt{\frac{T}{2}}$$

mirror area

photo-detection efficiency

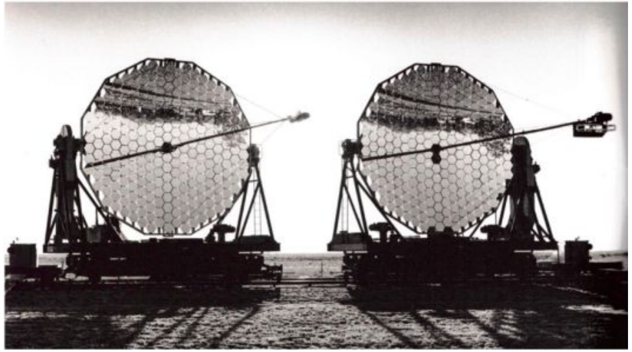
visibility curve

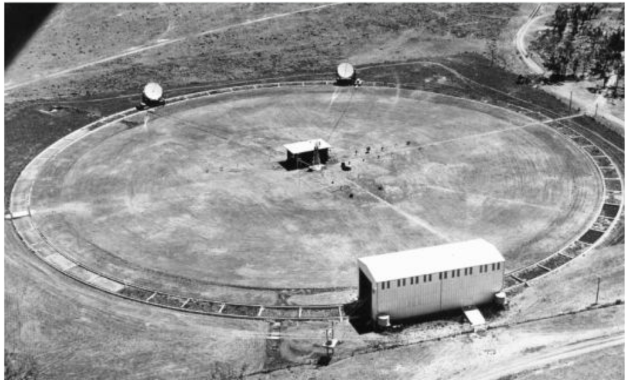
bandwidth

number of pixels

observation time

Competing with Michelson interferometers…

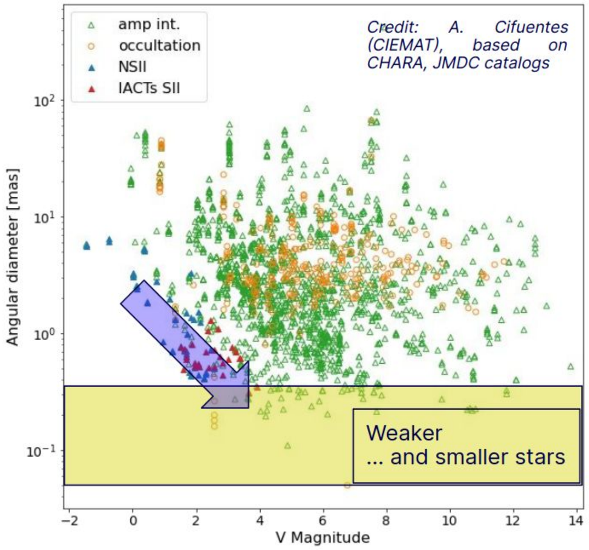


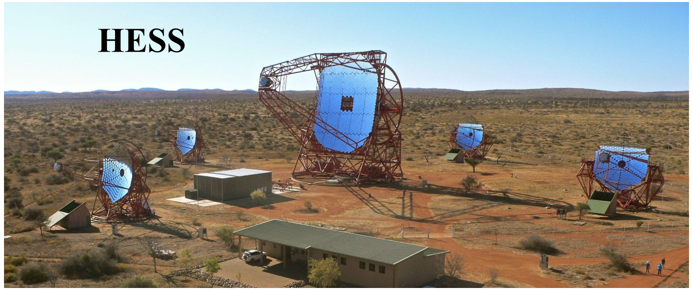


NSII - the last intensity interferometer?

Revived by current generation IACT

***Observations during moon time*: increase of IACT duty cycle!**

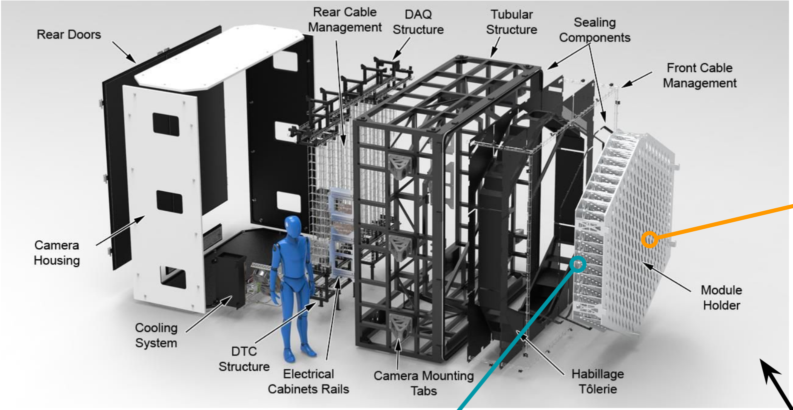




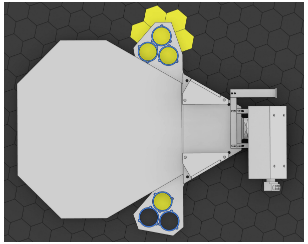
A vast science case:

Stellar diameters, winds, photosphere; Binary systems, accretion disks; Novae and other transient events; Rapid rotators; Exoplanet imaging; Stellar occultation: trans-Neptunian / Kuiper-belt objects

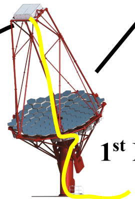
Modifications of the NectarCAM



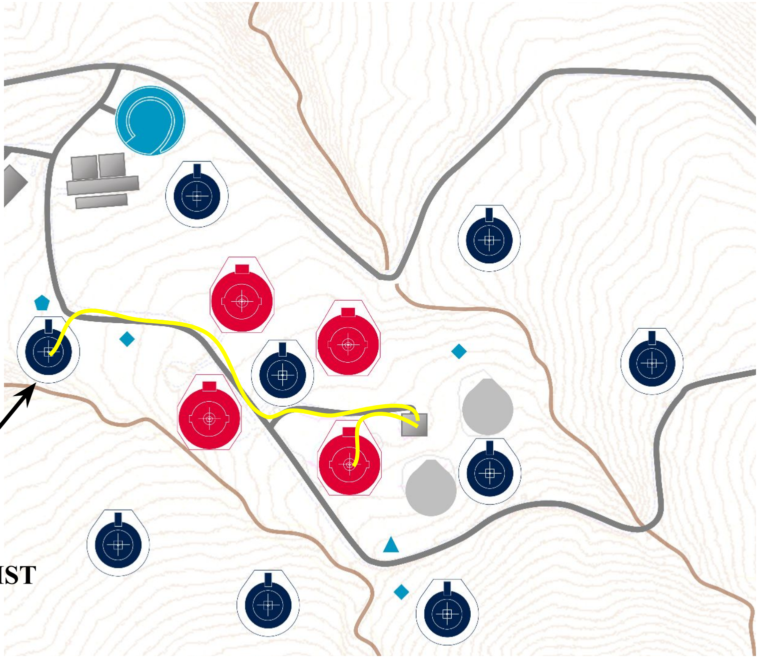
Movable filters
(two sets of ON/OFF)
Credits for NectarCAM
Kevin Pressard (IJCLab)

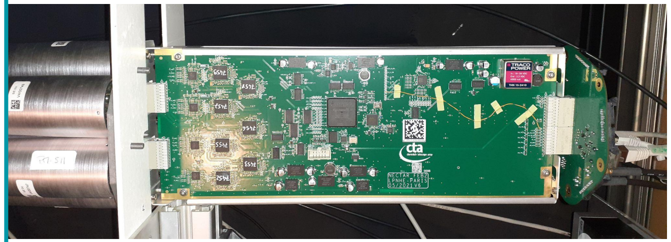


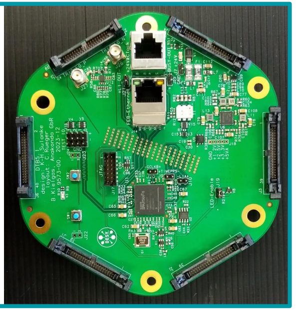
NectarCAM 1



1st MST





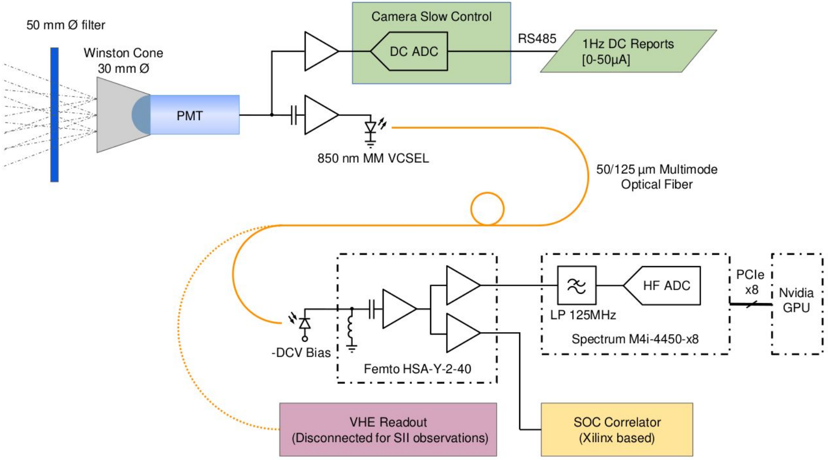


Kale Sulanke (DESY), François Toussenel (LPNHE),
David Fink (MPP), Eric Delagne (IRFU, CEA/Saclay)

Transmission of the signal

MAGIC system, implemented in LST-1

Credits: MAGIC SII paper



Electrical → Optical → Electrical → Digital → Analysis →

IDROGEN board (IJCLab) developed for radio astronomy

PAON4, experiment @ Nancay - Credits: Ansari+ 2019

Now: 2 channels with 0.5 GS/s @ 14 bits

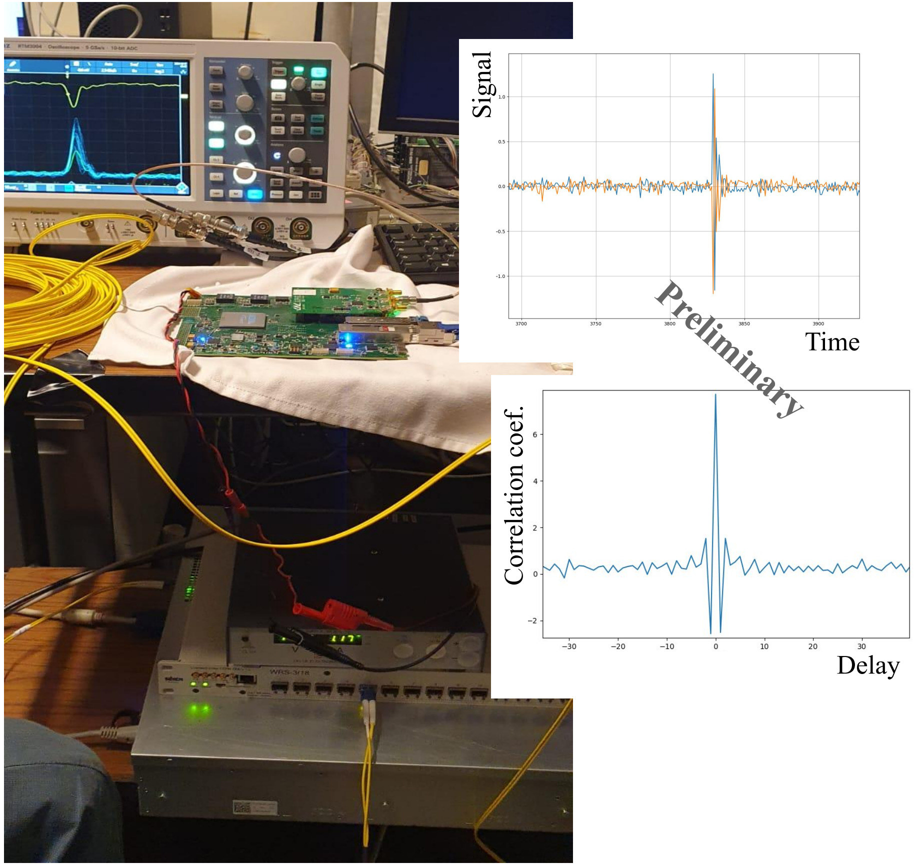
Electrical → Digital → Analysis →

Upcoming: 1 channel with 1 GS/s

Daniel Charlet (IJCLab), Cédric Esnault (IJCLab),
Monique Taurigna-Quéré (IJCLab)

Credits Jonathan Biteau, presented at the SII Workshop 2024

Transmission of the signal



IDROGEN board (IJCLab) developed for radio astronomy

PAON4, experiment @ Nancay - Credits: Ansari+ 2019

Now: 2 channels with 0.5 GS/s @ 14 bits

Electrical — **Digital** — **Analysis** →

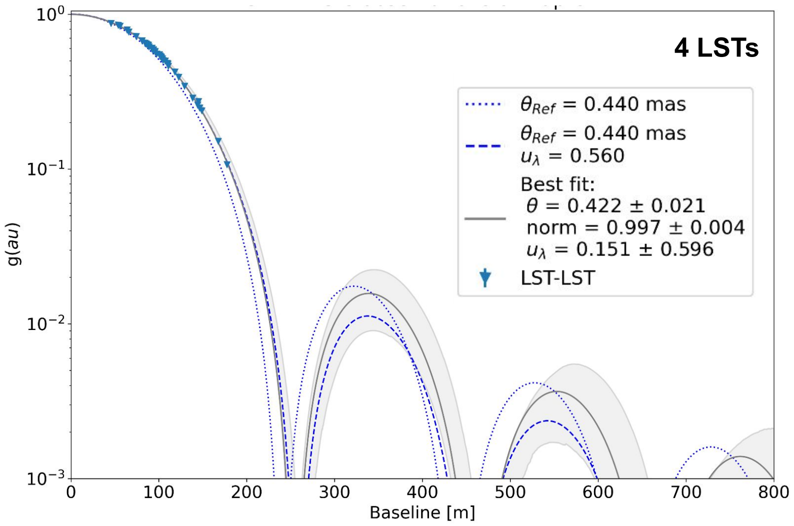
Upcoming: 1 channel with 1 GS/s

Example of science case: looking at limb-darkening

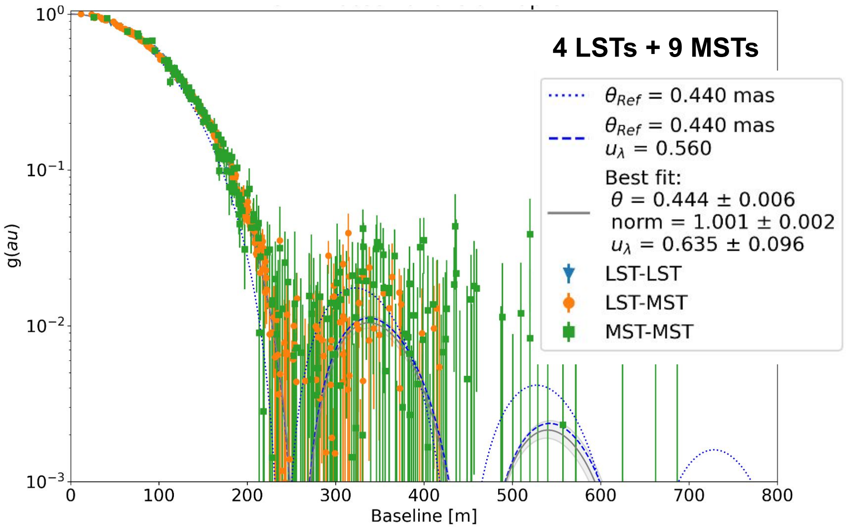
Credits: QL, Tarek Hassan, Jonathan Biteau

From the expected signal-to-noise ratio:

$$S/N \propto A \cdot \alpha(\lambda_0) \cdot q(\lambda_0) \cdot n(\lambda_0) \cdot |V|^2(\lambda_0, d) \cdot \sqrt{b_\nu} \cdot F^{-1} \cdot \sqrt{\frac{T}{2}}$$



κ Ori
θ = 0.44 mas
B mag. = 1.88
u_λ = 0.56



Example of science case: looking at limb-darkening

Credits: QL, Tarek Hassan, Jonathan Biteau

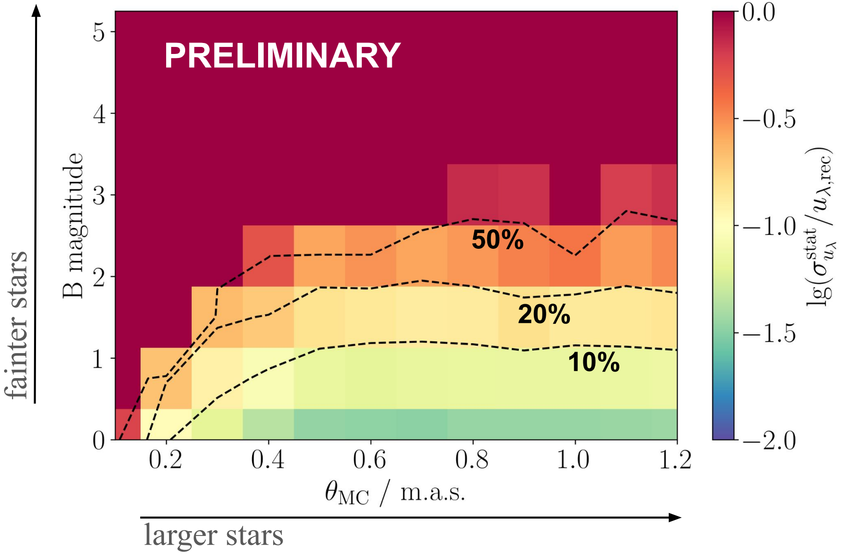
10% precision w/ eclipsing binaries

Binary		Measured u B	V	R
BS Dra	A	0.64 ± 0.04	0.50 ± 0.03	...
	B	0.64 ± 0.04	0.50 ± 0.03	...
EE Peg	A	0.62 ± 0.03	...	...
	B	0.75 ± 0.15	...	...
FS Mon	A	0.58	0.58	...
	B	0.594	0.591	...
GG Ori	A	0.50 ± 0.04	0.51 ± 0.03	0.23 ± 0.07
	B	0.50 ± 0.04	0.51 ± 0.03	0.23 ± 0.07
WW Cam	A	...	0.494 ± 0.017	...
	B	...	0.499 ± 0.017	...
V459 Cas	A	...	0.487 ± 0.008	...
	B	...	0.487 ± 0.008	...
MU Cas............	A	...	0.56 ± 0.07	...
	B	...	0.56 ± 0.07	...
WW Aur...........	A	0.616 ± 0.056	0.416 ± 0.060	...
	B	0.512 ± 0.078	0.418 ± 0.083	...
RW Lac............	A	...	0.55	...
	B	...	0.57	...

Credits: D. Heyrovsky, ApJ 2007

~2h30 of observations, 4 LSTs + 9 MSTs

$u_\lambda = 0.4$

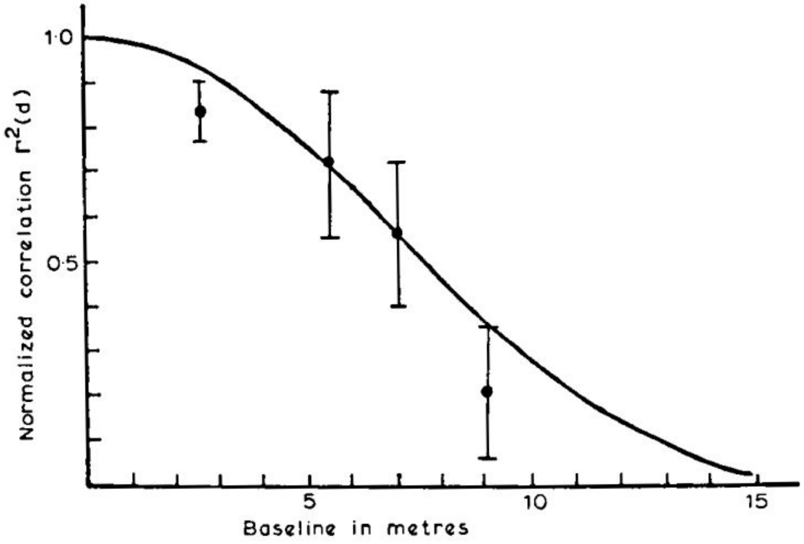


→ **4 LSTs:** ~ **10% precision on u_λ** for stars with B mag. < 0.5 and large radii (***θ*** > 0.8 mas)

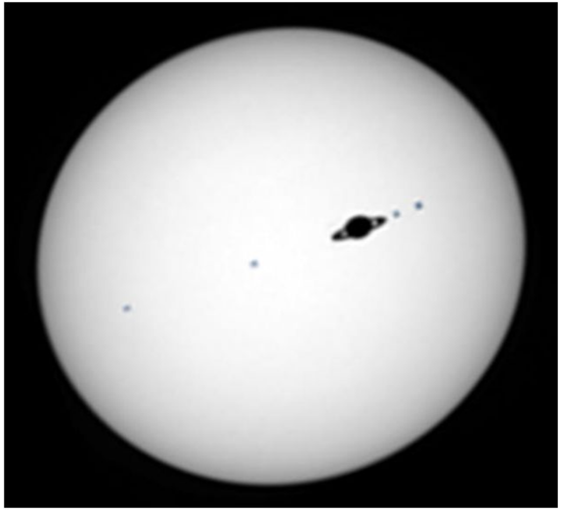
→ **4 LSTs + 9 MSTs:** ~ **10% precision on u_λ** for stars with B mag. < 1.2 (***θ*** > 0.2 mas)

Conclusion?

Measurements of Sirius A in 1956



Simulation of a 'Sirius A'-like star: d=2.6 pc, angular diameter=6 mas
Planets: Jupiter size with Saturn-type rings, angular diameter=350 μas
4 Earth-size objects



Next PhD cycles?

Credits: Hanbury-Brown and Twiss, Nature (1956)

Credits: Dravins and Lagadec (2014)

Trugarez!*

***Thank you!**

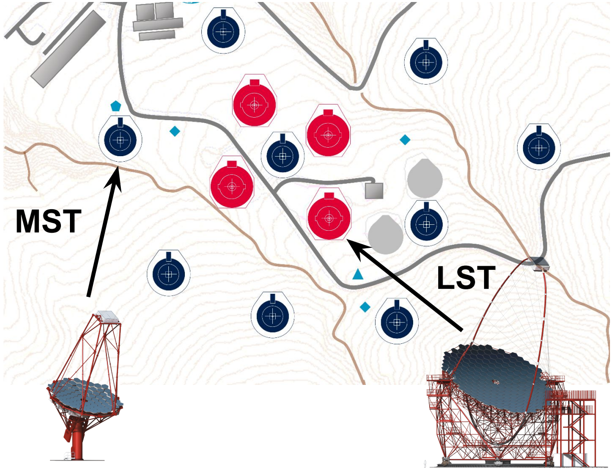
Back-up

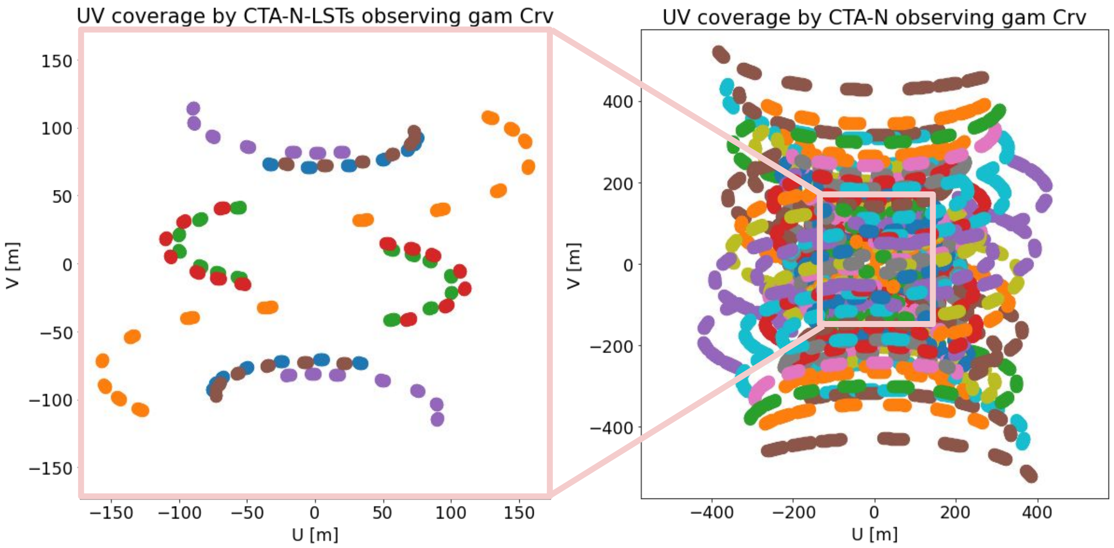
SII at CTAO-North

Including MSTs in the SII array improves:

· Extent of the coverage of spatial frequencies (*uv*-plane) → Order-of-magnitude improved precision on ~100 µas stellar radius

· Density of uv coverage: **never achieved so far**! → True capacity for “model-based” imaging (phase is unknown)



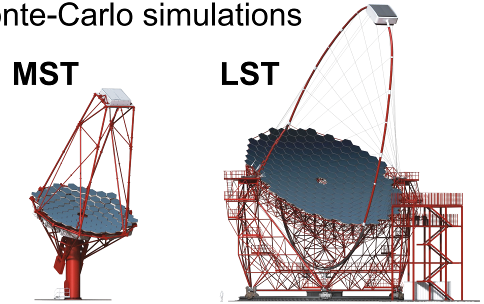


Credits: **Tarek Hassan**

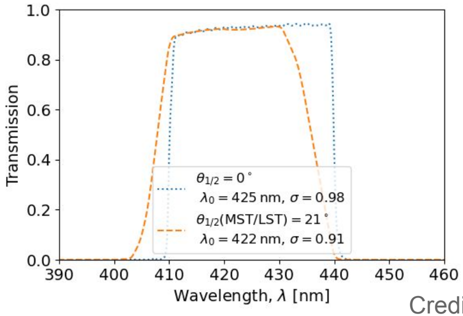
SII at CTAO-North

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

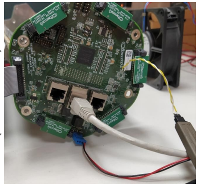
Credits: Jonathan Biteau

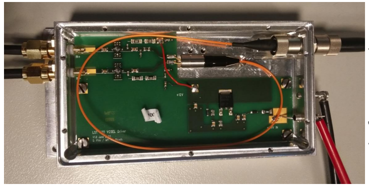
Transmission of the signal

Option 1: VCSEL-based system (MPI Phys.) as in LST & MAGIC

Amplification of anode current and optical transmission

Credits for LST1 Gustavo Martinez (CIEMAT)



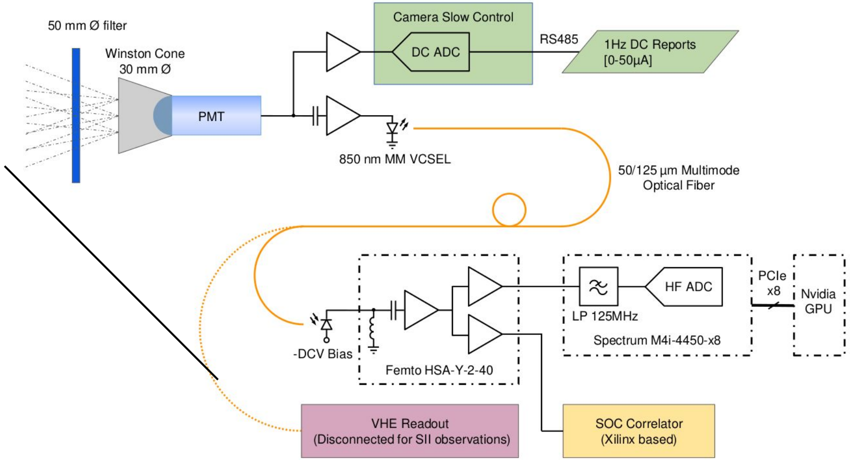


Credits for LST1 David Fink (MPI Phys)

sent through 50/125µm multi-mode fiber @ λ = 850 nm

Distance > 300 m?

Credits: MAGIC SII paper



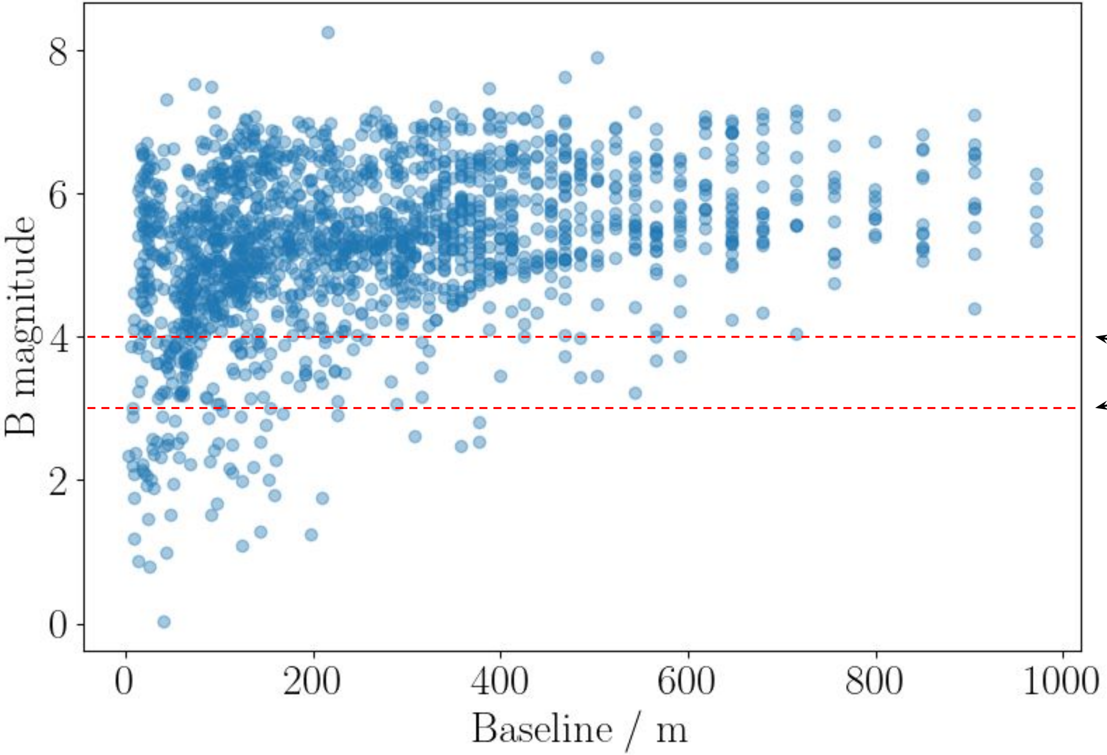
Electrical → Optical → Electrical → Digital → FFT →

Option 2: Off-the-shelf (equivalent?) as in VERITAS

sent through 10µm single-mode fiber @ λ = 1550 nm

Credits Jonathan Biteau, presented at the SII Workshop 2024

Angular diameter: Target stars

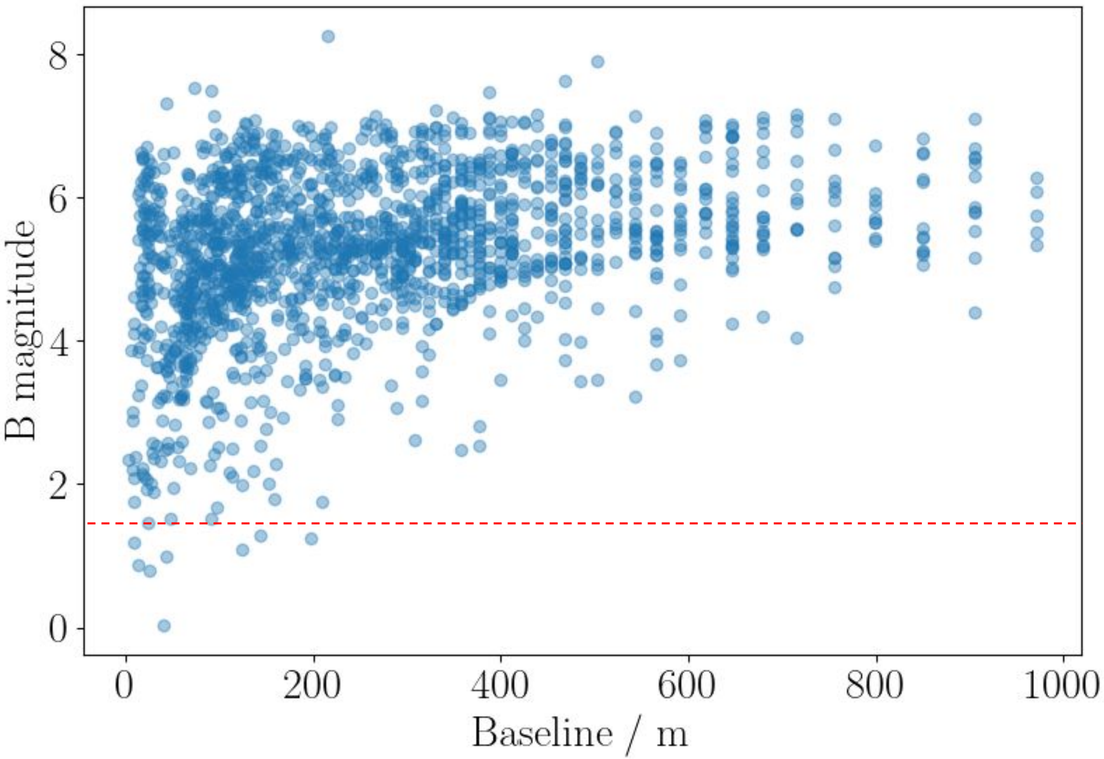


Number of stellar radii **reconstructed with a precision of 1%** in the Northern hemisphere

4 LSTs + 9 MSTs: **~170 stars**
4 LSTs: **~60 stars**
for T ~2h30

Credits: Lucijana Stanic
Adapted from https://target-stars-sii.streamlit.app

Looking at limb-darkening: Target stars



Number of stars **with 10% precision on limb-darkening coefficient** in the Northern hemisphere (B mag. < 1.2)

4 LSTs + 9 MSTs: **~10 stars**
(examples: αLyr, εCMa) **for T ~2h30**

Credits: Lucijana Stanic
Adapted from https://target-stars-sii.streamlit.app