Recent Advancements in Modern Stellar Intensity Interferometry

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VERITAS Collaboration

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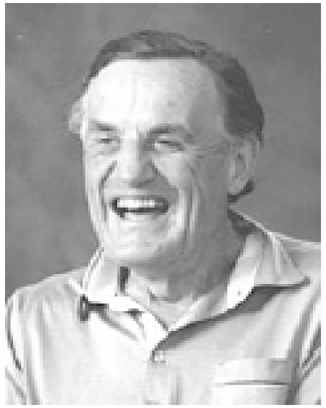
Outline

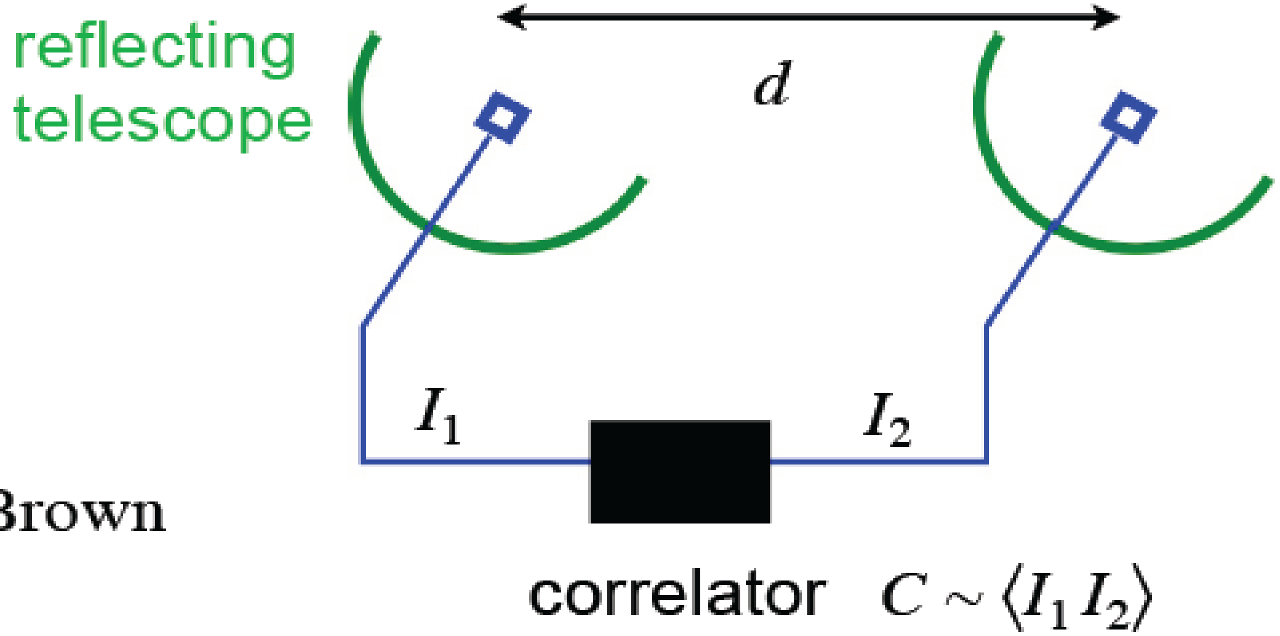
- Origins of HBT Stellar Intensity interferometry
- IACT arrays and HBT: A New Vision (2006)
- Laboratory tests & successes (2010-2016)
- First IACT telescope successes (2018 -2023)
- Improvements and advancements (2023-present)
- Towards the Future (2025+)

Origins of HBT Stellar Intensity interferometry (1956-1971)

Intensity interferometry



Robert Hanbury Brown
1916-2002



The current noise in two optical (or radio) telescopes should be correlated for sufficiently small separations d. Reminiscent of Michelson's interferometer to measure stellar diameters, but less sensitive to vibrations or atmospheric fluctuation.

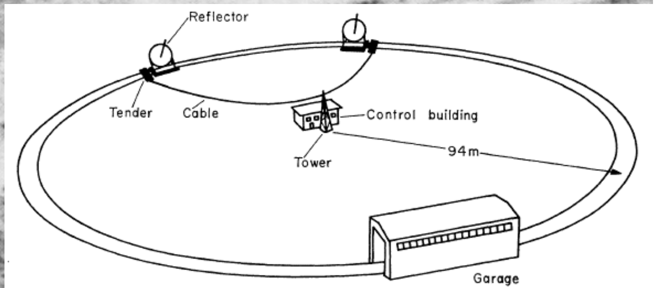
The correlation implies photon "bunching".

Stellar Intensity interferometry (SII) … 1956-1971

Narrabri observatory

with its circular railway track

R.Hanbury Brown: *BOFFIN. A Personal Story of the Early Days of Radar, Radio Astronomy and Quantum Optics* (1991)



32 stellar diameters measured

$m_V < 2.5$

0.41mas < Ø< 3.24mas

10 of them in the main sequence

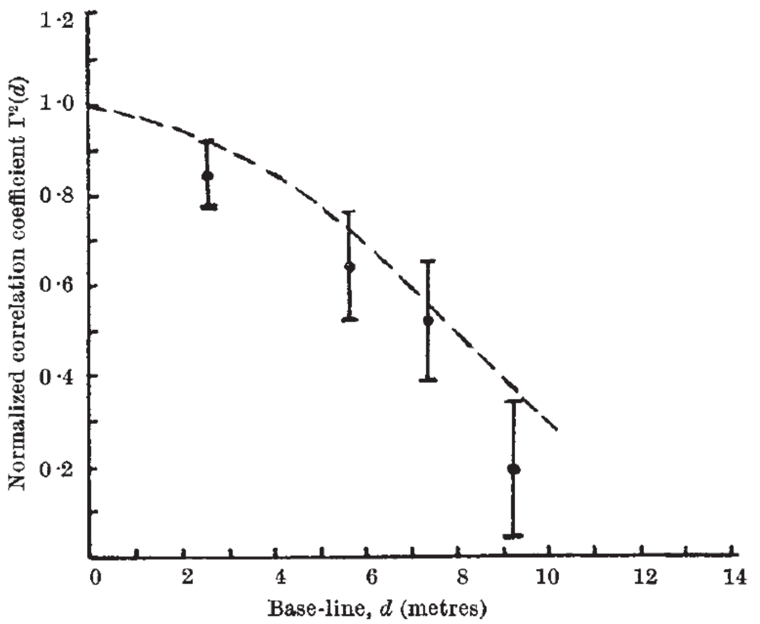
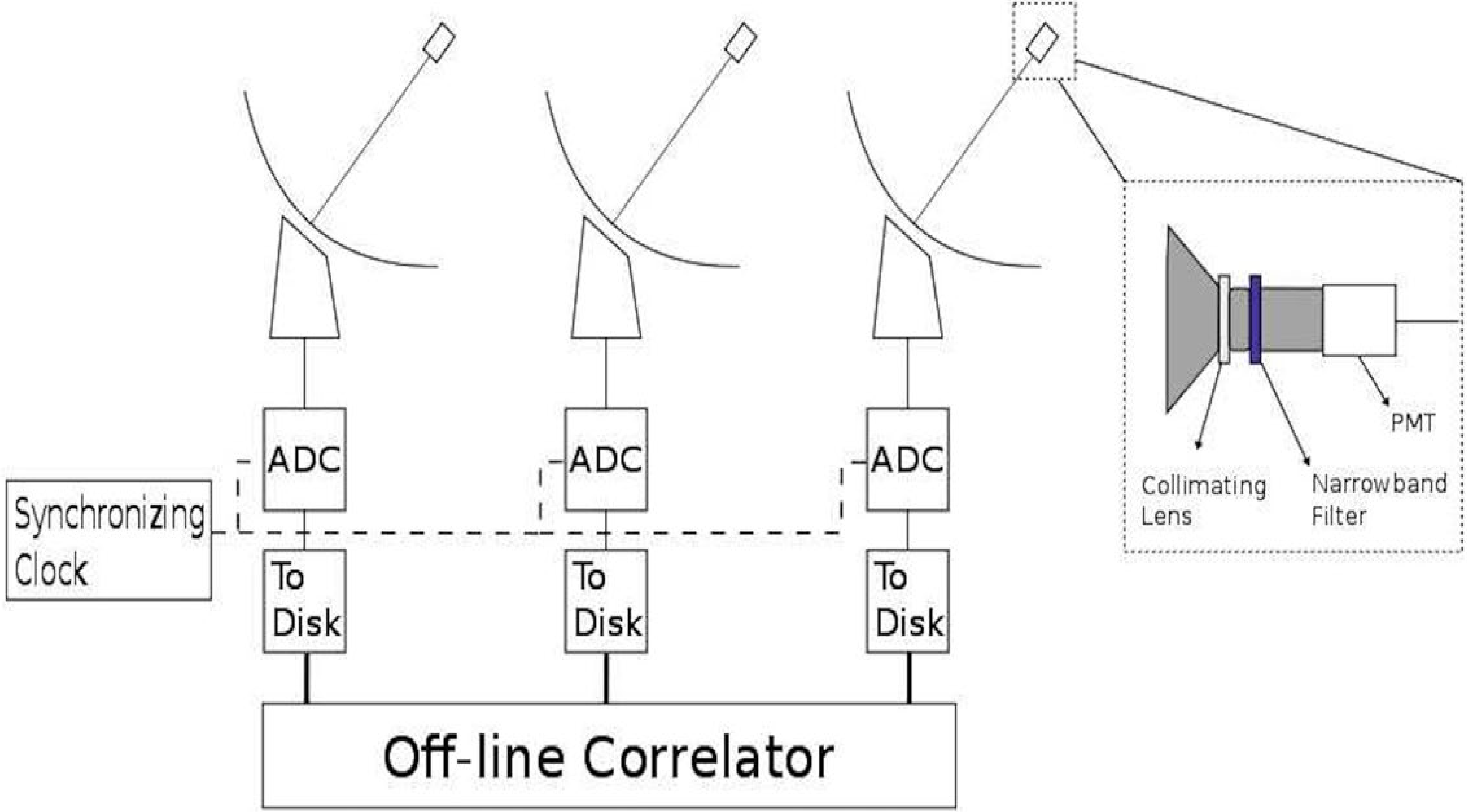


Fig. 2. Comparison between the values of the normalized correlation coefficient $\Gamma^2(d)$ observed from Sirius and the theoretical values for a star of angular diameter 0·0063". The errors shown are the probable errors of the observations

End of operations: 1971

Star number	Star name	Type	Angular diameter $\times 10^{-3}$ sec of arc $\theta_{UD} \pm \sigma$	$\theta_{LD} \pm \sigma$
472	α Eri	B 3 (Vp)	1·85 ± 0·07	1·92 ± 0·07
1713	β Ori	B 8 (Ia)	2·43 ± 0·05	2·55 ± 0·05
1790	γ Ori	B 2 (III)	0·70 ± 0·04	0·72 ± 0·04
1903	ε Ori	B O (Ia)	0·67 ± 0·04	0·69 ± 0·04
1948	ζ Ori	O 9·5 (Ib)	0·47 ± 0·04	0·48 ± 0·04
2004	κ Ori	B 0·5 (Ia)	0·44 ± 0·03	0·45 ± 0·03
2294	β CMa	B 1 (II–III)	0·50 ± 0·03	0·52 ± 0·03
2326	α Car	F 0 (Ib–II)	6·1 ± 0·7	6·6 ± 0·8
2421	γ Gem	A 0 (IV)	1·32 ± 0·09	1·39 ± 0·09
2491	α CMa	A 1 (V)	5·60 ± 0·15	5·89 ± 0·16
2618	ε CMa	B 2 (II)	0·77 ± 0·05	0·80 ± 0·05
2693	δ CMa	F 8 (Ia)	3·29 ± 0·46	3·60 ± 0·50
2827	η CMa	B 5 (Ia)	0·72 ± 0·06	0·75 ± 0·06
2943	α CMi	F 5 (IV–V)	5·10 ± 0·16	5·50 ± 0·17
3165	ζ Pup	O 5 (f)	0·41 ± 0·03	0·42 ± 0·03
3207	γ^2 Vel	WC 8 + O 9 (I)	0·43 ± 0·05	0·44 ± 0·05
3685	β Car	A 1 (IV)	1·51 ± 0·07	1·59 ± 0·07
3982	α Leo	B 7 (V)	1·32 ± 0·06	1·37 ± 0·06
4534	β Leo	A 3 (V)	1·25 ± 0·09	1·33 ± 0·10
4662	γ Crv	B 8 (III)	0·72 ± 0·06	0·75 ± 0·06
4853	β Cru	B 0·5 (III)	0·702 ± 0·022	0·722 ± 0·023
5056	α Vir	B 1 (IV)	0·85 ± 0·04	0·87 ± 0·04
5132	ε Cen	B 1 (III)	0·47 ± 0·03	0·48 ± 0·03
5953	δ Sco	B 0·5 (IV)	0·45 ± 0·04	0·46 ± 0·04
6175	ζ Oph	O 9·5 (V)	0·50 ± 0·05	0·51 ± 0·05
6556	α Oph	A 5 (III)	1·53 ± 0·12	1·63 ± 0·13
6879	ε Sgr	A 0 (V)	1·37 ± 0·06	1·44 ± 0·06
7001	α Lyr	A 0 (V)	3·08 ± 0·07	3·24 ± 0·07
7557	α Aql	A 7 (IV, V)	2·78 ± 0·13	2·98 ± 0·14
7790	α Pav	B 2·5 (V)	0·77 ± 0·05	0·80 ± 0·05
8425	α Gru	B 7 (IV)	0·98 ± 0·07	1·02 ± 0·07
8728	α PsA	A 3 (V)	1·98 ± 0·13	2·10 ± 0·14

IACT arrays and HBT: A New Vision (2006)



Digital implementation of an HBT interferometer using IACT array
Narrabri was an analog implementation of a single telescope pair

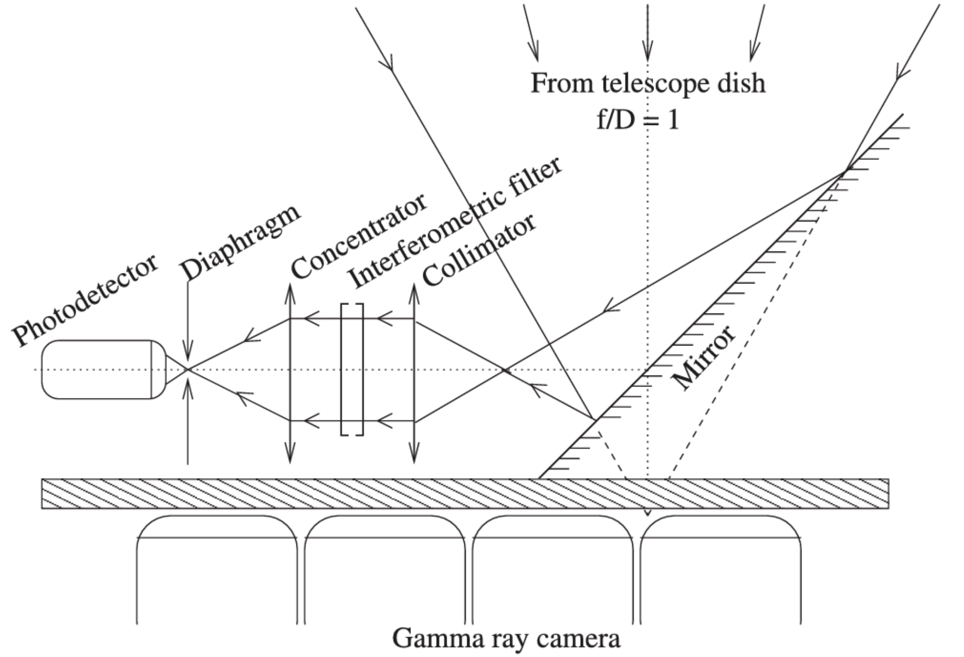


FIG. 3.—Light from the telescope is redirected sideways by a mirror; it is then collimated, filtered, and focused onto the photodetector.

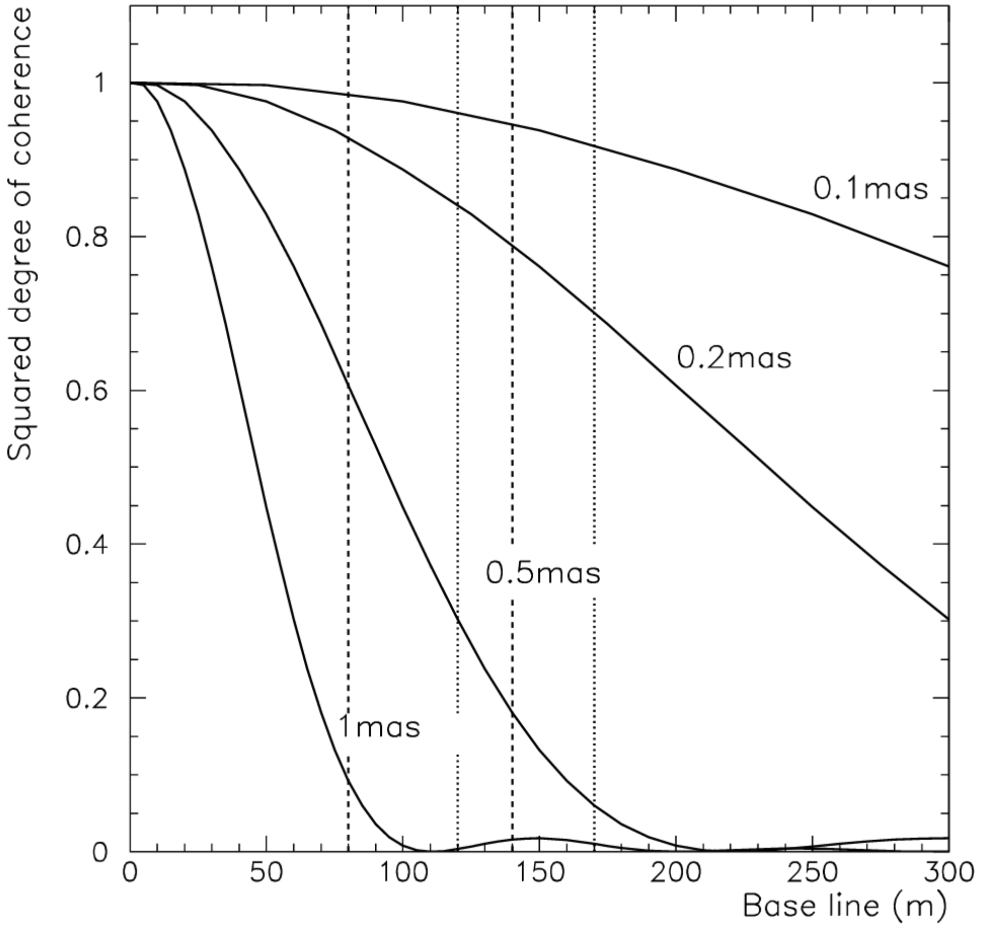


FIG. 2.—Squared modulus of the degree of coherence of the light at two telescopes as a function of the baseline for different stellar diameters. The dashed and dotted lines indicate the baselines at zenith in VERITAS-4 and HESS-4, respectively.

LeBohec & Holder 2006 (Ap.J)

TABLE 1

CHARACTERISTICS OF ACT ARRAYS AND CORRESPONDING CAPABILITIES AS INTENSITY INTERFEROMETERS

Array	N	A	n	$d_{\min} - d_{\max}$ (m)	$\theta_{\min} - \theta_{\max}$ (mas)	$V_{\max}$ (mag)	$T_{V=5}$ (hr)
MAGIC-II	2	227	1	85	1.2	4.7 (6.0)	0.16
CANGAROO...................	4	57	6	100–184	0.5–1.0	4.2 (5.5)	2.61
HESS-4............................	4	108	6	120–170	0.6–0.8	4.9 (6.1)	0.73
VERITAS-4......................	4	113	6	80–140	0.7–1.2	4.9 (6.2)	0.66
VERITAS-7[a]	7	113	21	80–160	0.6–1.2	5.6 (6.9)	0.66
HESS-16[a]	16	108	120	120–510	0.2–0.8	6.5 (7.8)	0.73
Next-Generation[b]	50	100	1225	80–1000	0.1–1.2	7.7 (9.0)	0.85
Narrabri	2	30	1	10 → 188	0.5–10	2.5 (3.8)	9.4

LeBohec & Holder 2006 (Ap.J)

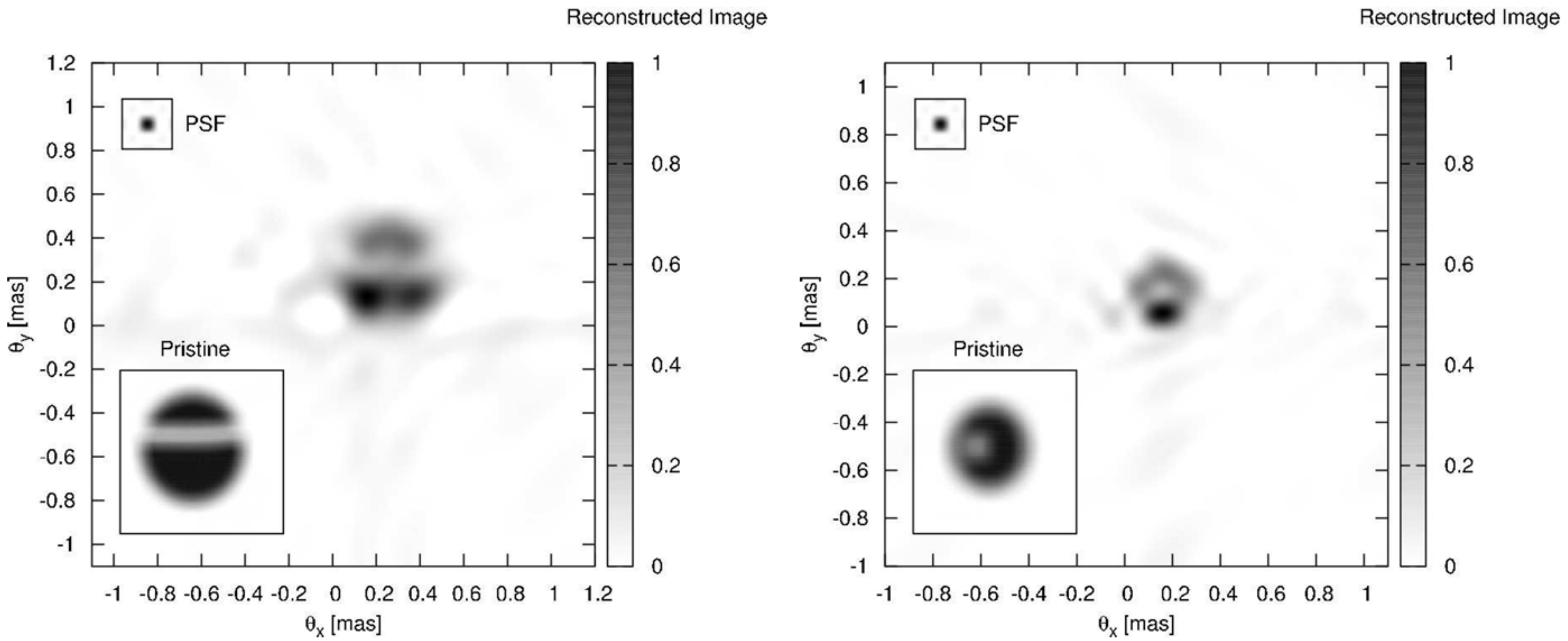


Figure 6. a) Simulated and reconstructed star obscured by a disk. This corresponds to magnitude 4 and 15 hours of observation time. b) Uniform disk of radius 0.2 mas with a dark spot of radius 0.05 mas. The simulation was done for magnitude 6 and 100 hours of observation time.

Simulated performance

For a CTAO-like IACT array
Using phase recovery with SII sampled Fourier plane
P. Nunez, et al., 2010 Proc. SPIE

Laboratory tests & successes (2010-2016)

D. Dravins et al.: Long-baseline optical intensity interferometry

Fig. 3. Components in the laboratory setup. *Left*: light from a 300 mW λ 532 nm laser is made chaotic by scattering from microscopic particles in a square-top cuvette and focused by a condenser onto artificial "stars", which are mechanical apertures in a rotatable holder. *Right*: the "stars" are observed by a group of (here) five small telescopes with 25 mm apertures, each equipped with a photon-counting SPAD detector. One unit perpendicular to the others uses a 45-degree mirror to obtain a particularly short baseline. Another pair of two telescopes behind one beamsplitter serves to measure zero baseline, as required for calibrations. Two-dimensional coverage is achieved by successively rotating the position angle of the source relative to the plane of the telescopes.

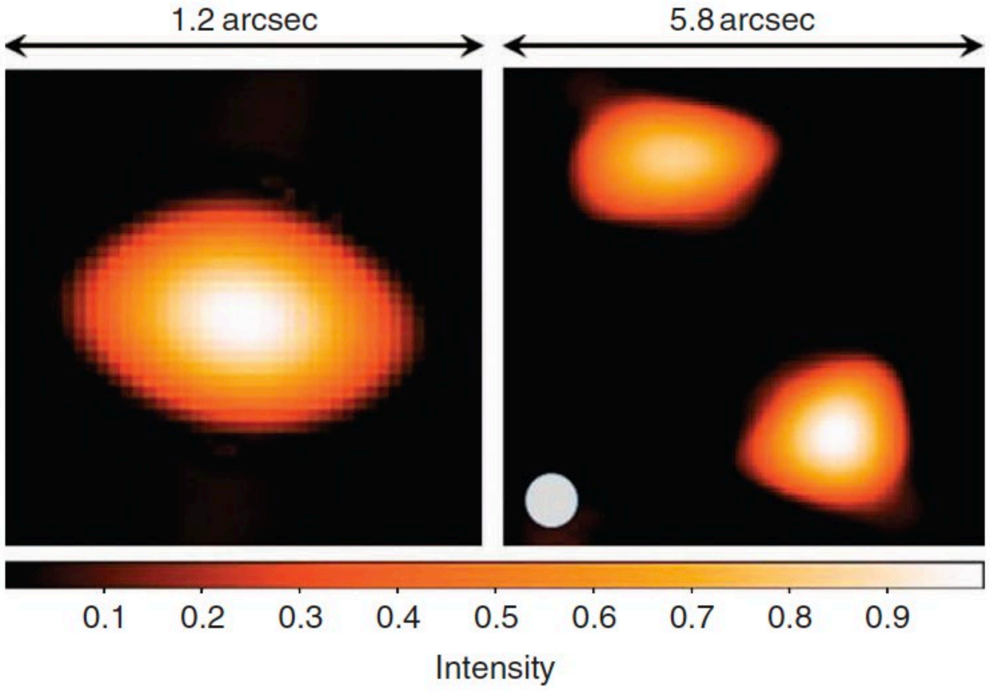
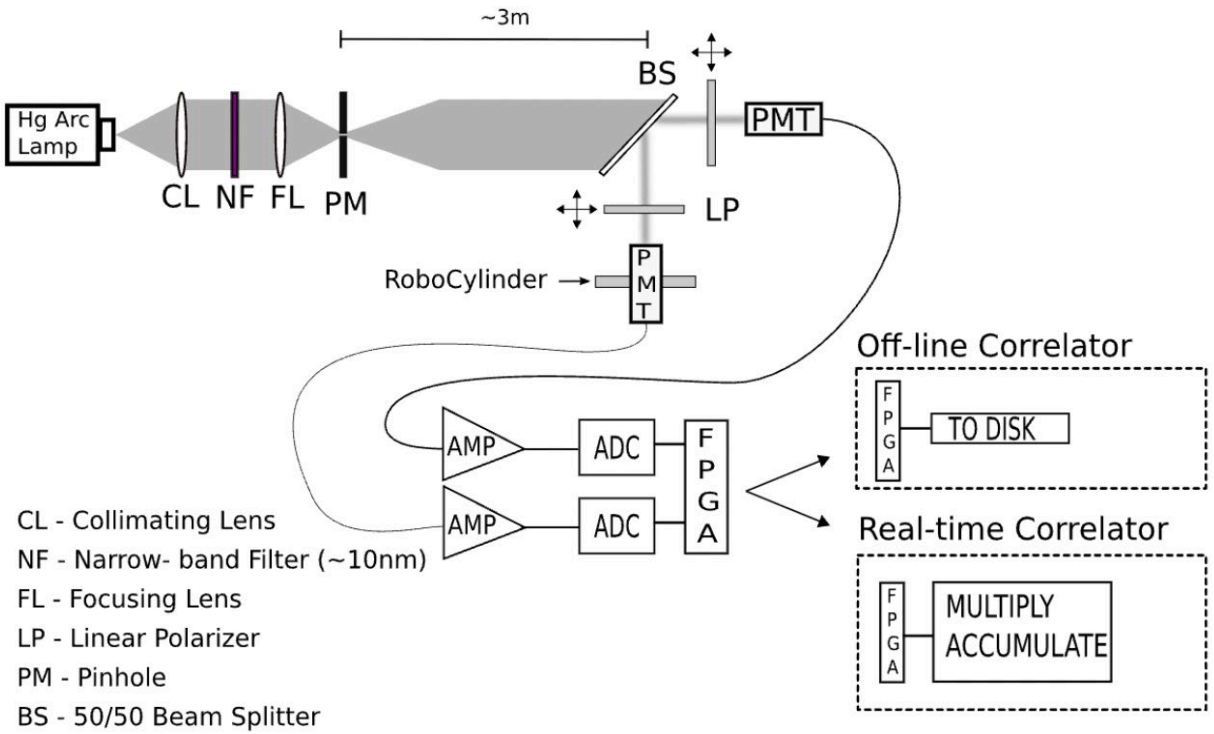


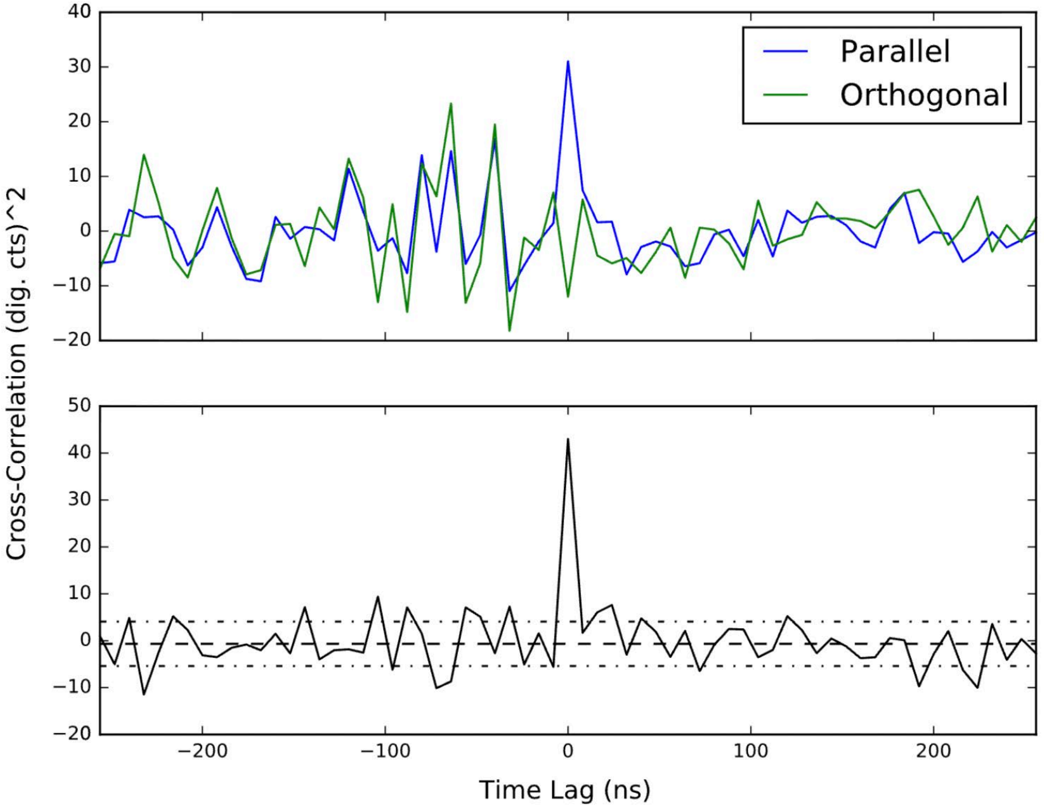
Figure 2 | Optical images reconstructed from electronic intensity interferometry; measurements with 100 and 180 baselines, respectively, of a single elliptical artificial 'star' and an asymmetric binary one (flux

Use of pseudo-random light
Use of array of sensors to sample Fourier plane
Use a digital correlator to extract Visitibilty
Reconstruction of simulated stars, binary systems

Dravins & Lanagadec
Nature Comm (2015)
Proc SPIE (2014)
A&A (2015)



Clearly demonstrated SII exploiting the polarization states of the BB light.



Laboratory measurement of 2-Telescope Correlation from Hg arc lamp.

FPGA digitizer & RAID disk storage
Post-DAQ software correlator used.

Measured diameters and orientations of Simulated stars (pinholes)

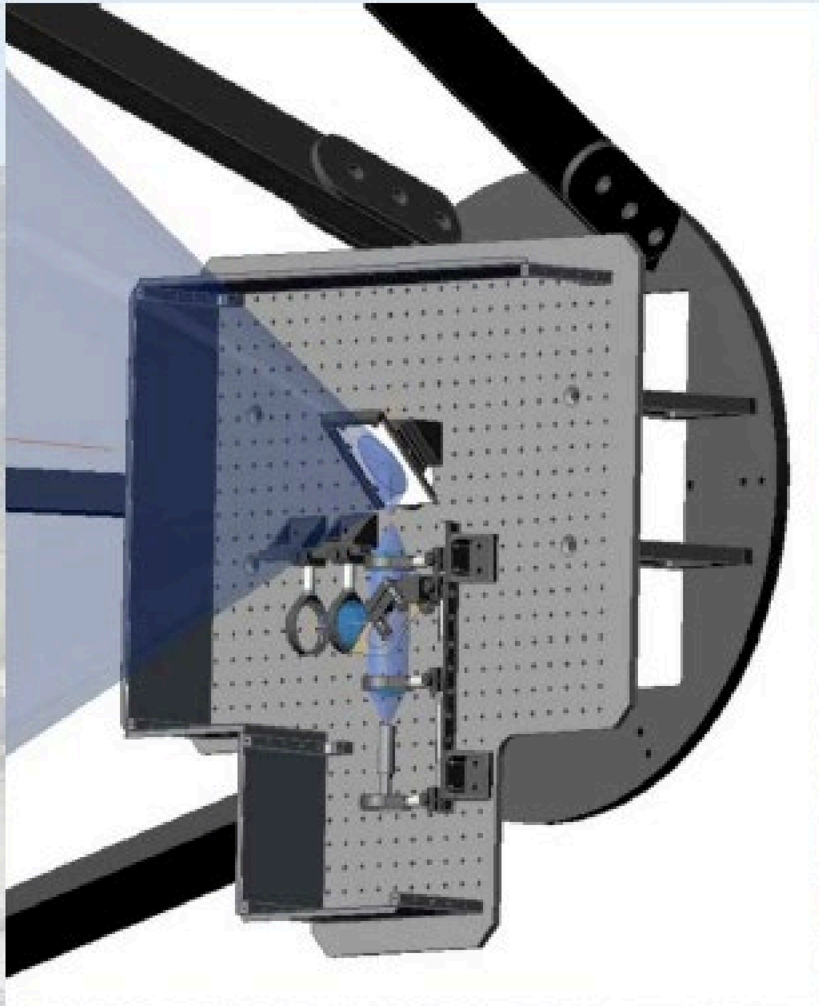
Matthew, Kieda & Lebohec (JMO 2017)

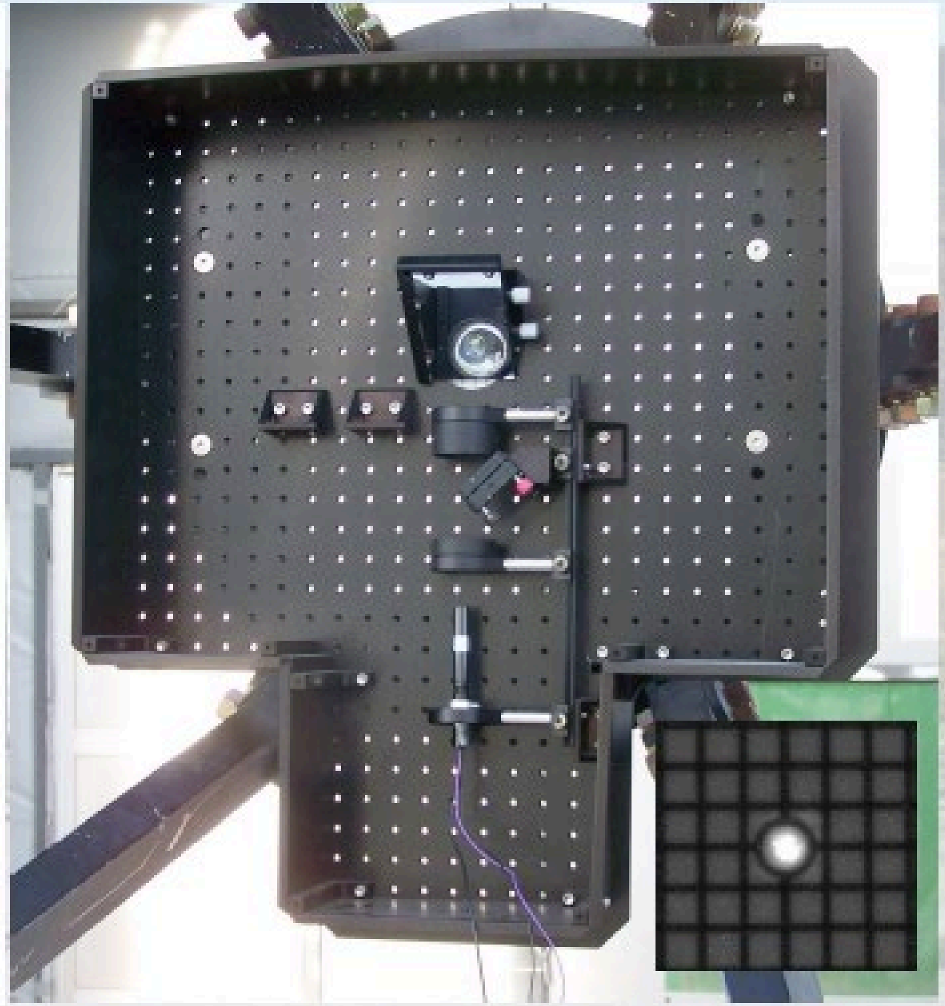
STAR BASE UTAH (near Salt Lake City)

Testbed for intensity interferometry & Cherenkov telescope instrumentation

The StarBase 3 m Cherenkov telescopes are protected by buildings which can be rolled open for observation. The control room is located between the two telescopes. (LeBohec et al. 2010)

Star Base SII prototype camera





Digitizer System

- NI Flex-Rio digitizer Digitizer (250 Mhz sampling) & Virtex5 FPGA Front end (4 channels, 14 bit resolution (Truncate to 8 bit))
- Record to high speed 12 TB RAID system (750 Mbyte/sec)

  Able to stream continuously for >6 hours
- Periodic GPS Time Stamp of FADC clock to better < 4 nsec rms

StarBase–Utah Initial results

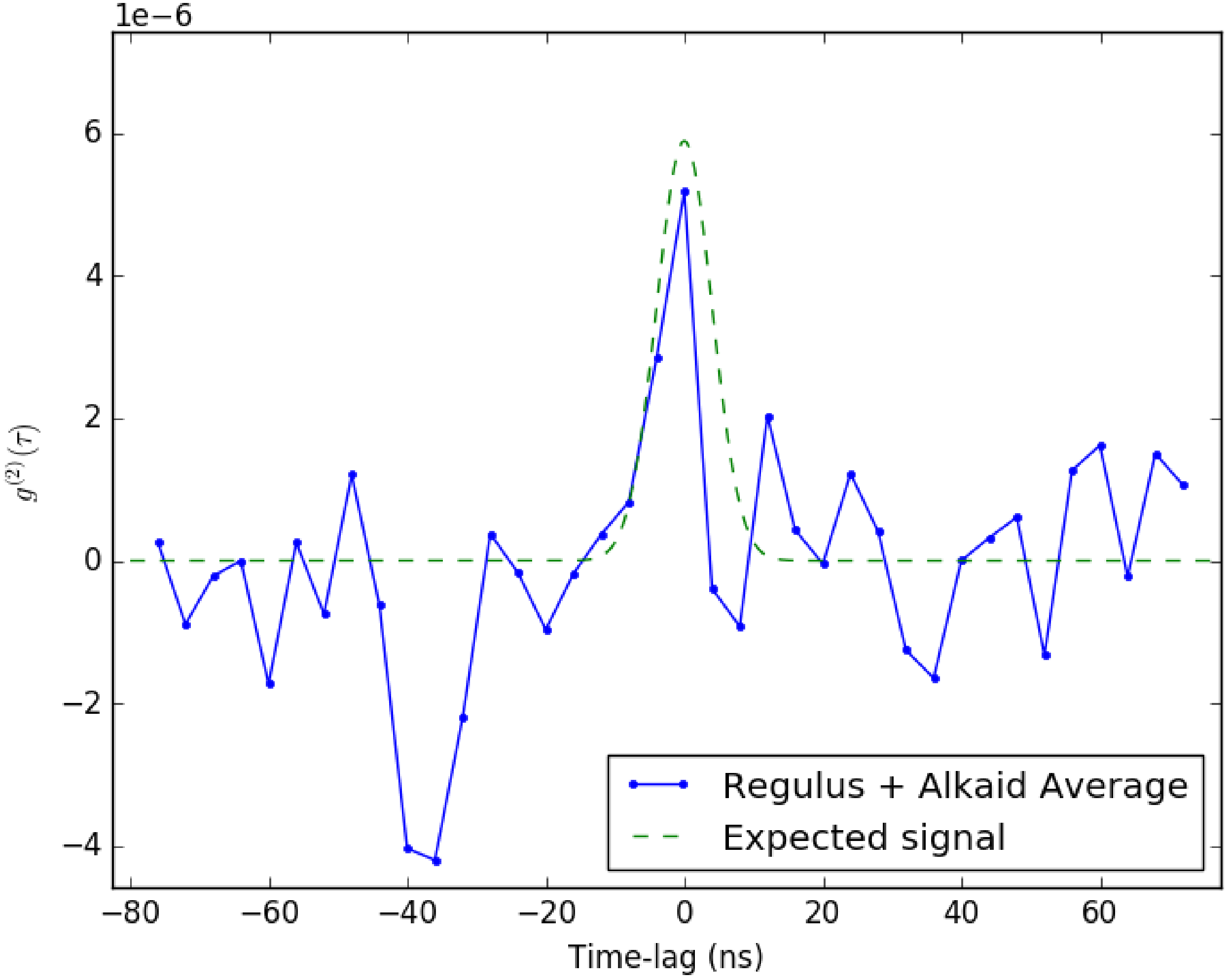
- Alkaid &
- Regulus (2018)

- 11 hours ON source

- several months of
- work for a ~2 $\boldsymbol{\sigma}$ result

- Getting to 5 $\boldsymbol{\sigma}$ would
- take ~1 year

- Easier to go to VERITAS
- (S/N α (Mirror Area)$\sqrt{time}$)



First IACT telescope successes (2018 -2023)

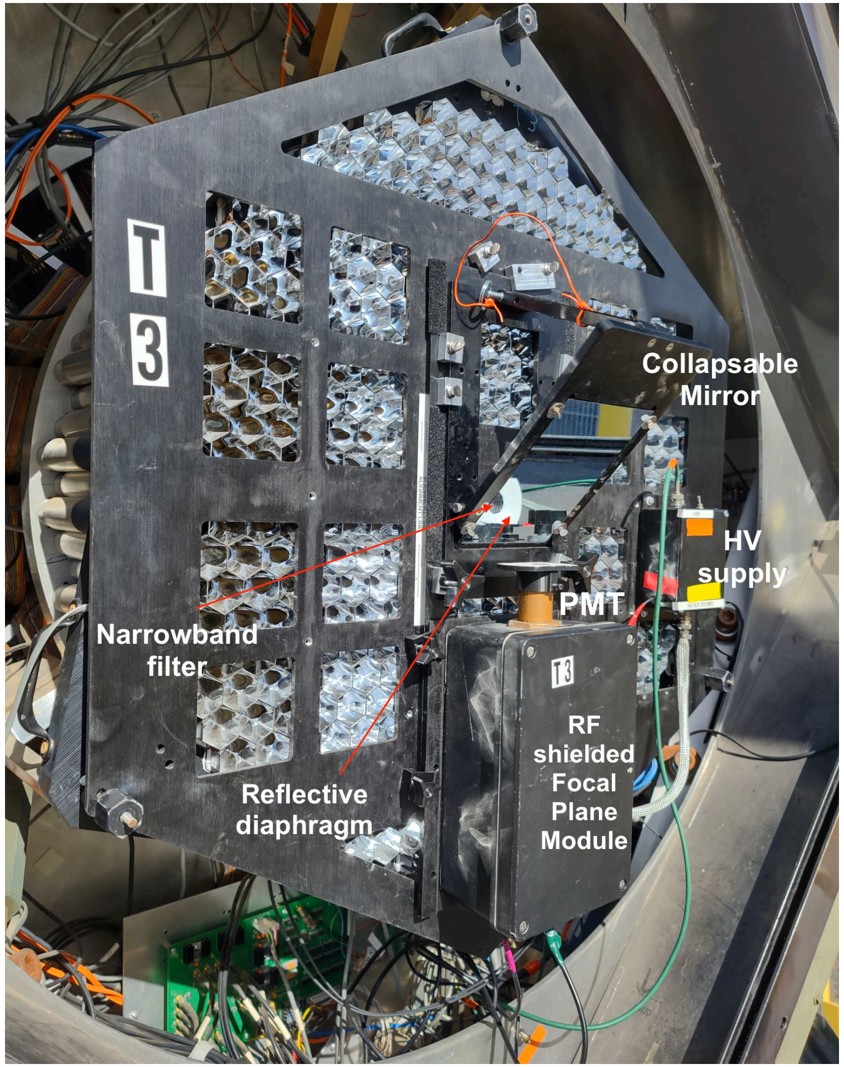
VERITAS-SII (VSII)

- Excellent instrument for SII
- Large photon collection area (~12 m Ø mirrors)
- 40 m to 150m baselines
- Optically isochronous (< 4 ns)
- 250 Mhz photocurrent sampling
- Telescope time available during Full Moon

Sub- milliarcsecond optical resolution @ 400 nm

- Multiple science topics
- Pathfinder for km-scale arrays (CTA-SII)

Removable VSII Camera Plates



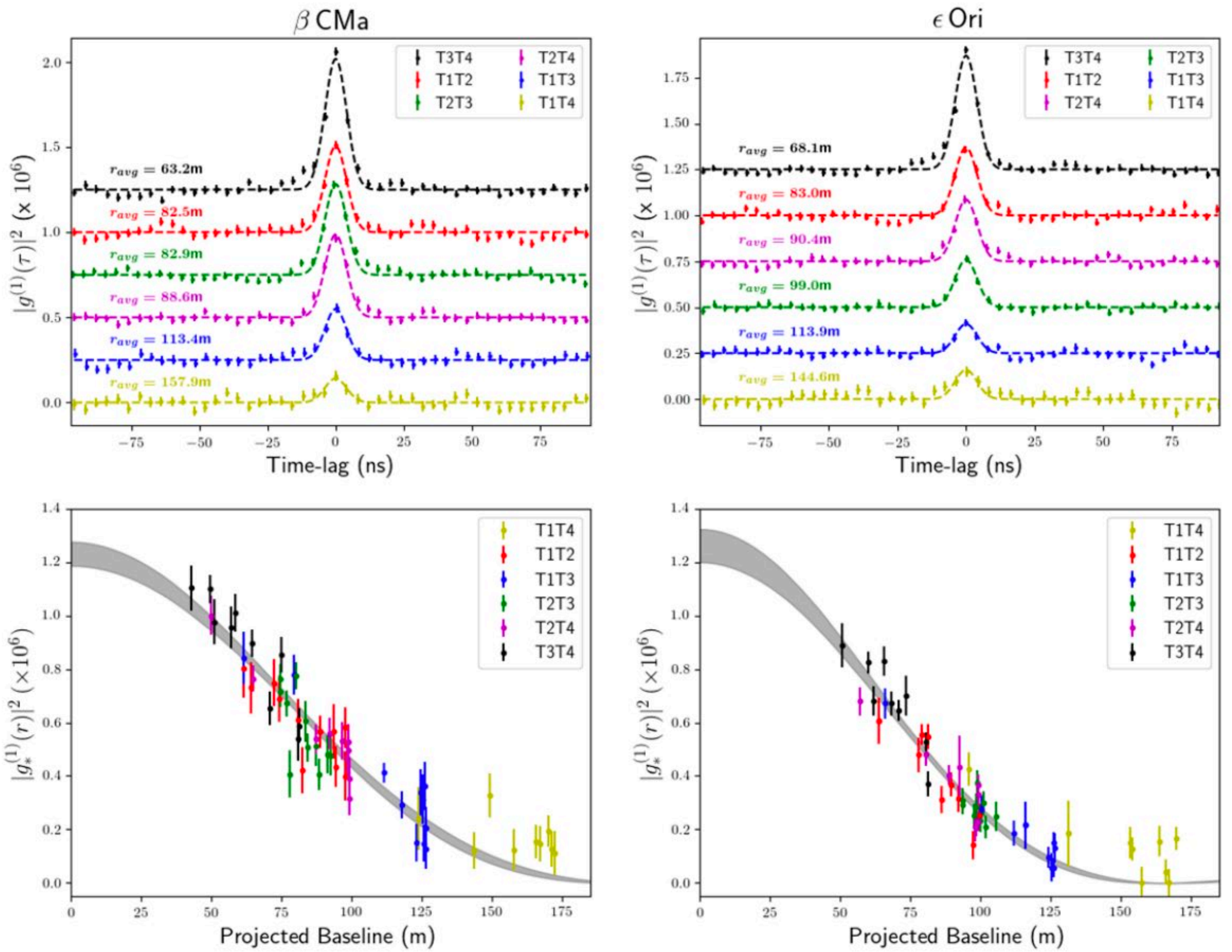
- The removable VSII Camera Plate mounts in front of the VERITAS Camera focal plane.
- Observer locates the VSII Plate onto each camera at beginning of full-moon period.
- Plate contains necessary focal plane optics, HV supply, photomultiplier and preamplifiers to perform VSII measurements.
- Quick connect to cables for signal, power, control
- At end of run the VSII plate is removed and stored in dust-proof box.
- About 20 minutes to install each plate

VERITAS 4 Telescope Observations

Each VERITAS Telescope
Measures essentially
Shot noise in a single PMT.

But when you correlate
Noise from two
Telescopes, a signal
"Magically" appears

VSII Measurement of Stellar Diameters



Source	θ_{UD} (mas)	T (h)	θ_{UD} (mas)	T (h)
β CMa	0.50 $\pm$0.03	63.4	0.523 $\pm$0.017	5.5
ϵ Ori	0.67 $\pm$0.04	56.0	0.631 $\pm$0.017	4.25

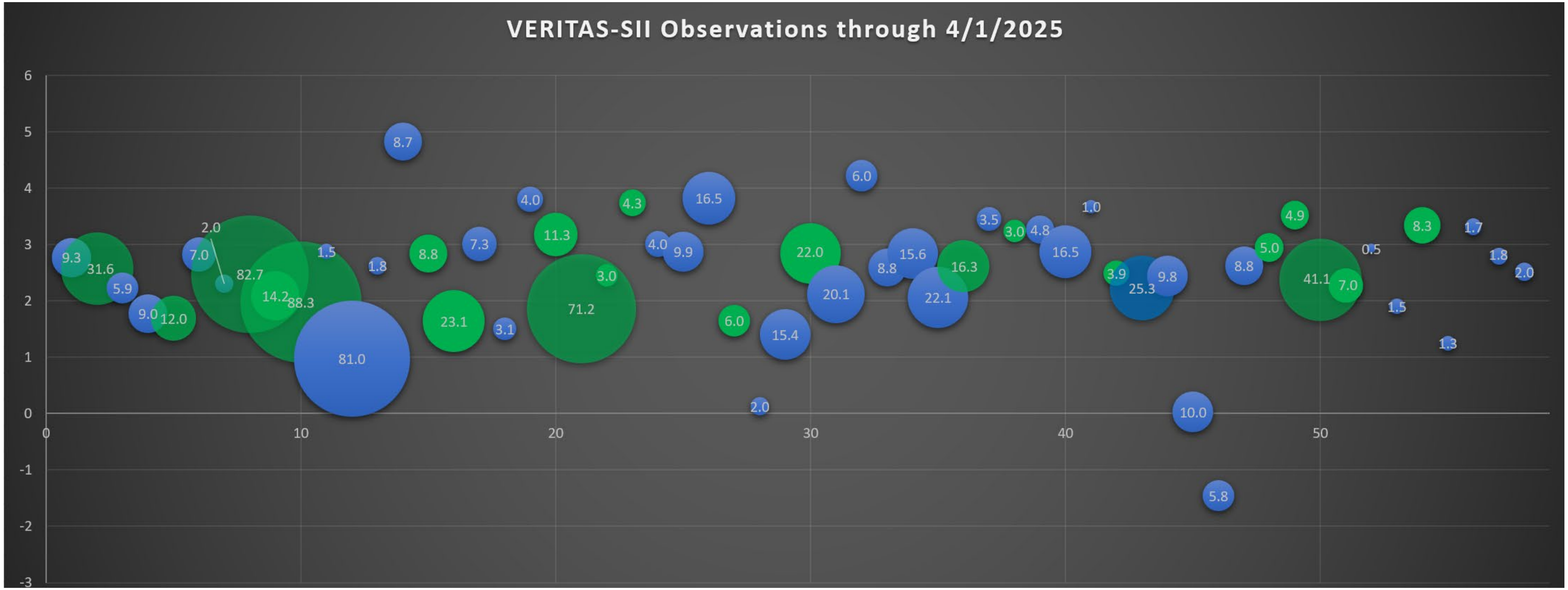
(T= Observation Time)

Narrabri SII
Observations 1970

VERITAS-SII
Nature Astronomy 2020

VSII Northern Sky Survey (up to Jun 1, 2025)

m_V



Primary star classification: O9 O9.5 B0 B0.5 B1 B2 B3 B7 B8 B9 A0 A1 A2 A8

Single star

Binary/multiple star

Circle area is the number of each star's exposure (hrs) (12/1/19 – 7/1/25)

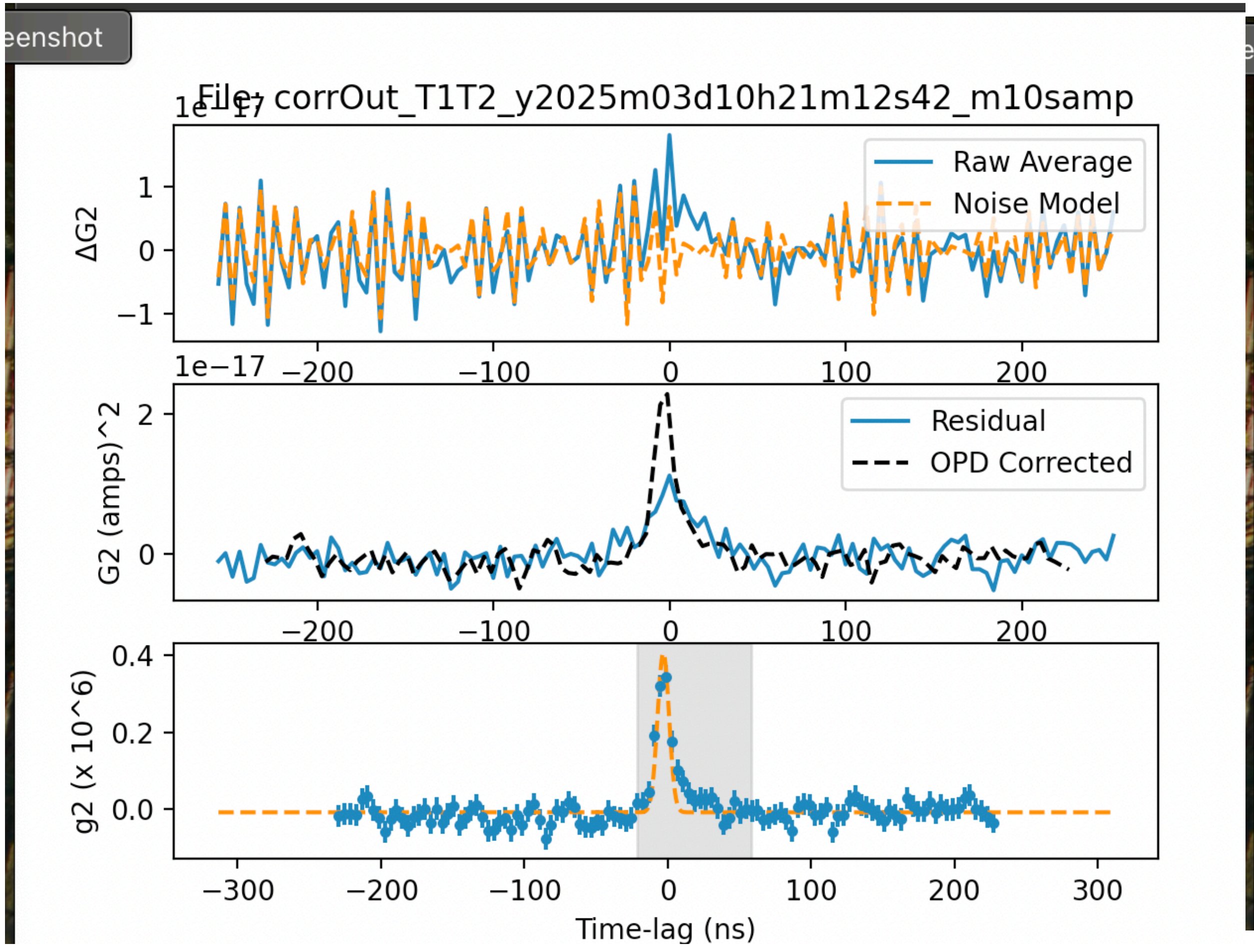
- 58 different targets
- 33 single
- 25 binary/multiple
- Total 877.6 hrs exposure
- 145.33 hours 2024-2025 obs season

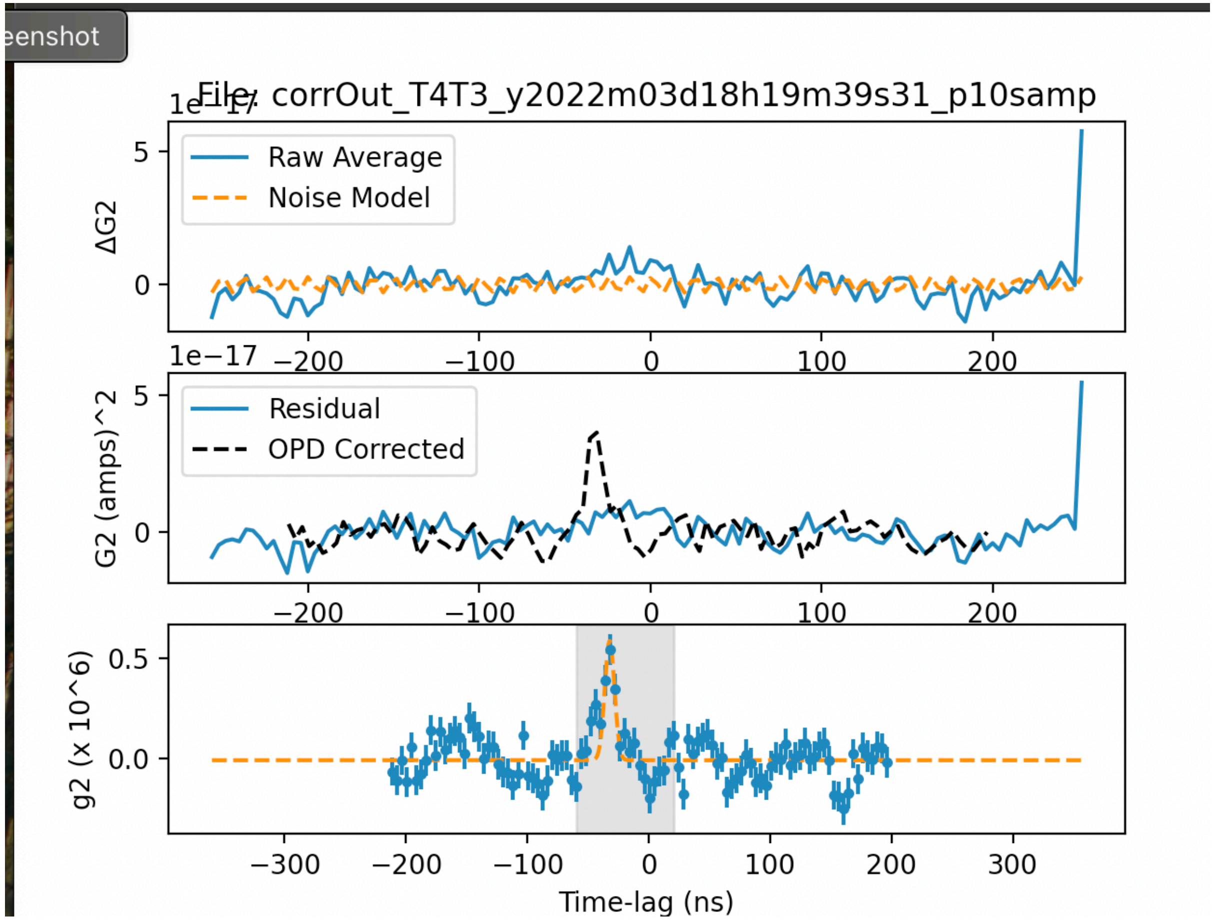
VSII Northern Sky Survey

(Preliminary results)

- Select only “green” telescope pairs correlations (clear signal)
- No corrections for weather
- No corrections for background light
- Simple UD model fitter

VSII observation database: Green designation

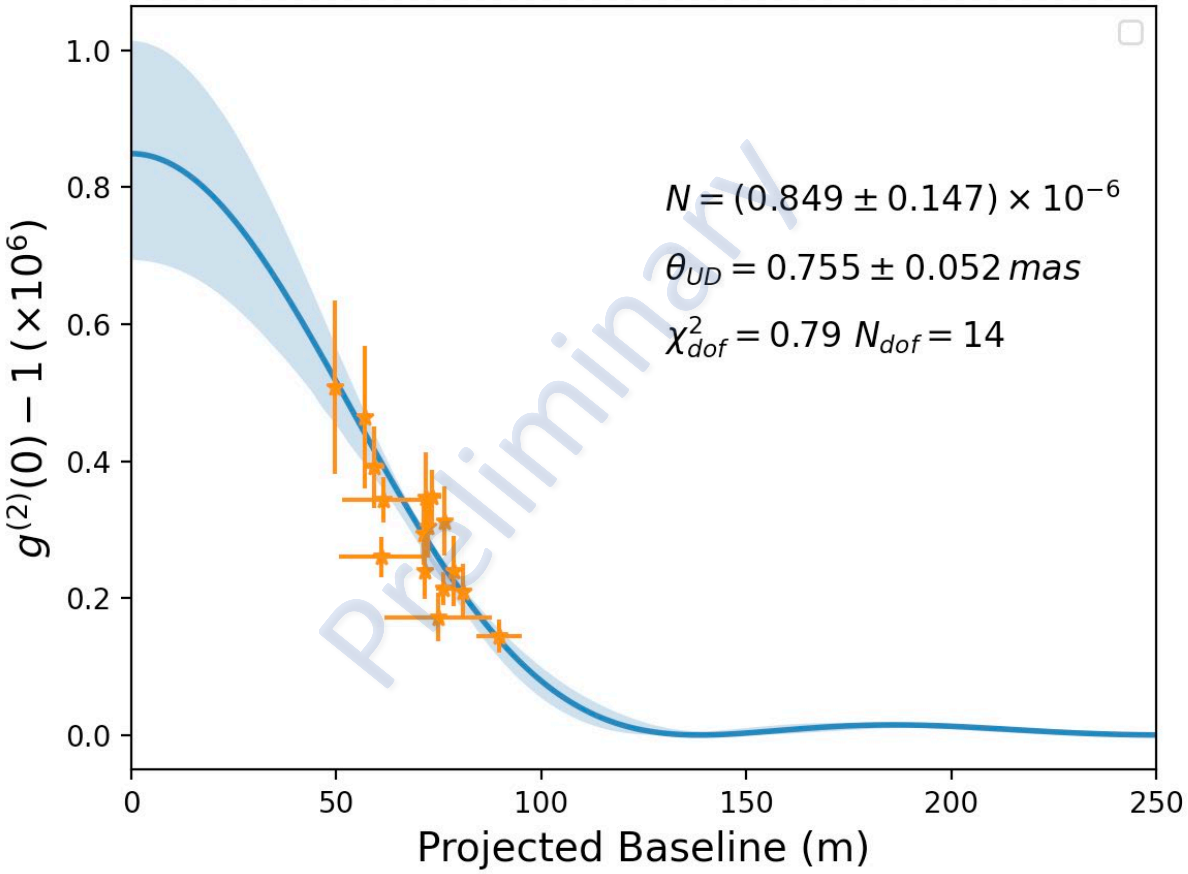


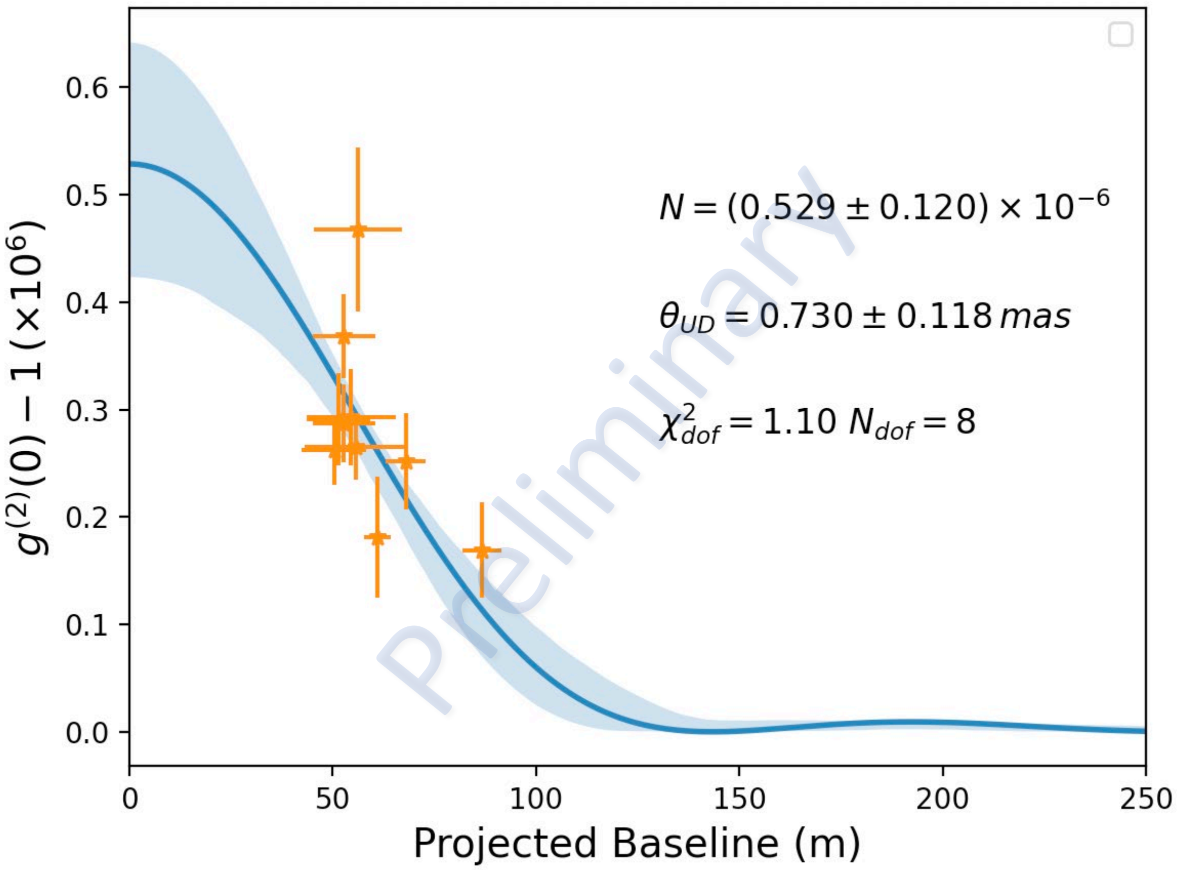


Single Stars (low rotation)

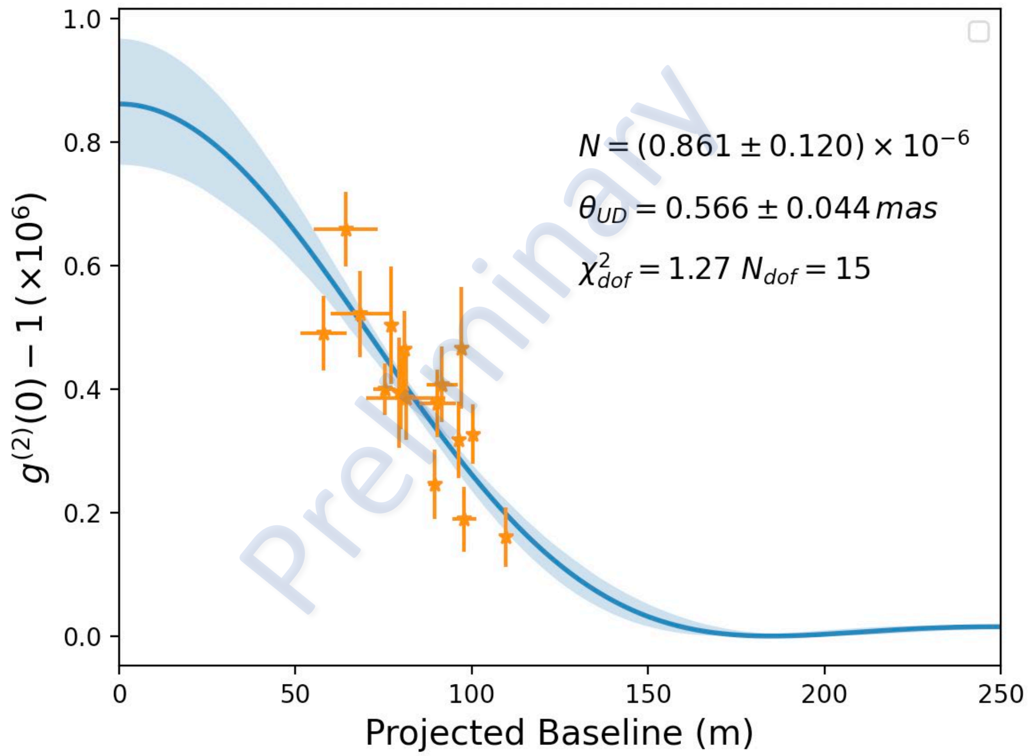
alp And: green only

alp Crb: green only

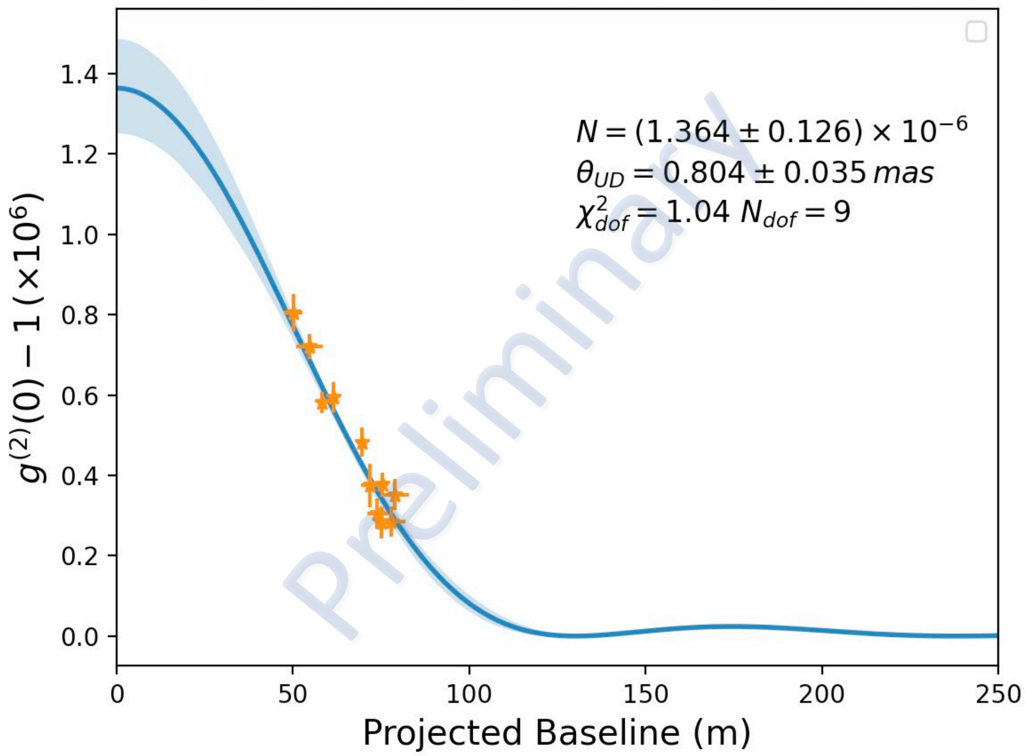




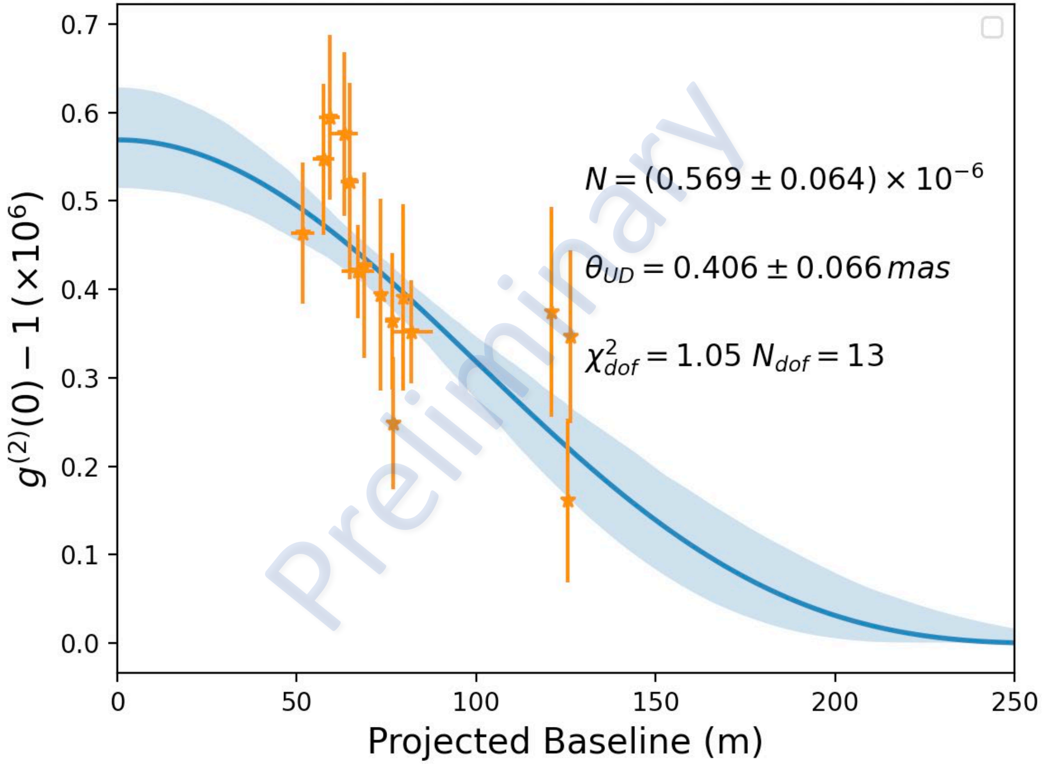
alp Cvn: green only



eps Cma: green only



del Cyg-green only



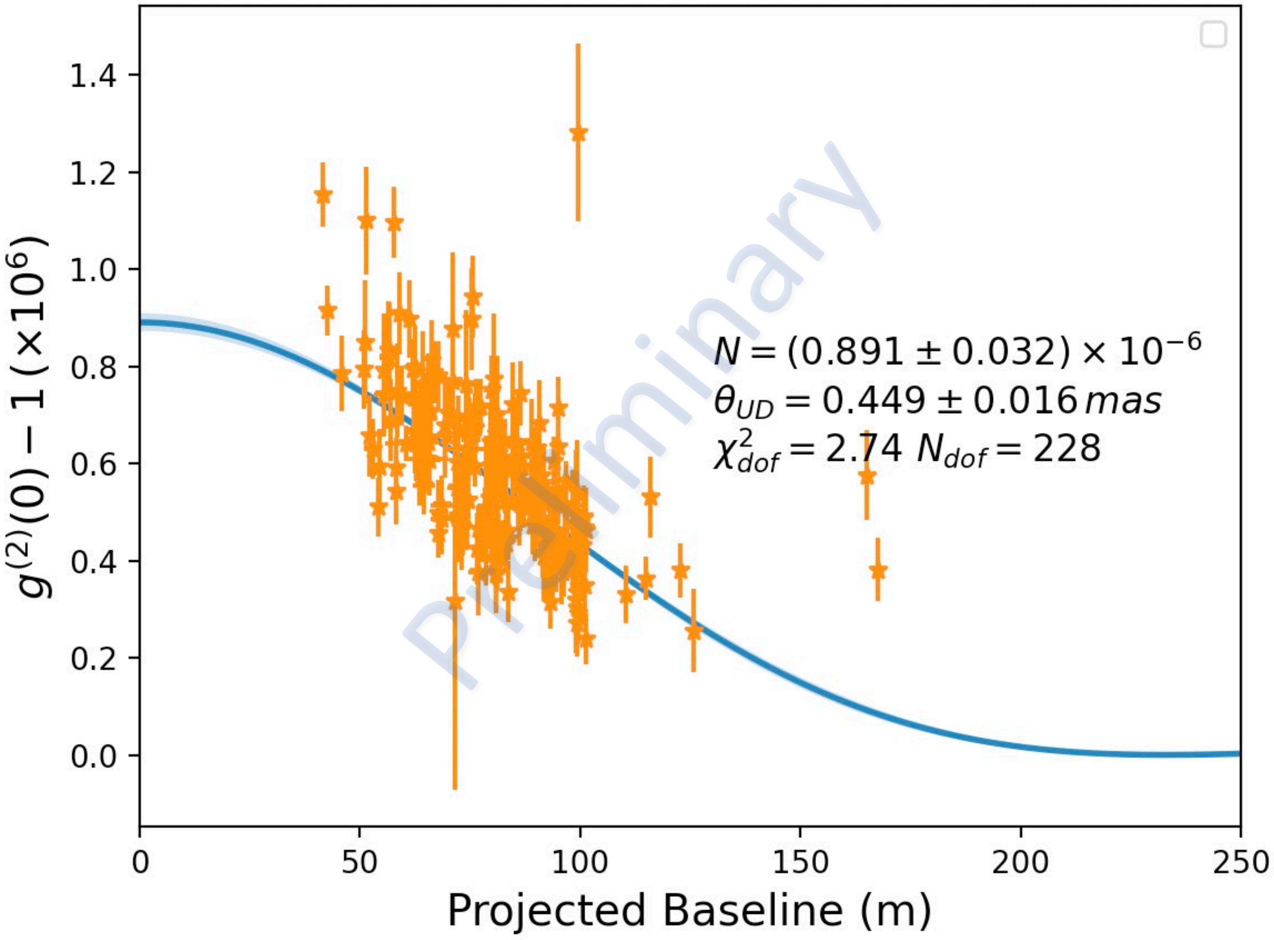
& many more single stars

Single (slow rotating) stars well fitted by Bessel function.

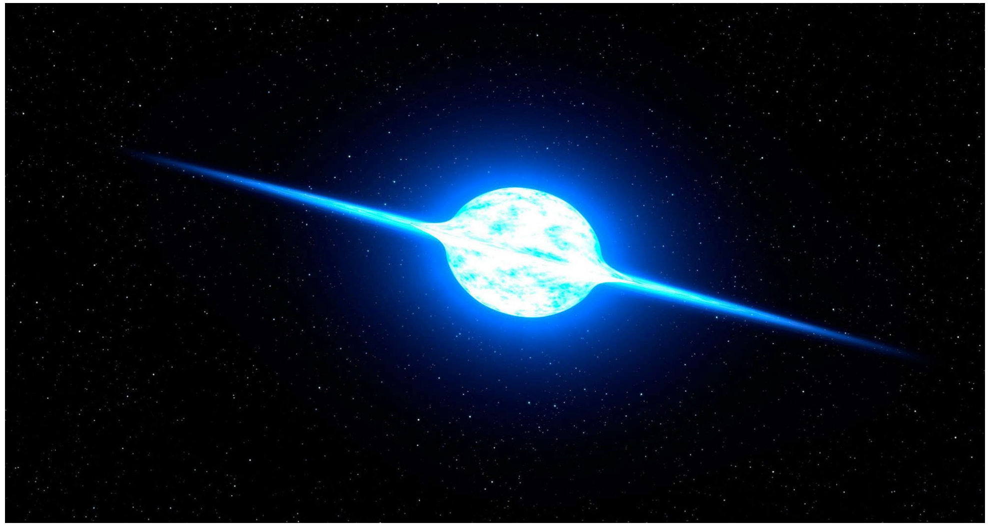
Note that single stars are a 1-D projection of a 2-D Fourier Plane: Rotational symmetry

Single Stars (rapid rotators)

gam Cas: green only

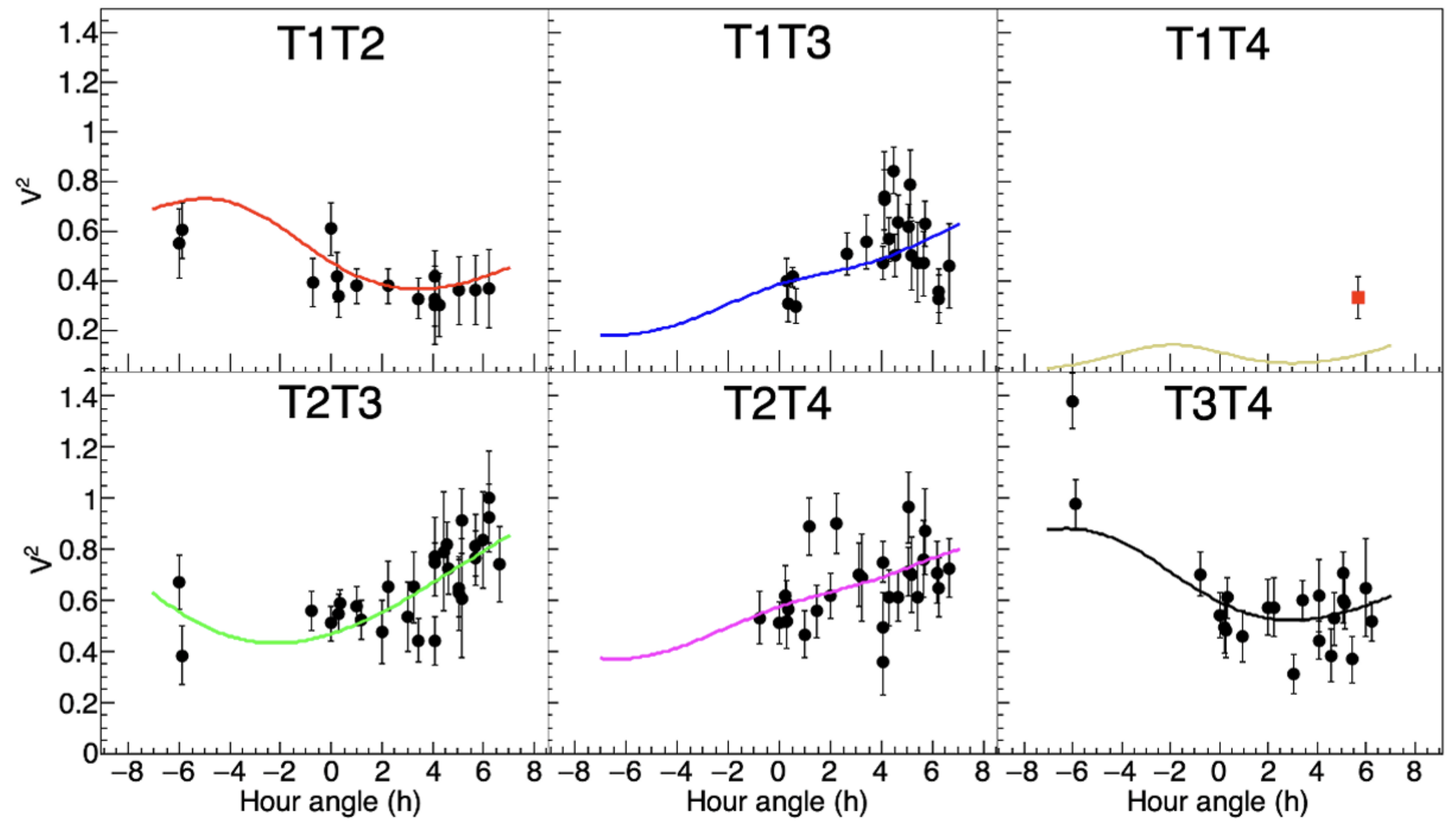


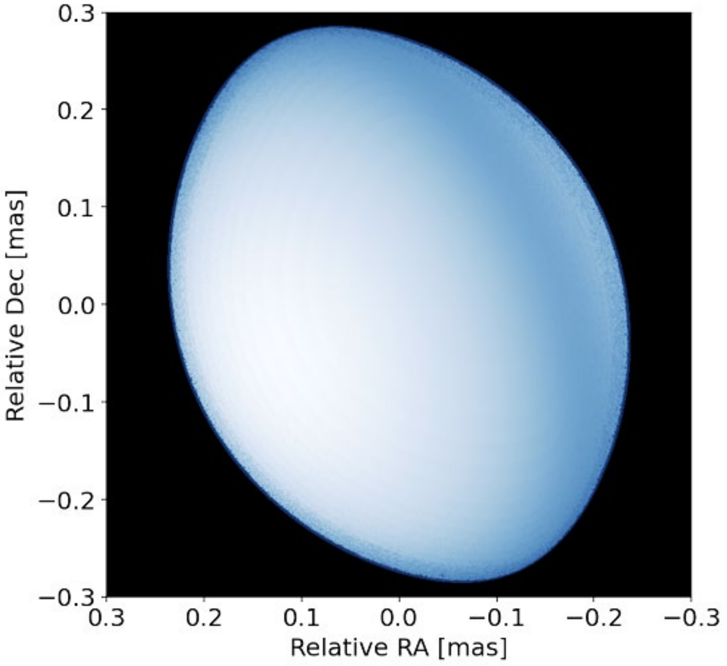
*Quantitatively different than slow rotator curve……



- 13 $M_\odot$ B0.5IVe Star, T = 25,000 K
- Prominent Variable star (V =1.6-3.0), average V =2.47
- 168 pc distant, multiple star system (T_{Aa}=203 d; T_{Ac}=60 yr)
- Radiation illuminates nearby gas clouds IC59/IC 63 (1 pc, Hα)
- Fast rotator (v sin i = 432 km/sec)

gam Cas full stellar model fit (Roche-von Zeipel)





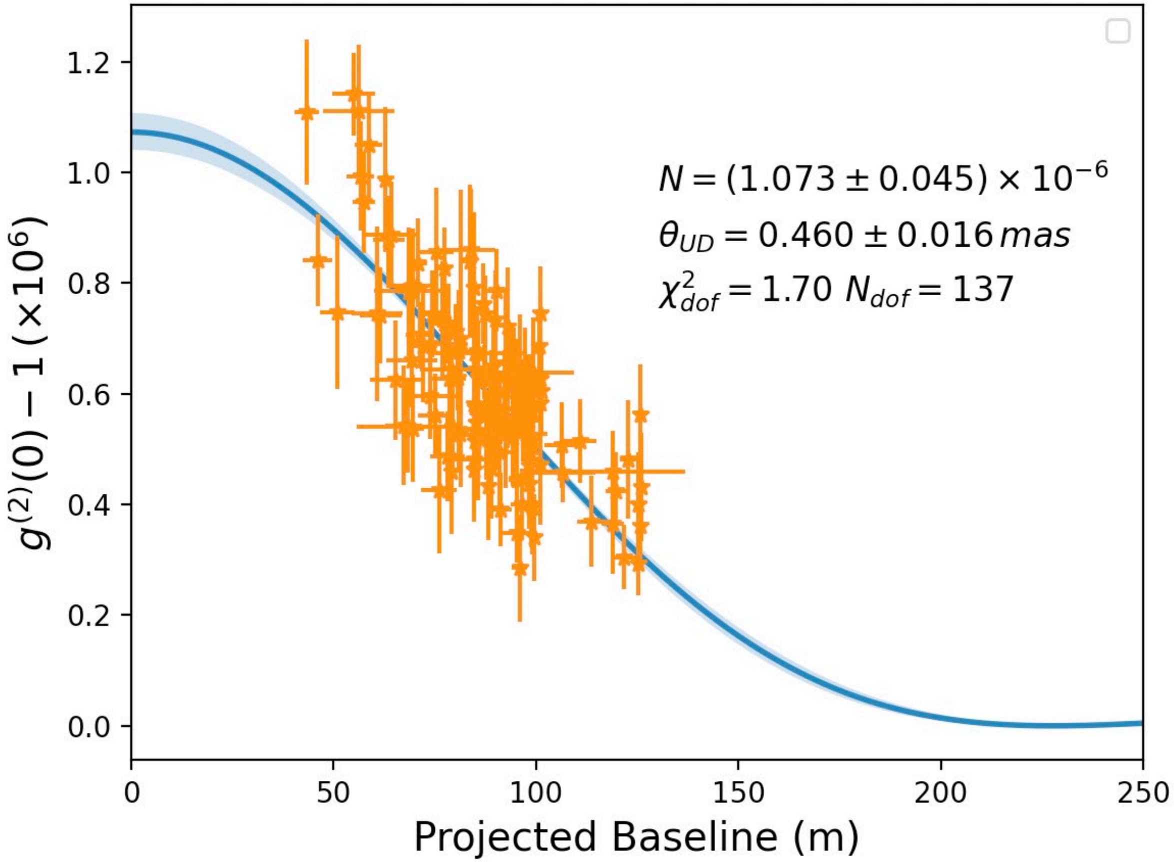
θ_{eq}=0.60 mas

Ω/Ω_{crit} =0.9888

$\phi^* = 114^c$

VERITAS 2025, to be published in Ap. J

zet Oph: green only

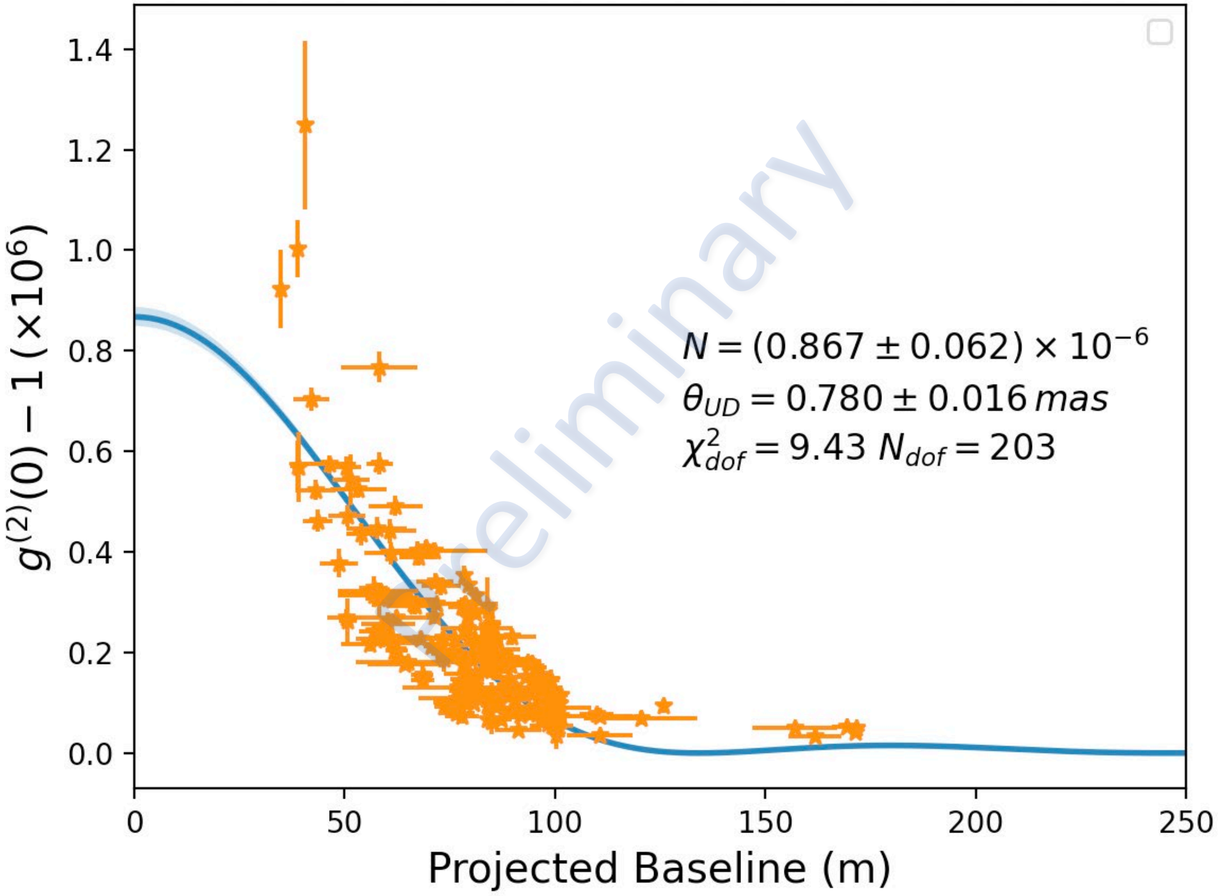


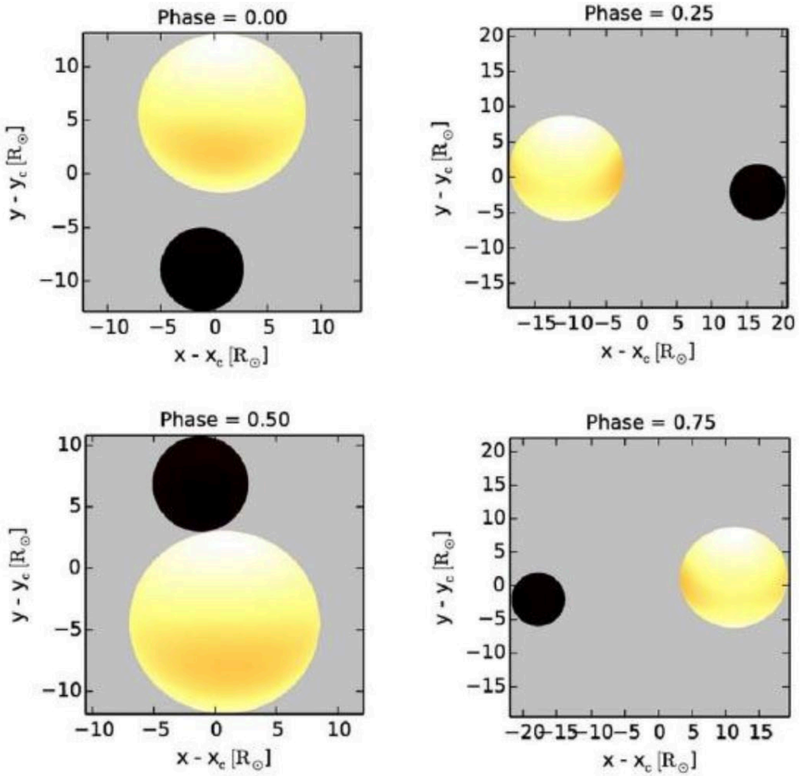
*Quantitatively different than slow rotator curve……

- 20.2 $M_\odot$ O9.5V Star, T = 30,000-39,000 K
- Prominent Variable star (V =2.56-2.58)
- 130 pc distant
- Fast rotator (v sin i = 400 km/sec)

Binary/ Multiple Star Systems

alp Vir: green only

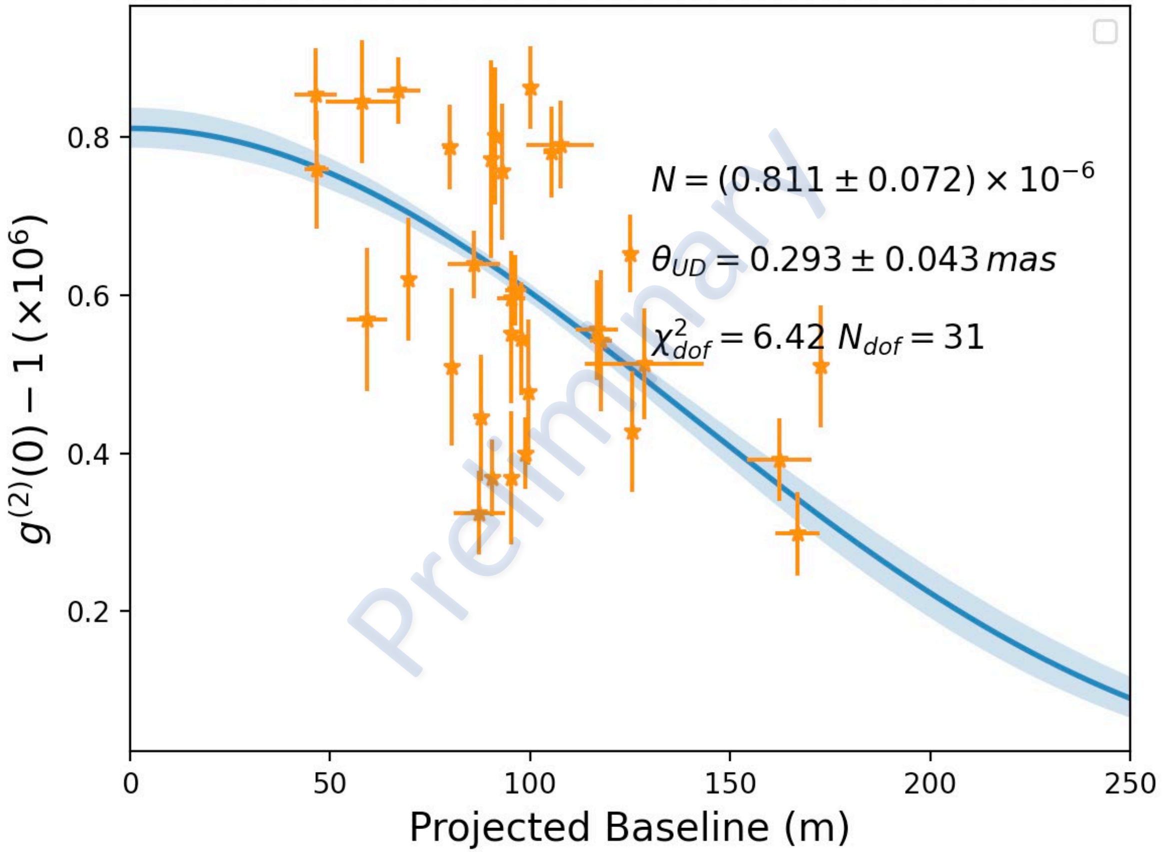




- B1III +B2V Star Binary system
- Prominent Variable star (V =0.97-1.04)
- 77 pc distant
- 4.01 day period
- See John Scott's Talk today!

*Quantitatively different than single star/fast rotator curve……

iot Ori: green only

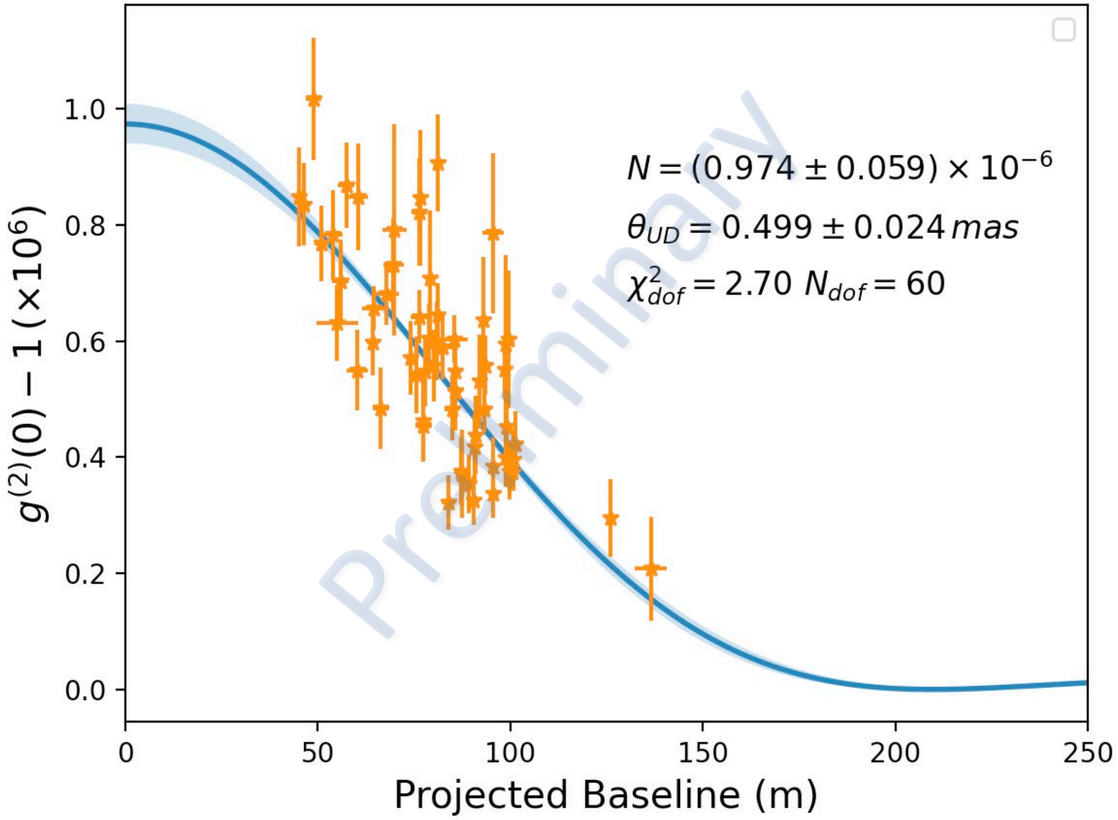


*Quantitatively different than single star/fast rotator curve……

- Multiple Star System O/B stars
- iot Ori Aa1 T = 31,000 K iot Ori Aa2 T = 18,300K
- Orbital period 29.1 days
- 412 pc distant

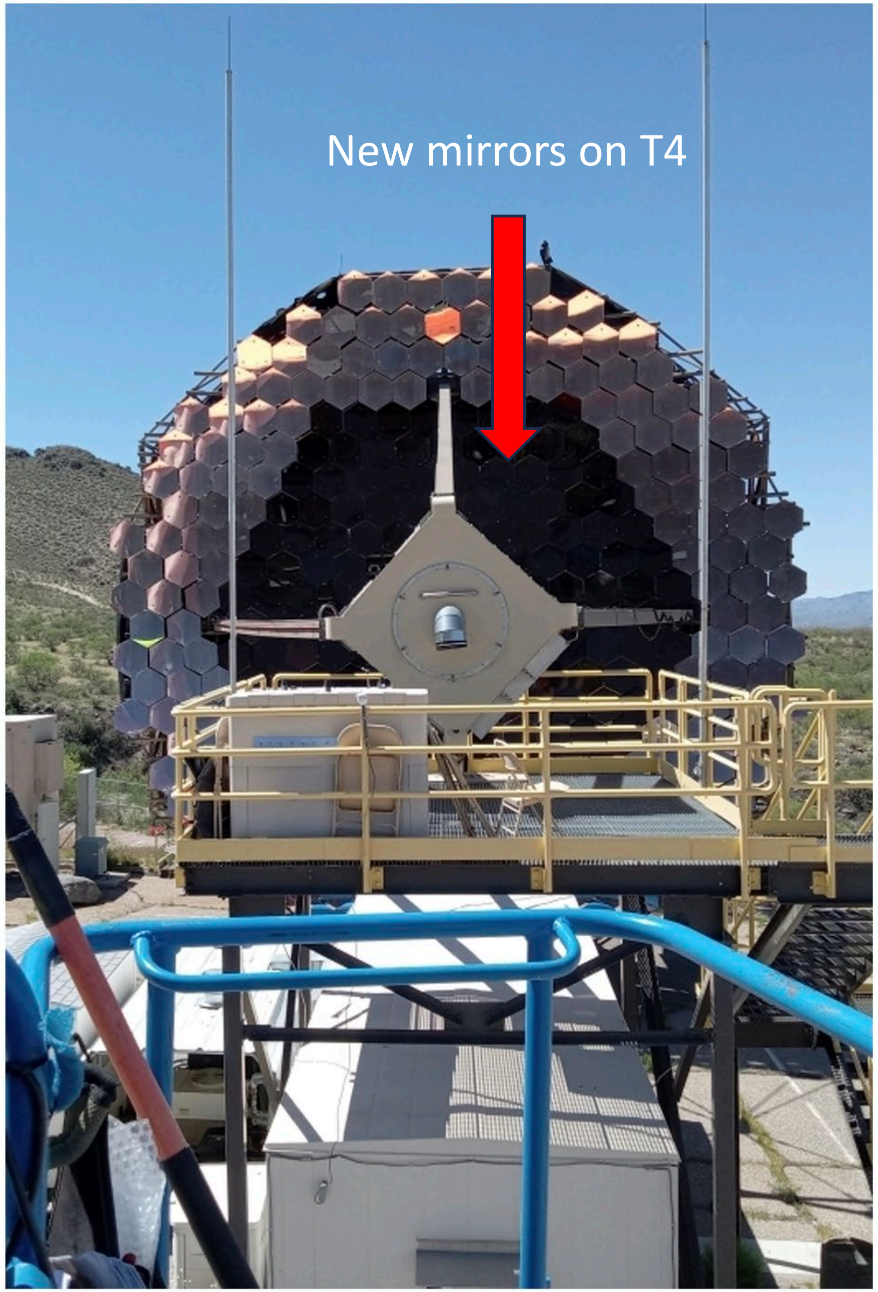
Something Interesting??

kap Ori: green only



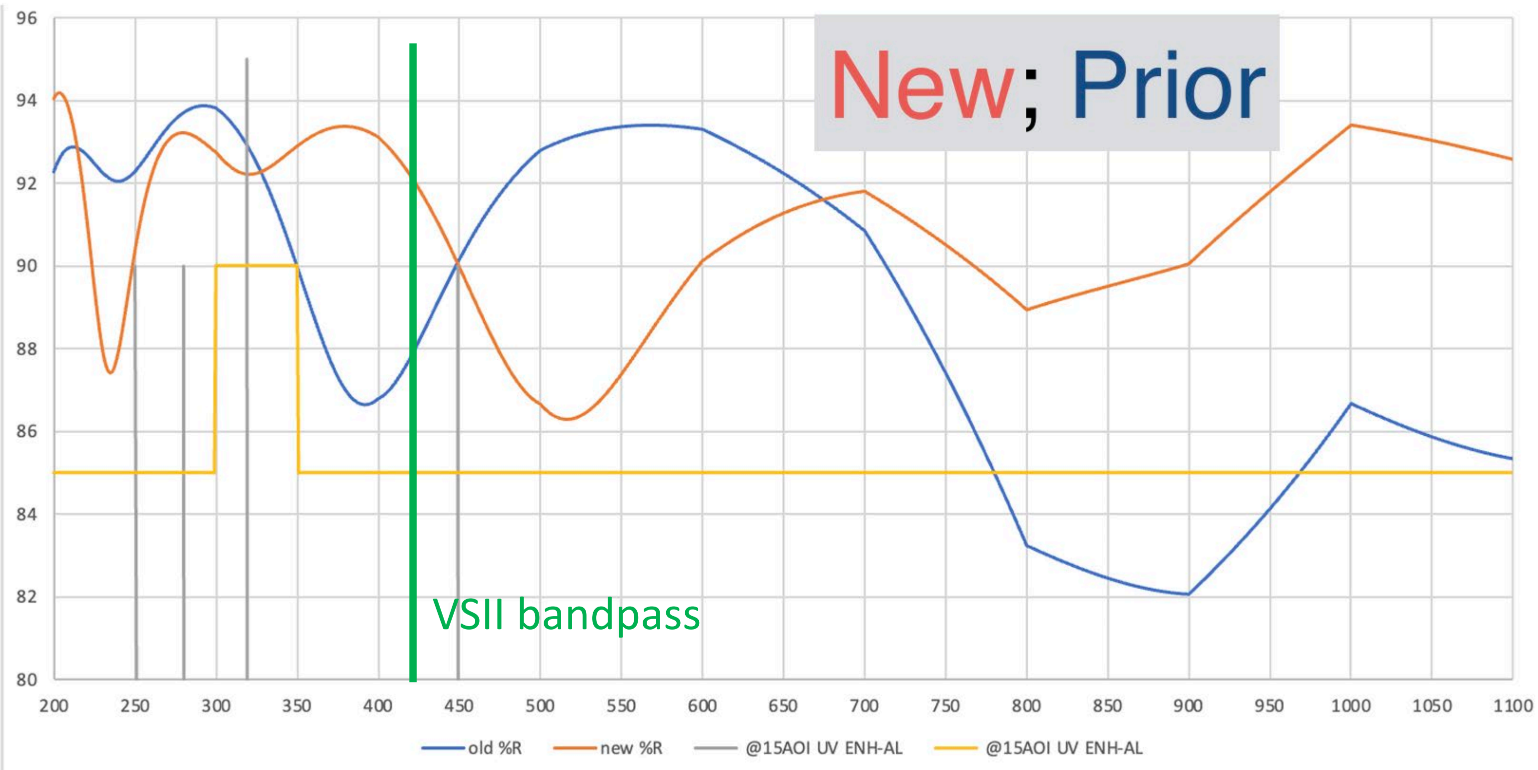
- B0.51a Star, T = 25,700 K
- Blue Supergiant, suspected variable star, strng stellar wind/mass loss
- 15-28 $M_{\odot}$ (discrepancy between parallax & spectral)
- 198 pc distant
- slow rotator (v sin i = 83km/sec)
- Not a multi star system?

T4: Black Object at 2F



VERITAS Mirror recoating (2023-2025)

Mirror recoating by commercial vendor (DOTI, Round Rock, TX)



1) Mirror Recoating increases overall telescope mirror reflectivity by **20%**
2) New DOTI coating formula increases reflectivity at VSII bandpass (420 nm) by additional **~5%**

VSII Sensitivity Improvements (2025+)

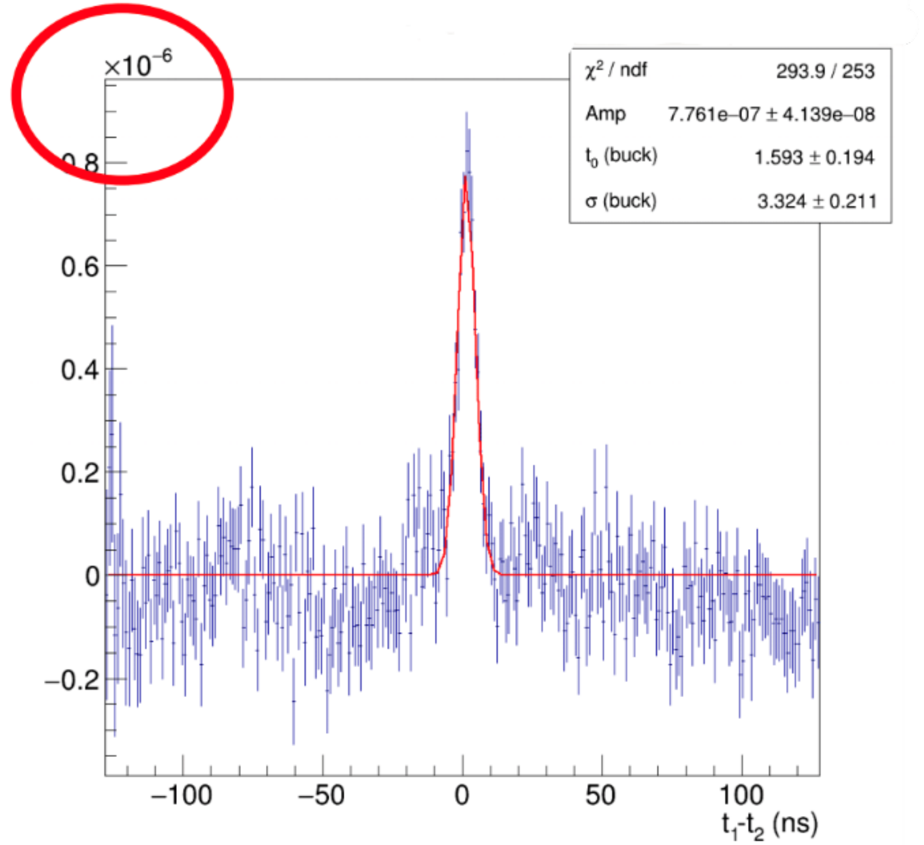
$$(S/N)_{RMS} = A\,\alpha\, n\,|\gamma(u,v)|^2\sqrt{(\Delta f\, T/2)} = \frac{\dot{N}_{p.e.}}{\Delta \nu}|\gamma(u,v)|^2\sqrt{(\Delta f\, T/2)}$$

25% gain in mirror reflectivity = 1.25^2 = x 1.4

50% gain in usable data (no RF noise) = x 1.5

clock rate 250 MHz -> 500 MHz = x 2.0

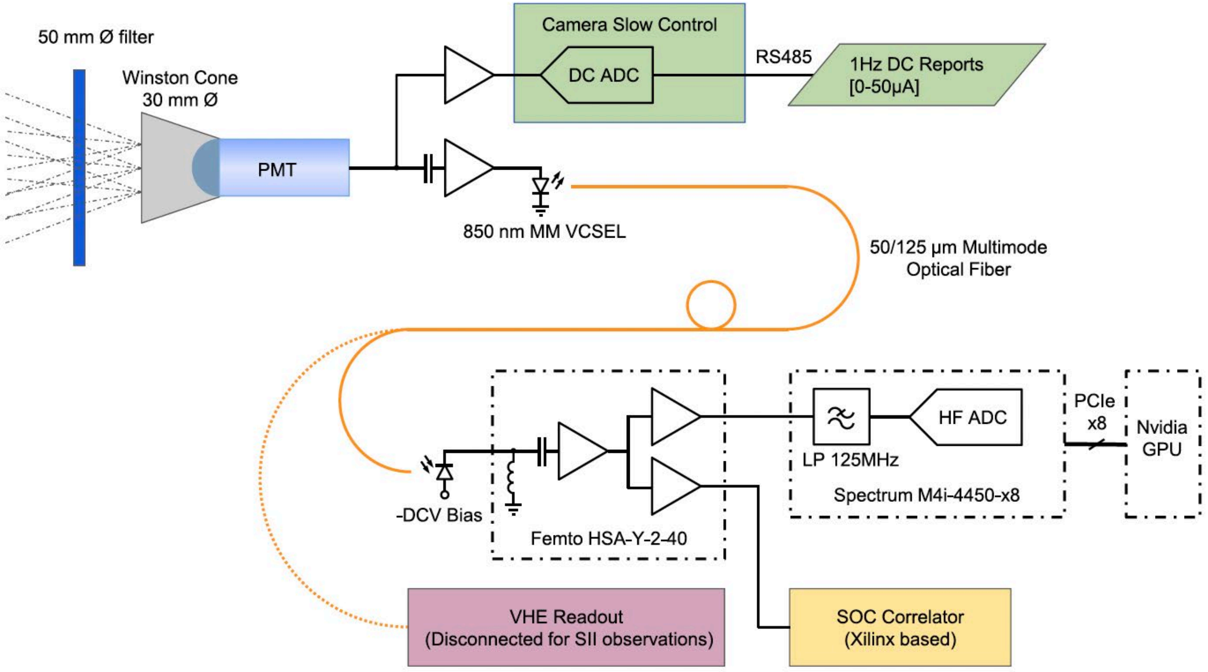
Total improvement = factor of 4.7

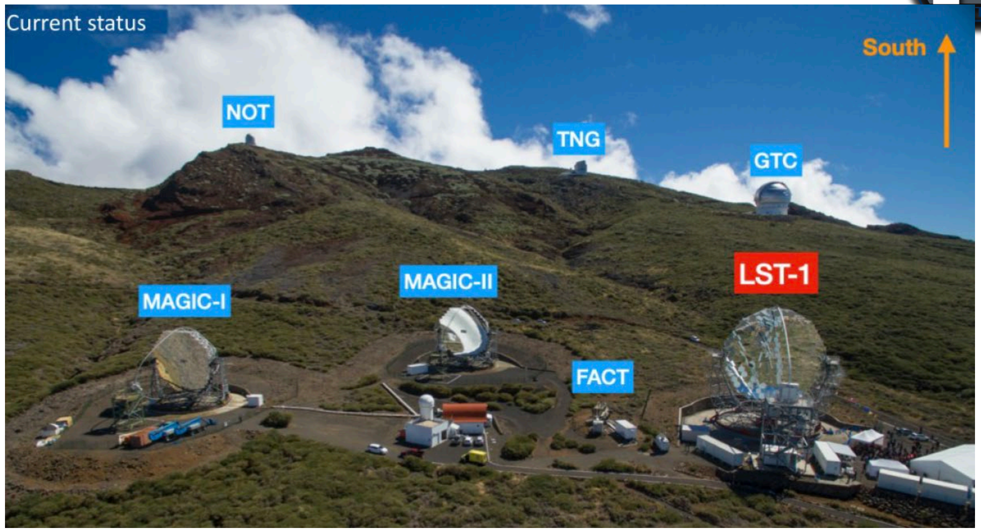


One hour of 2025+ observations = 4.7 hours previously

~200 hours (2025-2026) = all previous observations

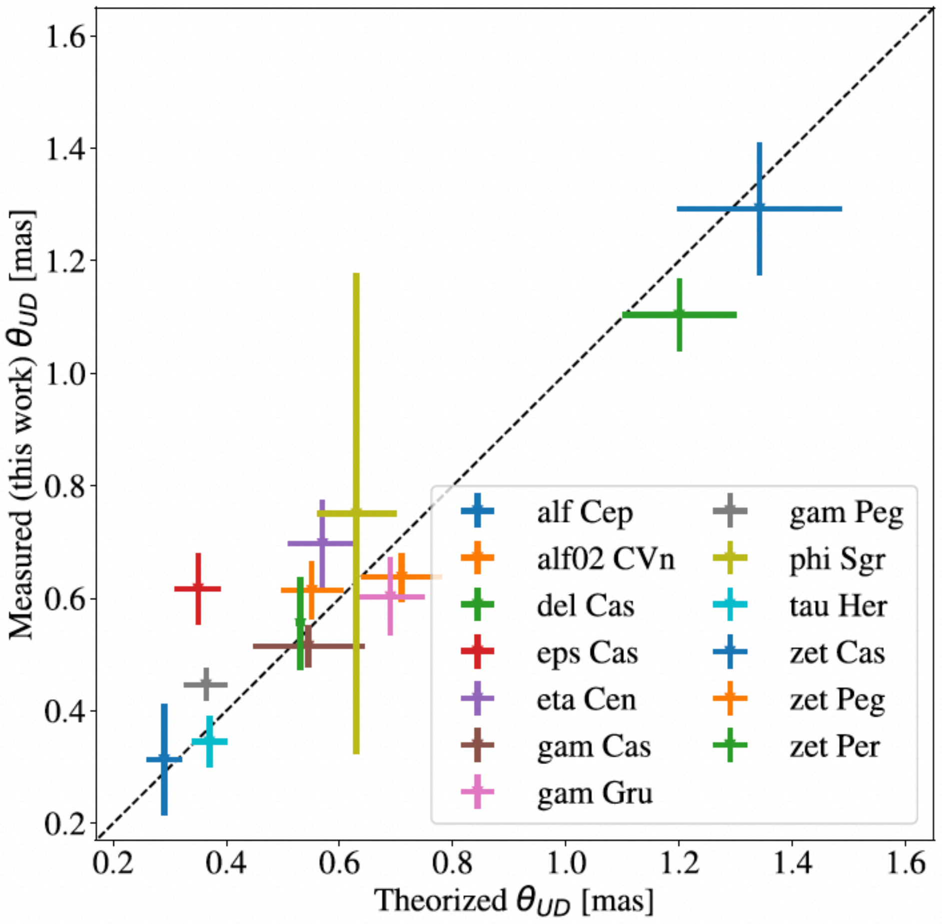
MAGIC IACT SII Array



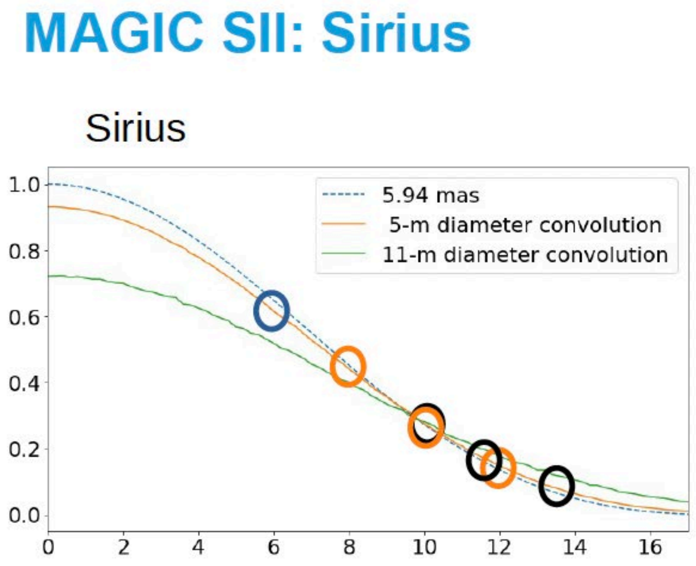


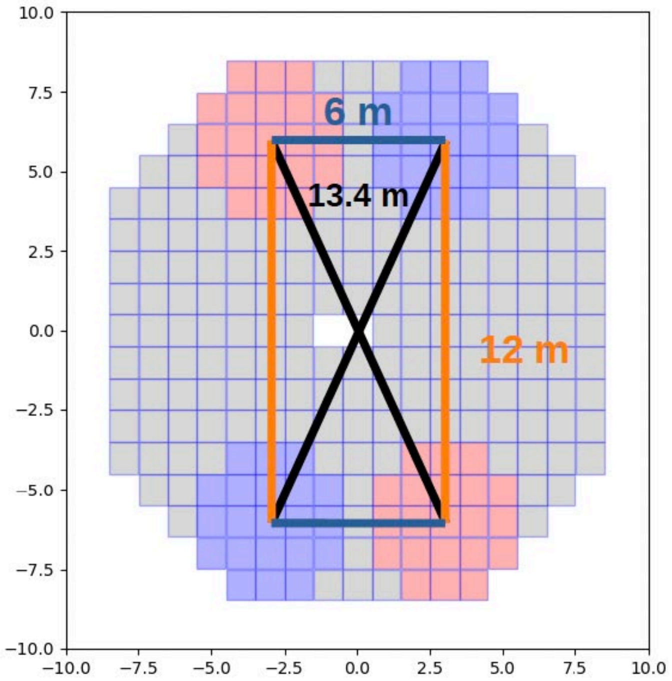
Single baseline (soon to include CTAO-LST1)
MAGIC array, Canary Is. (2023)

MAGIC IACT SII Array



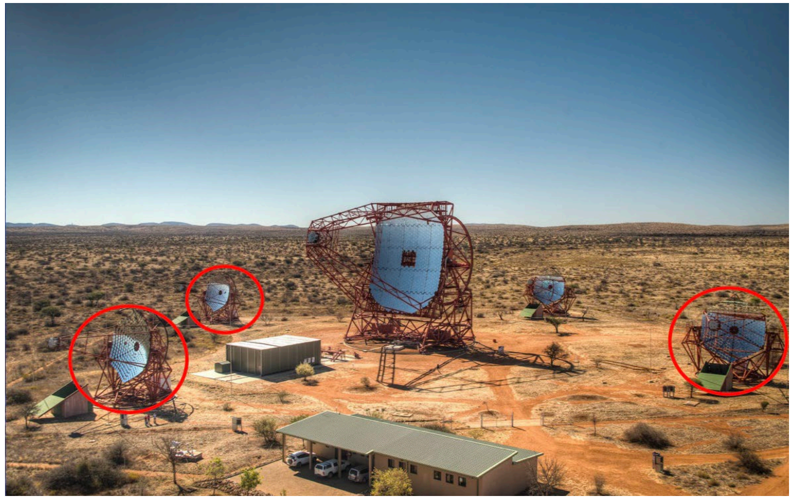
Magic Comparison with expected diameters
Single baseline





Create Short baseline observations using sub-mirrors

HESS IACT SII Array



Similar IACT.
Baselines to VERITAS

Extra 28 m HESS-s IACT

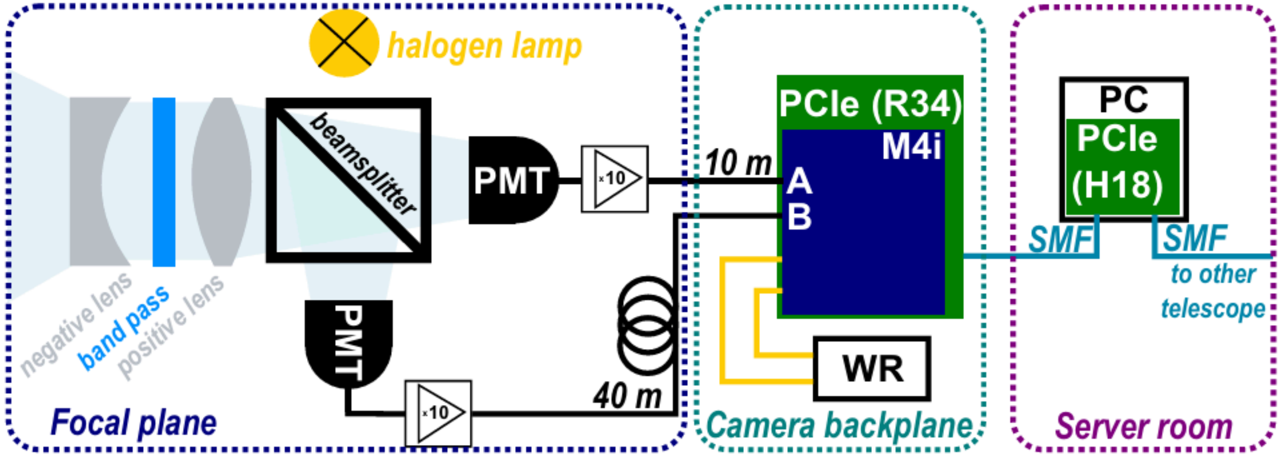
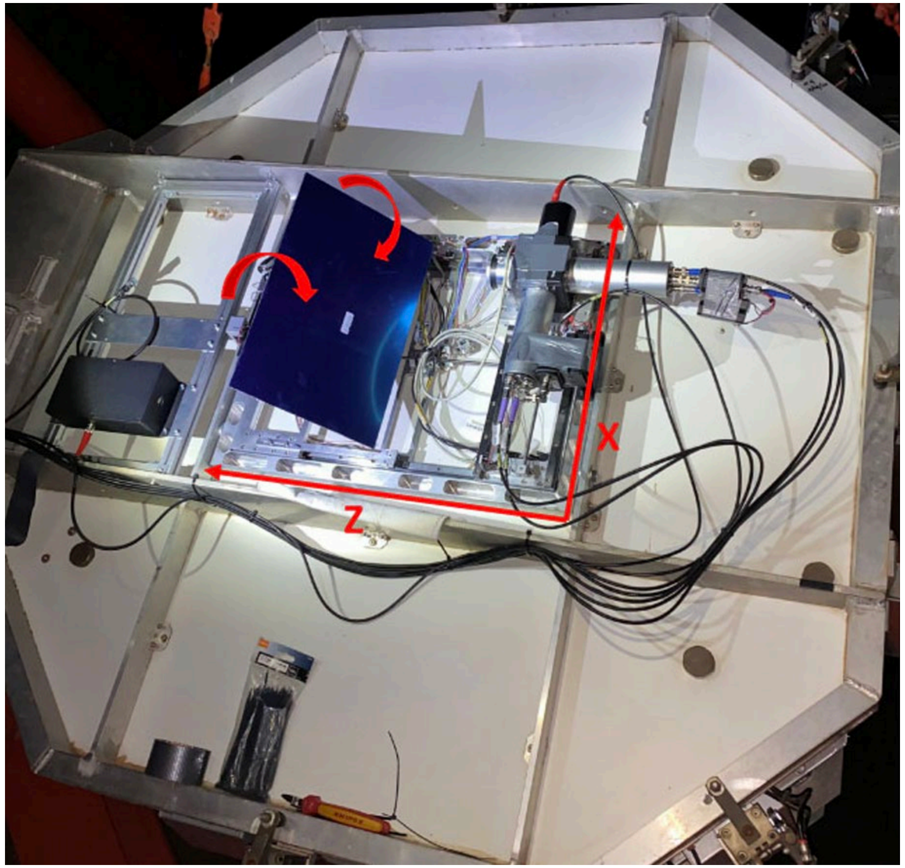
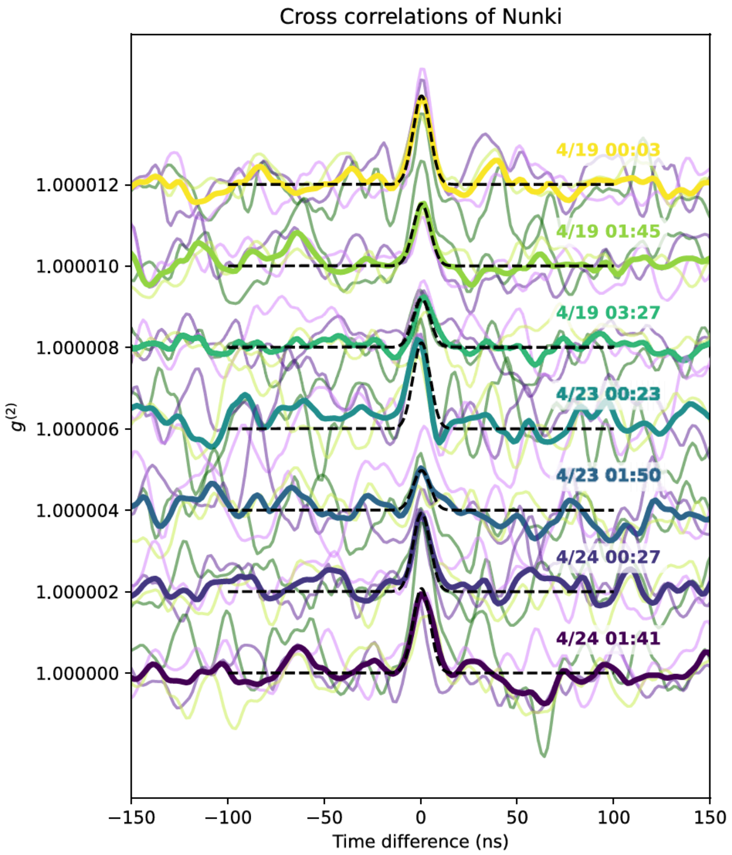


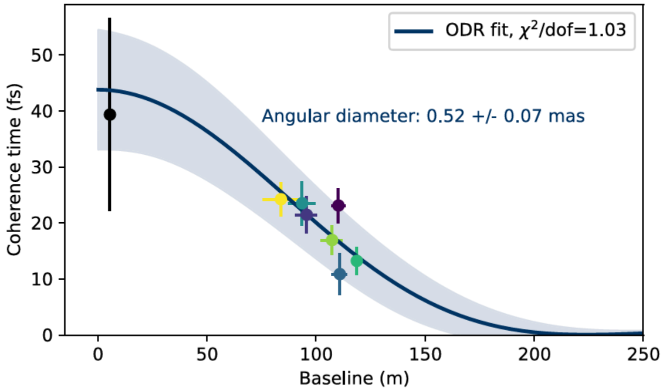
Figure 4. Schematic of the intensity interferometer for one of the telescopes. The setup is identical for each telescope.

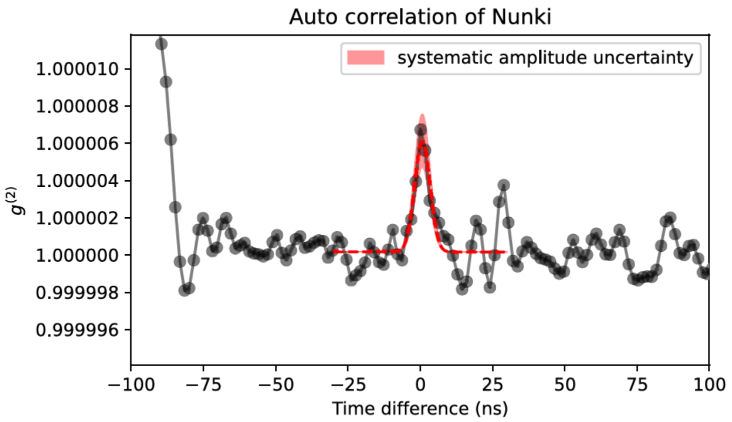


HESS array, Namibia (2023)

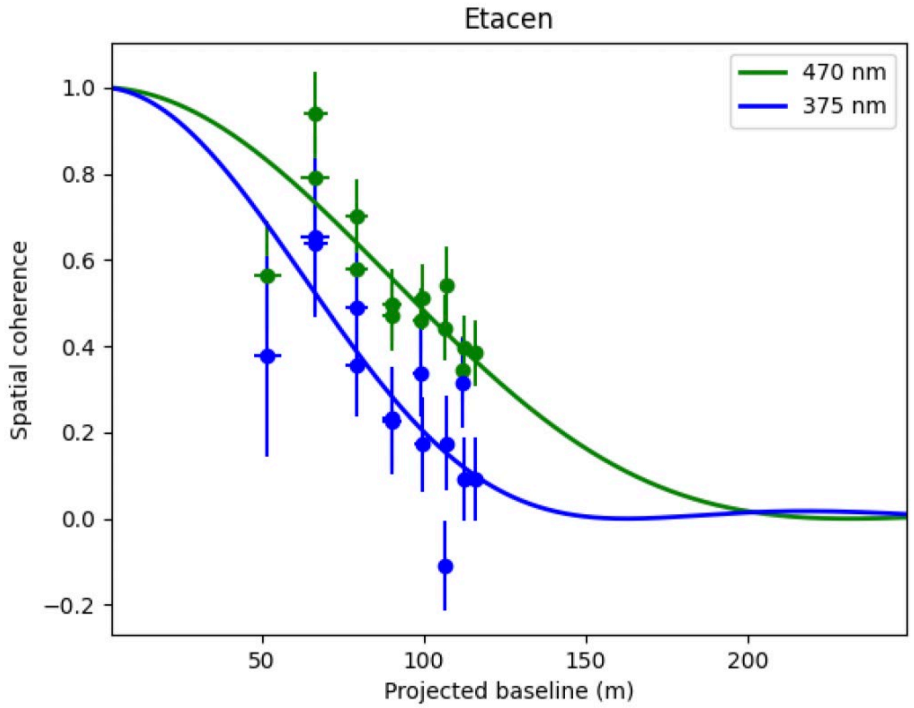
HESS IACT SII Array







HESS Southern Sky Survey (2023)



HESS two-color measurements (375 nm & 470 nm) (2024)

Recent IACT SII improvements

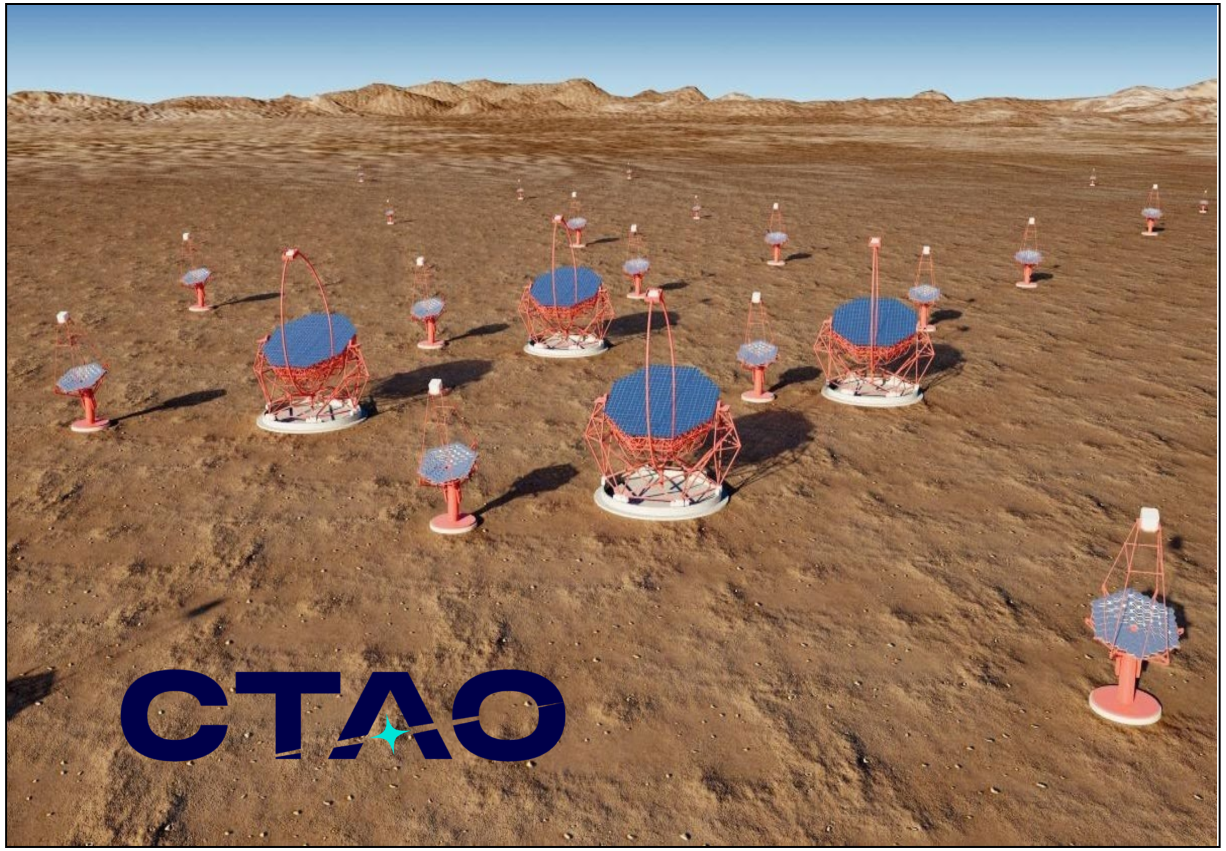
- Mult-baseline sampling of u-v Fourier plane (different position angles)
- Simultaneous multi-band observing
- Improved mirror reflectivity
- Elimination of RF pickup noise
- Higher speed digitization/synchronization
- Mirror subdivision for short/zero baseline measurements
- Faster sensors & electronics

Critical Factors for Success of IACT SII

- IACT array were middle-aged
  - 10+ years past first light (HESS, MAGIC, VERITAS: 2005-2007)
  - Willing to dedicate bright moon time to open new discovery space
- Atmospheric Cerenkov Light peaks 400-600 nm
  - Optical reflectivity/light sensors sensitive to BB spectral peak of hot stars
- Diameter of Cherenkov light pool ~80-100 m
  - Gives baseline which is compatible with 0.3-1.0 mas diameter hot stars (O/B/A) at BB spectral peak ~400 nm
- Availability of inexpensive White Rabbit Synchronization (2014)
  - Solves the backplane timing alignment to <100 psec over 100 me distances for $1000/telescope

Critical Factors for Success of IACT SII

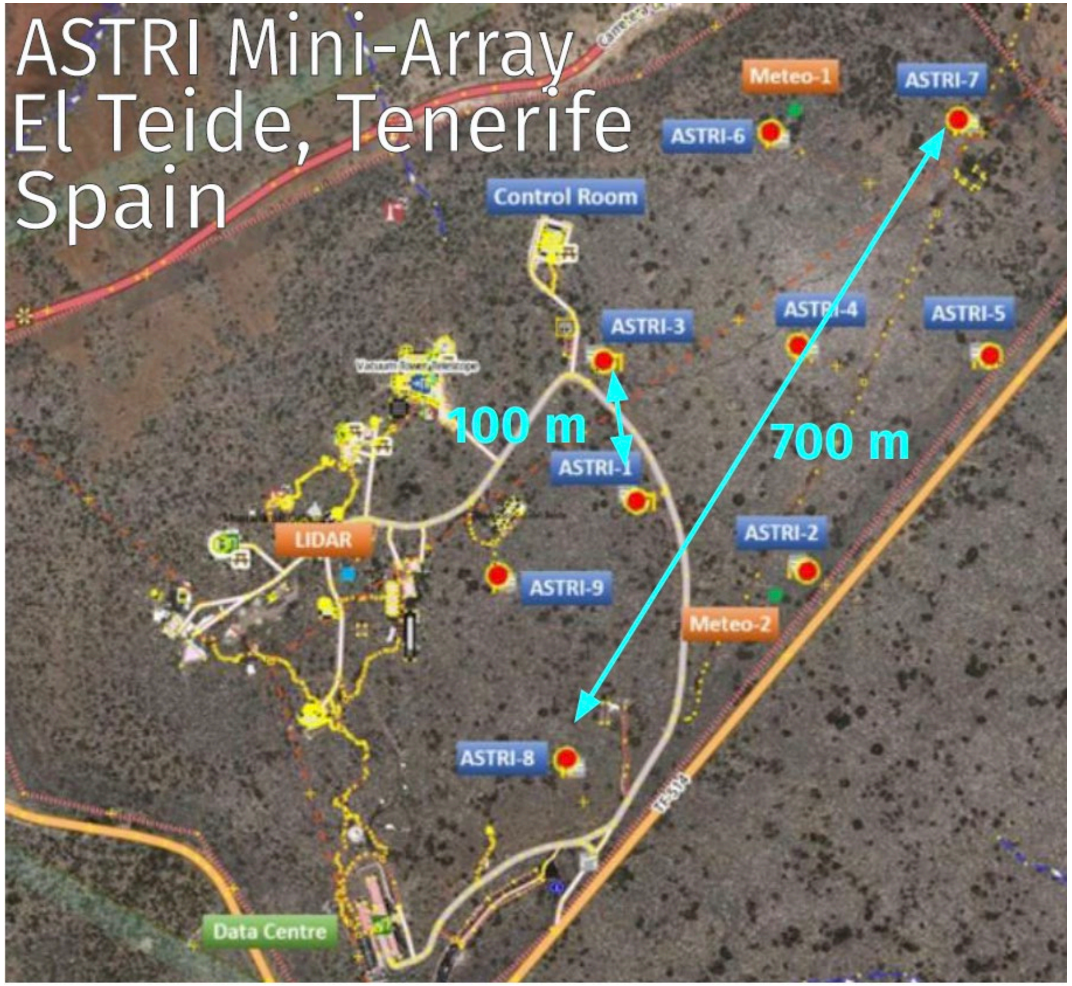
- Rapid improvements in High speed digitizers
  - By 2010 became inexpensive (500 MHz, $3k/channel)
  - Access to off the shelf (no engineering) technology
  - By 2015 becomes available as ”used on ebay”.
- 10 Gbit ethernet switches/transceivers (SFPs) (2010)
  - Works on existing single mode fiber (cheap)
  - By 2015 price dropped to less than 1 GB transceiver in 2010
  - Cross telescope correlations without need to move disks
- Rapid drop in disk space/RAID cost
  - In 2010: 2 TB HDD disk ~ $300; 12 disk RAID drive ~$20k
  - By 2022: 20 TB HDD disk $300; 5 disk RAID drive $500
- FPGA’s become very inexpensive
  - In 2010 VIRTEX-5 board $>10k
  - By 2020 VERITEX-5 board on ebay ~$1500
  - Now have very cheap correlators built on commercial electronics
- GPU/multicore computing gets really inexpensive
  - In 2010 80 core CPU , GHZ clock ~ 500k+
  - By 2025 80 core CPU/GPU , multi- GHZ clock $40k.
  - Real-time/near real-time two-telescope correlations



http://www.cta-observatory.org/

Towards the Future 2025+

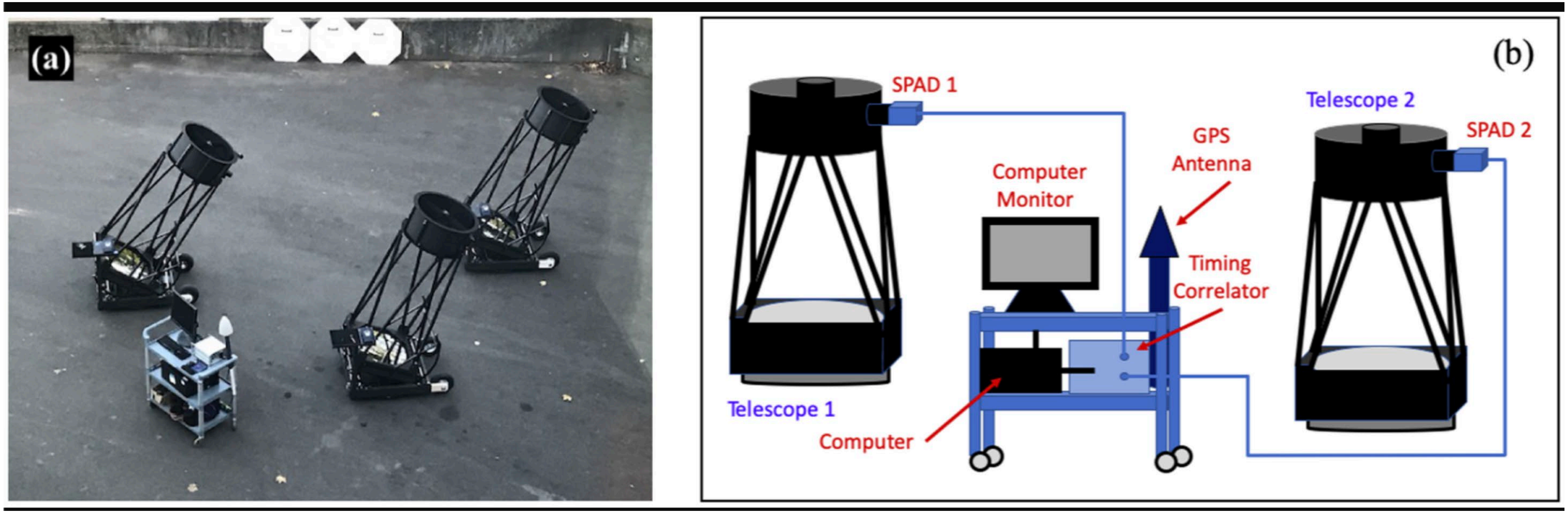
See Upcoming talks by
J. Biteau & L. Zampieri



IACT SII Technique Summary

- IACT SII has demonstrated high angular resolution observations (0.4-2.0 mas) at short optical wavelengths (~400 nm)
- Potential to provide higher contrast for hot stars (O, B, A)
- 3 IACT SII arrays now in regular operation
- ~2000 hours of observing experience so far
- Typical radius resolution (5 hours, m_V ~ 2.0) < 3-4 %.
  - <1-2% looks feasible
  - Approaching ability to measure stellar limb darkening
  - 2-D envelope and binary/multi star sensitivity demonstrated by VSII
- Data has significantly improved during last 2 years
  - Better S/N, better visibility curve fits
  - Improvements in data reduction and analysis
  - Baselines ranges demonstrated: 10 -150+ m
- Demonstrated 2-Telescope correlations down to m_V ~ 4.0
  - Bright sky limiting mag m_V ~ 6.0 appears justified
  - Dark sky observations may extend further (m_V ~ 9.0?)
  - Larger arrays -> Visible band imaging

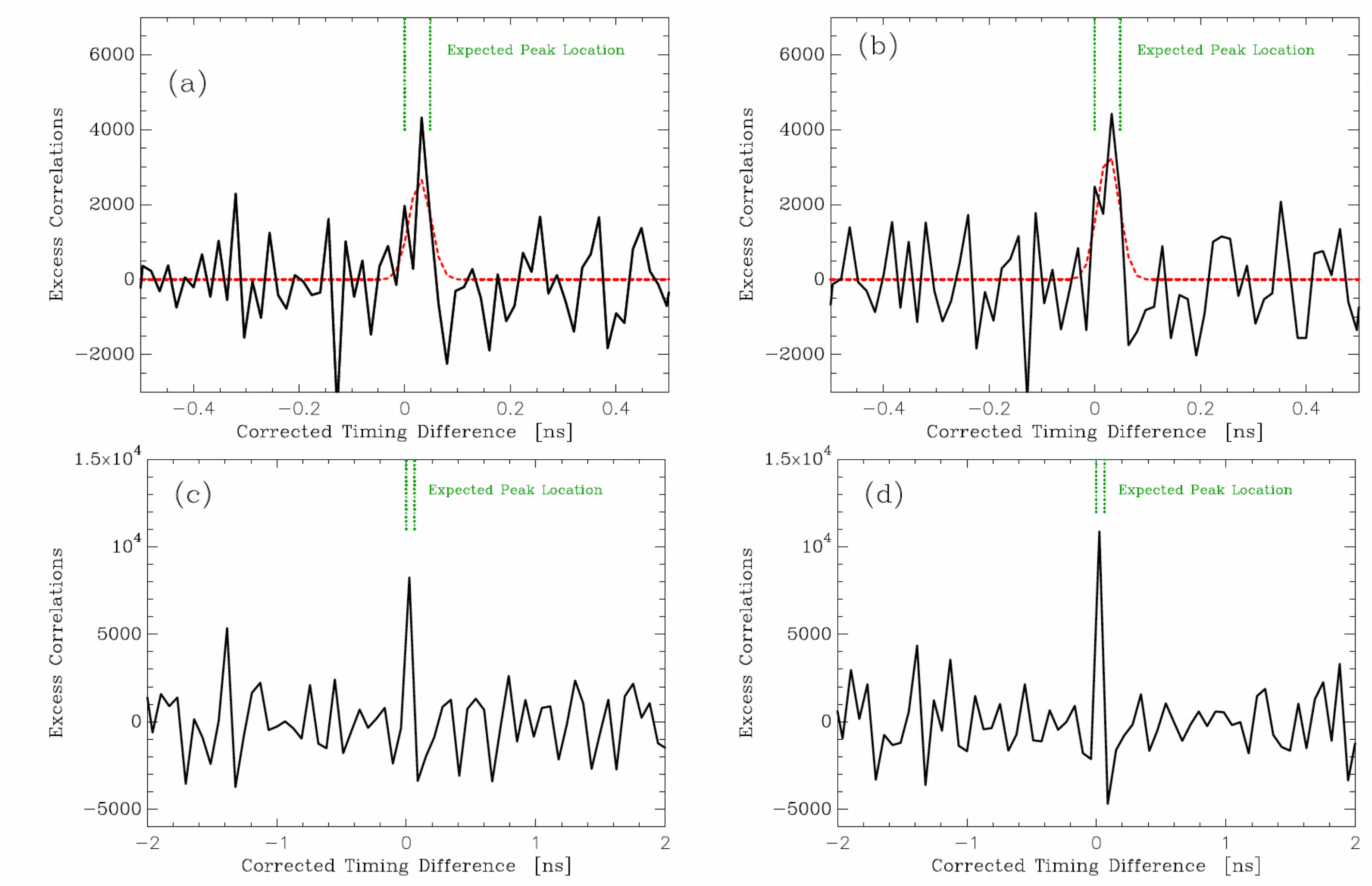
Other non-IACT SII observatories



Horch 2022

Southern Connecticut State College SII array using movable Dobsonian telescopes

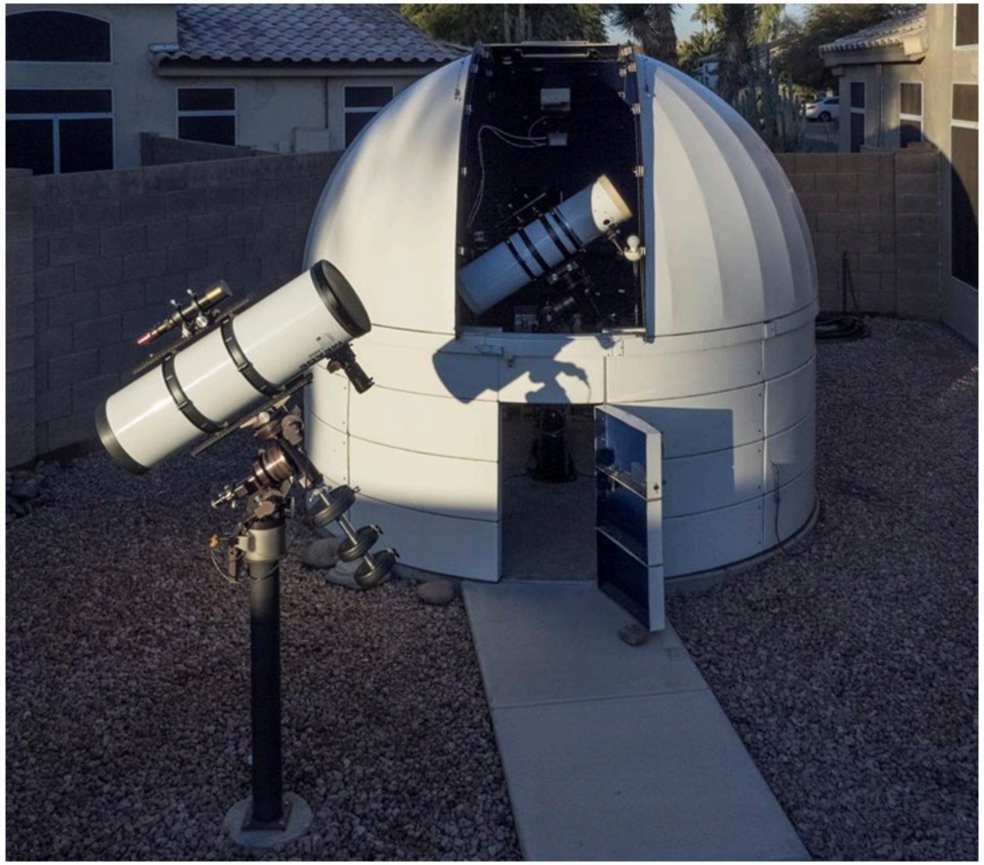
Other non-IACT SII observatories



Horch 2022

Detected 2-telescope Correlation on multiple Stars (Deneb, Arcturus, Vega)

Other non-IACT SII observatories



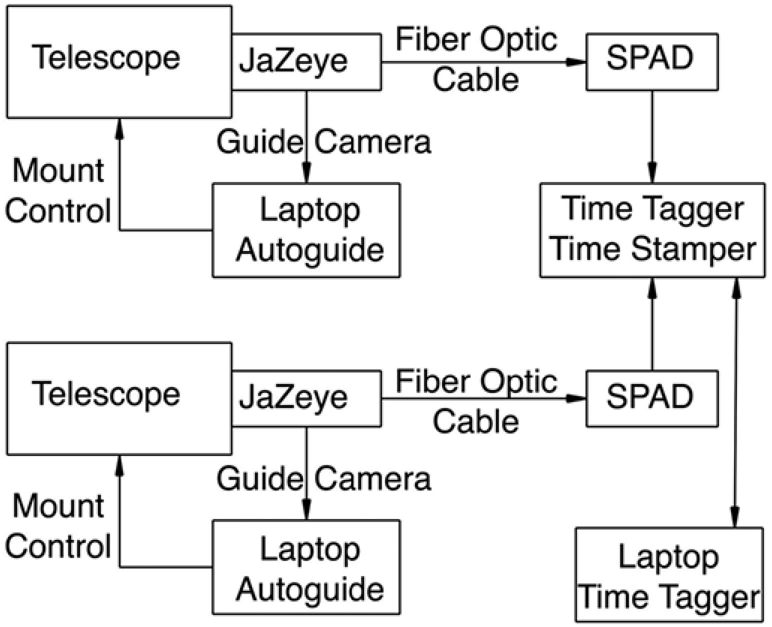
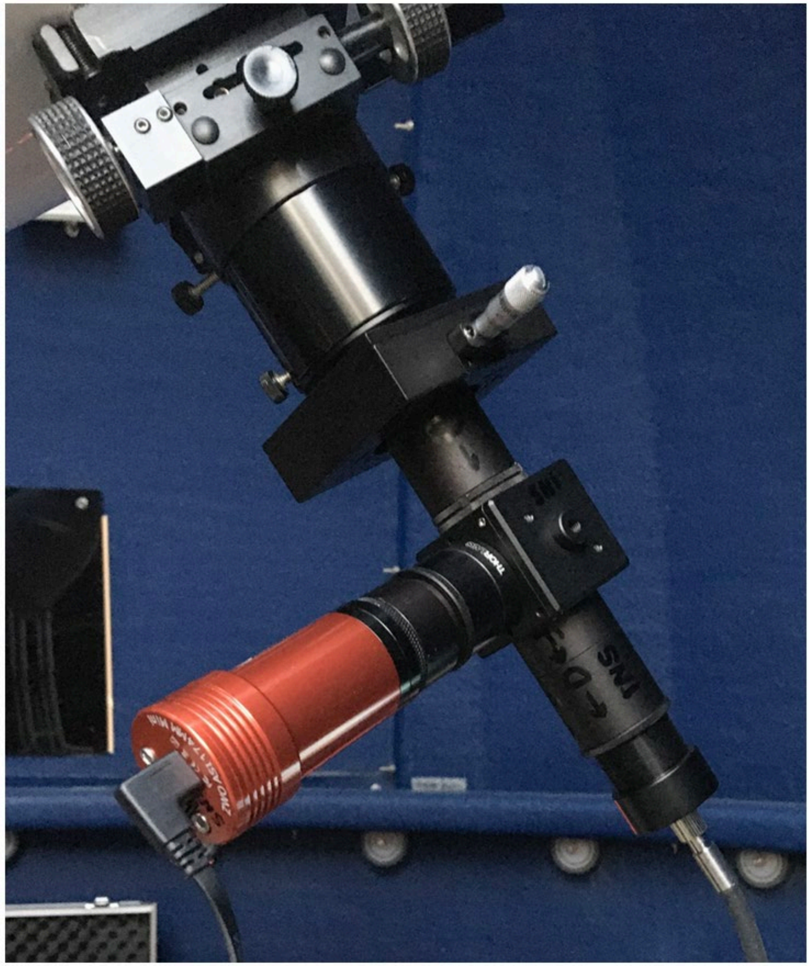
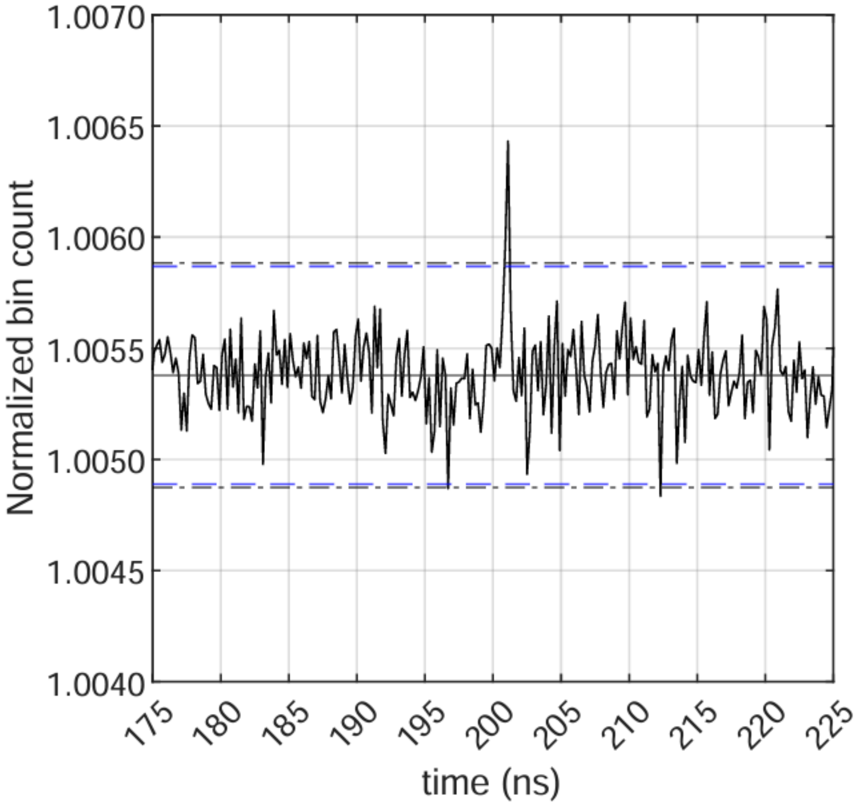


Figure 1. Block diagram of the two telescope intensity interferometer.

Mozdzen 2024
Using high time resolution SPAD detector on
Small commercially available astronomical telescopes

Other non-IACT SII observatories

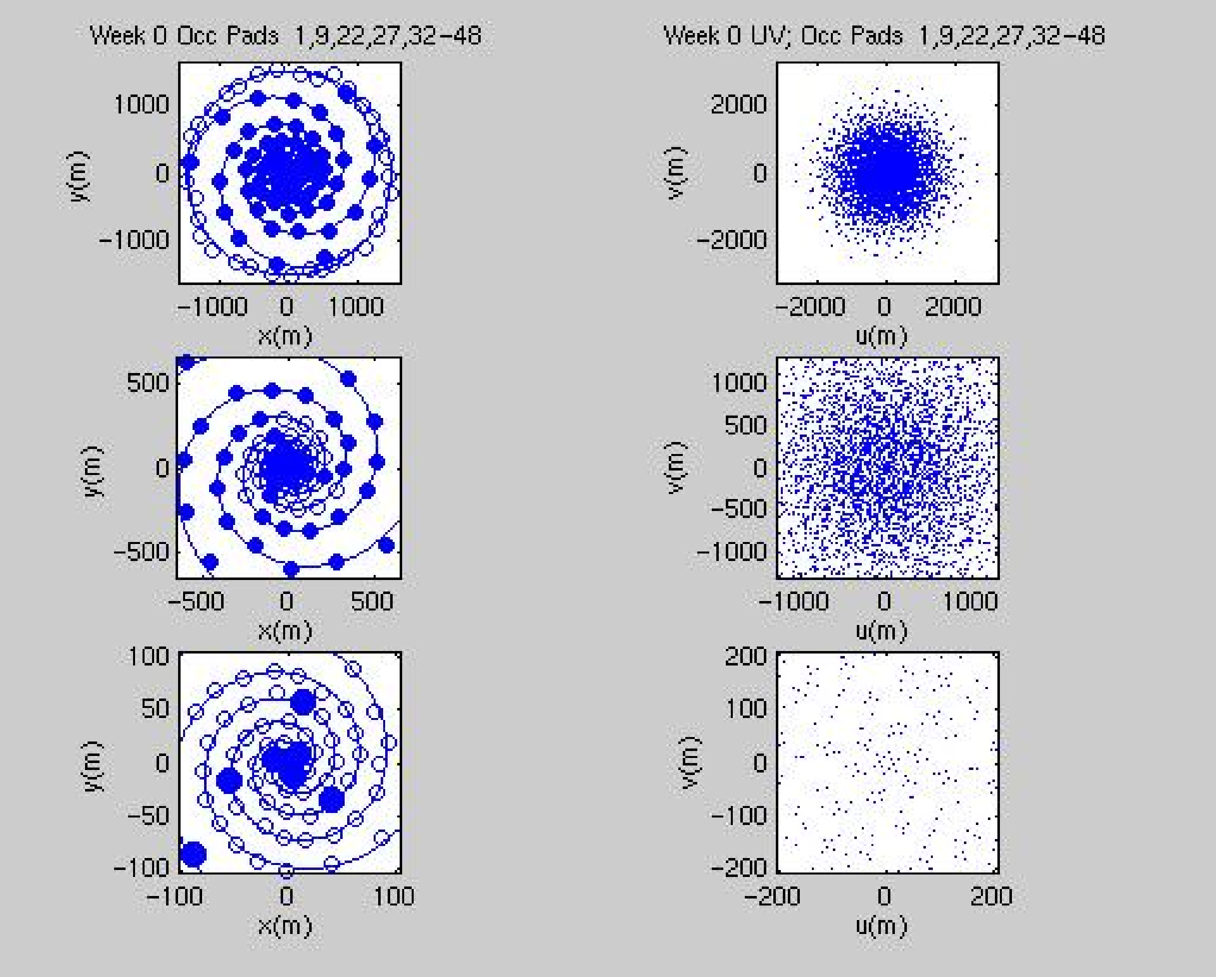




Mozdzen 2024

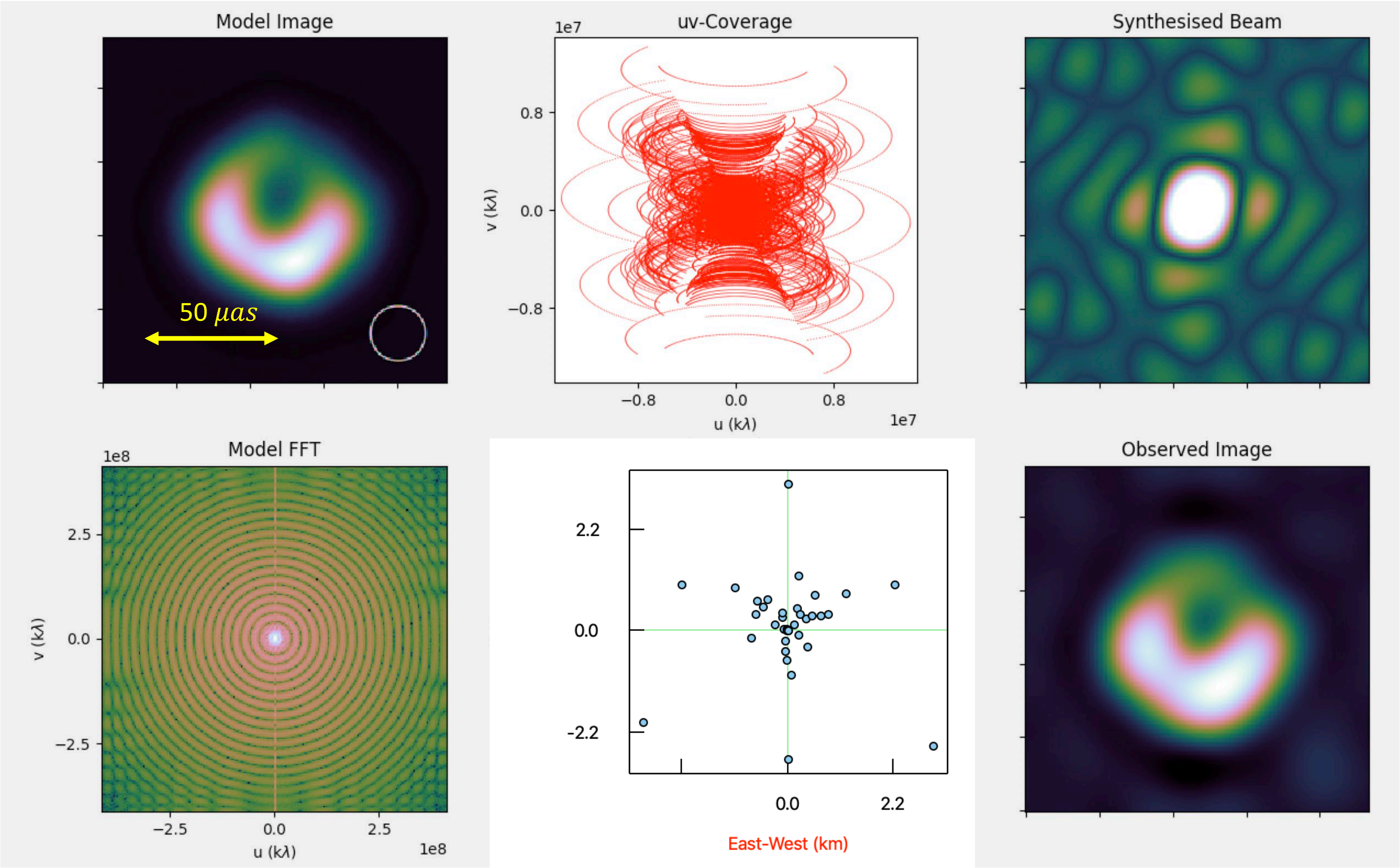
Detected 2-telescope
Correlation on Sirius

Reconfigurable Interferometric Array (ALMA)



- Digital (Offline) Fiber Optic Interferometry: up to 80 km baselines
- ALMA-Like array of interferometric telescopes in visible band
- Telescope observing customized to desired angular resolution

ASKAP–type configuration
SII Synthetic Image Reconstruction



Simulated
8 hours SII
Observation

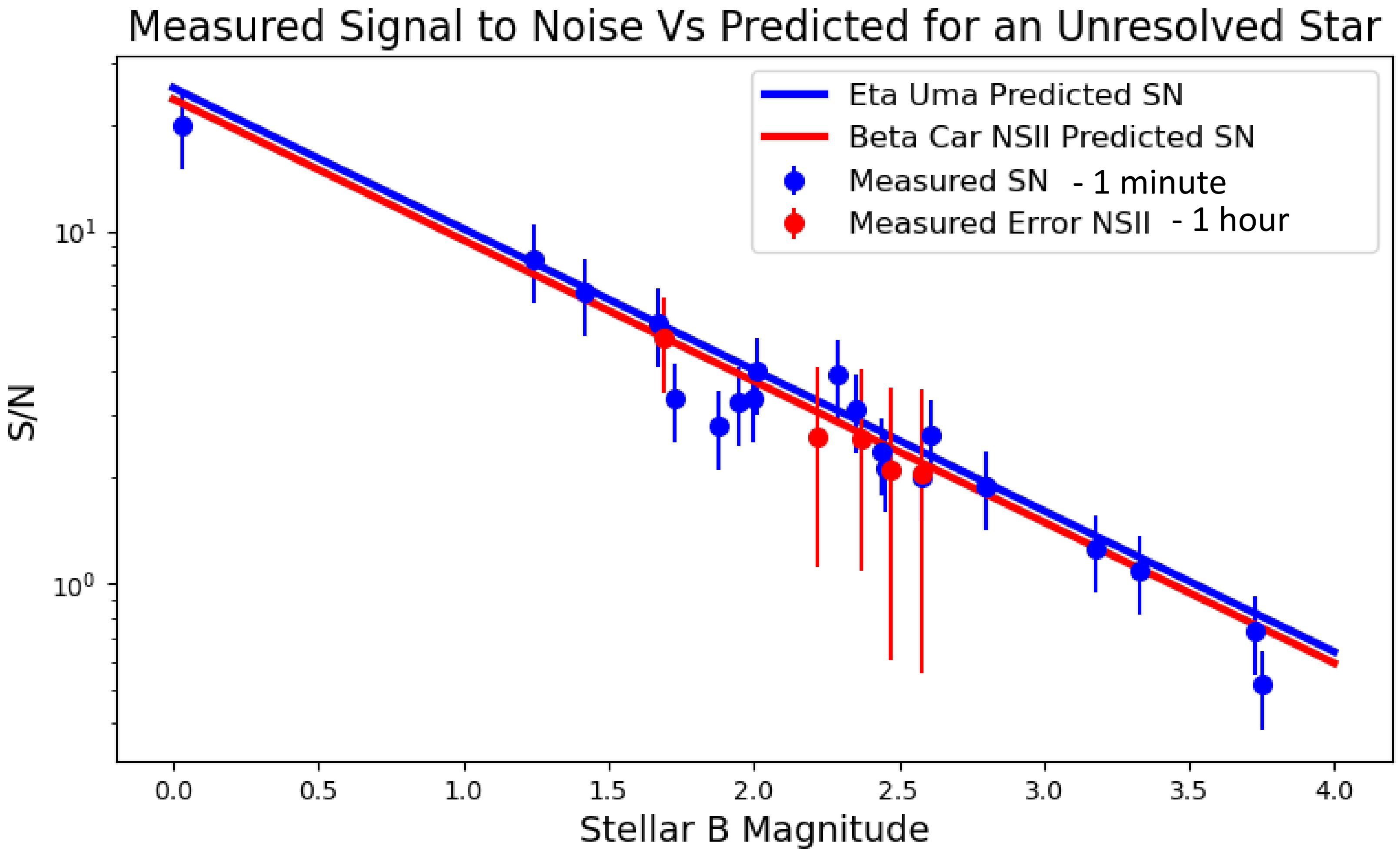
ASKAP Full_36
Telescope
configuration

420 nm

Only includes
FFT Sampling
effects

D. Kieda, *Friendly Stellar Intensity Interferometer:* A modification of the
Friendly Virtual Radio Interferometer: https://crpurcell.github.io/friendlyVRI/

VERITAS SII sensitivity v. Narrabri SII



VSII 1 minute sensitivity better than 1 hour NSII

Correlations detectable Down to $m_V = +3.75$

Extrapolated limiting Mag $m_V = +5$

Improvements can push down further ($m_V = +7?$)

J Davis, MS Thesis Cornell U. (2022)