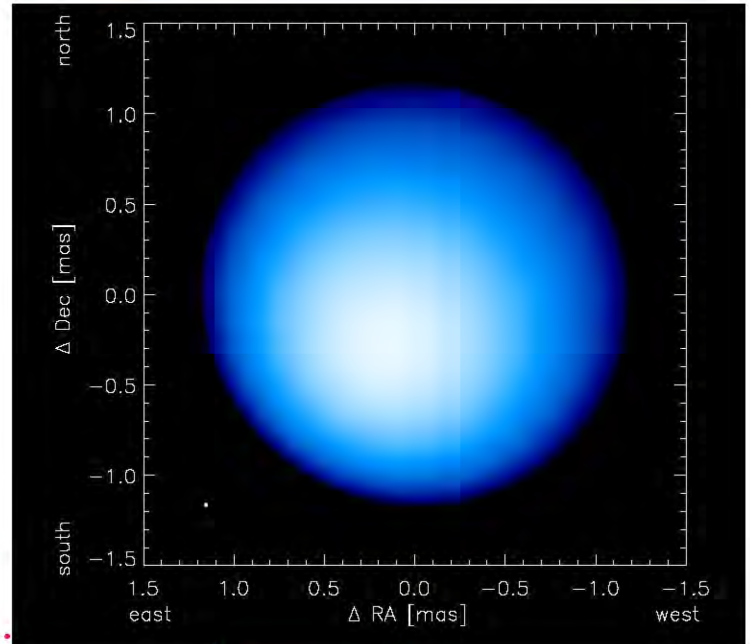
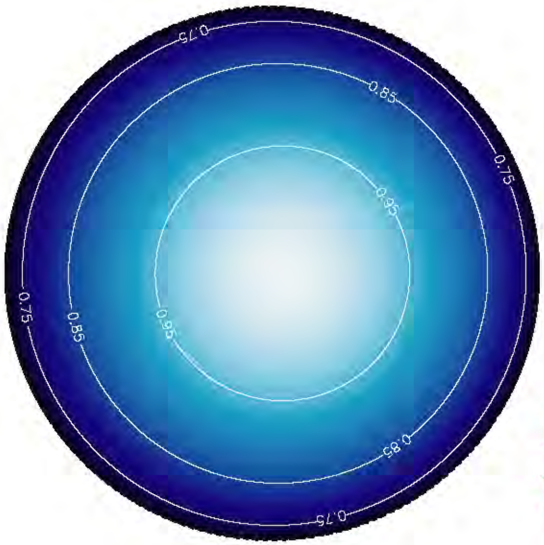
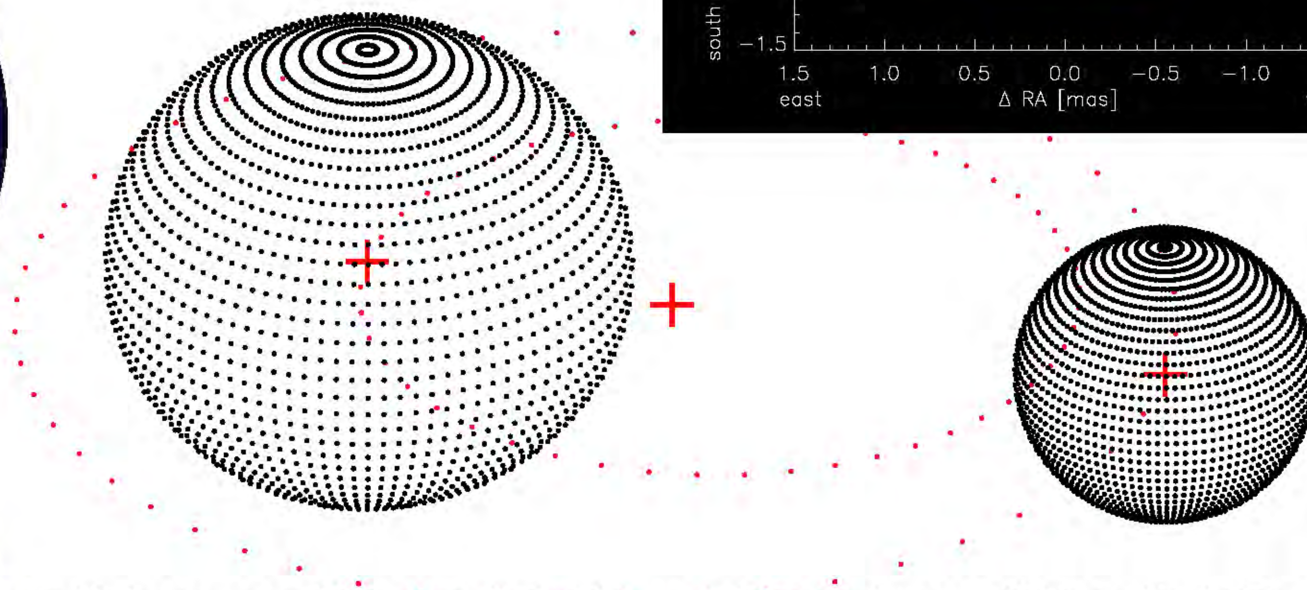
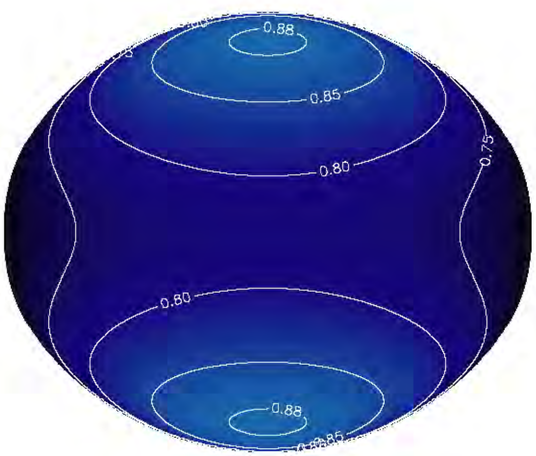
# "Spinning and Limb Darkening" Vega, Deneb, & Spica

**Jason Aufdenberg**
Embry-Riddle Aeronautical University



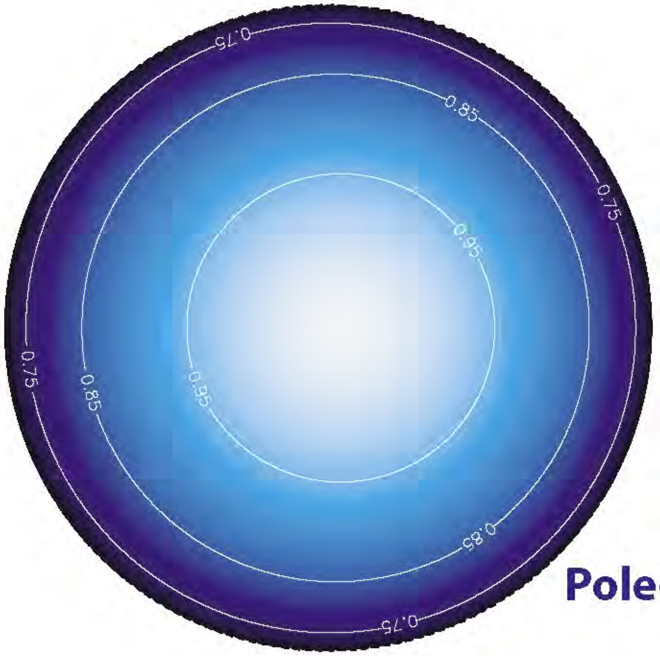



Collaborators: M. Ireland, A. Mérand, S. T. Ridgway, V. Coudé du Foresto, W. Bagnuolo, D. R. Gies, T. A. ten Brummelaar, H. A. McAlister, L. Sturmann, J. Sturmann, D. H. Berger, N. H. Turner, P. Kervella, O. Absil, E. Di Folco

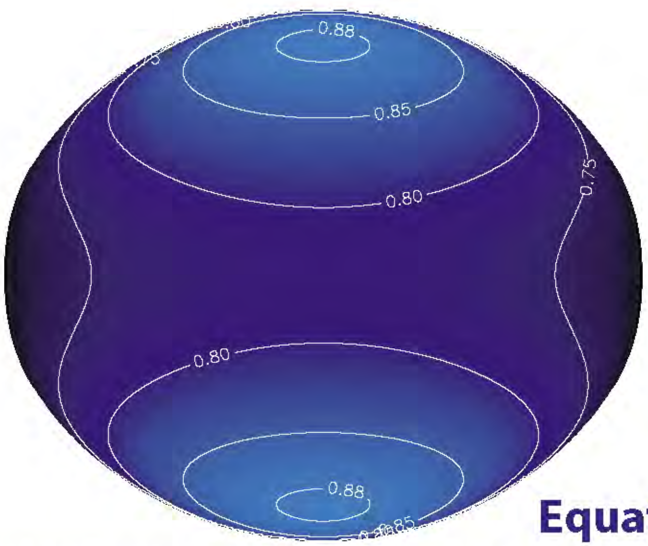
Acknowledgement: Michelson Postdoctoral Fellowship, JPL/NASA

# Limb Darkening and Gravity Darkening (Brightening)

**Rapidly Rotating Model with both Limb and Gravity Darkening**




**Pole-on view**



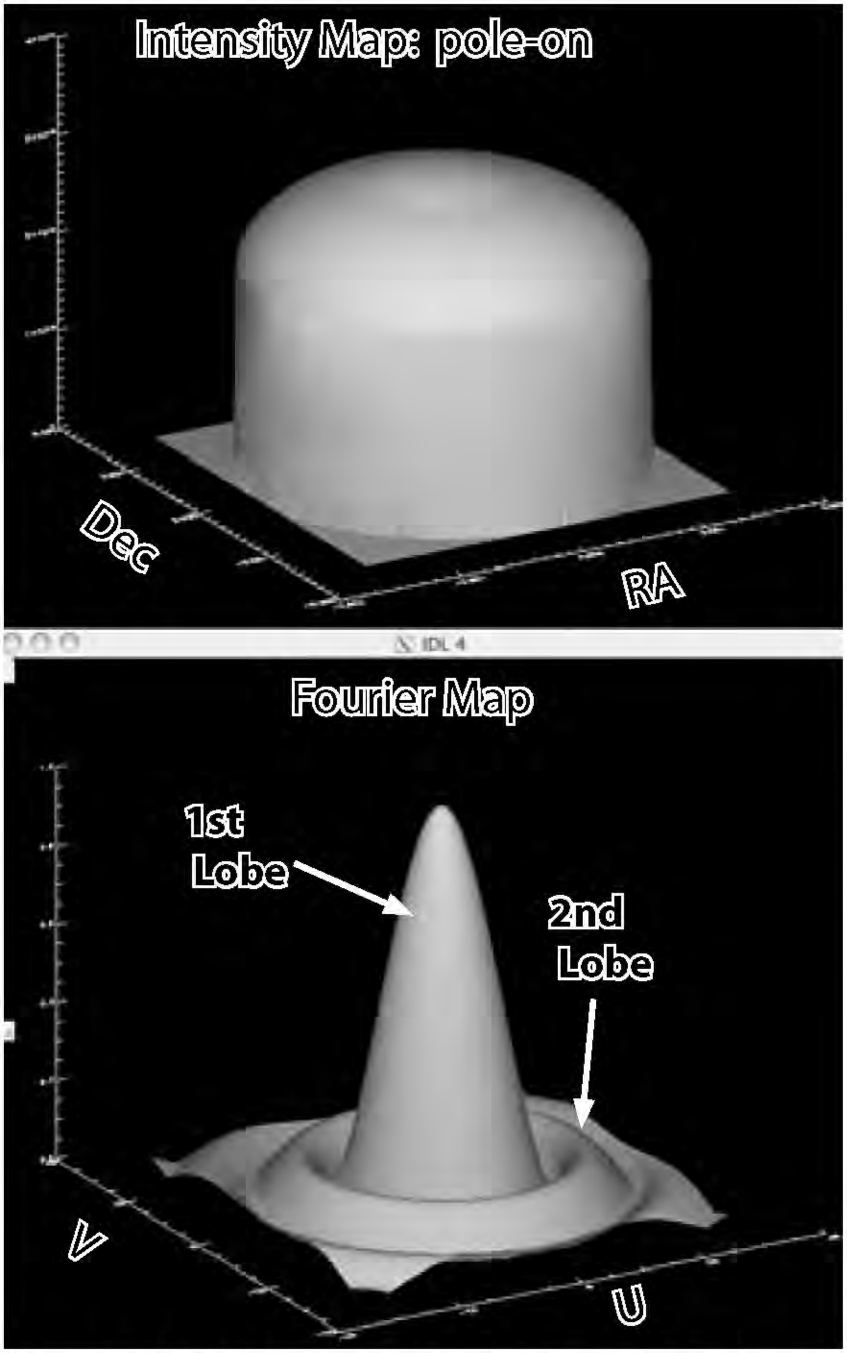

**Equator-on view**

Aufdenberg et al. (2006) ApJ, 645, 664

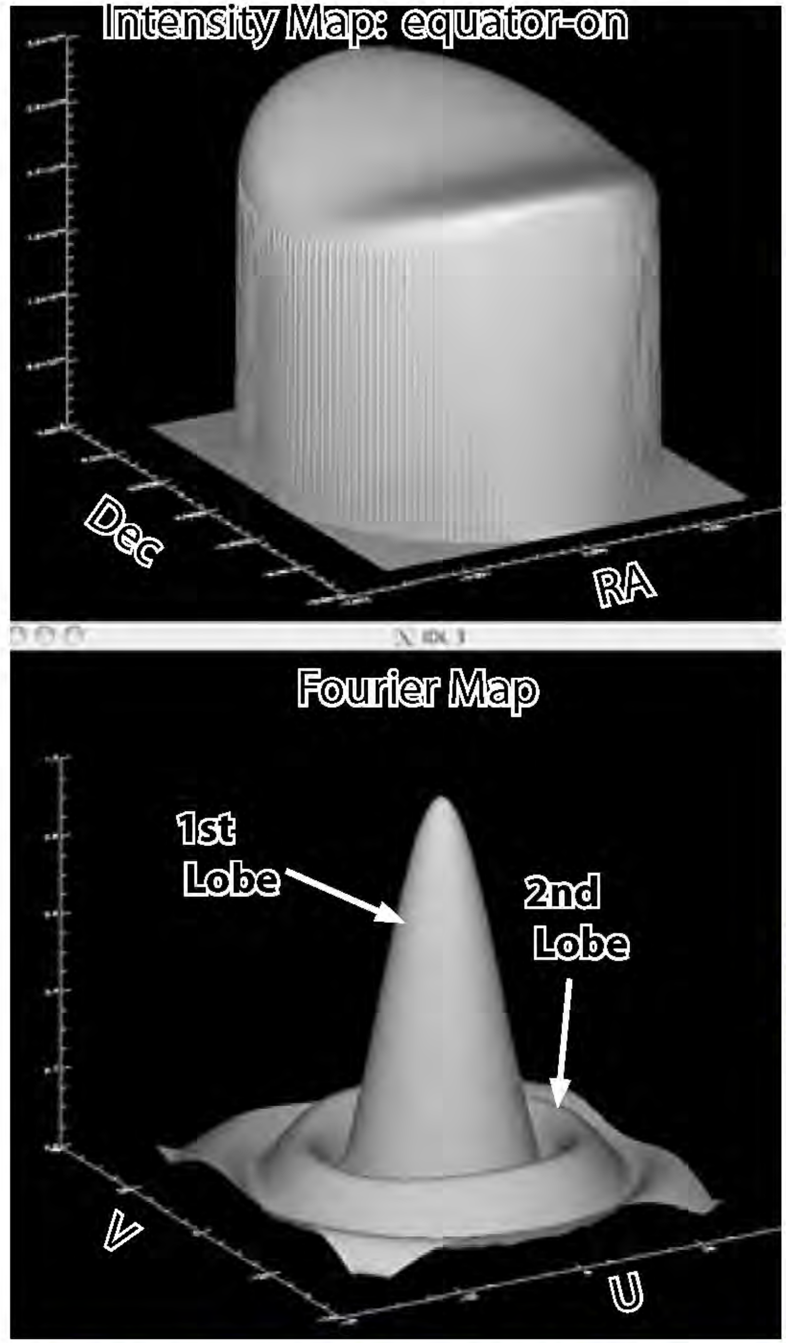
**Limb darkening:** *An observer-dependent effect in which the intensity across a stellar surface varies due to a radial or depth-dependent temperature gradient.*

**Gravity darkening:** *Intrinsic to the star, a pole-to-equator effective temperature gradient resulting from rapid rotation. Local Teff on surface correlates with local gravity (e.g., Teff* $\propto$ *$g^{1/4}$). From the work of H. Von Zeipel (1924). H.N. Russel finds observational evidence for GD in photometry of eclipsing binaries (1939).*

# Interferometric Signatures of Limb and Gravity Darkening




Fast Fourier Transform—»

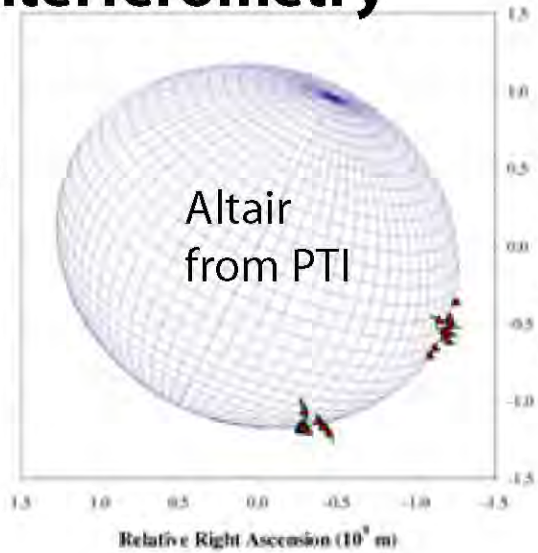


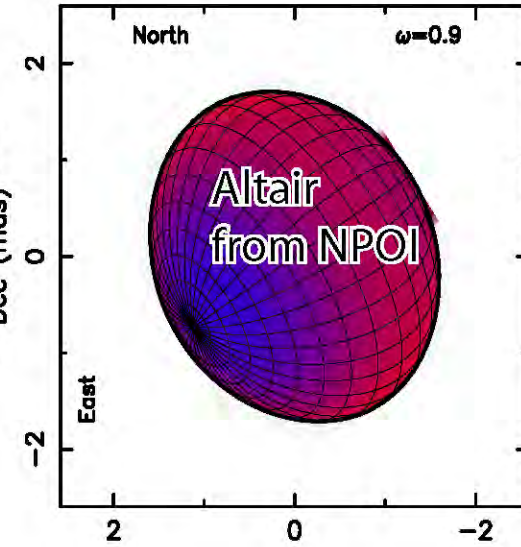

On the sky...

... what an interferometer samples

# Resolved Rapid Rotators from Interferometry

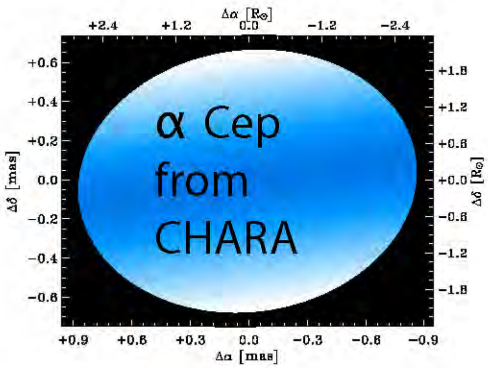
*Disk of **Altair** (A7 V) resolved as ellipsoid by the Palomar Testbed Interferometer (van Belle et al. 2001) Axial ratio: 1.140±0.029



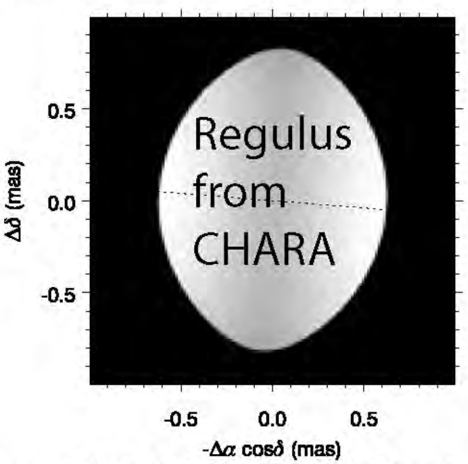



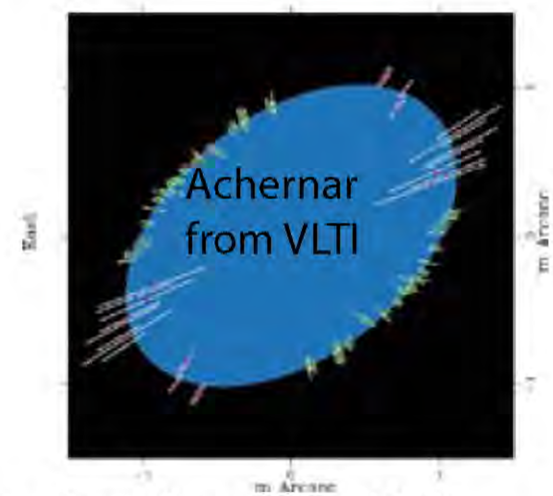

Peterson et al. (2006) Apl, 636, 1087

*Disk of **Alderamin** (A7 IV-V) resolved as an ellipsoid by CHARA (van Belle et al. 2006). Axial ratio: 1.298±0.051




*Disk of **Regulus** (B7 V) resolved as ellipsoid by CHARA (McAlister et al. 2005). Axial ratio: 1.32±0.02



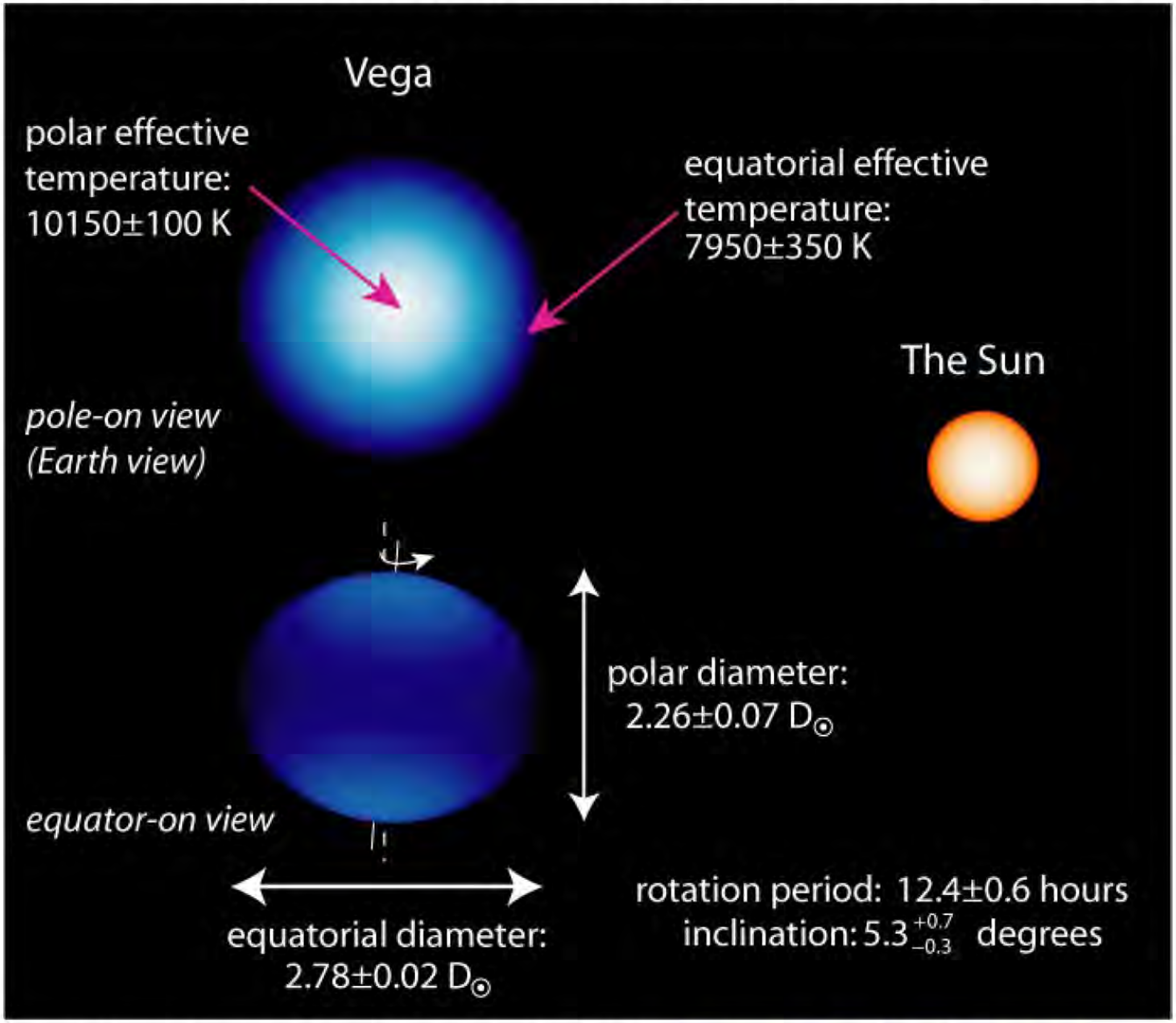




*Disk of **Achernar** (B3 Vpe) resolved as ellipsoid by VLTI (A. Domiciano de Souza et al. 2003). Axial ratio: 1.56±0.05

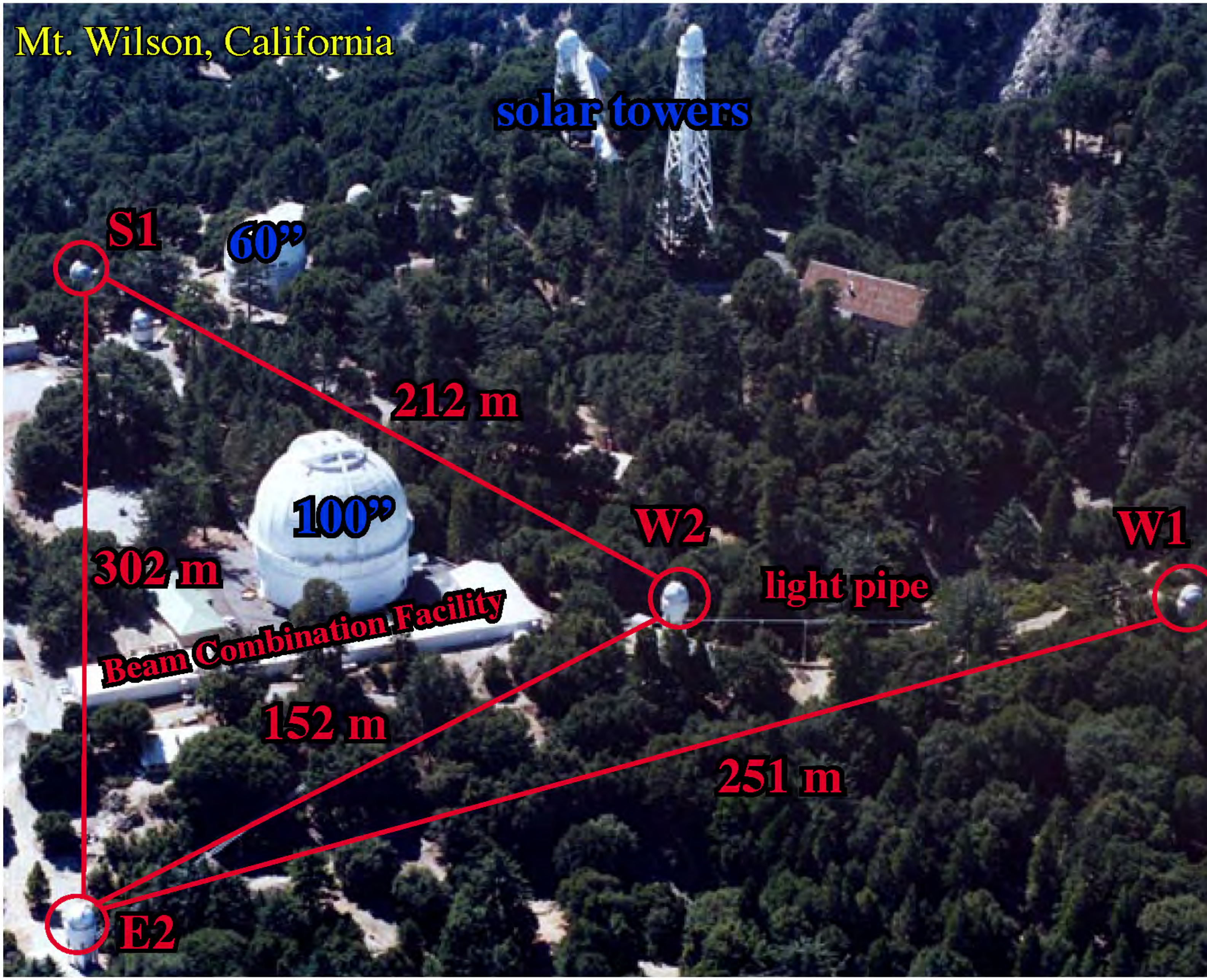
# Vega: The Nearest Rapid Rotator

R. Gray (1985, 1988) concludes Vega is a pole-on rapid rotator.

**1)** Vega is 60% larger (in Radius) than Sirius. **2)** Vega is 50% too luminous.



# CHARA (Center for High Angular Resolution Astronomy) Array



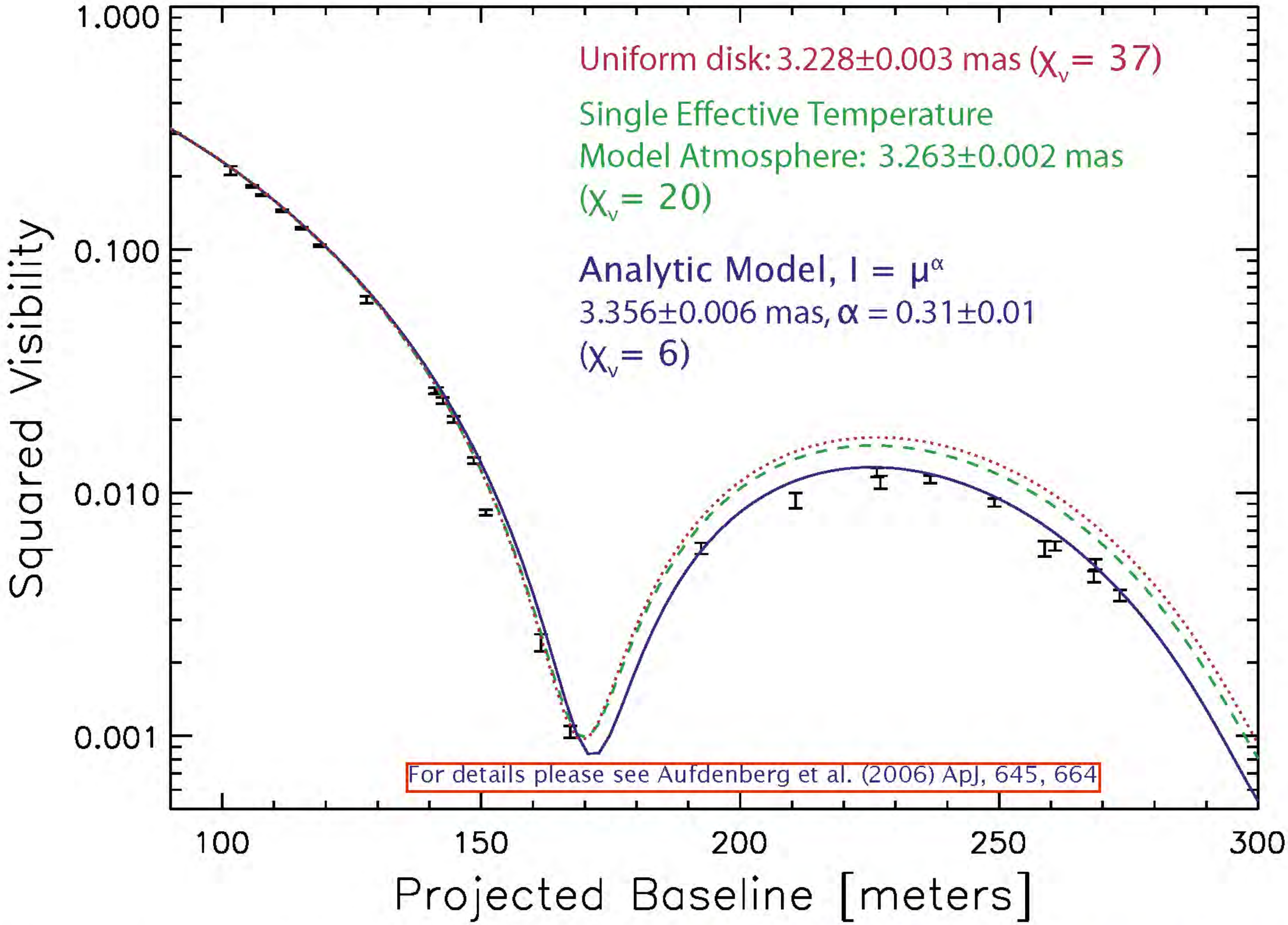

Vega Observations
May, June2005

K-band
$\lambda = 2.2\ \mu m$

**F**iber
**L**inked
**U**nit for
**O**ptical
**R**ecombination

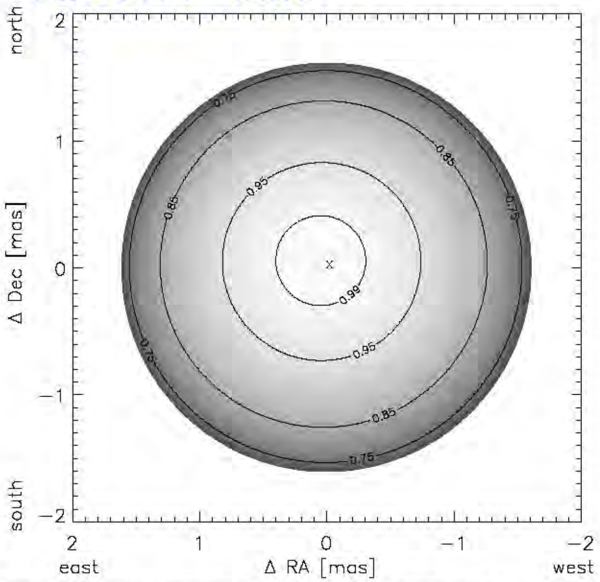
beam combiner

# Vega Visibilities from CHARA/FLUOR and Different Models

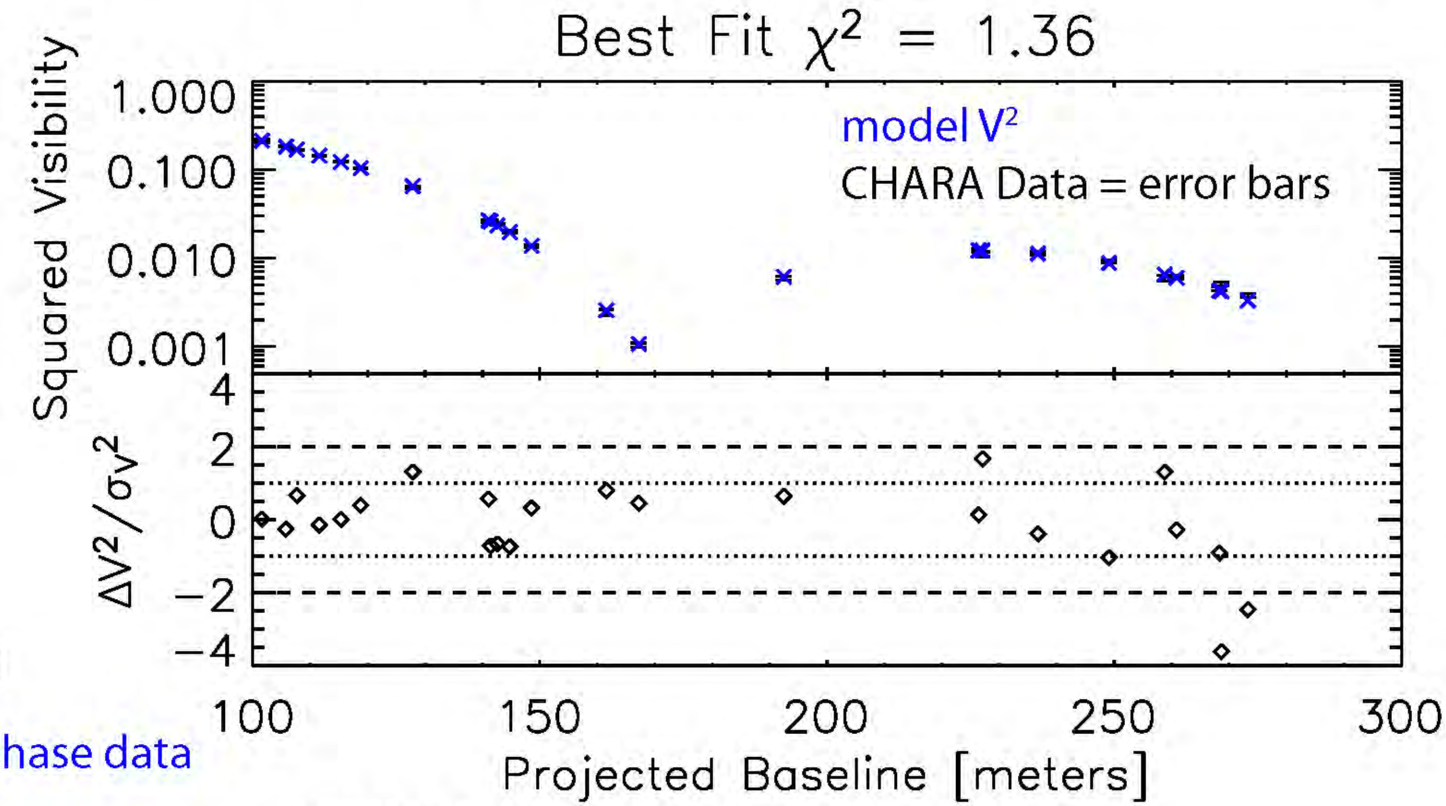


# Rapidly Rotating Models for Vega from Independent Interferometric Data

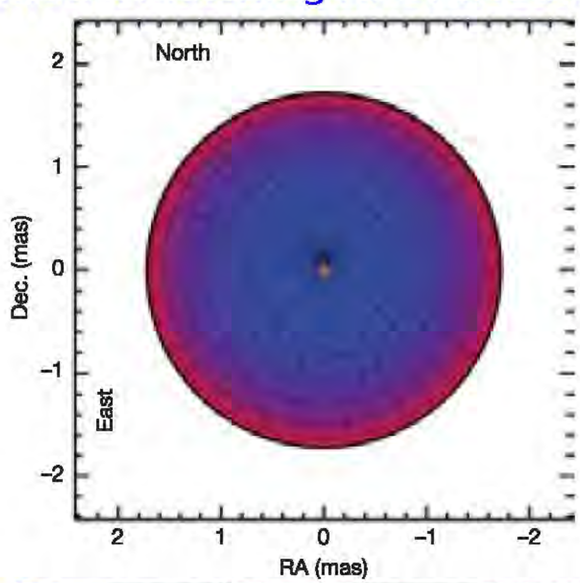
## Model matching CHARA/ FLUOR $V^2$ data




Aufdenberg et al. (2006) ApJ, 645, 664

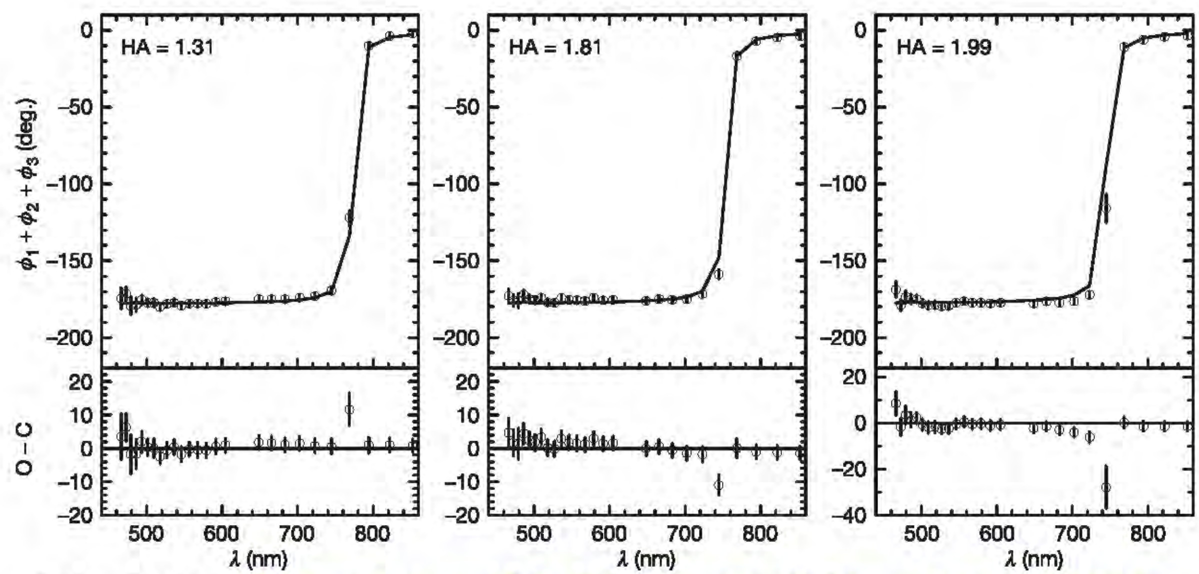



## Model matching NPOI closure phase data

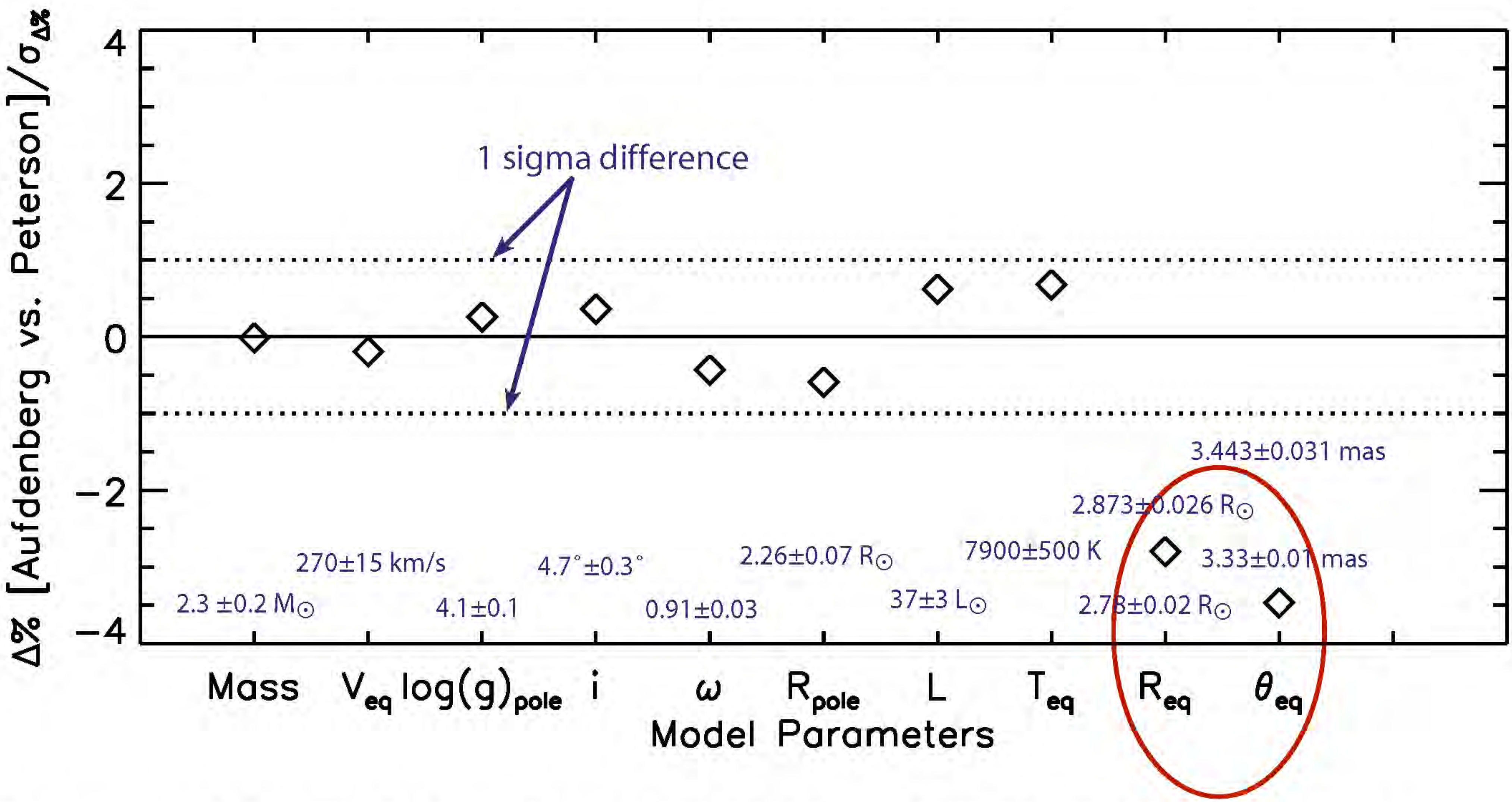



Peterson et al. (2006) Nature, 440, 896

NPOI data

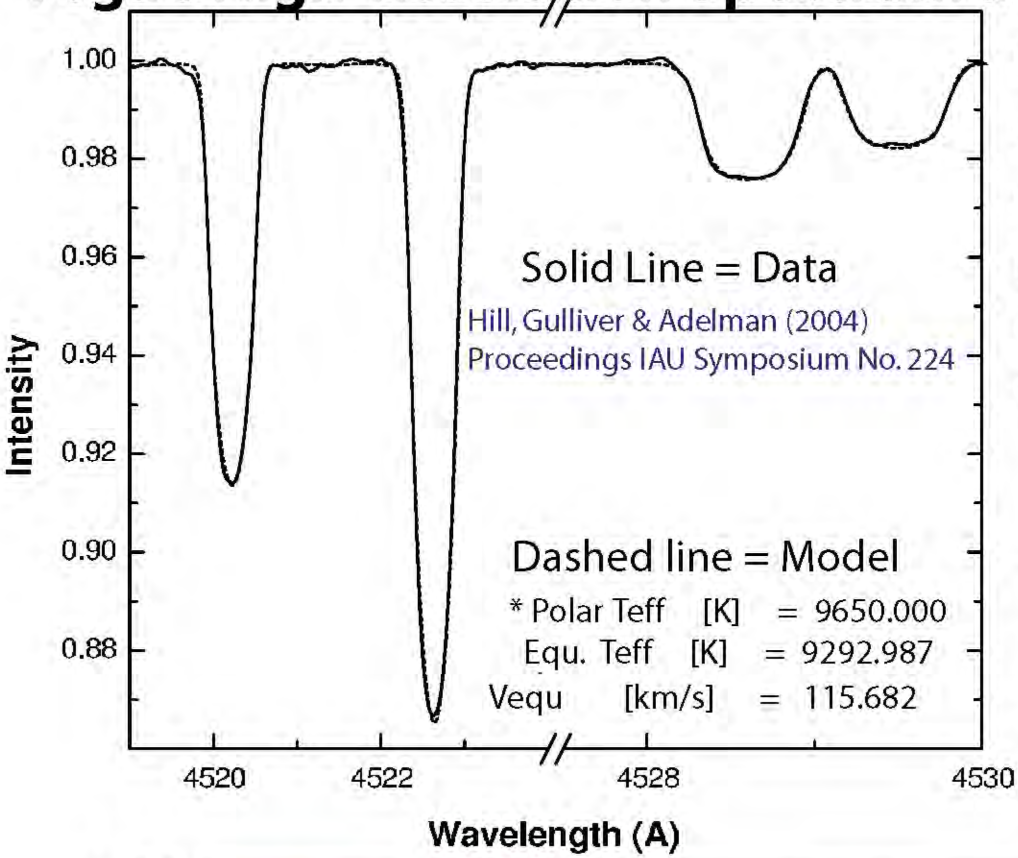


# A Comparison of Parameters for Vega from Aufdenberg et al. (2006) and Peterson et al. (2006)



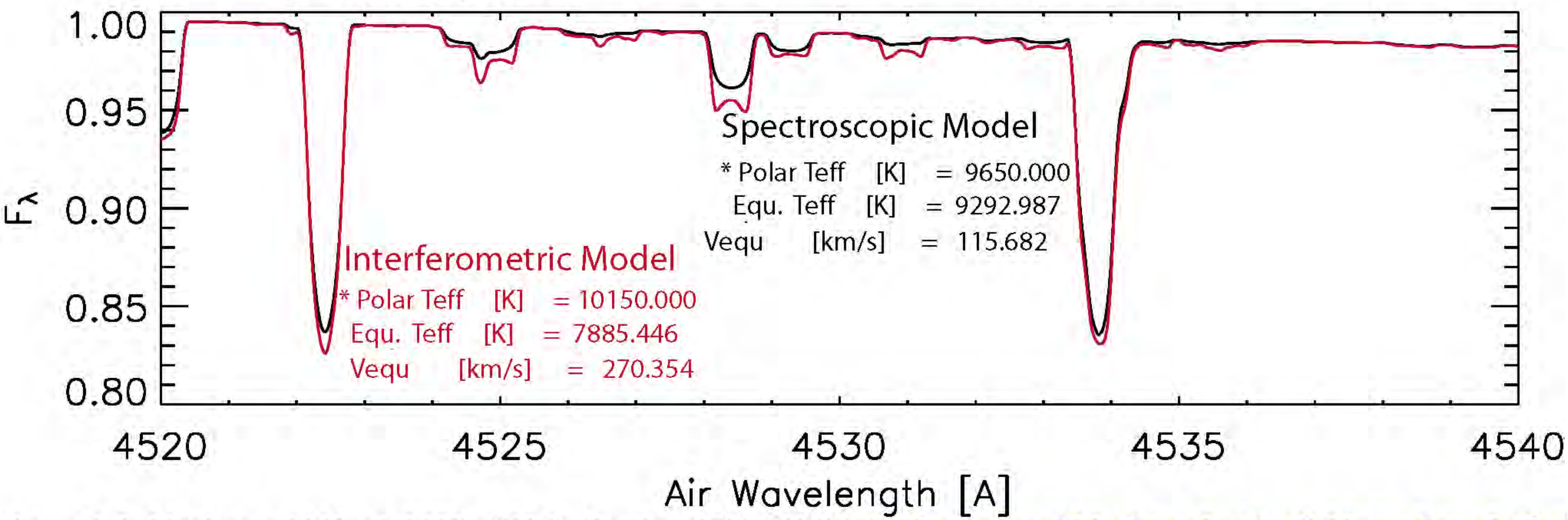

The equatorial radii derived from CHARA (IR) and NPOI (Visible) data are not consistant. Moreover, CHARA and NPOI parameters don't match spectroscopy.

# Vega's High-Resolution Spectrum at Odds with Interferometry Results




**Our independent model for Vega's high dispersion spectrum confirms the results of Hill, Gulliver and Adelman who find a more slowly rotating Vega: ($V_{equ}$ = 115 km/s vs. $V_{equ}$ = 270 km/s) than suggested by interferometry.**

**Solutions:**
**equatorial convection?**
**large scale circulation?**
**Can we expect other rotators to be better behaved?**

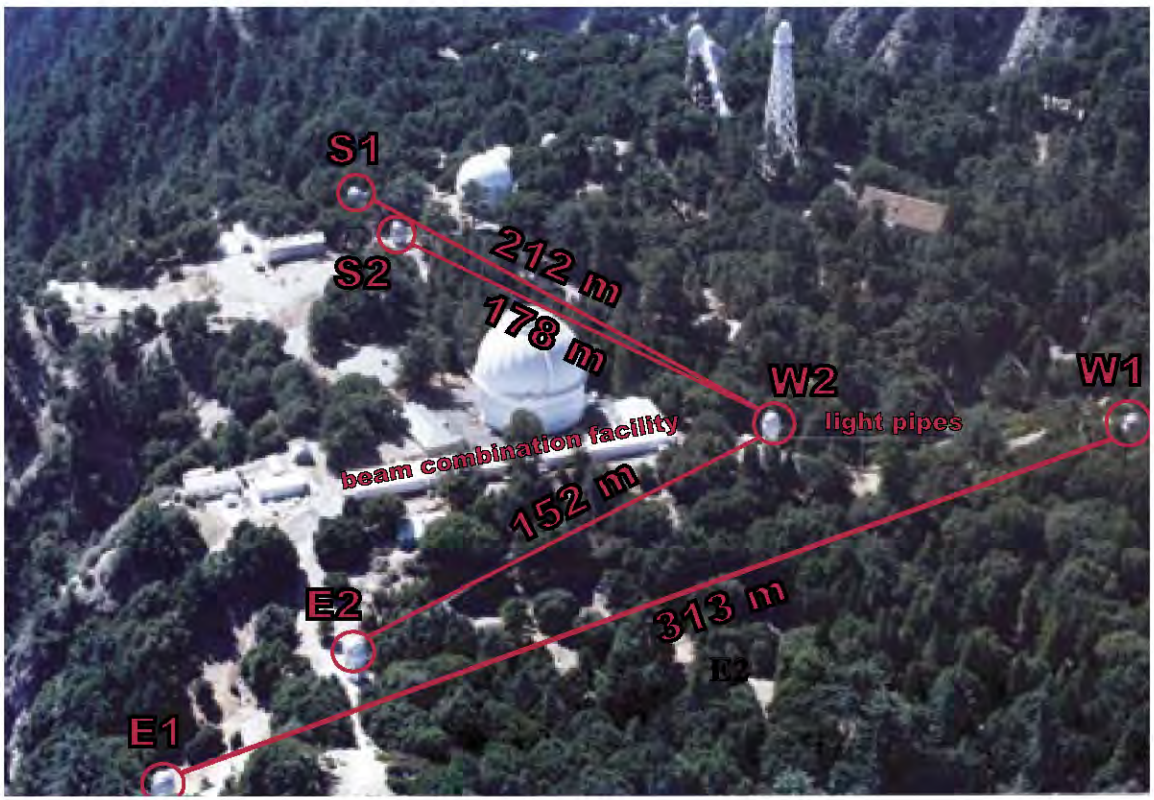


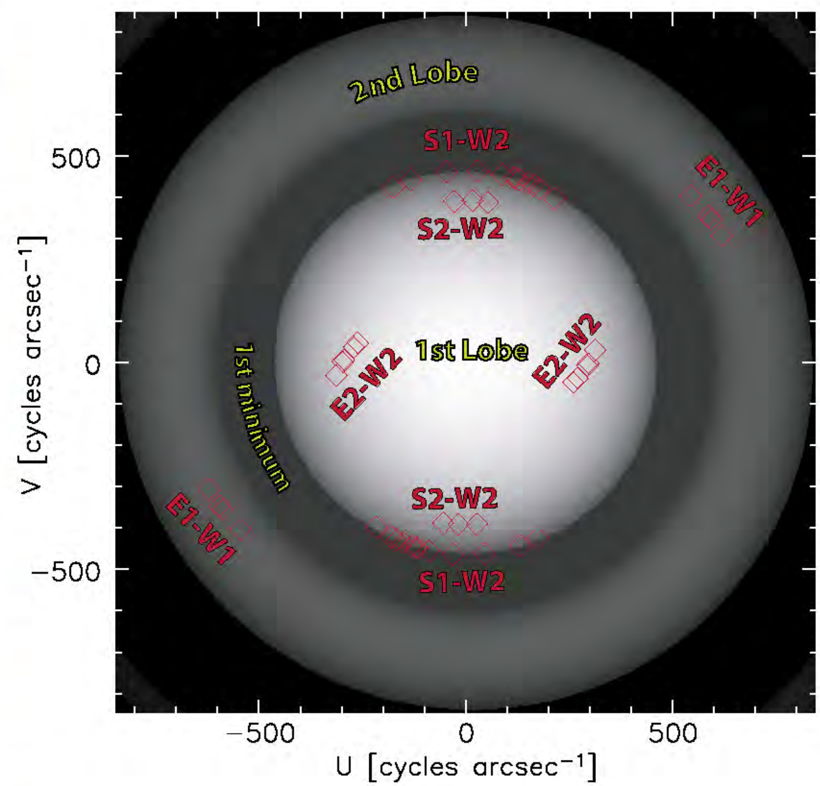
α Cygni HR 7924 HD 197345
Blue Supergiant A2 Ia

# Deneb

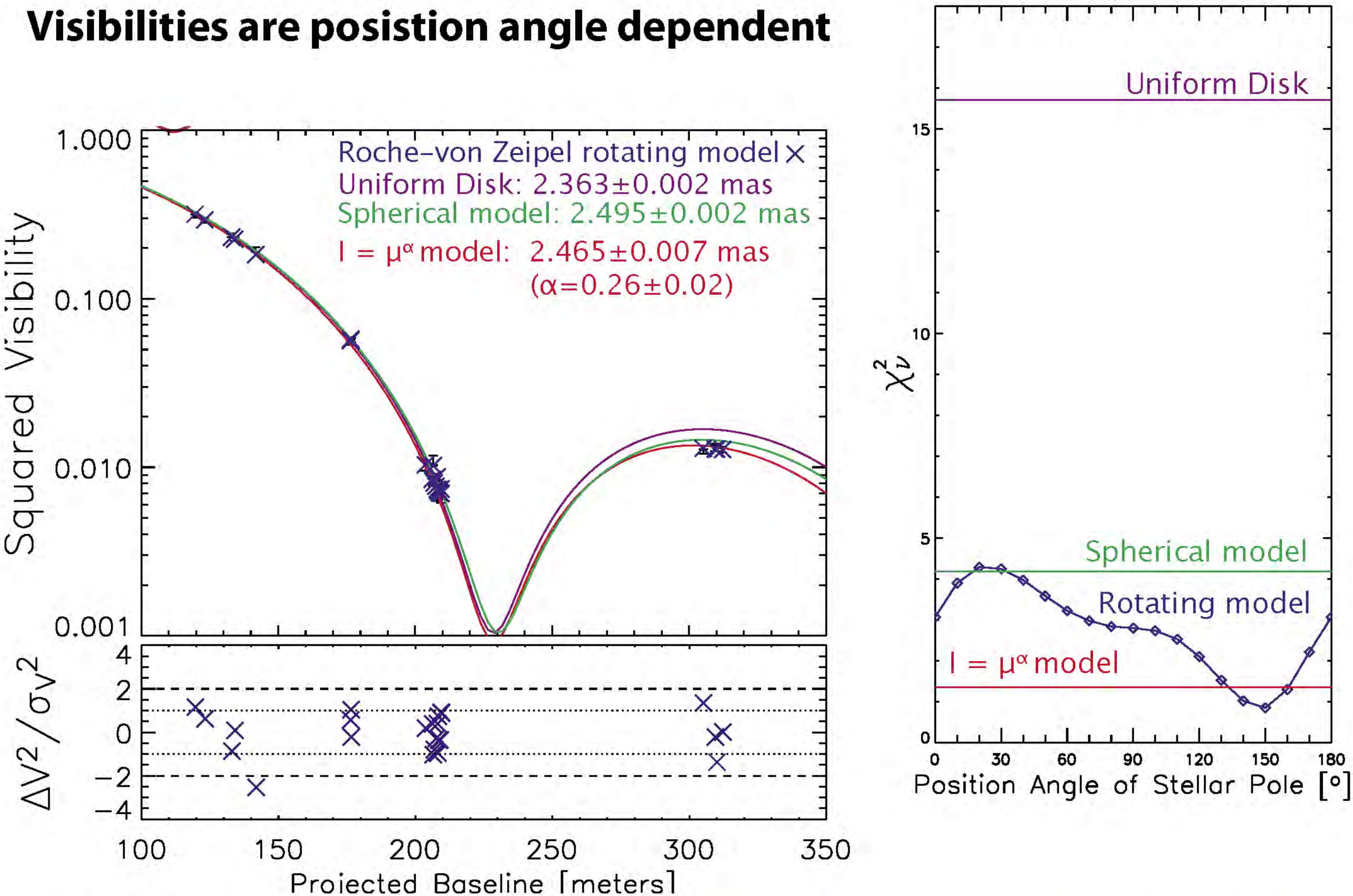
## Deneb's stellar wind predicted (Aufdenberg et al. 2002) to strengthen limb darkening. But this star is more complicated that expected...

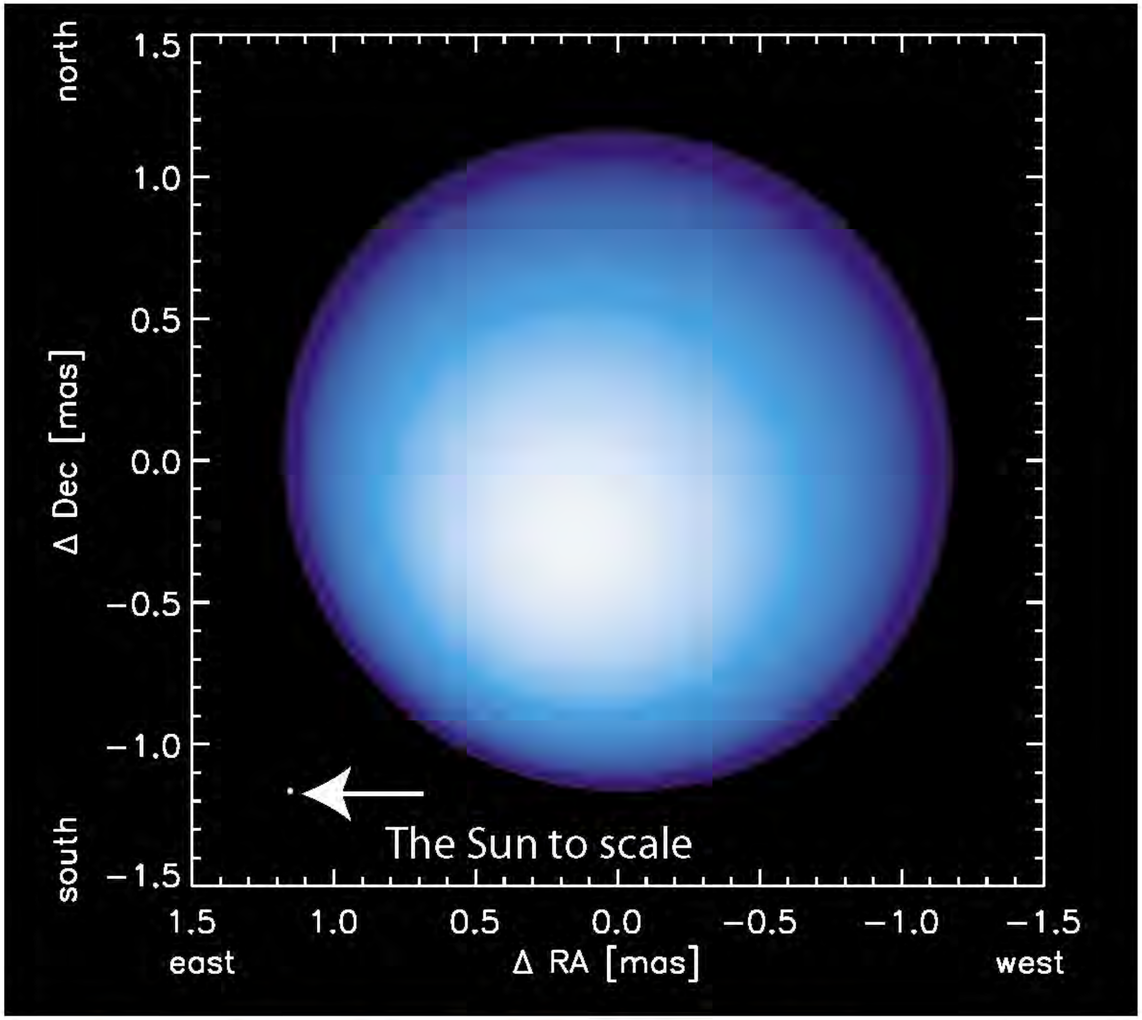
### CHARA/FLUOR Measurements 2004-2005



# Weak 2nd lobe found *and* Visibilities are posistion angle dependent






**Deneb's stellar wind is ignored in this model.**

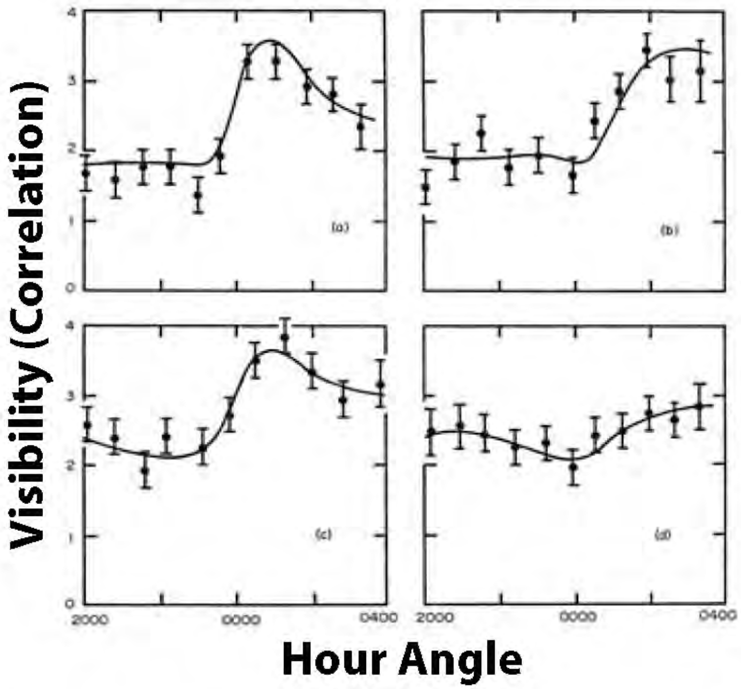
**Next step: Add in the stellar wind...**

## Rotating Model Parameters

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $\theta_{equ}$ [mas] | 2.460 | Polar Log(g) [cgs] | 1.240 |
| $R_{pole}$ [$R_\odot$] | 167.913 | M [$M_\odot$] | 17.882 |
| $R_{equ}$ [$R_\odot$] | 181.098 | L [$L_\odot$] | 137752.630 |
| $R_{equ}/R_{pole}$ | 1.079 | Break-up fraction, ω | 0.650 |
| Inclination [°] | 33.481 | $P_{rotation}$ [days] | 168.553 |
| Projected $R_{equ}/R_{pole}$ | 1.027 | $V_{equ}$ / $V_{equ\_crit}$ | 0.467 |
| Polar $T_{eff}$ [K] | 8800.000 | $V_{equ\_crit}$ [km/s] | 116.359 |
| Equatorial $T_{eff}$ [K] | 8119.544 | $V_{equ}$ [km/s] | 54.382 |
| | | Projected $V_{equ}$ [km/s] | 30.000 |

# SPICA: Resolved by the Intensity Interferometer

Hebrison-Evans et al. (1971)



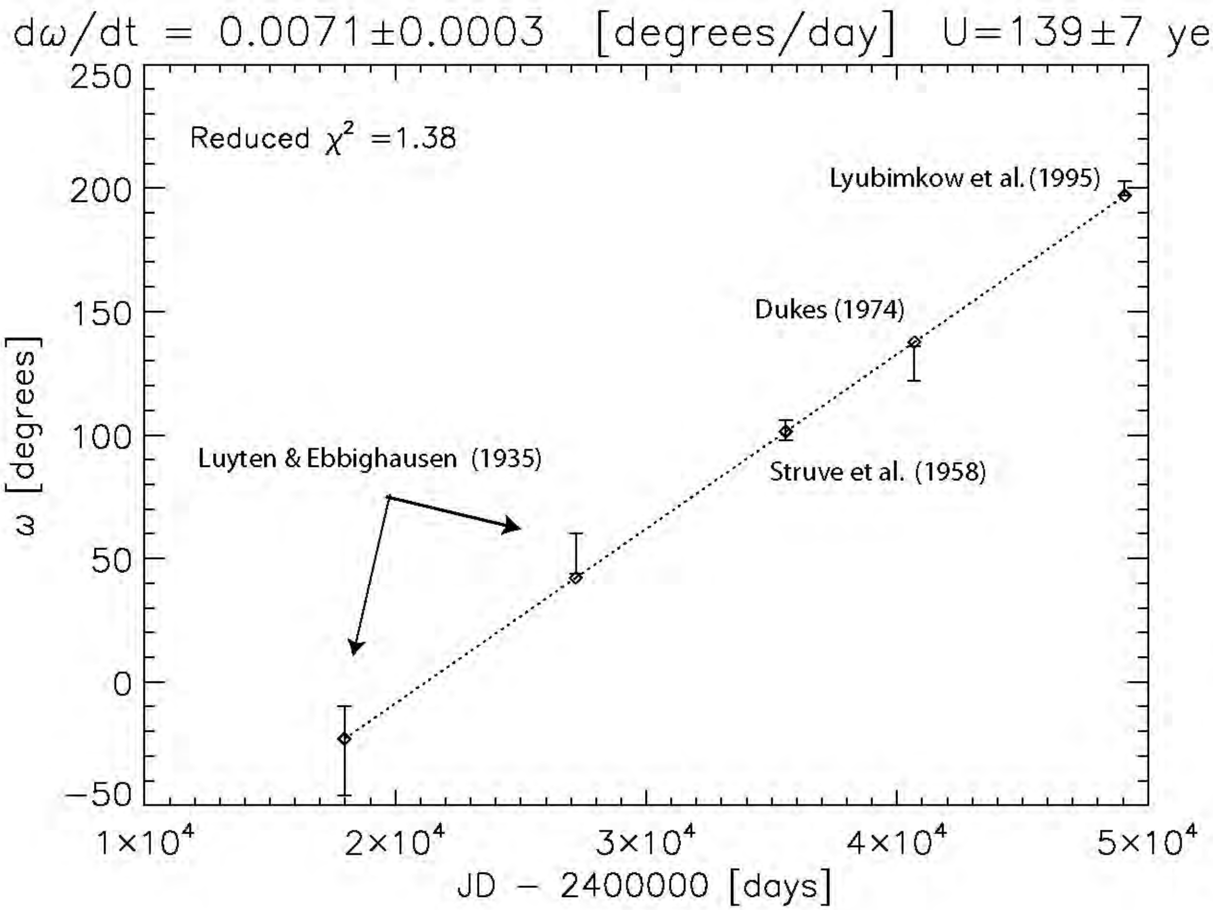

*Spica, the second spectroscopic binary to be resolved interferometrically (after Capella).

*P= 4.01 days, a ~ 1.8 mas, distance = 80 pc or ~ 10 times more distant than Vega.
*Massive components: ~11 and ~7 Msun

*Apsidal motion provides probe to internal structure of components.

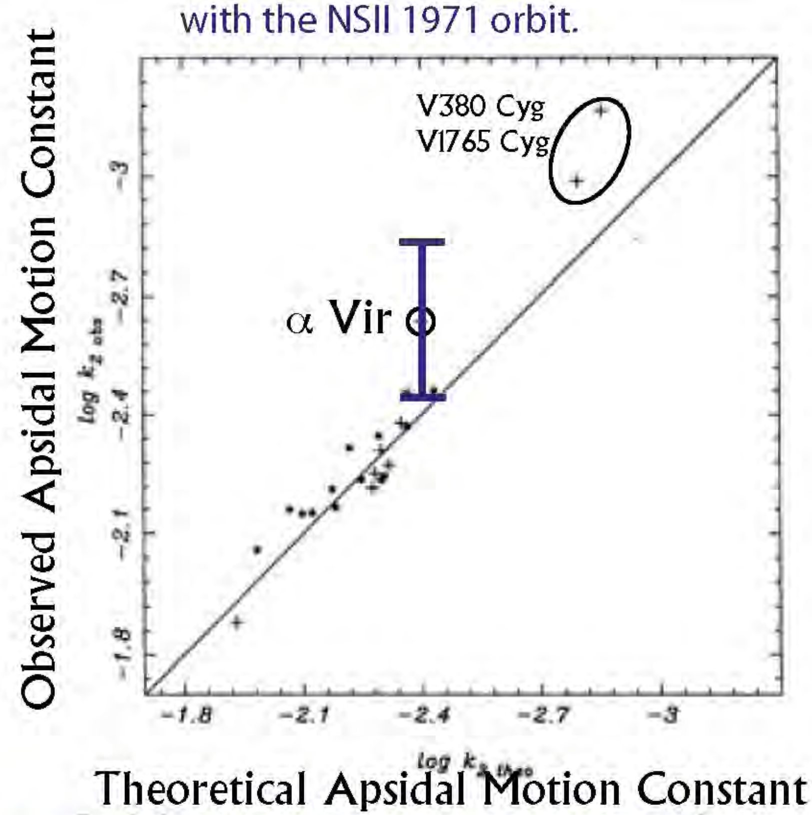
*Complexities include: Asynchronous rotation -- mutual irradiation -- limb and gravity darkening -- tidal distortion -- non-radial oscillations in Spica A

# Spica: Its Apsidal Nature




$$\bar{k}_{2obs} = f(U, P, e, m_A, m_B, v_B \sin i, v_B \sin i)\left(\frac{\theta_A}{\theta_\alpha}\right)^5$$

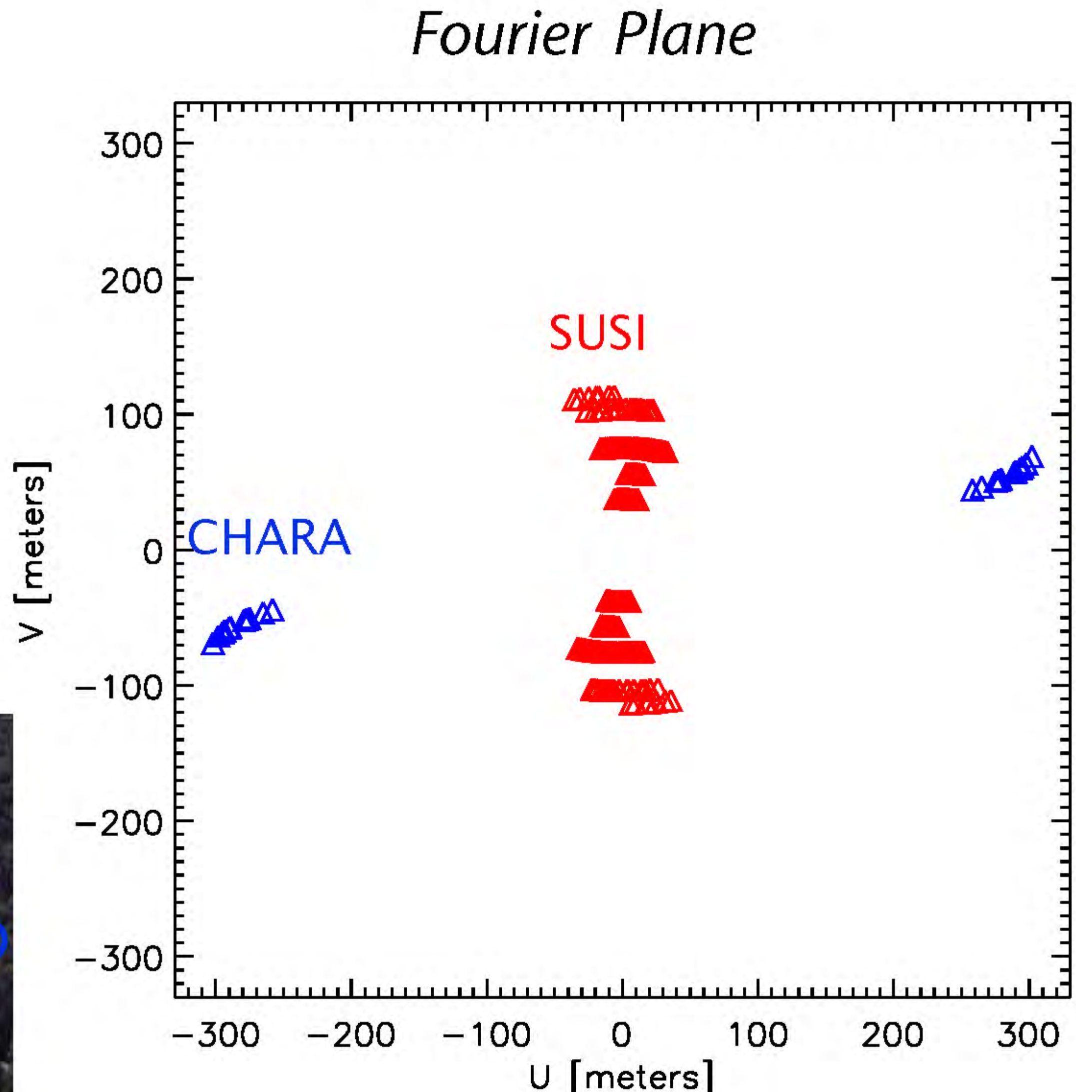
Figure adapted from Claret and Gimenez (1993), adding Spica with the NSII 1971 orbit.



# Fourier Coverage of Spica from SUSI *and* CHARA

Sydney University Stellar Interferometer
North-South Baselines (up to ~ 100 m)

CHARA Array East-West Baseline (~ 313 m)

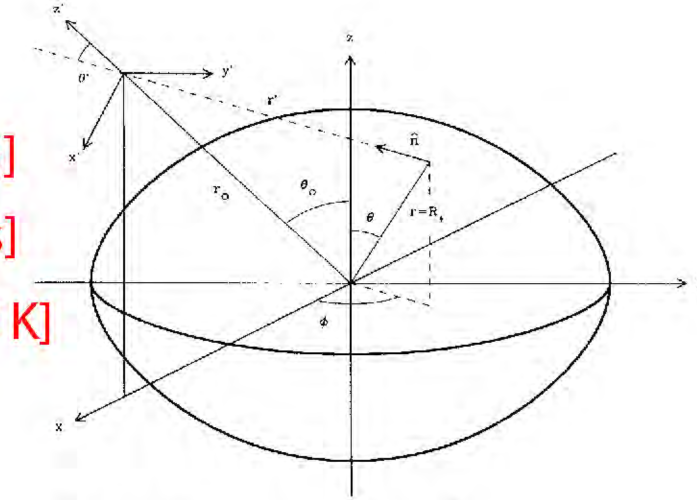



SUSI Data thanks to Mike Ireland and Andrew Jacob.

# Building a Binary Model for Spica

preliminary values

| | | |
|---|---|---|
| $\omega$ | Fraction of the angular break-up speed | [0.50, 0.25] |
| $\theta_{\mathrm{equ}}$ | Equatorial angular diameter | [1.076 mas , 0.45 mas] |
| $T_{\mathrm{eff}}^{\mathrm{pole}}$ | Effective temperature at the pole | [25900 K, 20850 K] |
| $g_{\mathrm{pole}}$ | Surface gravity at the pole (Spica A) | 3.67 |
| $\beta$ | Von Zeipel exponent | [0.25, 0.25] |
| $P$ | Period (periastron to periastron) | 4.01459 days |
| $T_0$ | Epoch of periastron | 2440678.09 |
| $\omega_0$ | Longitude of periastron at $T_0$ | 138° |
| $U$ | Apsidal period | 116 years |
| $i$ | Orbital inclination | 63.7° |
| $\Omega$ | Longitude of the line of nodes | 121.3° |
| $\theta_{\alpha}$ | Angular size of the semi-major axis | 1.82 mas |
| $K_1$ | Semi-amplitude velocity of Spica A | 124 km/s |
| $K_2$ | Semi-amplitude velocity of Spica B | 199 km/s |
| $\gamma$ | Radial velocity of the center of mass | -5.8 km/s |
| $\pi$ | Orbital parallax (distance) | 13.3 mas |
| $e$ | Orbital Eccentricity | 0.146 |

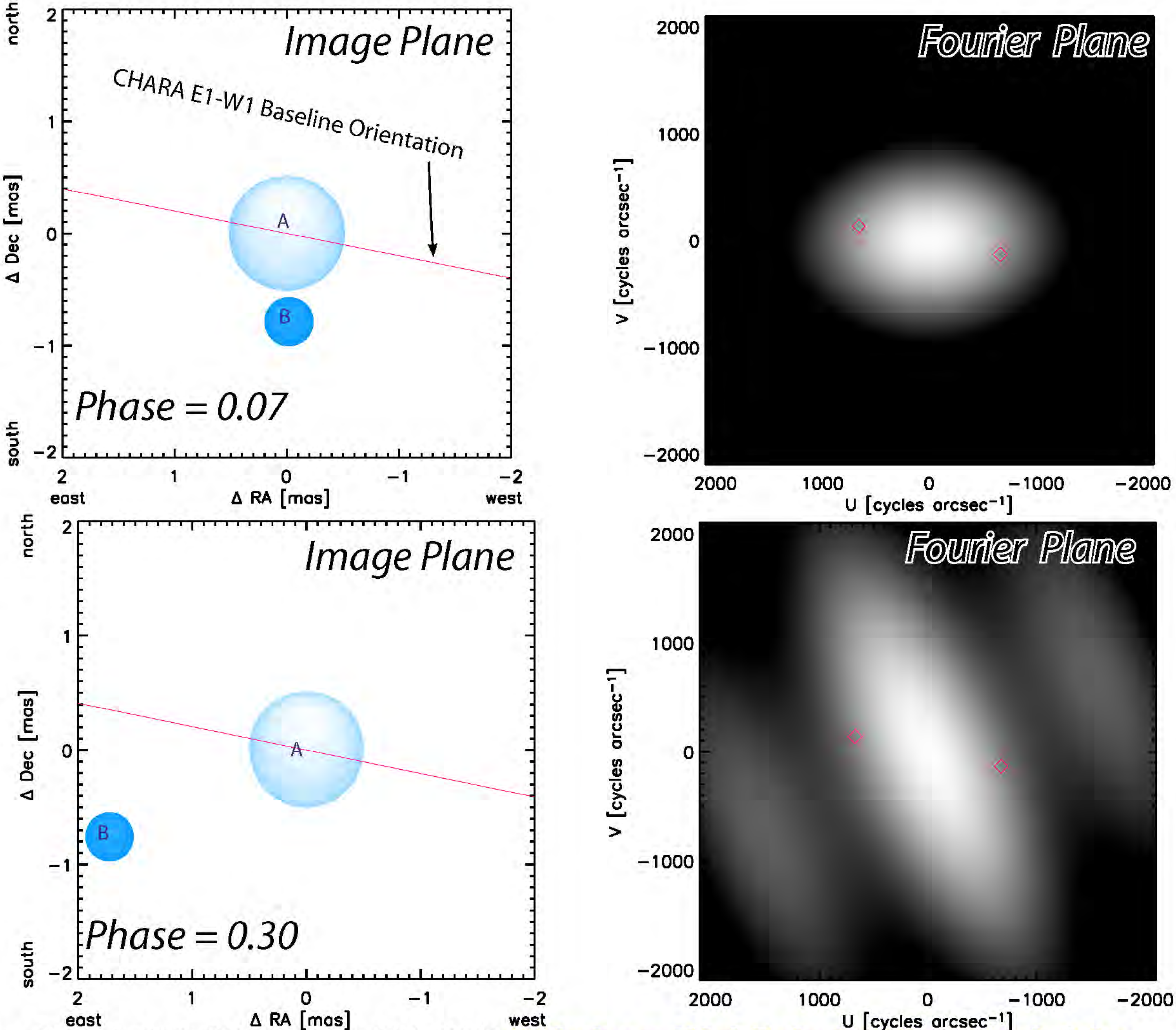


$$\frac{T_{\mathrm{eff}}(\vartheta)}{T_{\mathrm{eff}}^{\mathrm{pole}}} = \left(\frac{g(\vartheta)}{g_{\mathrm{pole}}}\right)^{\beta}$$

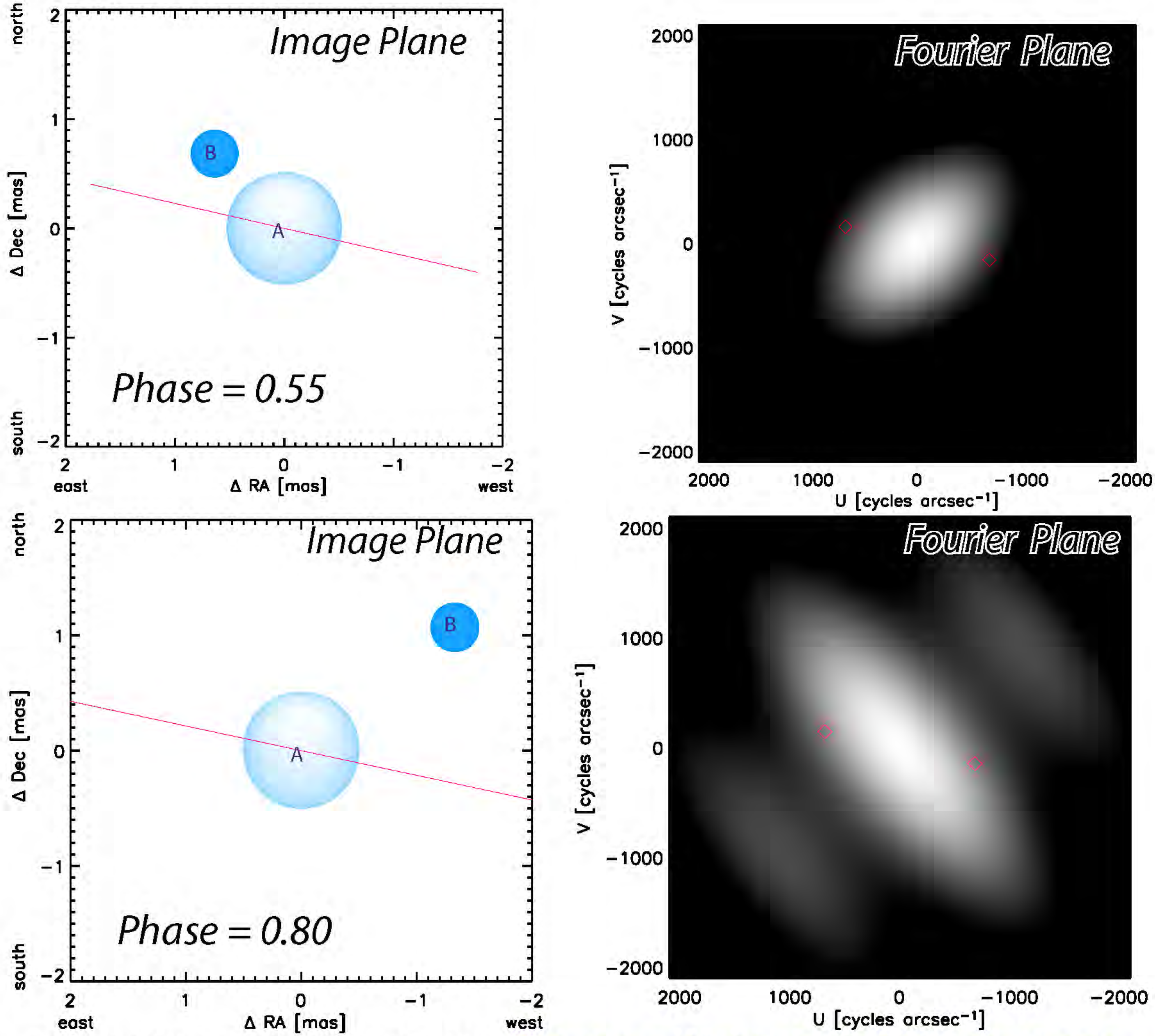
The intensity at each latitude, longitude point is interpolated from a grid of ~200 1-D non-LTE PHOENIX (Hauschildt et al.) model atmosphere radiation fields.

Interpolate $I_{\lambda}$ at each Teff, log(g), $\lambda$, $\mu$

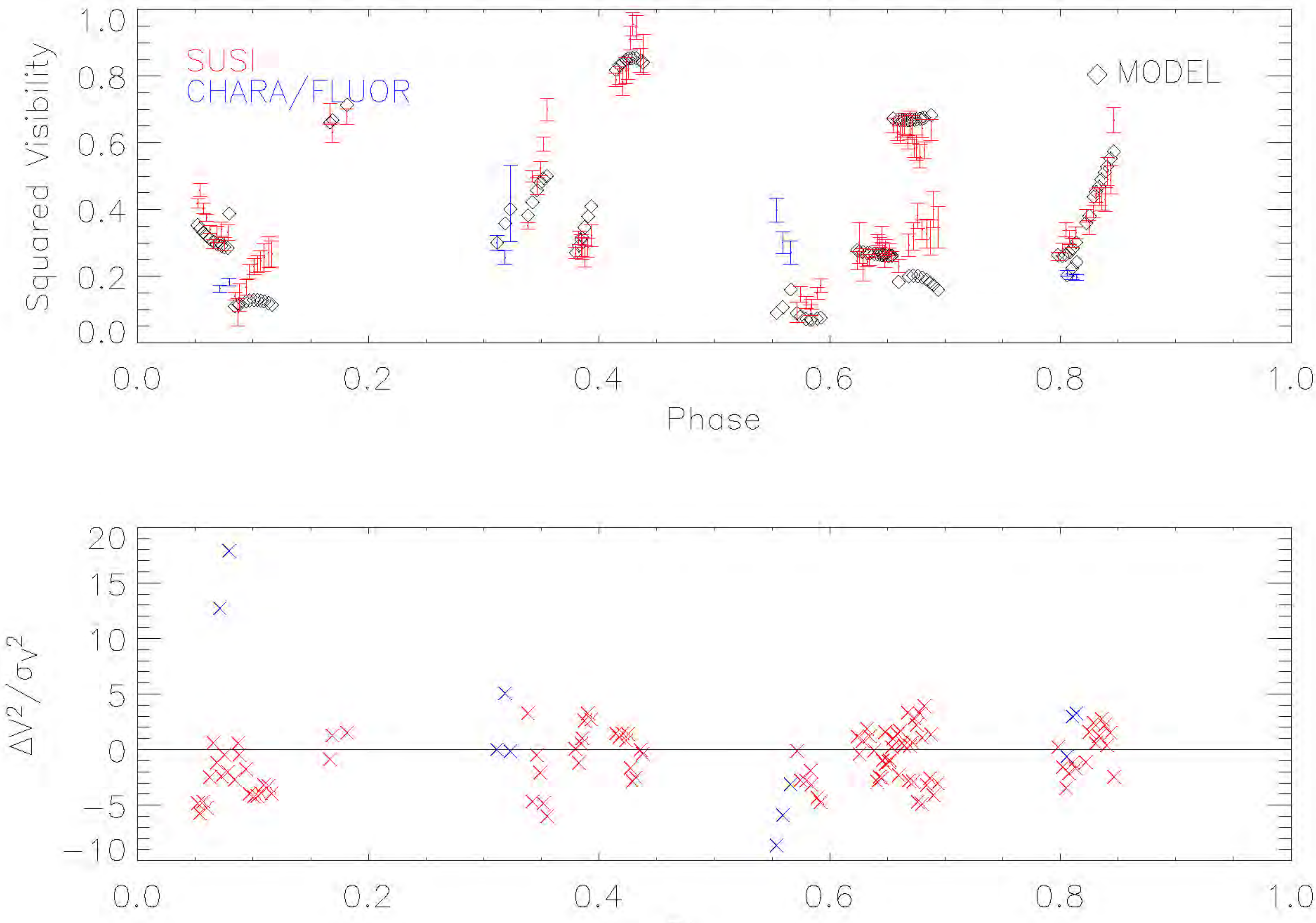
# Interferometric Simulation



# Interferometric Simulation



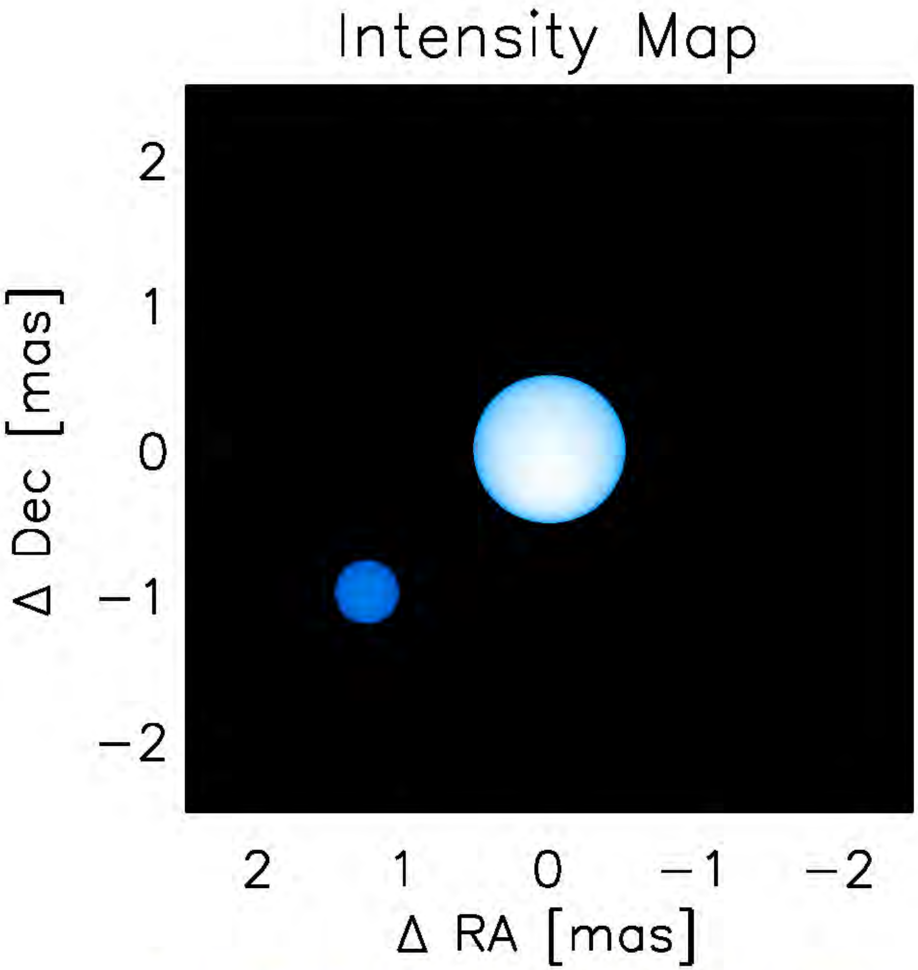
# Preliminary Model Comparison to SUSI+CHARA Visibility Data



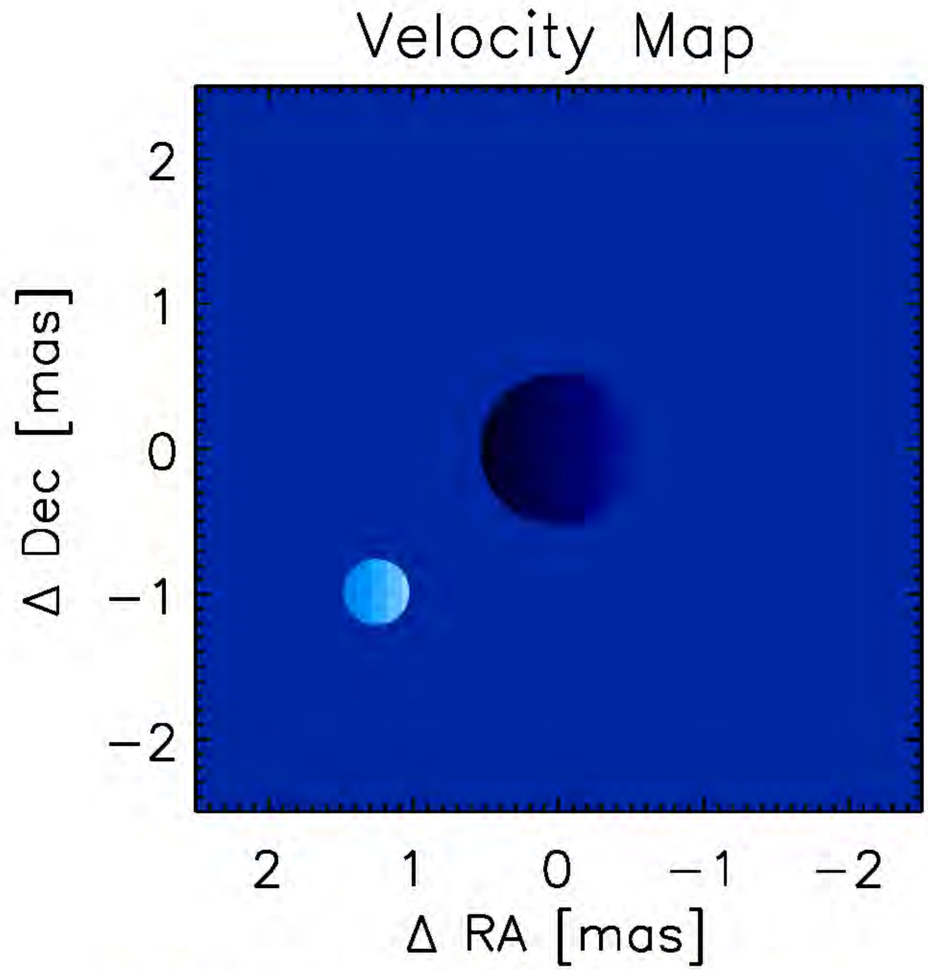

Phase from Periastron

# Consistant Modeling the Orbital and Rotational Velocity Field

*including rotational distortion, limb and gravity darkening*

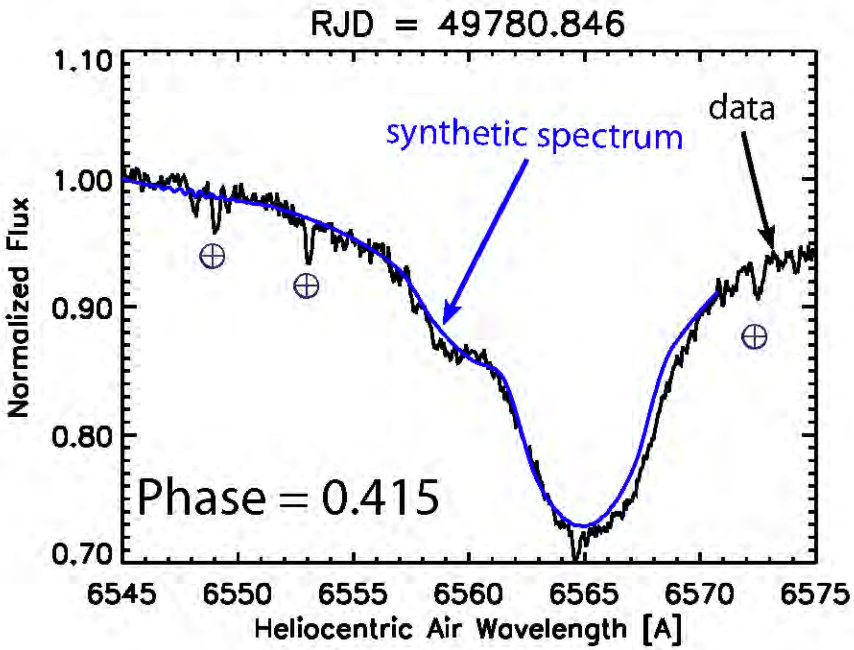


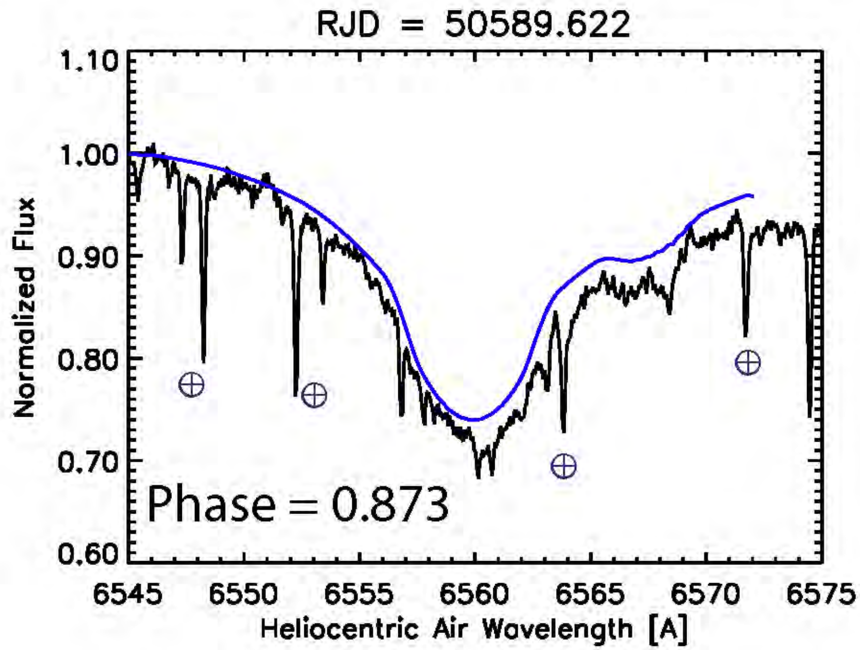

Specific Fouier components of this synthetic image are computed for a visibility simulation

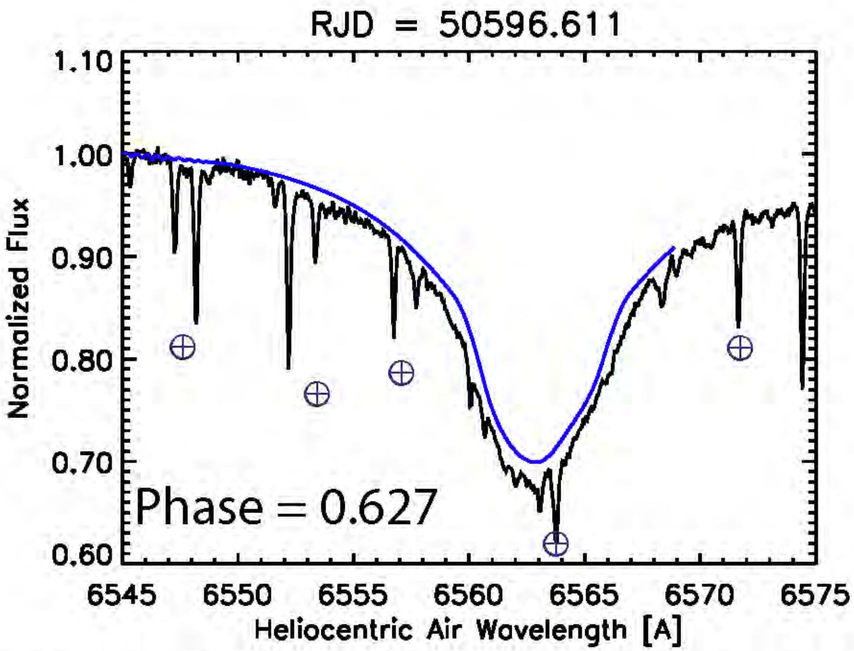



Rest frame wavelengths on the stars are mapped to observer's frame for a high dispersion spectrum simulation

# Model Comparison to High Dispersion Spectroscopy



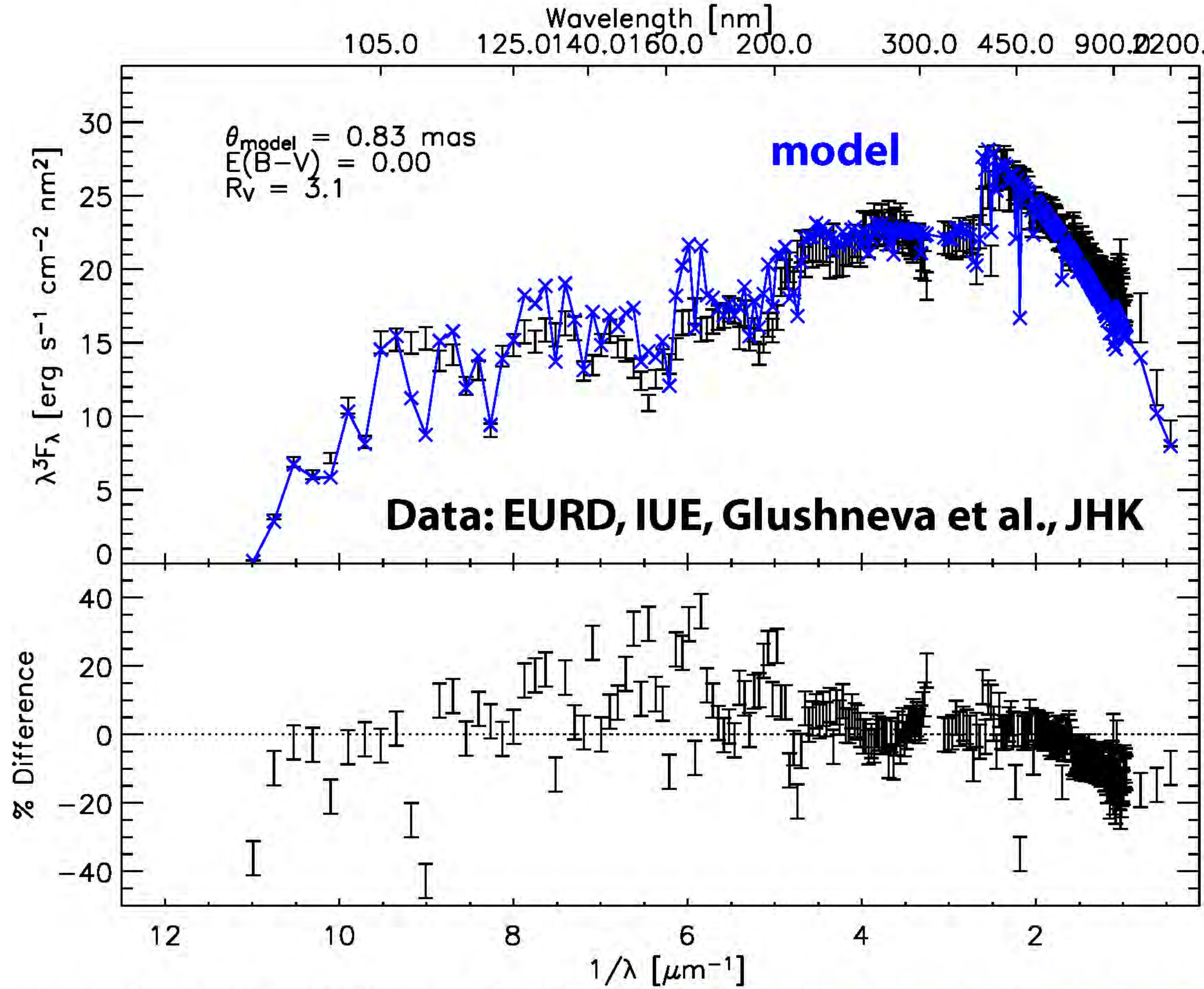



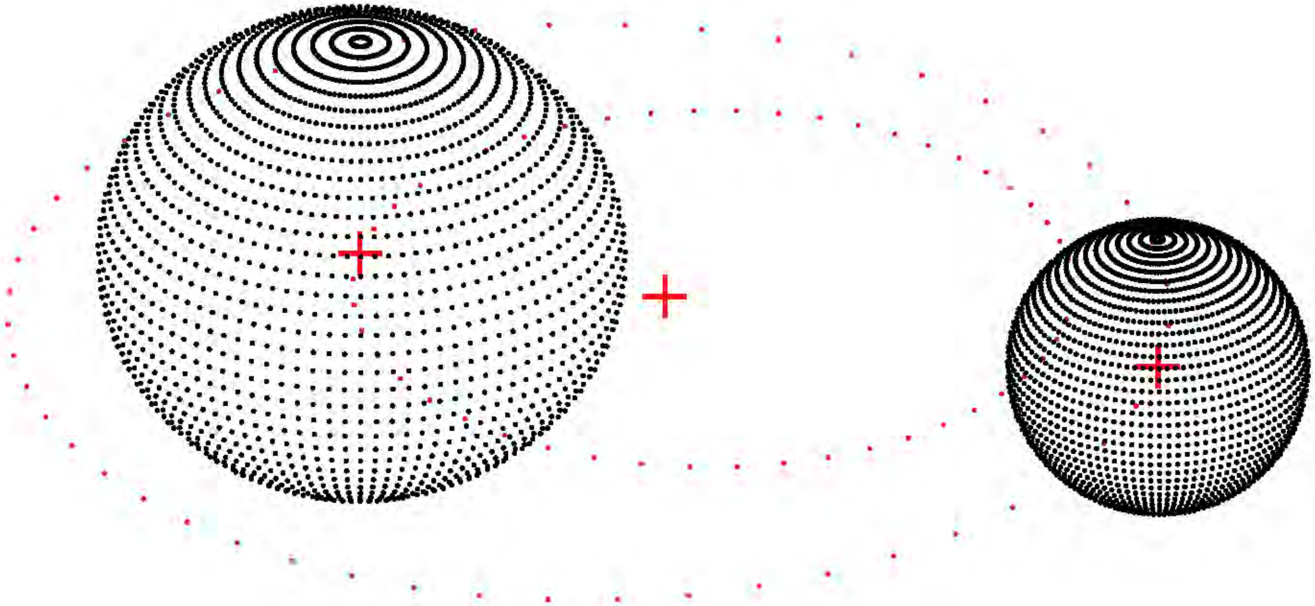




Finally... spectra are in physical units, so we predict the spectral energy distribution for Spica.

**Data: Ritter Astrophysical Observatory (U. of Toledo)**

# Model Comparison to Spectral Energy Distribution





## What’s next for Spica?

## Closure phase with MIRC

## Mapping model intensities on to tidally distored stars

## Computing mutually irradiated models

## Analysis of spectroscopic data

# Thanks Dave! Thanks CHARA!

# *Resolving the* Faces *of* Stars

Nestled among the venerable telescope domes on Mount Wilson, a mile-high peak overlooking Los Angeles, is the highest-resolution optical instrument in the world.

Inside several hundred meters of evacuated pipe, beams of star light from six 1-meter (39-inch) telescopes converge on a central facility to be matched up light wave for light wave. The result allows measurements of details as small as a thousandth of an arcsecond wide — the apparent size of a penny in Los Angeles seen from Atlanta. Georgia State University's Center for High Angular Resolution Astronomy (CHARA) built and runs the instrument under the directorship of Harold McAlister. The CHARA Array is currently the largest of several new installations around the world applying 21st-century technology to an old idea: optical interferometry.

The concept of interferometry predates photographic film, but astronomers didn't really put it into practice until the early 1920s (see "Milestones in Optical Interferometry," page 44). Now, nearly a century later, technology is catching up with theory. Astronomers are using a new breed of giant interferometers to measure some of the most difficult fundamental parameters in stellar astrophysics, in particular the sizes and shapes of stars (S&T: May 2003, page 30).

These parameters are most easily studied for the nearest and brightest stars, those dear to skygazers' hearts. The CHARA Array has resolved the disks of familiar stars such as Vega and Regulus, revealing new aspects of their structures. It is now in its third year of scientific operations. Its capabilities will be enhanced over the next two years, with up to six telescopes operating simultaneously and its working wavelength moving from the near infrared into the visual. These improvements will sharpen the array's power to image stars and their environments.

By David H. Berger, Jason P. Aufdenberg, and Nils H. Turner

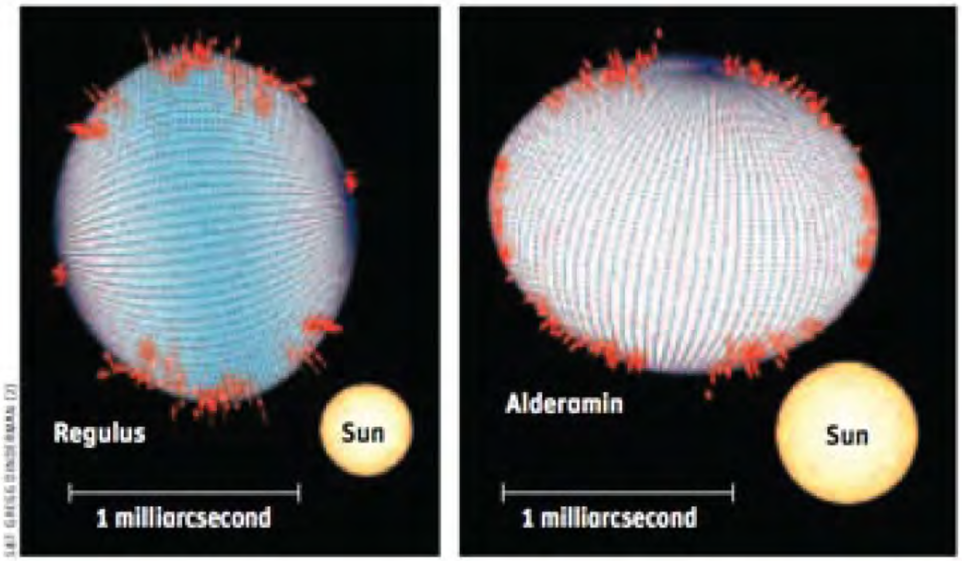
The CHARA Array is one of several facilities on Mount Wilson, a 1,740-meter (5,710-foot) peak that overlooks Los Angeles, California. The array's telescopes are located in several of the smaller domes around the large dome for the Hooker telescope. The CHARA domes are connected by pipes, seen in the photo as thin white lines.

**THE QUEST FOR HIGH RESOLUTION**

Astronomers often define resolution as how close together two points can be seen as separate objects. For telescopes with just one primary mirror or lens, the resolving power is set by the size of the primary optic and the observed wavelength of light. In theory, either using a larger mirror or observing at shorter (bluer) wavelengths will yield higher resolution. But Earth's atmosphere usu








The CHARA Array has resolved the disks of Regulus and Alderamin (Alpha Cephei), allowing astronomers to measure their angular diameters across their equatorial and polar axes. Both stars rotate so rapidly — about 317 and 280 km per second at the equator — that they are within 20% of breakup speed. If the Sun were located at Regulus's 77 light-year distance, it would present a disk just 0.4 milliarcsecond across. At Alderamin's 49 light-year distance, it would be 0.6 milliarcsecond across.