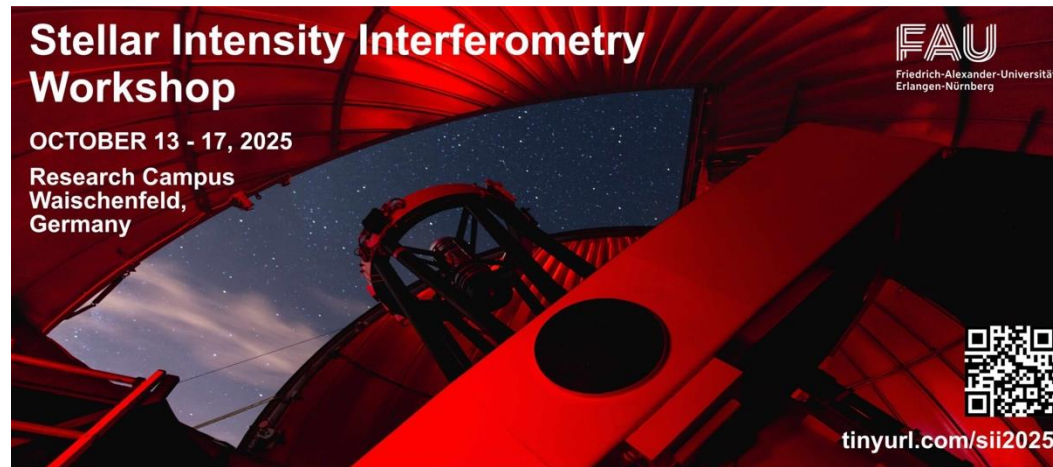




Status of modeling VERITAS measurements on Spica

Workshop talk: preliminary fit to preliminary data

Mike Lisa, Ohio State University
for the VERITAS Collaboration



α Virginis



- binary of blue giant with main-sequence secondary: period 346853 sec (4.0145 days)
- beyond spectroscopic binary - imaged by Hanbury Brown at Narrabri [1]
- Both members are rapid rotators (gravitational darkening etc)
- Close proximity (semi-major axis ≈ 1.5 mas $\sim \theta_1 \approx 0.9$ mas)
 - gravitationally distorted
 - mutual reflectivity [2]
 - potentially affected by stellar winds [3]

Two orbiting circular stars is
clearly a crude approximation
... nevertheless...

[1] Herbison-Evans et al, MNRAS (1971) **151** 161

[2] Bailey et al, Nature Ast. **3** (2019) 636

[3] Geis et al, ApJ **479** (1997) 408

Modeling a binary system



Symbol	Name	note		HB 1971
P	Period	Known. Not a fit parameter	4.0145 days	given
T	Time of periastron	From spectroscopy	HJD 2454189.40 ± 0.2 days	given
e	Eccentricity	From time dep. of doppler-shifted spectral lines.	Several estimates exist Fit param	given 0.146
ω	Longitude of periastron (line of apsides, major axis)	From spectroscopy – evolves with time over 120 years	Spectroscopy uncertainties significant -> Fit param	given
Ω	Position angle of line of nodes		Fit param	fitted
i	Inclination		Fit param	fitted
a	Semimajor axis		Fit param	fitted
$\theta_{UD,1}$	UD ang. diam. of primary		Fit param	fitted
$\theta_{UD,2}$	UD ang. diam. of secondary	Dimmer. Reduced sensitivity.	Fit param (often fixed)	Fixed 0.4 mas
R	Brightness ratio (>1)		Fit param	fitted
Norm	Instrumental normalization	zero-baseline $ V ^2$	Fit param	fitted

Modeling a binary system

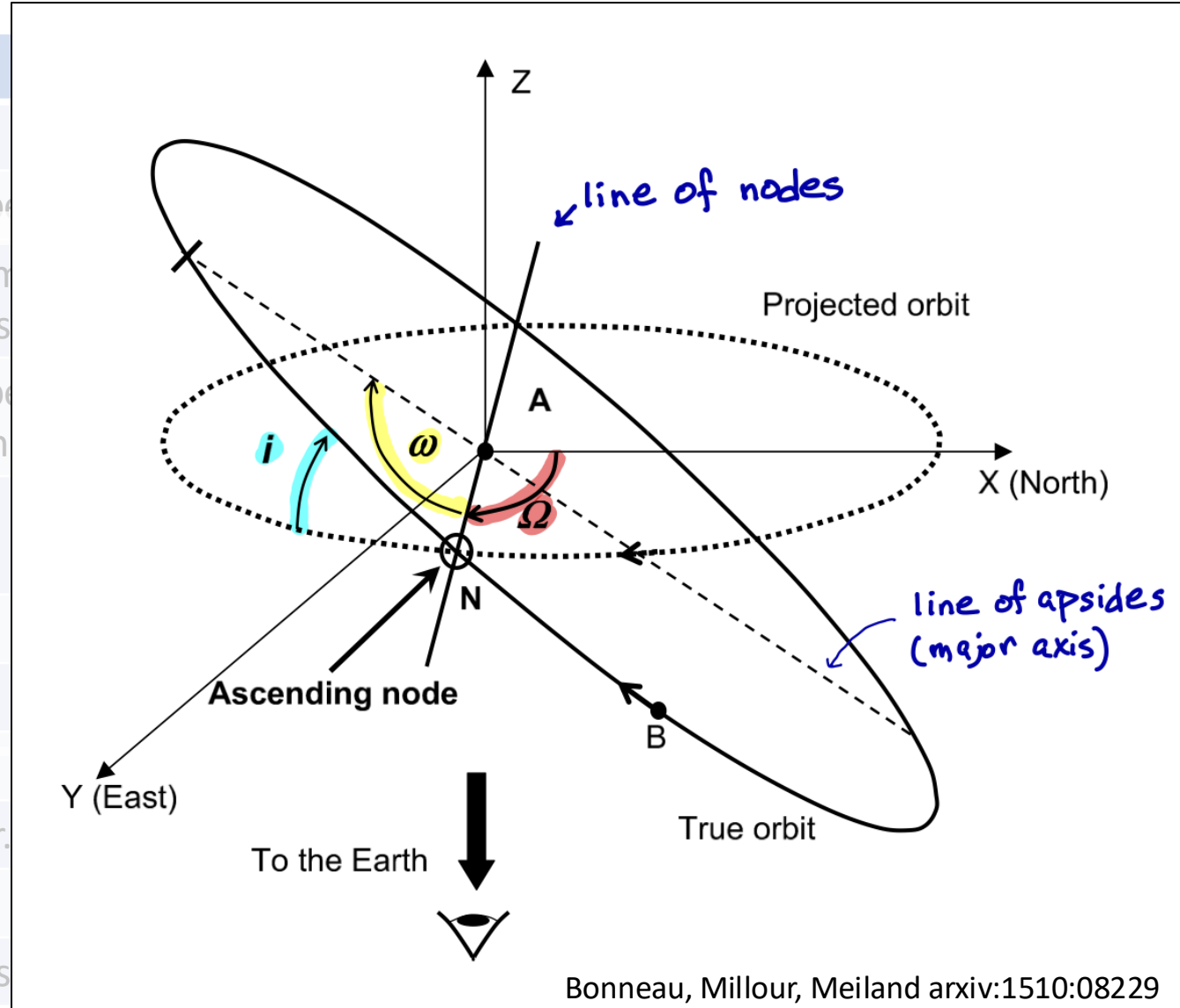


971

0.146

0.4 mas

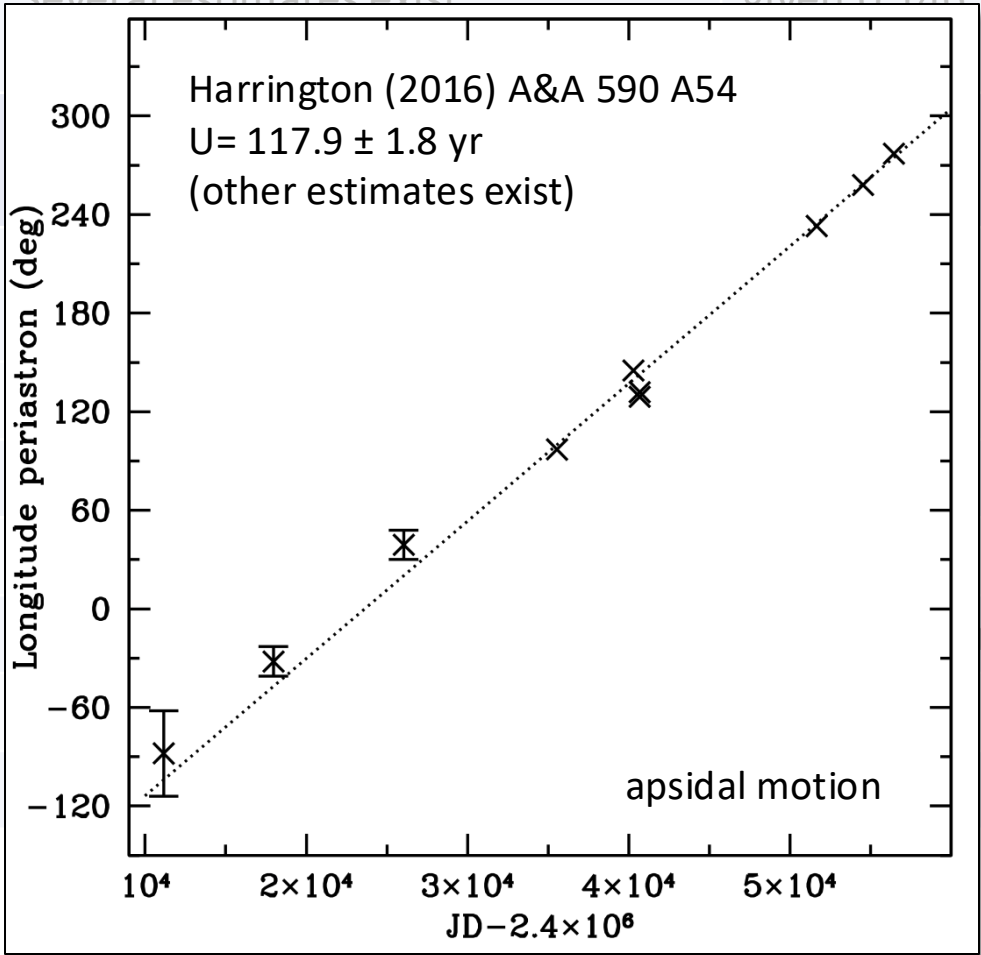
Symbol	Name	note
P	Period	Known.
T	Time of periastron	From spe
e	Eccentricity	From tim shifted s
ω	Longitude of periastron (line of apsides, major axis)	From spe with tim
Ω	Position angle of line of nodes	
i	Inclination	
a	Semimajor axis	
$\theta_{UD,1}$	UD ang. diam. of primary	
$\theta_{UD,2}$	UD ang. diam. of secondary	Dimmer.
R	Brightness ratio (>1)	
Norm	Instrumental normalization	zero-bas



Modeling a binary system



Symbol	Name	note		HB 1971
P	Period	Known. Not a fit parameter	4.0145 days	given
T	Time of periastron	From spectroscopy	HJD 2454189.40 $\pm$ 0.2 days	given
e	Eccentricity	From time dep. of doppler-shifted spectral lines.	Several estimates exist	given 0.146
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$\theta_{UD,1}$	UD ang. diam. of primary			
$\theta_{UD,2}$	UD ang. diam. of secondary	Dimmer. Reduced sensitivity.		
R	Brightness ratio (>1)			
Norm	Instrumental normalization	zero-baseline $ V ^2$		

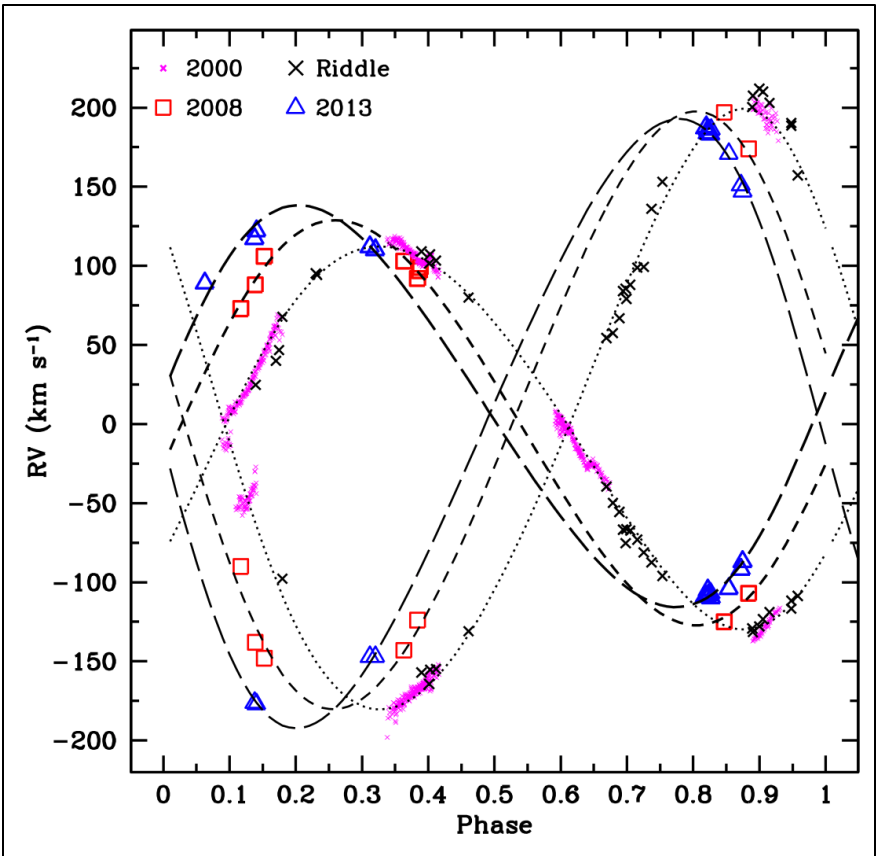


Modeling a binary system



Symbol	Name	note		HB 1971
P	Period	Known. Not a fit parameter	4.0145 days	given
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ω
Ω
i
a
$\theta_{UD,1}$
$\theta_{UD,2}$
R
Norm



Radial velocity measurements of Si III 4552 Å line yield spectroscopic determination of e, compiled by Harrington.

- Determination is non-trivial (see e.g. Harrington), and several estimates exist:
- 0.067 ± 0.014 Riddle (2000) PhD Georgia State
 - 0.108 ± 0.014 Harrington (2016) A&A 590 A54
 - 0.133 ± 0.017 Tkachenko (2016) MNRAS 458, 1964
 - 0.146 ± 0.009 Struve (1958) ApJ 128, 310 - used by HB

Calculating the positions and squared visibility



1. Solve (numerically, binary search works well) Kepler's equation for the eccentric anomaly (E) at time t , knowing the period P , the time of periastron T , and the eccentricity e :

$$\frac{2\pi}{P} (t - T) = E - e \sin E \quad (1)$$

2. Compute rectangular coordinates X and Y for unit orbit with E and e

$$X = \cos E - e \quad (2)$$

$$Y = \sin(E) \sqrt{1 - e^2} \quad (3)$$

correcting for
apsidal motion

3. Compute the four Thiele-Innes constants using a (in mas), ω , Ω , and i :

$$A = a (+ \cos \omega \cos \Omega - \sin \omega \sin \Omega \cos i) \quad (4)$$

$$B = a (+ \cos \omega \sin \Omega + \sin \omega \cos \Omega \cos i) \quad (5)$$

$$F = a (- \sin \omega \cos \Omega - \cos \omega \sin \Omega \cos i) \quad (6)$$

$$G = a (- \sin \omega \sin \Omega + \cos \omega \cos \Omega \cos i) \quad (7)$$

4. The separations, in right ascension and declination are:

$$S_r = BX + GY \quad (8)$$

$$S_d = AX + FY \quad (9)$$

The squared visibility for the binary system is given by

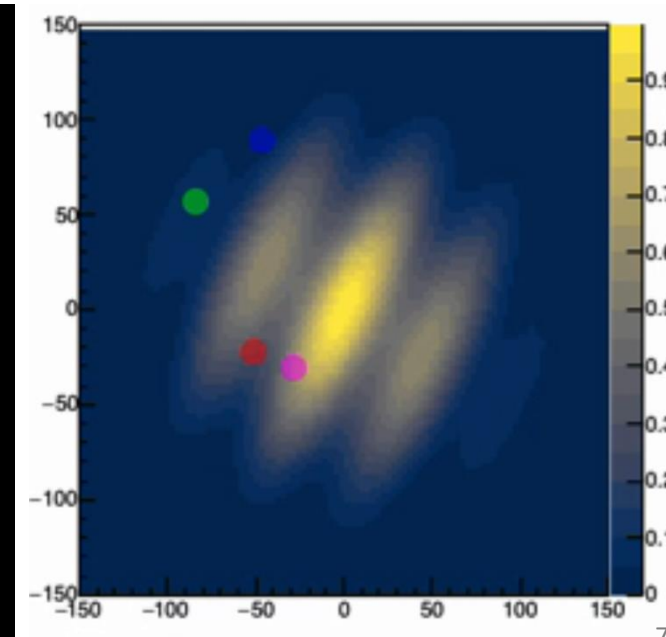
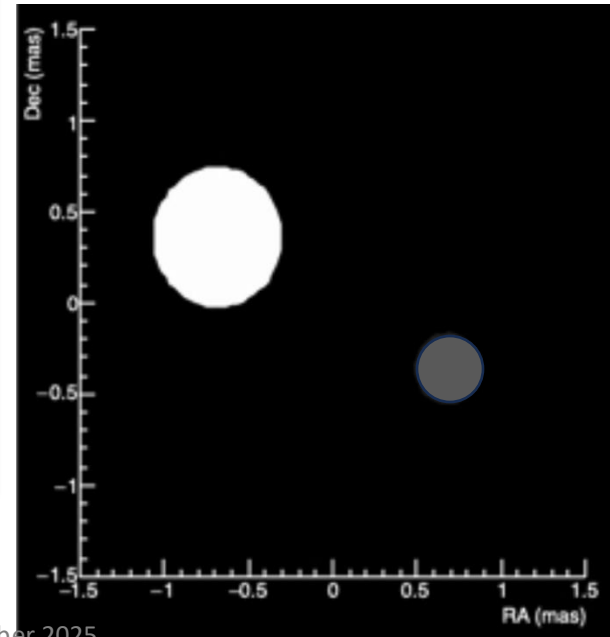
$$|V|^2(u, v) = \frac{\Gamma^2(\theta_1) + R^2 \Gamma^2(\theta_2) + 2R \Gamma(\theta_1) \Gamma(\theta_2) \cos \eta}{(1 + R)^2}, \quad (10)$$

where

$$\Gamma(\theta) \equiv 2 \frac{J_1(\pi B \theta / \lambda)}{\pi B \theta / \lambda}, \quad (11)$$

is the visibility of a single uniform disk, and

$$\eta \equiv \frac{2\pi}{\lambda} (US_r + VS_d). \quad (12)$$



Following Pan (2000) and Aufdenberg

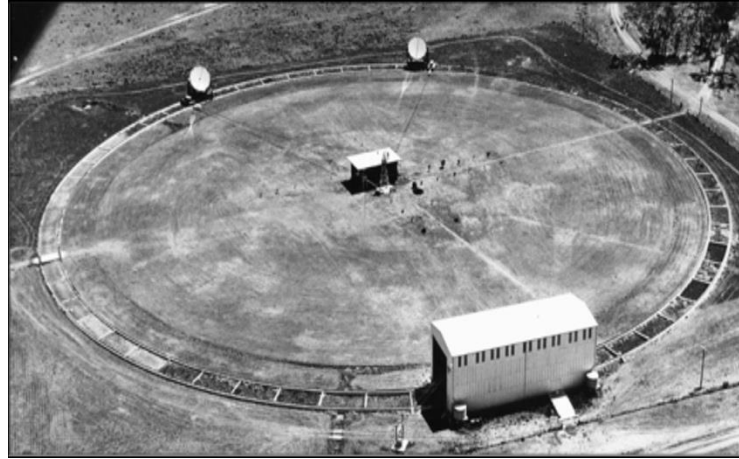
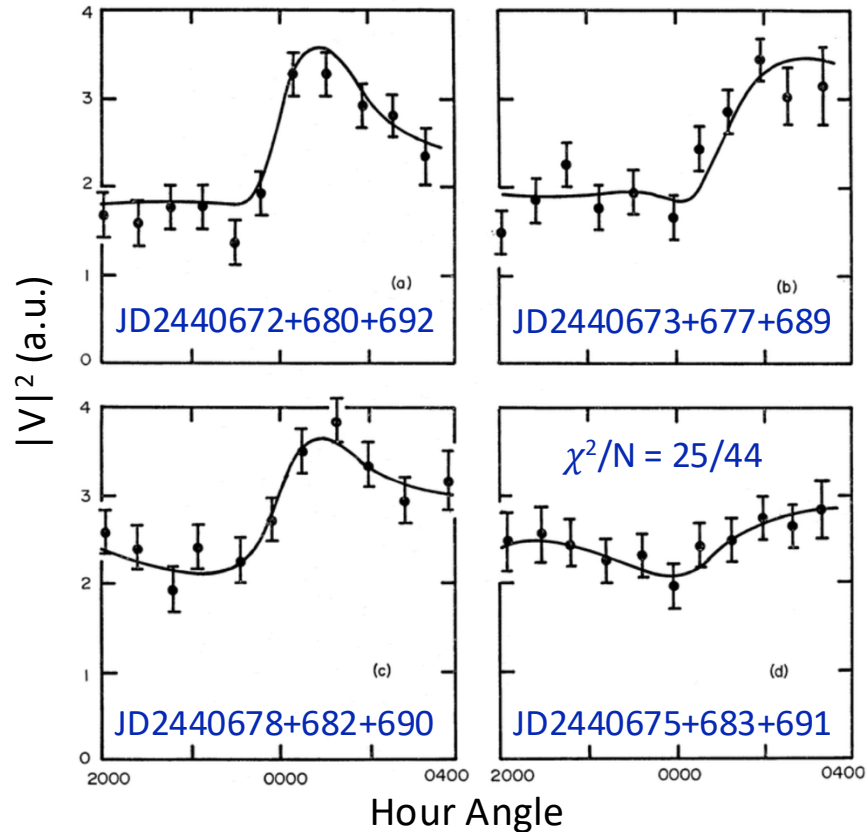
Hanbury Brown measurement of Spica

MNRAS (1971) **151** 161

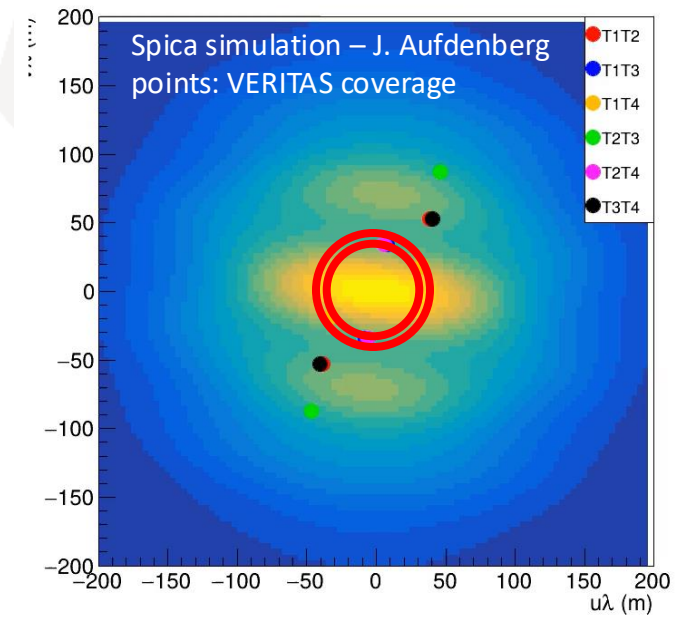
A STUDY OF α VIRGINIS WITH AN INTENSITY INTERFEROMETER

D. Herbison-Evans, R. Hanbury Brown, J. Davis and L. R. Allen

$|b| = 39.1$ m. data every ~ 48 minutes



Separation of telescopes constant and baseline $\perp$ line of sight to star
 $\rightarrow$ Wiggles imply non-circular shape



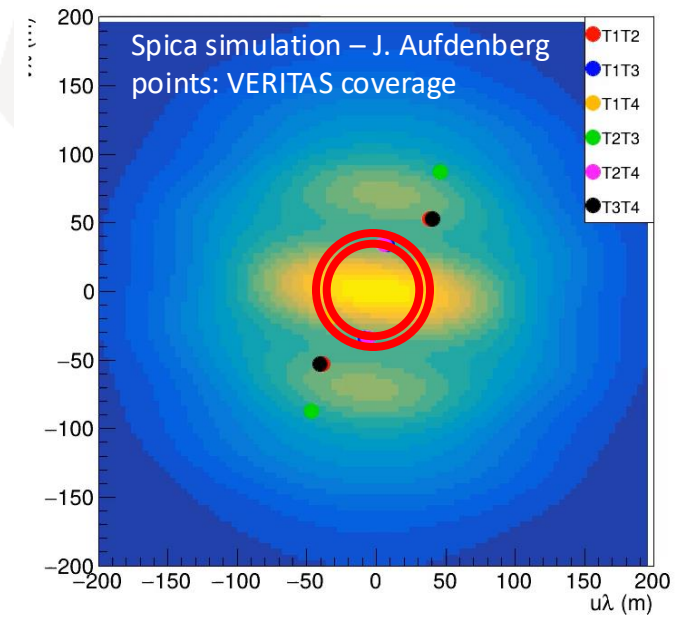
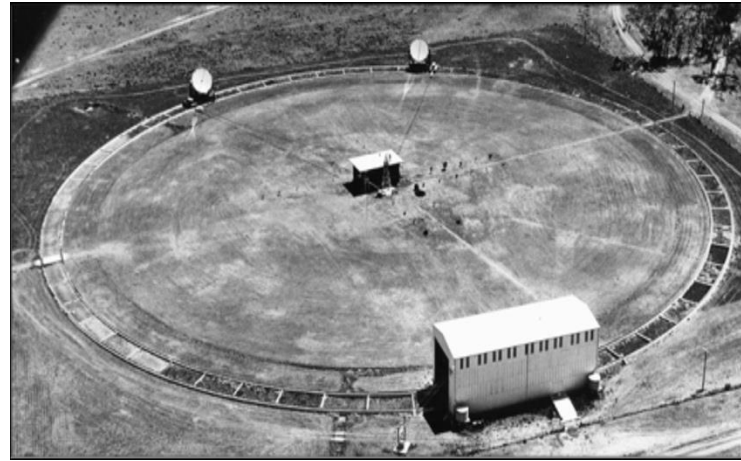
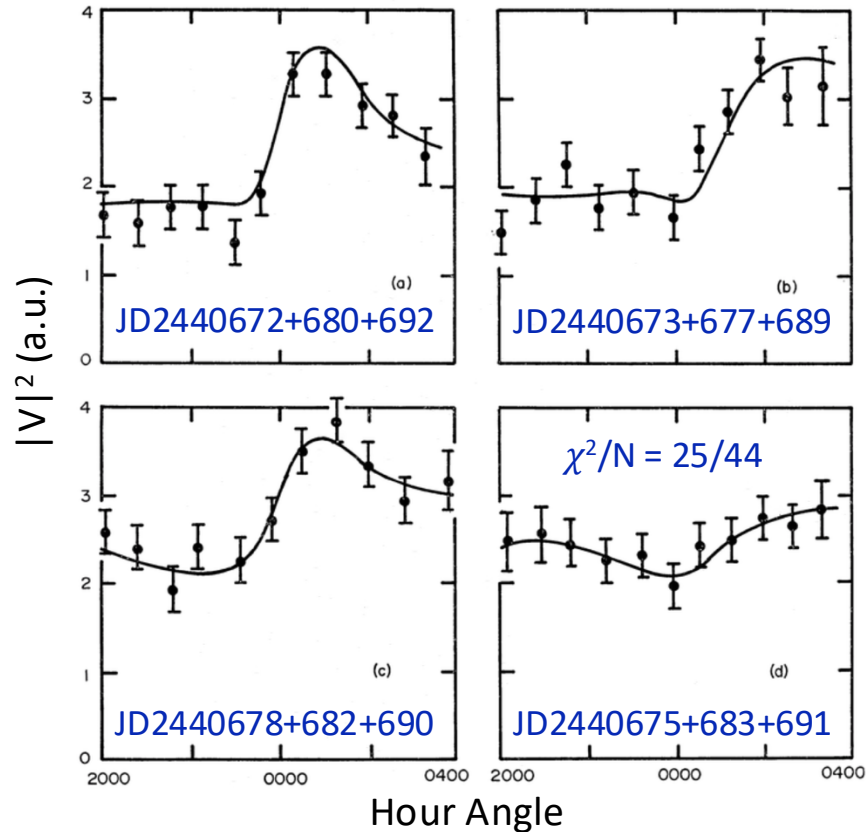
Hanbury Brown measurement of Spica

MNRAS (1971) **151** 161

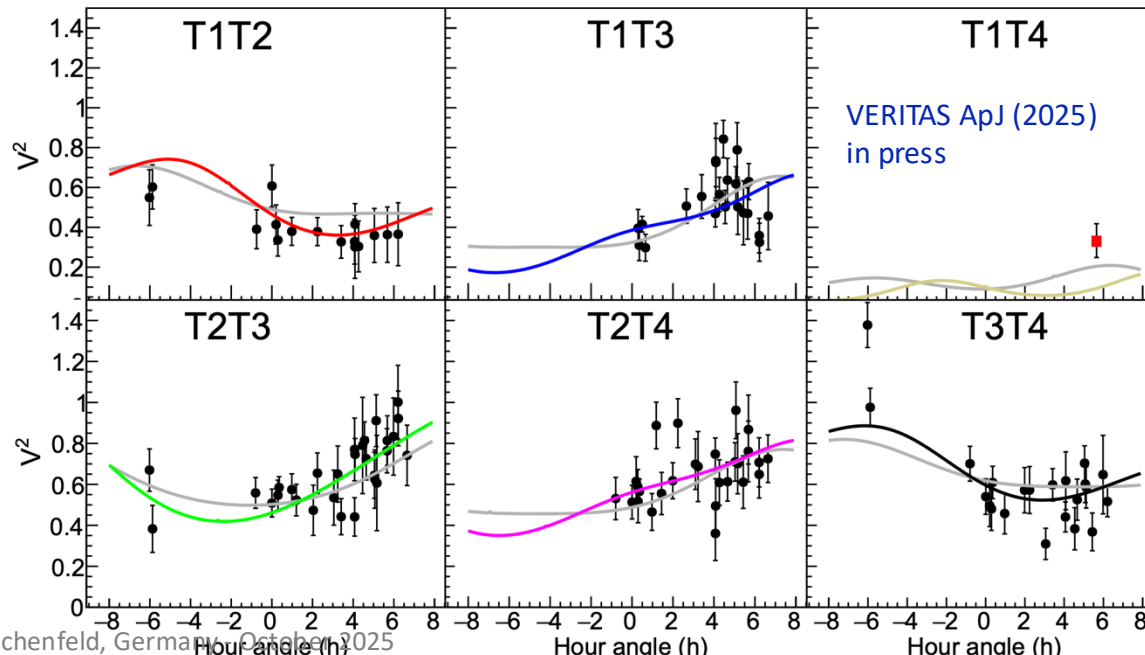
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Separation of telescopes constant and baseline $\perp$ line of sight to star
 $\rightarrow$ Wiggles imply non-circular shape (not so for fixed-telescope arrays)



$\leftarrow \gamma$ Cas:
 $\theta_{\max}/\theta_{\max} = 1.28 \pm 0.04$

(grey curves for round star wobble, too!)

Important to see data with errors vs theory

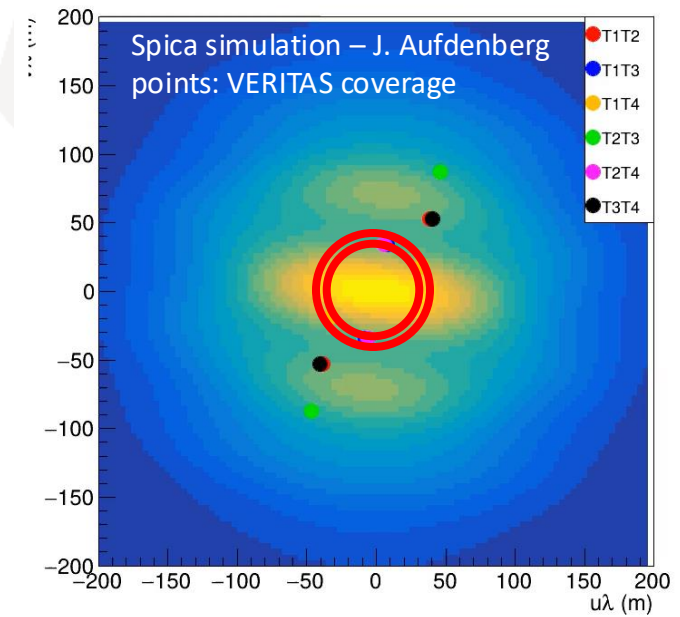
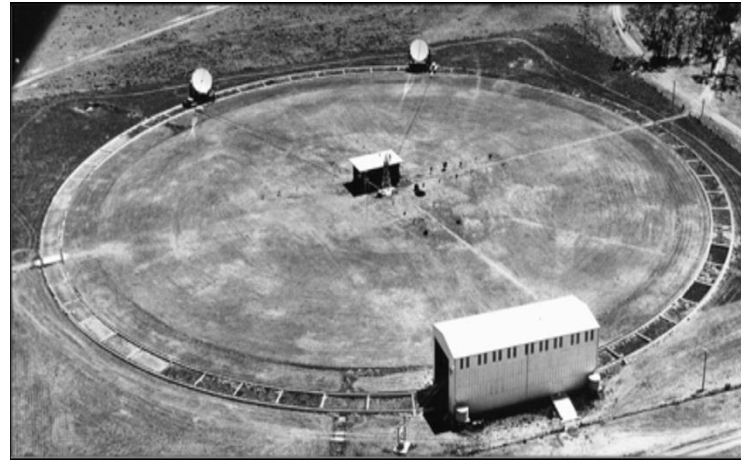
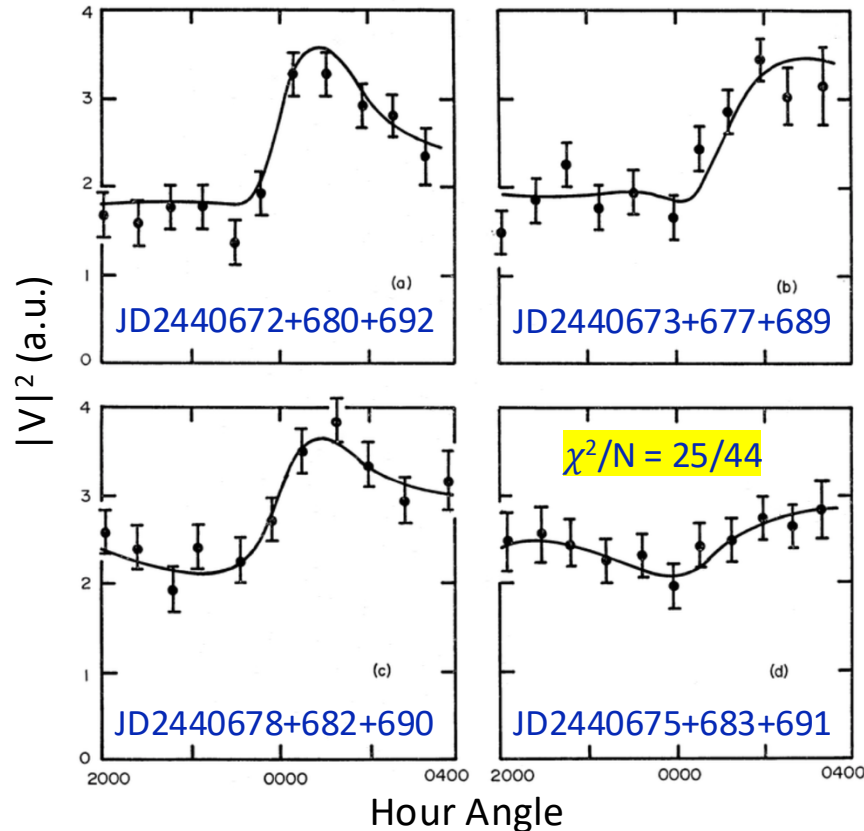
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$|b| = 39.1$ m. data every ~ 48 minutes



Separation of telescopes constant and baseline $\perp$ line of sight to star
 $\rightarrow$ Wiggles imply non-circular shape (not so for fixed-telescope arrays)

Day-to-day variations clearly demonstrate dynamic system

- consistent with ~ 4 -day period of Spica

Detailed lists of all the observations are available and the authors will be glad to supply them to anyone who is interested. We have not included them in the present paper because they are lengthy and we judge that they are not of sufficient interest to justify the space.

800 observation intervals were fitted (19 rejected as outliers)

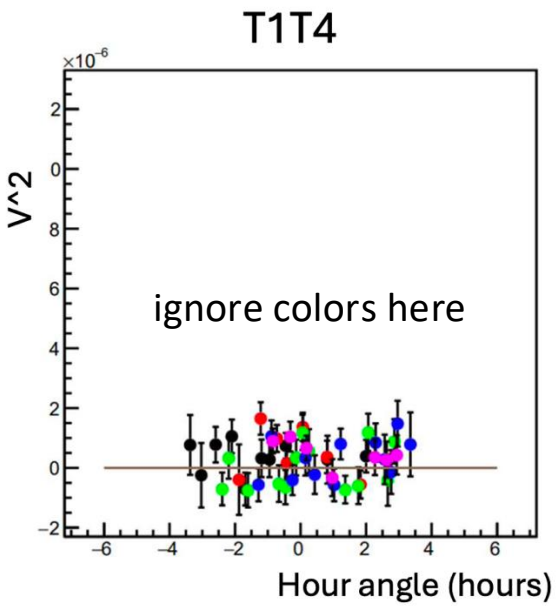
Important to see data
with errors vs theory



Relevant for Spica: T1T2 T2T3 T2T4 T3T4 (T1T3 and T1T4 had too low signal/noise)



T1T3 & T1T4 too large baseline to measure signal above noise
- see talk of John Scott



The data



Period = 4.0145 days

		Night #	Date (UTC)	# tel. pairs	Observation time (h)	Pair-hours (h)	Pair-hours not T1T3 or T1T4
83 days = 82.7 $\frac{1}{4}$ -cycles	2 days {	0	2024-02-22	6	5.41	30.8	21.6
		1	2024-02-24	6	5.66	34.0	22.6
	{	2	2024-05-17	6	0.98	5.9	3.9
		3	2024-05-23	3	1.80	5.4	5.4
		4	2024-05-24	1	2.71	2.7	2.7
77 days = 76.7 $\frac{1}{4}$ -cycles	1 day {	5	2024-05-25	6	3.85	23.1	15.4
		6	2024-05-26	6	2.05	12.3	8.2
57 days = 56.8 $\frac{1}{4}$ -cycles	1 day {	7	2025-03-10	3	5.17	15.5	10.3
		8	2025-03-11	3	6.40	19.2	12.8
	8 days {	9	2025-05-07	3	5.41	16.2	5.41
		10	2025-05-15	6	4.92	29.5	19.7
	1 day {	11	2025-05-16	6	5.17	31.0	20.7
		Total			49.53	225.6	147.8

~400 datapoints (~15-minutes) fitted

The data

Period = 4.0145 days

83 days = 82.7 $\frac{1}{4}$ -cycles

77 days = 76.7 $\frac{1}{4}$ -cycles

57 days = 56.8 $\frac{1}{4}$ -cycles

2 days {

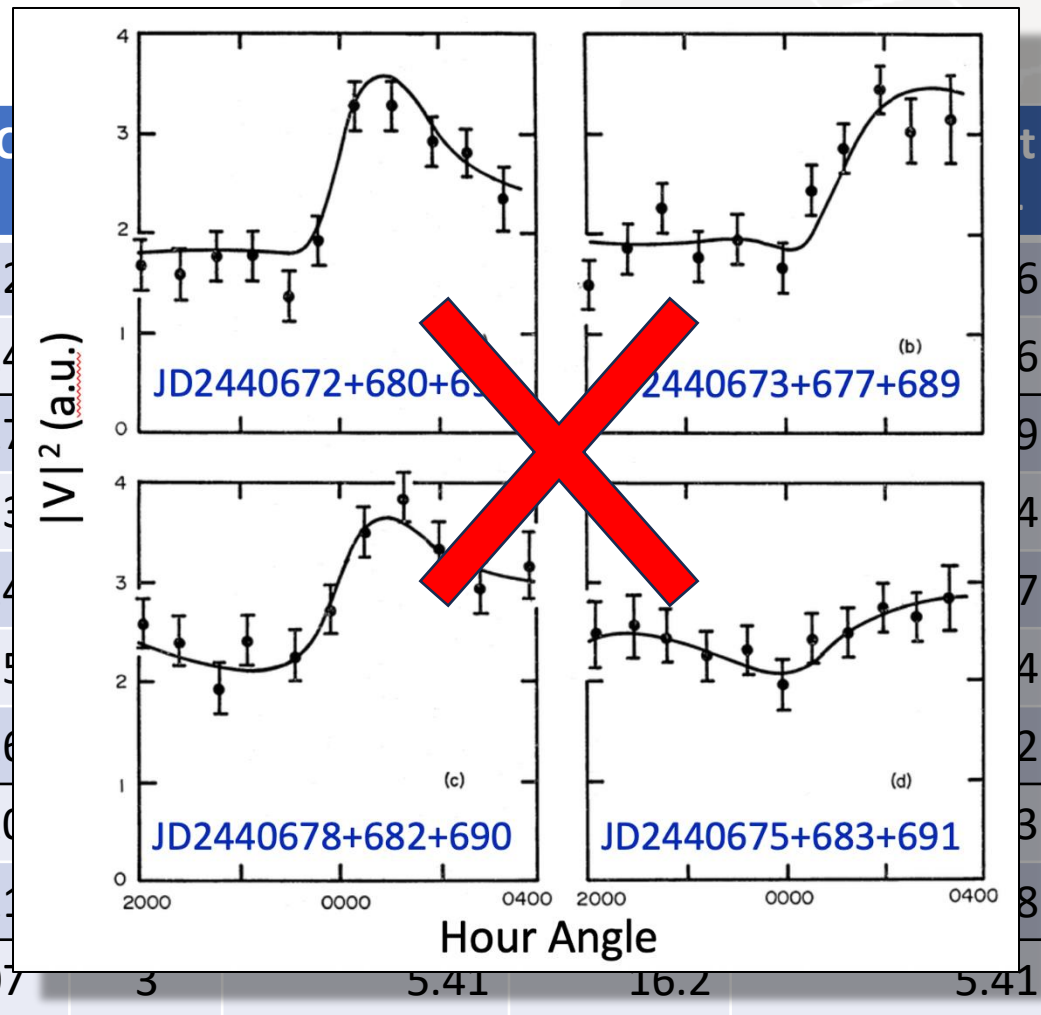
1 day {

1 day {

8 days {

1 day {

Night #	Date (UTC)
0	2024-02-22
1	2024-02-24
2	2024-05-17
3	2024-05-23
4	2024-05-24
5	2024-05-25
6	2024-05-26
7	2025-03-10
8	2025-03-11
9	2025-05-07
10	2025-05-08
11	2025-05-09
Total	



For a fixed-position telescope pair, visibility for a dynamic system depends on two independent clocks

49.53

225.6

147.8

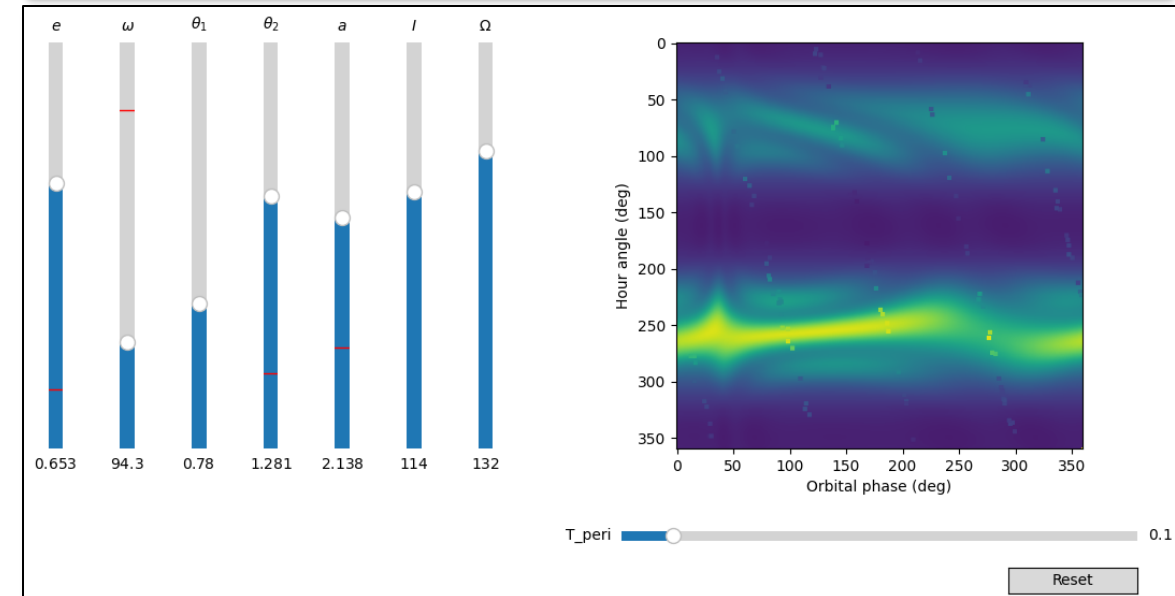
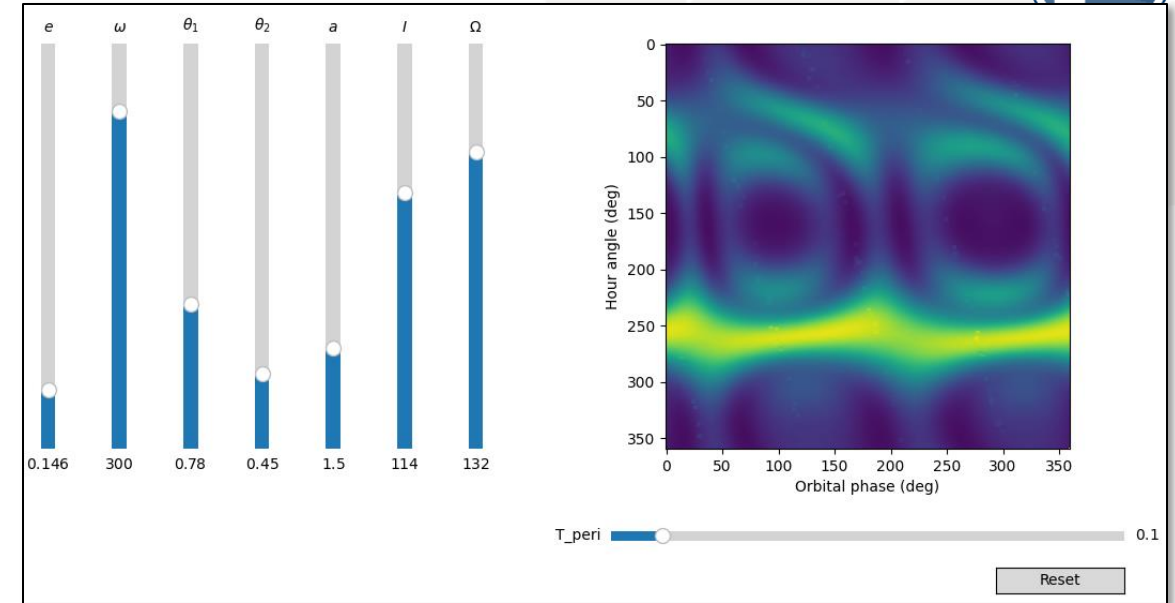
~400 datapoints (~15-minutes) fitted



The camouflage plot: A very cool concept by Prasenjit et al.



- Choose a telescope pair
- Choose orbital parameters
- Visibility pattern shown in 2D (time-versus-time)
- In principle, can place measurements in this space and adjust orbital parameters until the data “disappear”
- Still playing with this, but errorbars/fluctuations in real data may limit its utility



Fit 7 – Single Round Star



Chi2/ndf = 1352 / 377 = 3.6

T = 7.6823400e+04 (fixed) [HB:-9.90e+01 +/- 0.00e+00]

e = 6.0000000e-02 (fixed) [HB:1.46e-01 +/- 0.00e+00]

omega = 5.3349500e+00 (fixed) [HB:2.41e+00 +/- 0.00e+00]

OMEGA = 2.2100000e+00 (fixed) [HB:2.30e+00 +/- 4.00e-02]

i = 1.9000000e+00 (fixed) [HB:1.15e+00 +/- 3.00e-02]

a[mas] = 1.7100000e+00 (fixed) [HB:1.54e+00 +/- 5.00e-02]

ThUD1[mas] = 7.4616809e-01 +/- 7.61e-03 [HB:8.70e-01 +/- 4.00e-02]

ThUD2[mas] = 1.0000000e+03 (fixed) [HB:4.00e-01 +/- 0.00e+00]

R = 9.9999990e+06 (fixed) [HB:6.40e+00 +/- 1.00e+00]

Norm = 7.7704367e+00 +/- 1.80e-01 [HB:-9.90e+01 +/- 0.00e+00]

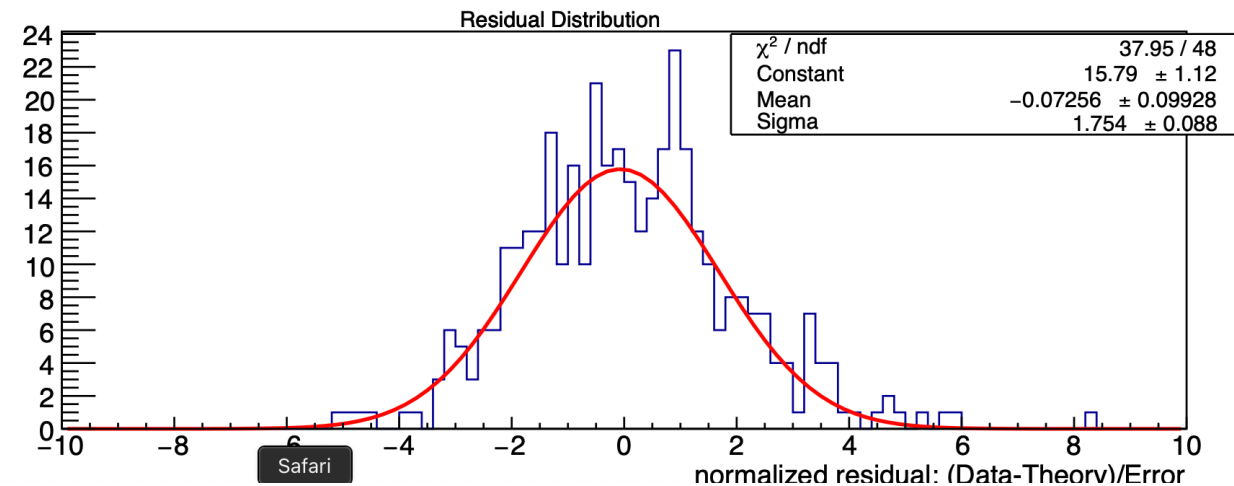
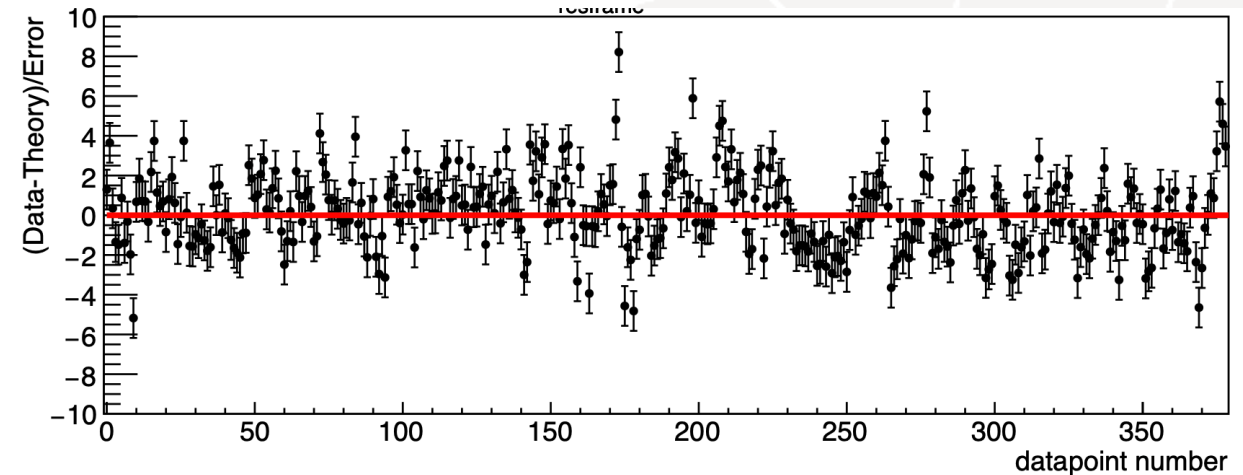
Datapoints excluded from fit:

V2obs<3.00e-01 : #points excluded = 24

T1T4 pairs : #points excluded = 65

T1T3 pairs : #points excluded = 78

zoom.us



Fit 7 (single round star) – Nights 5,6 – 1 day apart



24-25 May 2024 MST 5 runs - 4.5h

Chi2/ndf = 1352 / 377 = 3.6

T = 7.6823400e+04 (fixed) [HB:-9.90e+01 +/- 0.00e+00]
e = 6.0000000e-02 (fixed) [HB:1.46e-01 +/- 0.00e+00]
omega = 5.3349500e+00 (fixed) [HB:2.41e+00 +/- 0.00e+00]
OMEGA = 2.2100000e+00 (fixed) [HB:2.30e+00 +/- 4.00e-02]
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R = 9.9999990e+06 (fixed) [HB:6.40e+00 +/- 1.00e+00]
Norm = 7.7704367e+00 +/- 1.80e-01 [HB:-9.90e+01 +/- 0.00e+00]

25-26 May 2024 MST 2 runs - 2h

Chi2/ndf = 1352 / 377 = 3.6

T = 7.6823400e+04 (fixed) [HB:-9.90e+01 +/- 0.00e+00]
e = 6.0000000e-02 (fixed) [HB:1.46e-01 +/- 0.00e+00]
omega = 5.3349500e+00 (fixed) [HB:2.41e+00 +/- 0.00e+00]
OMEGA = 2.2100000e+00 (fixed) [HB:2.30e+00 +/- 4.00e-02]
i = 1.9000000e+00 (fixed) [HB:1.15e+00 +/- 3.00e-02]
a[mas] = 1.7100000e+00 (fixed) [HB:1.54e+00 +/- 5.00e-02]
ThUD1[mas] = 7.4616809e-01 +/- 7.61e-03 [HB:8.70e-01 +/- 4.00e-02]
ThUD2[mas] = 1.0000000e+03 (fixed) [HB:4.00e-01 +/- 0.00e+00]
R = 9.9999990e+06 (fixed) [HB:6.40e+00 +/- 1.00e+00]
Norm = 7.7704367e+00 +/- 1.80e-01 [HB:-9.90e+01 +/- 0.00e+00]

Fit 7 (single round star) – Nights 7,8 – 1 day apart



09-10 Mar 2025 MST
4 runs - 5.5h no T3

Chi2/ndf = 1352 / 377 = 3.6

T = 7.6823400e+04 (fixed) [HB:-9.90e+01 +/- 0.00e+00]
e = 6.0000000e-02 (fixed) [HB:1.46e-01 +/- 0.00e+00]
omega = 5.3349500e+00 (fixed) [HB:2.41e+00 +/- 0.00e+00]
OMEGA = 2.2100000e+00 (fixed) [HB:2.30e+00 +/- 4.00e-02]
i = 1.9000000e+00 (fixed) [HB:1.15e+00 +/- 3.00e-02]
a[mas] = 1.7100000e+00 (fixed) [HB:1.54e+00 +/- 5.00e-02]
ThUD1[mas] = 7.4616809e-01 +/- 7.61e-03 [HB:8.70e-01 +/- 4.00e-02]
ThUD2[mas] = 1.0000000e+03 (fixed) [HB:4.00e-01 +/- 0.00e+00]
R = 9.9999990e+06 (fixed) [HB:6.40e+00 +/- 1.00e+00]
Norm = 7.7704367e+00 +/- 1.80e-01 [HB:-9.90e+01 +/- 0.00e+00]

10-11 Mar 2025 MST
5 runs - 6.5h no T3

Chi2/ndf = 1352 / 377 = 3.6

T = 7.6823400e+04 (fixed) [HB:-9.90e+01 +/- 0.00e+00]
e = 6.0000000e-02 (fixed) [HB:1.46e-01 +/- 0.00e+00]
omega = 5.3349500e+00 (fixed) [HB:2.41e+00 +/- 0.00e+00]
OMEGA = 2.2100000e+00 (fixed) [HB:2.30e+00 +/- 4.00e-02]
i = 1.9000000e+00 (fixed) [HB:1.15e+00 +/- 3.00e-02]
a[mas] = 1.7100000e+00 (fixed) [HB:1.54e+00 +/- 5.00e-02]
ThUD1[mas] = 7.4616809e-01 +/- 7.61e-03 [HB:8.70e-01 +/- 4.00e-02]
ThUD2[mas] = 1.0000000e+03 (fixed) [HB:4.00e-01 +/- 0.00e+00]
R = 9.9999990e+06 (fixed) [HB:6.40e+00 +/- 1.00e+00]
Norm = 7.7704367e+00 +/- 1.80e-01 [HB:-9.90e+01 +/- 0.00e+00]

Fit 7 (single round star) – Nights 10,11 – 1 day apart



14-15 May 2025 MST
5 runs - 5.2h

Chi2/ndf = 1352 / 377 = 3.6

T = 7.6823400e+04 (fixed) [HB:-9.90e+01 +/- 0.00e+00]
e = 6.0000000e-02 (fixed) [HB:1.46e-01 +/- 0.00e+00]
omega = 5.3349500e+00 (fixed) [HB:2.41e+00 +/- 0.00e+00]
OMEGA = 2.2100000e+00 (fixed) [HB:2.30e+00 +/- 4.00e-02]
i = 1.9000000e+00 (fixed) [HB:1.15e+00 +/- 3.00e-02]
a[mas] = 1.7100000e+00 (fixed) [HB:1.54e+00 +/- 5.00e-02]
ThUD1[mas] = 7.4616809e-01 +/- 7.61e-03 [HB:8.70e-01 +/- 4.00e-02]
ThUD2[mas] = 1.0000000e+03 (fixed) [HB:4.00e-01 +/- 0.00e+00]
R = 9.9999990e+06 (fixed) [HB:6.40e+00 +/- 1.00e+00]
Norm = 7.7704367e+00 +/- 1.80e-01 [HB:-9.90e+01 +/- 0.00e+00]

15-16 May 2025 MST
5 runs - 5.3h

Chi2/ndf = 1352 / 377 = 3.6

T = 7.6823400e+04 (fixed) [HB:-9.90e+01 +/- 0.00e+00]
e = 6.0000000e-02 (fixed) [HB:1.46e-01 +/- 0.00e+00]
omega = 5.3349500e+00 (fixed) [HB:2.41e+00 +/- 0.00e+00]
OMEGA = 2.2100000e+00 (fixed) [HB:2.30e+00 +/- 4.00e-02]
i = 1.9000000e+00 (fixed) [HB:1.15e+00 +/- 3.00e-02]
a[mas] = 1.7100000e+00 (fixed) [HB:1.54e+00 +/- 5.00e-02]
ThUD1[mas] = 7.4616809e-01 +/- 7.61e-03 [HB:8.70e-01 +/- 4.00e-02]
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R = 9.9999990e+06 (fixed) [HB:6.40e+00 +/- 1.00e+00]
Norm = 7.7704367e+00 +/- 1.80e-01 [HB:-9.90e+01 +/- 0.00e+00]

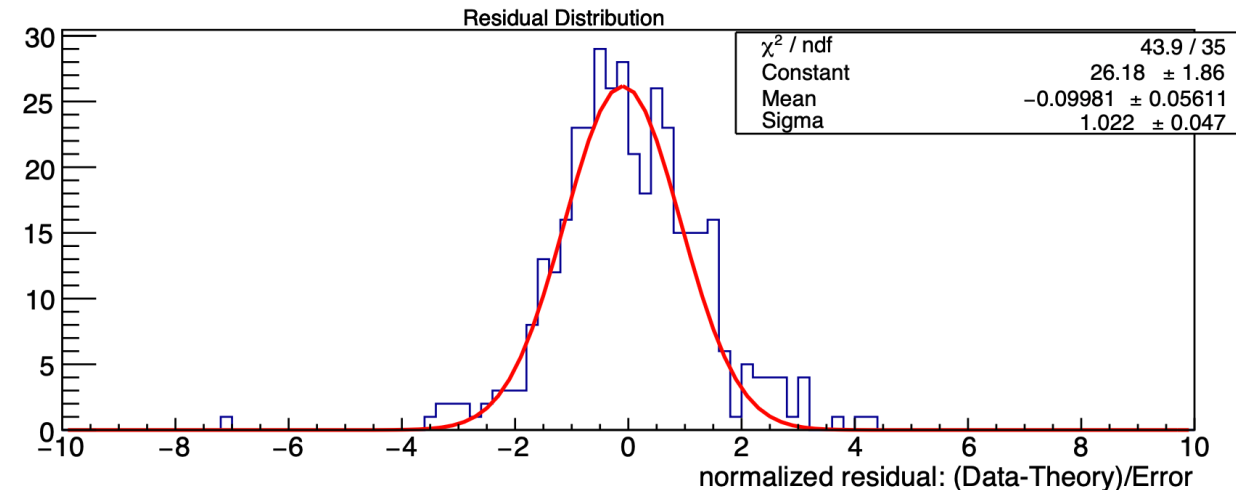
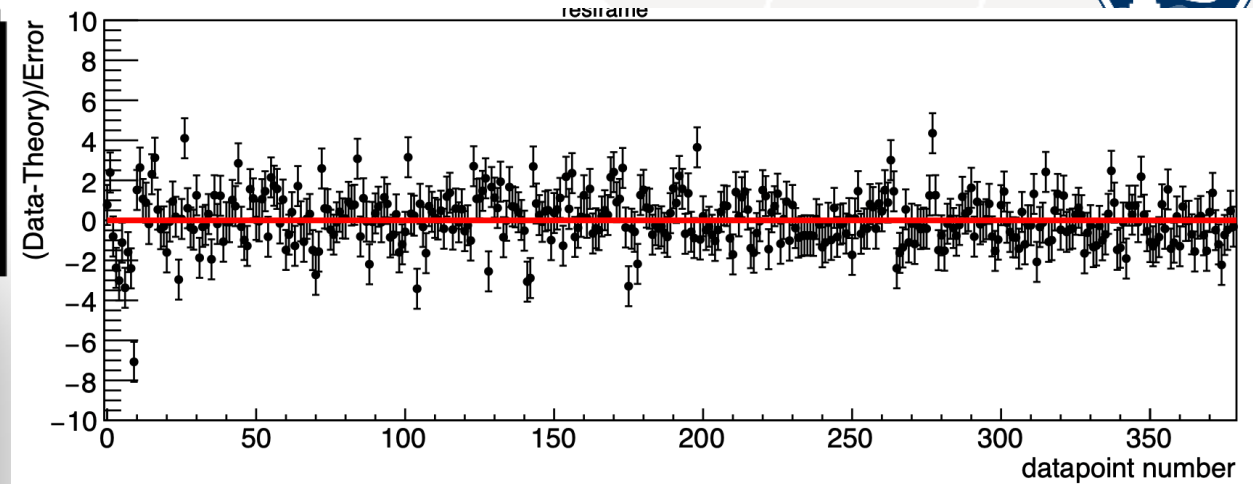
Fit 3 - Binary Star with $e=0$ and T shifted 1.9 hours



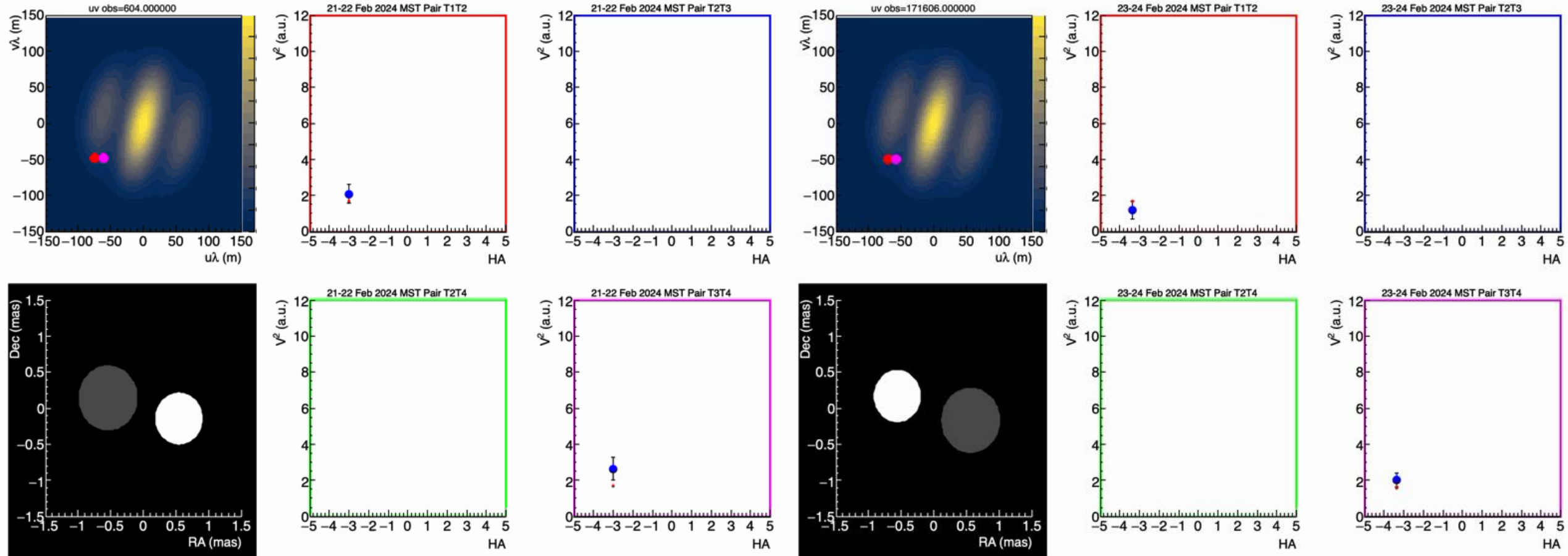
$\chi^2/\text{ndf} = 634 / 372 = 1.7$

$T = 6.9912000\text{e}+04$ (fixed) [HB:-9.90e+01 +/- 0.00e+00]

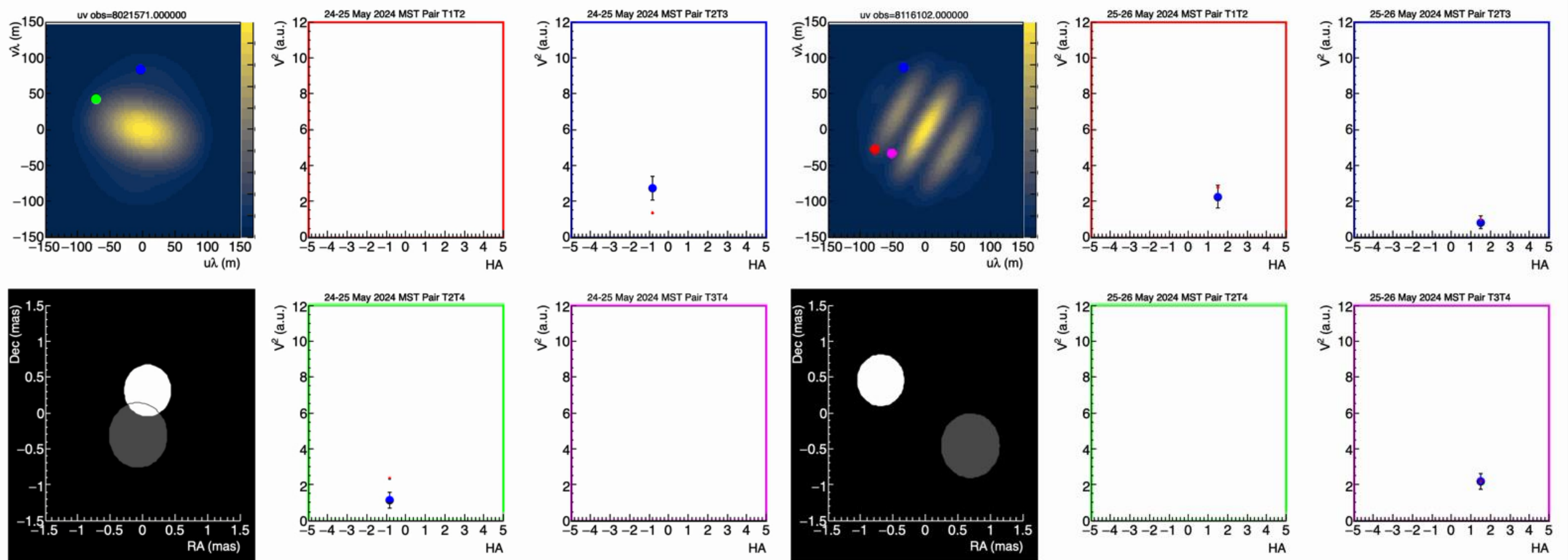
$e = 0.0000000\text{e}+00$ (fixed) [HB:1.46e-01 +/- 0.00e+00]



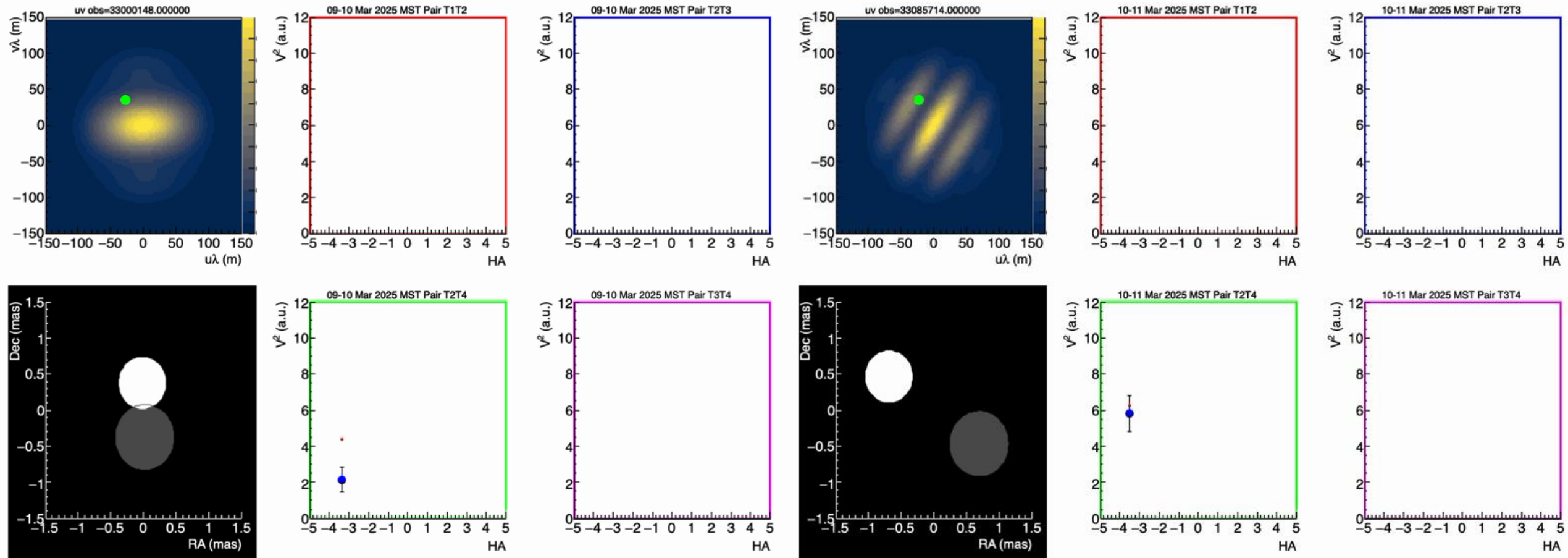
Fit 3 - $e=0$ - Nights 0,1 – 2 days apart



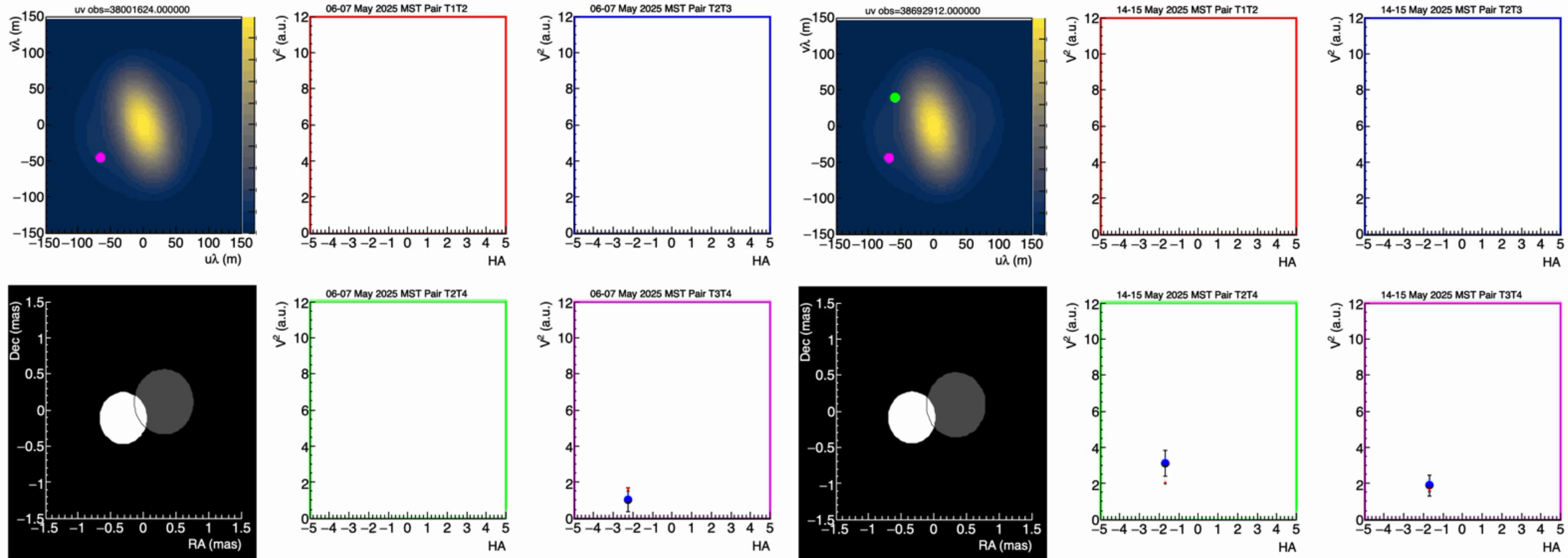
Fit 3 - $e=0$ - Nights 5,6 - 1 day apart



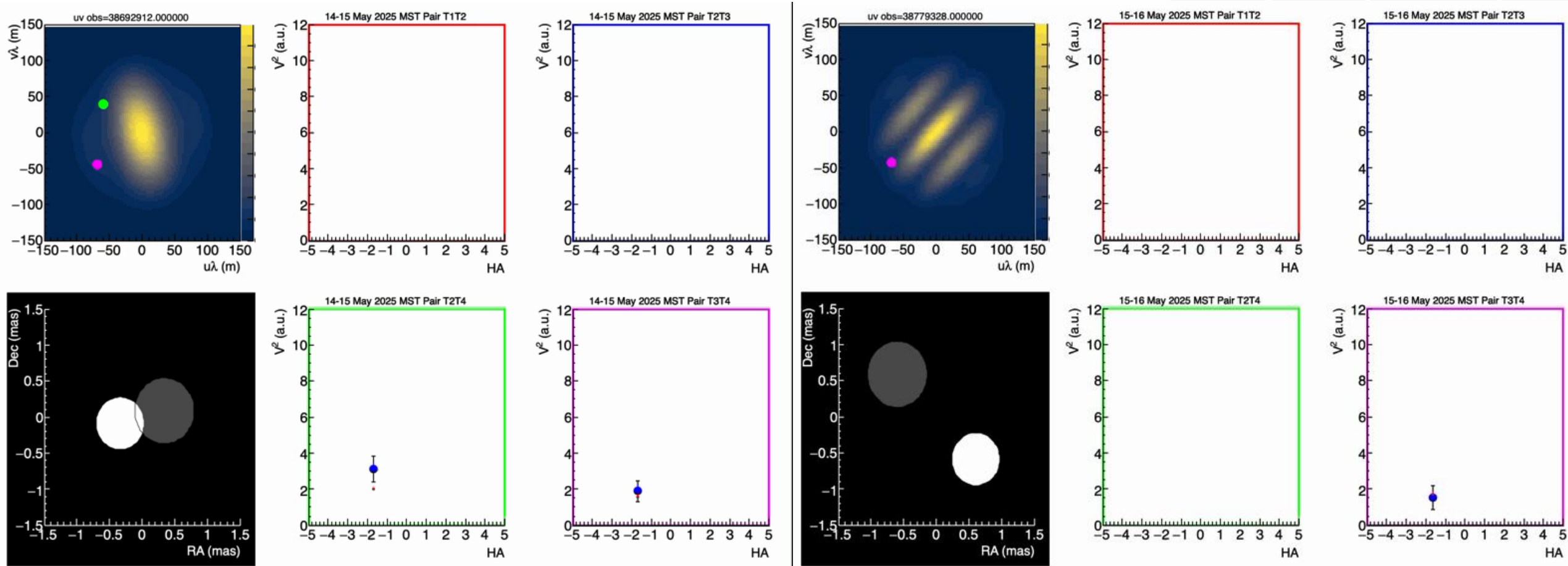
Fit 3 - $e=0$ - Nights 7,8 - 1 day apart



Fit 3 - e=0 – Days 9,10 – 8 days apart



Fit 3 - e=0 – Days 10,11 – 1 day apart

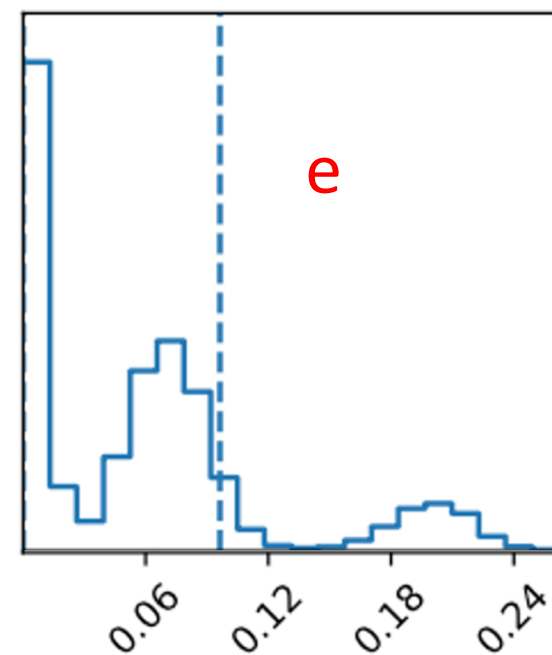
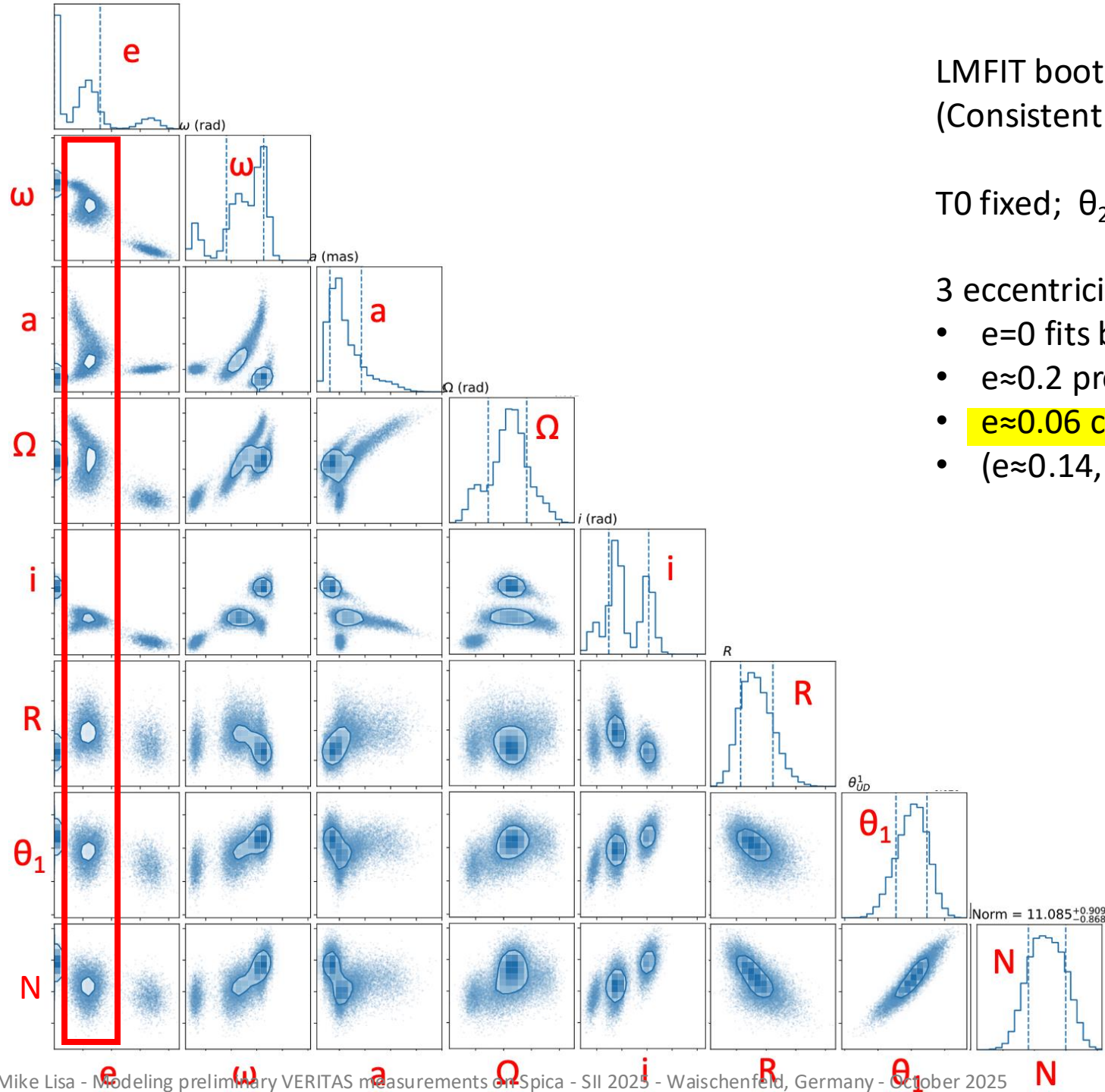


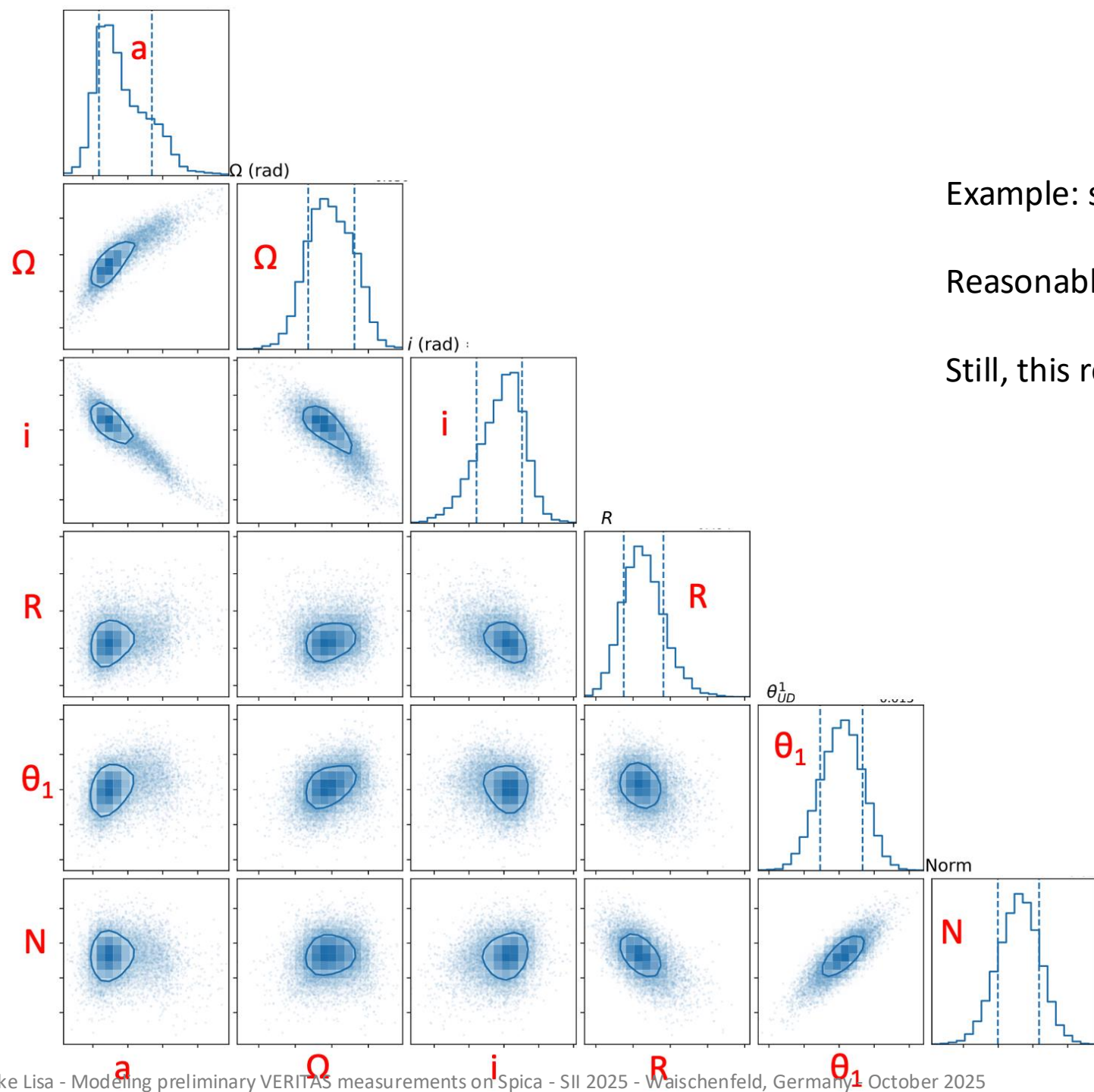
LMFIT bootstrap of 20,000 variations
(Consistent with TMinuit fit)

T_0 fixed; $\theta_2 = 0.4$ mas, as per HB

3 eccentricity regions:

- $e=0$ fits best, but discrepant with spectroscopy by $>3\sigma$
- $e \approx 0.2$ produces eclipses which are not observed
- $e \approx 0.06$ consistent with some spectroscopic reports
- ($e \approx 0.14$, taken as given by HB, is disfavored)





Example: setting $e=0.05$ (not necessarily the “best”)

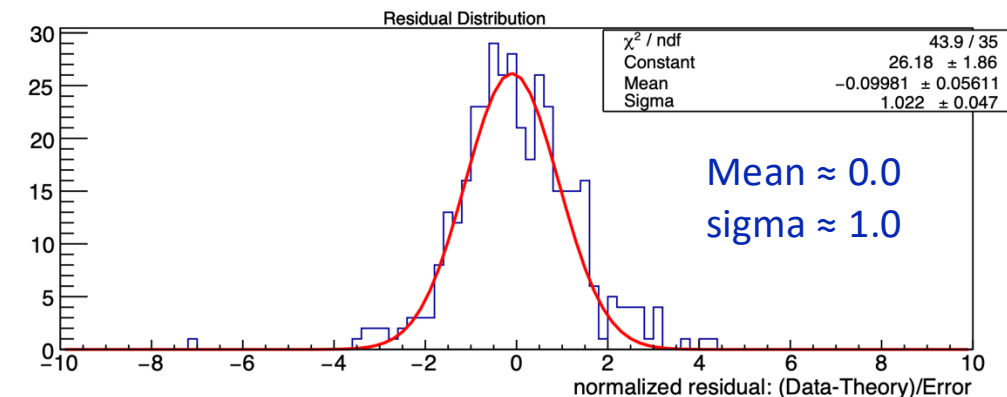
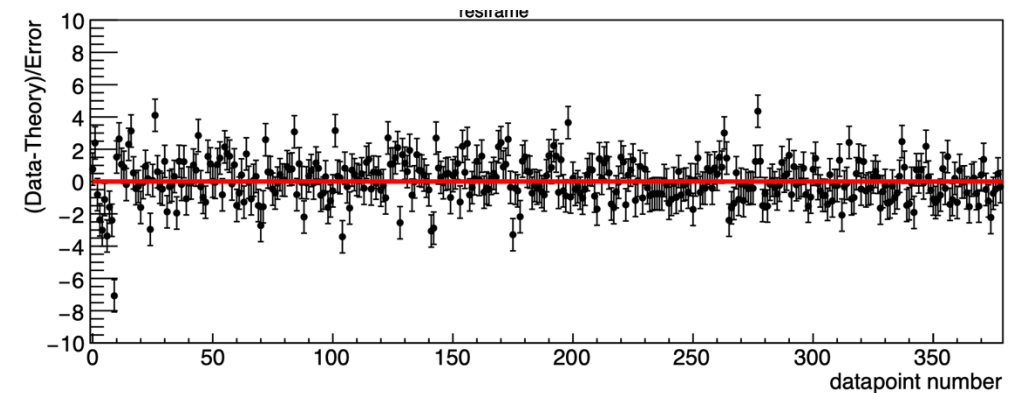
Reasonable, well defined/constrained orbital parameters

Still, this remains a *work in progress*

Summary



- VERITAS has analyzed ~150 pair-hours of observations on Spica with good coverage in (u,v)
 - another ~90 pair-hours not yet fully analyzed
- While a fitting code can/will return parameters, visualizing data-theory is valuable
- Display/comparison of data-vs-theory is non-trivial for fixed telescope arrays
- Visibility measured by any pair on a dynamic system depends on 2 independent times, further complicating visualization
- A standard binary star model is being used to fit **preliminary** VERITAS data
 - reasonable fits are achievable
 - **preliminary** result: perhaps somewhat low eccentricity
 - **preliminary** result: sensitivity to time of periastron, line of apsides which have non-negligible uncertainties from spectroscopy
 - *may have statistical power to probe love number*
- *21st century SII is continuing its steps towards more complex sources*



Thanks for your attention

