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Continually Growing Stellar Intensity Interferometry: From Present Results to CTA Implementation Prospects

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For the **CTA Stellar Intensity Interferometry Working Group**

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Outline

- Stellar Intensity Interferometry and the Narrabri Intensity Interferometer
- The MAGIC, VERITAS and HESS IACTs (Imaging atmospheric Cherenkov telescopes) interferometers: Scientific highlights
- The ASTRI Mini-Array SII implementation
- What can be done with CTA and what can be done in the future
- How to do it with CTA? SII implementation modes

Light can carry more information than simply its intensity, spectrum, and polarization... (Foellmi 2009)

To say it ironically... “Astronomers use ‘very little’ of light”, as Cesare Barbieri told me anecdotally reporting a conversation with Tito Arecchi

Stellar Intensity Interferometry (SII)

SII consists in a measurement of the **spatial correlation of the intensities of the light from a star with two telescopes** at distance **d** (Hanbury Brown & Twiss 1957, 1958)

Time averaged cross-correlation of the intensities: $< I_1\, I_2 > = \lim\, (1/2T) \int I_1(t)\, I_2(t-\tau)\, dt$

Under quite general assumptions: $< I_1\, I_2 > - < I_1 >< I_2 > = ½\, |\Gamma(u,v)|^2$

Complex **Visibility**

In terms of **correlation functions** (Glauber 1963): $G2(1,2,2,1) - G1(1,1)G1(2,2) = G1(1,2)G1(2,1)$

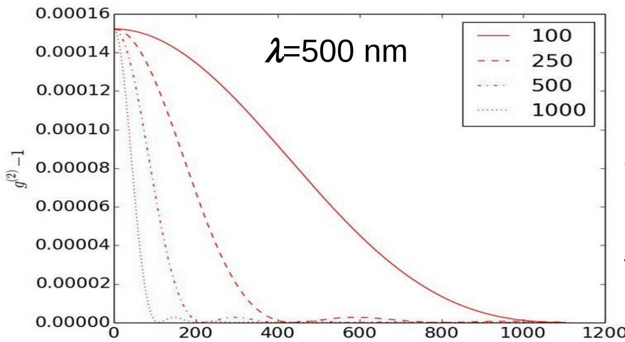
2nd order corr. **1st order corr.**

2nd order degree of coherence $g^{(2)} = G2(1,2,2,1)/[G1(1,1)G1(2,2)] = < I_1\, I_2 >/[<I_1><I_2>]$

Photon counting SII

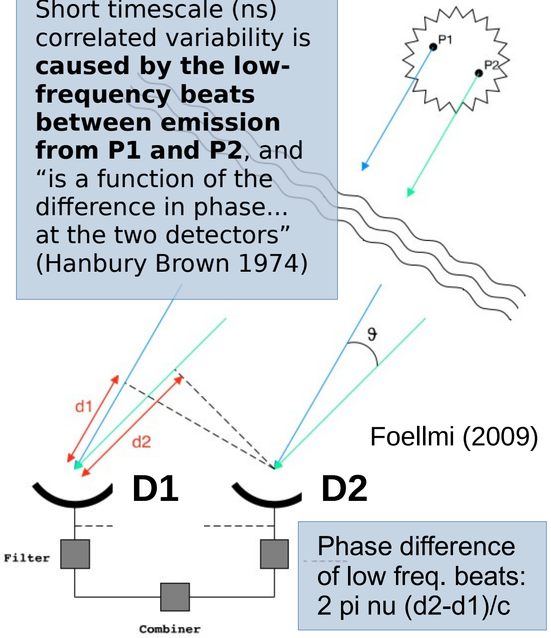
If photons are detected with a **sampling time dt in N intervals**, then g2 is calculated from:

$g^{(2)} = N_{12}\, N / (N_1\, N_2)$



Discrete degree of coherence of a source (uniform disc approx.) with angular size θ (in μarcsec) as a function of the telescope separation (in m)

Short timescale (ns) correlated variability is **caused by the low-frequency beats between emission from P1 and P2**, and "is a function of the difference in phase… at the two detectors" (Hanbury Brown 1974)



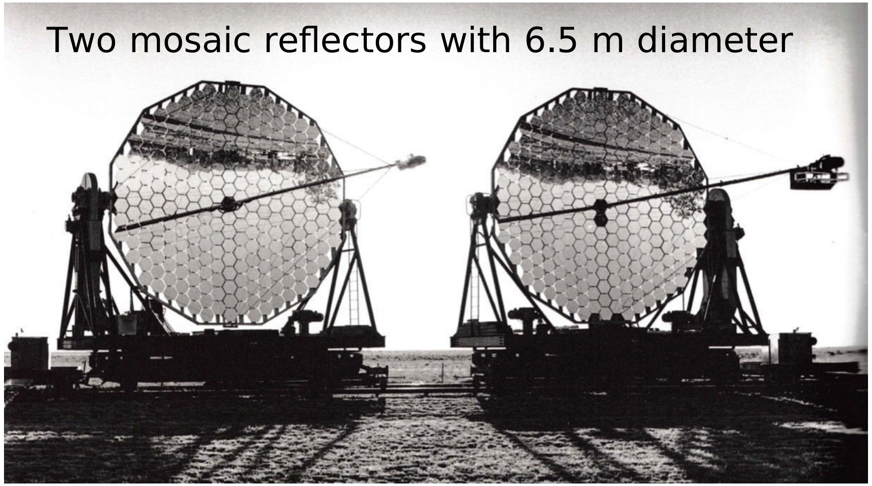
Phase difference of low freq. beats: 2 pi nu (d2-d1)/c

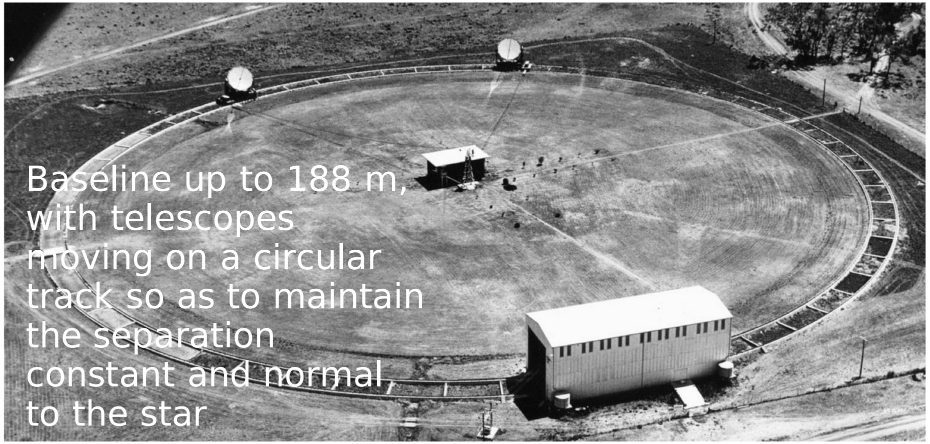
Foellmi (2009)

N_1, N_2 = number of photons detected at D1 and D2 in time **T**
N_{12} = number of simultaneous detections in bins **dt** (random + quantum excess)
N = number of intervals (**T/dt**)

The Narrabri Stellar Intensity Interferometer

The **first Intensity Interferometer** for the measurement of the (2nd order) degree of coherence of a star was built by **Hanbury Brown & Twiss** in Narrabri, Australia (Hanbury Brown 1956; Hanbury Brown & Twiss 1957, 1958)





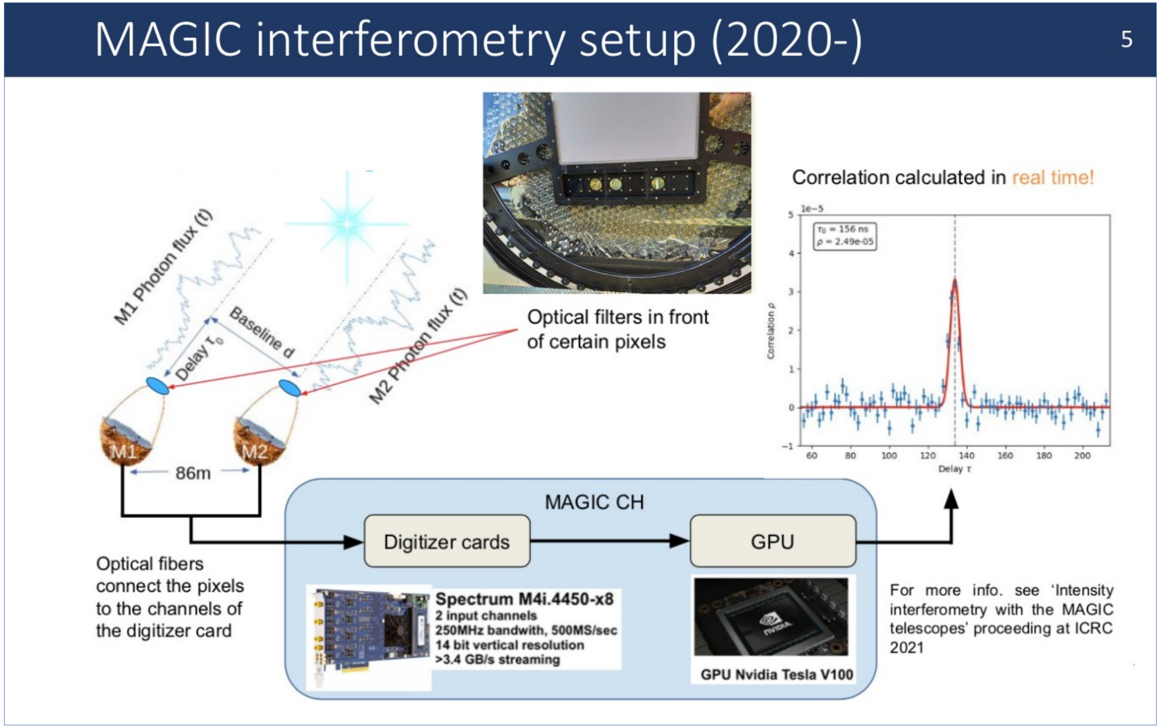
From 1963 through 1974 direct interferometric **measurements of the diameters of 32 single stars** of O-F spectral type (Hanbury Brown et al. 1974; Hanbury Brown 1974)

Then, overshadowed by developments in Michelson interferometry...

Arguments for a *SII mode on IACTs* in general (LeBohec & Holder 2005) and CTA in particular (Dravins et al. 2012, 2013) have been elaborated in the literature, and summarised in the `Intensity Interferometry with CTA' white paper (Kieda et al. 2019)

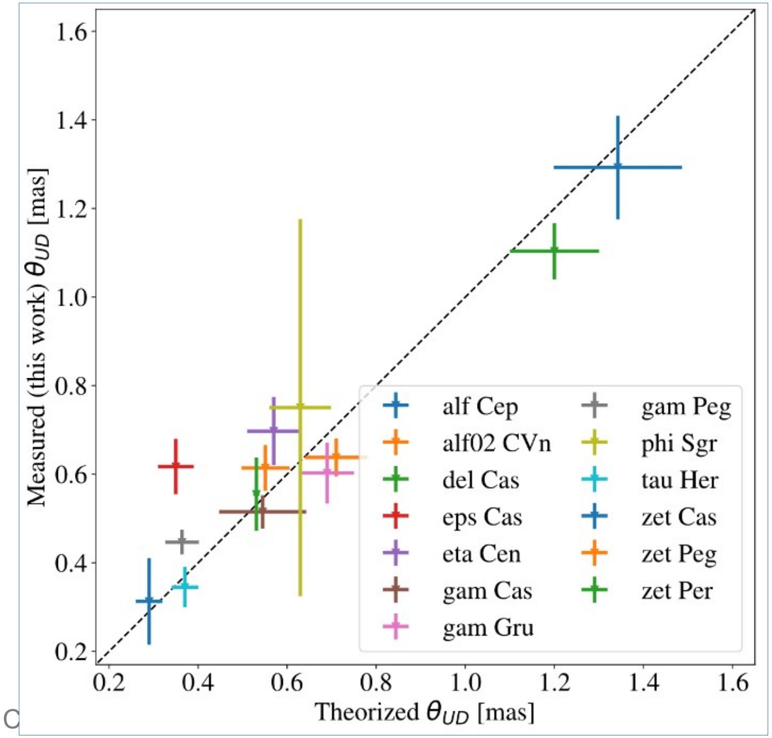
- Diffraction-limited resolution with **~km baselines** would be achievable, not affected by atmospheric seeing
- All pairs of telescopes could be simultaneously used, providing a **dense coverage of the interferometric (U, V) plane**

MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov) Telescopes



MAGIC successfully implemented SII and tested it (Acciari et al. 2020)

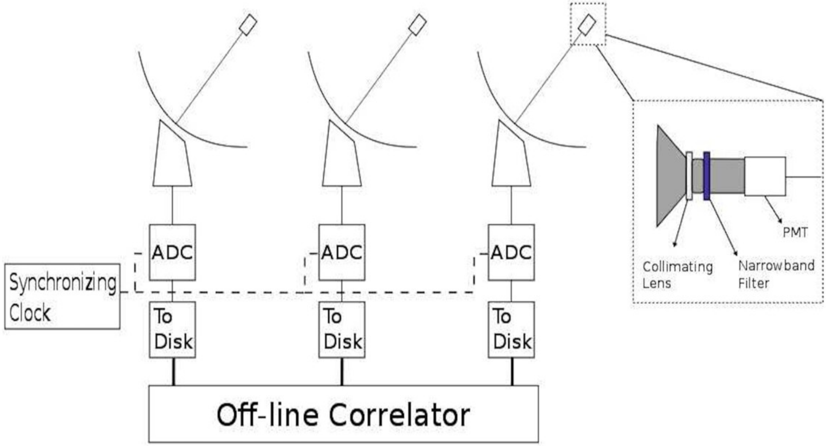
First science results with full instrument recently published (Abe et al. 2024)



Dedicated talk by Juan Cortina to follow

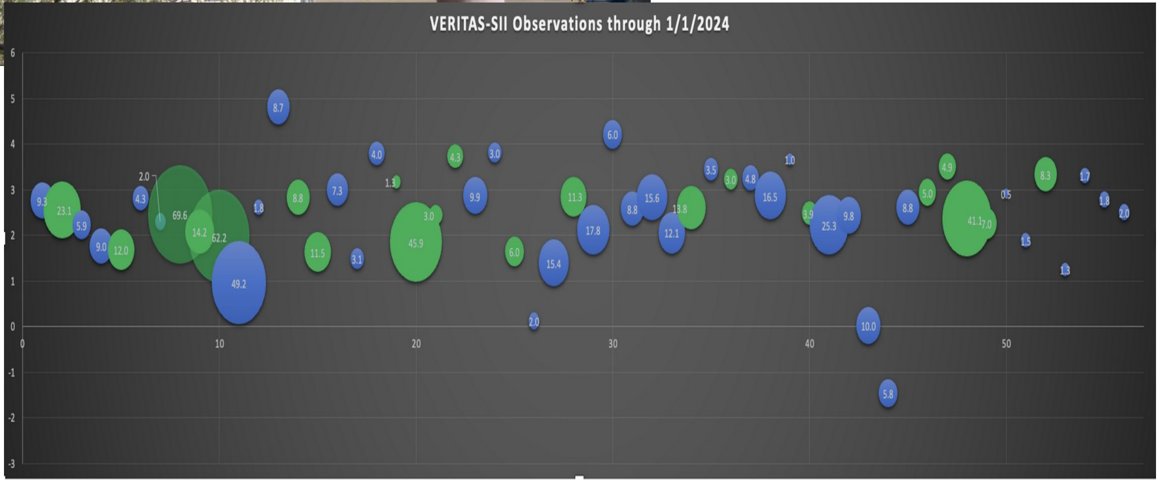
VERITAS (Very Energetic Radiation Imaging Telescope Array System)

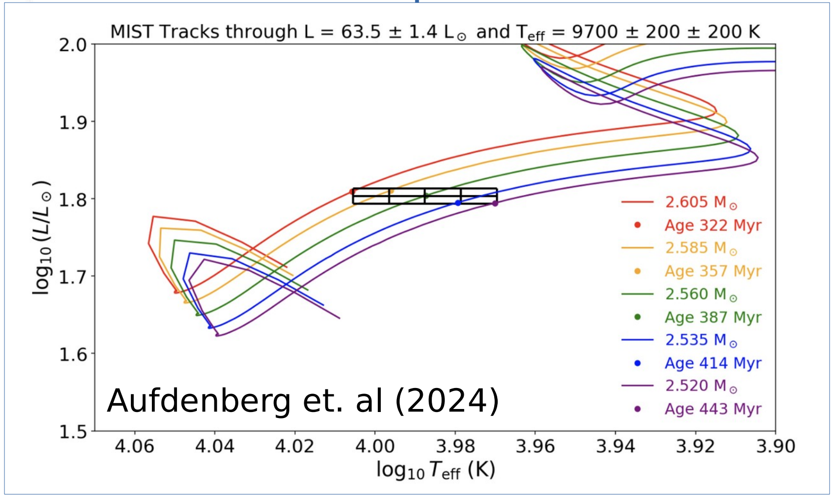
VERITAS successfully implemented and tested SII (Abeysekara et al. 2020)



Highlight: Merak (beta UMa)

Measured age (390 ± 29 ± 32 Myr) is consistently lower than the age measured by CHARA (408 ± 6 Myr) due to the smaller angular diameter (hotter star)





H.E.S.S. (High Energy Stereoscopic System)

Measurement campaigns in April 2022 (2 telescopes) and May 2023 (3 telescopes) during moonlight break

Motorized external setup is mounted to the lid of the Cherenkov camera

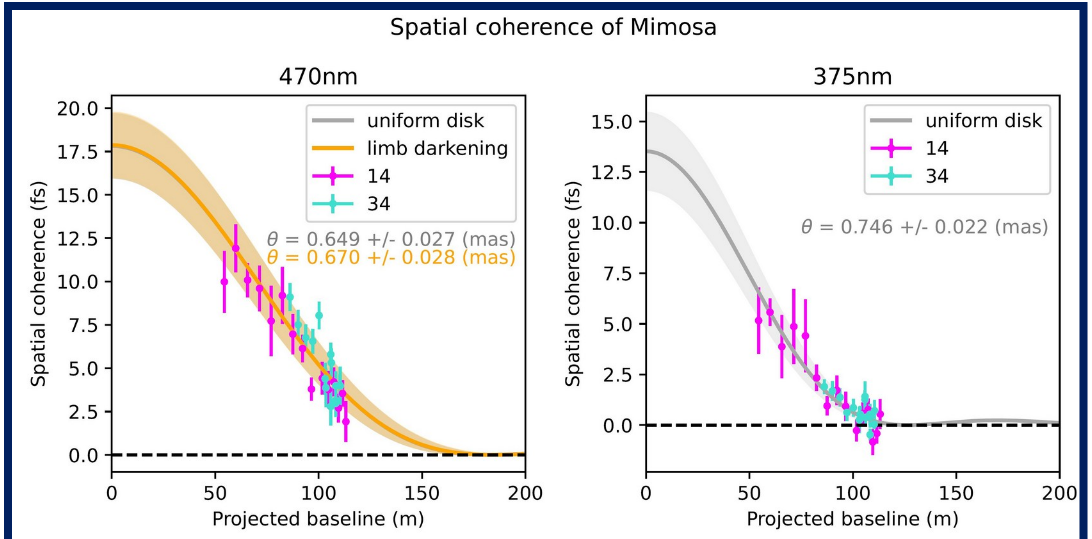
→ Correct for telescope mispointing

→ Toggle between gamma-ray and SII within minutes

2023: simultaneous two-color measurements

Discrepancy between the colors might vanish with thorough investigation

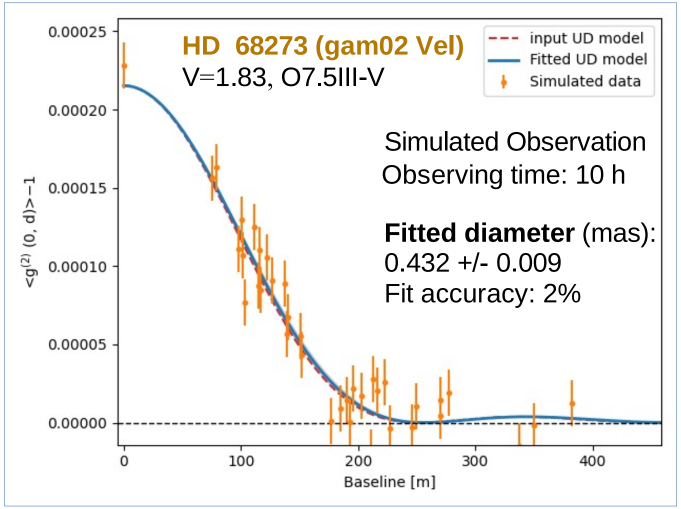
Source	Mimosa (Beta Crux)
Magnitude (mag)	1.2
HBT diameter (mas)	0.702 +/- 0.022
HBT Time (h)	178.7
HESS Time (h)	6.5



ASTRI (Astrofisica con Specchi a Tecnologia Replicante Italiana) Mini-Array

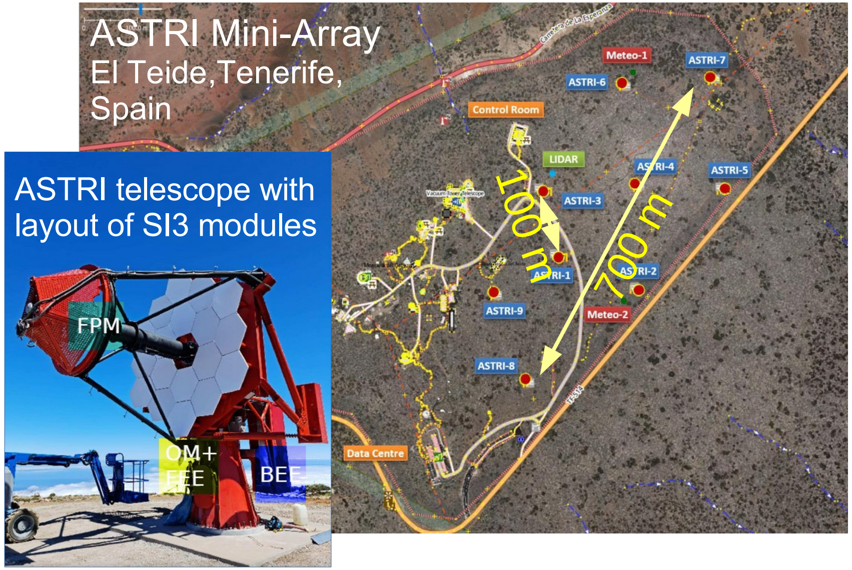
The **ASTRI Mini-Array** is under construction at El Teide (Scuderi et al. 2022; the first telescope is on site) and provides a suitable infrastructure for performing **SII observations on many (36), long (up to ~700 m) baselines**

The 9 ASTRI Mini-Array telescopes will be equipped with the **Stellar Intensity Interferometry Instrument (SI3)** (Zampieri et al. 2022, 2024)



Photon counting approach: degree of coherence **g2** of a star calculated in post-processing from coincidences of photon arrival times (with sampling time **~1 ns**) in a narrow optical band (**~1-8 nm**)

Fit accuracy ~10% for a V=4.5 mag star in ~10 hrs



The **ASTRI Mini-Array** is an International collaboration, led by the Italian National Institute for Astrophysics (INAF), that is constructing and operating an array of nine Imaging Atmospheric Cherenkov Telescopes to study gamma-ray sources at very high energy (TeV) and **perform optical stellar intensity interferometry observations**

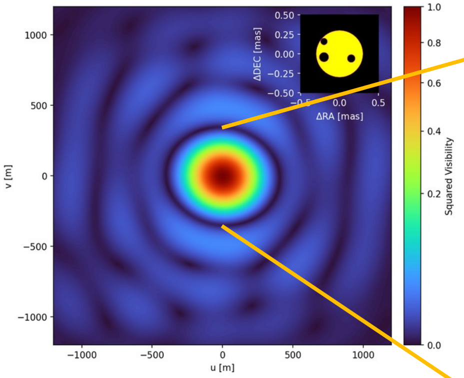
What can be done with CTA SII observations of solar-type stars

Join the CTA SII session at the CTA Science Meeting for more!

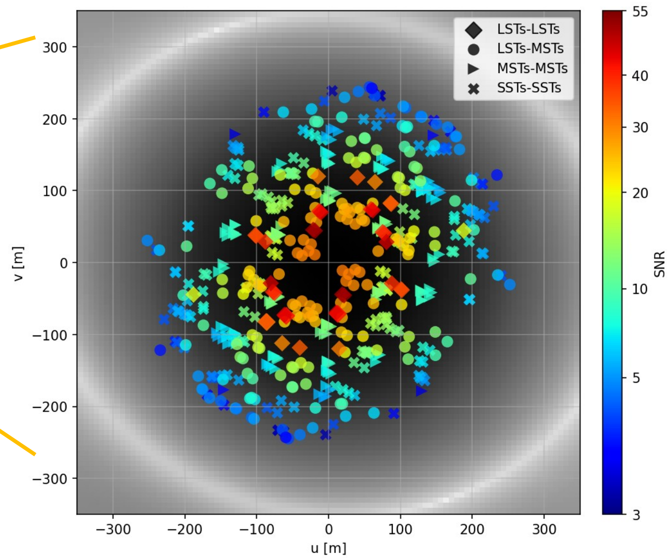
Solar-type stars are crucial for understanding the properties of the Sun in relation to other stars and for exploring the habitability conditions of exo-planets around stars similar to the Sun (e.g. Soderblom and King 1998; Charbonneau 2014; Ragulskaya 2018)

~**100 G-type stars** with **V < 5 mag** visible from each CTA site

Simulated coherence on (U, V) plane of **F/G-type stars with spots** related to stellar activity:



Coherence of a solar-type star with ~100 micro-arcsec spots on the surface (inset)



- Several telescope pairs at CTA-South give measurements with a signal-to-noise ratio larger than 3 in 10 hours
- Coherence is well sampled

Allow for 2D model fitting of the coherence and hence the determination of the star diameter and spots size

Unique capabilities of CTA in terms of coverage of the U-V plane and angular resolution

What can be done with CTA
SII observations of recurrent novae

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In 2024 the recurrent (~80 years) nova **T CrB** will explode, reaching a magnitude of ~2.5 mag at maximum and offering for the first time ever the opportunity of SII observations during the expansion phase

Symbiotic Binary: RG + WD
M_{WD}=1.37 $M_\odot$
M_{RG} = 1.12 $M_\odot$

Distance = 806 pc

Orbital Period = 227 day
separation a = 0.54 AU
eccentricity = 0
inclination i = 67^0

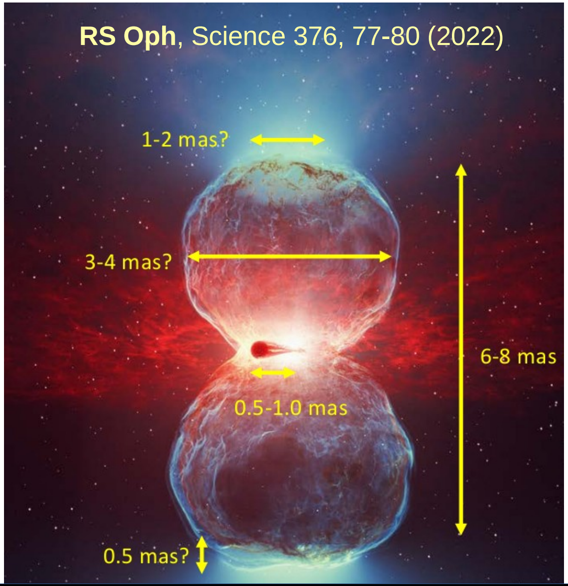
Angular separation = 0.56 mas

Kieda (2023)

Might have structure on several angular scales (as RS Oph)

Hα , Hβ exp. Vel. ~ 4000 km/s
Expansion to 1.2 mas ~8 hours

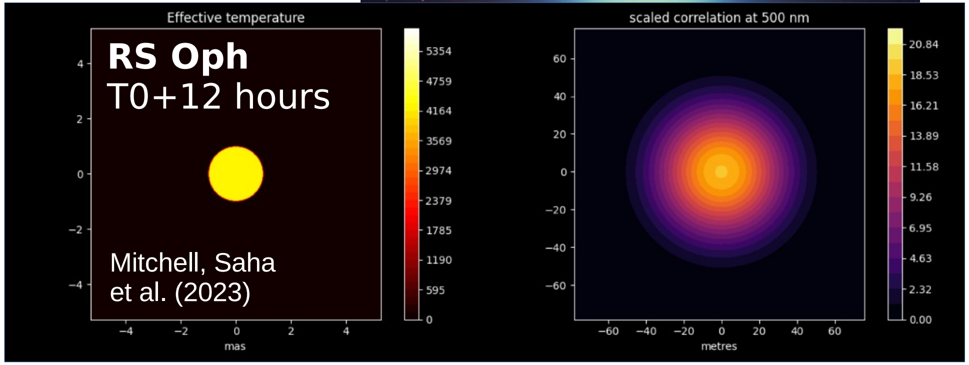
But N, O, Si, Fe have vexp ~ 1000 km/s. Hence 32 hour expansion?



CTA science opportunity

10 known Galactic recurrent novae with time spans 8-98 years (Pagnotta & Schaefer 2014) and Vmax = 2.5-9.5 mag (but considerably brighter in Halpha/Hbeta; e.g. Ciardullo et al. 1983)

Possibility of joint VHE/SII observations

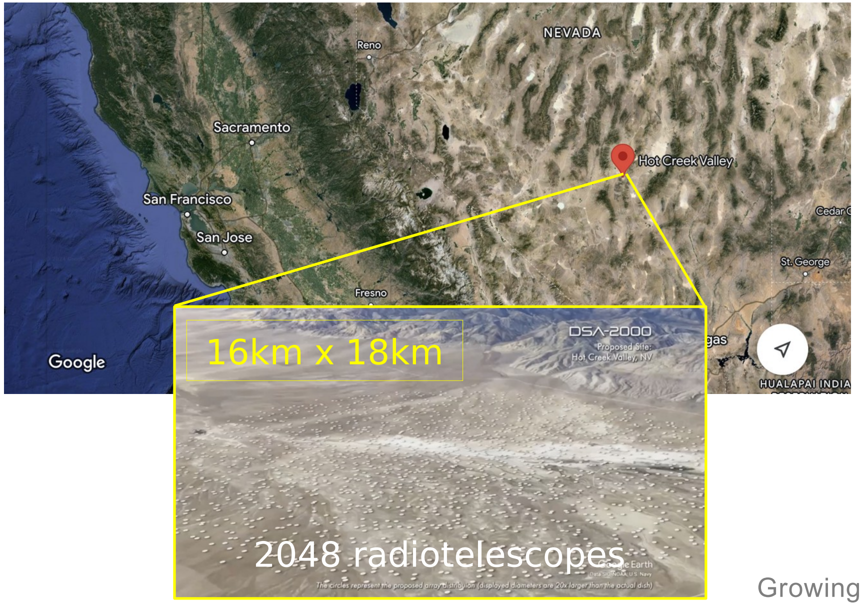


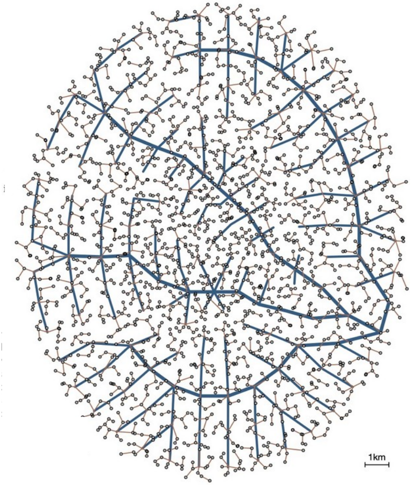
What is really ambitious to do
The Future of Intensity Interferometry beyond CTA

(Carlile, Dravins & Thorsbro 2024)

A purpose-built Observatory for SII - SIITAR

Let’s think BIG – inspired by DSA-2000 (Hallinan et al. 2024) with its 2048 radiotelescopes

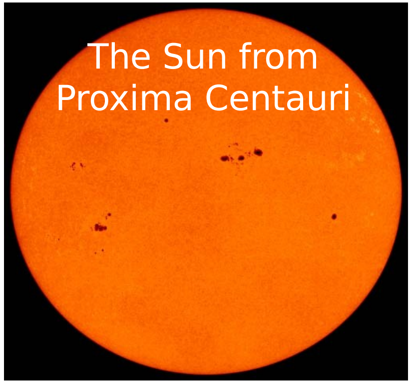




▲ **THE PLAN** This map shows the DSA-2000’s configuration — a vast oval spanning 19 by 15 kilometers, with each dot representing a 5-meter dish. A network of fiber-optic cables (red and blue lines) will link the telescopes together into an array.

Let’s have 2048 optical telescopes !

2.5 micro-arcsec angular resolution!
2 million pixels



How to do it on CTA?
SII implementation modes

Join the CTA SII session at the CTA Science Meeting for more!

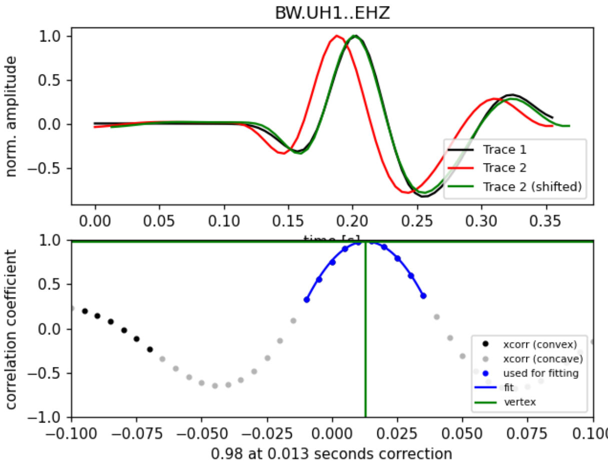
Digital SII

Measurements at **high photon rates**: photon counting detectors *in integration mode*

Continuously sampling and digitizing the photo-currents (at ~ 1 GHz)

‘Counts’/waveforms directly proportional to the instantaneous light intensity/number of photons per time bin (with Direct Current coupling)

Coherence computed by **cross-correlating synchronized waveforms from two telescopes** (a la` Hanbury Brown & Twiss)



https://docs.obspy.org/tutorial/code_snippets/xcorr_pick_correction.html

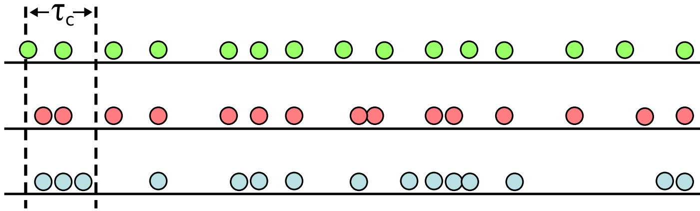
Photon Counting SII

Measurements at **low photon rates**: photon counting detect. *in single-phot-counting mode*

Continuously sampling and time-tagging photon-events with a time-to-digital converter (at ~ 1 ns)

Exploiting the quantum properties of the star light (bosons giving a joint detection probability greater than that for two independent events)

Coherence computed by **counting simultaneous detections at two telescopes**



https://en.wikipedia.org/wiki/Photon_antibunching

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Continuously sampling and digitizing the photo-currents (at ~ 1 GHz)

'Counts'/waveforms directly proportional to the instantaneous light intensity/number of photons per time bin (with Direct Current coupling)

Coherence computed by **cross-correlating synchronized waveforms from two telescopes** (a la` Hanbury Brown & Twiss)

Suitable for bright targets with the LSTs/MSTs

Strengths: Possibility to use pixels of the Cherenkov camera as detectors, in post-processing checking for systematics and tuning the analysis

Photon Counting SII

Measurements at **low photon rates**: photon counting detect. *in single-phot-counting mode*

Continuously sampling and time-tagging photon-events with a time-to-digital converter (at ~ 1 ns)

Exploiting the quantum properties of the star light (bosons giving a joint detection probability greater than that for two independent events)

Coherence computed by **counting simultaneous detections at two telescopes**

Suitable for SSTs, and LSTs/MSTs observing weak targets or equipped with narrow band filters

Strengths: Spectrally resolving SII (~ 1 nm), boosting sensitivity with channel multiplexing, checking for systematics and tuning the analysis, computing the correlations among three or more telescopes

Conclusions

- Intensity interferometry may be a second observing mode of IACTs, in which the ultrafast photon counting capabilities of these instruments is used to reconstruct visible-light images of stars at otherwise unachievable angular resolutions
- Demonstration of an II mode in current IACTs is provided by the MAGIC, VERITAS and HESS, with the ASTRI Mini-Array implementation in the development stage
- CTA offers an unprecedented opportunity for SII in terms of angular resolution at optical wavelengths and coverage of the U-V plane
- Suitable and complementary implementation modes for CTA are ‘digital SII’ and ‘photon-counting SII’
- Many novel and ongoing scientific questions will be addressed in stellar astrophysics with an II observing mode on CTA