

# Science from the CHARA Array



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*Future Directions in Interferometry*  
NOAO, Tucson  
13 November 2006



# CHARA/GSU Participants

## *CHARA Staff:*

Theo ten Brummelaar\* - Associate Director  
Bob Cadman\* - Site Manager  
Chris Farrington\* - Array Operator  
Steve Golden\* - Assistant Site Manager  
P.J. Goldfinger\* - Array Operator  
Alexandra Land - Business Manager  
Antoine Merand\* - Research Associate  
Harold McAlister - Director  
Laszlo Sturmann\* - Senior Engineer  
Judit Sturmann\* - Research Scientist  
Dwayne Torres - Instrument Maker  
Nils Turner\* - Research Scientist

\* Mt. Wilson-based

## *Affiliated GSU Faculty:*

William Bagnuolo - Associate Professor  
Andrew Boden – Adjunct Professor (Caltech)  
Douglas Gies - Professor  
Todd Henry - Professor  
Stephen Ridgway - Adjunct Professor (NOAO)  
New appointment soon

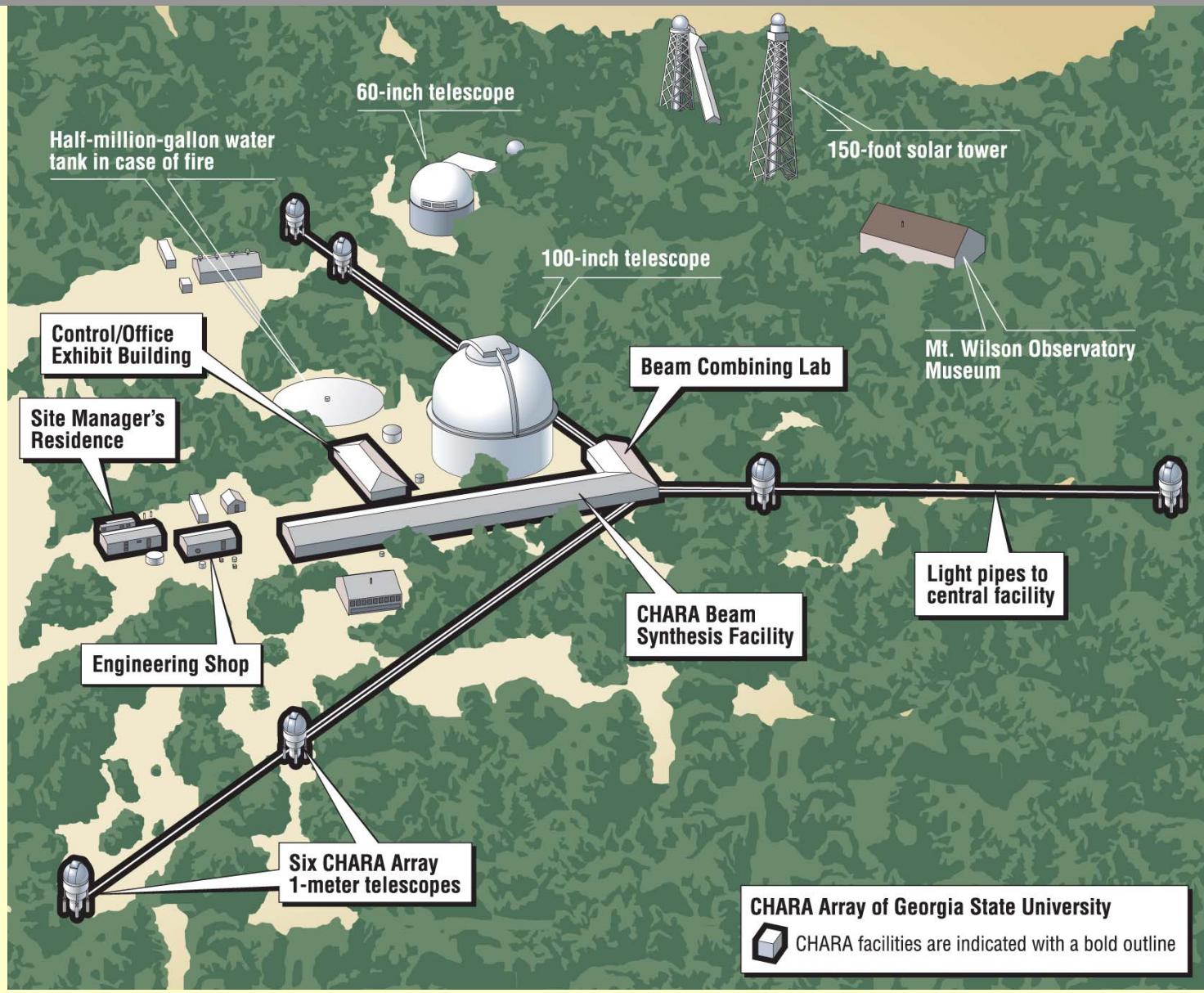
## *GSU Graduate Students:*

Ellyn Baines  
Tabetha Boyajian  
Chris Farrington\*  
David O'Brien  
Deepak Raghavan

# The CHARA Collaboration

- **CHARA/GSU**
  - Provides faculty, staff & graduate students
  - Operations management & budget
- **National Optical Astronomy Observatory**
  - Steve Ridgway
  - Member of original core design team
- **University of Paris (Meudon)**
  - Vincent du Foresto
  - Provides the FLUOR 2-way beam combiner for high precision V<sup>2</sup>
- **University of Sydney**
  - Peter Tuthill
  - Provides southern hemisphere access at SUSI
- **University of Michigan**
  - John Monnier
  - Developing IR fringe tracking and the MIRC 4-way beam combiner for closure phase measurements
- **Michelson Science Center, JPL/Caltech**
  - Provide scientific and technical expertise & funding

# Layout of the CHARA Array



# A Few Initial Science Examples

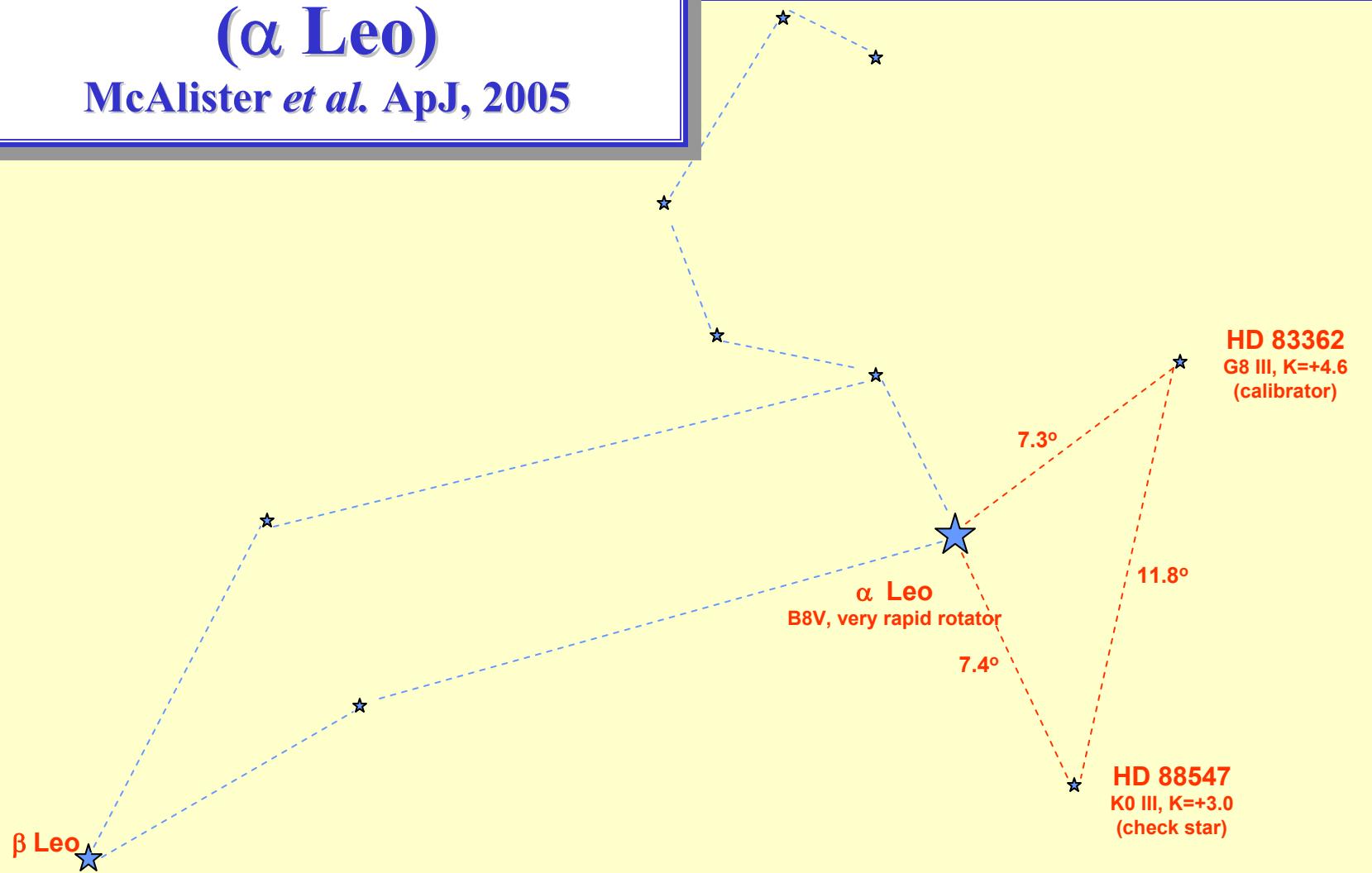
## *Since Initiating Routine Observing in 2005*

- Rotationally induced stellar oblateness & gravity darkening
  - The rapid rotators Regulus, Alderamin and Vega
- Calibrating the Cepheid period-luminosity relation
  - By reverse calibrating the Baade-Wesselink method for  $\delta$  Cephei
- Diameters of M dwarf stars
  - Now accessible in fairly large numbers to our long baselines
- The Disks of Be Stars
  - Modeling these transient phenomena
- Separated Fringe Packet Binary & Triple Star Systems
  - High-precision astrometry and “Self-calibration” of triples

# The Shape of Regulus

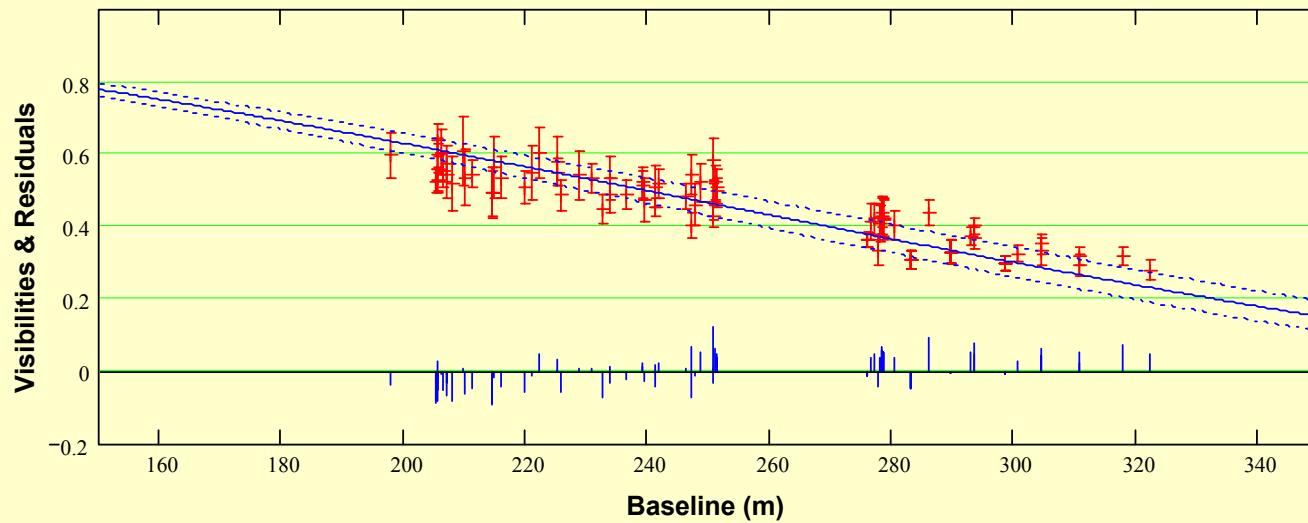
## ( $\alpha$ Leo)

McAlister *et al.* ApJ, 2005



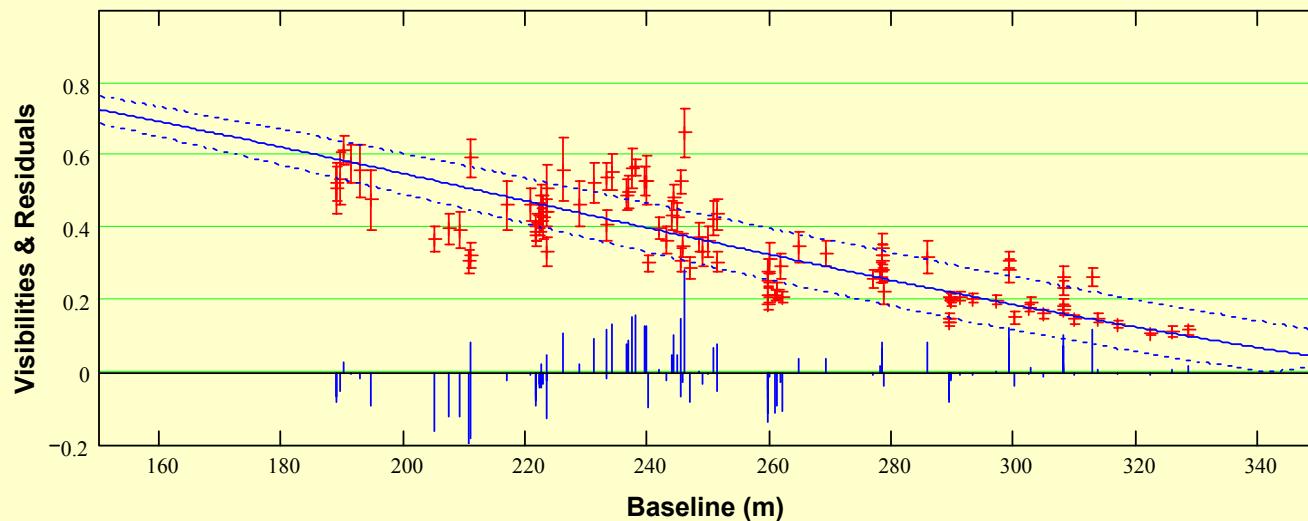
## Check Star Diameter Determination

$\theta = 1.297 \pm 0.056$  (UD) mas       $\sigma_{\text{Resid}} = \pm 0.037$  in V  
(Systematics are not understood)

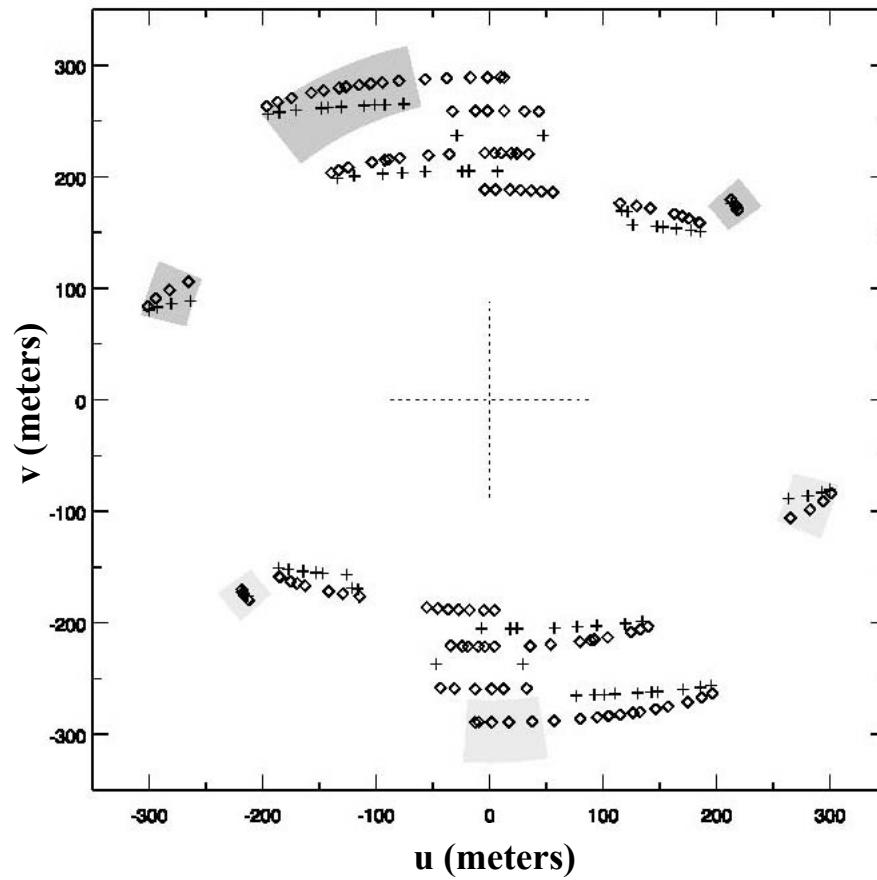


## Regulus Diameter Determination

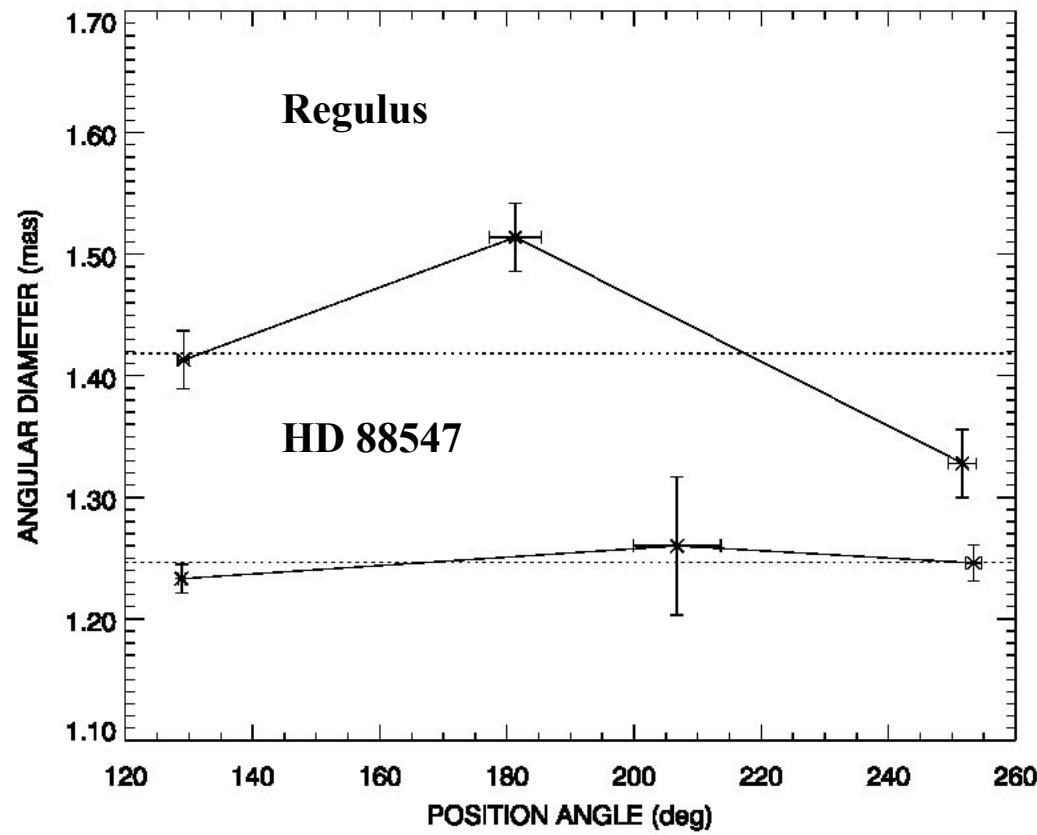
$\theta = 1.459 \pm 0.111$  (UD) mas       $\sigma_{\text{Resid}} = \pm 0.071$  in V  
(Star is obviously not round)



## (u,v)-Plane Coverage for Regulus



## Simple Check for Roundness

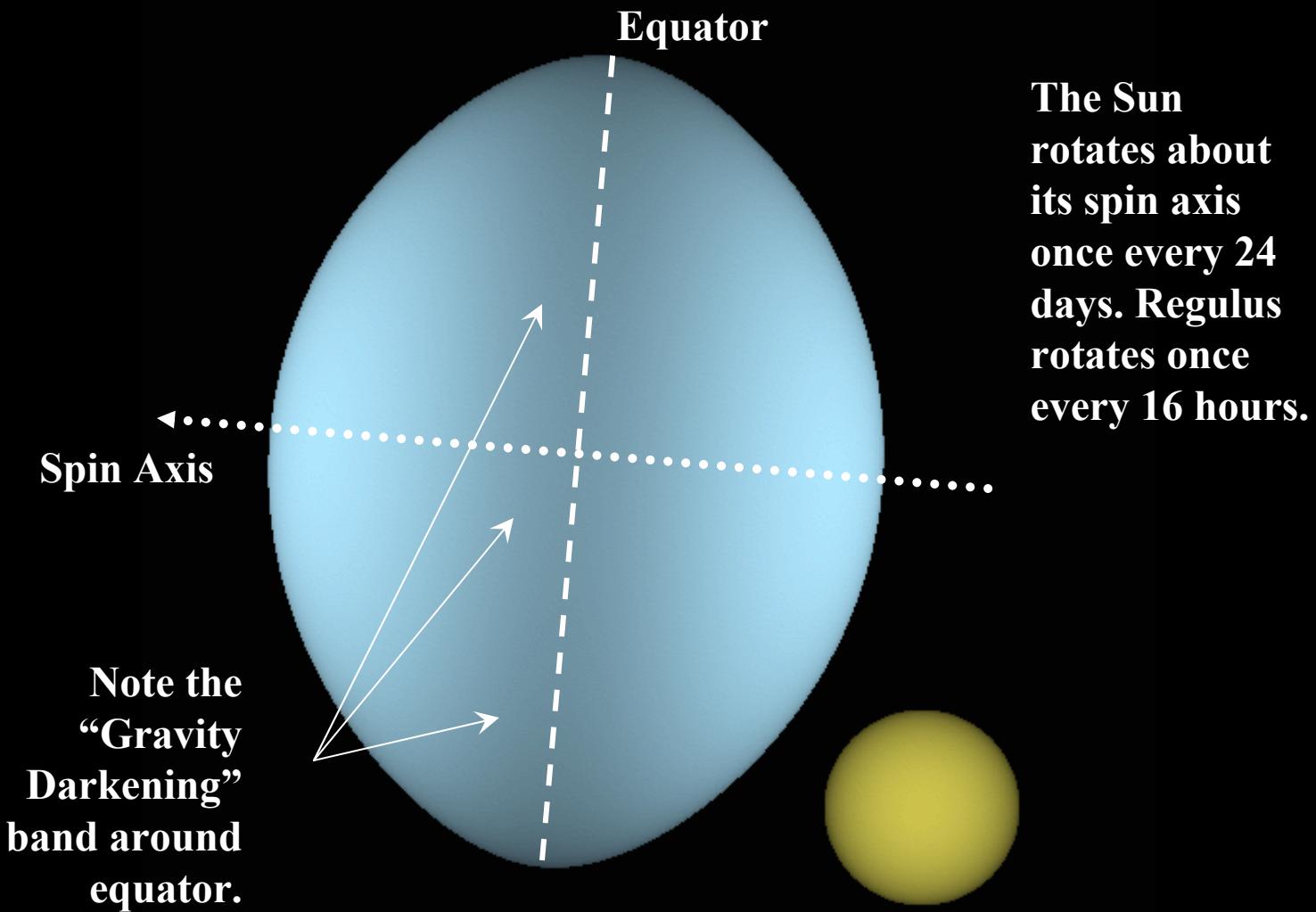


## Final Parameters for Regulus

Parameter	Value
$\Theta_{\text{minor}}$ (mas) ...	$1.25 \pm 0.02$
$\Theta_{\text{major}}$ (mas) ...	$1.65 \pm 0.02$
$\alpha$ (deg) .....	$85.5 \pm 2.8$
$i$ (deg) .....	$90^{+0}_{-15}$
$\beta$ .....	$0.25 \pm 0.11$
$V \sin i$ (km s <sup>-1</sup> )	$317 \pm 3$
$V_e/V_c$ .....	$0.86 \pm 0.03$
$R_p$ ( $R_\odot$ ) .....	$3.14 \pm 0.06$
$R_e$ ( $R_\odot$ ) .....	$4.16 \pm 0.08$
$M$ ( $M_\odot$ ) .....	$3.4 \pm 0.2$
$T_p$ (K) .....	$15400 \pm 1400$
$T_e$ (K) .....	$10314 \pm 1000$
$< T >$ (K) ....	$12901 \pm 500$
$L$ ( $L_\odot$ ) .....	$347 \pm 36$
$d$ (pc) .....	$23.5 \pm 0.4$
$A_V$ (mag) ....	$0.016 \pm 0.010$

Regulus is over-luminous for its mass in comparison with non-rotating star

# Regulus & the Sun



# Alderamin ( $\alpha$ Cep)

Van Belle *et al.* ApJ, 2006

$\alpha$  Cep = HR 8162:

Sp. Type = A7 IV

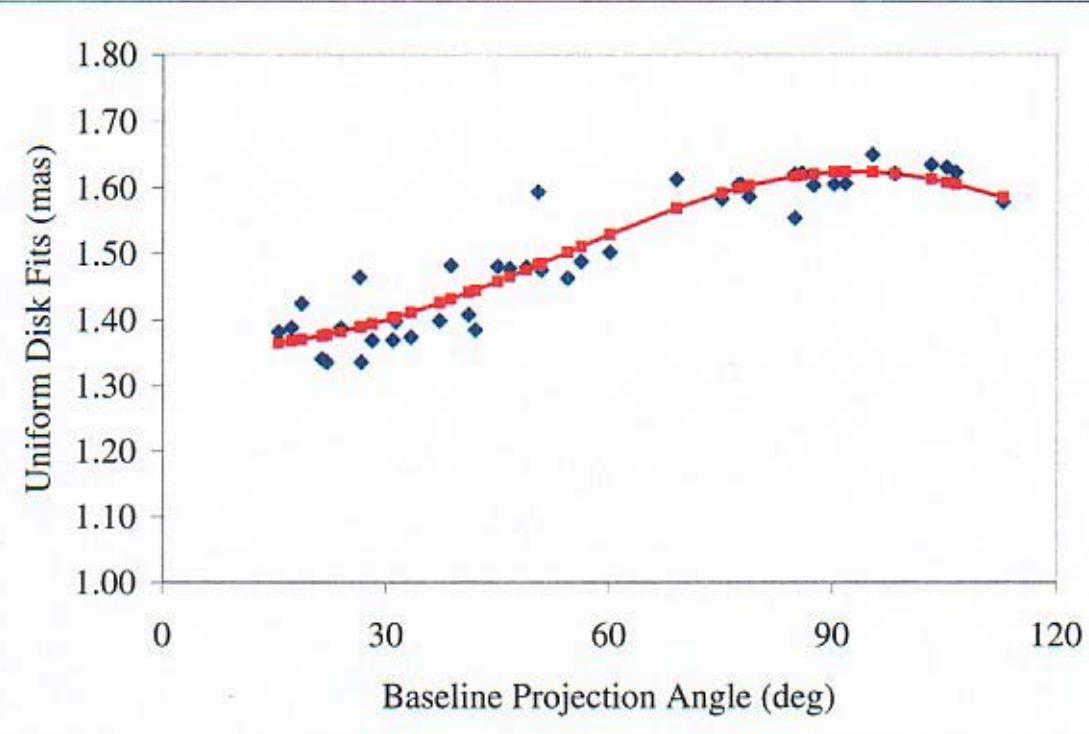
$\pi_{\text{Hipp}} = 66.8 \pm 0.5$  mas

V = 2.44

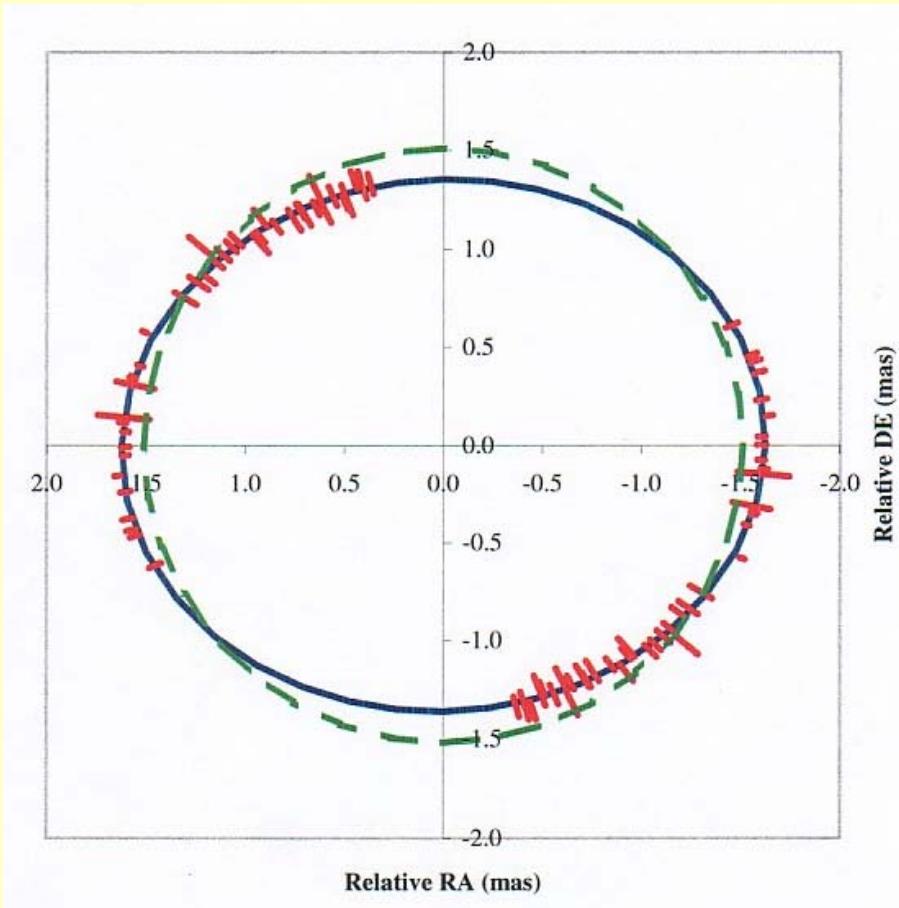
V sin i values range from 180 to 265 km/s

*Observations obtained on 8 nights during June 2004 using CHARA's three longest baseline pairs. As with Regulus, a calibrator and a check star were observed alternatively with Alderamin.*

# UD Ellipsoidal Fit to Alderamin



# Simple Elliptical Fit to Alderamin Diameters

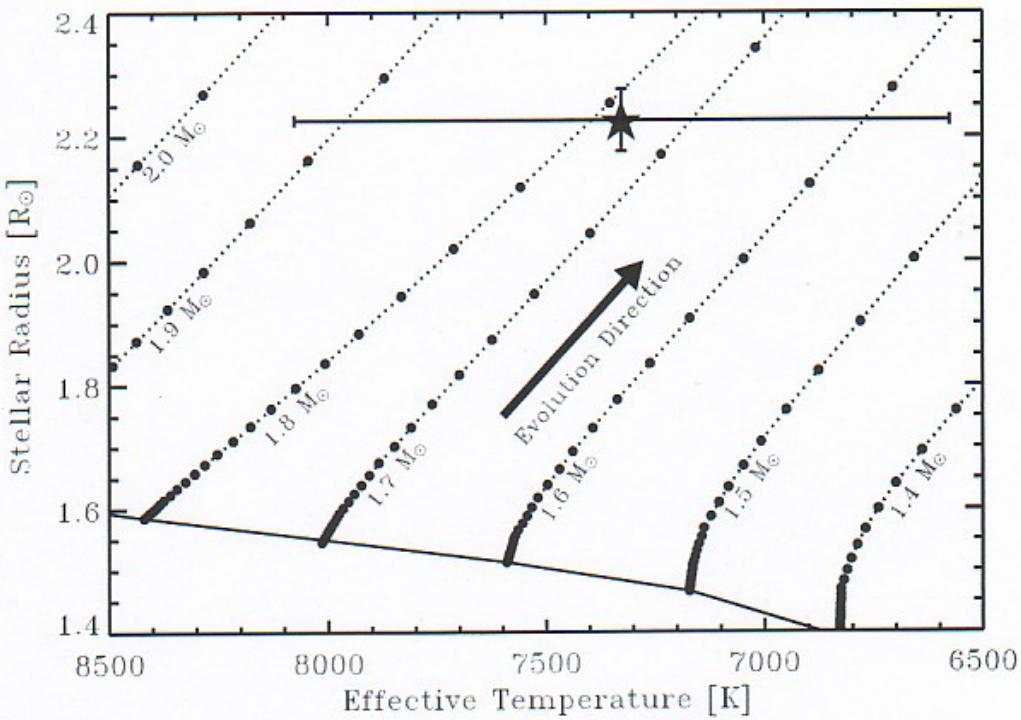


$$\theta_a = 1.626 \pm 0.056 \text{ mas}$$

$$\theta_b = 1.355 \pm 0.080 \text{ mas}$$

$$\theta_a/\theta_b = 1.20 \pm 0.07$$

# Alderamin – Evolutionary Status



Star is evolved off the main sequence with an age of ~800 Myr.

Star is now larger and hence was rotating much closer to critical velocity when it formed.

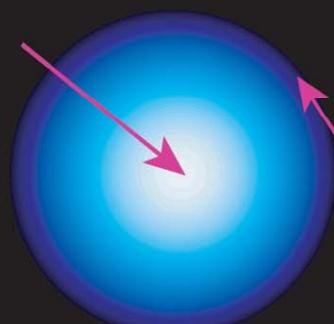
Or, evolutionary models don't adequately consider rotation.

# Vega – A Pole-on Rapid Rotator with a Debris Disk

Shape: Aufdenberg *et al.* ApJ, 2006 - Disk: Absil *et al.* A&A, 2006

Pole-on view (as seen from Earth)

polar surface  
temperature:  
 $17,900^{\circ}\text{F}$



equatorial surface  
temperature:  
 $13,800^{\circ}\text{F}$

The Sun

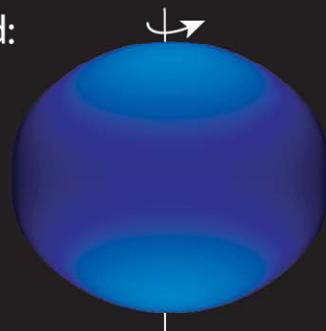


surface  
temperature:  
 $10,000^{\circ}\text{F}$

Equator-on view

rotation period:  
12.5 hours

←  
to debris disk



→  
to debris disk

rotation period:  
24 to 30 days

# **$\delta$ Cephei – Prototype of the Cepheids**

Merand *et al.* A&A, 2005

*The Cepheid Period-Luminosity Relation:*

$$\log L = \alpha \log P + \beta$$

*The determination of  $\alpha$  is straightforward*

*Any bias in determining the zero-point  $\beta$ , which is related to distance, directly impacts the scale of the Universe*

*Parallaxes are rarely available for Cepheids, and the Baade-Wesselink approach can be used to determine distance. This is based upon comparing the linear and angular amplitudes of Cepheid pulsation.*

*Because  $\delta$  Cep does have a known parallax ( $d = 274 \pm 11$  pc), determining its BW distance is a check on the method.*

# $\delta$ Cephei – Its Projection Factor

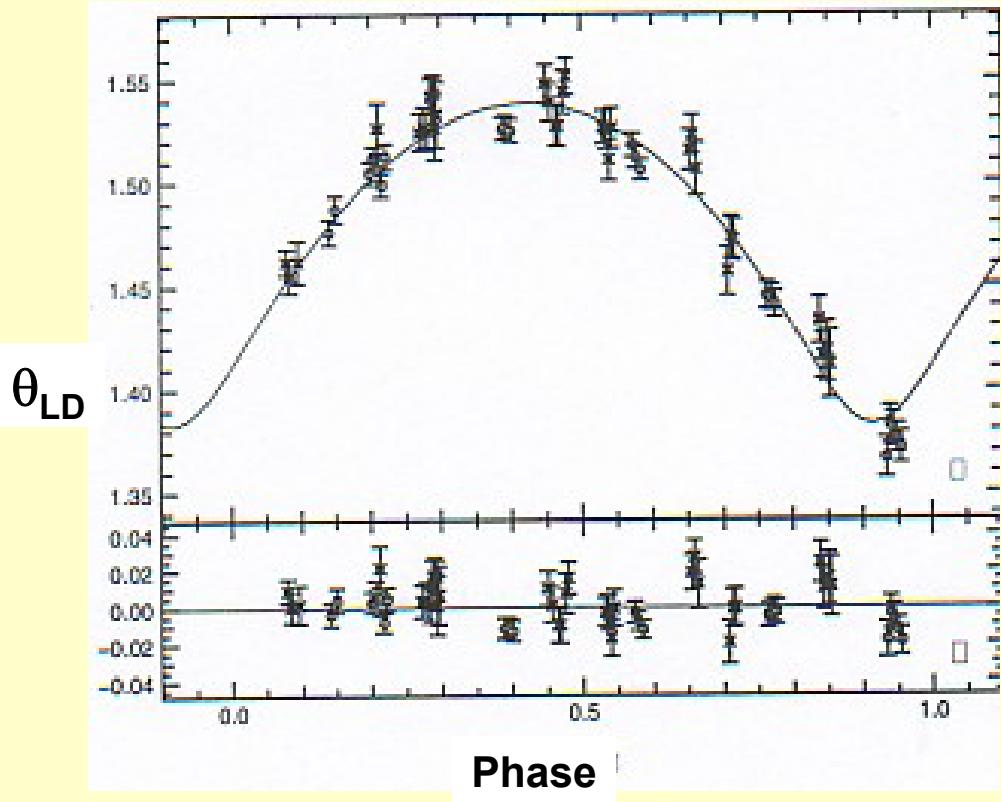
*The BW method is complicated by the fact that we measure radial velocity rather than pulsational velocity. BW takes this into account by defining a “projection factor” as:*

$$p = V_{\text{puls}} / V_{\text{rad}}$$

*The p-factor is affected by the stellar shape and limb darkening and its theoretical determination requires dynamical modeling of line formation in a pulsating atmosphere.*

*The trig parallax of  $\delta$  Cep is currently the best known of all Cepheids. It is based on HST/FGS observations by Benedict et al. (2002). Having this value, one can invert the BW method to get the p-factor*

# $\delta$ Cephei – P Factor Determination



The angular diameter with phase is shown following the adjustment of the p-factor in order to follow the radial velocity fit (solid line).

$\Theta_{\text{mean}} = 1.475 \pm 0.004 \text{ mas}$   
corresponding to

$R_{\text{star}} = 43.3 \pm 1.7 R_{\text{sun}}$

# **$\delta$ Cephei – Conclusions**

*This p-factor determination is the first model independent such value. The result is*

$$p = 1.27 \pm 0.06$$

*which is within  $1.5\sigma$  of the generally accepted value of  
 $p = 1.36$*

*Sabbe et al. (1995) incorporated dynamical effects in models and suggested a 5% increase in  $p$ . Nardetto et al. (2004) computed  $p$  specifically for  $\delta$  Cep finding  $p = 1.27$  for continuum measurements, however Gieren et al. (2005) find  $p = 1.47$ .*

*The CHARA and VLTI interferometers are expected to measure the distance of about 30 Cepheids in coming years.*

# M Dwarf Diameters

Berger *et al.* ApJ, 2006

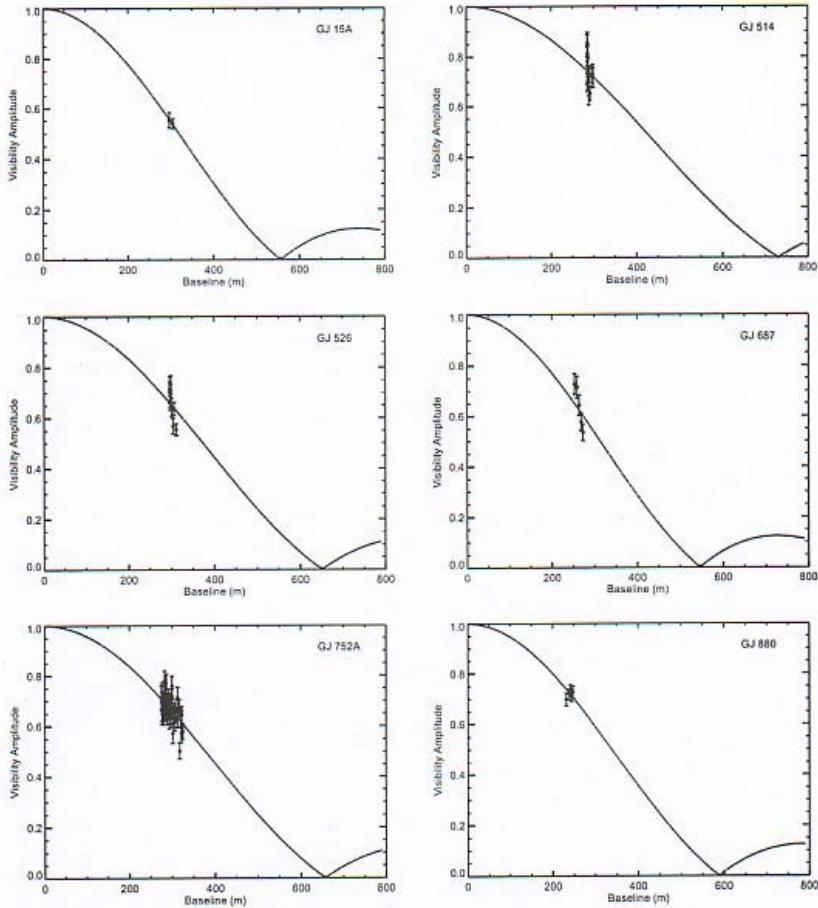
*Large (V-K) colors and the long baselines of the  
CHARA Array make these stars accessible*

*To date, only 14 radii from eclipsing binaries  
7 radii from interferometry*

*With Todd Henry's advise, Dave Berger assembled  
a CHARA target list. The first six of these are  
now published.*

# New CHARA Diameters of M Dwarfs

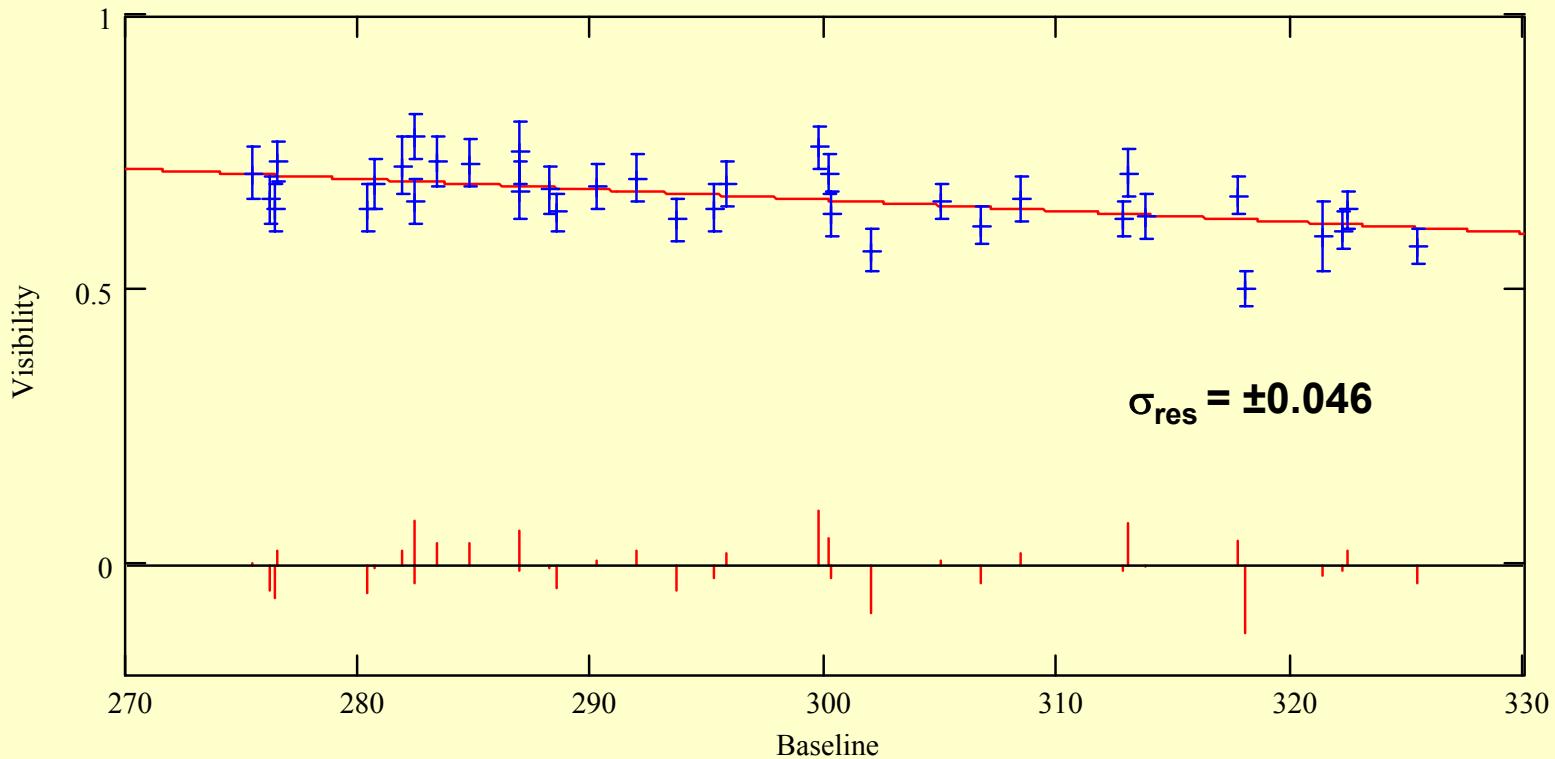
*In the Range M1V to M3V*



GJ	$\theta_{LD}$	$R/R_{\text{SUN}}$	$T_{\text{EFF}}$	$\log g$
15	$0.988 \pm 0.016$	$0.379 \pm 0.006$	3747	4.89
514	$0.753 \pm 0.058$	$0.611 \pm 0.047$	3377	4.59
526	$0.845 \pm 0.057$	$0.493 \pm 0.033$	3662	4.75
687	$1.009 \pm 0.054$	$0.494 \pm 0.035$	3142	4.66
752	$0.836 \pm 0.056$	$0.529 \pm 0.045$	3390	4.68
880	$0.934 \pm 0.041$	$0.689 \pm 0.031$	3373	4.53

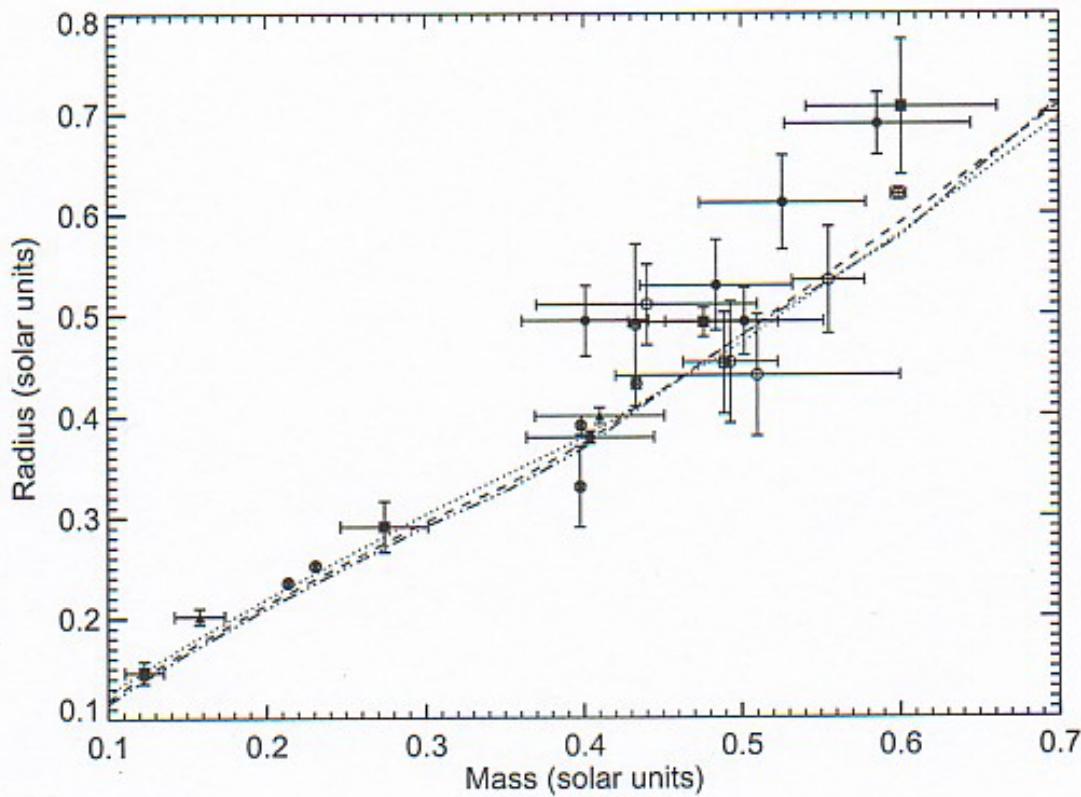
# UD Fit to GJ 752A (Ross 652)

$V = 9.1, K = 4.7, \pi = 171 \text{ mas}, M3V$



# M Dwarf Mass-Radius Relation

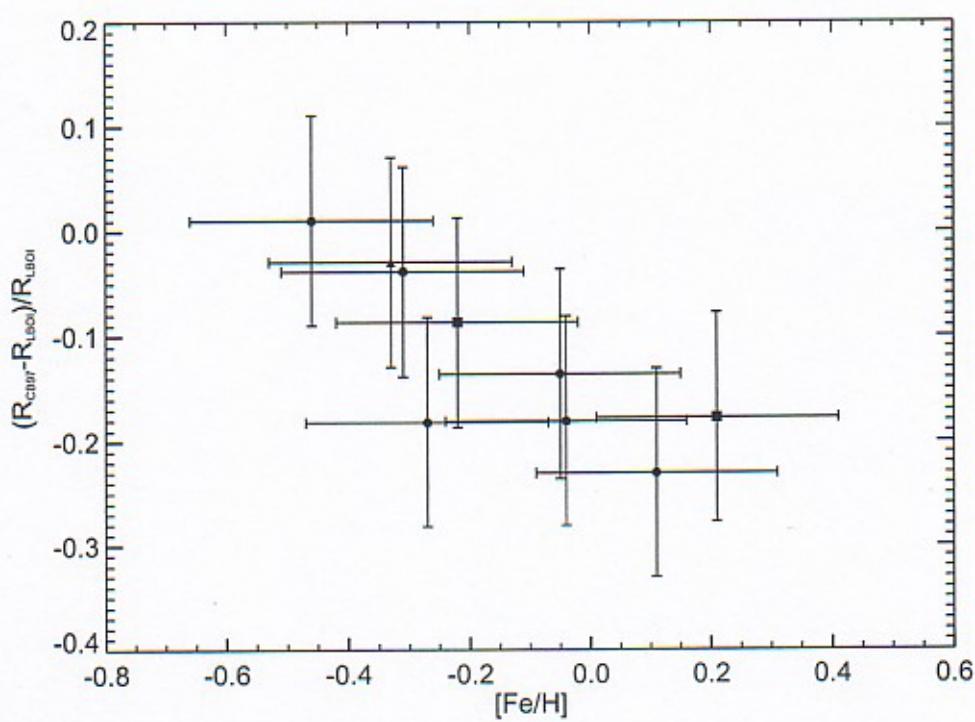
*Against Models with [Fe/H] = 0.0, -0.5, -1.0*



Models predict little metallicity sensitivity of radius for a given mass

But, the systematic effect, which is independent of observer or technique, is obvious

# Radius Sensitivity to Metallicity

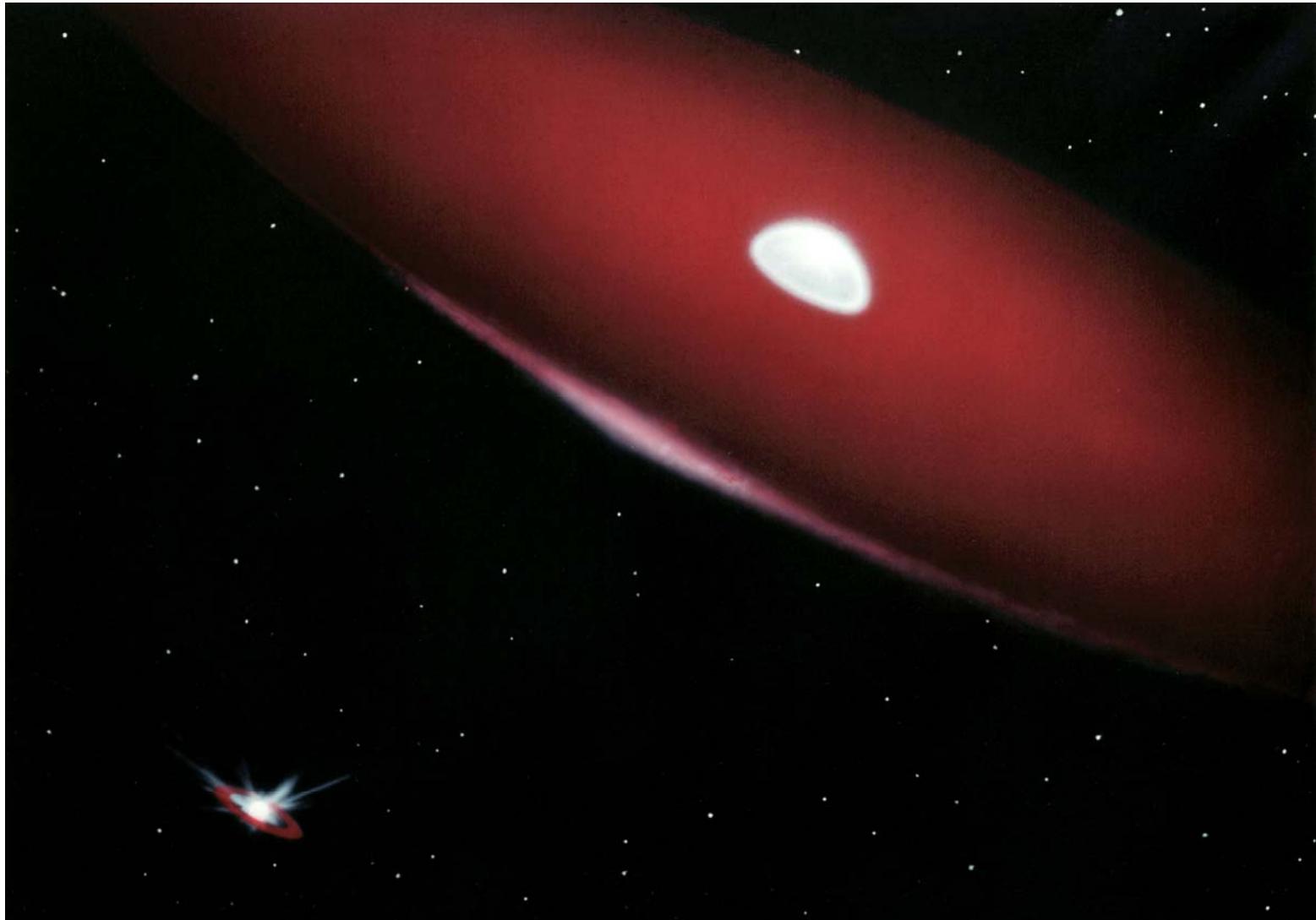


Models predict little metallicity sensitivity of radius for a given mass, but that's clearly not the case.

This suggests that some opacity component, whose effect increases with increasing metallicity, is overlooked in current models.

# The Disks of Be Stars

Gies *et al.* ApJ, 2007



φ Persei Painting by Bill Pounds (Courtesy of Doug Gies)

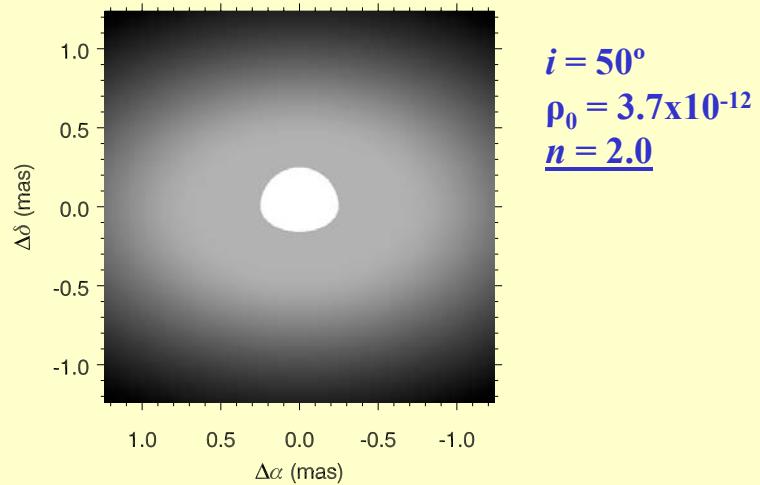
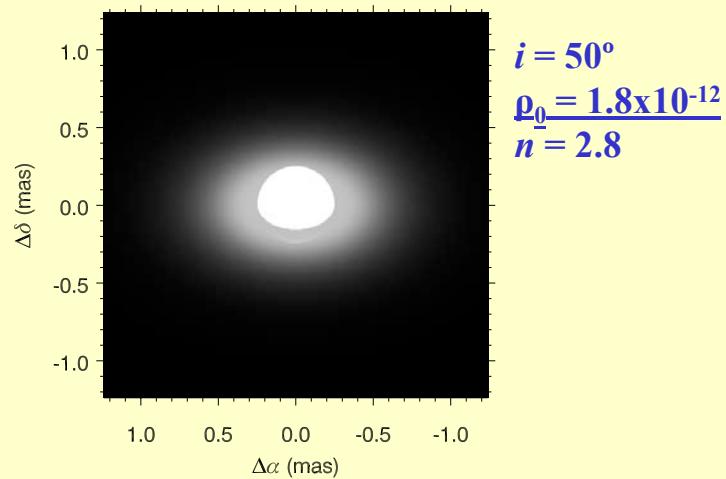
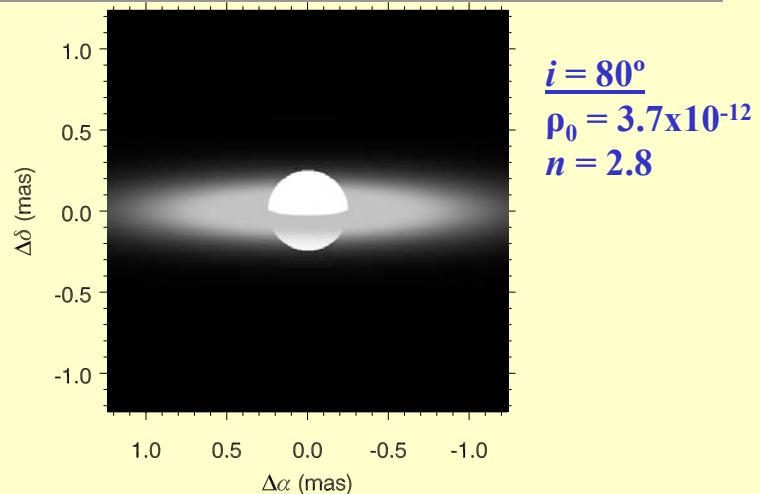
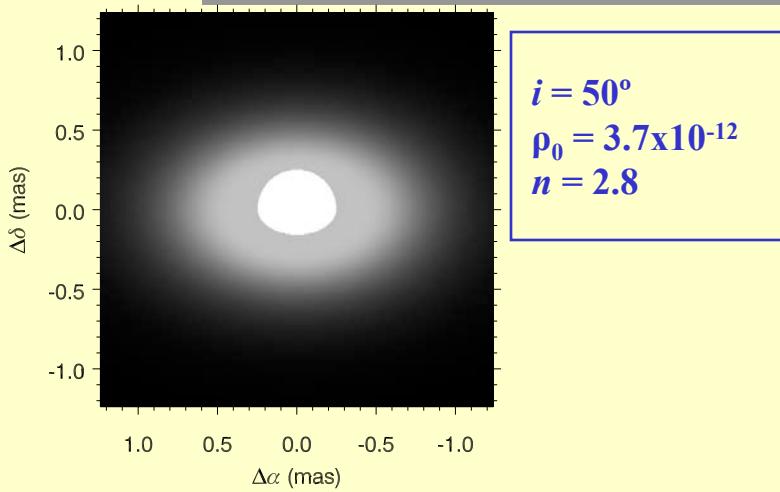
# **CHARA Classic K-band Be Star Program**

- $\gamma$  Cas:      **W1/S2 (2003),  
W1/W2 (10/2005)**
- $\phi$  Per:        **W1/S2 (2003),  
W1/W2 (10/2005)**
- $\zeta$  Tau:        **S1/E1, W1/S1 (2004),  
W1/W2 (12/2005)**
- $\kappa$  Dra:        **S1/S2, S1/E1 (4/2005),  
W1/W2 (12/2005)**

# Models of K-band Visibility

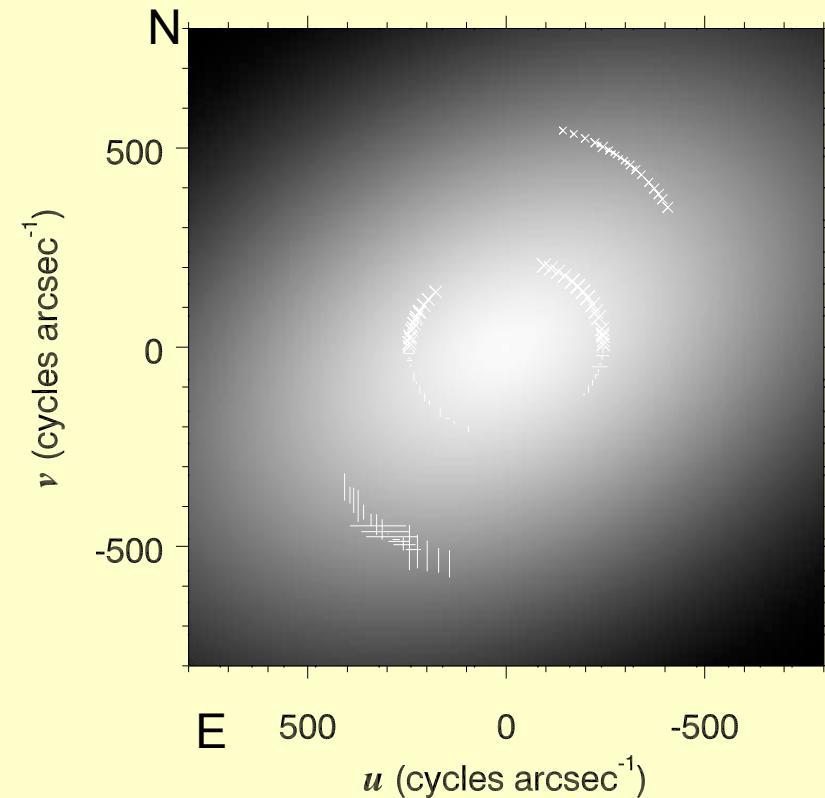
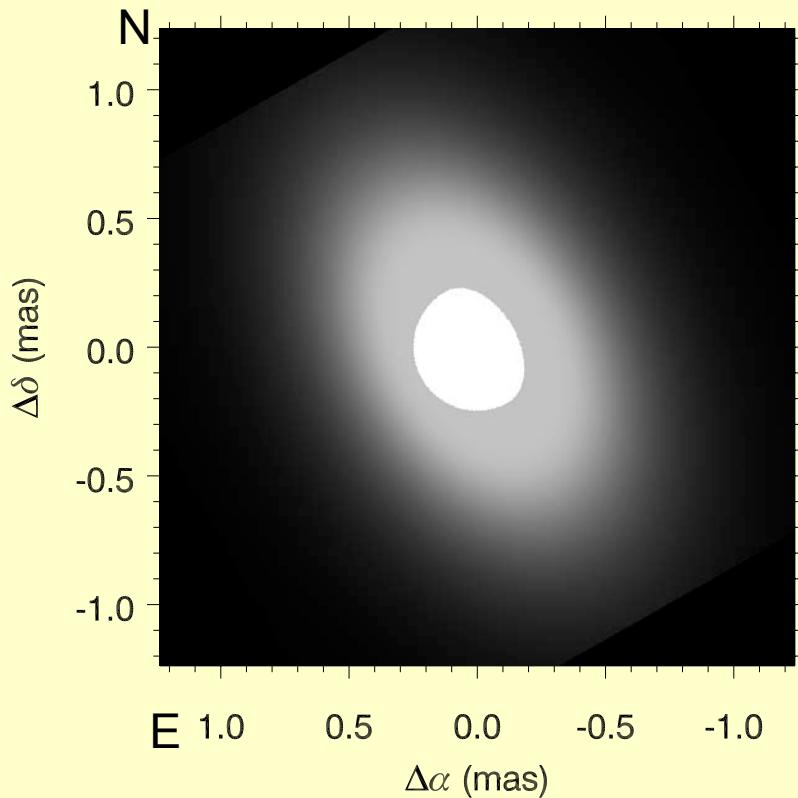
- K-band disks should be several times brighter than H $\alpha$  disks.
- Uniform disk star with set angular diameter ( $\pi$ )
- Disk geometry (Hummel & Vrancken 2000)  
$$\rho(R,Z) = \rho_0 R^{-n} \exp[-0.5(Z/H(R))^2]$$
$$\rho_0 = \text{base density (g cm}^{-3}\text{)}$$
$$n = \text{radial density exponent}$$
$$H(R) = R^{3/2} C_s / V_K \text{ disk scale height}$$
- Observer parameters  
 $i$  = inclination of disk normal  
 $a$  = position angle (E from N) of disk normal

# $\gamma$ Cas Model Effects



# $\gamma$ Cas

$i = 50^\circ, \rho_0 = 3.7 \times 10^{-12}, n = 2.0, \alpha = 118^\circ$



# Comparison With H $\alpha$ Interferometry

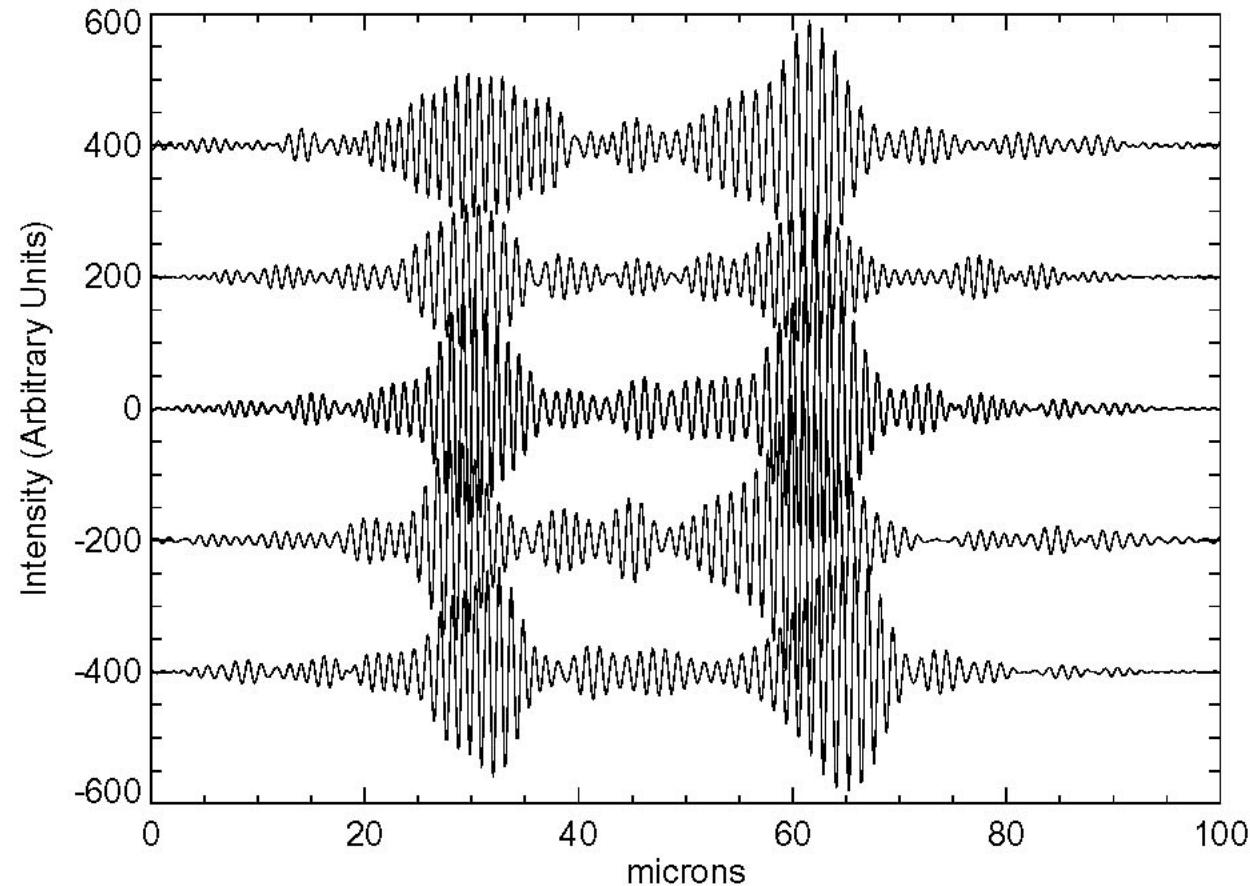
Parameter	$\gamma$ Cas	$\phi$ Per	$\zeta$ Tau	$\kappa$ Dra
$\alpha$ (MkIII)	109	28	32	...
$\alpha$ (NPOI)	121	29	28	...
$\alpha$ (CHARA)	118	45	38	101
$i$ (MkIII)	46	63	>74	...
$i$ (NPOI)	55	>55	>74	...
$i$ (CHARA)	50	90	90	72
$\theta$ (MkIII)	3.5	2.7	4.5	...
$\theta$ (NPOI)	3.6	2.9	3.1	...
$\theta$ (CHARA)	1.4	1.0	1.9	3.2

## **Summary for Be Stars**

- **Be disks resolved in CHARA Classic K-band**
- **Disk orientation similar to that found in prior H $\alpha$  interferometry**
- **MIRC ideal for studying disk structures  
(holes, spirals, bright edges, time evolution)**
- **FLUOR best for bright  $\gamma$  Cas**
- **More to come!**

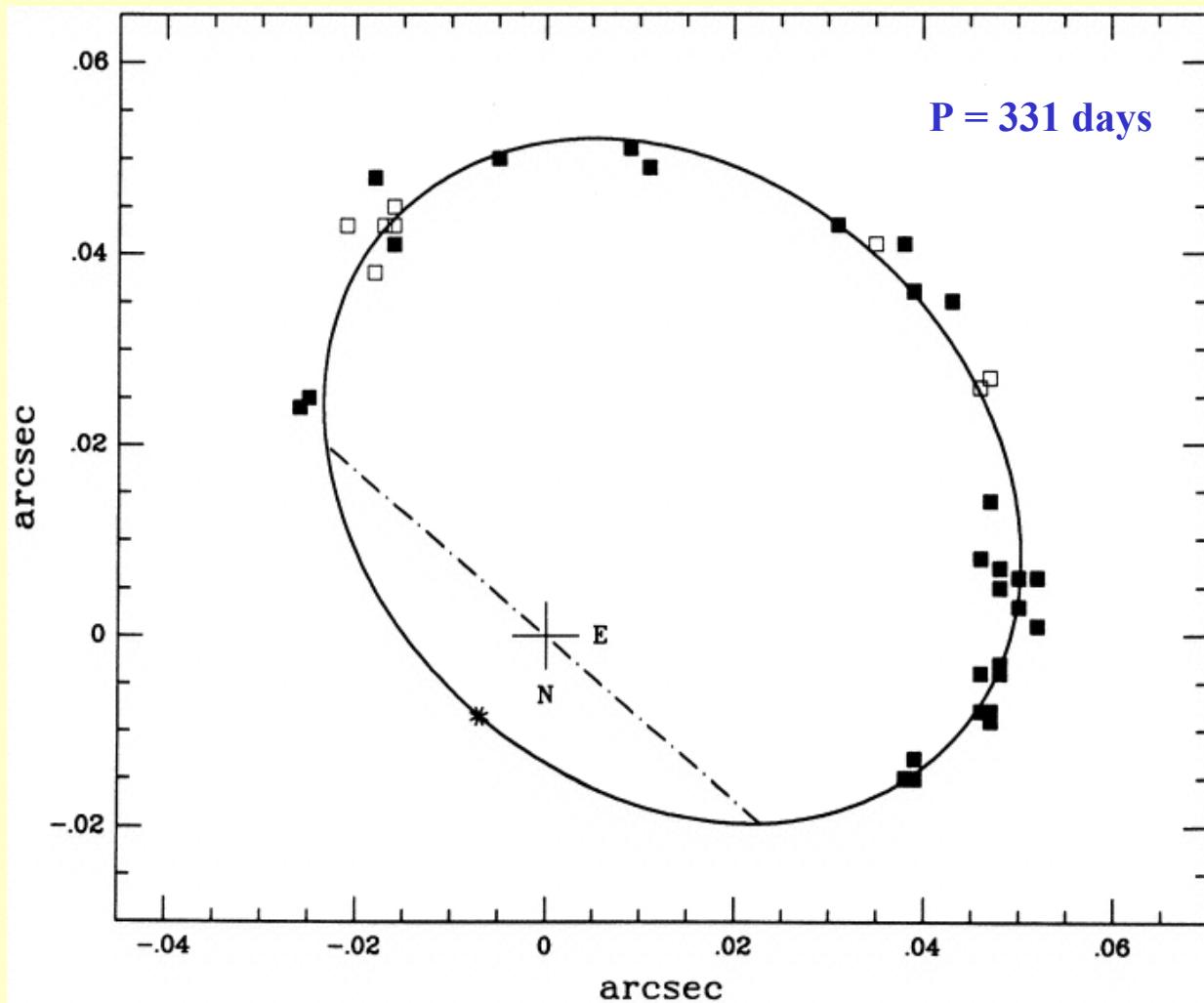
# Applications of Separated Fringe Packets

12 Persei - Bagnuolo *et al.* ApJ, 1996

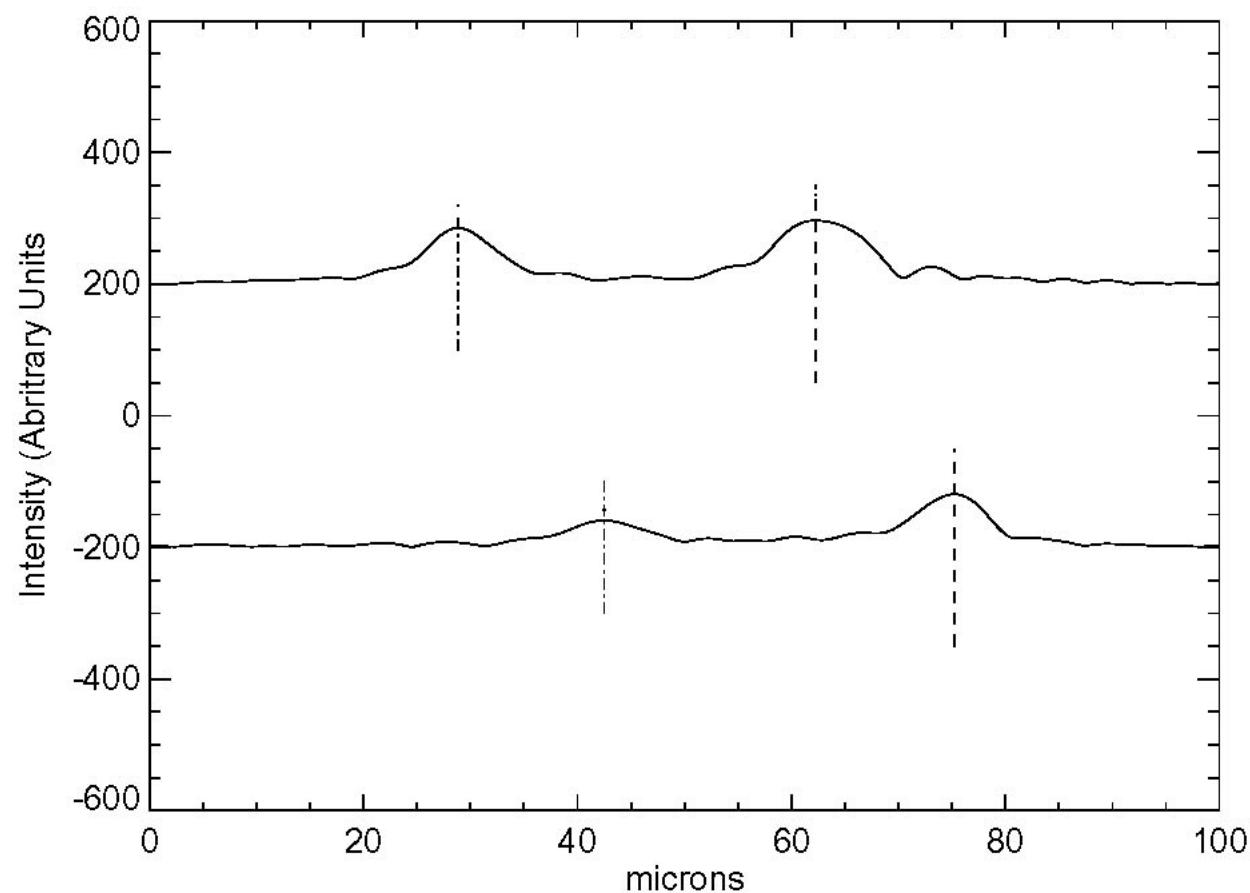


# Orbit of Barlow *et al.* V.

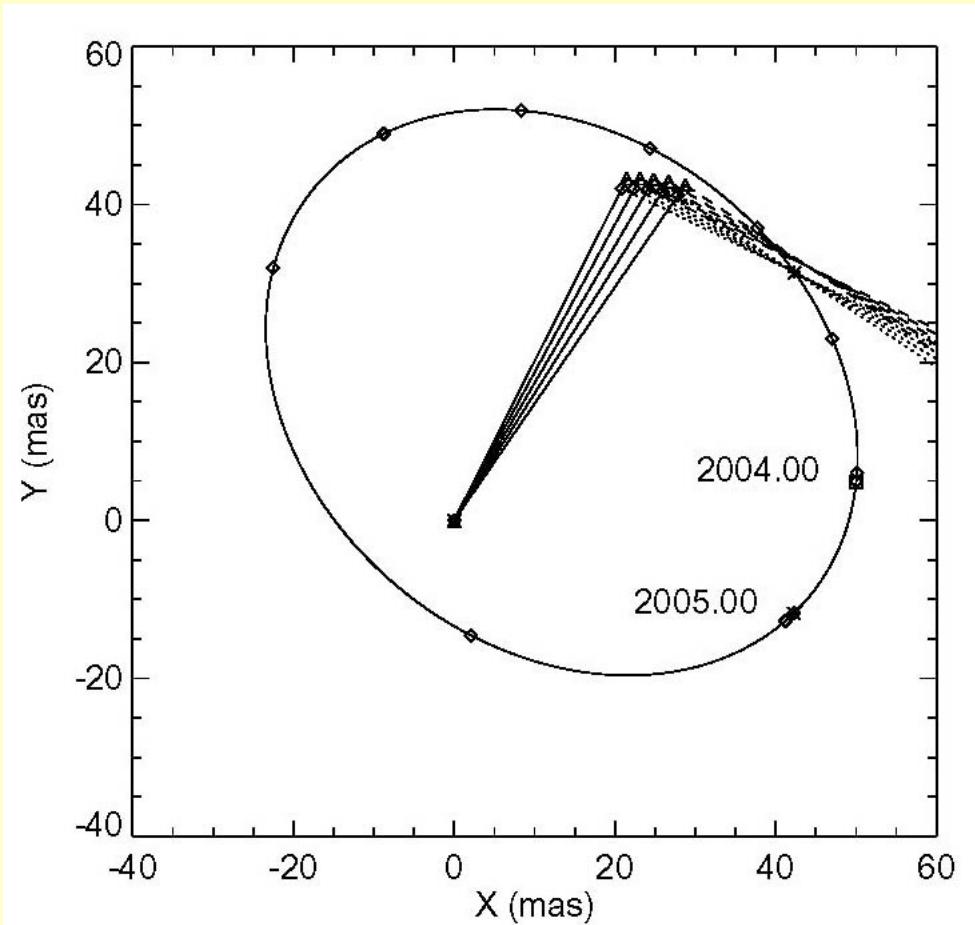
*A.J., 115, 2555, 1998*



# Consecutive Fringe Envelopes & Maxima

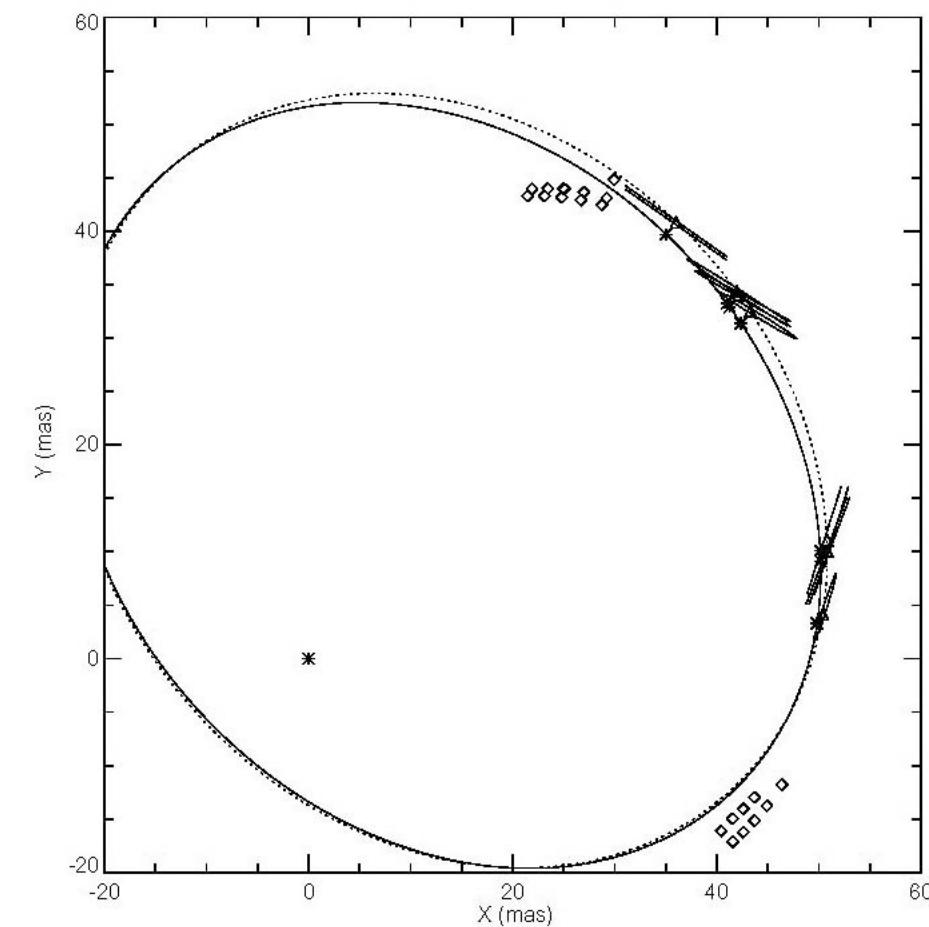


## Vector Separation Fits

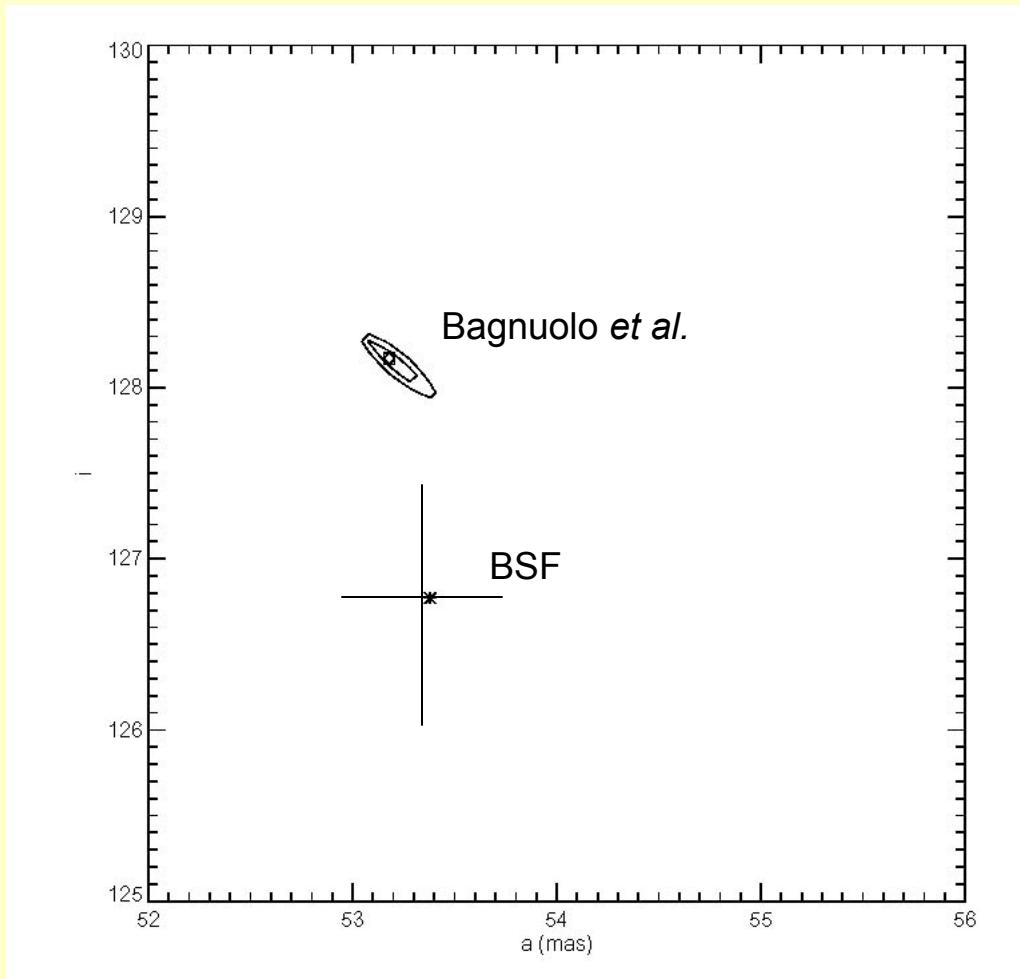


Precision of individual vector separations as good as  $\pm 25 \mu\text{as}$  enhanced by a “vernier” effect from sidelobe modulation.

# Revising the Orbit



## Modified a and i Values

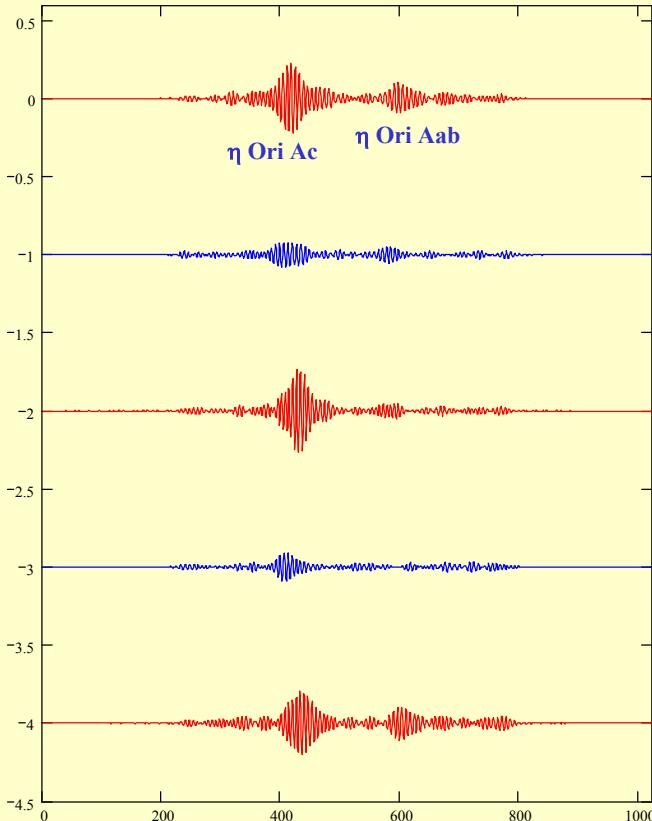


Masses are ~5% larger than those of BSF.

Mass errors due to interferometry alone are ±0.2%

# Separated Fringe Packet Triple Systems

## *Work in Progress*



Normalized visibility for star A:

$$V_A = A_A / \langle I_A \rangle$$

for star B:

$$V_B = A_B / \langle I_B \rangle$$

When observed in the same scan we actually measure:

$$V_{A'}^* = A_A / \langle I_A + I_B \rangle$$

and

$$V_{B'}^* = A_B / \langle I_A + I_B \rangle$$

$$= A_A / (\langle I_A \rangle + \langle I_B \rangle)$$

$$= A_B / (\langle I_A \rangle + \langle I_B \rangle) .$$

Assume an intensity ratio  $\beta$  such that

$$\beta = \langle I_B \rangle / \langle I_A \rangle = 10^{0.4\Delta m}, \quad \text{where } \Delta m = m_A - m_B .$$

Thus,

$$V_{A'}^* = A_A / (\langle I_A \rangle + \beta \langle I_A \rangle) \quad \text{and} \quad V_{B'}^* = A_B / (\langle I_B \rangle / \beta + \langle I_B \rangle)$$

$$= [1/(1+\beta)] [A_A / \langle I_A \rangle] \quad = |\beta/(1+\beta)|$$

$$\beta] [A_B / \langle I_B \rangle]$$

$$= [1/(1+\beta)] V_A$$

$$= |\beta/(1+\beta)| V_B .$$

So,

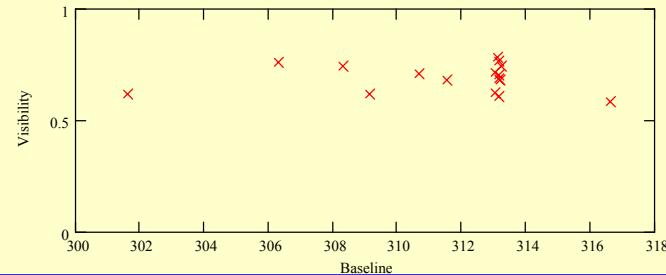
$$V_A = (1 + \beta) V_{A'}^*$$

and

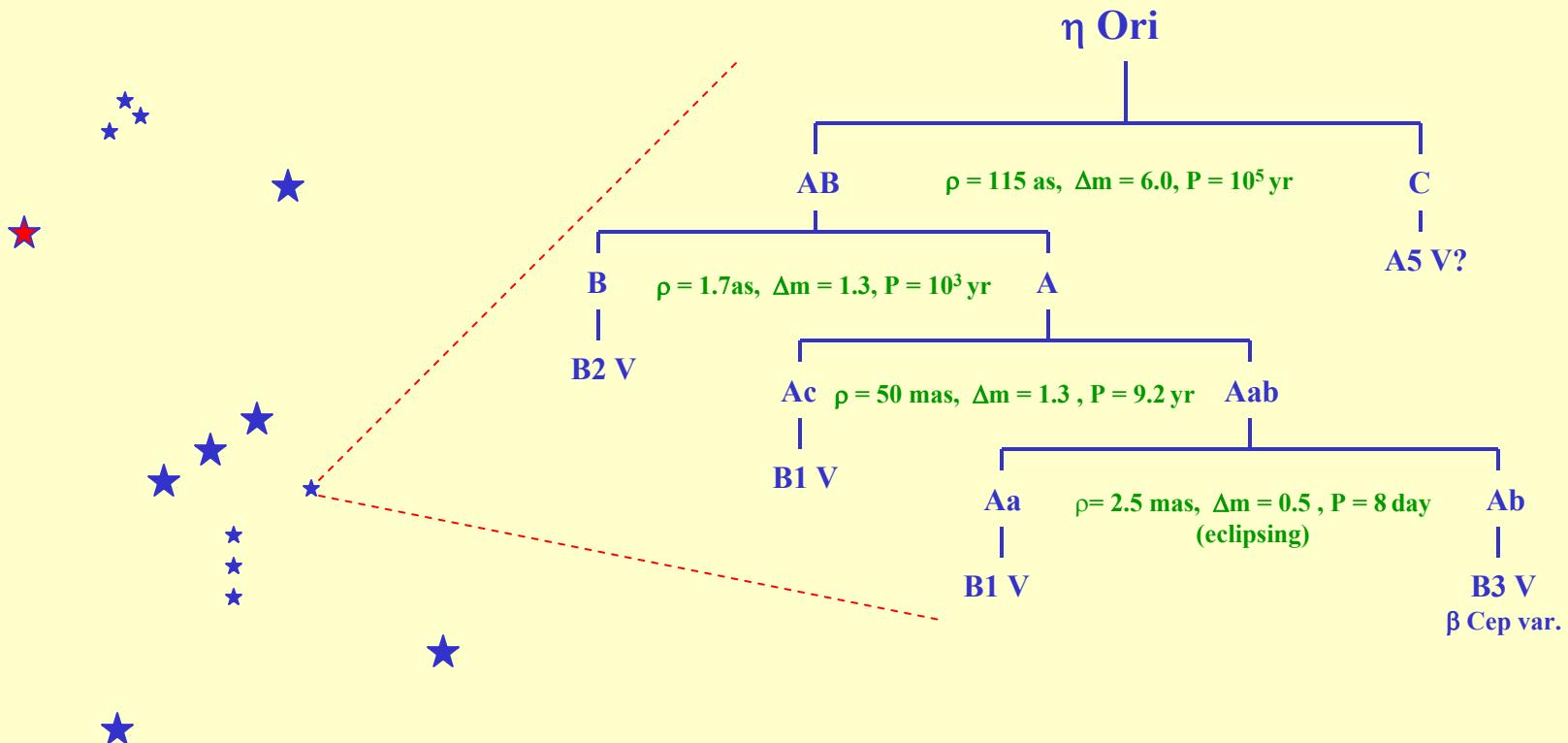
$$V_B = [(1 + \beta)/\beta] V_{B'}^*$$

which gives the simple dependency

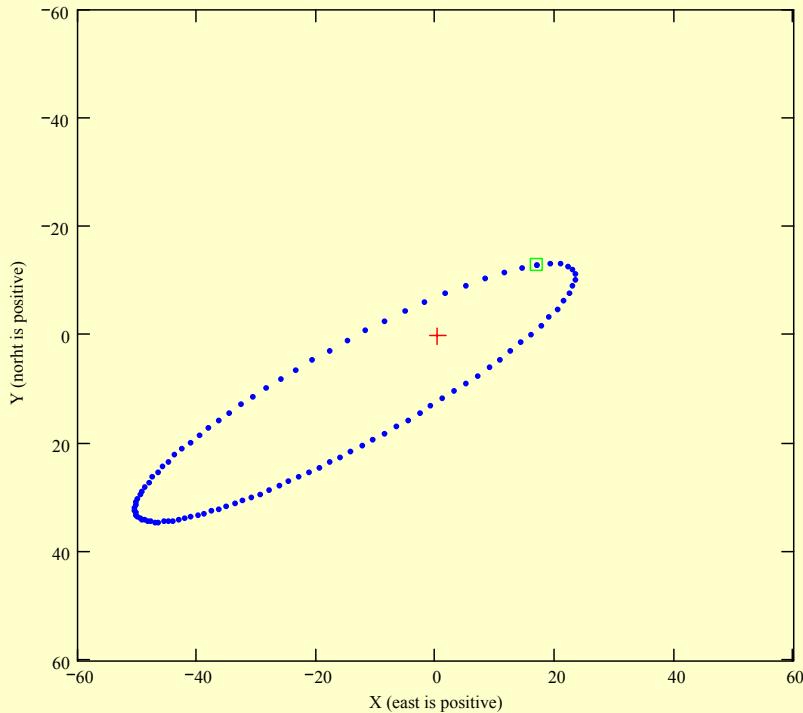
$$V_A / V_B = \beta V_{A'}^* / V_{B'}^*$$



# $\eta$ Orionis – A Hierarchical Quintuple System



# $\eta$ Orionis – Inner and Outer Orbits



P = 9.442 years

T = 1991.020

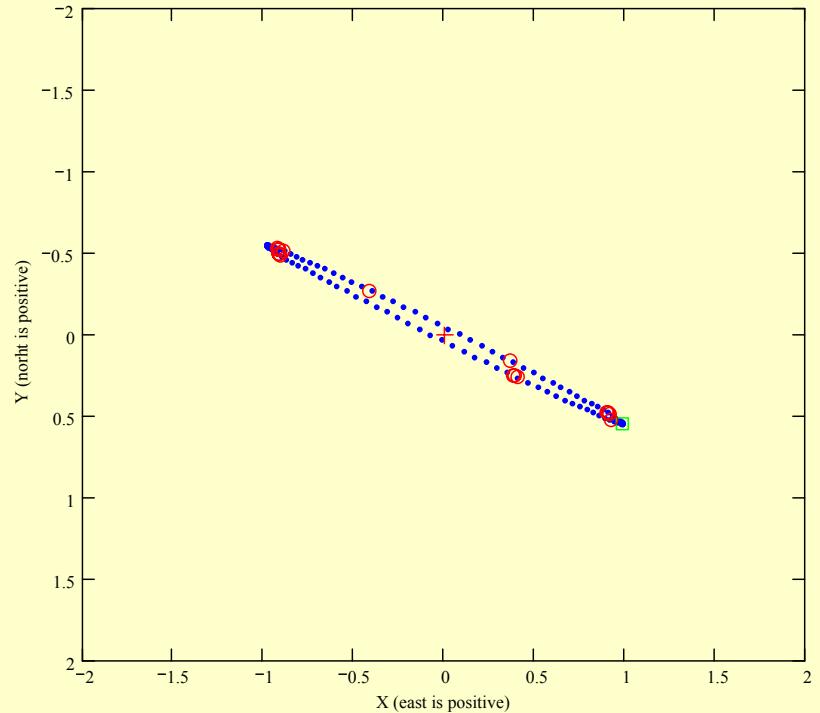
a = 44.1

e = 0.450

i = 102.80

$\Omega$  = 300.40

$\omega$  = 150.000



P = 7.989 days

T = 46390.131

a = 1.13

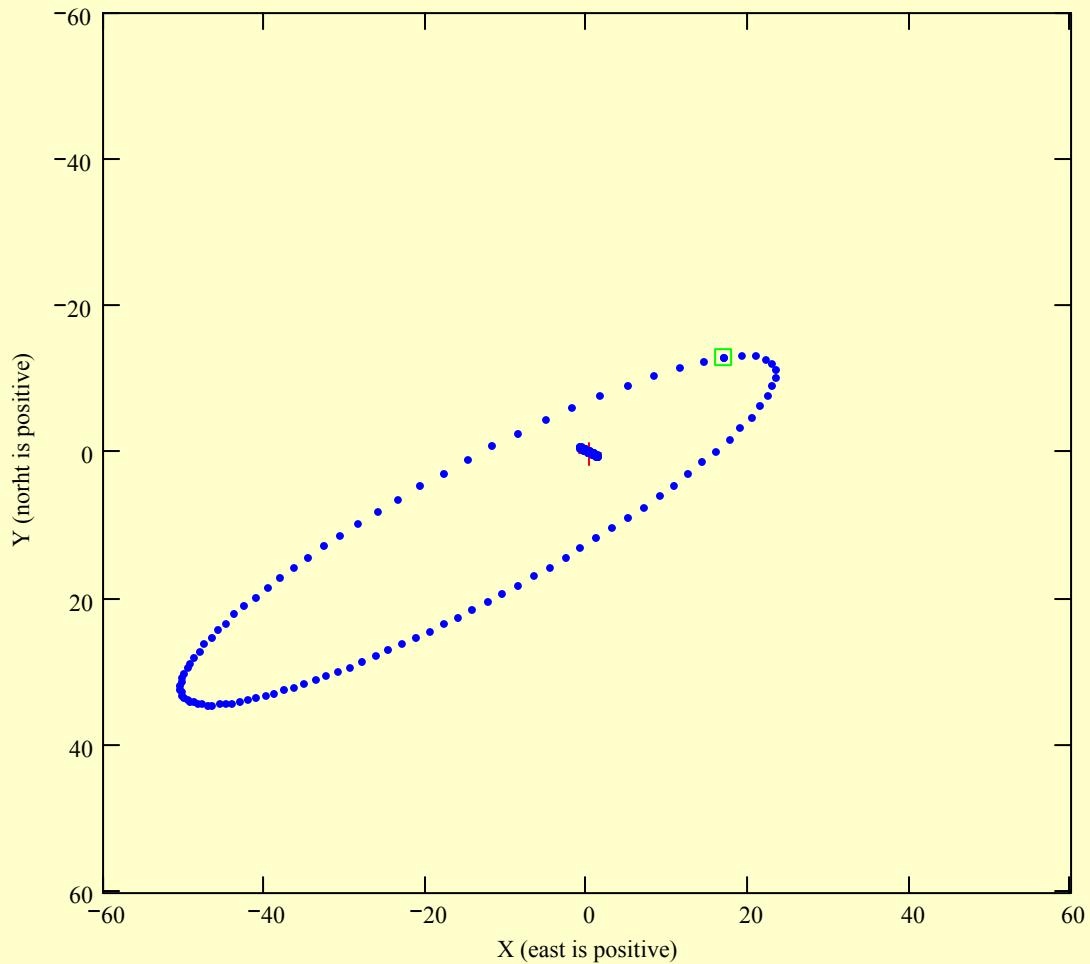
e = 0.000

i = 88.00

$\Omega$  = 61.00

$\omega$  = 0.000

# $\eta$ Orionis – Orbits Overlaid to Scale



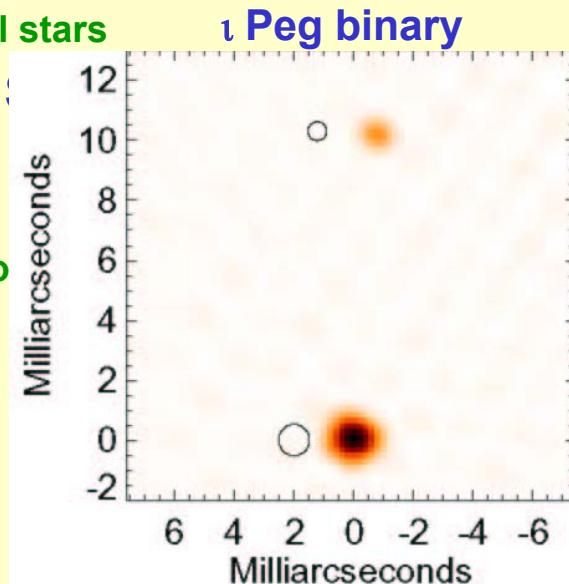
*Other SFP Triples:*

CHARA 96 – ten Brummelaar,  
in progress – an O star  
system

~30 additional “self calibrating”  
SFP triples identified by  
O’Brien

# Forthcoming Science

- **Diameter of Transit Planet Host Star**
  - First direct measurement of an exoplanet diameter
- **Oblateness, Gravity Darkening & Mass Loss of Deneb**
  - Further exploitation of high accuracy V<sup>2</sup> with FLUOR
- **Structure of Young Stellar Objects**
  - Shapes and disks surrounding primordial stars
- **Circumstellar Material Surrounding :**
  - Maybe remnant planetary disk
- **Survey of Exoplanet Host Stars**
  - Rule out face-on binaries and explore evo
- **Imaging with MIRC**
  - First images now in hand!



*CHARA Research Sponsored  
by*

National Science Foundation  
W. M. Keck Foundation  
GSU College of Arts & Sciences  
GSU Vice President for Research



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