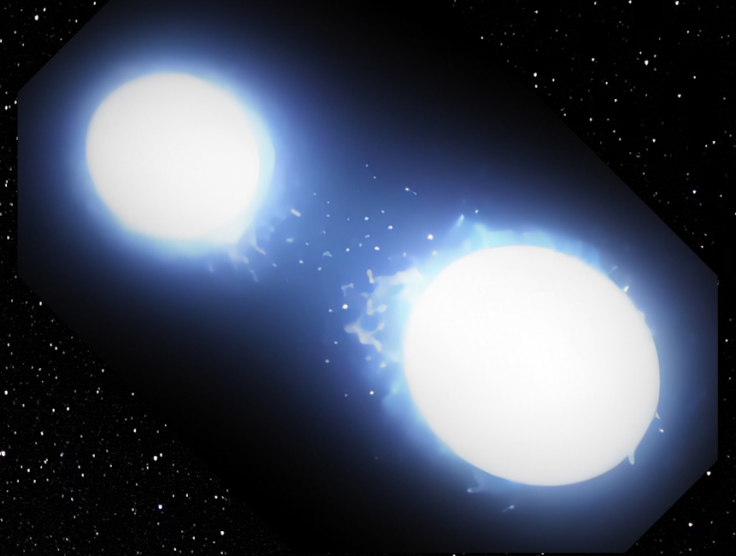


VERITAS II

Measurements on α Virginis

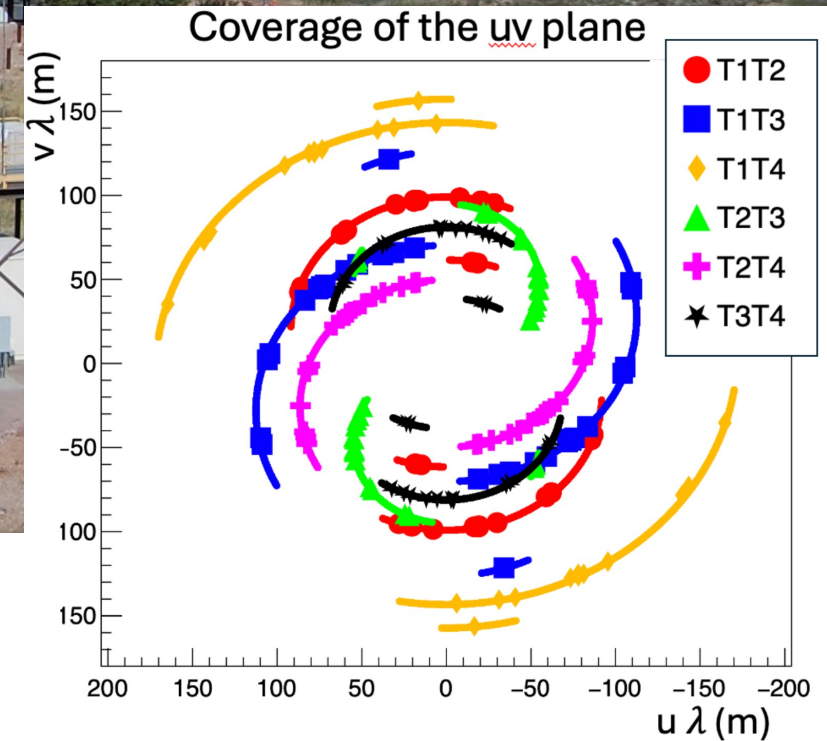
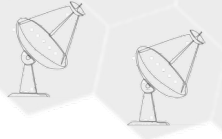


Mike Lisa
for the VERITAS Collaboration

Workshop on Stellar Intensity Interferometry
La Palma, Spain, October 2026

VERITAS: Very Energetic Radiation Imaging Telescope Array System

VERITAS SII



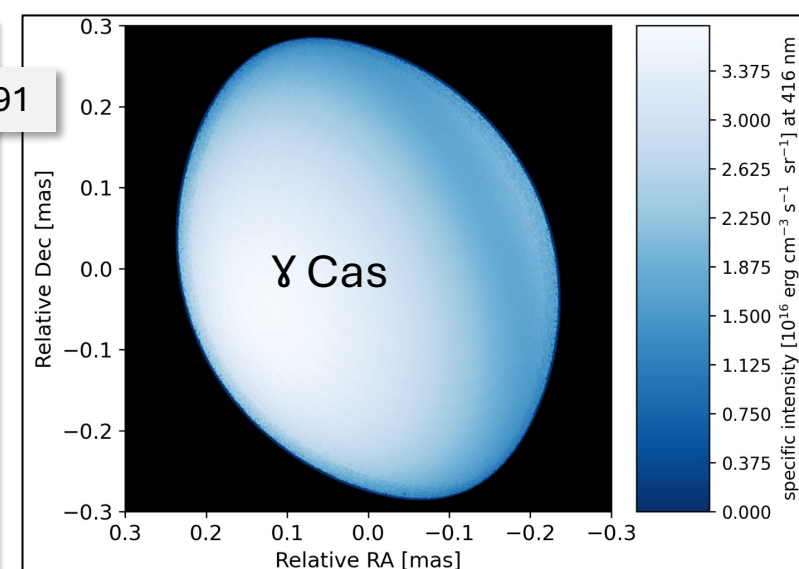
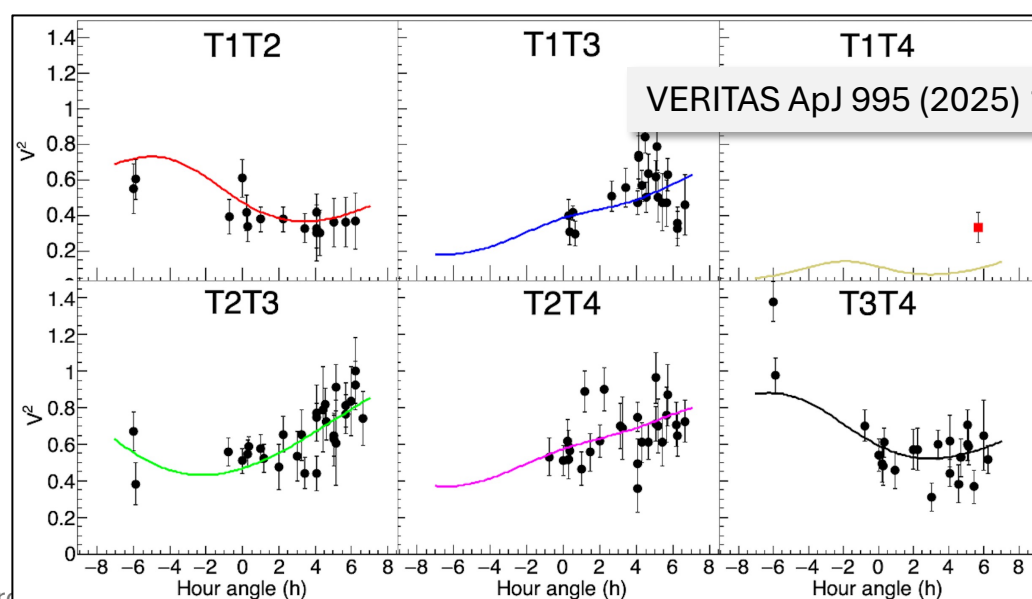
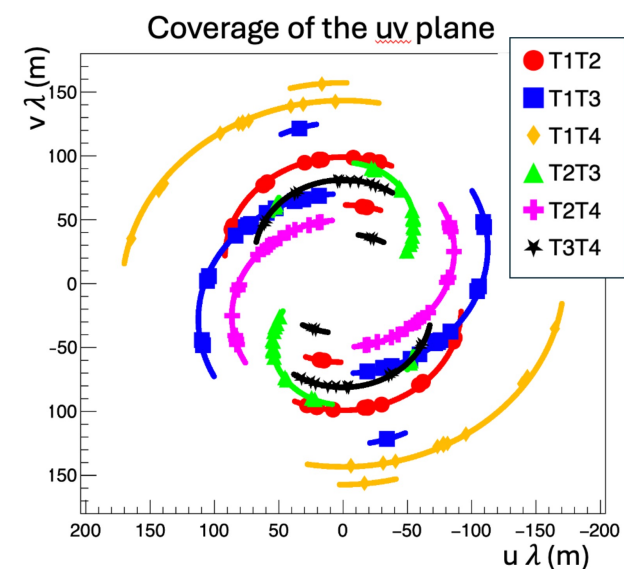
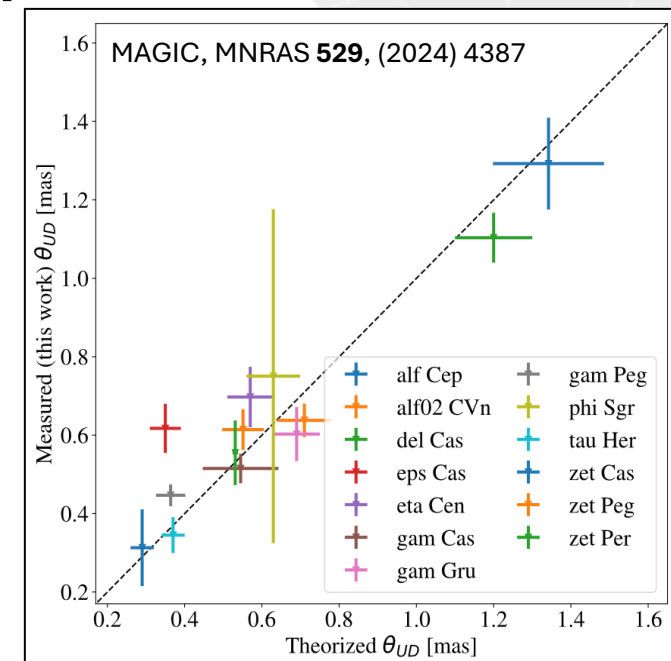
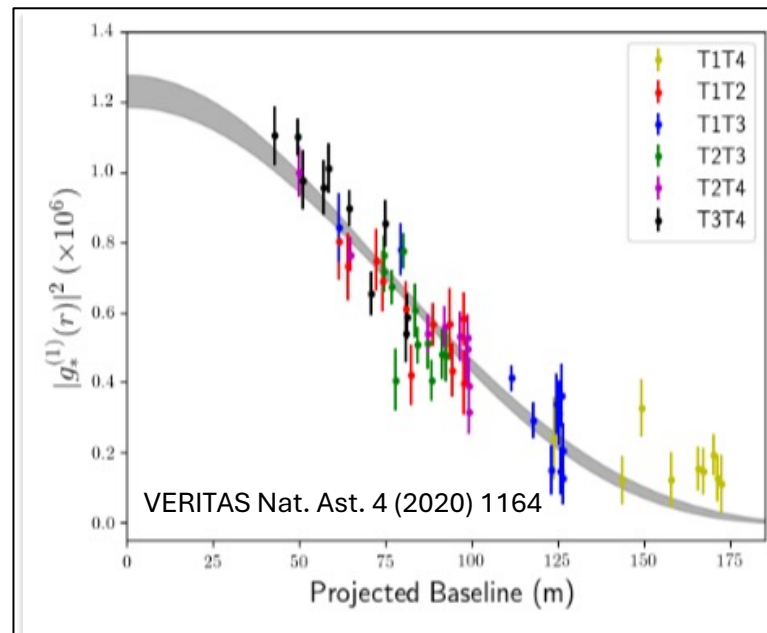
Pushing modern SII reach & scientific impact

Growing catalog of stellar **radii**

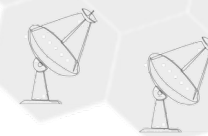
- $|V|^2$ versus **b**
- age determination, etc.

First measurements of **size & shape**

- $|V|^2$ versus **(u,v)** [$b^2=u^2+v^2$]
- e.g. rapid rotators
- system response to extreme conditions
- pole brightening, etc.



Pushing modern SII reach & scientific impact



Growing catalog of stellar **radii**

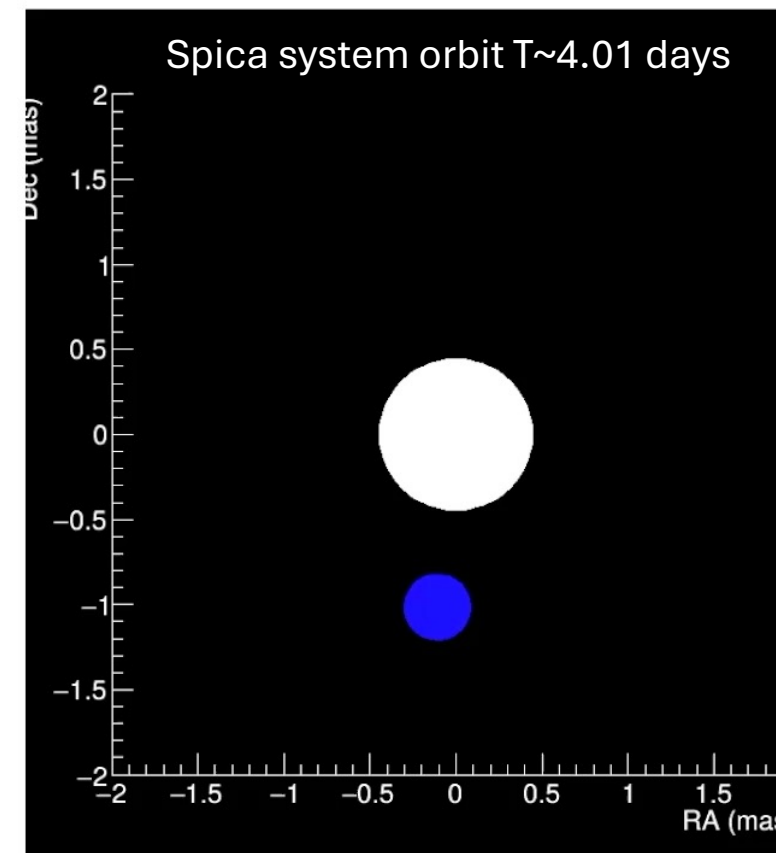
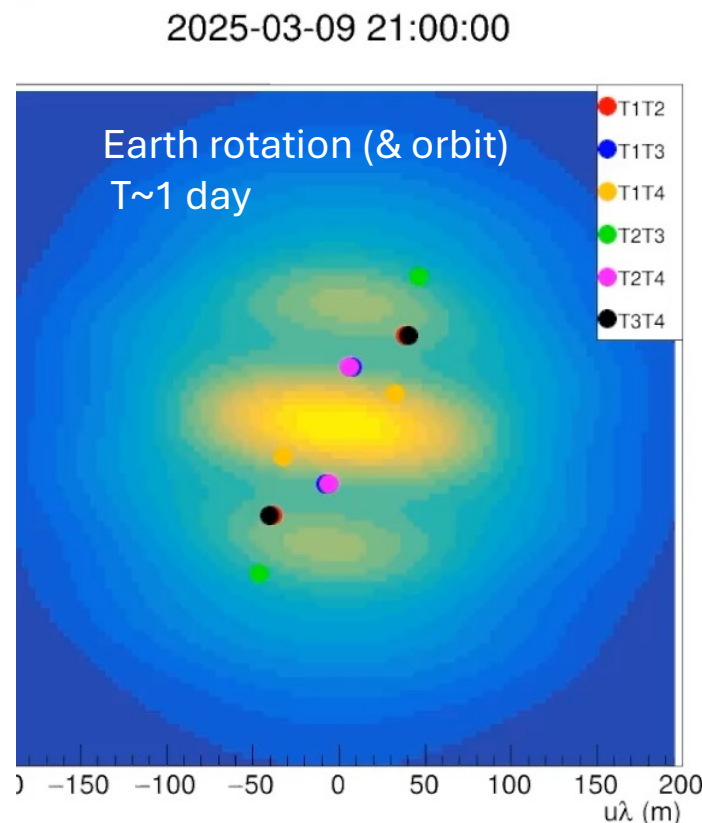
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First measurements of size & **shape**

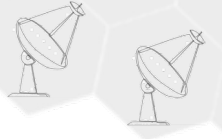
- $|V|^2$ versus **(u,v)** [$b^2 = u^2 + v^2$]
- e.g. rapid rotators
- system response to extreme conditions
- pole brightening, etc.

Measure **dynamic** system

- $|V|^2$ versus **(u,v,t)**
 - t = time of observation
- e.g. **binary system**
- precise mass, age measurement
- structure constant (mass distribution)
- degree of evolution
- “eccentricity problem,” “mass discrepancy problem”...
- modeling tides / orbit-rotation coupling – apsidal motion

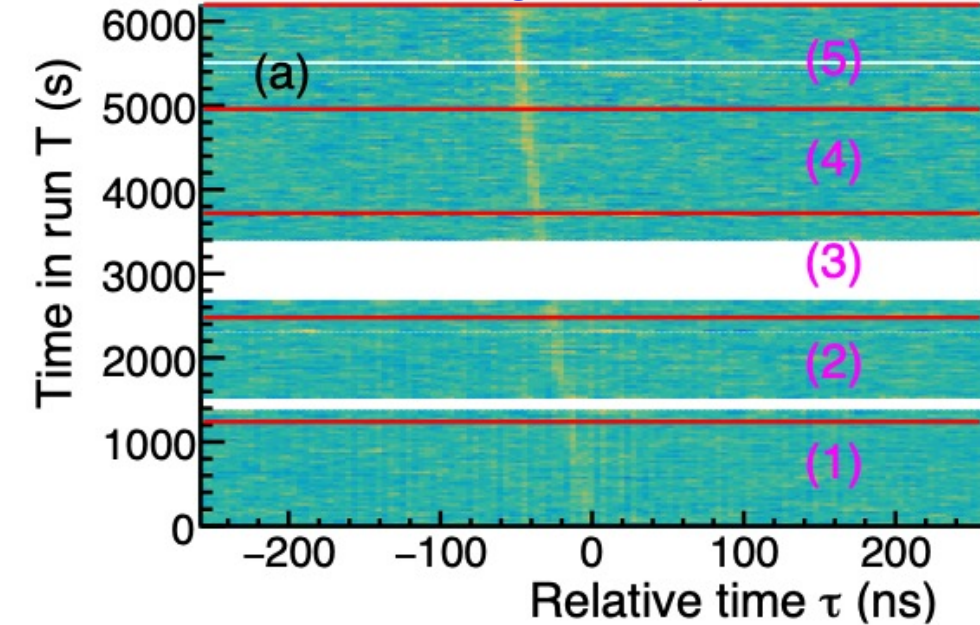


Data from VERITAS

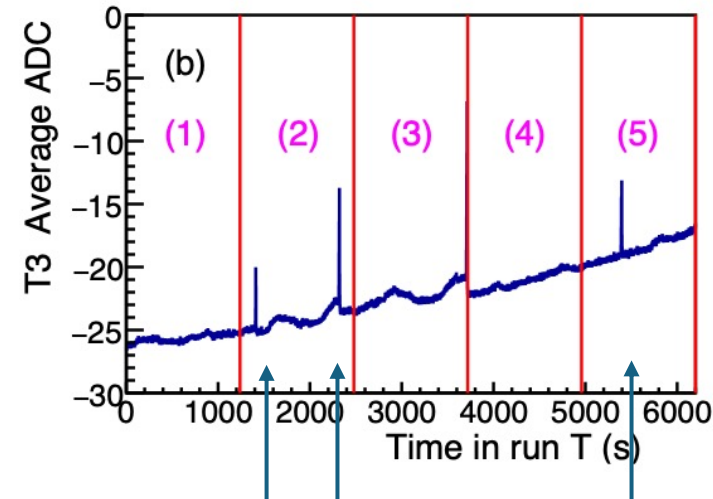


- 150 good pair-hours over 4 years (spans ~ 350 orbits of Spica)

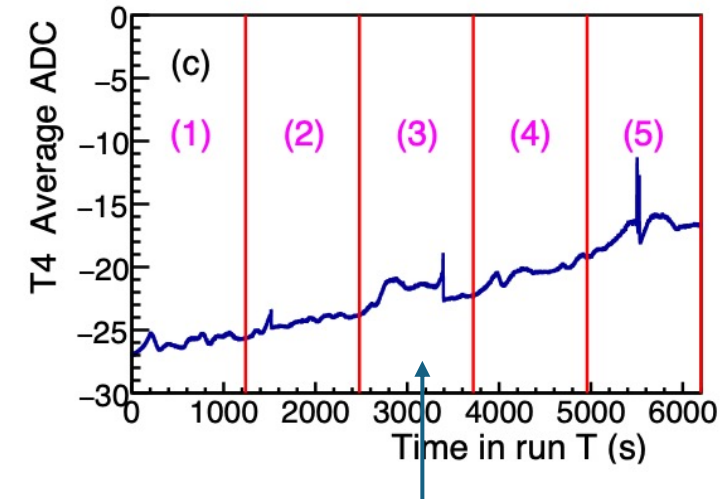
1.7 hour-long run with pair T3T4



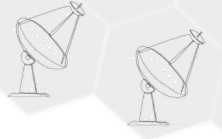
T3 average current



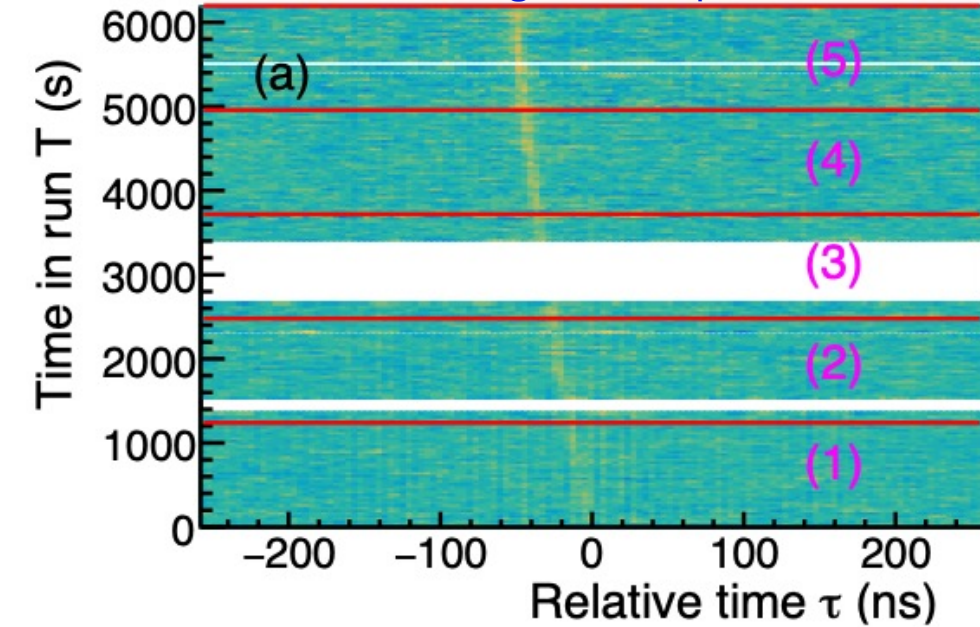
T4 average current



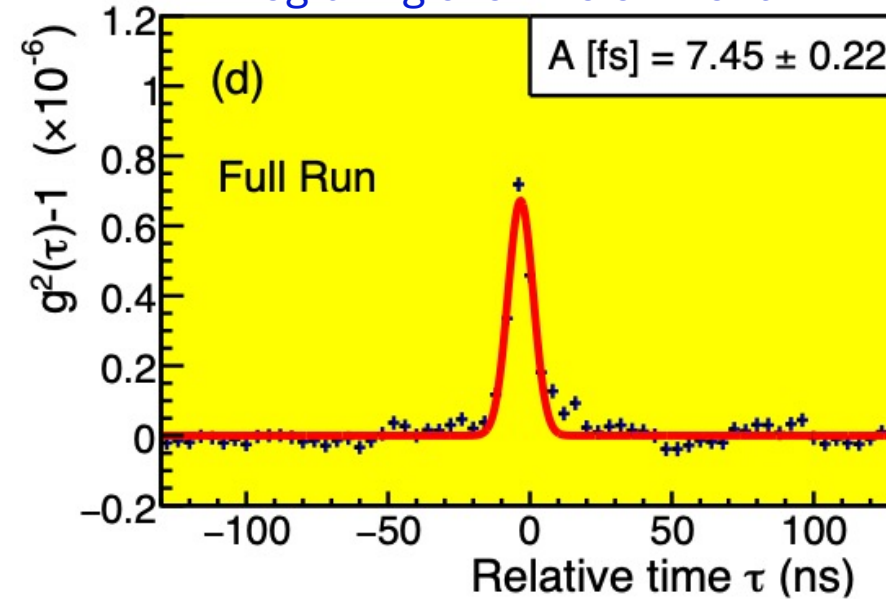
Data from VERITAS



1.7 hour-long run with pair T3T4



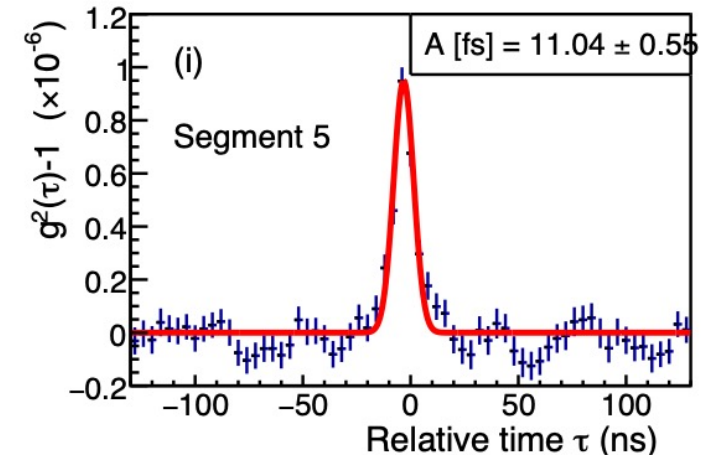
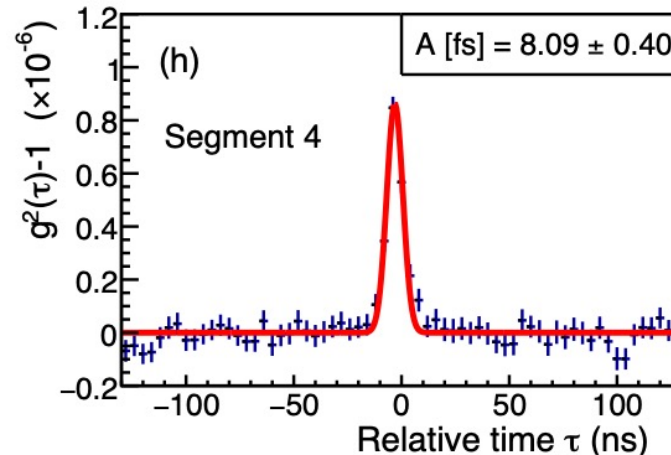
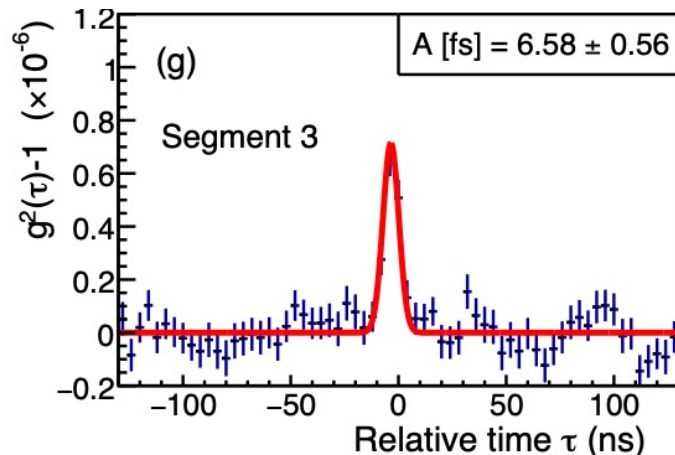
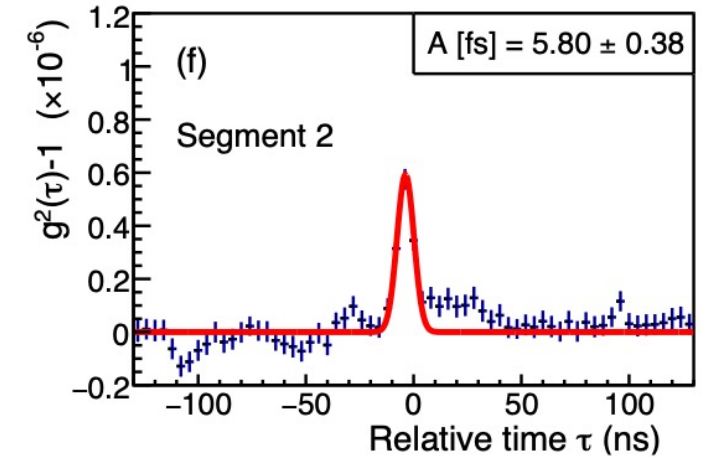
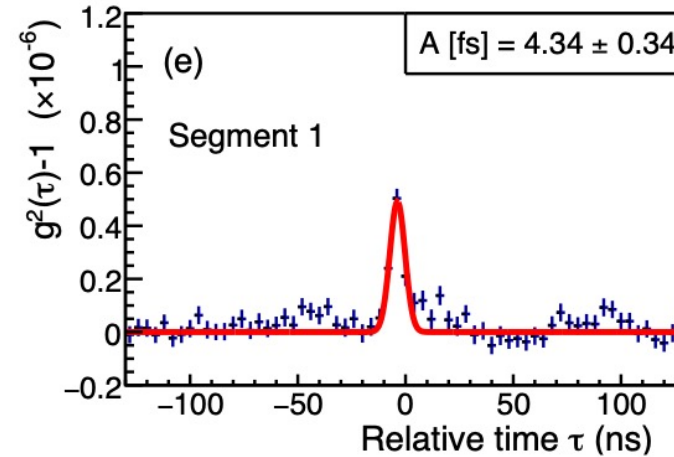
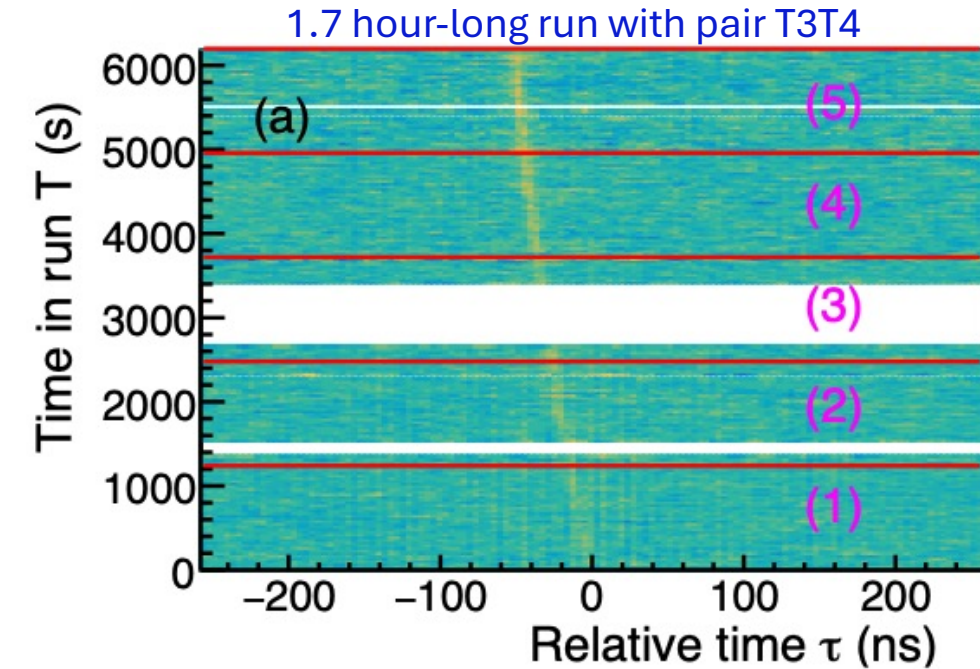
Integrating over the entire run



Data from VERITAS

The visibility changes significantly over ~20 minutes

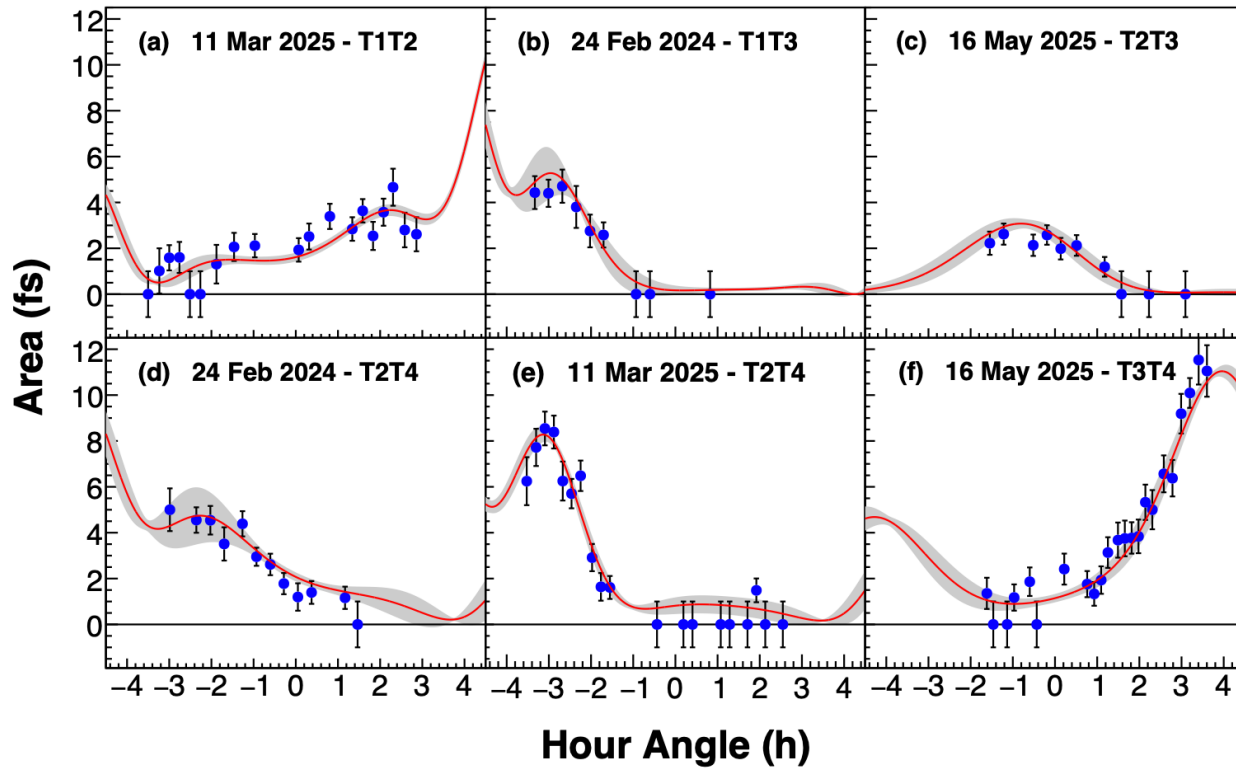
- Spica is bright $\rightarrow$ can measure $|V|$ in ~12-minute chunks



Visibility versus hour-angle

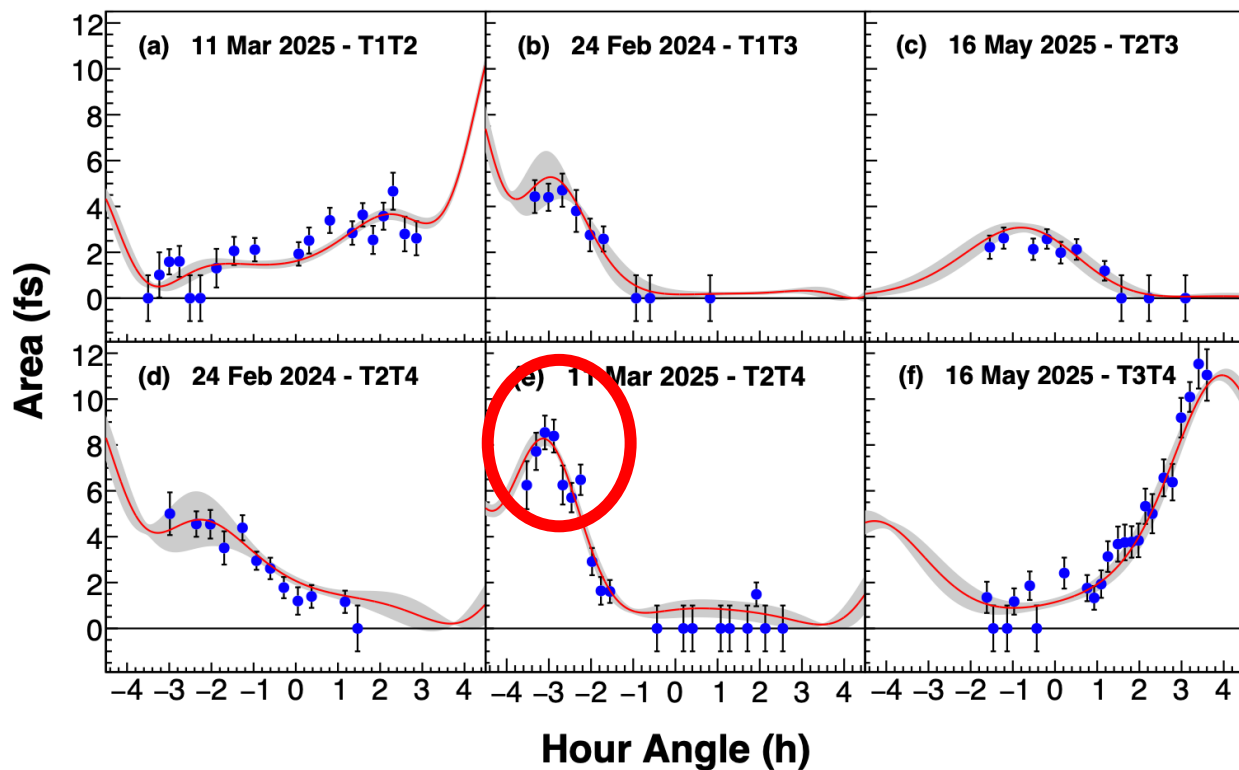
The visibility changes significantly over ~ 20 minutes

- Spica is bright $\rightarrow$ can measure $|V|$ in ~ 12 -minute chunks



Examples of single telescope pairs on single nights

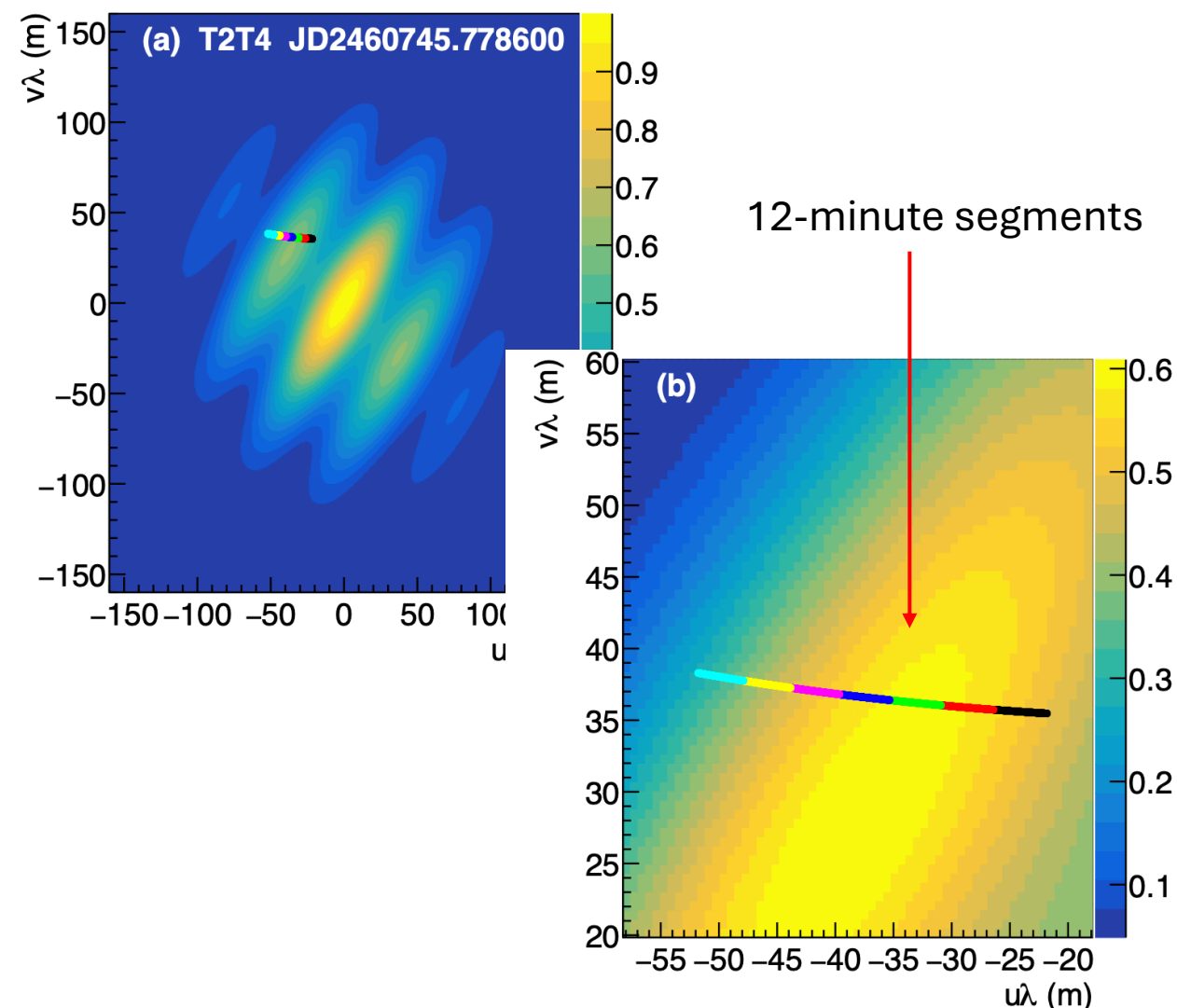
Visibility versus hour-angle



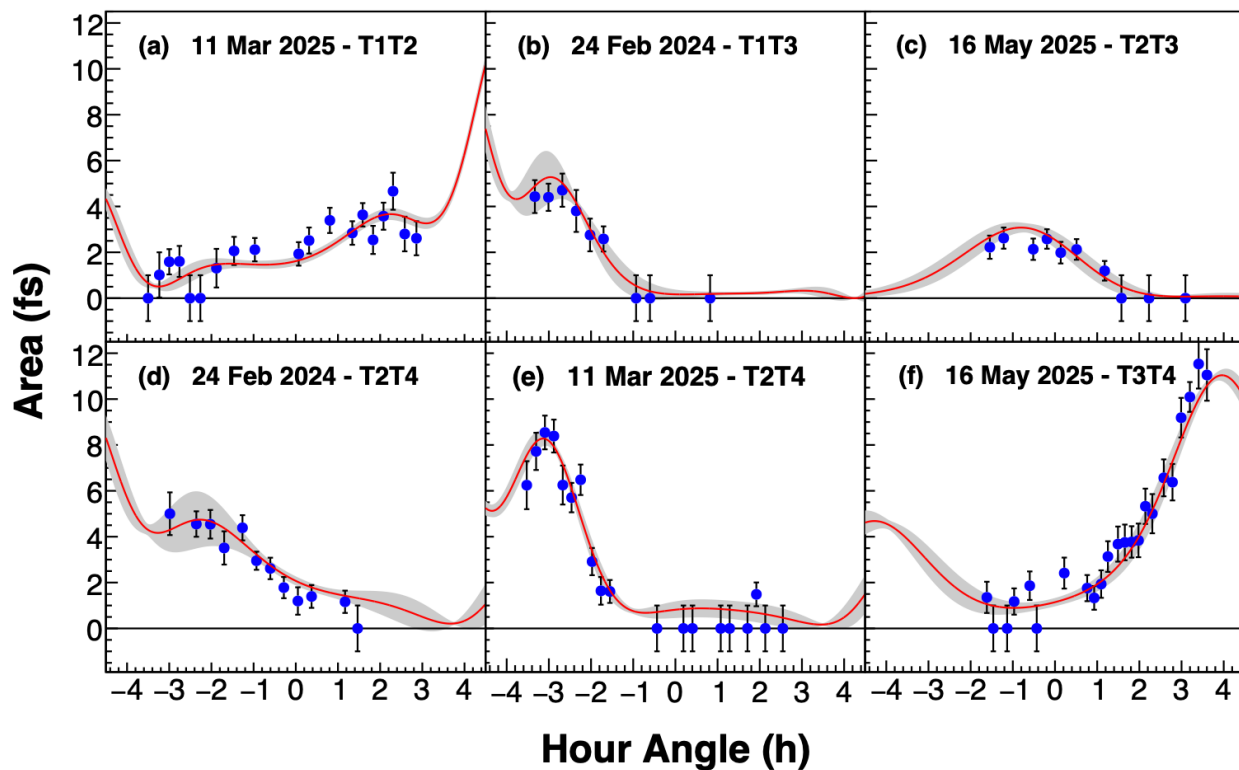
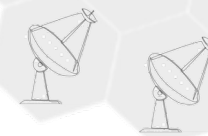
Examples of single telescope pairs on single nights

The visibility changes significantly over ~20 minutes

- Spica is bright → **can** measure $|V|$ in ~12-minute chunks
- Sharp fringes → **must** measure in short chunks!



Visibility versus hour-angle

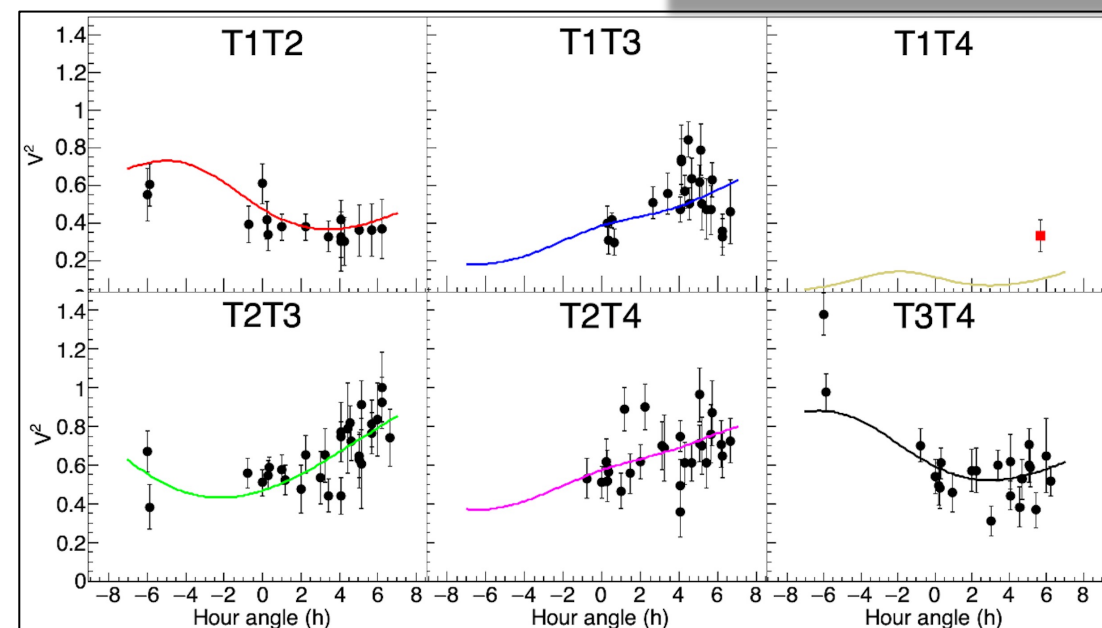
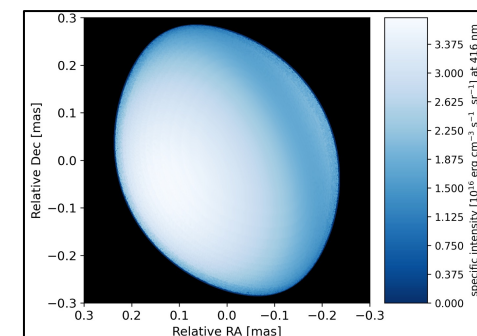


Examples of single telescope pairs on single nights

- For a non-evolving source (even a non-round one) $|V|$ for a given telescope pair depends only on HA
 $\rightarrow$ can combine multiple nights in a plot
- Untrue** for dynamic binary star system
 $\rightarrow$ each night has different $|V|$ vs HA

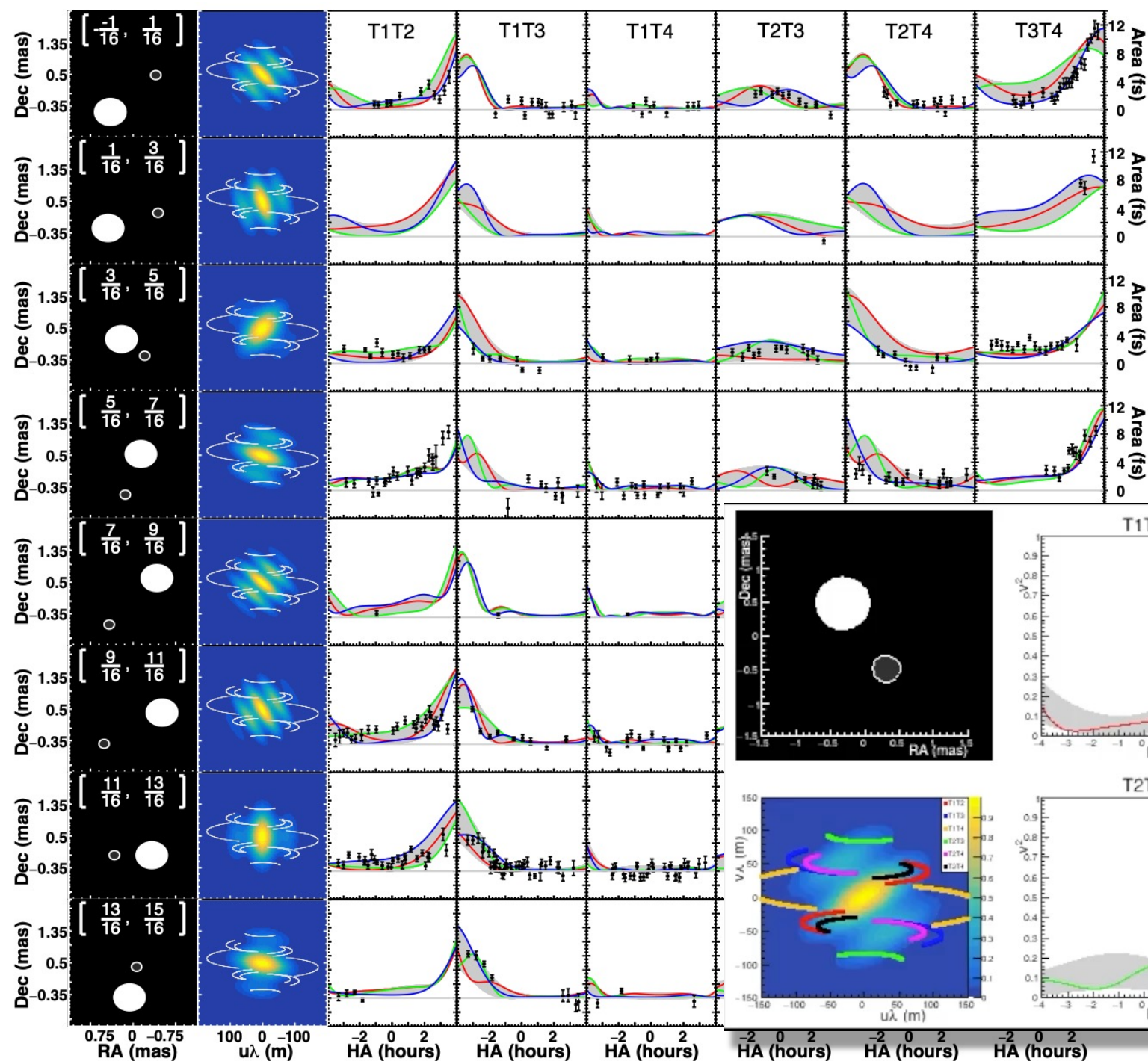


Oblateness of γ Cas
 VERITAS ApJ 995:191 (2025)

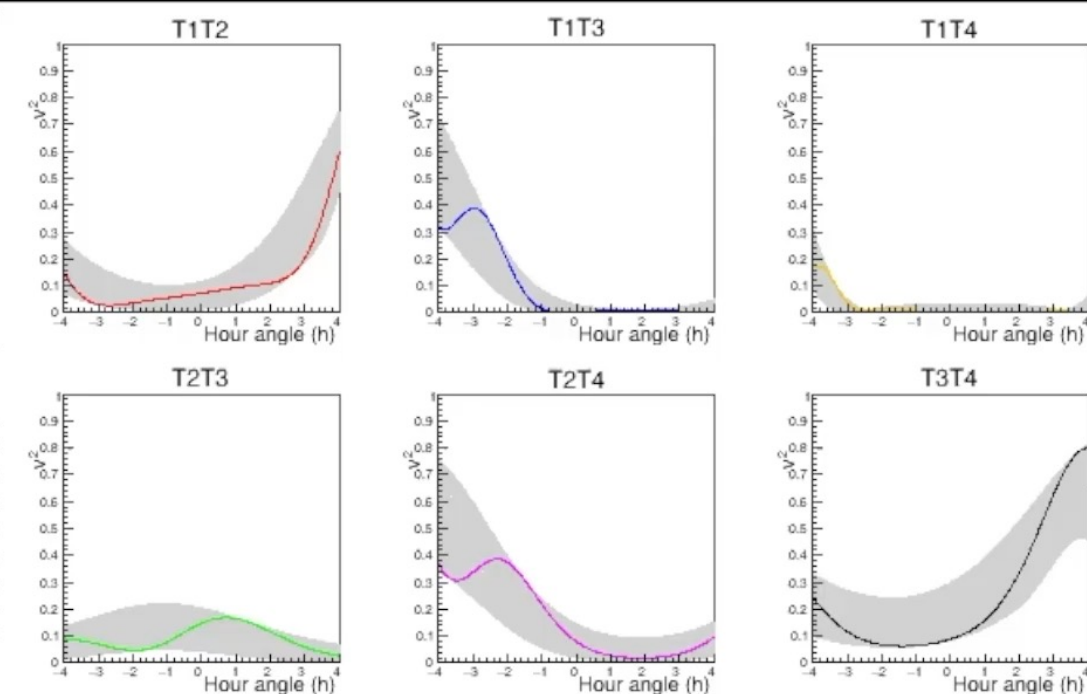
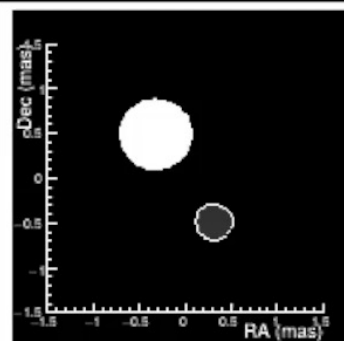


$|V|$ versus HA in 8 slices of the orbital phase

- careful - expect scatter!

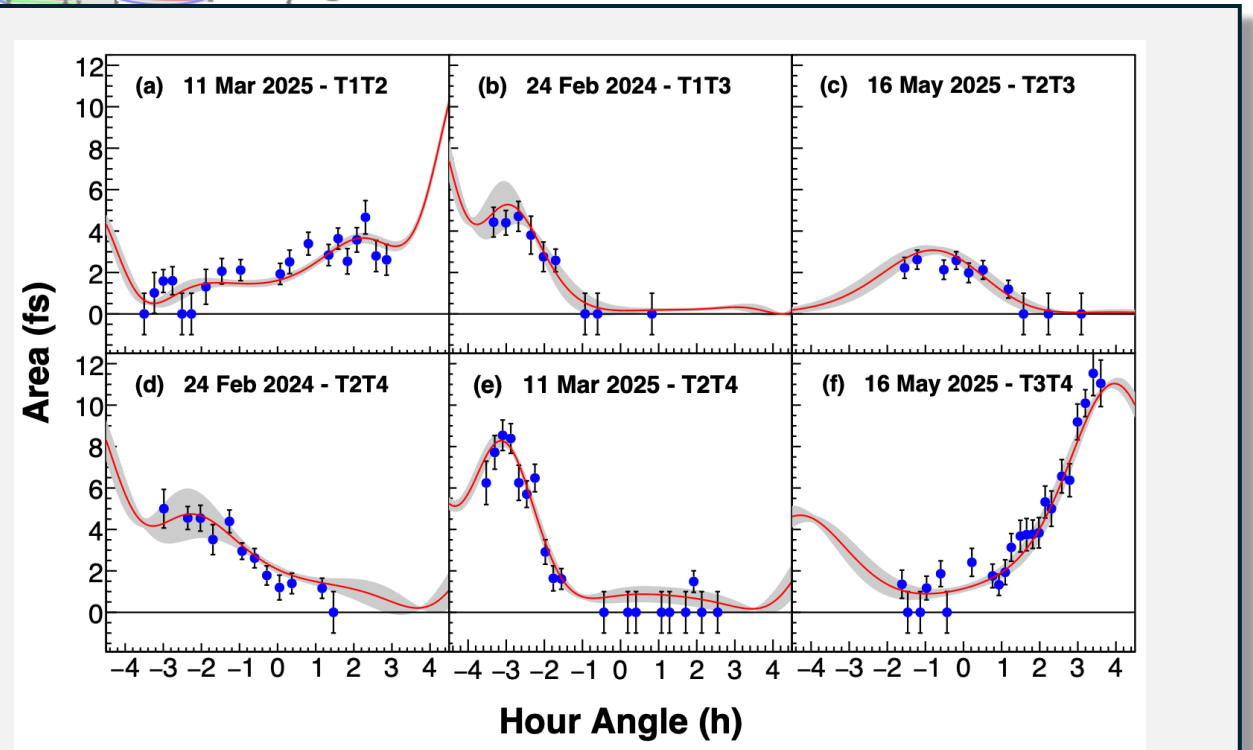
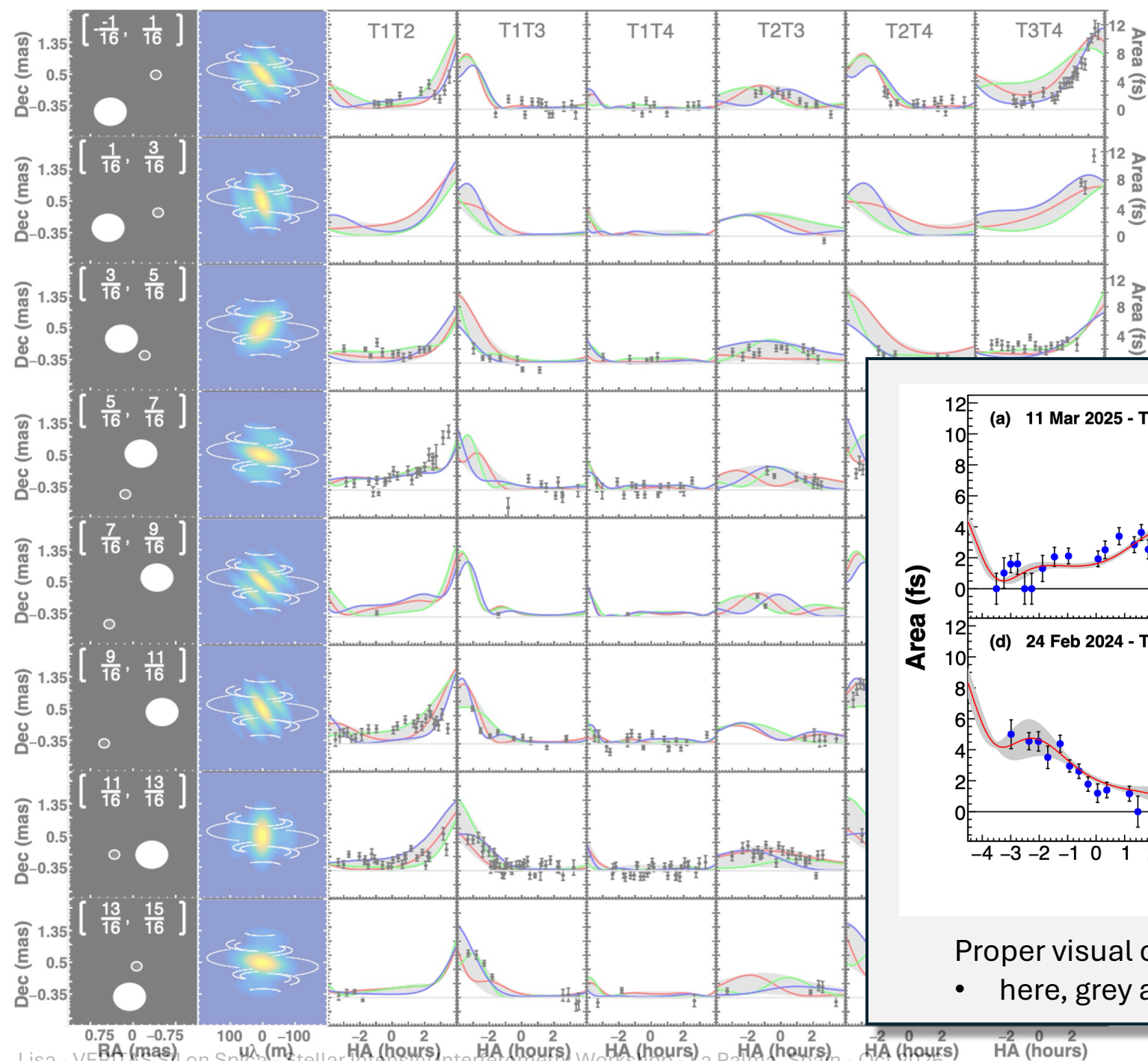


- $|V|$ at start of phase slice
 - $|V|$ at middle “ “
 - $|V|$ at end of “ “
- shaded region:
- bounds of variation over phase slice
 - not an error band



$|V|$ versus HA in 8 slices of the orbital phase

- careful - expect scatter!



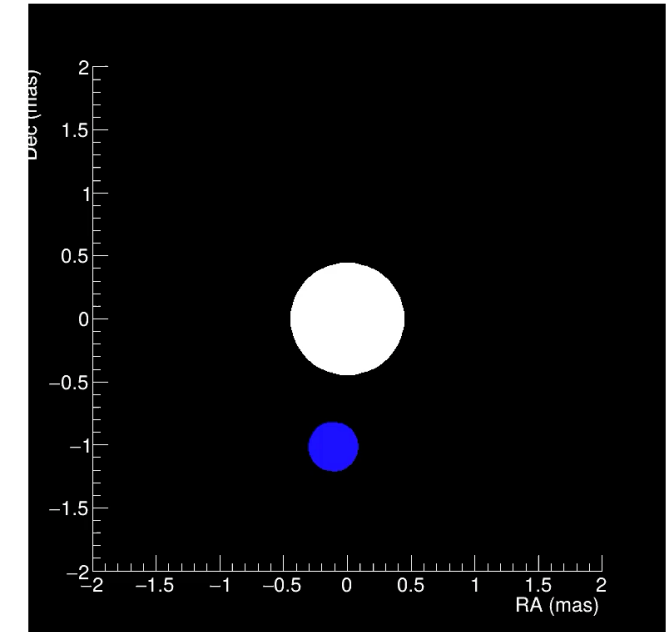
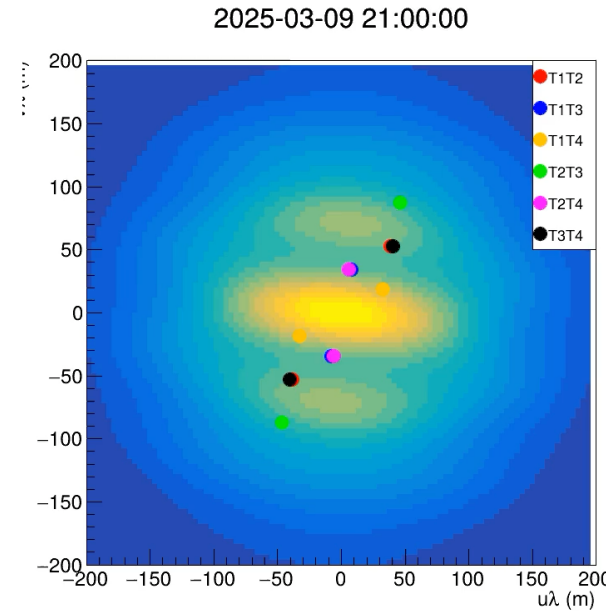
Proper visual comparison to theoretical fit through such plots

- here, grey area is the error band

Modeling the data - Two uniform disks in elliptical orbit

$V^2(u,v,t)$ depends on 10 parameters

Symbol		Name
6 orbital parameters	T	Time of periastron
	e	Eccentricity
	ω_0	Longitude of periastron (line of apsides, major axis) at periastron
	Ω	Position angle of line of nodes
	i	Inclination
	a	Semimajor axis
3 stellar parameters	$\theta_{UD,1}$	UD ang. diam. of primary
	$\theta_{UD,2}$	UD ang. diam. of secondary
	R	Brightness ratio (>1)
	Norm	Instrumental normalization



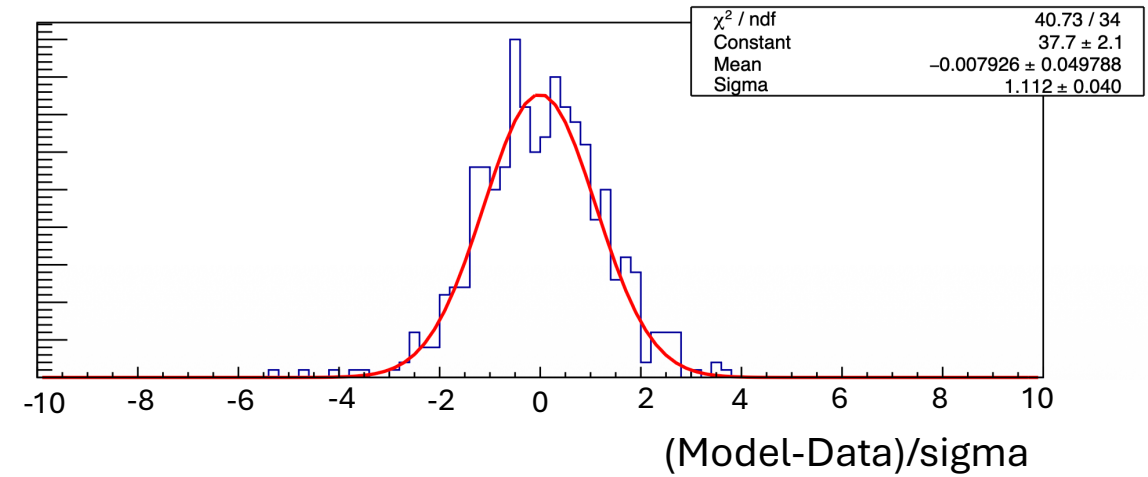
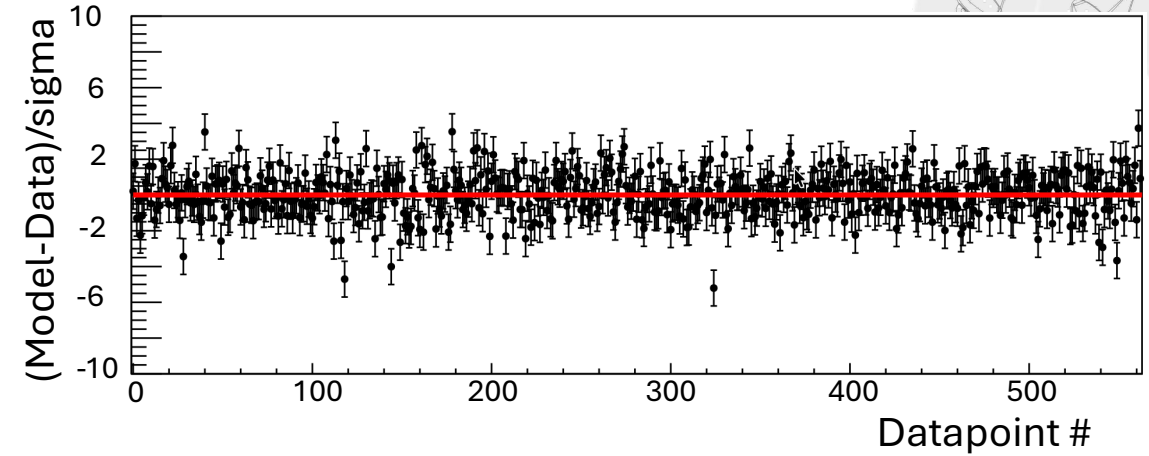
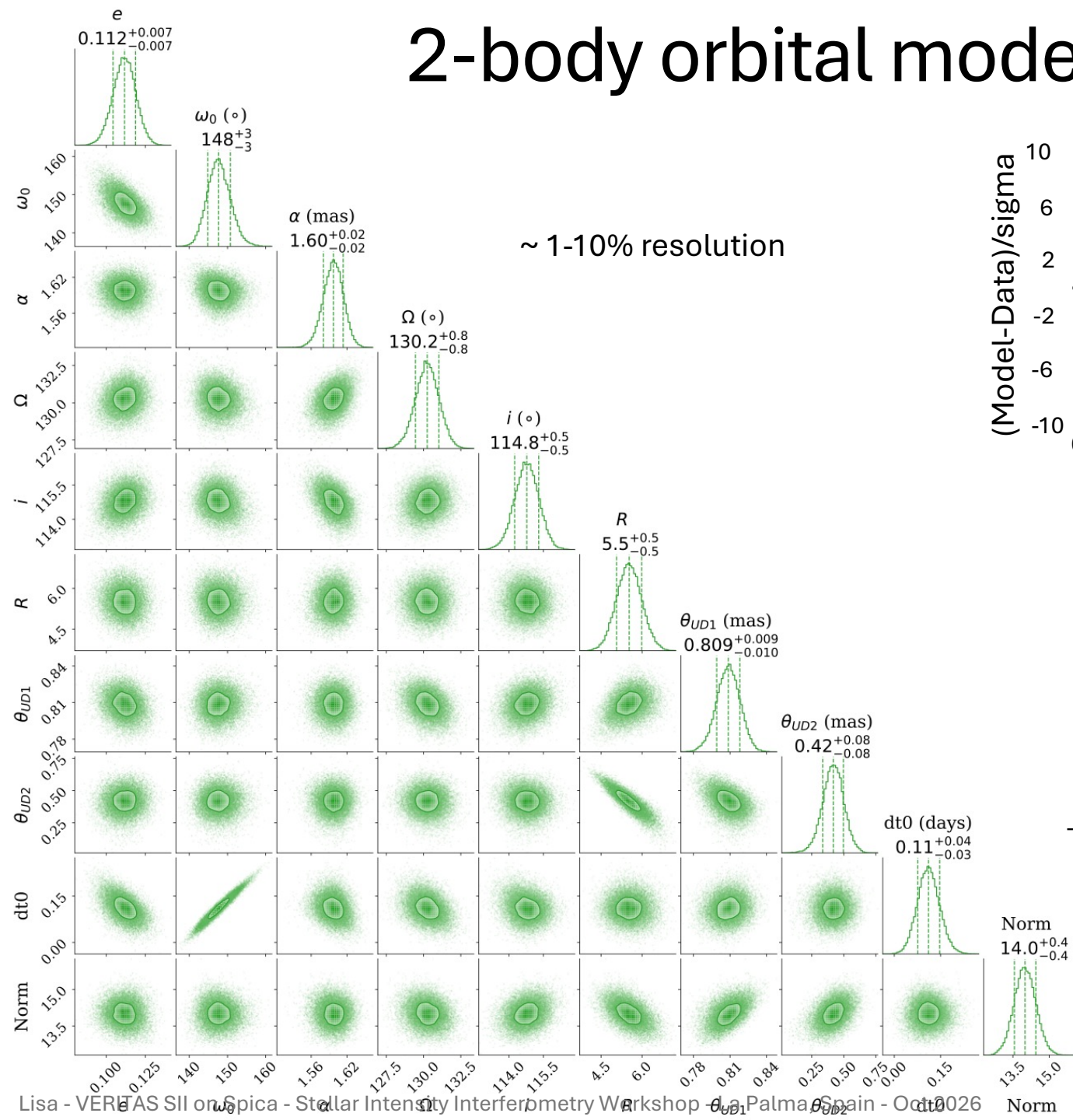
Also depends on

- orbital period
- apsidal period (tidal interactions)

Use values from other sources, though we vary these, too

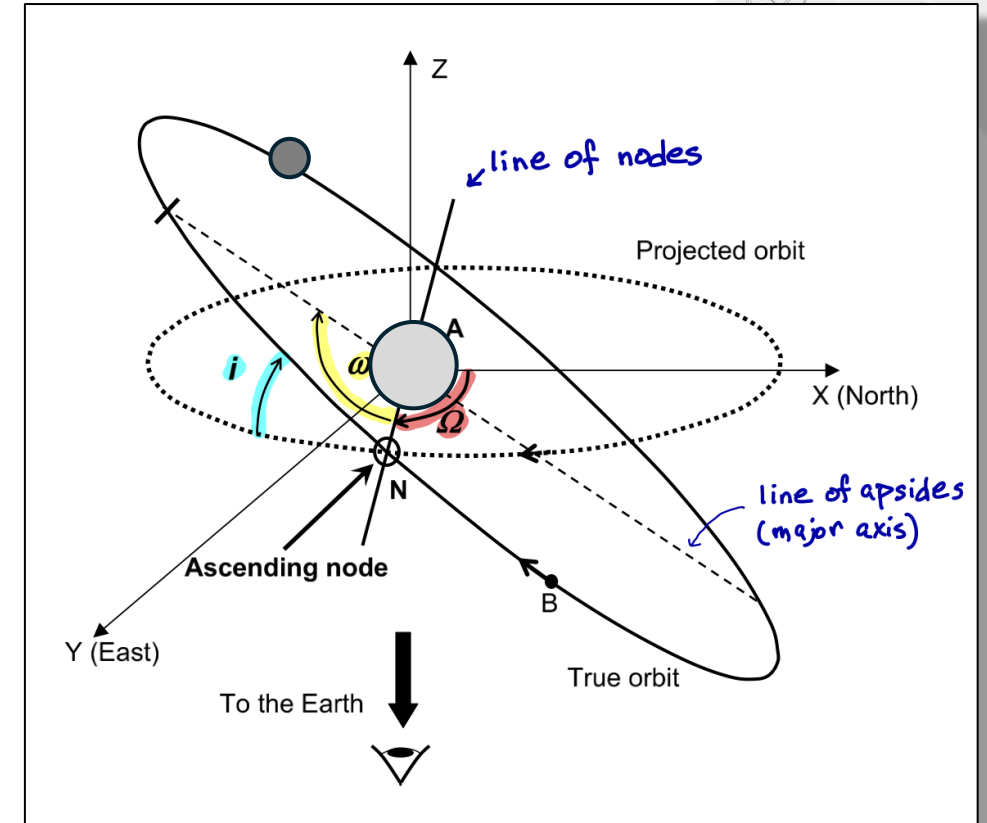
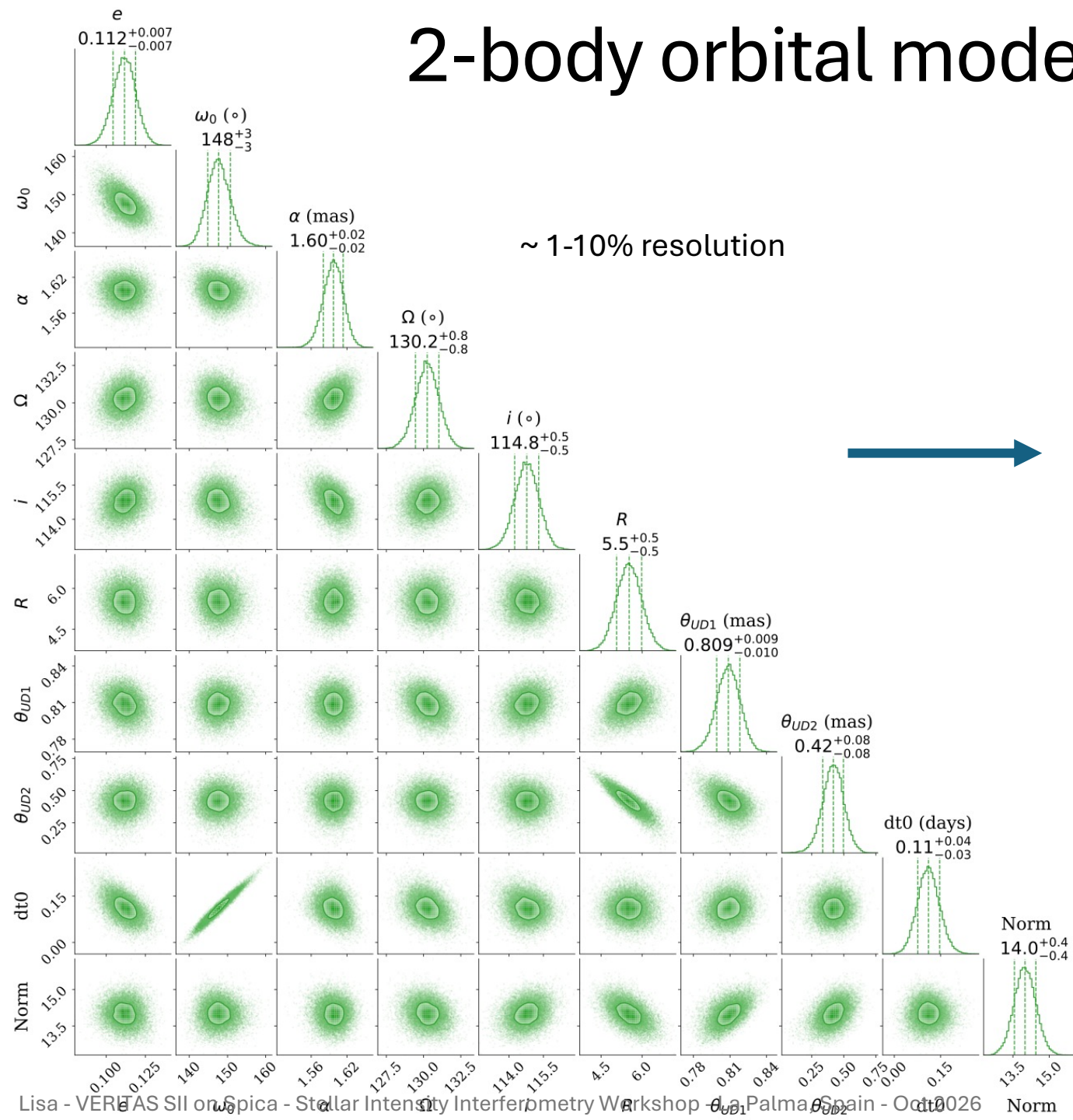
Following formalism of Pan et al, ApJ, 356, 641 (1990)

2-body orbital model on (only) SII

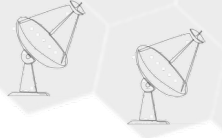


- Fit 562 datapoints accumulated 06/2021-05/2025
 - ~350 orbital cycles
- Good fit

2-body orbital model on (only) SII



- Each star's size
- relative brightness
- full orbital information

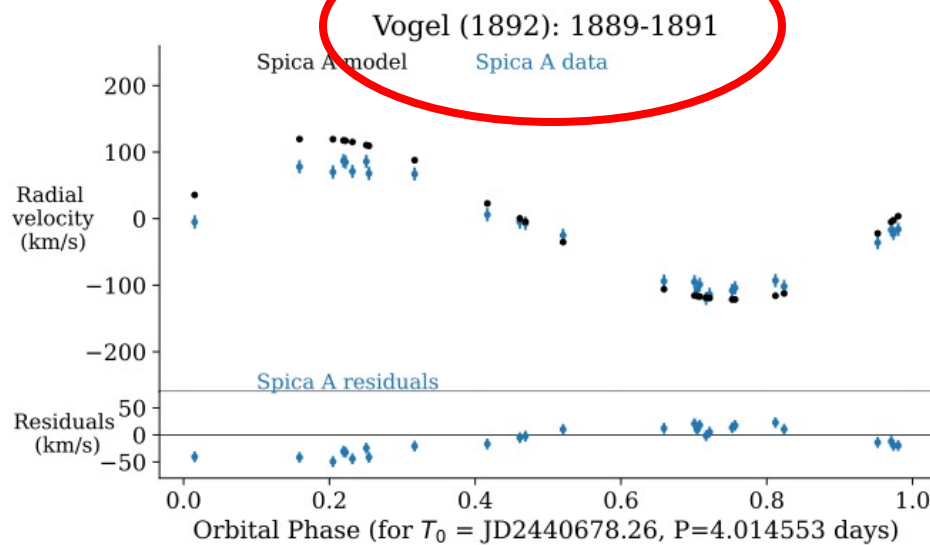


Combine / compare with independent (non-SII) measures

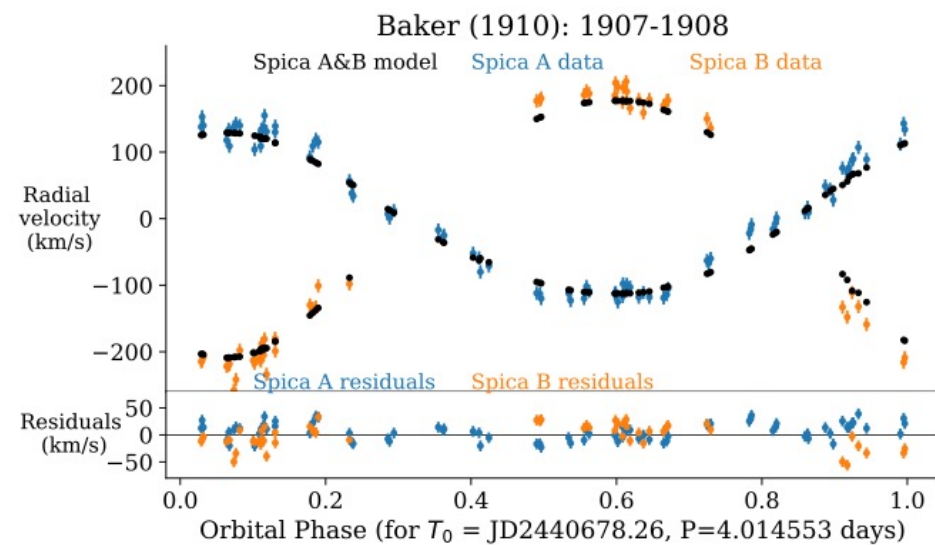
Information from spectroscopy

Radial velocity curves sensitive to

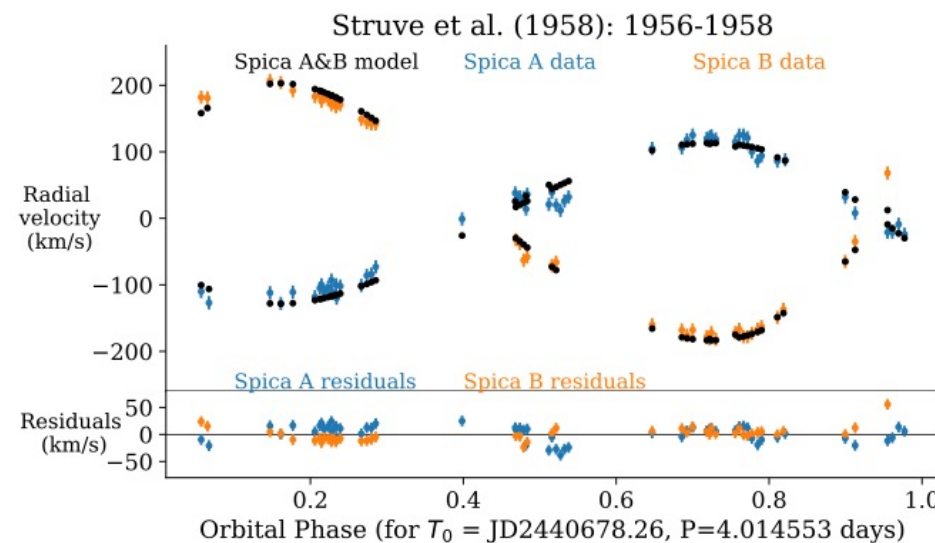
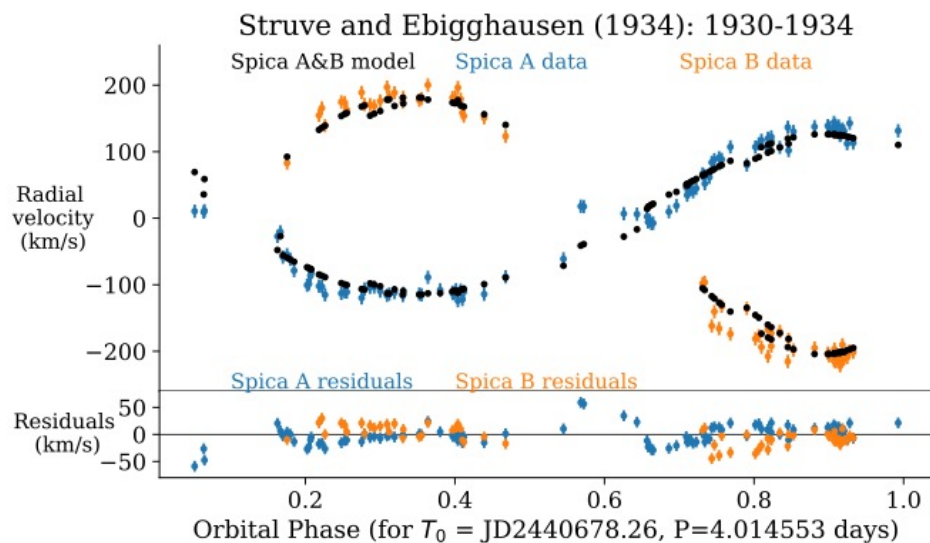
- **eccentricity e**
- epoch of periastron (T_0)
- longitude of periastron (ω_0)



(a)

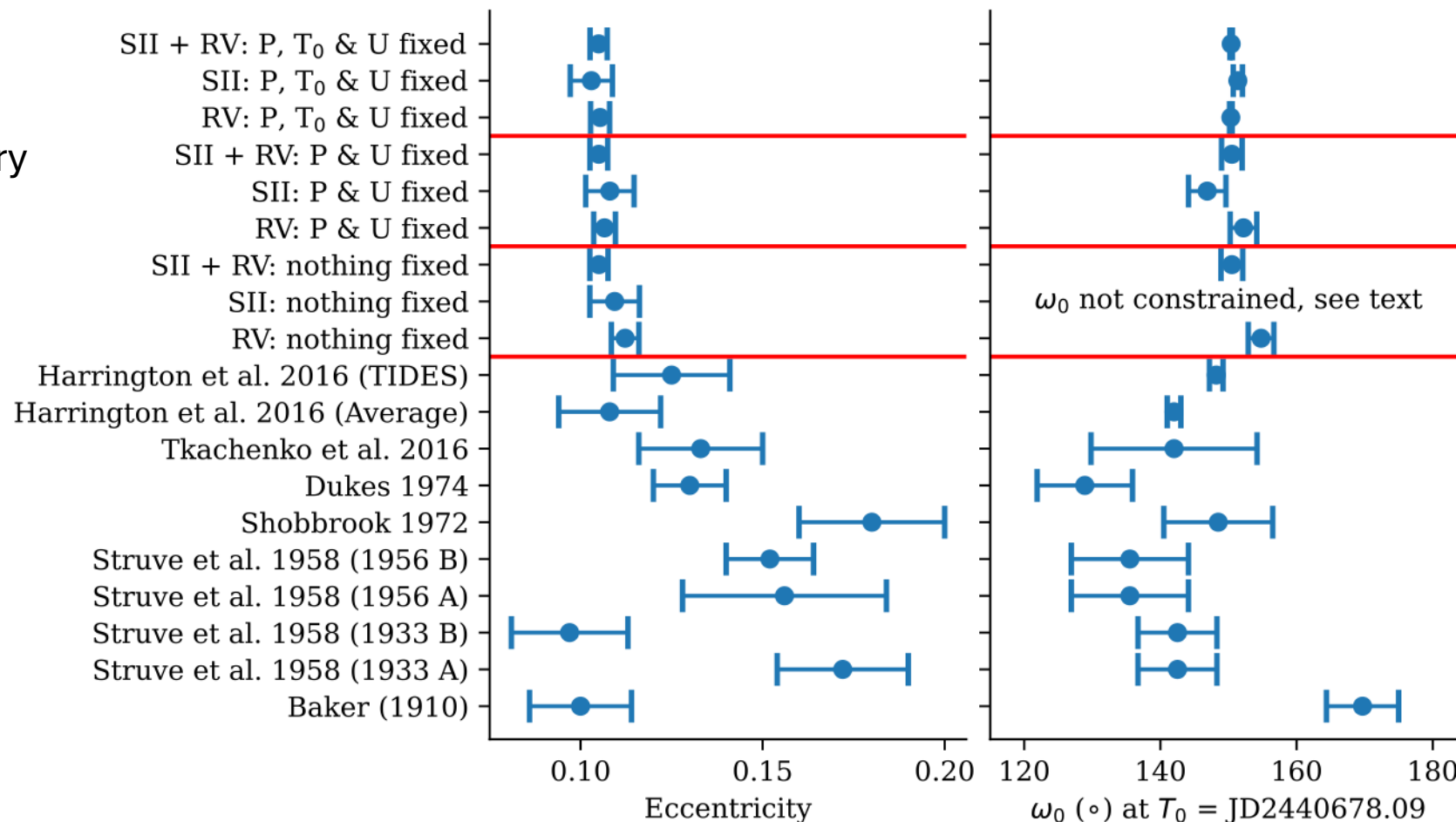


(b)



Resolution of the “eccentricity problem”

- ϵ : crucial input to binary models
- estimates of ϵ from RV curves vary strongly
- may be due to subtle line-shift issues in the technique and epoch of measurement [1]



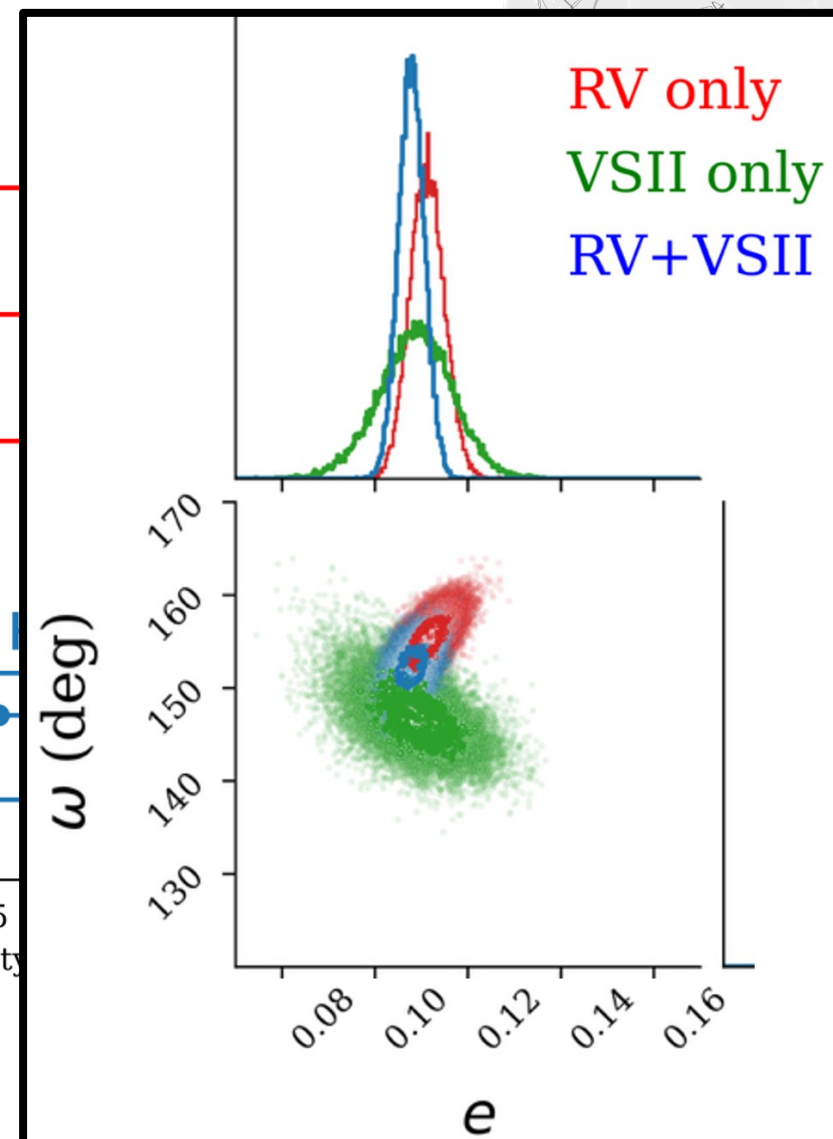
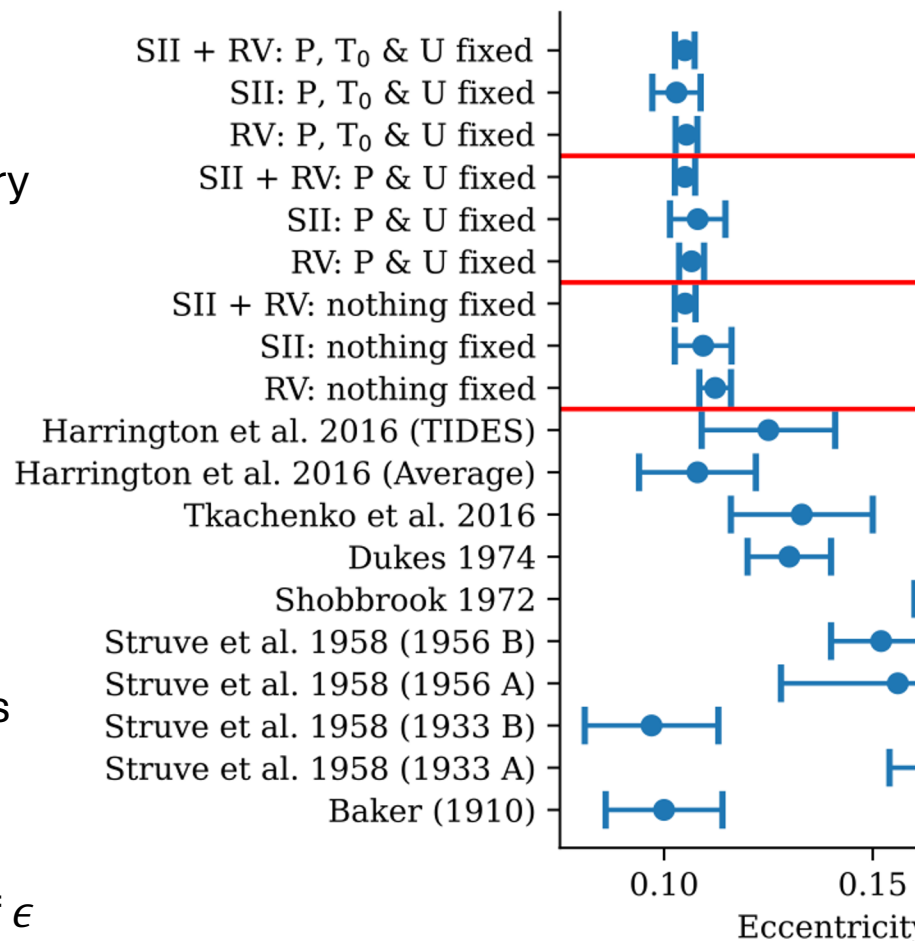
[1] Harrington et al A&A, 590, A54 (2016)

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SII

- completely independent measurement w/ diff correlations
- promotes Spica from a spectroscopic to a visual binary
- accurate and precise measure of ϵ



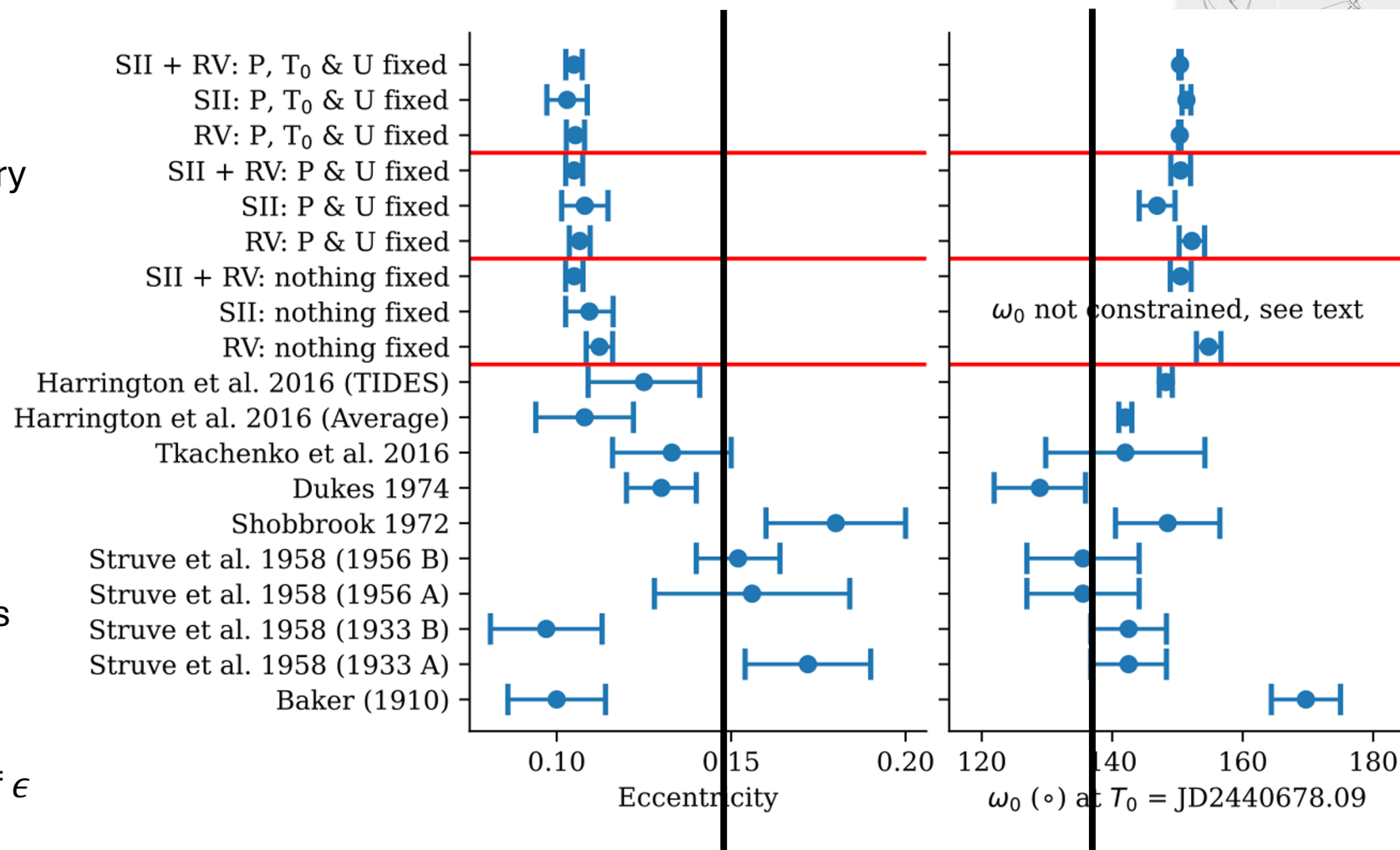
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- Hanbury Brown [2] *fixed* $\epsilon = 0.146$, $\omega_0 = 138^\circ$ (& other parameters...)

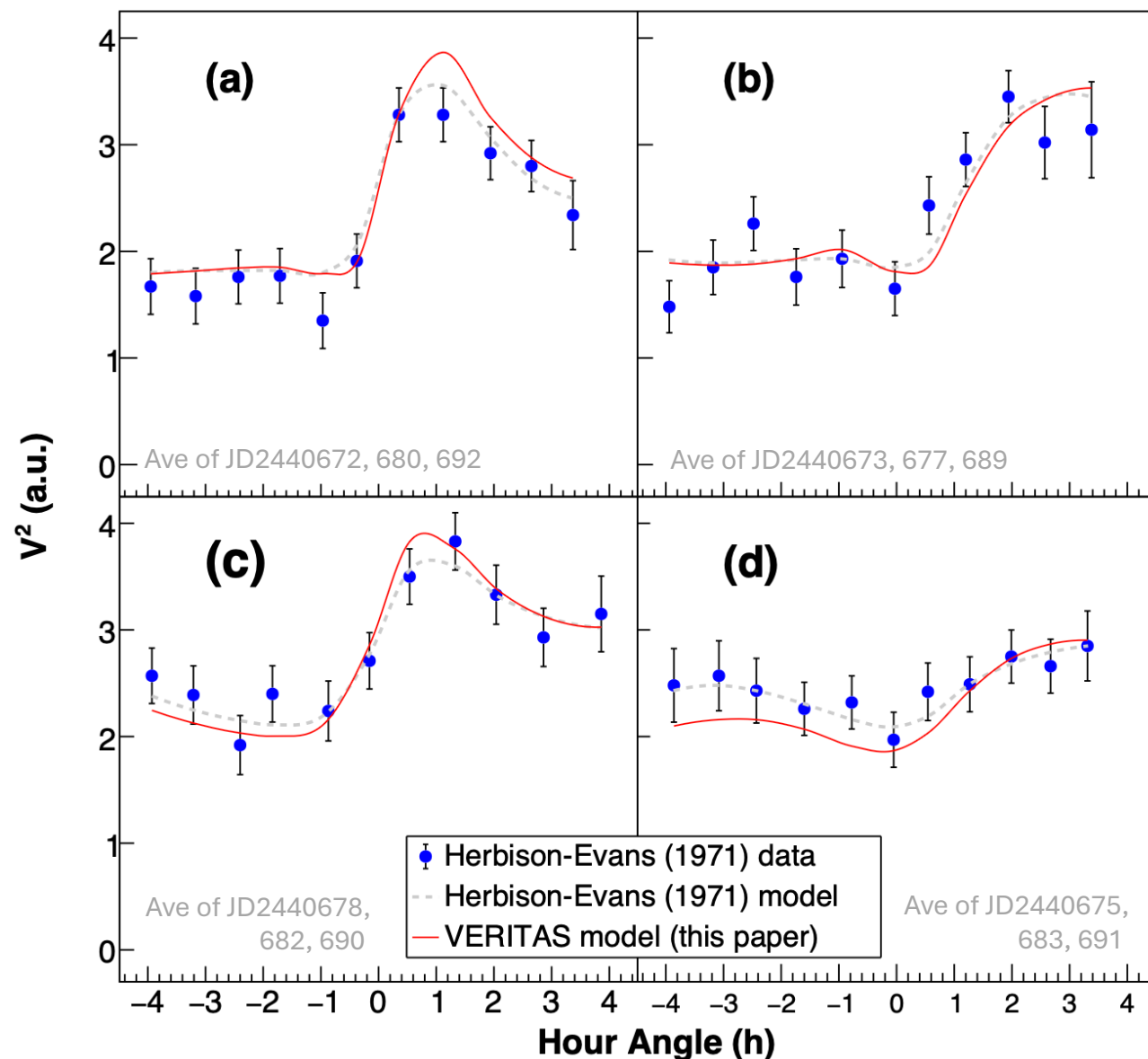
[1] Harrington et al A&A, 590, A54 (2016)

[2] Herbison-Evans et al (1971)

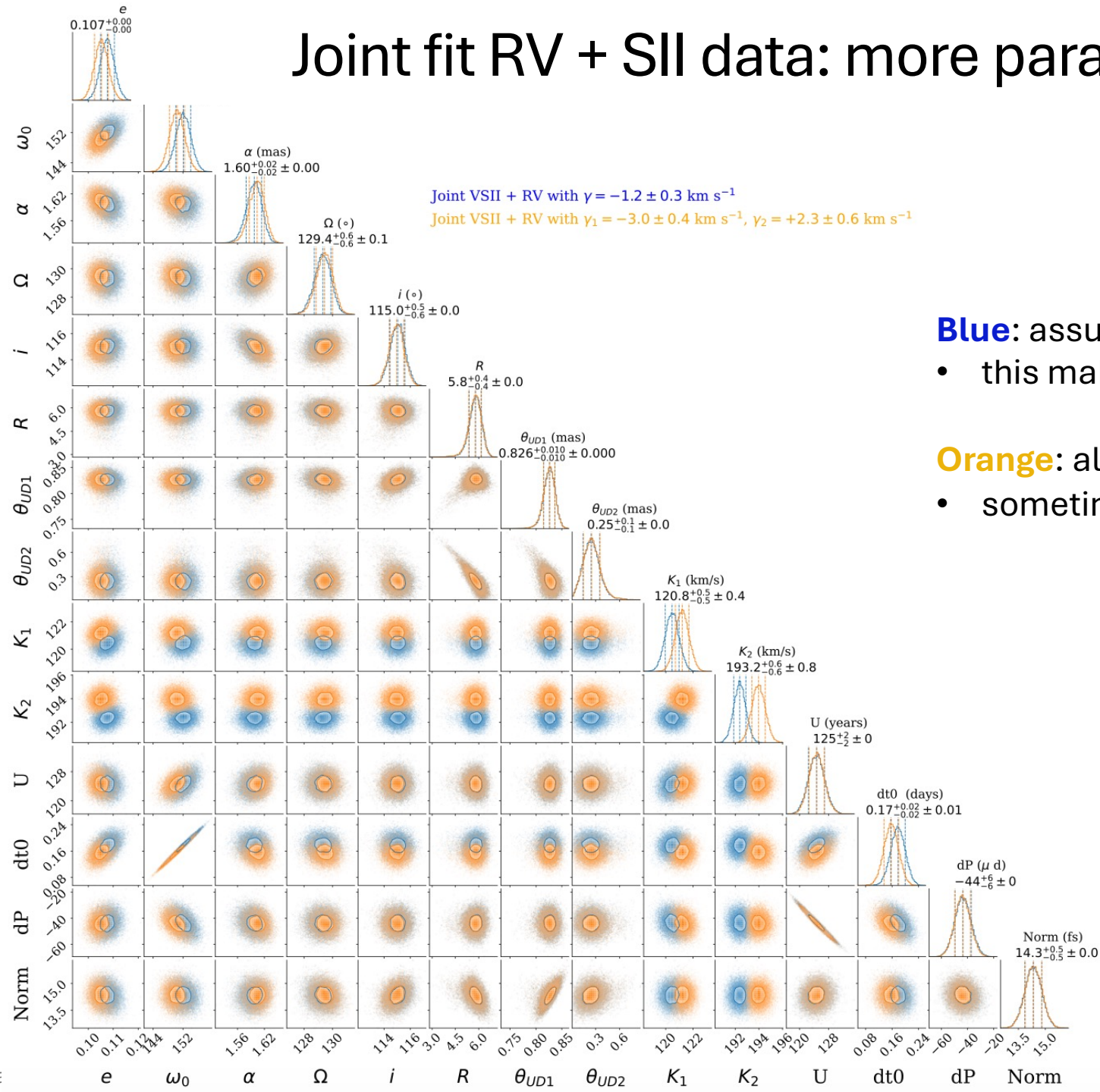
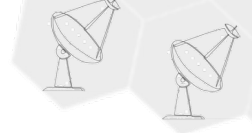
Comparison to Narrabri data



- Herbison-Evans (~5000 cycles ago!) measured 900+ visibilities, but only provided 45
- ✓ Binary calculation with our parameters in reasonable agreement
- ✓ While orbital parameters disagree (due to previous assumption), we don't disagree with **data**



Joint fit RV + SII data: more parameters $\rightarrow$ *more physics!*



Blue: assumes common average velocity for Spica A and B

- this makes sense for a binary

Orange: allows separate average velocity

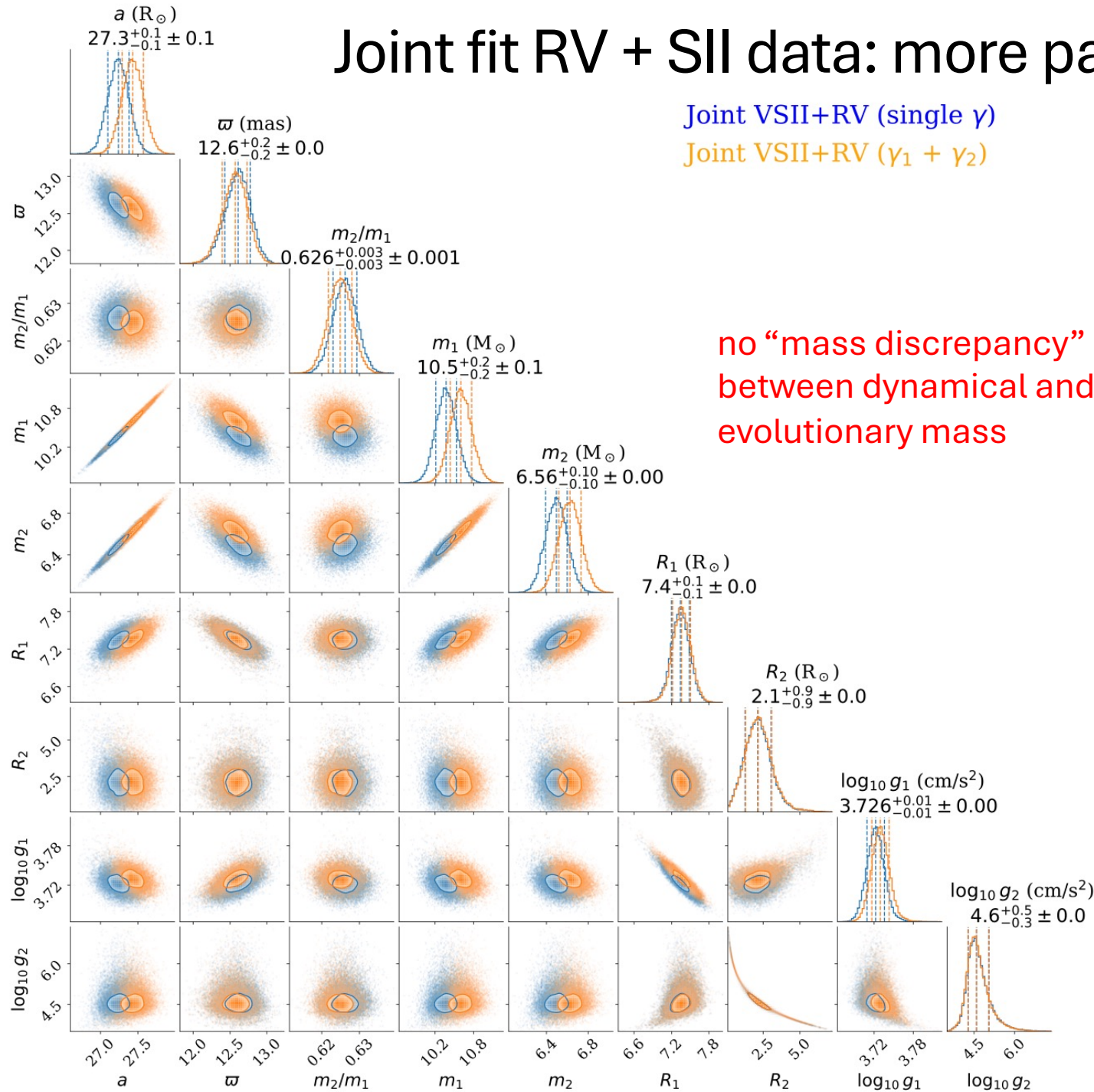
- sometimes done in the literature

(there will be a pop quiz after my talk)

Joint fit RV + SII data: more parameters $\rightarrow$ *more physics!*

Joint VSII+RV (single γ)

Joint VSII+RV ($\gamma_1 + \gamma_2$)



Parameter	This paper	Ref.
Orbital Parallax, ϖ (mas)	12.6 ± 0.2	1
Semi-major axis, a ($R_{\odot}$)	27.3 ± 0.2	
Mass ratio, m_2/m_1	0.626 ± 0.004	
Spica A mass, m_1 ($M_{\odot}$)	10.5 ± 0.3	
Spica B mass, m_2 ($M_{\odot}$)	6.56 ± 0.10	
Spica A Radius, R_1 ($R_{\odot}$)	7.4 ± 0.1^b	
Spica B Radius, R_2 ($R_{\odot}$)	2.1 ± 0.9^c	
Spica A surface gravity, $\log_{10} g_1$ (cm s^{-2})	3.726 ± 0.010	
Spica B surface gravity, $\log_{10} g_2$ (cm s^{-2})	$4.6^{+0.5}_{-0.3}$	
Additional Constraints		
Spica A luminosity, $\log_{10} L_1$ ($L_{\odot}$)	4.27 ± 0.04^d	
Spica A evolutionary mass ($M_{\odot}$)	$10.5 - 11.0^e$	
Spica A evolutionary age (Myr)	20 ± 2^e	

distance: 79.5 ± 1.1 pc

Scientific impact

SII + spectroscopic (RV) measurements

inclined elliptical orbital disk
binary, with apsidal motion

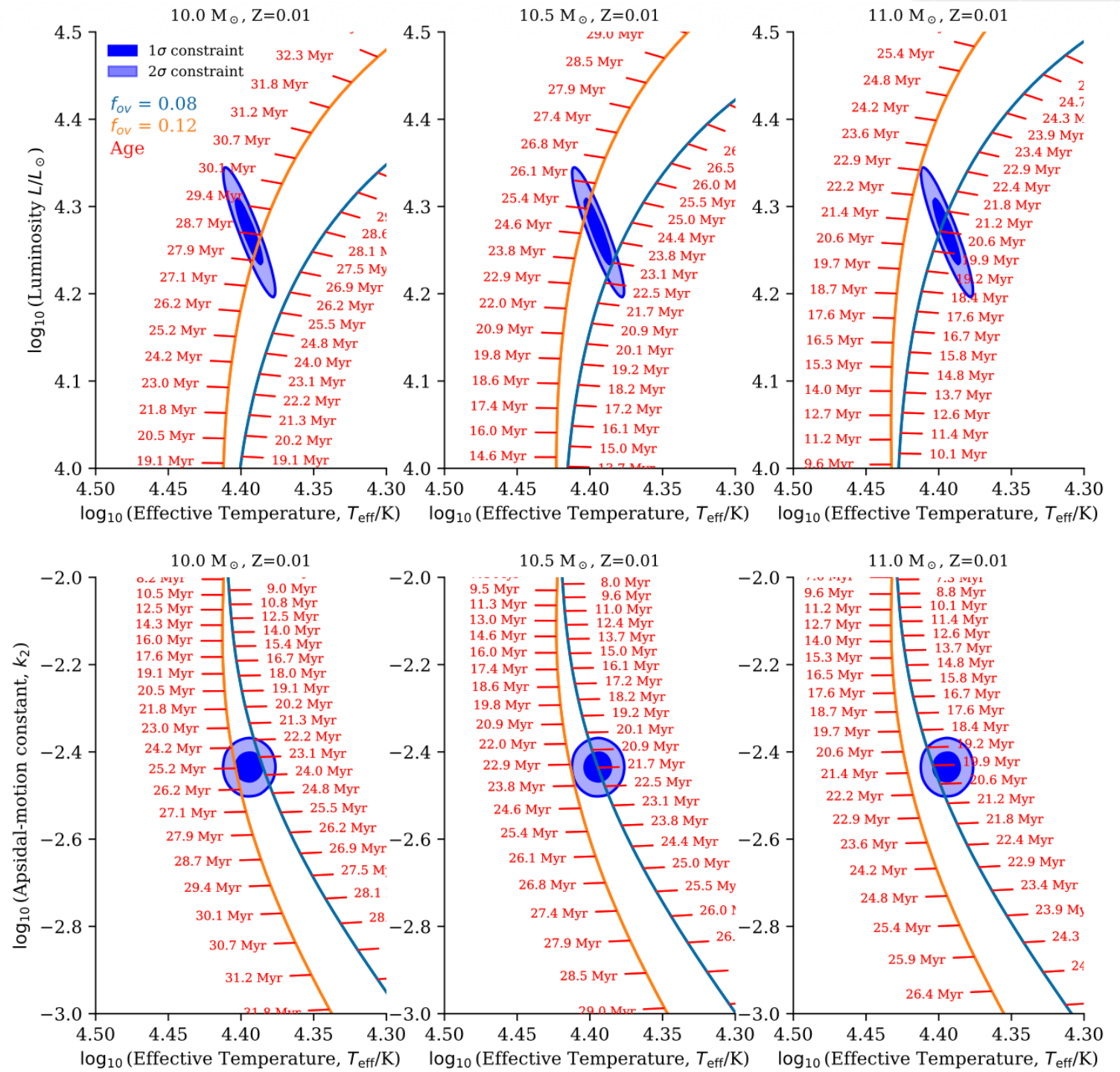
extracted params:

- sizes, masses, full orbital params
- structure (apsidal motion) const k_2
- (luminosity, temp)

compare to MESA trajectories
Jason Aufdenberg

Unprecedented constraints on

- (evolutionary) mass
- age: 20 ± 2 Myr
- overshoot f_{ov} (core H/He mixing)
- ...

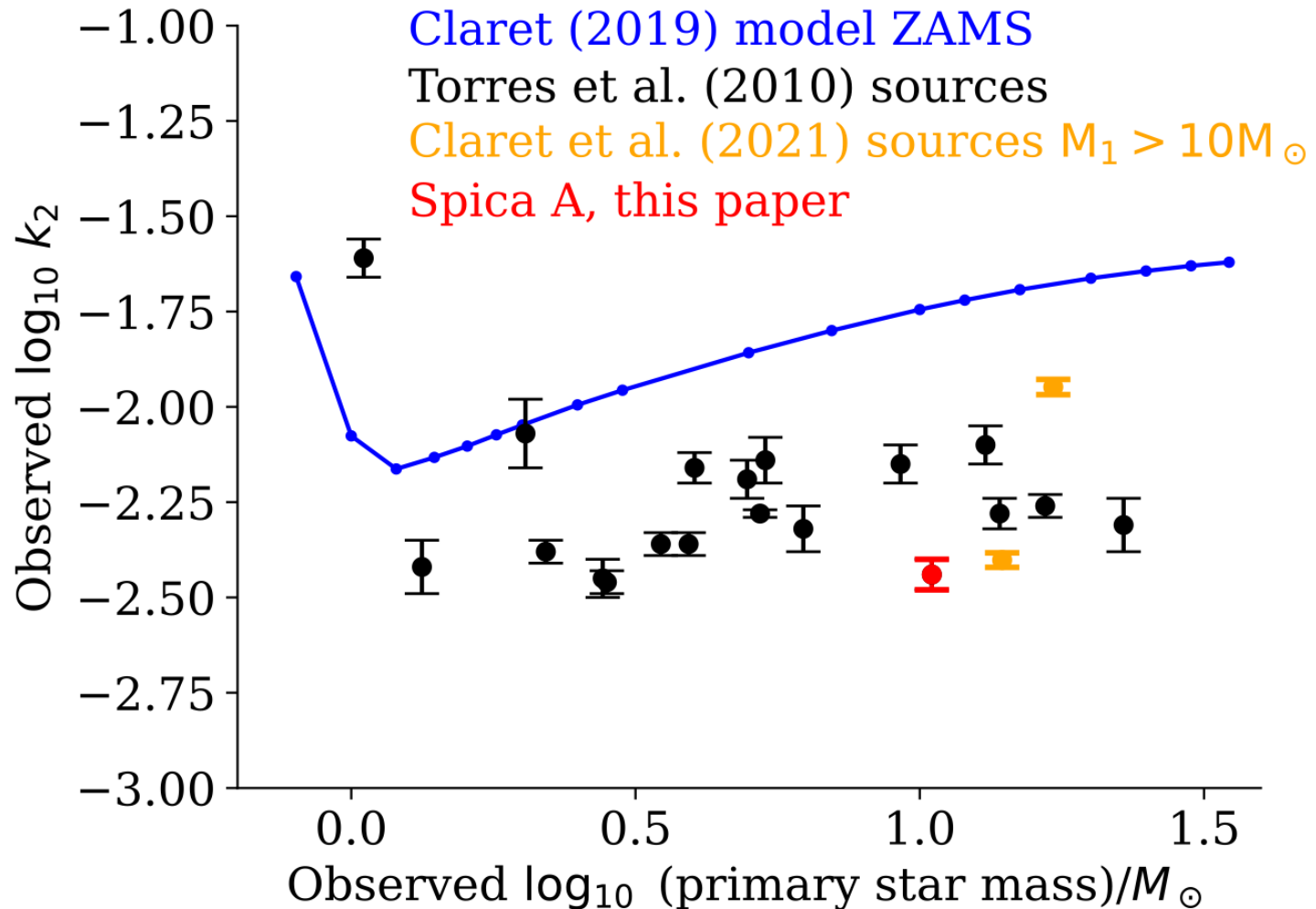


Admission into an elite club

The stars with sufficiently precise masses and structure constants to “seriously constrain stellar models” [1]

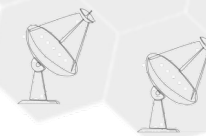
$$k_2 \approx \frac{16\pi}{5MR^5} \int_0^R dr r^7 \rho(r)$$

Spica A is most compressed $M > M_\odot$ star in this club.



[1] Torres et al (2010): $\delta \log_{10} k_2 < 0.1$ (Spica A ~ 0.03)

Summary: VERITAS SII study of Spica



- **Crucial:** multiple **baselines**; 150 **pair-hours**; large **mirrors** and/or bright source
- **Modern SII takes another step forward**
 - ✓ broad catalog of **sizes**
 - ✓ **shape** of rapid rotators
 - ✓ orbital **dynamics** of binary system
- **Complete orbital parameters & sizes**
 - spectroscopic binary → visual binary
 - consistent with historical RV spectroscopic data
 - resolution of the “eccentricity problem”
- **Unprecedented precision → crucial input to stellar theory**
 - masses, interactions directly accessible with binaries
 - determination of stellar mass, radius, age, mass distribution
 - no “mass discrepancy”
 - apsidal constant → tides, ang. mom. coupling (beyond range of current study)

Gracias por su atención

