

VERITAS SII OBA Star Survey & 2026-2028



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VERITAS Collaboration: VSII working group

2026 Workshop
La Palma, Canary
Islands
10/6/2026

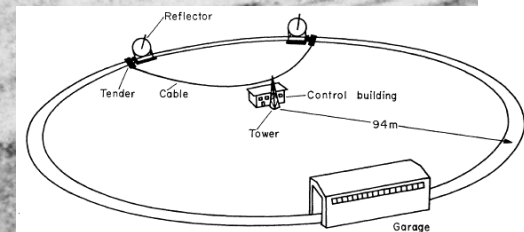
Stellar Intensity interferometry (SII) ... 1956-1971

The Past

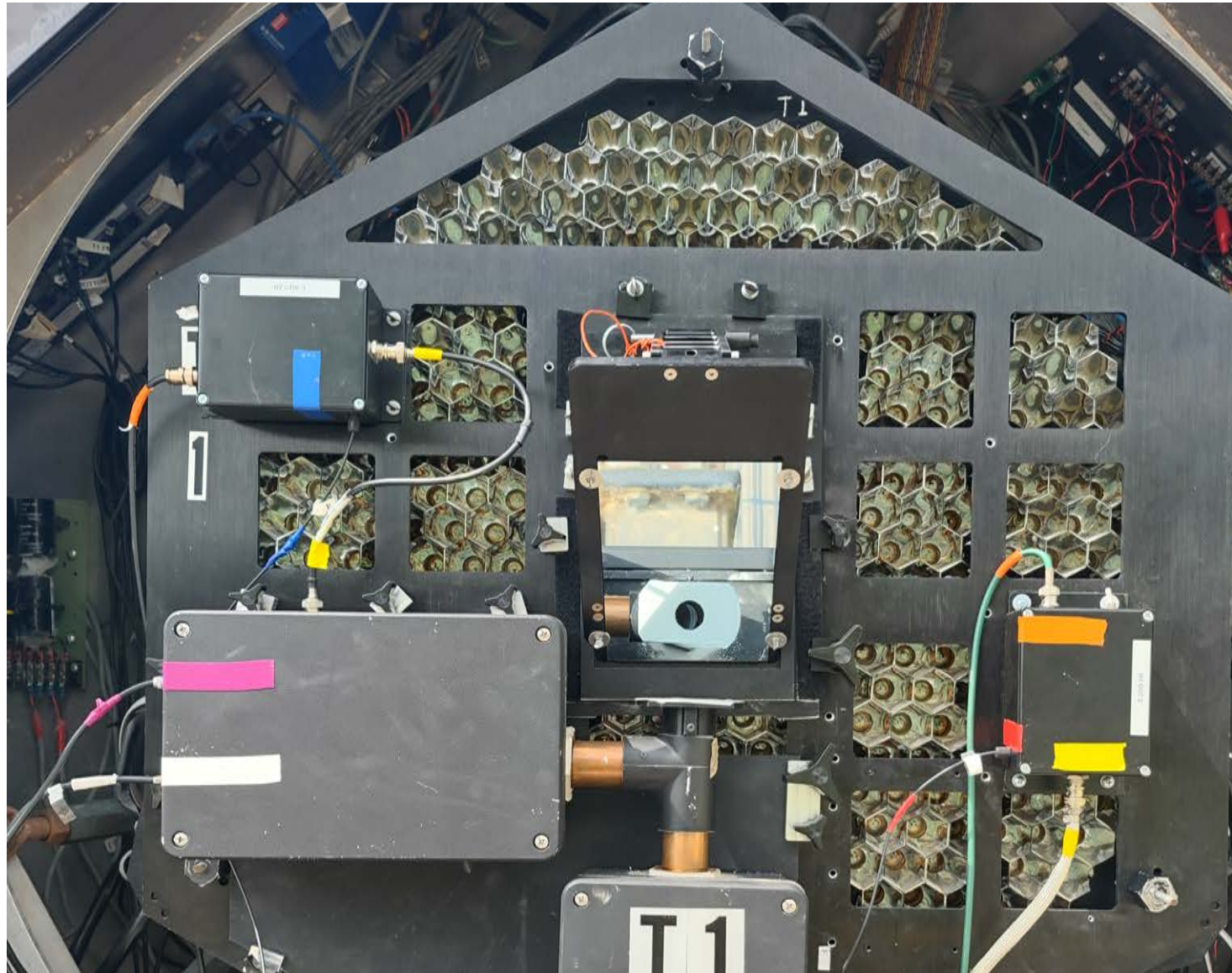


Narrabri observatory
with its circular railway track

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



VSII Retrospective 2019-2026



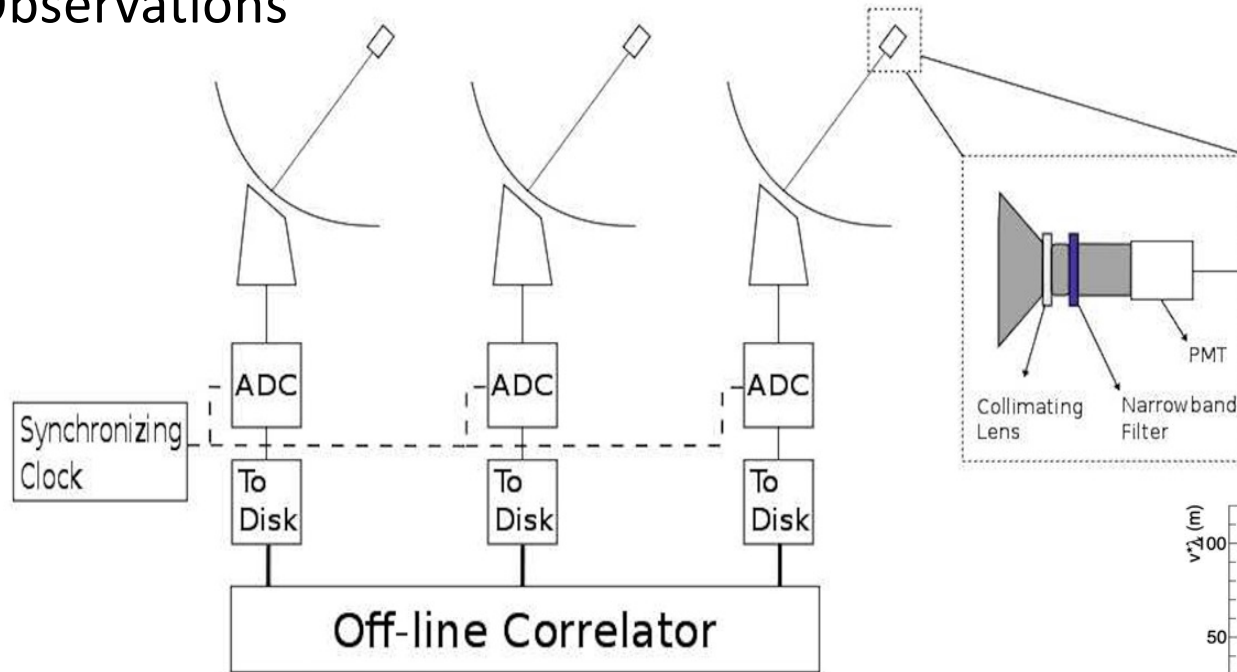
VERITAS-SII (VSII)



- Excellent instrument for SII
- Large photon collection area (~ 12 m $\varnothing$ 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***

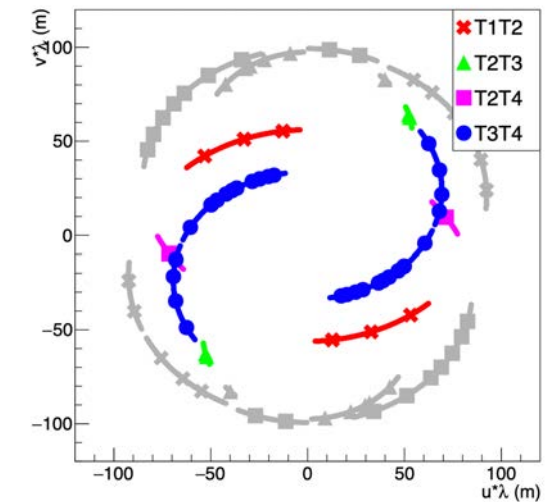
VSII Observations



$$\frac{\langle I_A I_B \rangle}{\langle I_A \rangle \langle I_B \rangle} = g^{(2)}(u, v, t) = 1 + |g^{(1)}(u, v, t)|^2$$

$$g^{(1)}(u, v, 0) = \iint I(l, m) e^{-2\pi i(lu + mv)} dl dm$$

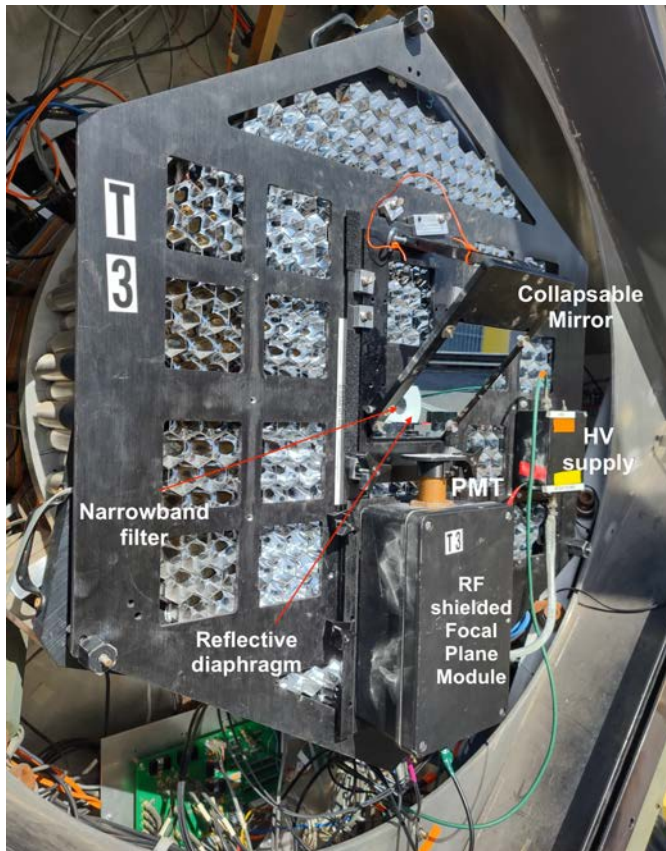
$I(l, m)$ is the stellar image size and brightness distribution on the sky



VSII Sampling of Fourier Image Plane

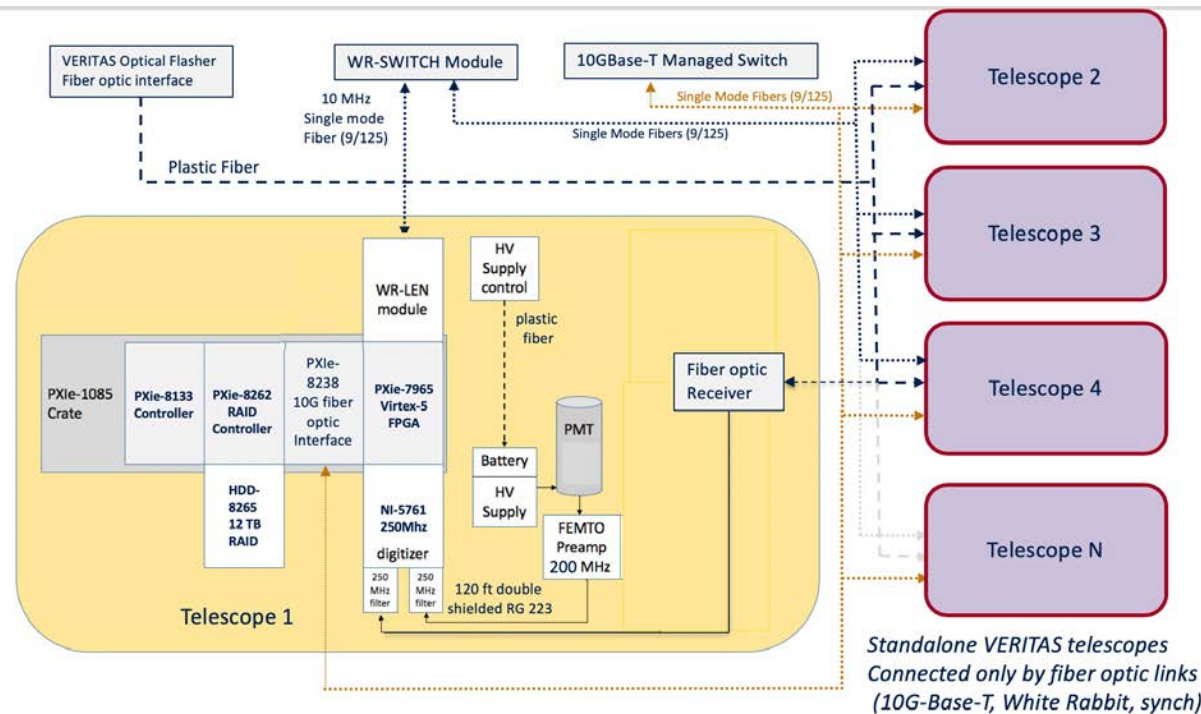


Removable SII Camera Plates



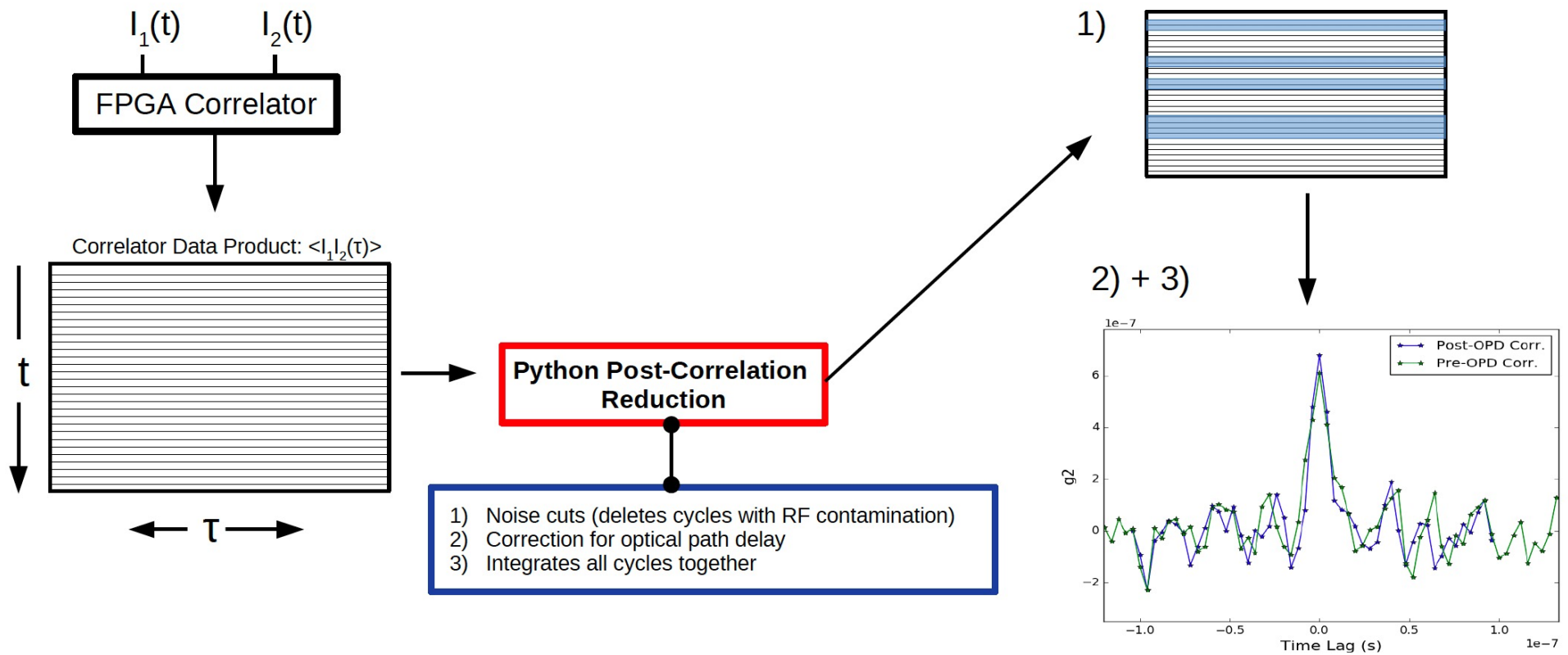
- The removable SII Camera Plate mounts in front of the VERITAS Camera focal plane.
- Observer locates the SII Plate onto each camera at beginning of full-moon period.
- Plate contains necessary focal plane optics, HV supply, photomultiplier and preamplifiers to perform SII measurements.
- Quick connect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

VERITAS SII DACQ system (2018-2026)



- Each telescope records data independently
- White Rabbit Synchronization of clocks at each telescope (Single mode fiber)
- 10G data transport network allows cross mounting of disk
- Correlations computed offline /next day

FPGA-based Data Reduction



Versii – dedicated correlator server

Funded by NSF MRI



DELL PowerEdge 750 Server
RedHat Enterprise Linux 8

Two Intel Xeon Platinum 2.3 GHz CPUs

- 40 cores (hyperthreaded) *each* – **80 cores total**

GPU-ready; single Nvidia Tesla T4 for prototyping

6 Gbps SATA SSDs

- 2 x 480 GB
- 10 x 3.84 TB in 2 x RAID-0

On-site power & cooling upgraded

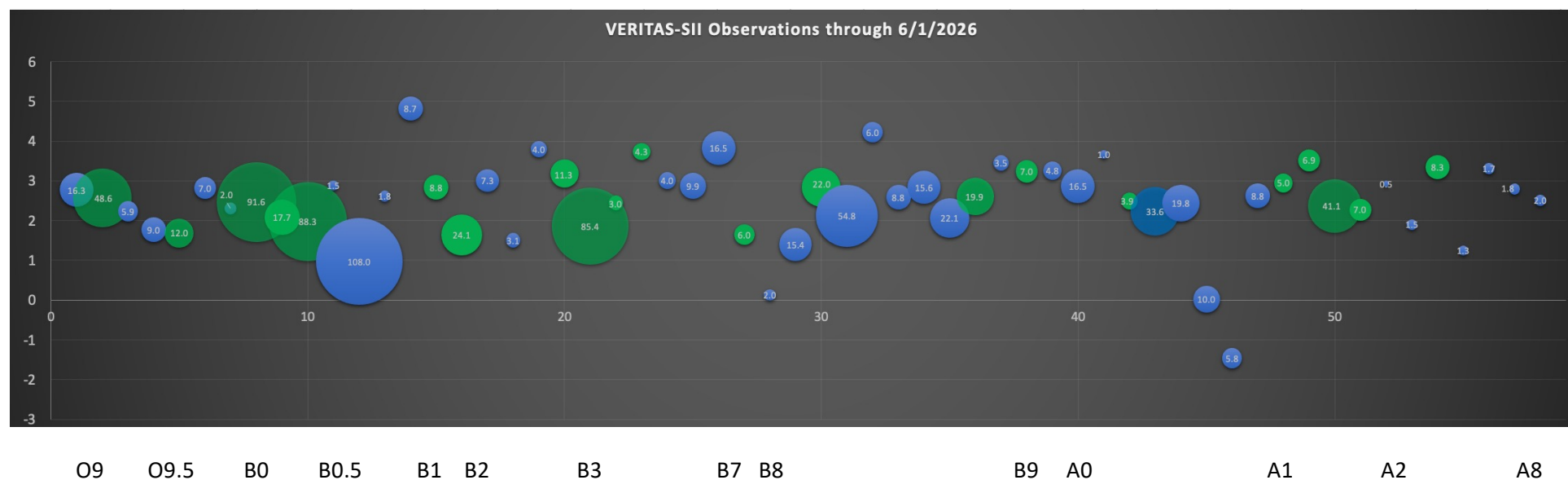


VSII Observations (2021-present)

The VSII Survey Dataset (through Jun 1, 2026)



m_V

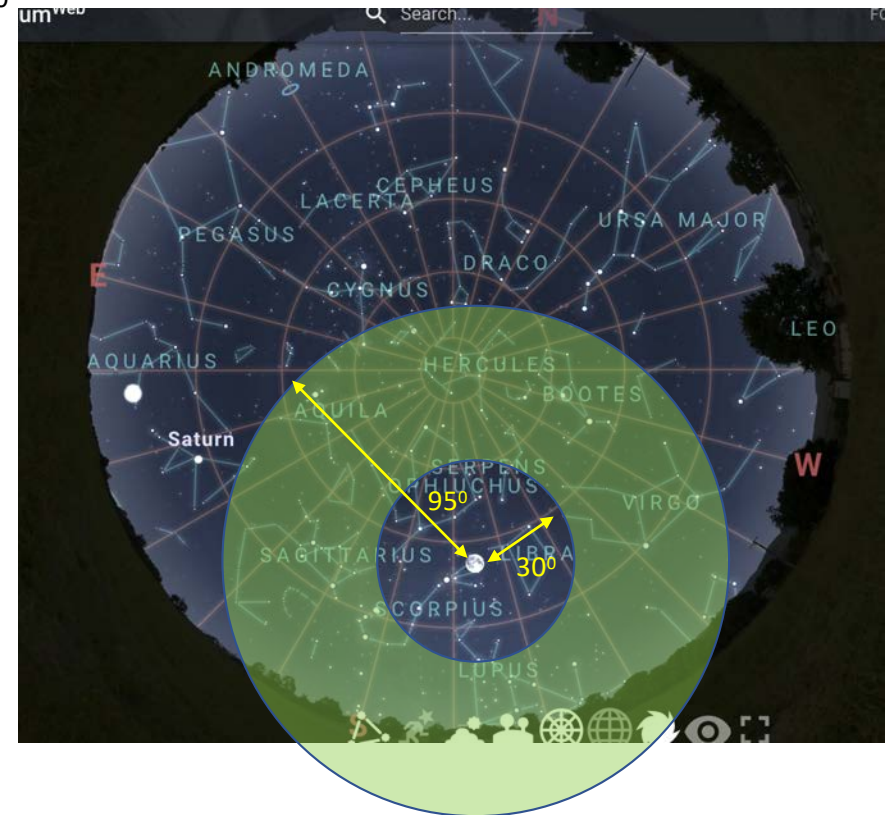


- 58 different targets
- 33 single
- 25 binary/multiple
- Total 964 hrs exposure
- 88 hours 2025-2026 obs season



VSII Survey Observing Strategy

- Moonlight is the main constraint
 - Atmospheric scattering of moonlight for moon angle $< 30^\circ$
 - Direct light on focal plane for moon angle $> 95^\circ$
 - Optimal sky darkness : moon angle $\sim 80-90^\circ$
-
- List of observable targets change every night
 - Try to select brightest targets
 - Prefer O, B, then A stars
 - Need at least 1 hour of observation





The VSII dataset

- Almost 1000 hours of SII data (9/2019-present)
- 58 sources (33 single stars, 25 binary/multiple)
- $-1.46 < m_V < +4.82$
- FPGA processed data (to start)
- Independent VERSII Dataset (starting 2022)

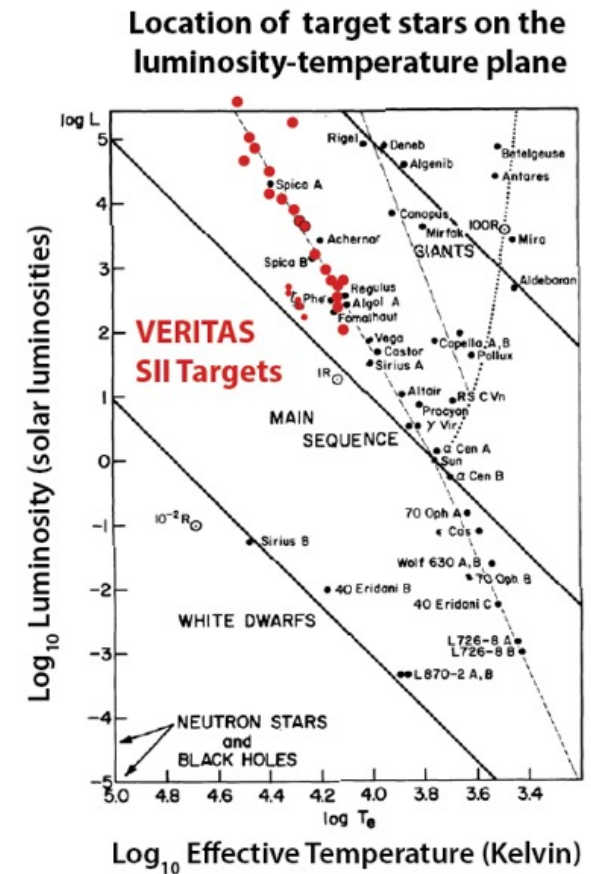


Figure from Iben, *The Astrophysical Journal Supplement Series*, 76:55-114, 1991 May

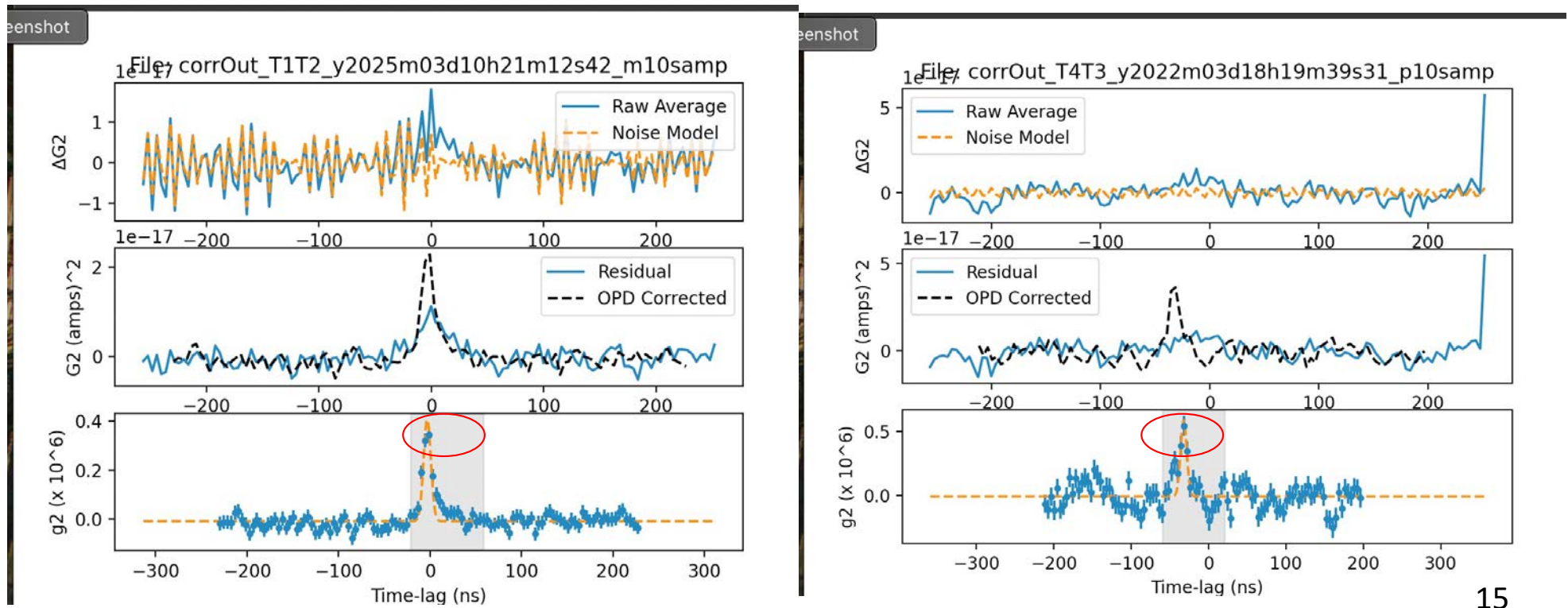


Analysis strategy

- Process each observing run to assess whether a clear peak is seen or not
- Characterize each run according to Signal-to-Noise
 - High- clean, unambiguous peak. Multiple standard deviations above background. Error bar is simple
 - Marginal- likely peak , but signal/noise is 1-3 std devs so needs some TLC to estimate error bar.
 - Low- no clear peak. Might be useful for an upper limit.
- Visual classification of each run (~9,000 manual scans)



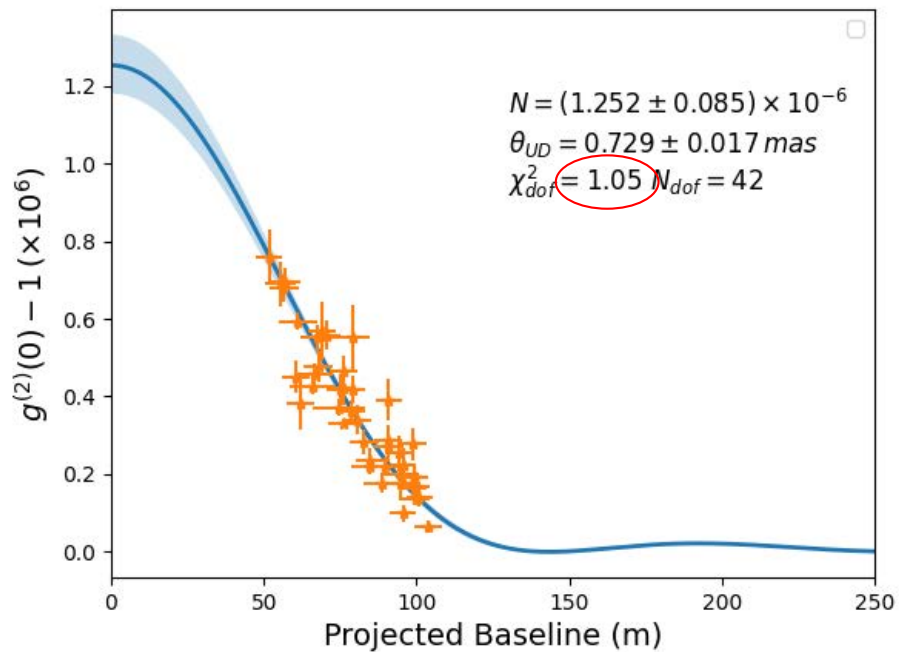
VSII Catalog: High S/N Selection



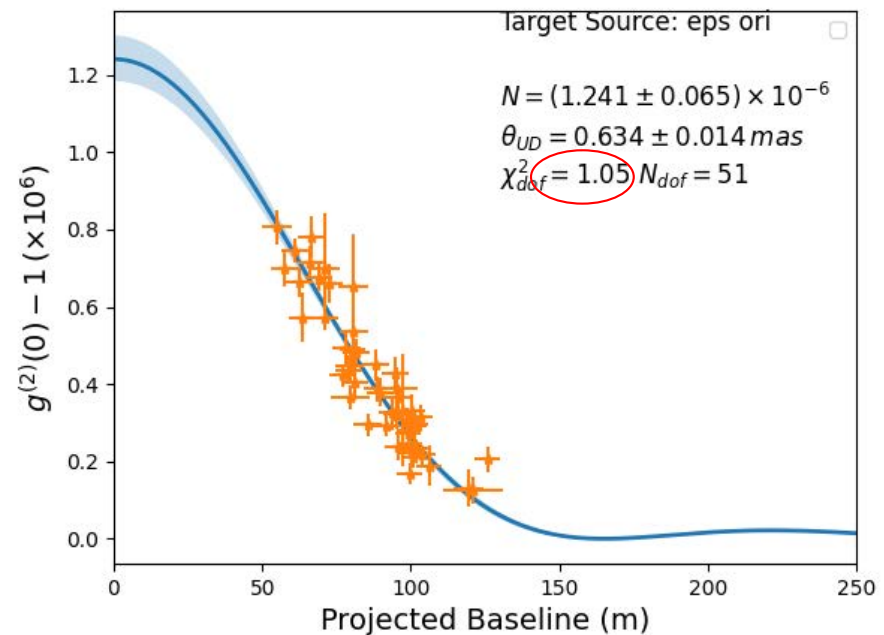
Single Stars (slow rotation)



gam Ori: High S/N

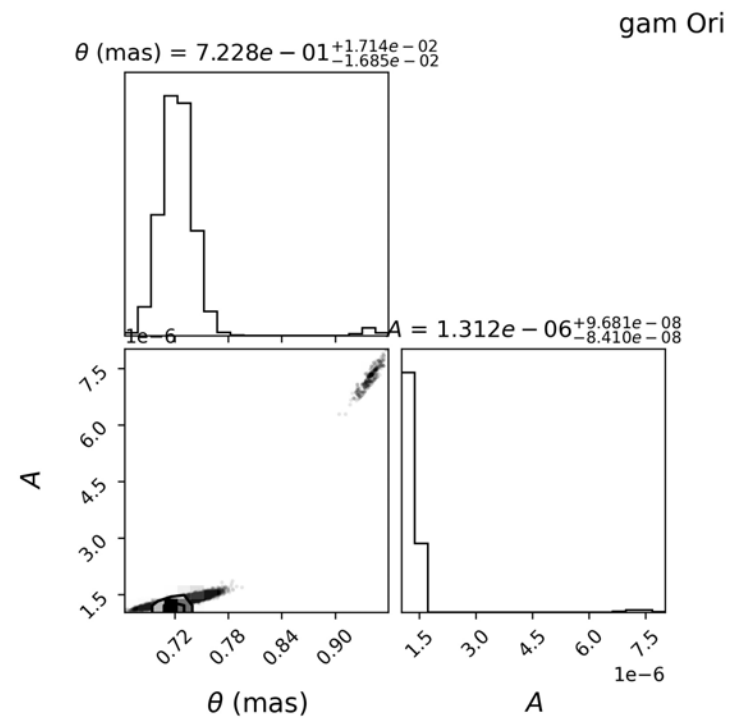
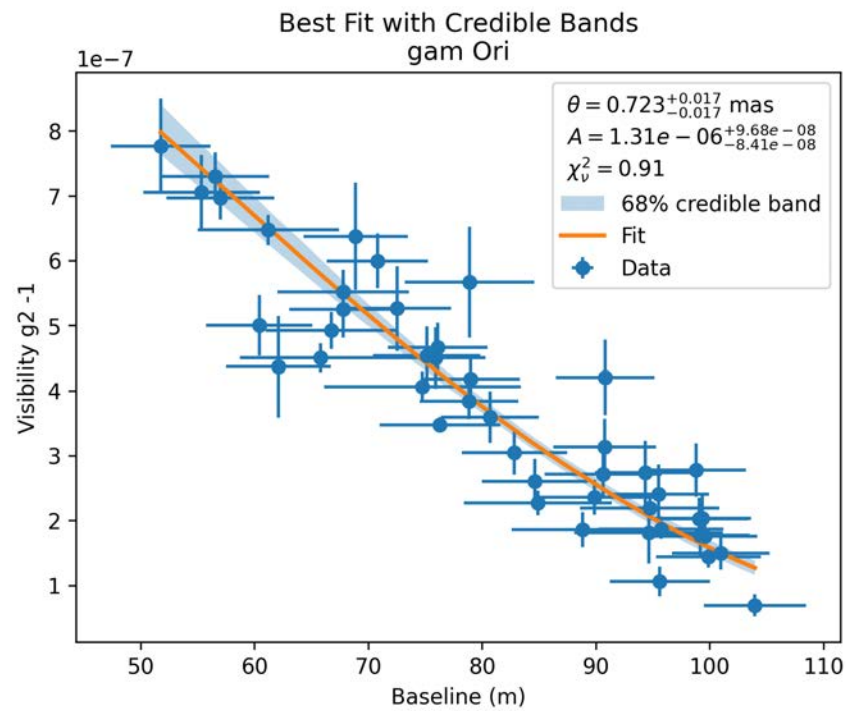


eps Ori: High S/N

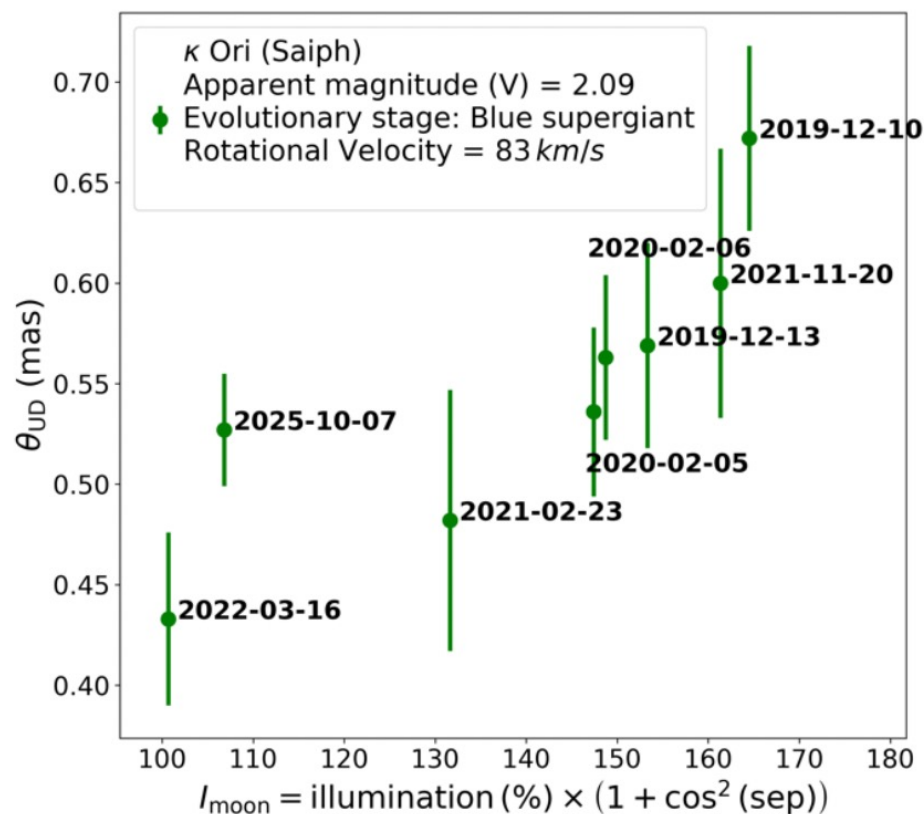




Gam Ori (Bellatrix) : high S/N



Moonlight effects on SII Observations



Observed trend: The fitted angular diameter increases as the Moon becomes brighter and approaches the target.

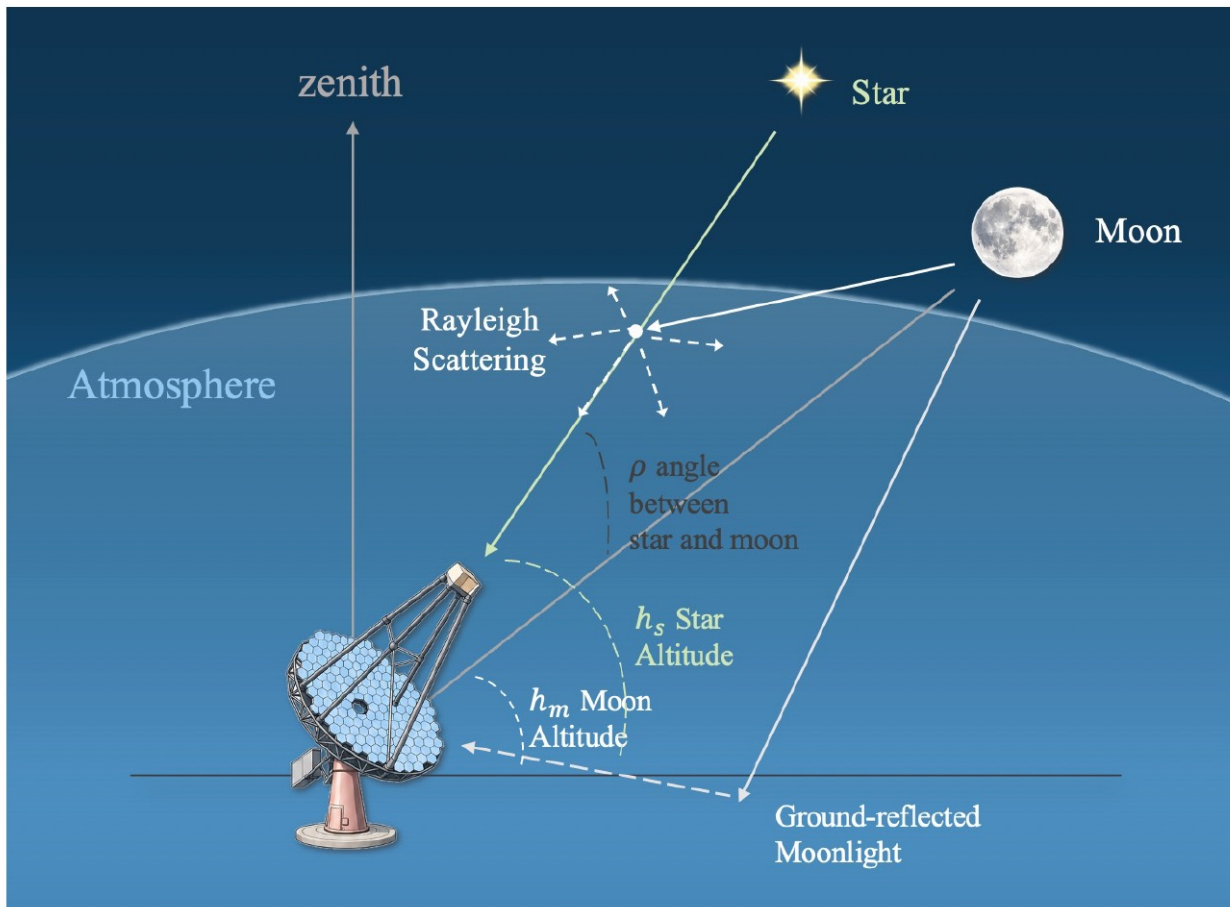
Cause: Uncorrelated moonlight dilutes the stellar intensity correlation and lowers the measured squared visibility.

Bias: Without correction, the inferred angular diameter is biased.

$$\Delta g_{\text{obs}}^{(2)} = \frac{\Delta g_{\text{star}}^{(2)}}{(1 + m_1)(1 + m_2)}$$

$$m_i = \frac{I_{\text{bkg},i}}{I_{\text{star},i}}, \quad \Delta g^{(2)} \equiv g^{(2)} - 1$$

Moonlight Correction Model



Included effects:

(1) Lunar flux after atmospheric attenuation

$$F_{M,B}^* = 10^{4.724 - 0.0104\alpha - 1.6 \times 10^{-9}\alpha}$$

$$F_{obs,B} = F_B^* 10^{-0.4kX_{ext}}$$

(2) Rayleigh-scattered moonlight:

$$B_{M,V} = f_R(\rho) I_{M,V}^* 10^{-0.4kX_{m,scat}} [1 - 10^{-0.4kX_{s,scat}}]$$

$$f_R(\rho) = 2.27 \times 10^5 (1.06 + \cos^2(\rho))$$

$B_{M,V}$ is converted to B -band flux within camera pixel to obtain $F_{Rayleigh}$

(3) Ground-reflected moonlight:

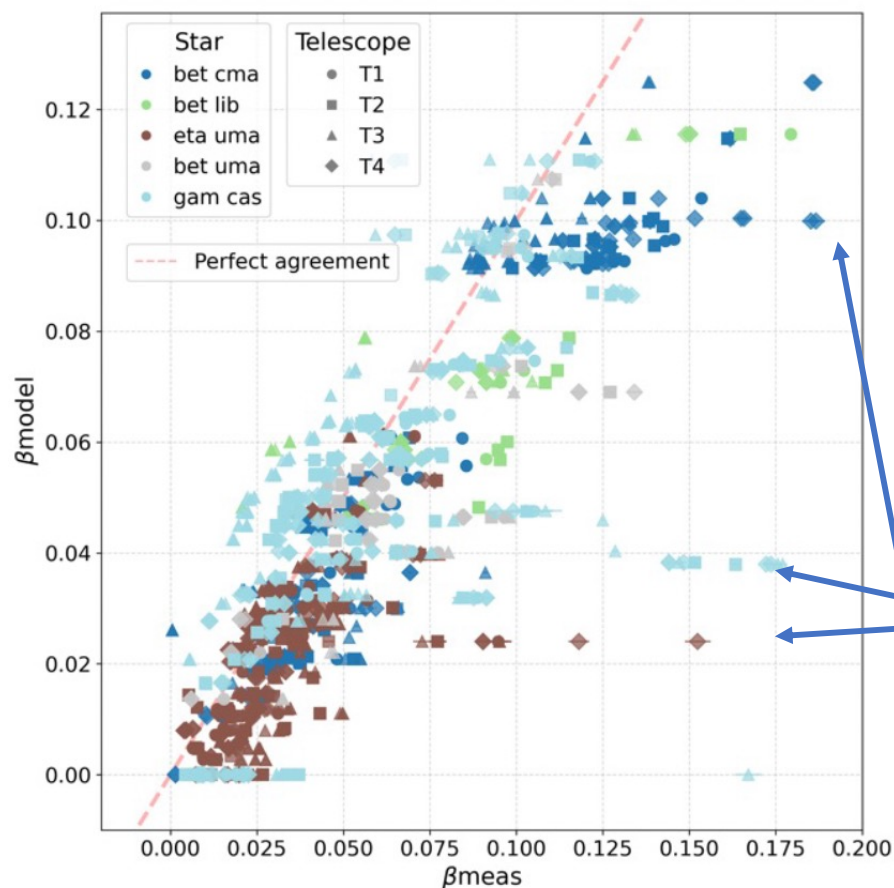
$$F_{ground} = f_g F_{obs,M} \cos(Z_m) \cos(Z_s)$$

(4) Total contamination and correction:

$$m = \frac{I_{bkg}}{I_{star}} = \frac{F_{bkg}}{F_{obs,star,B}} = \frac{F_{Rayleigh} + F_{ground}}{F_{obs,star,B}}$$

$$|V(B)|^2 = \Delta g_{star} = \Delta g_{obs} (1 + m_1)(1 + m_2)$$

Moonlight Model Validation

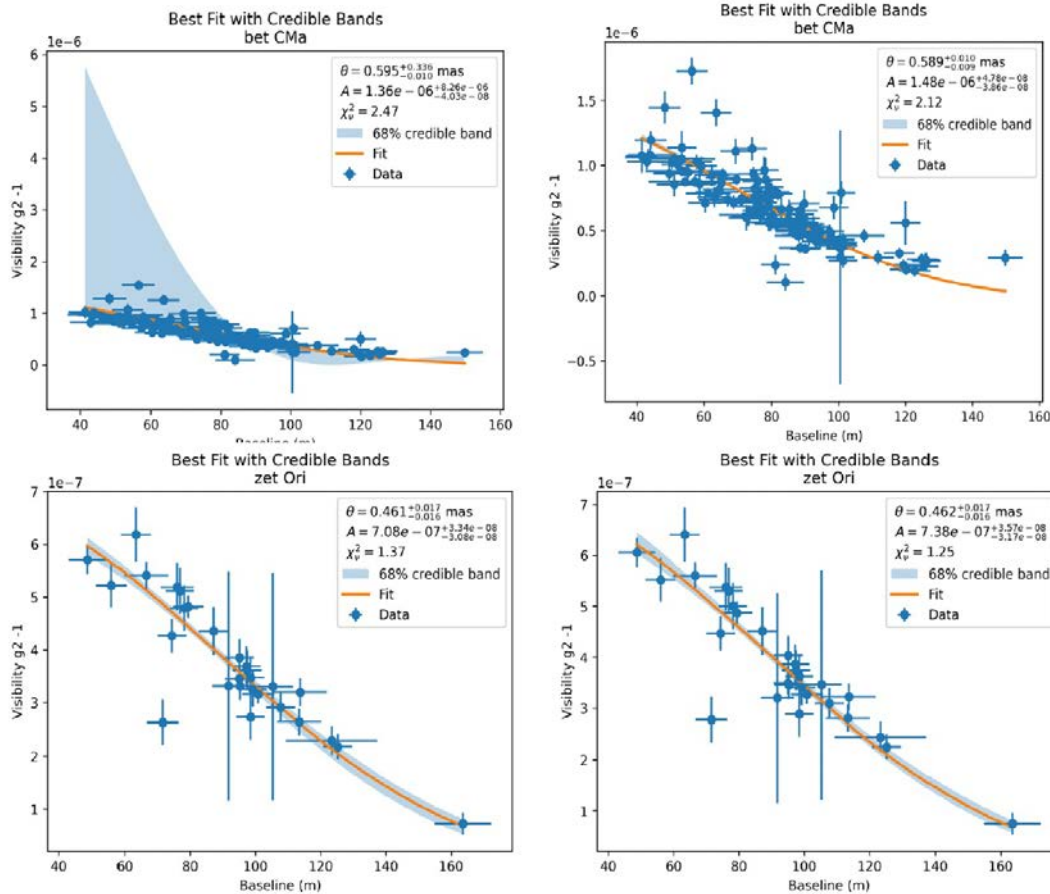


$$\beta_{real} = \frac{I_{off}}{I_{on}} \quad vs. \quad \beta_{model} = \frac{m}{1+m}$$

Allows measurement for the ground scattering factor F_{ground} for each telescope (each telescope is different)

Stragglers on single observing nights-----clouds scattering?

Effects on Angular Diameter Measurements



target	Correction	$\theta(mas)$	A	χ^2_ν
β Cma	before	$0.595^{+0.336}_{-0.010}$	1.36×10^{-6}	2.47
	after	$0.589^{+0.010}_{-0.009}$	1.48×10^{-6}	2.12
ζ Ori	before	$0.461^{+0.017}_{-0.016}$	0.708×10^{-6}	1.37
	after	$0.462^{+0.017}_{-0.016}$	0.738×10^{-6}	1.25

Generally improves quality of fit

Some effect on the angular diameter in certain observations

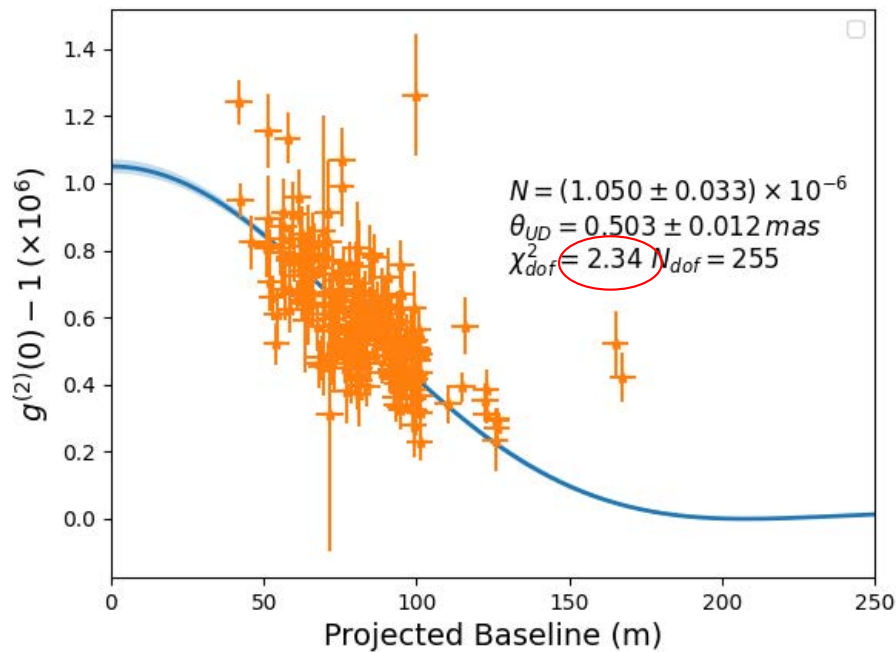
Depends upon specific observing details

- Stellar brightness m_V
- moon phase
- moon elevation
- Angle to moon, etc



Single Stars (rapid rotators)

gam Cas: High S/N



*Quantitatively different than slow rotator curve.....

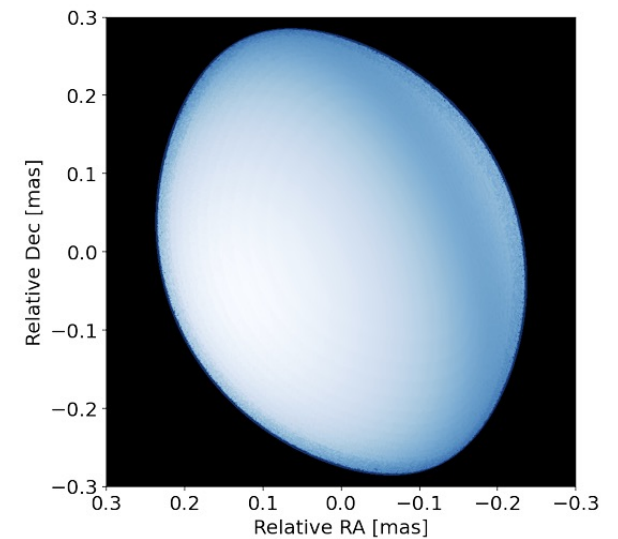
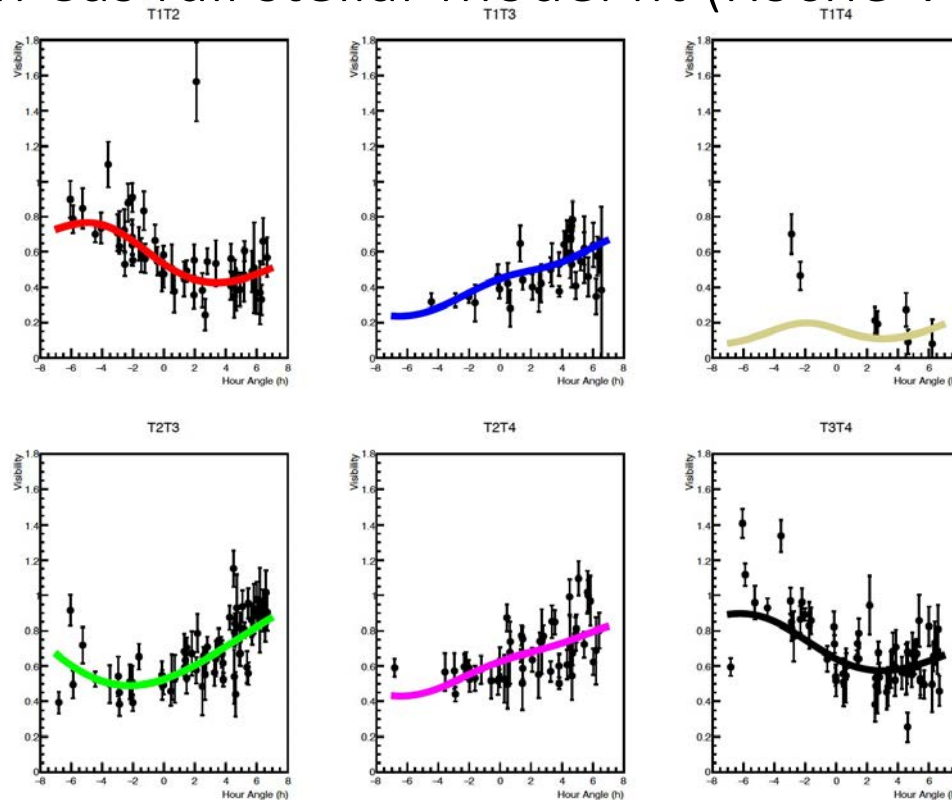


- $13 M_{\odot}$ B0.5Ive Star, $T = 25,000 \text{ K}$
- Prominent Variable star ($V = 1.6-3.0$), average $V = 2.47$
- 168 pc distant, multiple star system ($T_{Aa} = 203 \text{ d}$; $T_{Ac} = 60 \text{ yr}$)
- Radiation illuminates nearby gas clouds IC59/IC 63 (1 pc)
- Fast rotator ($v \sin i = 432 \text{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



Single Stars (rapid rotators)

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



$$\theta_{\text{eq}} = 0.60 \text{ mas}$$

$$\Omega/\Omega_{\text{crit}} = 0.9888$$

$$\phi^* = 114^\circ$$

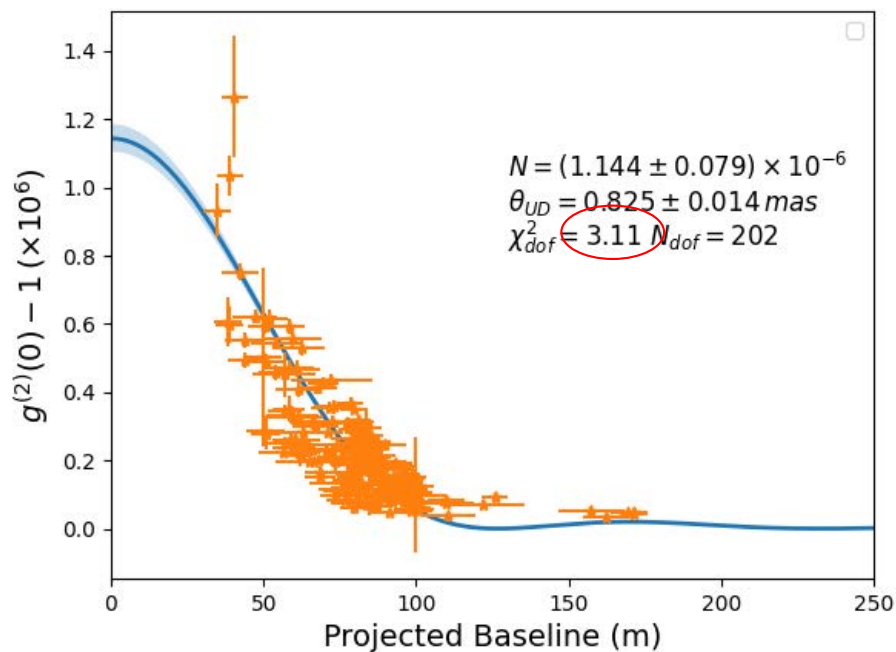
23

Also see Limited VERSII data set results (VERITAS, published in Ap. J 2025)



Binary/ Multiple Star Systems

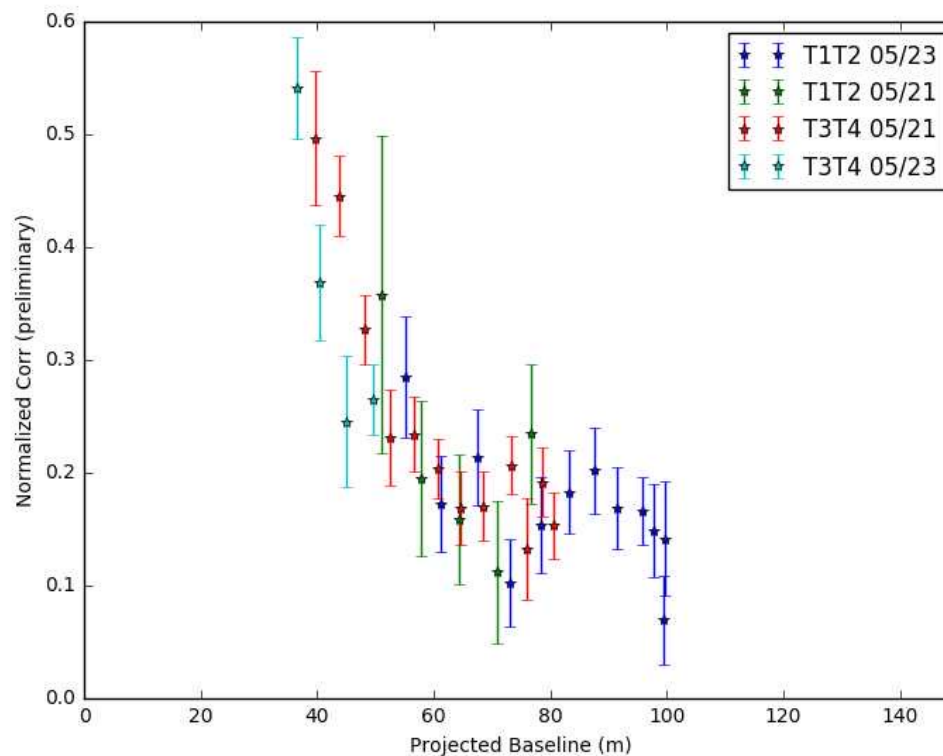
alp Vir: high S/N



- B1III + B2V Star Binary system
- Prominent Variable star ($V = 0.97-1.04$)
- 77 pc distant
- 4.01 day period

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

VERITAS-SII 4 Telescope Observations 'Generic' Binary System (May 21-23, 2019) [Spica]



25 x 20 min 4-telescope observations (over 2 nights)

Preliminary analysis:

'Standard' T2-T3 correlations
(40-70m baselines)

'New' T1-T2 correlation
(40-100m baselines)

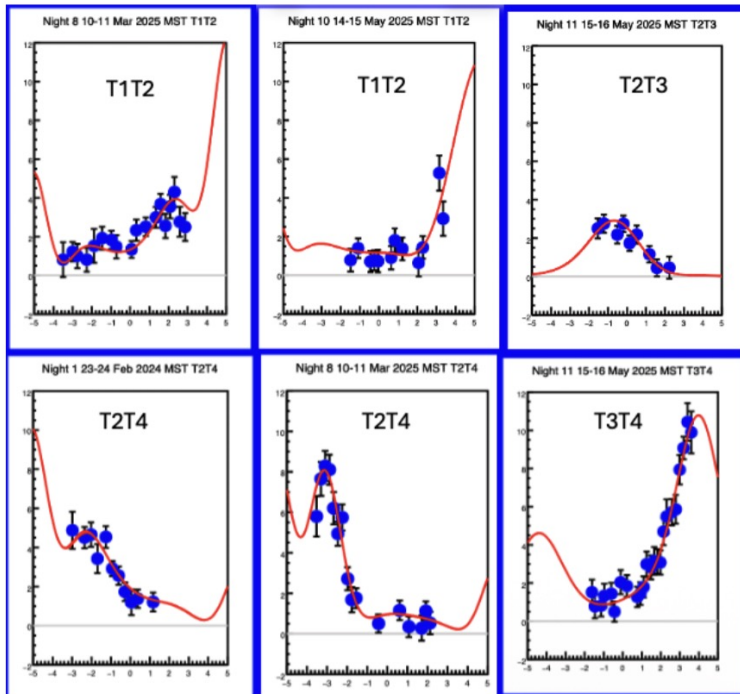
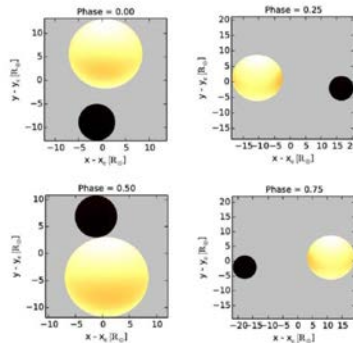
Strong evidence for
secondary interference
peak ~90m (binary system)

T1-T4 correlations: TBD
(120-150 m baselines)

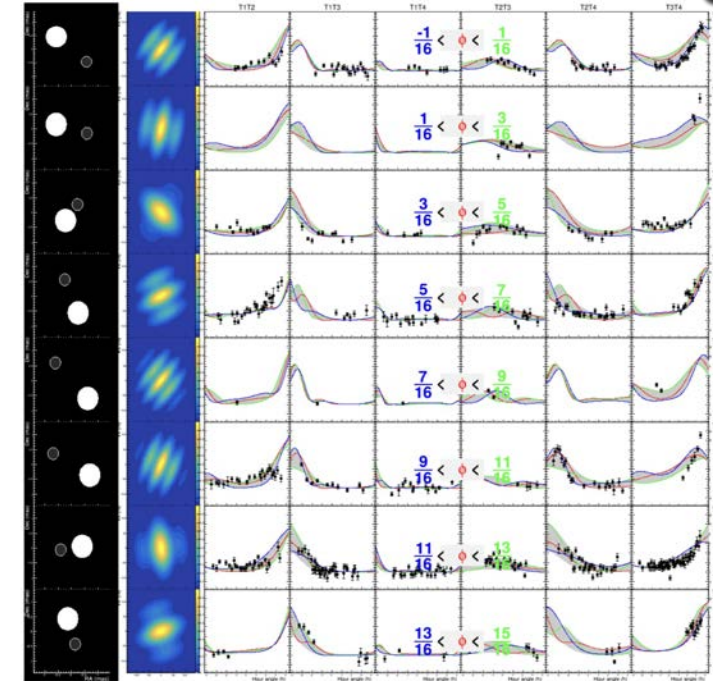
Preliminary look is great!

(caveat emptor...please wait
for a full science analysis)

Binary System measurements of binary alpha Vir (Spica)



Resolving visibility as
a function of both
orbital phase and
observational hour
angle



Use SII + Spectroscopy to fit orbital parameters

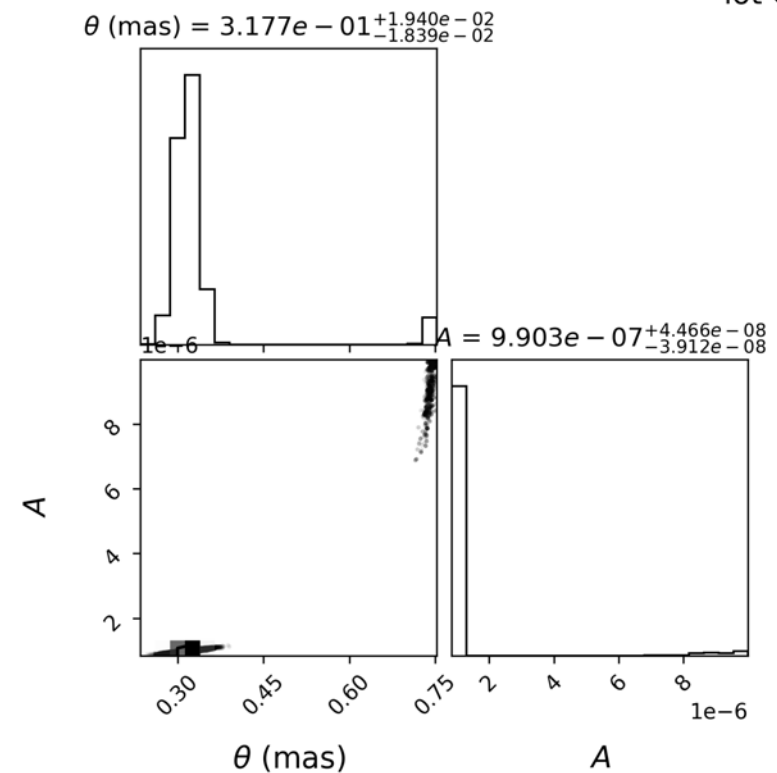
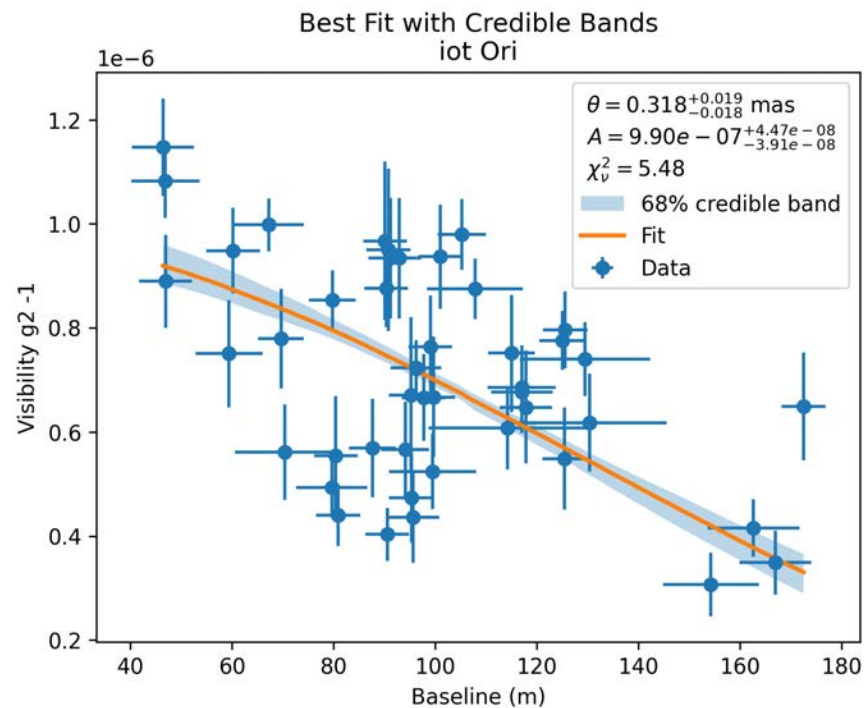
See Mike Lisa's excellent talk on Wednesday!
)



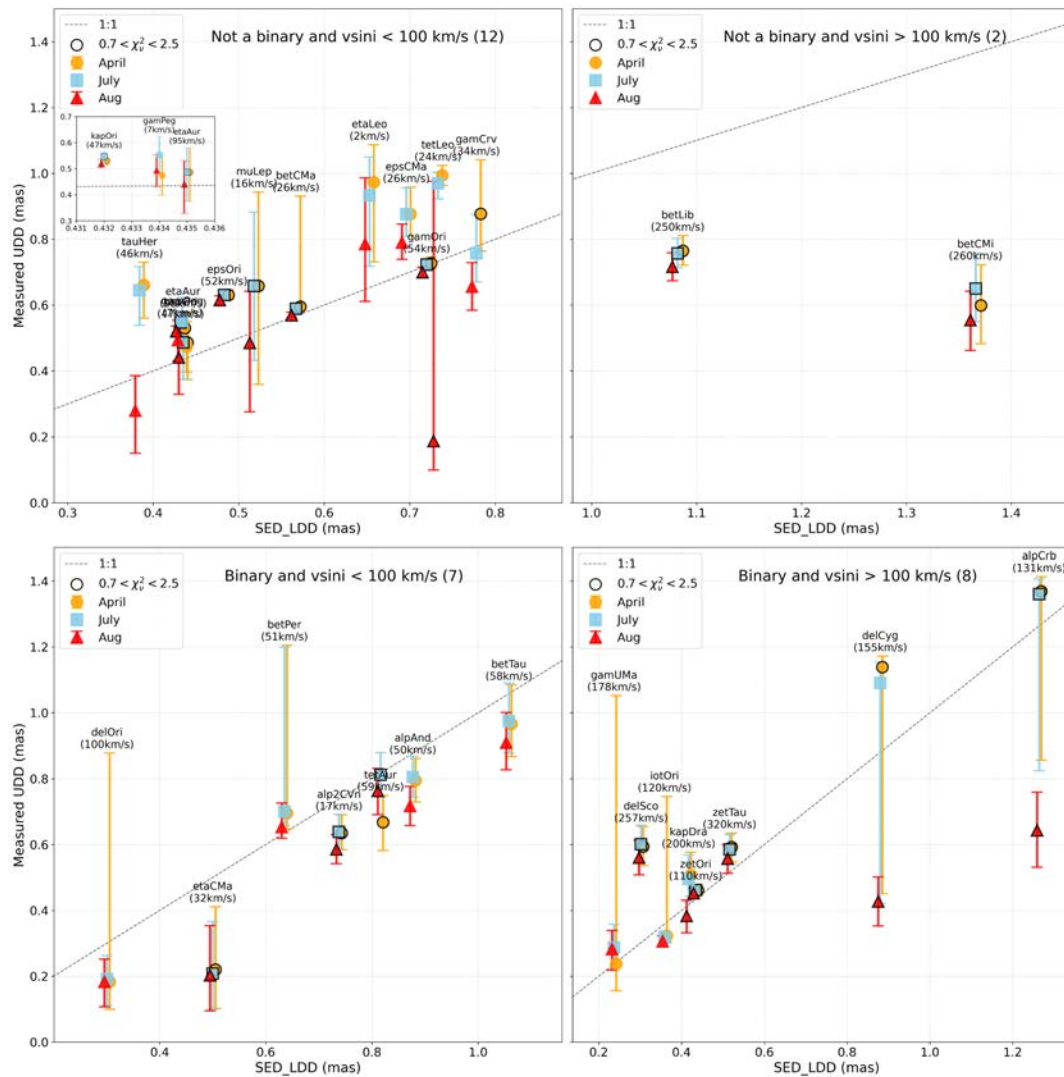
iot Ori (Na'ir al Saif) : another high S/N binary



iot Ori

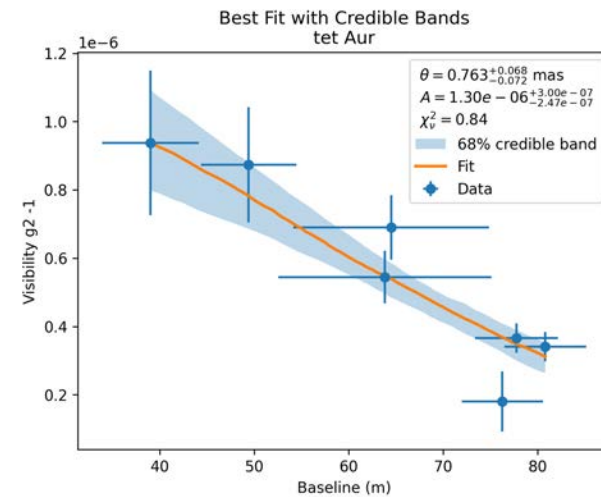
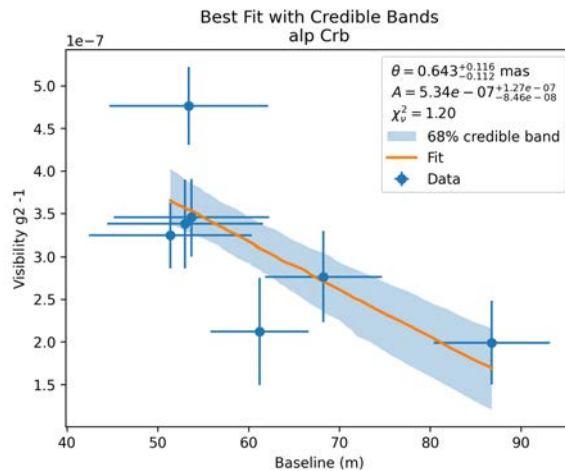
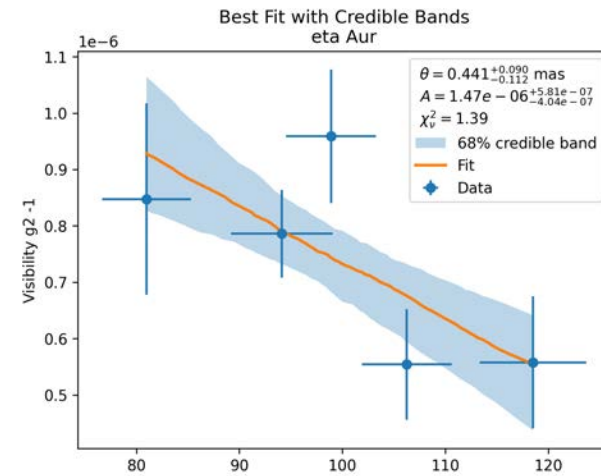
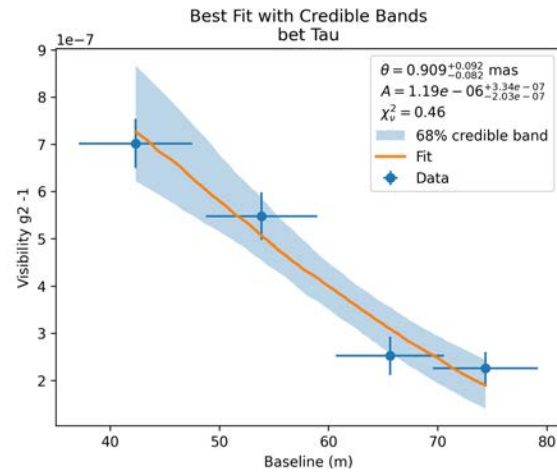


VSII OBA Survey Quality Improvements



- Getting better agreement with Stellar modelling as Survey Pipeline Analysis Improves
- Some high S/N stars have very short exposures (< 5 hours): dominates the error in diameter measurements
- Need additional observations of these sources (2026-2028) to reduce error bars.

Short observation time sources (High S/N)



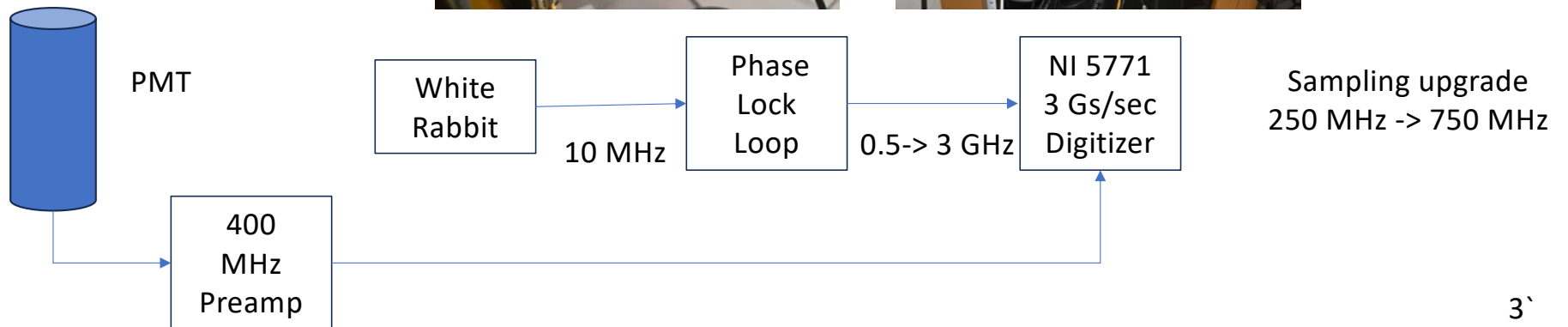
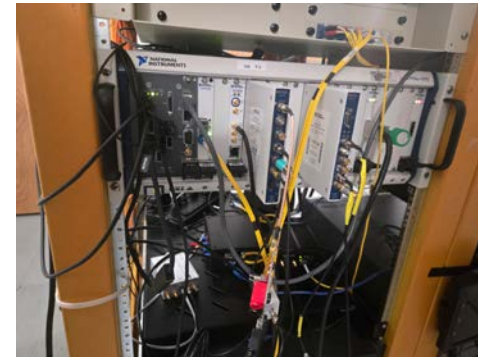
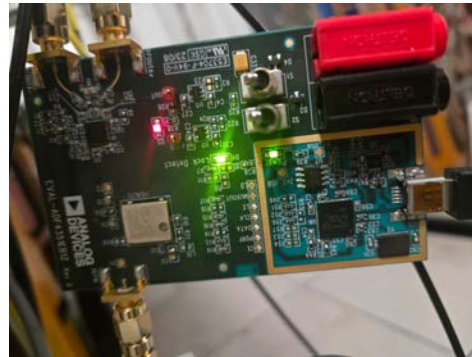
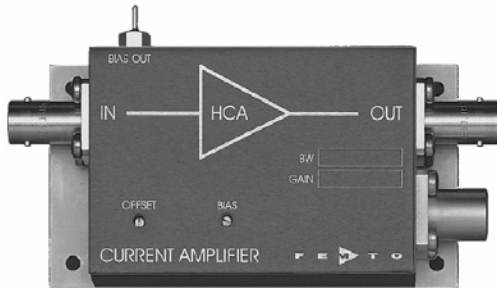


VSII Northern OBA Survey 10/6/2026

- High S/N database of VSII Observations (FPGA dataset)
- Corrected for Moonlight/sky background effects, weather, tracking corrections
- Text format output – easy to read
- Two standard analysis fitters provided: Scipy ODR + MCMC
- Specialized analysis to use standard analysis fitters: HA analysis, orbital analysis, etc.
- Parallel path for VERSII processed data (not all FPGA data)
- “Out of the box” accessibility: We can send a link to database & analysis tools to any interested person. Only requires python (+ libraries astropy, scipy, emcee, etc). About 5 minutes to do your first analysis



VERITAS-SII Hardware upgrades Sept 2026



VSII Observations (2026-2028)

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

25% gain in mirror reflectivity = $1.25^2 = \times 1.4$

50% gain in usable data (no RF noise) = $\times 1.5$

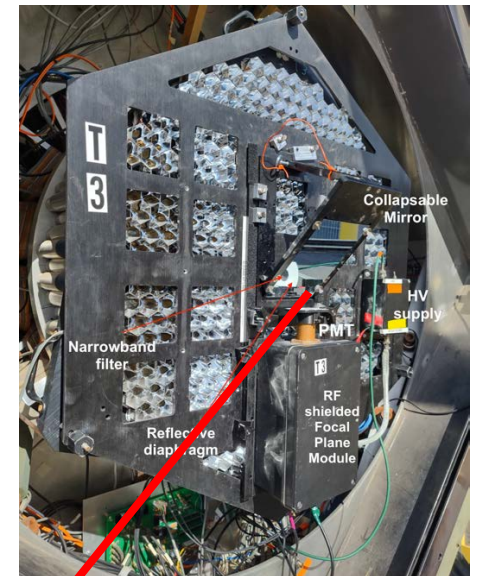
clock rate 250 MHz -> 750 MHz = $\times 3.0$

Total improvement = factor of 6

One hour of 2025+ observations = 6 hours previously
~160 hours (2026-2028) ~ all previous observations

Follow more rapid variations of fast evolving binaries (Spica)

Masking off VSII mirror which
points to open sky or ground



Summary



- VSII Northern Sky Survey: 1000 hours of observation (2019-2026)
- Approaching 1% resolution in visibility curve
 - Demonstrated measurements of slow & fast rotating stellar envelopes
 - Resolution of orbital & mass parameters for binary systems
 - Measurements at shorter wavelength (417 nm) provide complementary astrophysical information to longer wavelengths (CHARA, VLTI)
- Publication of full VSII Survey is nearing completion and will be submitted for publication (Fall 2026)
- Future provision of VSII observations to community with standard tools (eg. OIFITS) (~ 1 year)



Key Science Motivators for SII

- Stellar diameters, winds, photosphere structure
- Rapid Rotators, Cepheid variables
- Resolving Binary Systems, accretion disks
- Stellar Novae (transient events)
- Astrophysical lasers and emission lines

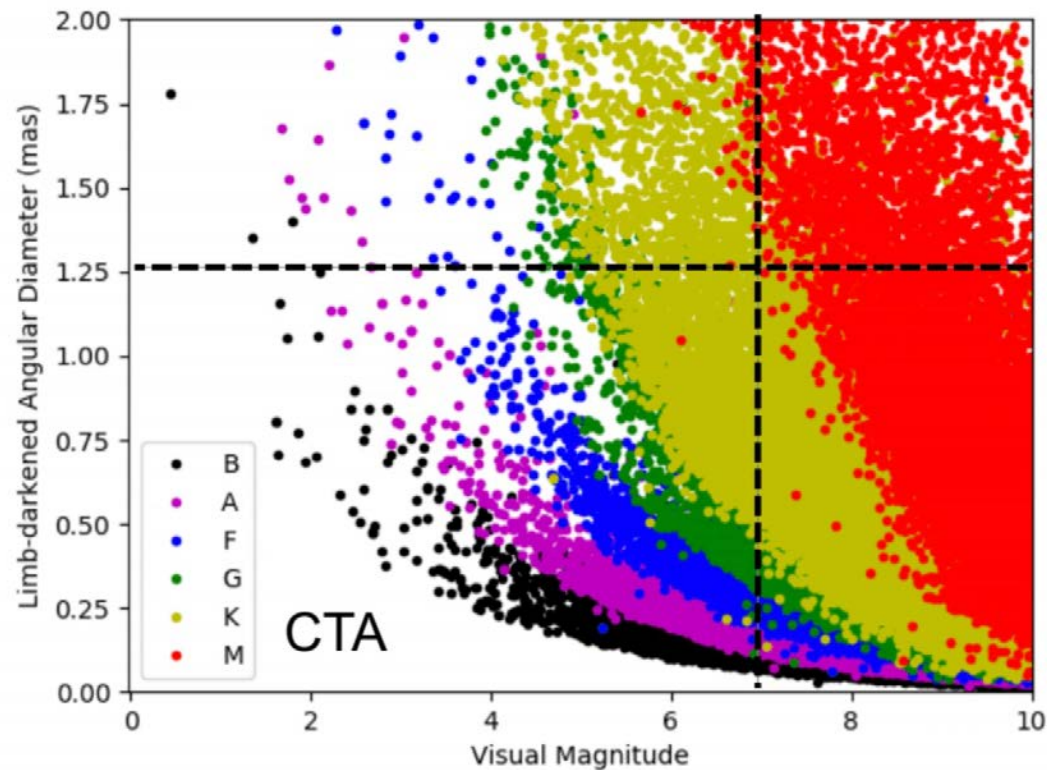
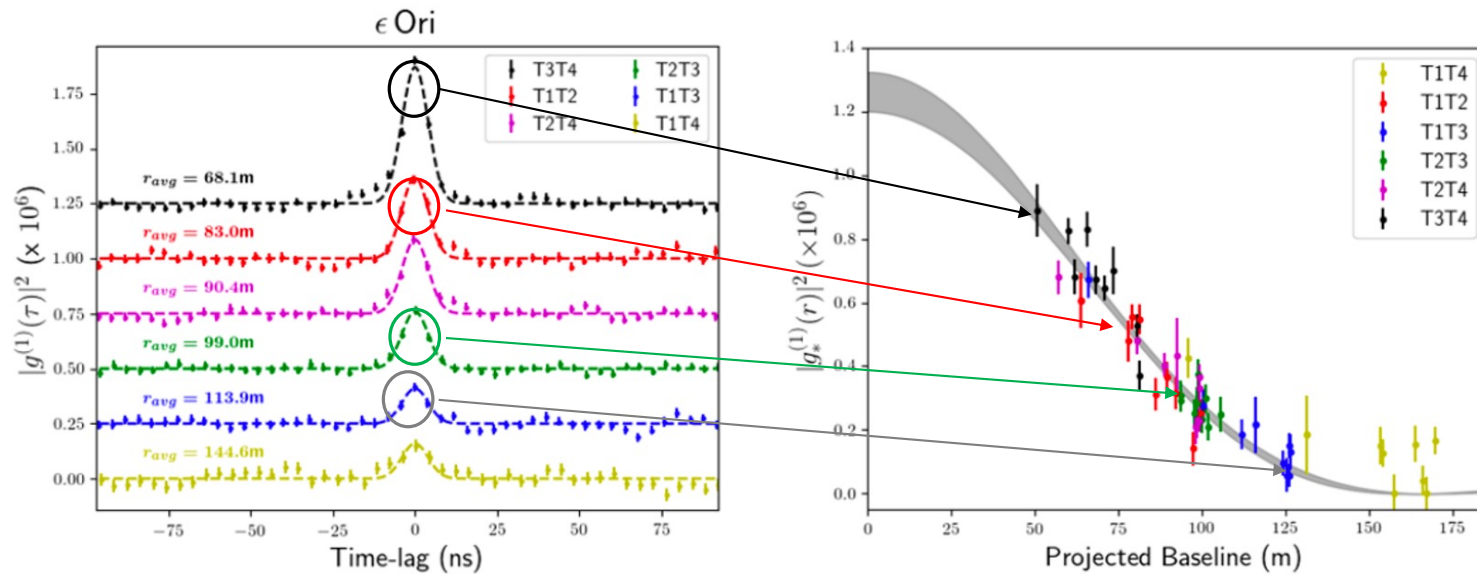


Image credit: N. Matthews (JSDC Stellar Catalogue)



VERITAS-SII 2020 Observation of ϵ Ori



$$g^{(2)}(\tau = 0, d) - 1 = |V(d)|^2$$

Uniform disk model:

$$V(d) = 2 \frac{J_1(\pi\theta(d/\lambda))}{\pi\theta(d/\lambda)}$$

$$\theta_{UD} = 0.631 \pm 0.017 \text{ mas (4.25 hours)} \quad \lambda = 417 \text{ nm}$$

$$\text{NSII: } \theta_{UD} = 0.67 \pm 0.04 \text{ mas (56 hours)}$$

