Title: The VERITAS SII Observatory

Speakers: Dave Kieda

Collection/Series: Future Prospects of Intensity Interferometry

Subject: Cosmology

Date: October 30, 2024 - 11:35 AM

URL: https://pirsa.org/24100095

Abstract:

The VERITAS Imaging Atmospheric Cherenkov Telescope array was augmented in 2019 with high-speed focal plane electronics to allow VERITAS for Stellar Intensity Interferometry (VSII) observations. Since December 2019, VSII has been used to measure angular diameters of bright (OBA) stars at an effective wavelength of 416 nm. VSII observations have also served as a testbed to explore hardware and analysis improvements to advance the instrument's sensitivity. VSII has performed more than 730 hours of moonlit observations on 56 bright stars and binary systems ($ -1.46 < m_V < 4.22$). This talk will describe the VSII observatory, highlight selected observations made by the VSII observatory, and describe ongoing improvements in detector instrumentation and analysis.

The VERITAS Stellar Intensity Interferometry (VSII)
& Future Potential

Dave Kieda
University of Utah
For the VERITAS Collaboration

Oct 30, 2024

Stellar Intensity interferometry (SII) … 1956-1971

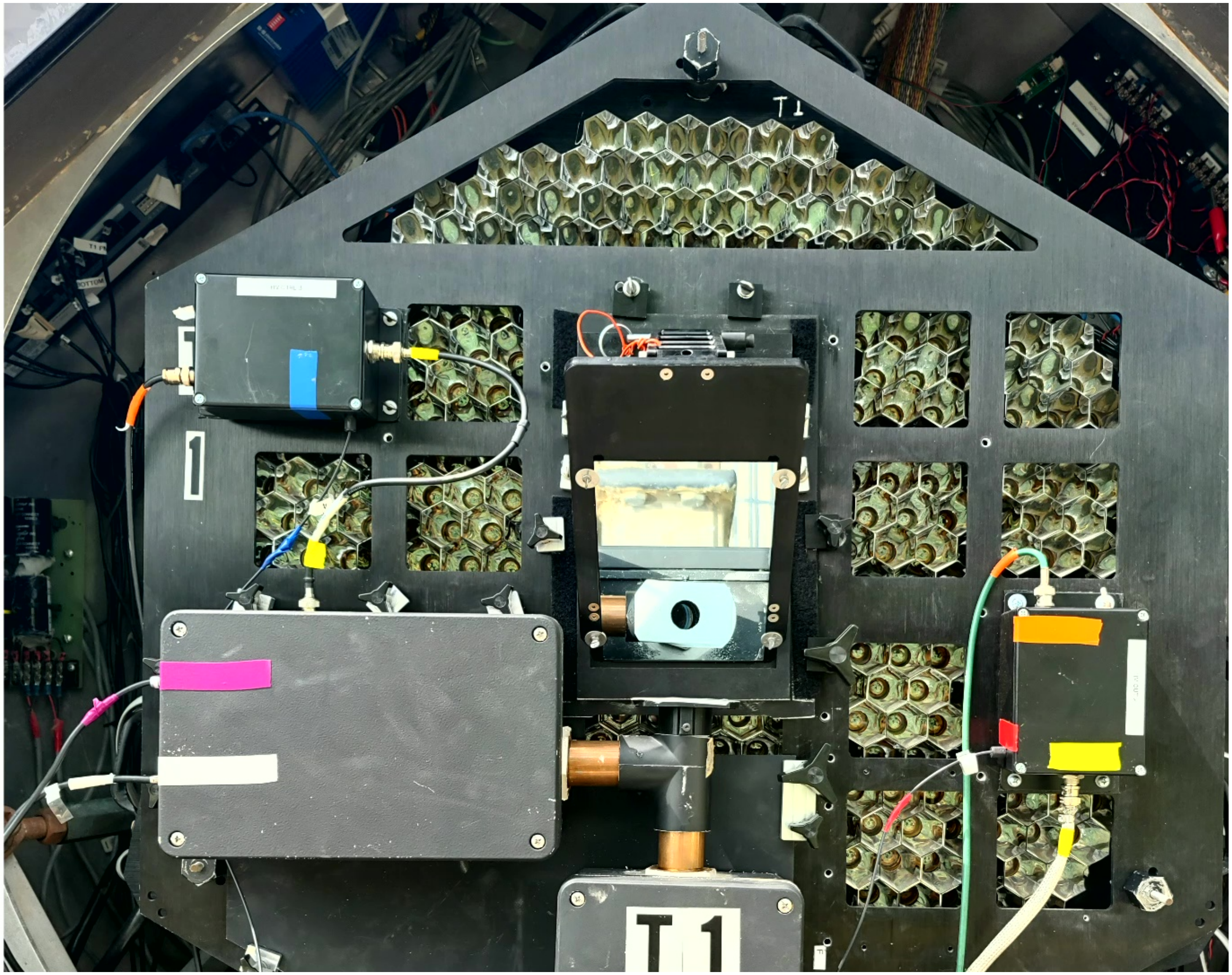
The Past

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 Observatory 2019-2024



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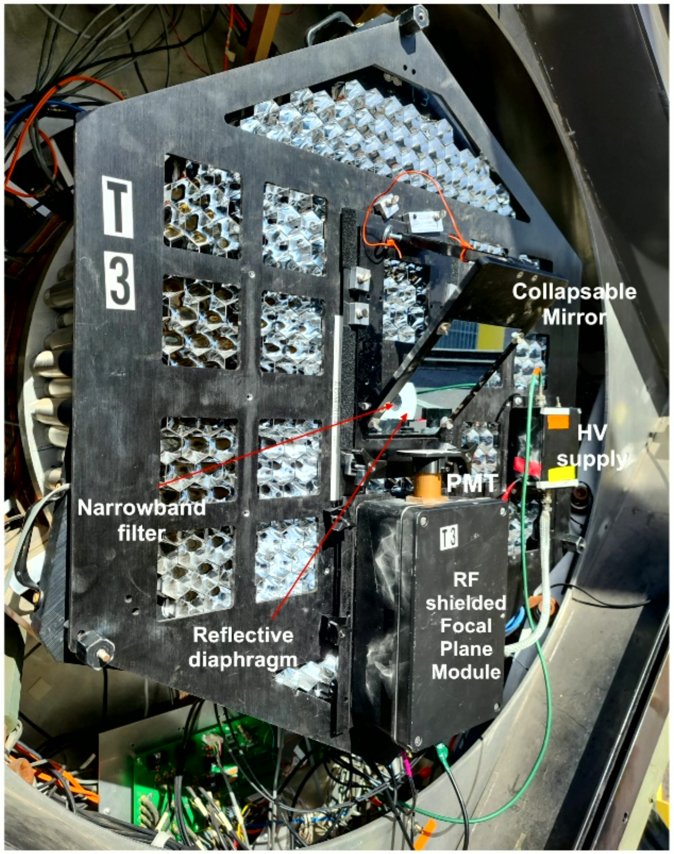
VERITAS-SII (VSII)

- 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

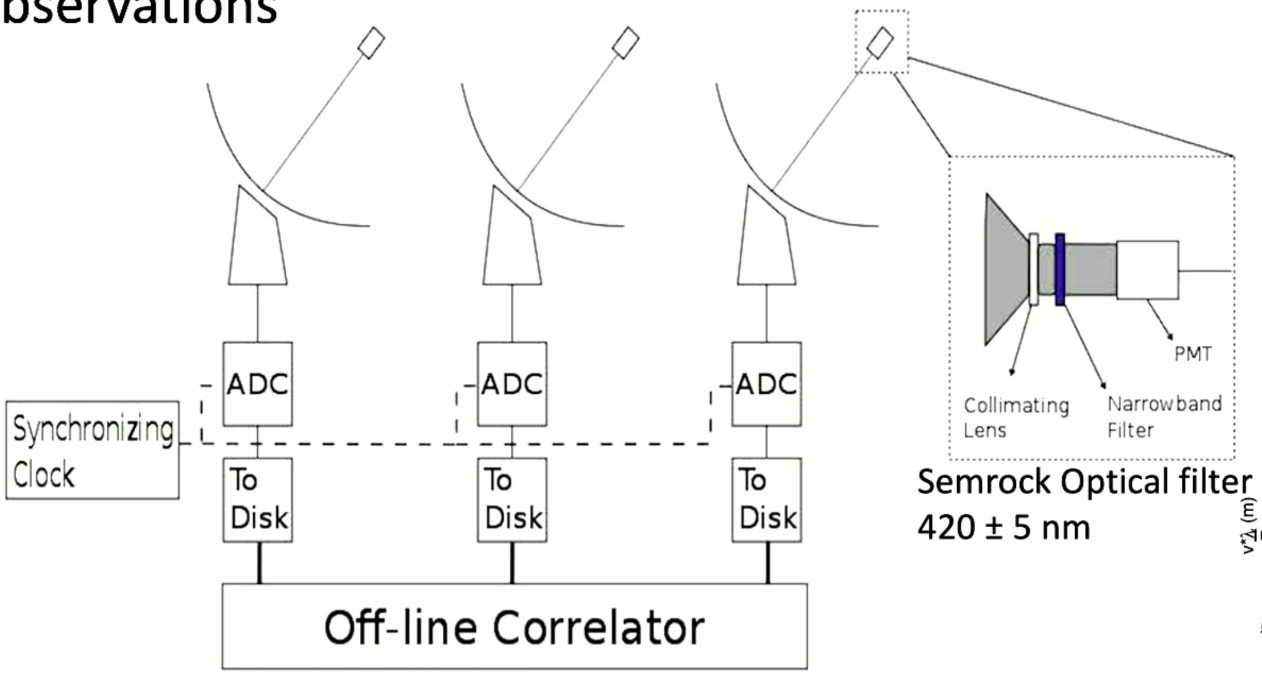
- Multiple science topics
- Pathfinder for km-scale arrays (CTAO-SII)

Removable VSII Camera Plates



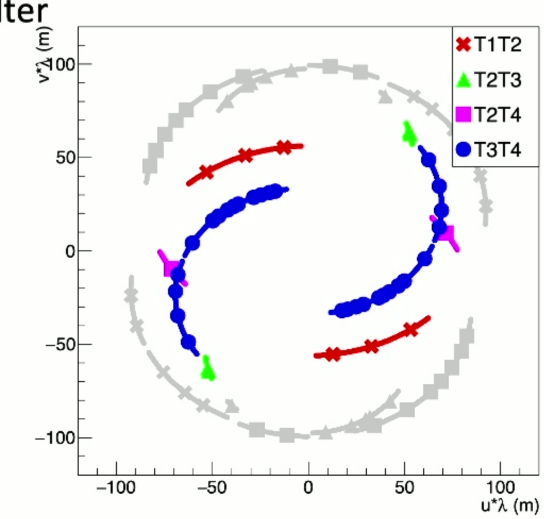
- The removable VSII Camera Plate mounts in front of the VERITAS Camera focal plane.
- Observer locates the VSII Plate onto each camera at beginning of full-moon period.
- Plate contains necessary focal plane optics, HV supply, photomultiplier and preamplifiers to perform VSII measurements.
- Quick connect 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

VSII Observations



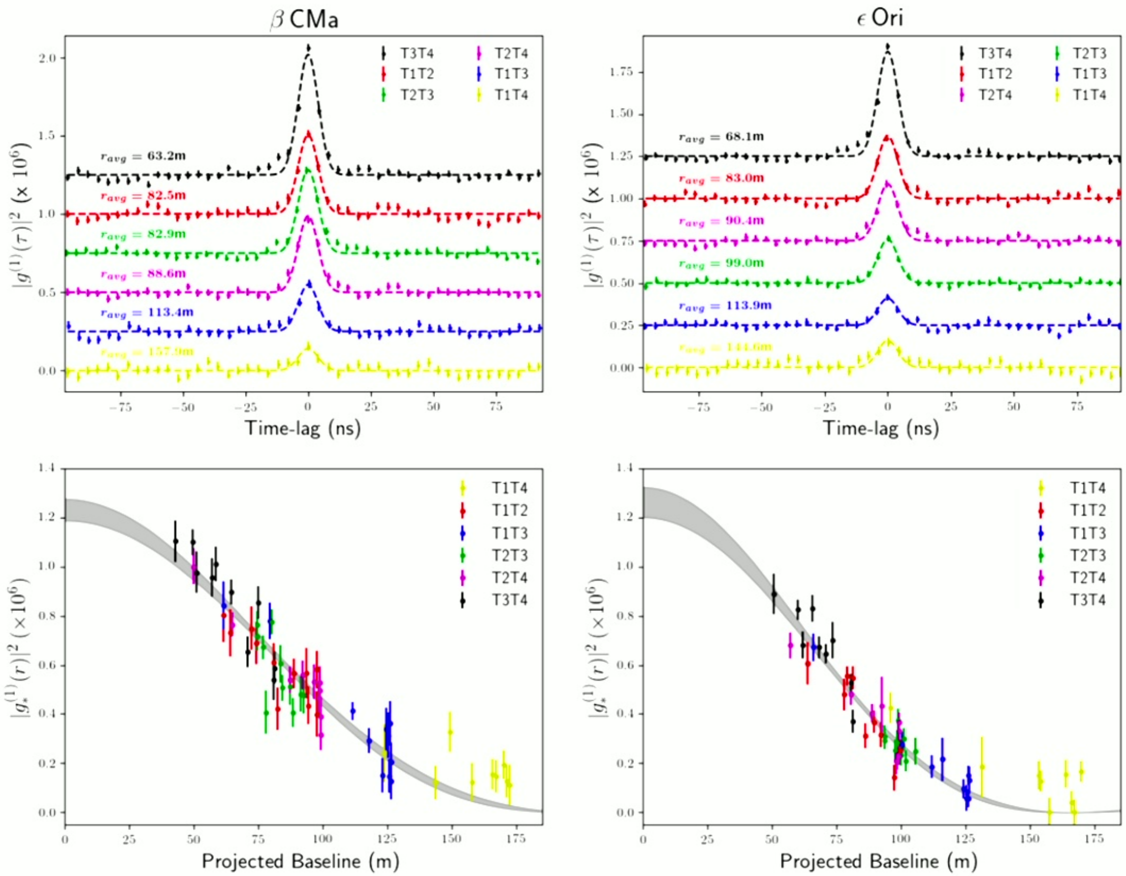
$$\frac{<I_A I_B>}{<I_A><I_B>} = g^{(2)}(u, v, t) = 1 + \left| g^{(1)}(u, v, t) \right|^2$$

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



4 $I(l, m)$ is the stellar image size and brightness distribution on the sky

VSII Sampling of Fourier Image Plane



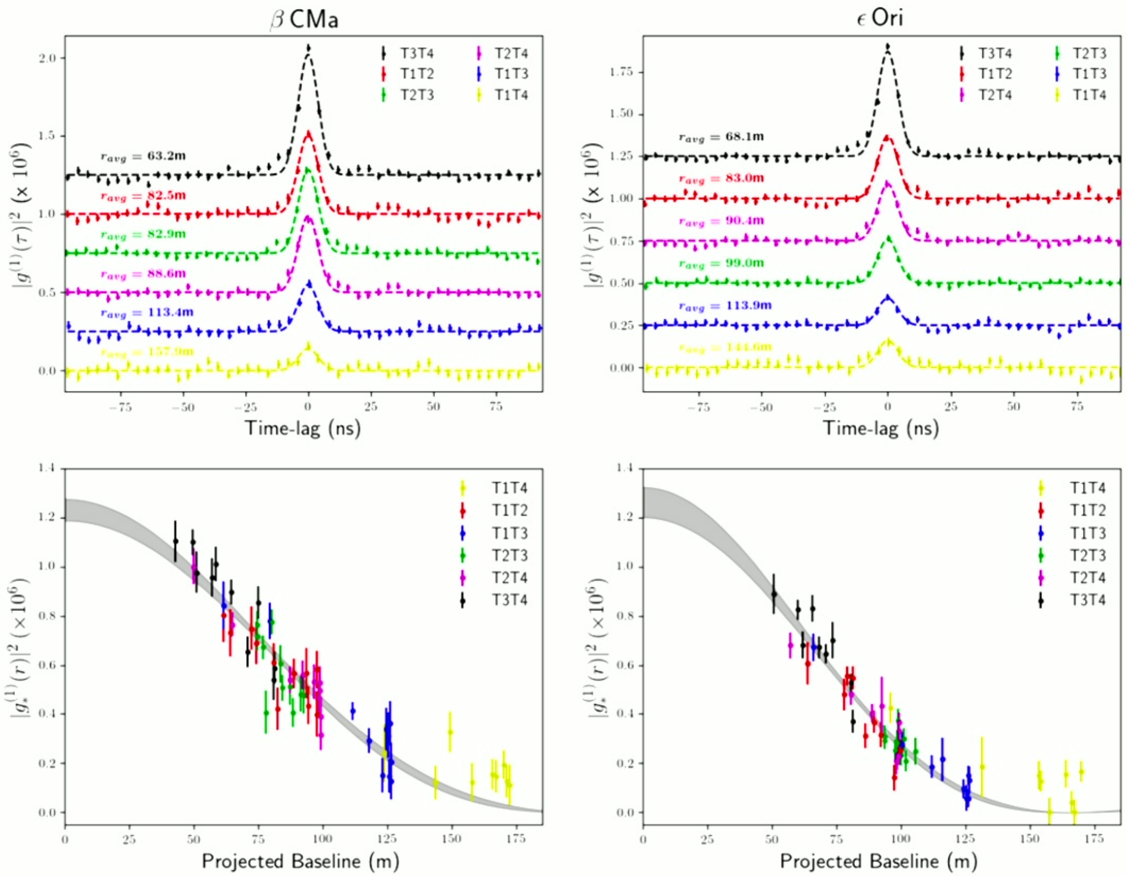
Source	θ_{UD} (mas)	T (h)	θ_{UD} (mas)	T (h)
β CMa	0.50 ±0.03	63.4	0.523 ±0.017	5.5
ϵ Ori	0.67 ±0.04	56.0	0.631 ±0.017	4.25

(T= Observation Time)

First demonstration of SII telescope on an array With multiple baselines

First demonstration of offline software correlation

A. Abeysekara, Nature Astronomy 2020



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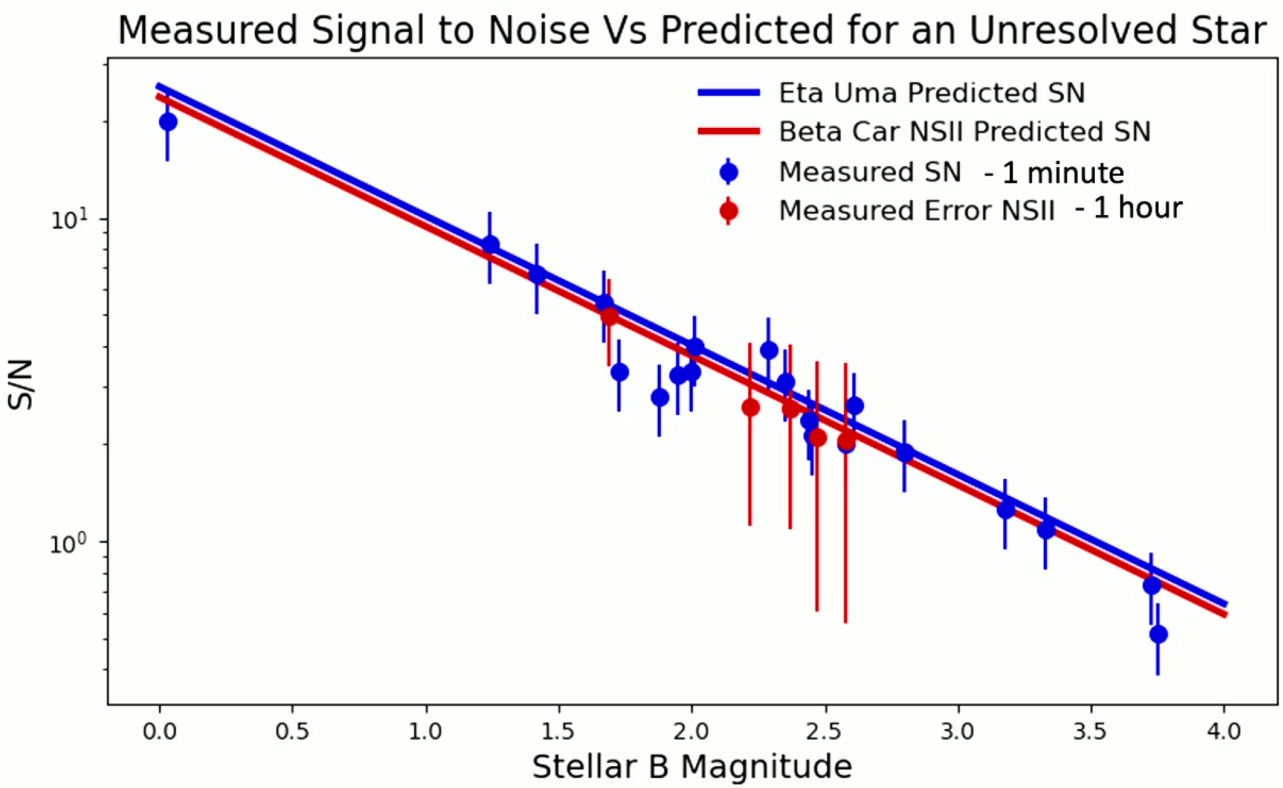
Narrabri SII Observations 1970

VERITAS-SII Nature Astronomy 2020

A. Abeysekara, Nature Astronomy 2020

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)

VSII Observations (2021-present)

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

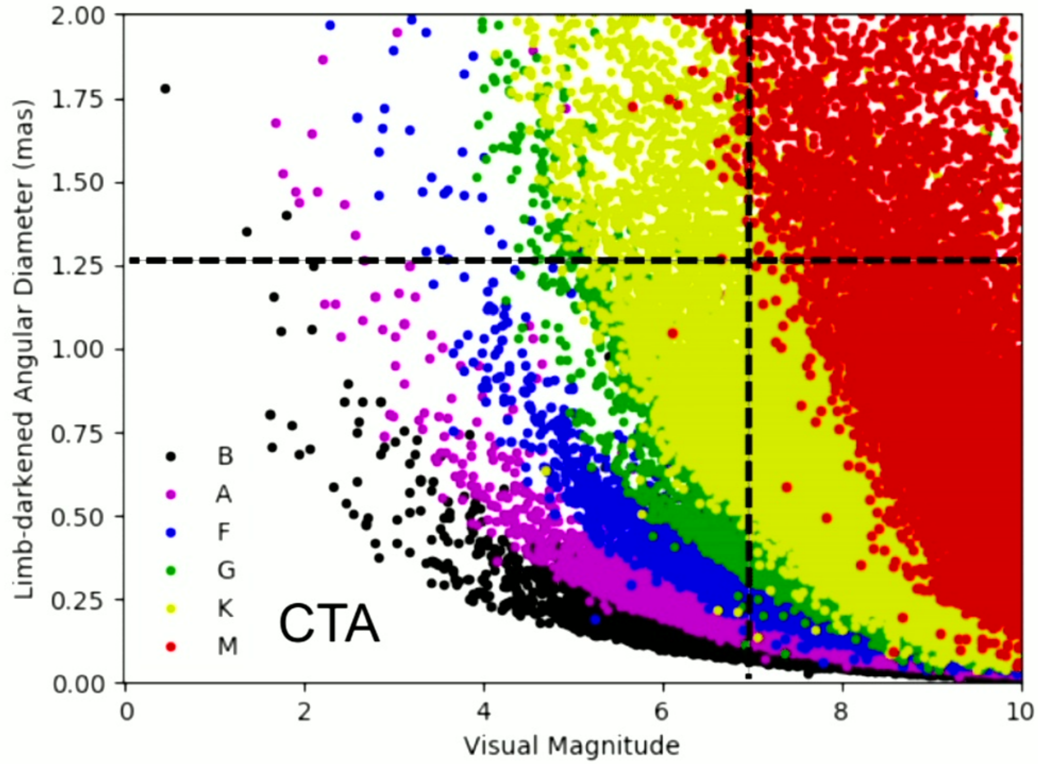


Image credit: N. Matthews (JSDC Stellar Catalogue)

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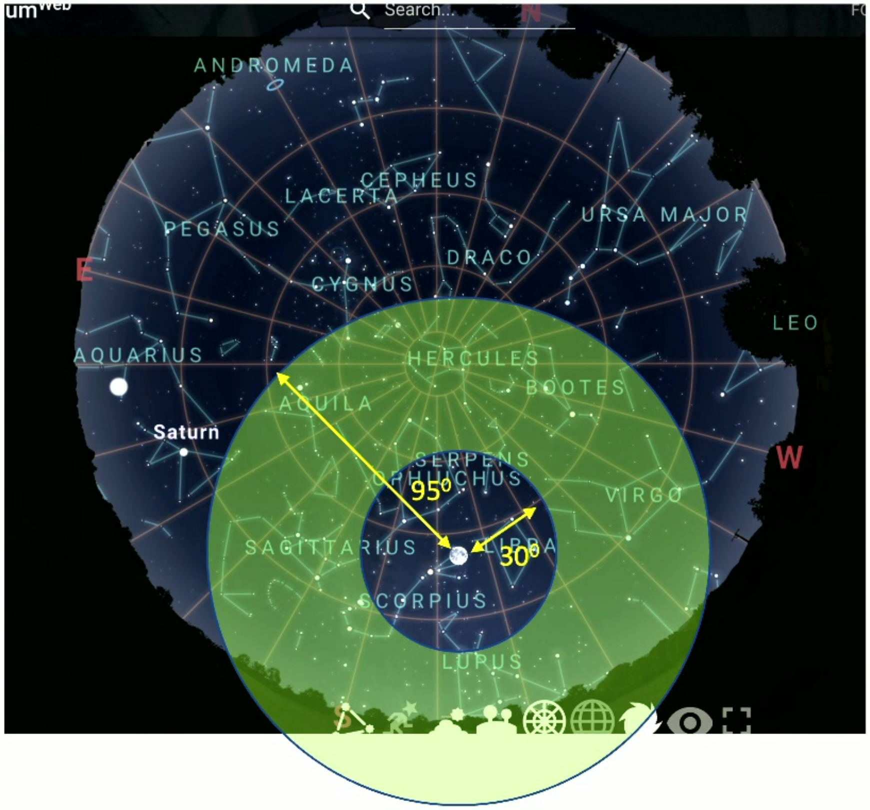
VSII Survey Observing 2021-2024

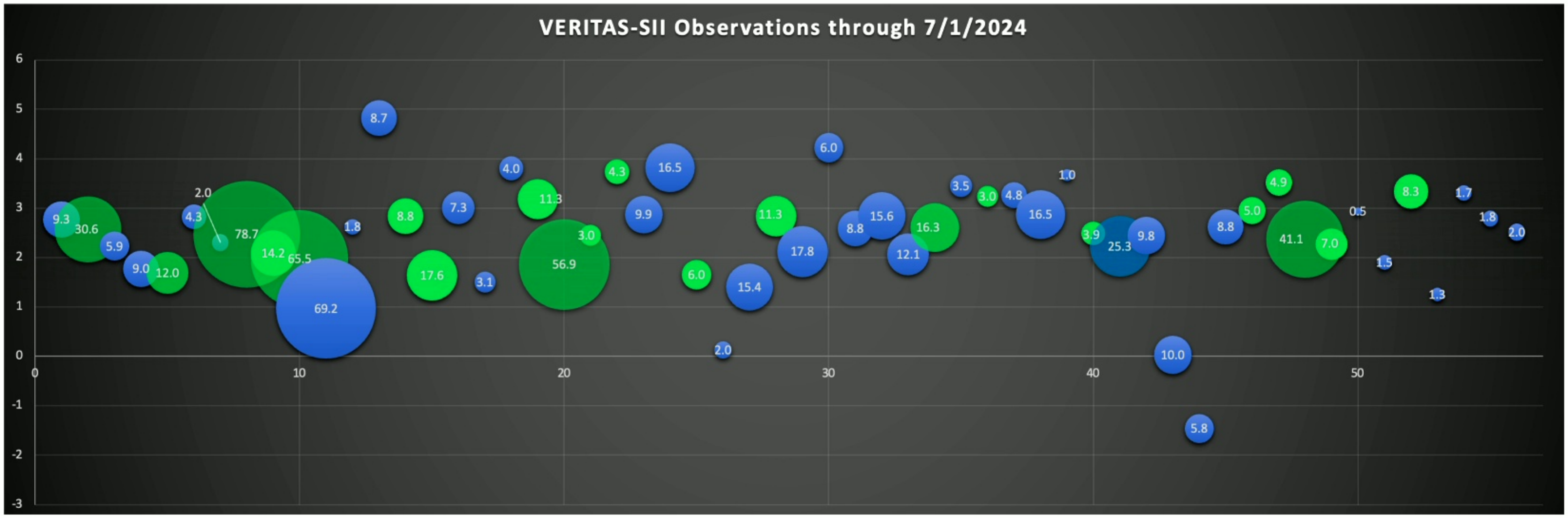
- Moonlight is the main constraint
- Atmospheric scattering of moonlight for moon angle < 30^0
- Direct light on focal plane for moon angle > 95^0
- Optimal sky darkness: moon angle ~80-90^o

- 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



VSII Observations (Jul 1, 2024)

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 – 7/1/24)

- 56 different targets
- 33 single
- 23 binary/multiple
- Total 732.3 hrs exposure
- 125.8 hours 2023-2024 obs season

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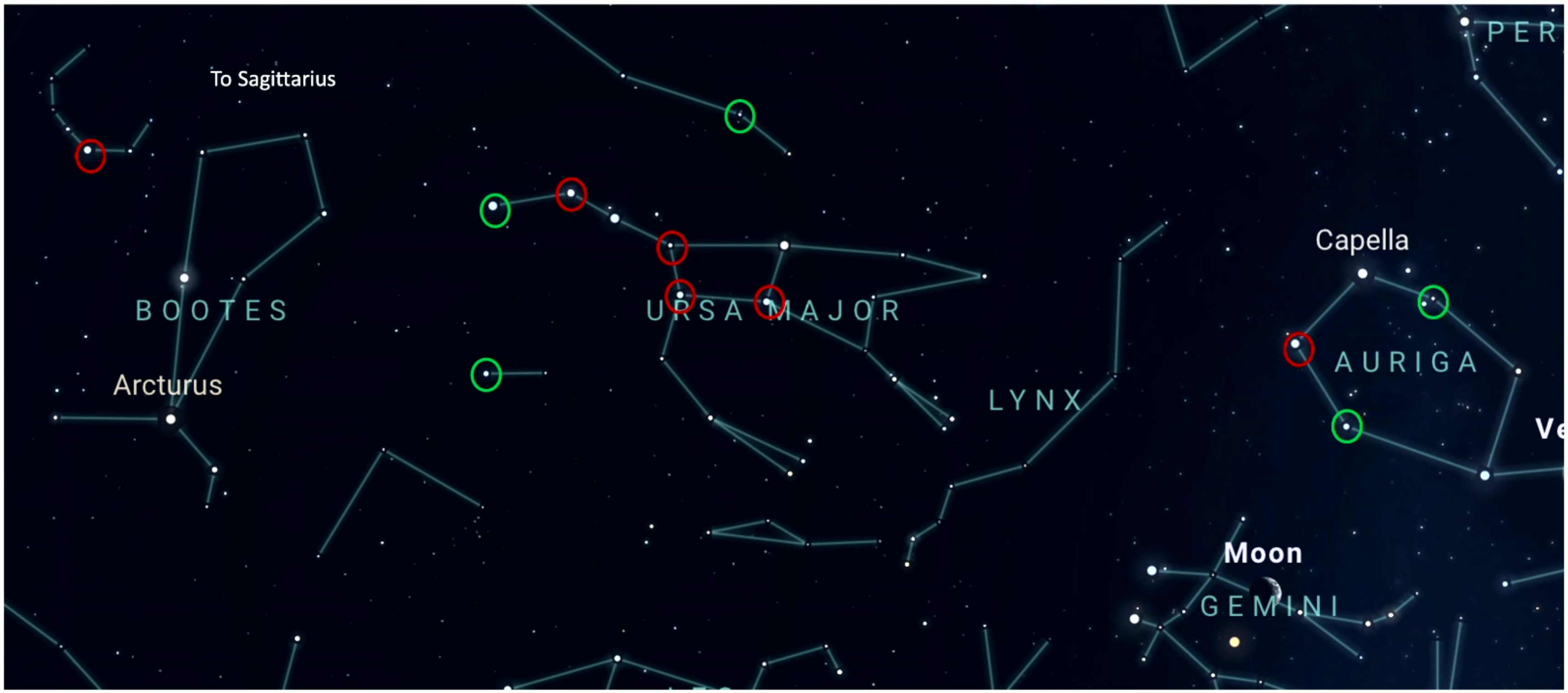
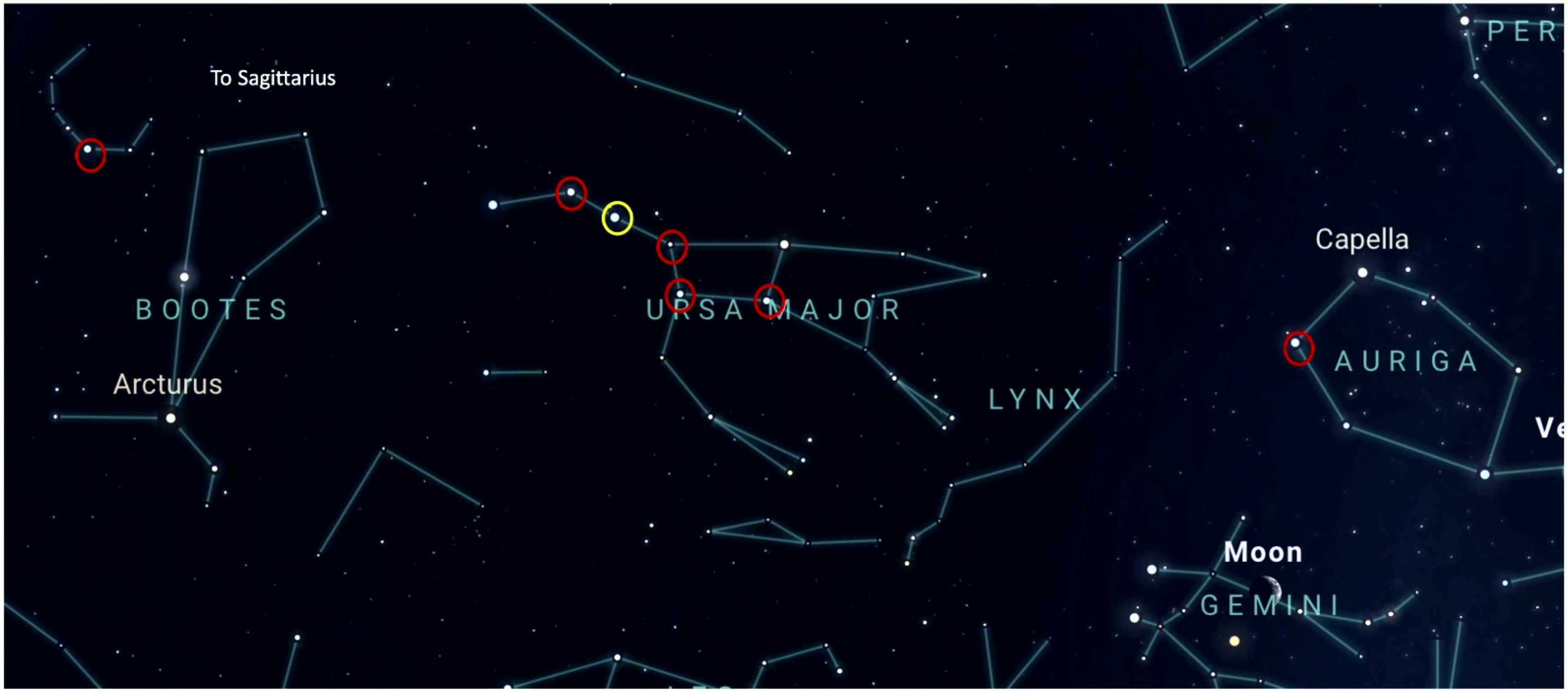
VSII Observations Near Ursa Major



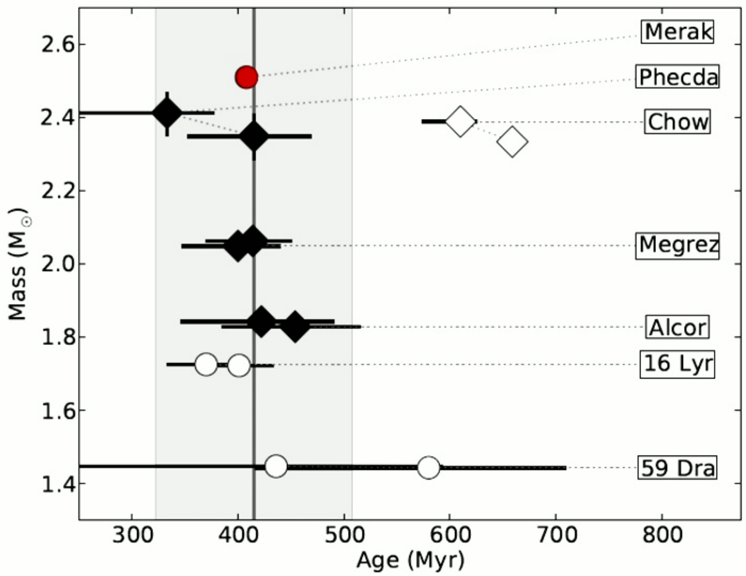
VSII Observations Near Ursa Major



Ursa Major Moving Group

- 25 psc away
- 15 stars in Ursa Major nucleus
- 47 stream stars outside nucleus
- Common 15 km/sec motion towards Sagittarius
- Origin in open cluster formed 500 My ago
  - All are A stars or cooler
  - CHARA observation provide tightest age constraints
  - Some potential issues with fast rotators

10-20% constraint



J. Jones, CHARA Collaboration (Ap. J, 2015)

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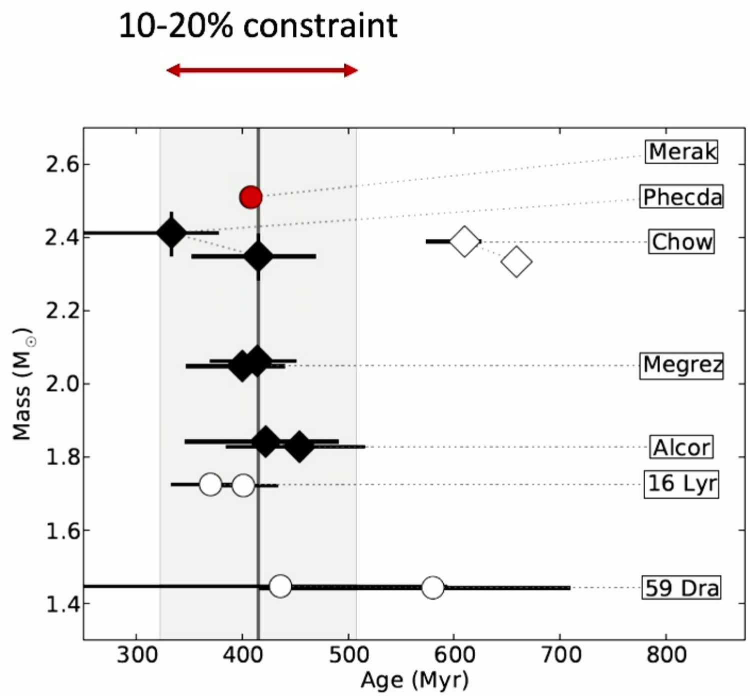
A 3% constraint in θ_{LD} *by VSII measurement gives (post-MS star)*

- *1.5% constrain on* T_{eff}
- *6 % constraint on* t_{age}
- *0.6% constraint on* M_{star}

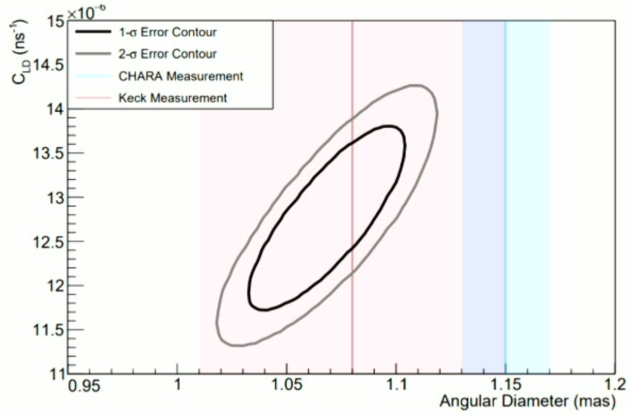


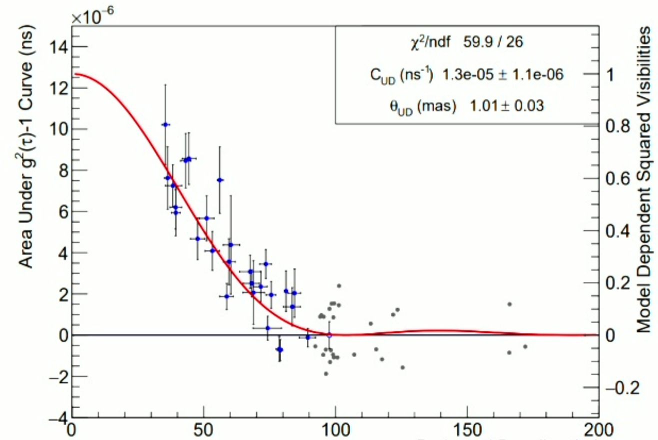
J. Jones, CHARA Collaboration (Ap. J, 2015)

VSII- Merak Analysis

- 37.4 hours, 4 Telescope observations (12/21-3/22)
- 2 independent analysis (standard & Bayesian)
- Measured age: 390 Myr – Slightly younger, Smaller radius, hotter temperature, better match to UV spectra

A. Acharyya et al, Ap. J 966, 1, 28 (2024)
[arXiv:2401.01853](https://arxiv.org/abs/2401.01853)





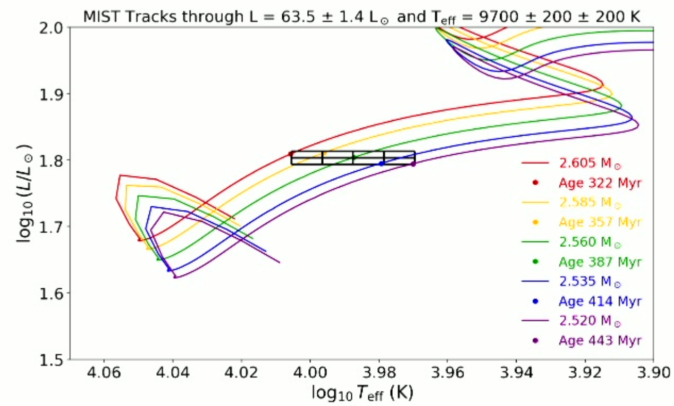
Stellar Properties

Table 3. Fundamental Stellar Parameters for β UMa

Parameter	Value	Reference
Limb-darkened angular diameter, θ_{LD} (mas)	$1.07 \pm 0.04 \pm 0.05$	This paper
Bolometric flux at Earth, F_{bol} (erg s^{-1} cm^{-2})	$(340 \pm 7) \times 10^{-8}$	Boyajian et al. (2012)
Effective temperature, T_{eff} (K)	$9700 \pm 200 \pm 200$	derived, $[4F_{bol}/\sigma\theta_{LD}^2]^{1/4}$
Parallax, ϖ (mas)	40.90 ± 0.16	van Leeuwen (2007)
Radius, R ($R_\odot$)	$2.81 \pm 0.11 \pm 0.13$	derived, $\theta_{LD}/2\varpi$
Luminosity, L ($L_\odot$)	63.5 ± 1.4	derived, $4\pi F_{bol}/\varpi^2$
Mass, M ($M_\odot$)	$2.56 \pm 0.03 \pm 0.02$	MIST tracks (Dotter 2016; Choi et al. 2016)
$\log_{10}$ surface gravity, $\log g$ (cm s^{-2})	$3.93 \pm 0.03 \pm 0.05$	derived, $g = GM/R^2$
Age (Myr)	$390 \pm 29 \pm 32$	MIST tracks (Dotter 2016; Choi et al. 2016)
Projected rotational velocity, $v \sin i$ (km s^{-1})	47 ± 3	Royer et al. (2002)

- Using previously measures quantities and MESA stellar evolution models we can compile various fundamental properties for this star including age.

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



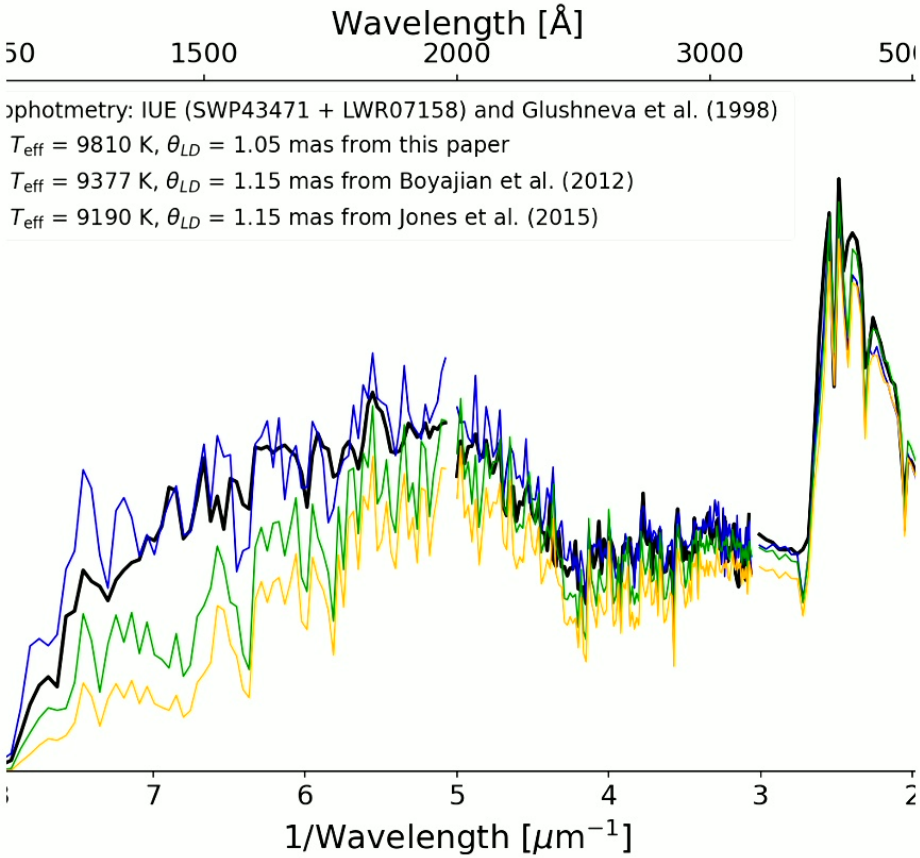
A. Acharyya et al, Ap. J 966, 1, 28 (2024)

17 arXiv:2401.01853

Stellar Spectra

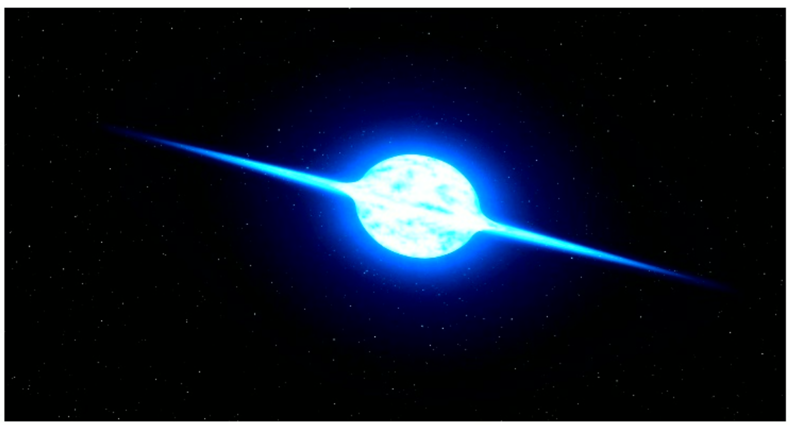
- VSII Smaller Merak Diameter -Requires hotter star
- Simulated Merak UV spectra better matched to observations

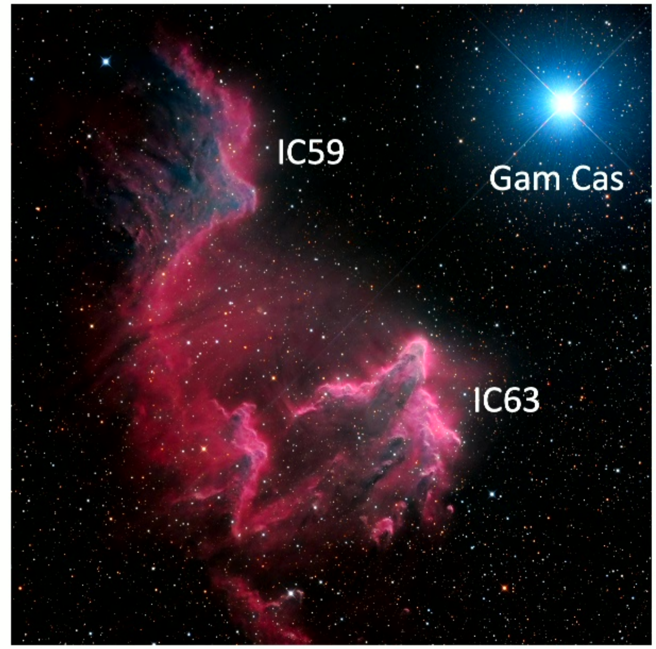
J. Aufdenberg et. al 2024



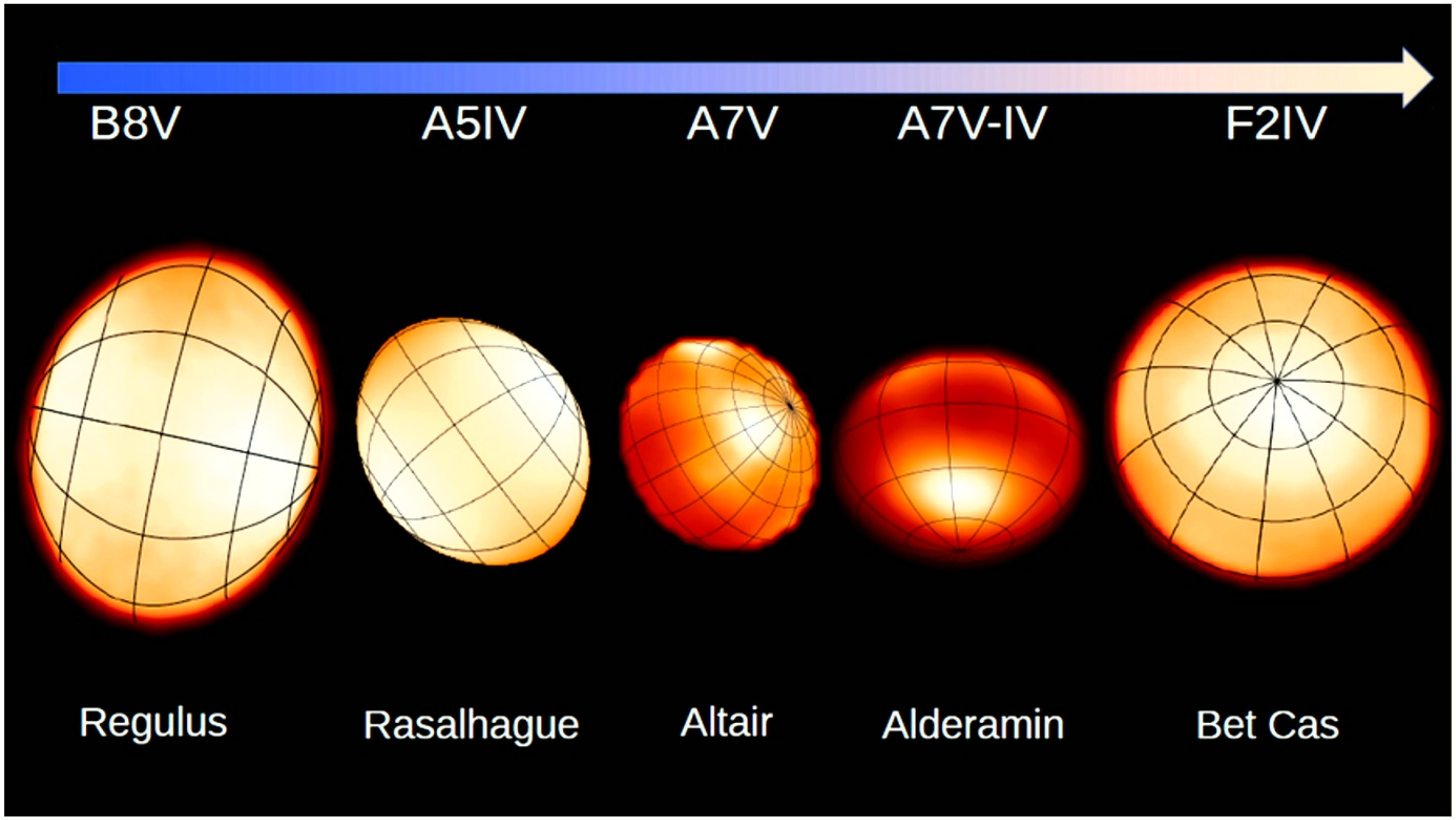
Gamma Cas ("Navi")

- 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)
- Prominent decretion disk around equator
- Common name is "Ivan" in reverse (Apollo astronaut Gus Grissom)





Gruntz and Bax, APOD 10/28/23



CHARA/MIRC , Monnier et al.

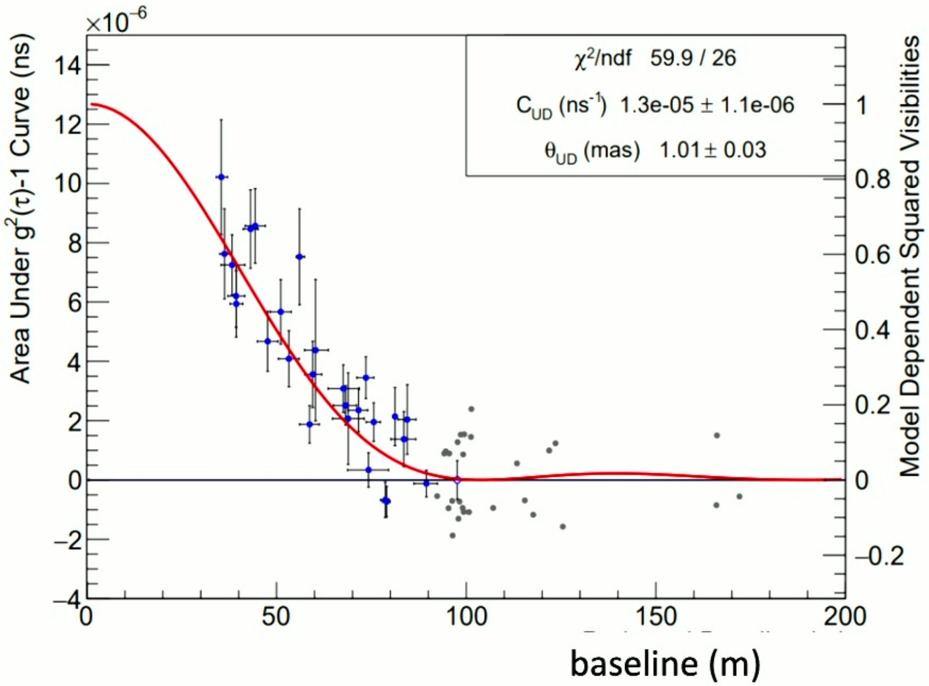
Fast Rotators and Stellar Envelope Deformation

Percieved Stellar Envelope Shape depends upon orientation of axis to line of sight

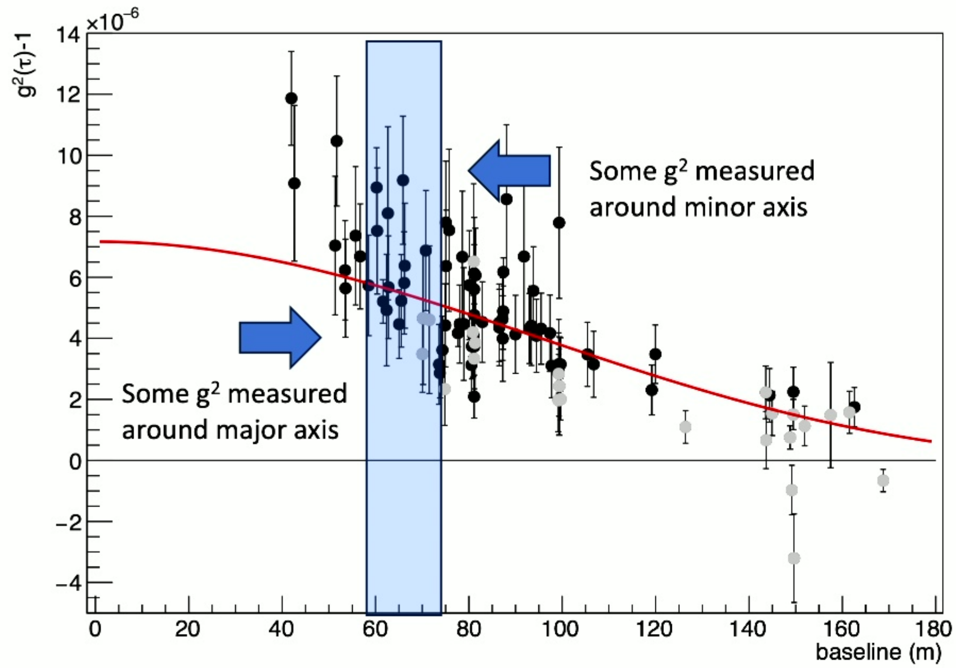
Gravity darkening at equator Due to larger optical depth to stellar core (von Zeipel effect)

Images taken by CHARA Michaelson Interferometer In IR band.

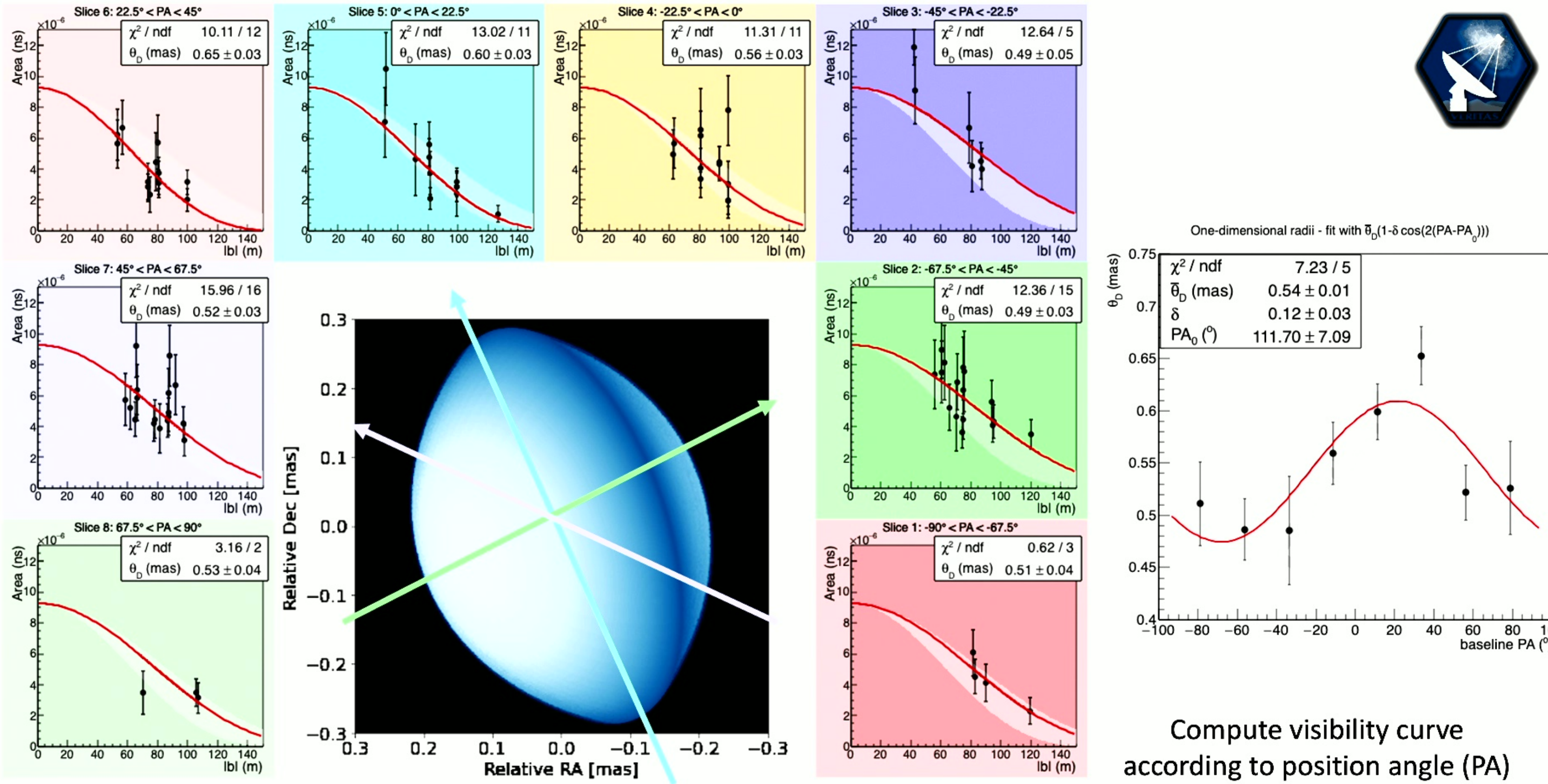
Round Stellar Envelope vs Elliptical



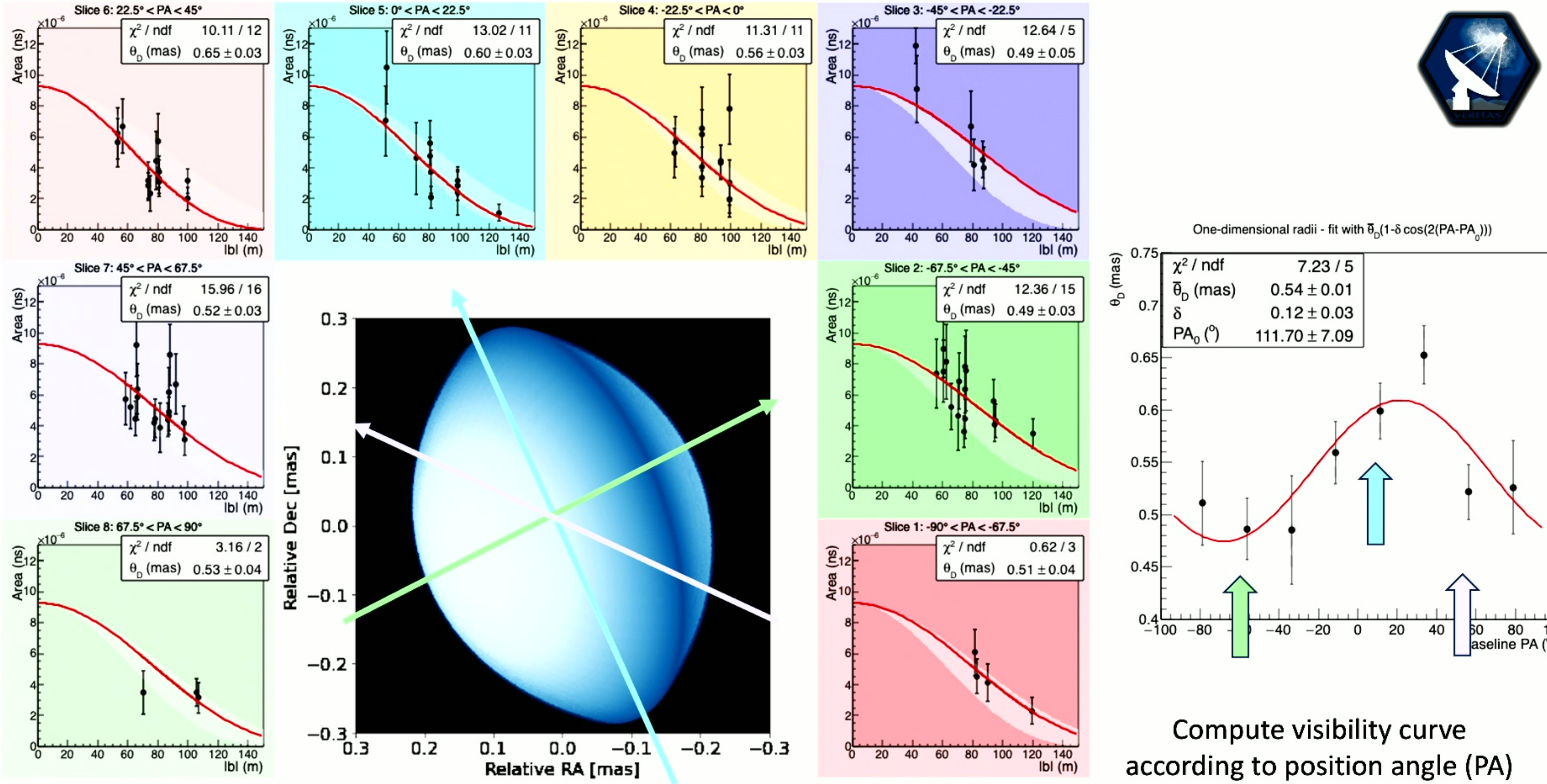
Merak (round envelope)



Gam Cas (elliptical envelope)



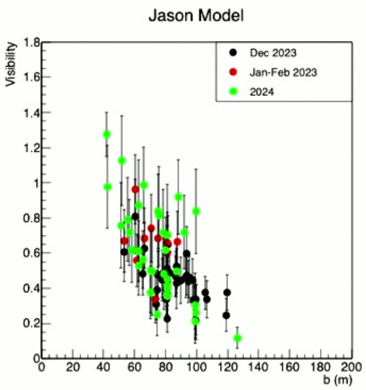
Compute visibility curve
according to position angle (PA)
VSII, in preparation 2024



Compute visibility curve according to position angle (PA)

VSII, in preparation 2024

gam Cas full stellar model fit



SingleNorm = 9.30e-06 ± 6.95e-07

ignore1 = -9.99e+02 ± 0.00e+00

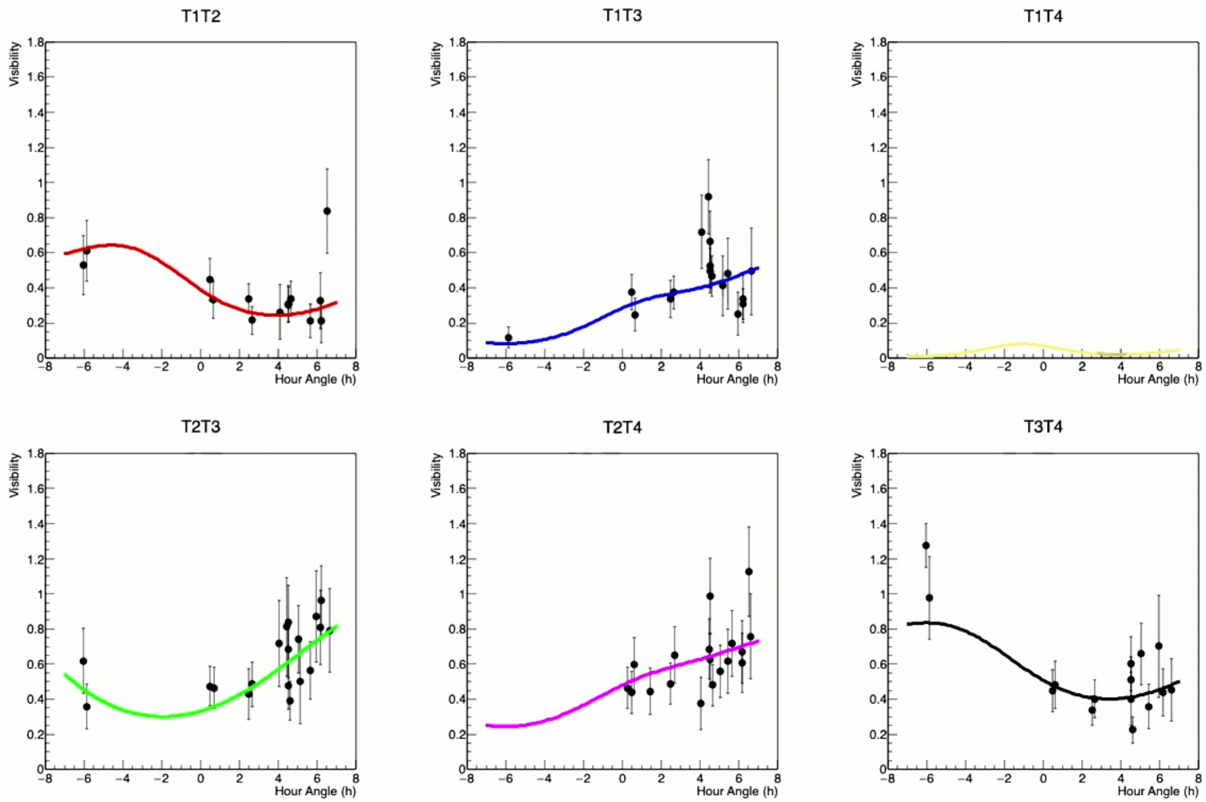
ignore2 = -9.99e+02 ± 0.00e+00

EqDiam = 7.05e-01 ± 4.20e-02

omega = 9.96e-01 ± 8.60e-03

PA = 1.08e+02 ± 6.16e+00

χ^2 / ndf = 83 / 77

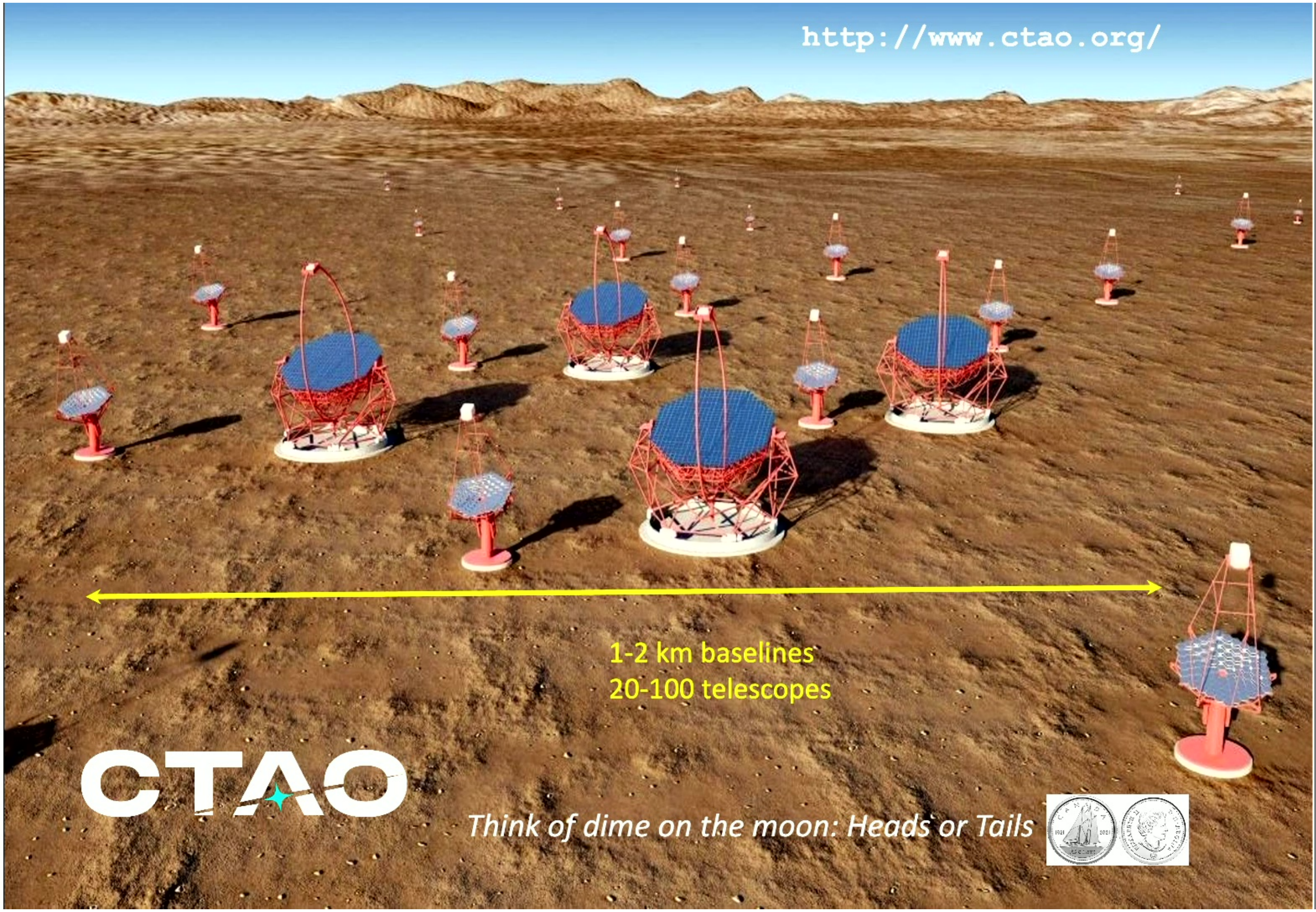


Measure PA Identical to CHARA Measurement (110^0)

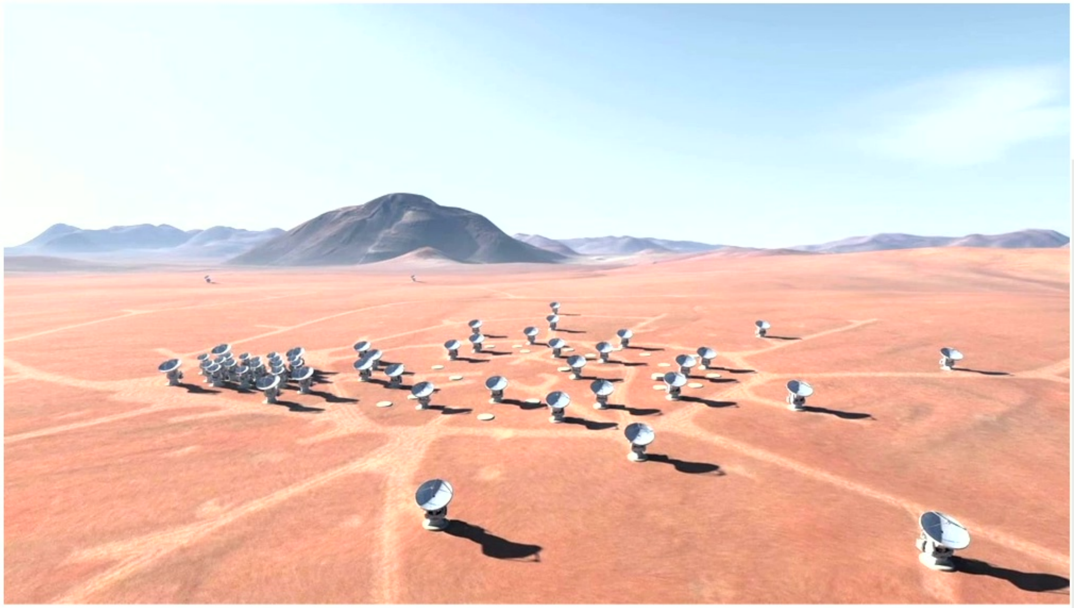
Axis ratio, equatorial Diameter also in good agreement (1.2, 0.75 mas)

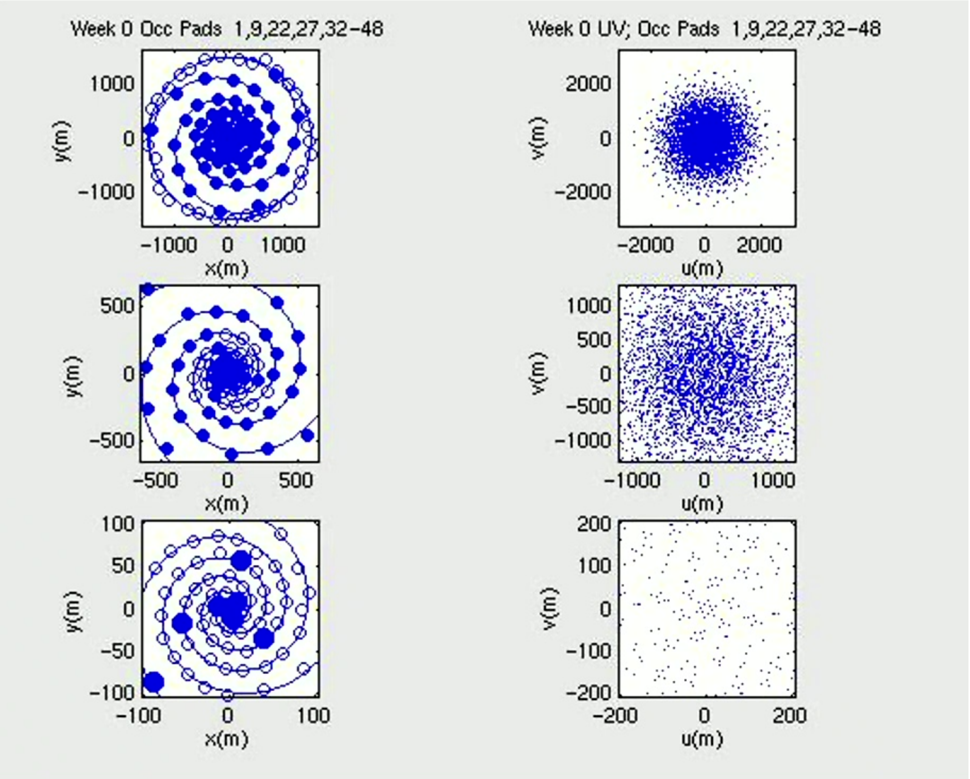
First measurement of elongated stellar envelope by SII

VSII 2024, in preparation


http://www.ctao.org/
1-2 km baselines
20-100 telescopes
CTAO
Think of dime on the moon: Heads or Tails

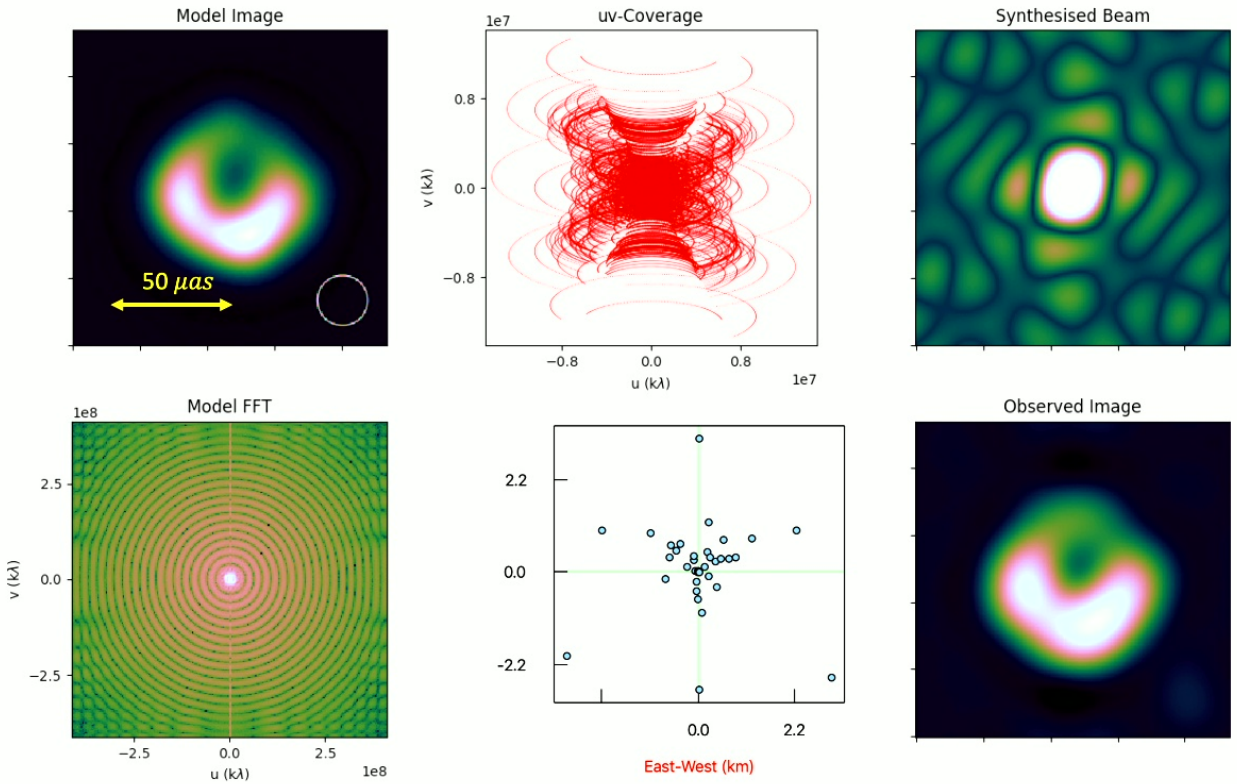
Reconfigurable Interferometric Array (ALMA)





- 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
Stellar Intensity Interferometry & Beyond 2024

- Ongoing observations with significantly improved instrument
- 1-D analysis of stars (Merak) : stellar parameters to few % level
- Demonstrated 2-D analysis of Fast Rotators (gam Cas) - **Now**
- Analyze & Publish. archival survey data **(This year)**
- Joint VHE/SII T Cor Bor and other nova (if lucky) **TBD**

- Approaching 1% resolution in visibility curve
  - Improvements in 1-D & 2-D fast rotator analysis
  - Explore Limb Darkening constraints (Dark Time observations?)
  - Multi-orbit observations of short term binaries (days/weeks)
  - Model dependent fitting of general 2-D images (binaries)
  - We still have a lot room to improve……

- Technology & simulation development for future implementations
  - Use of VERITAS post-gamma ray (2028+): larger f/ optics, improved camera, multi-spectral, etc
  - CTAO-SII
  - & beyond