Resolving the Structure of Disks Around Be Stars

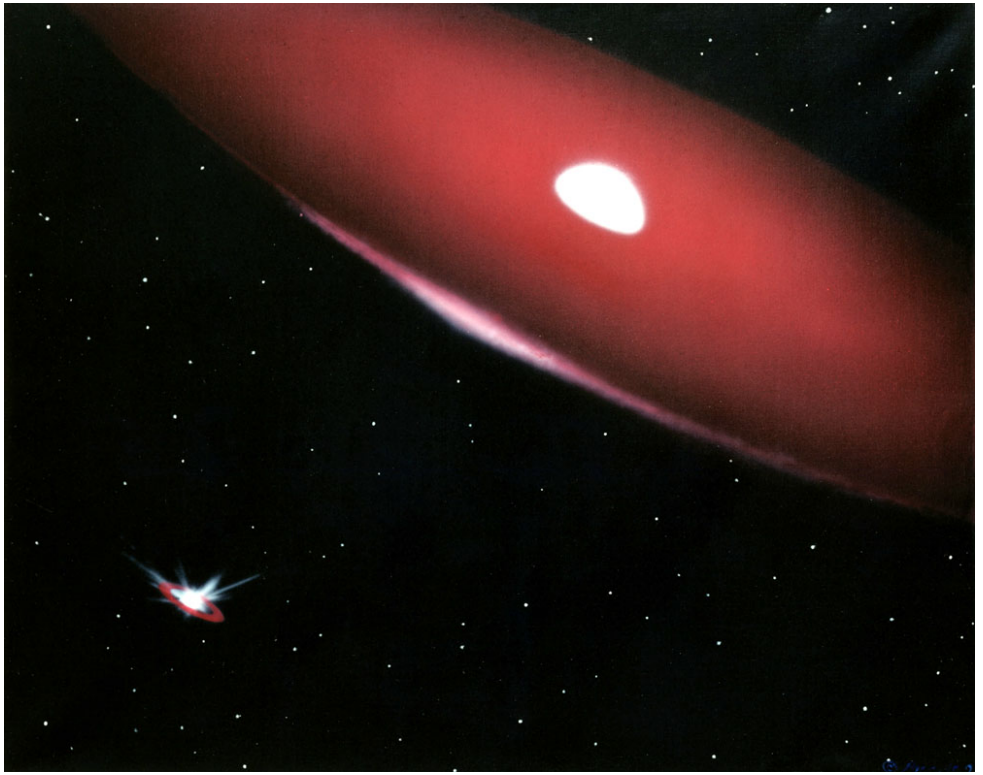
Gail Schaefer

The CHARA Array of
Georgia State University

Collaborators:
Doug Gies (GSU)
John Monnier (U. Michigan)
Yamina Touhami (GSU)
Xiao Che (U. Michigan)

Be Stars

- Rapidly rotating massive stars that eject gas into a circumstellar disk



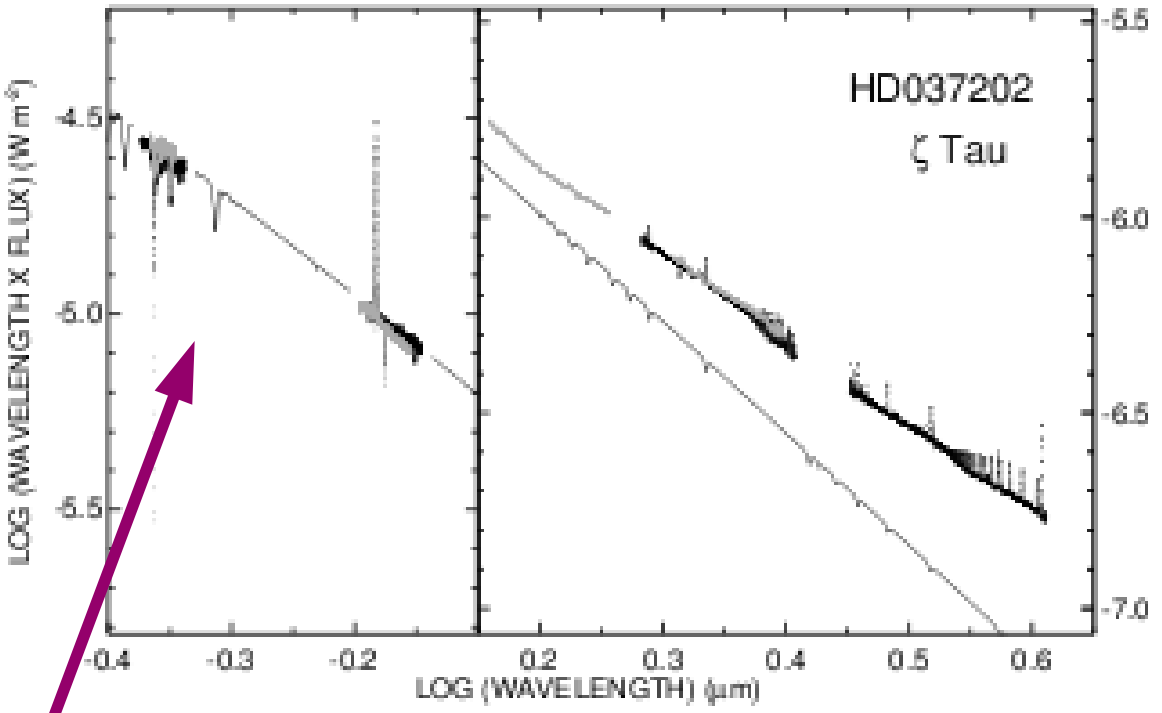
Bill Pounds

Review: Porter & Rivinius 2003

Outline

- Properties of Be stars
- Interferometric observations of Be stars
  - Geometry and size of Be star disks
  - Multi-wavelength structure of the disks
  - Small scale asymmetries in the light distribution of the disk
  - Long-term campaign to monitor changes in the disk of Be stars

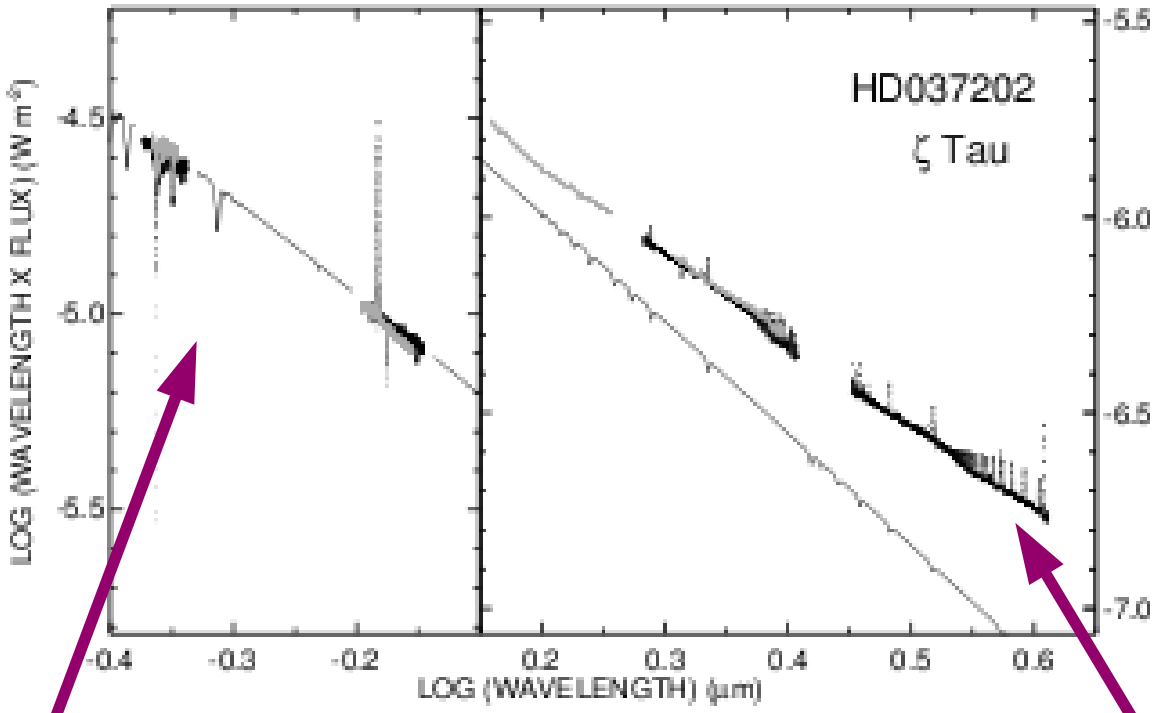
Evidence for Disks Around Be Stars: Infrared Excess



Touhami et al. 2010

Visible spectrum matches stellar spectral energy distribution

Evidence for Disks Around Be Stars: Infrared Excess

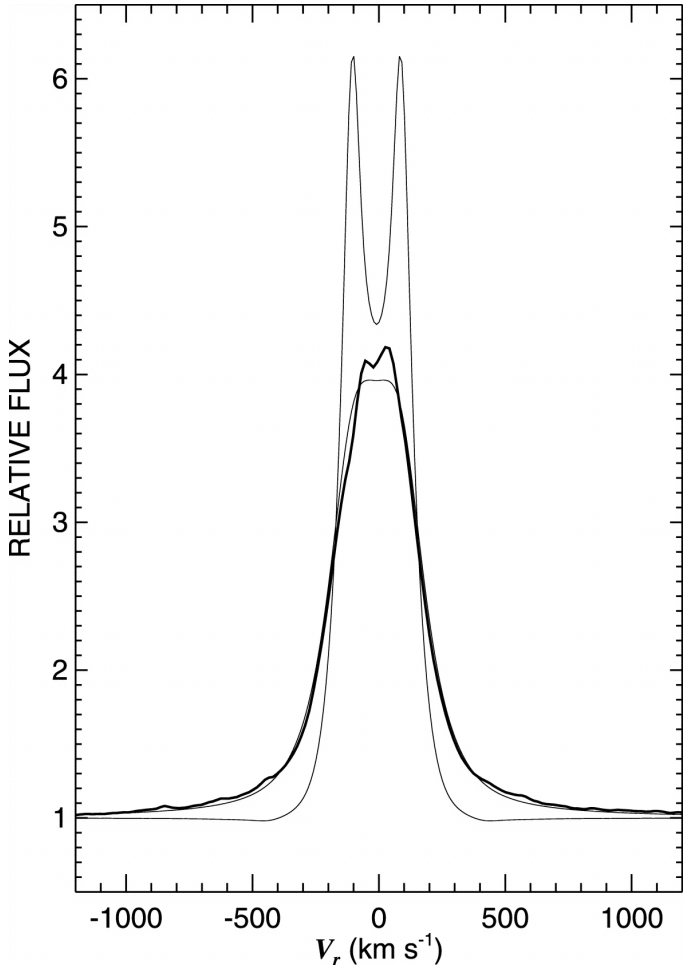


Touhami et al. 2010

Visible spectrum matches stellar spectral energy distribution

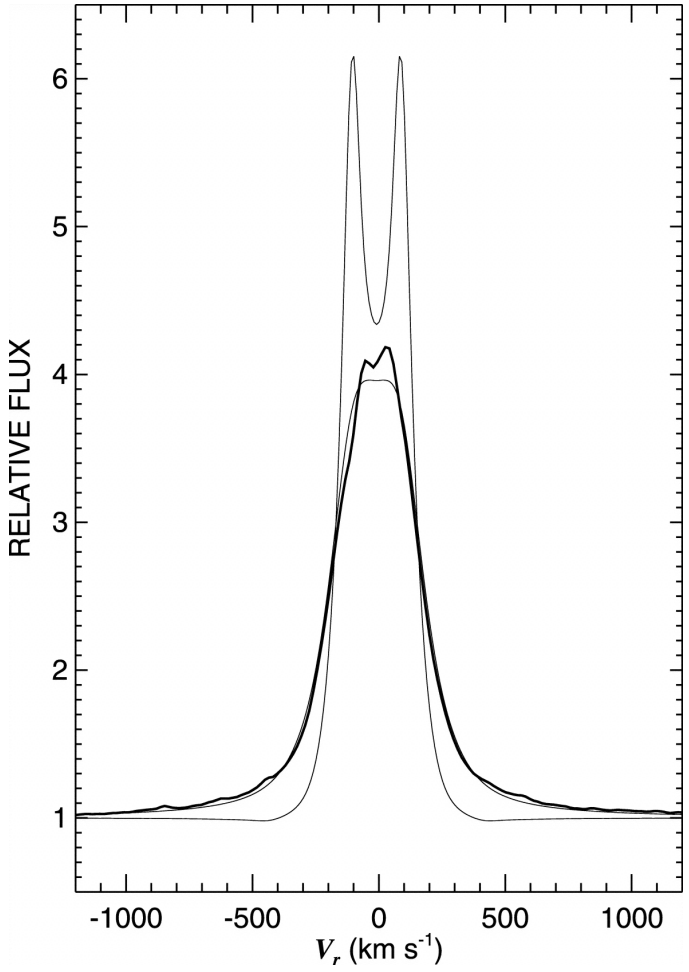
Infrared excess above stellar spectrum

Evidence for Disks Around Be Stars: Hα Emission Line Profiles

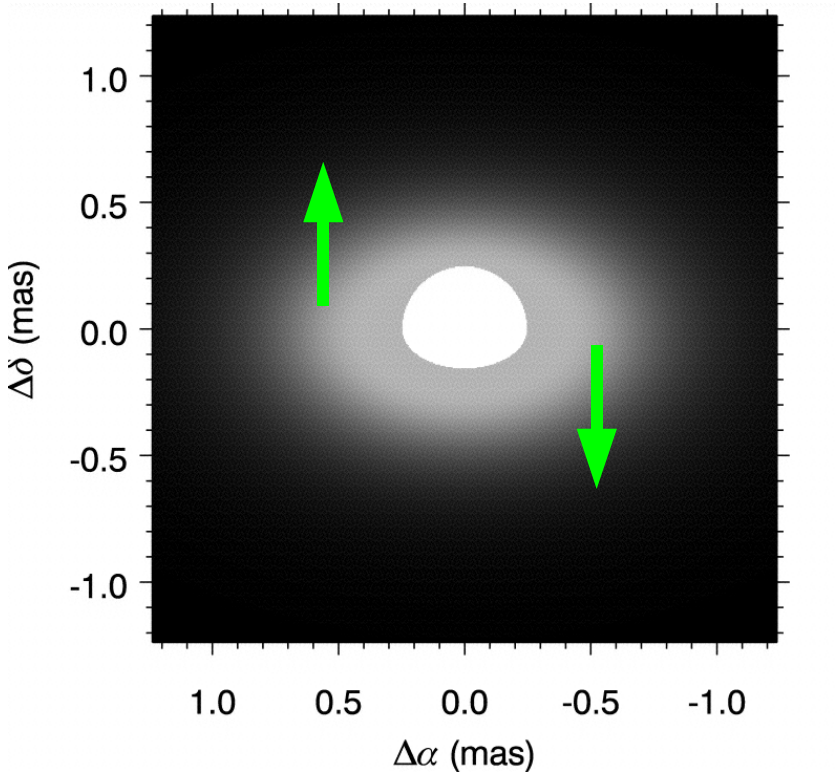


Gies et al. 2007

Evidence for Disks Around Be Stars: Hα Emission Line Profiles

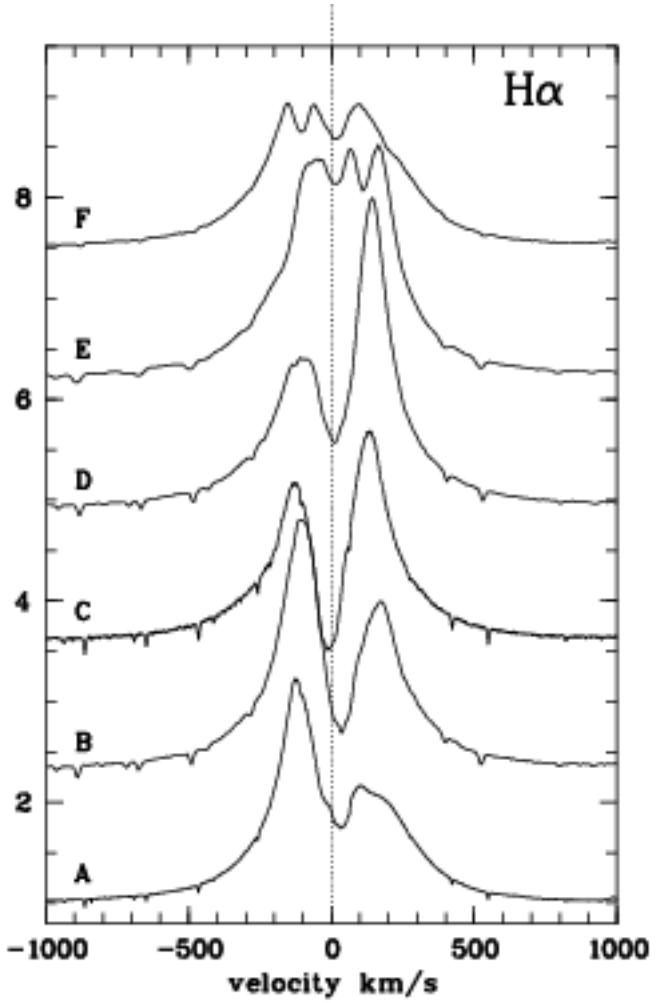


Gies et al. 2007



Rotation of circumstellar disk

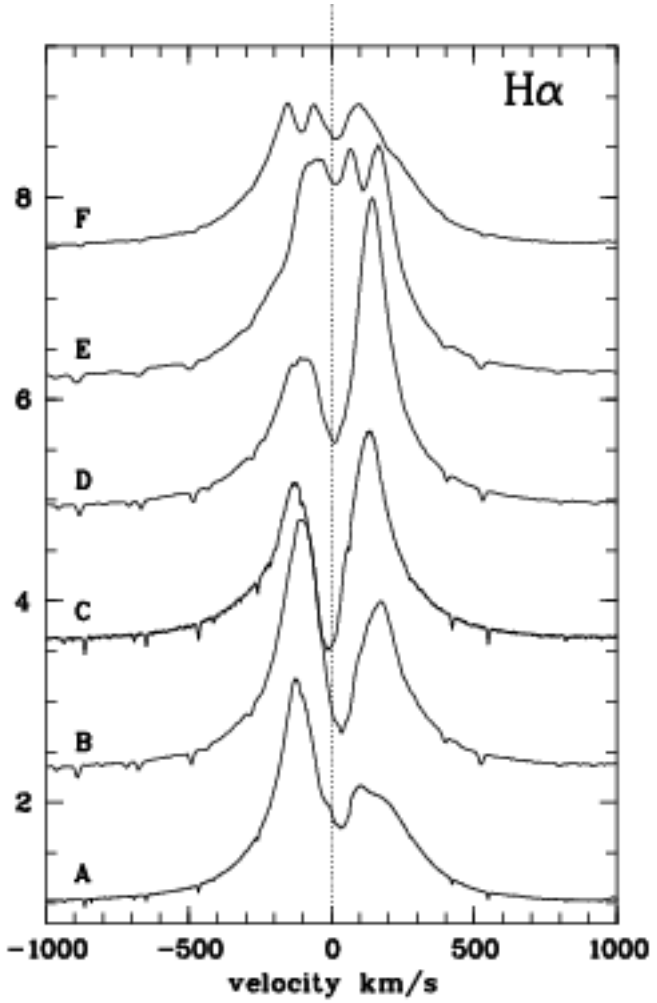
Time Variability of Hα Emission Lines



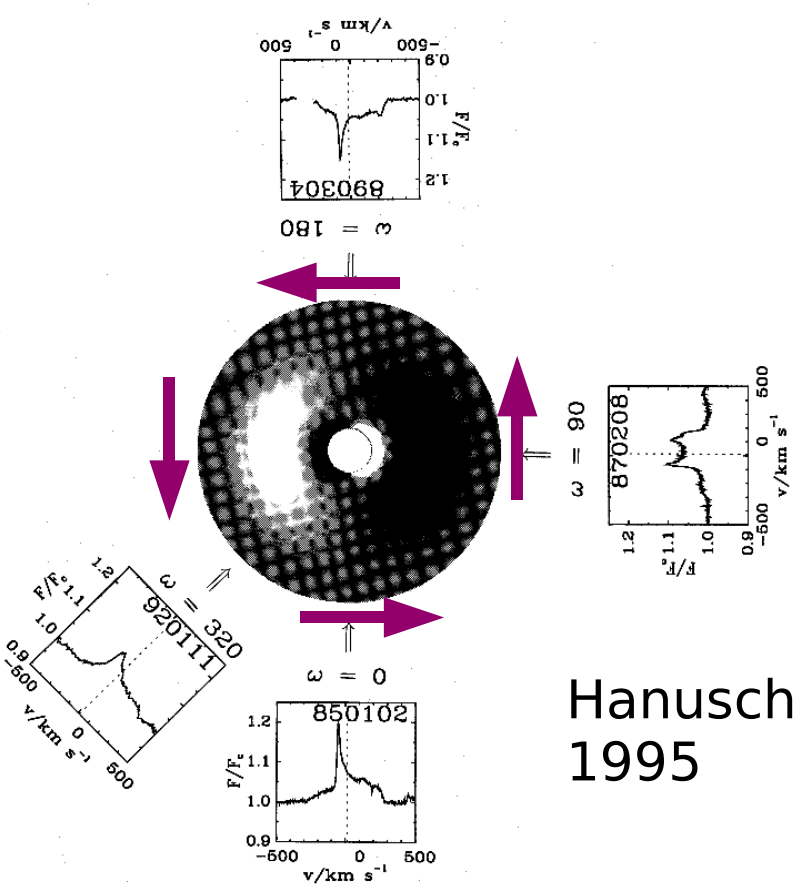
Stefl et al. 2009

- V/R variations
- Variable on timescales of days to decades

Time Variability of Hα Emission Lines



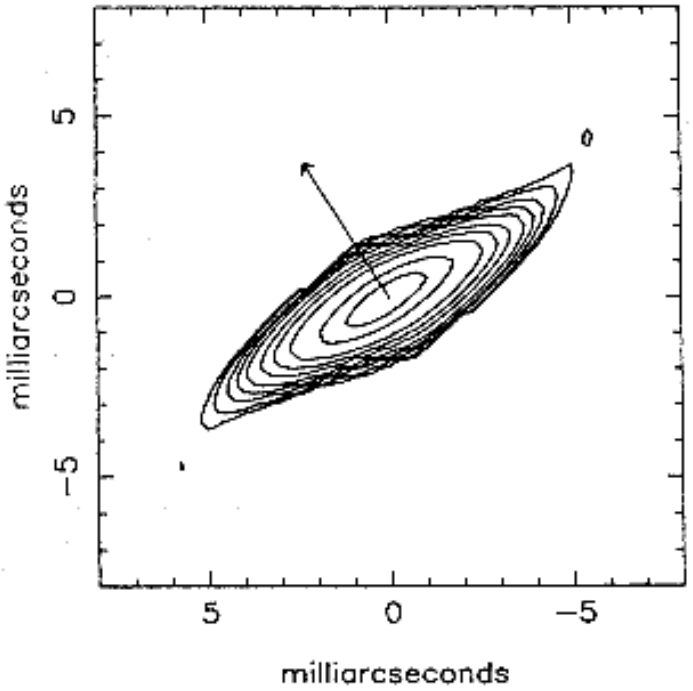
Stefl et al. 2009



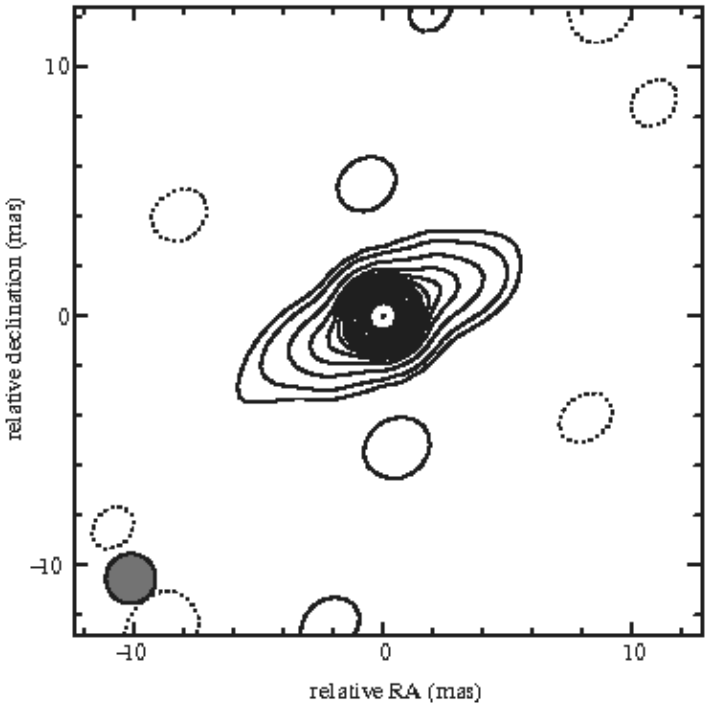
Hanuschik et al. 1995

Density wave enhancement

Evidence for Disks Around Be Stars: Spatially Resolving the Disk with Long Baseline Interferometry



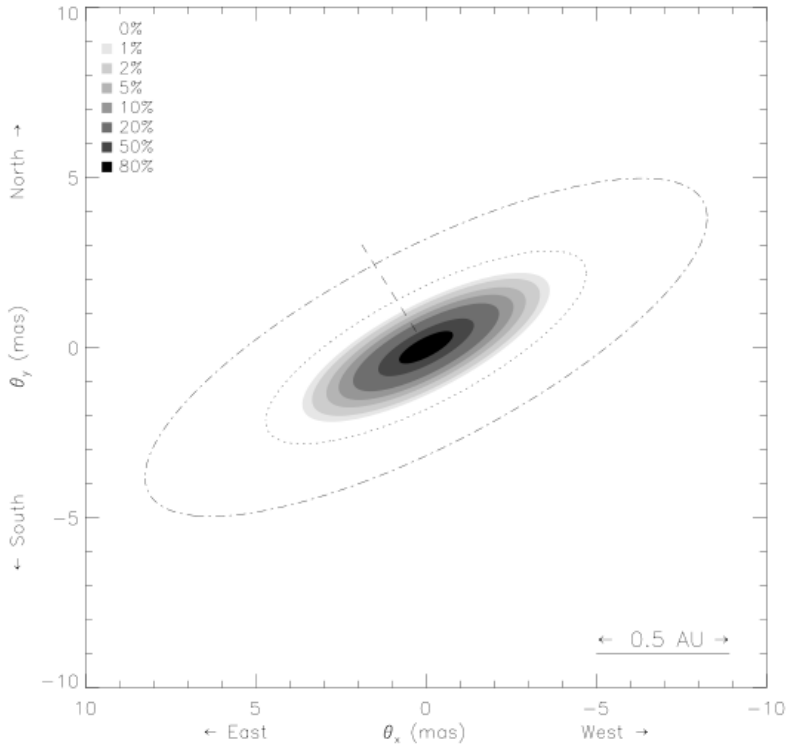
Quirrenbach et al. 1994
Mark III Interferometer



Baldwin & Haniff 2002
COAST Interferometer

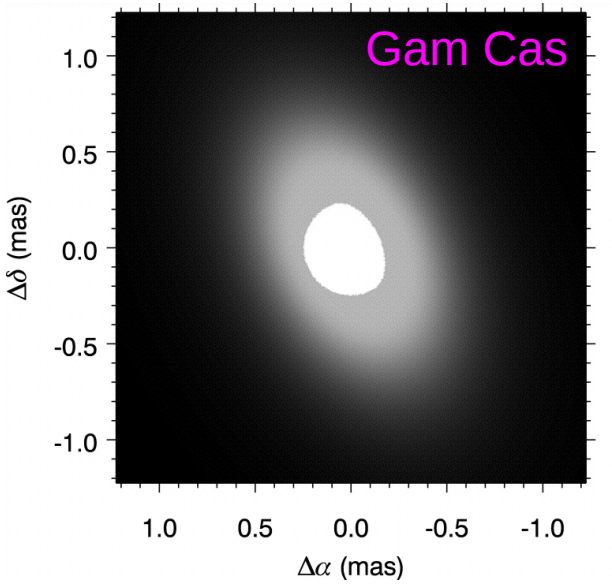
Geometry of Be Star Disks Measured using Interferometry

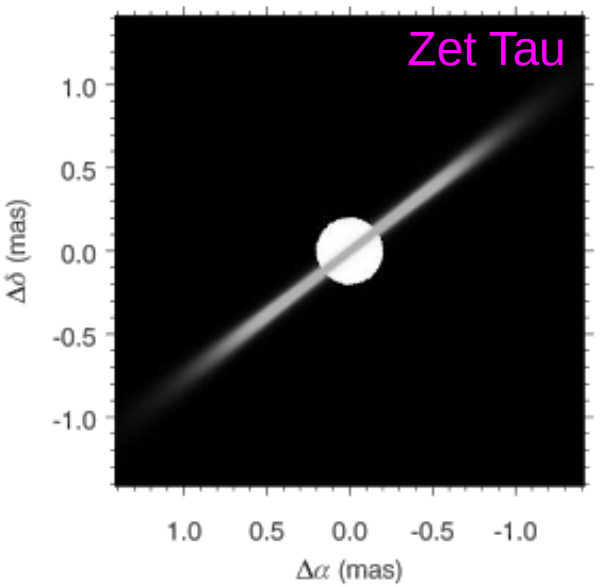
Geometric Models of Be Star Disks

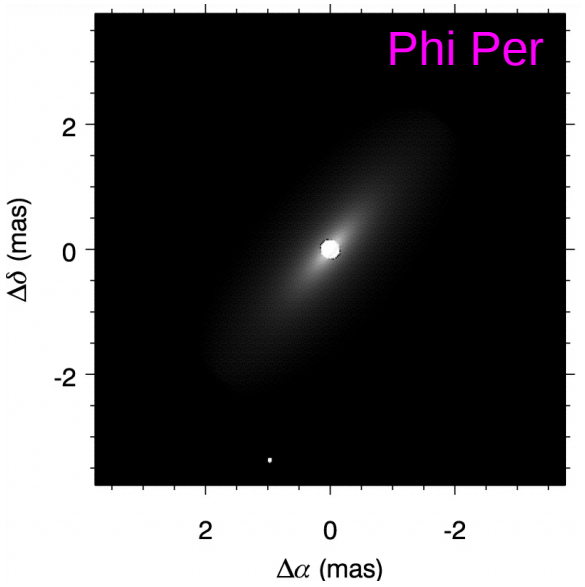


- Zeta Tau observed in Hα emission at NPOI
- Elliptical Gaussian model
- Flattened disk inclined nearly edge-on
- Tycner et al. 2004

Physical Model: Isothermal Disk in Keplerian Rotation

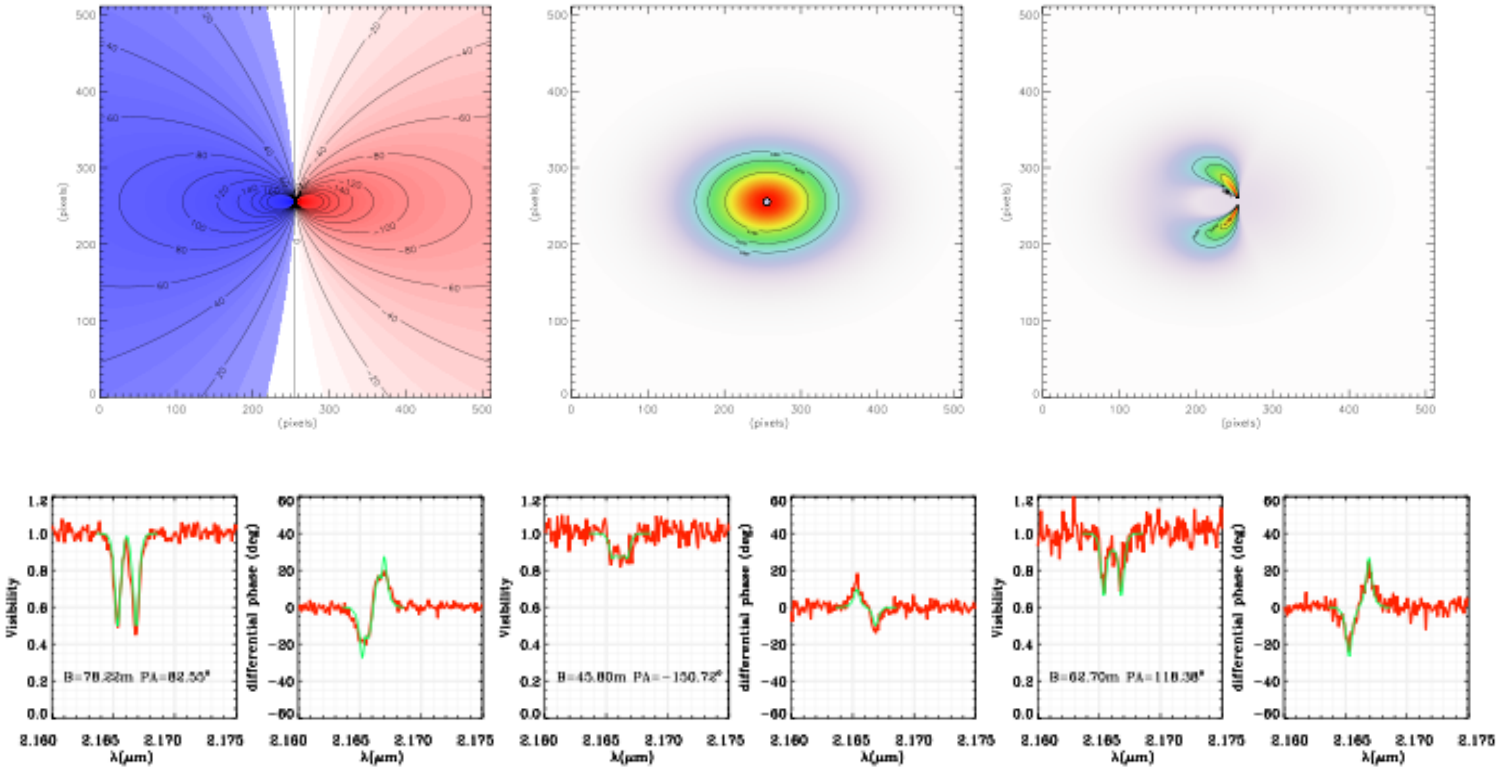






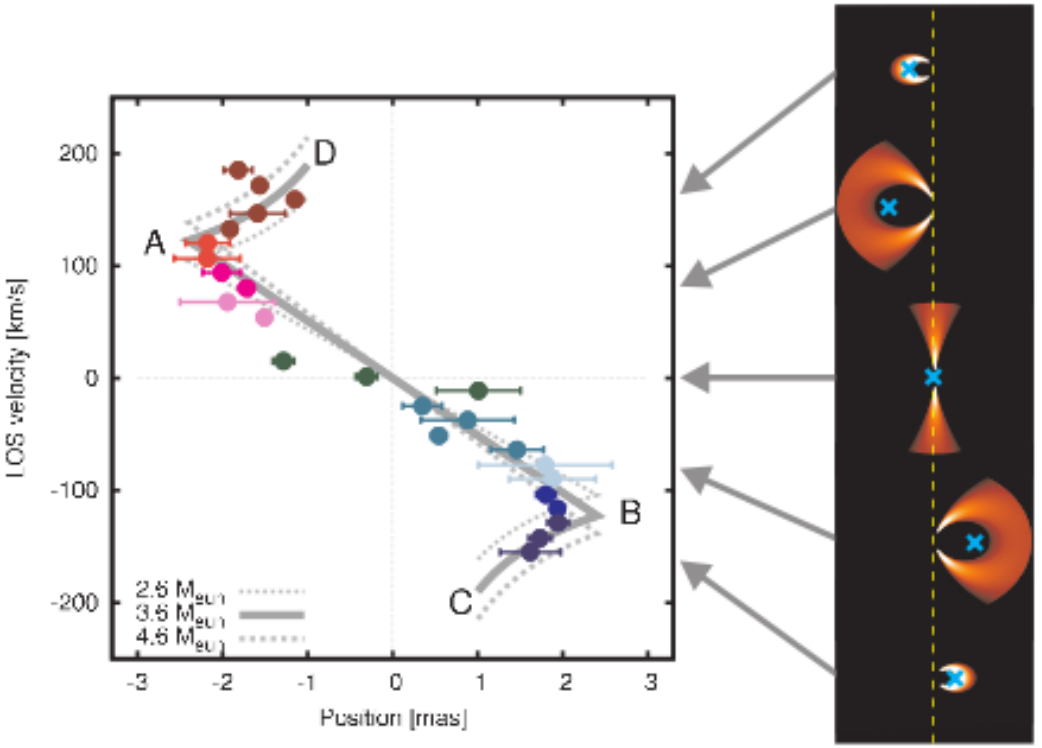
- Geometry and density structure of the disk
- CHARA Classic K-band measurements
- Gies et al. 2007

Kinematic Model of Rotating Disk: High Spectral Resolution



- VLTI/AMBER Bry emission
- Visibilities and differential phase
- Meilland et al. 2012

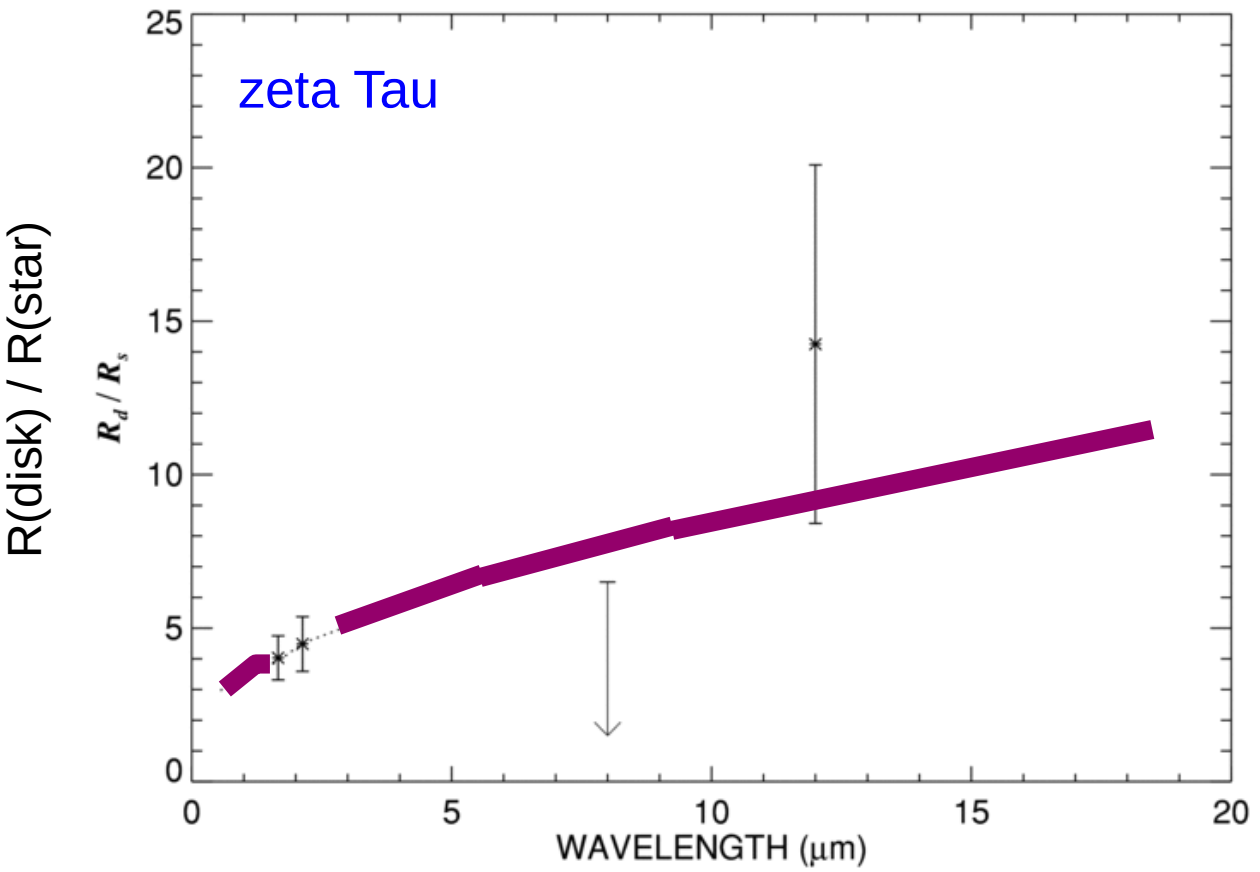
Kinematic Model of Rotating Disk: High Spectral Resolution



- VLTI/AMBER Bry emission
- Kraus et al. 2012

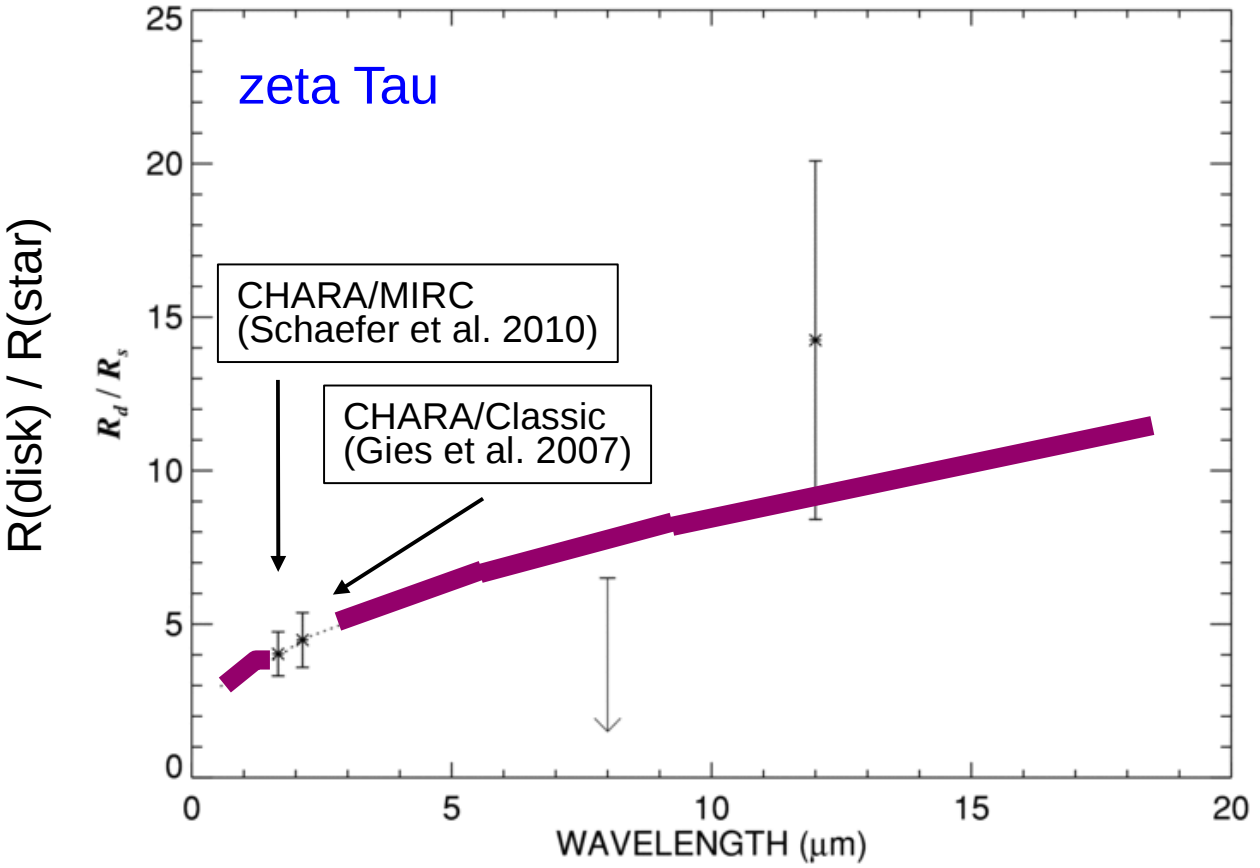
Multi-Wavelength Sizes of Be Star Disks

How Does Disk Size Depend on Wavelength?



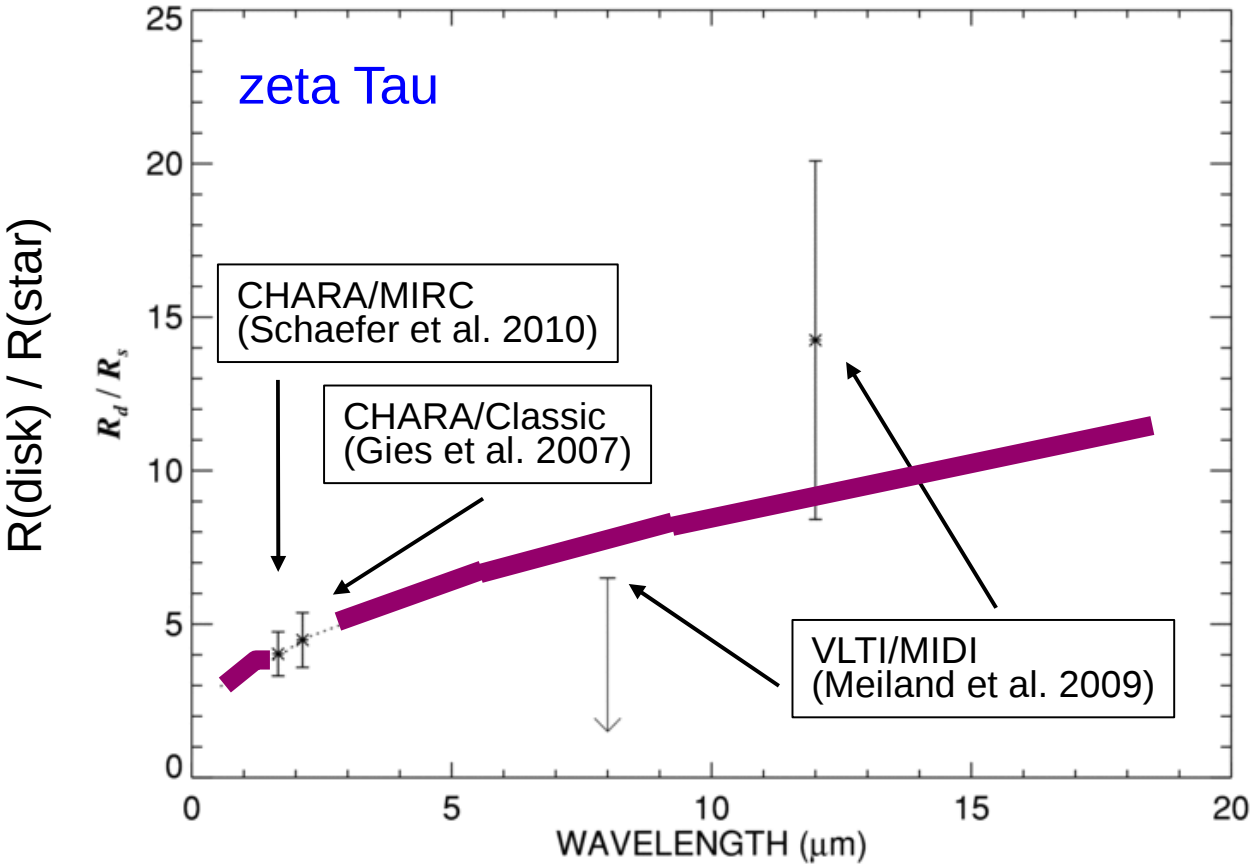
Touhami et al. 2011

How Does Disk Size Depend on Wavelength?



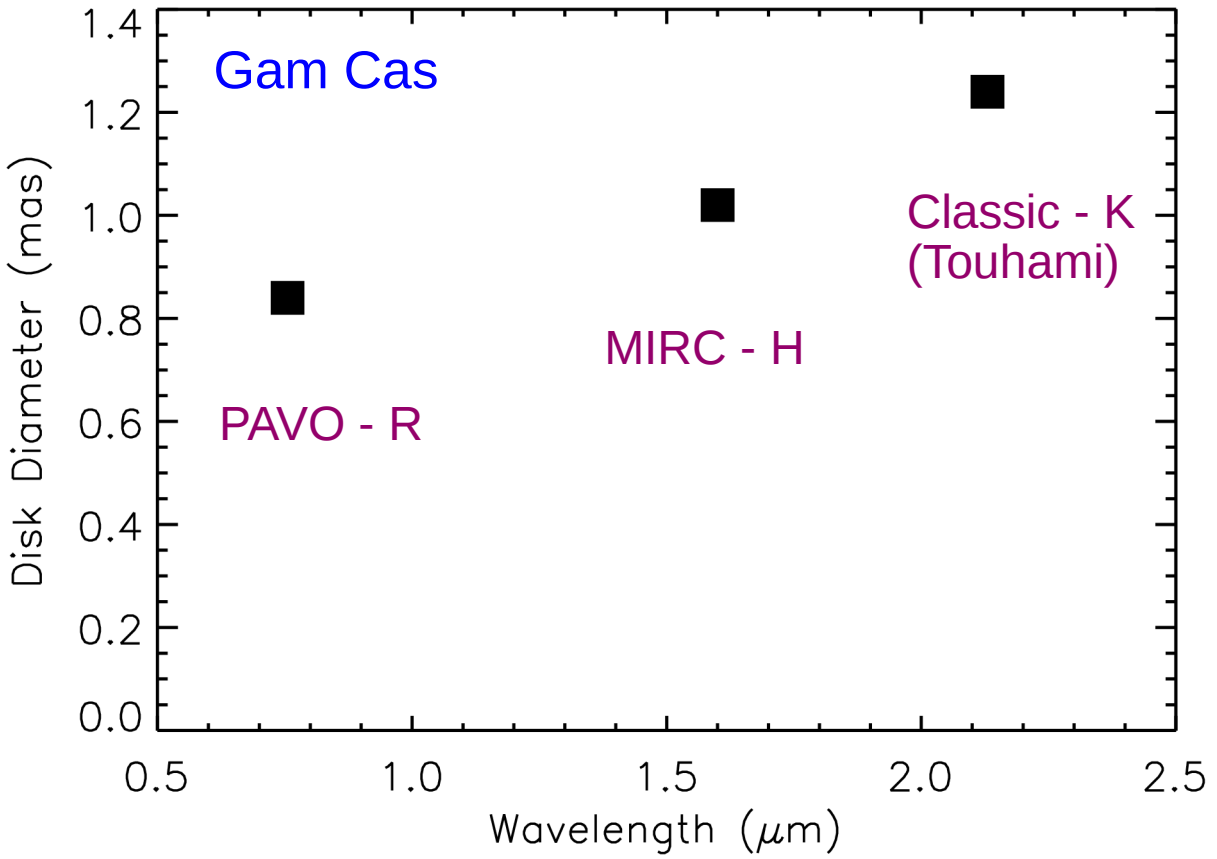
Touhami et al. 2011

How Does Disk Size Depend on Wavelength?



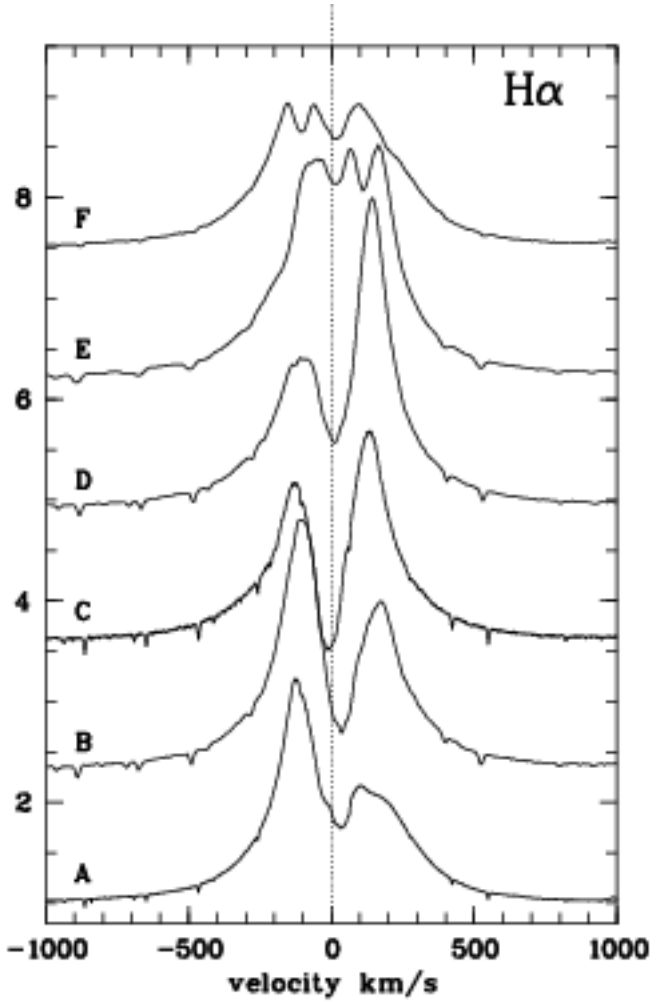
Touhami et al. 2011

Multi-wavelength Disk Diameters

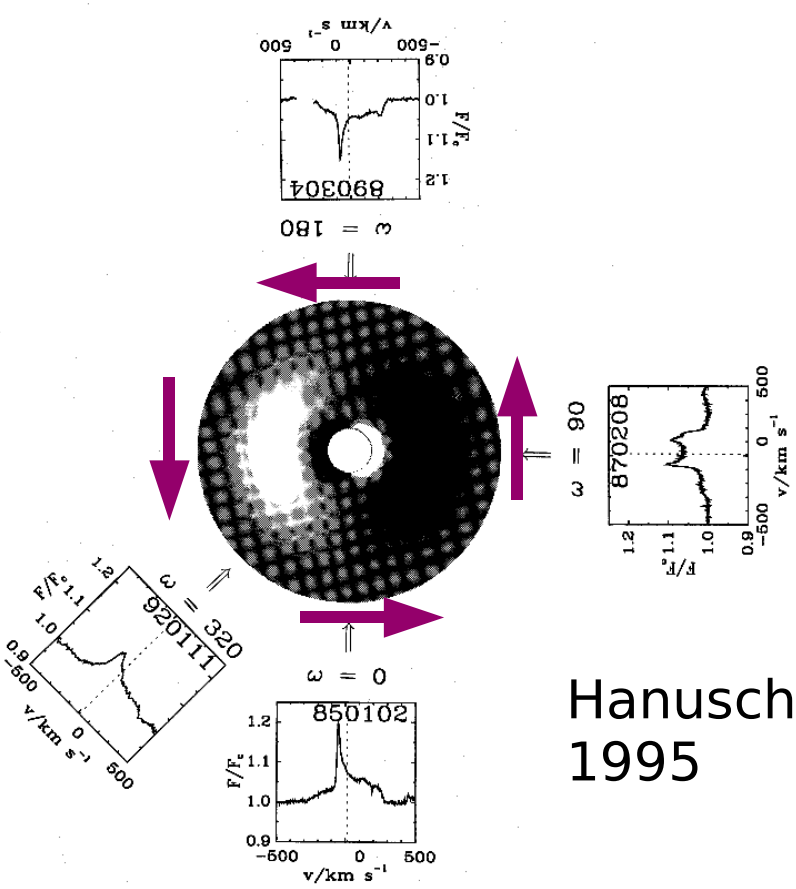


Asymmetries in Be Star Disks

Time Variability of Hα Emission Lines



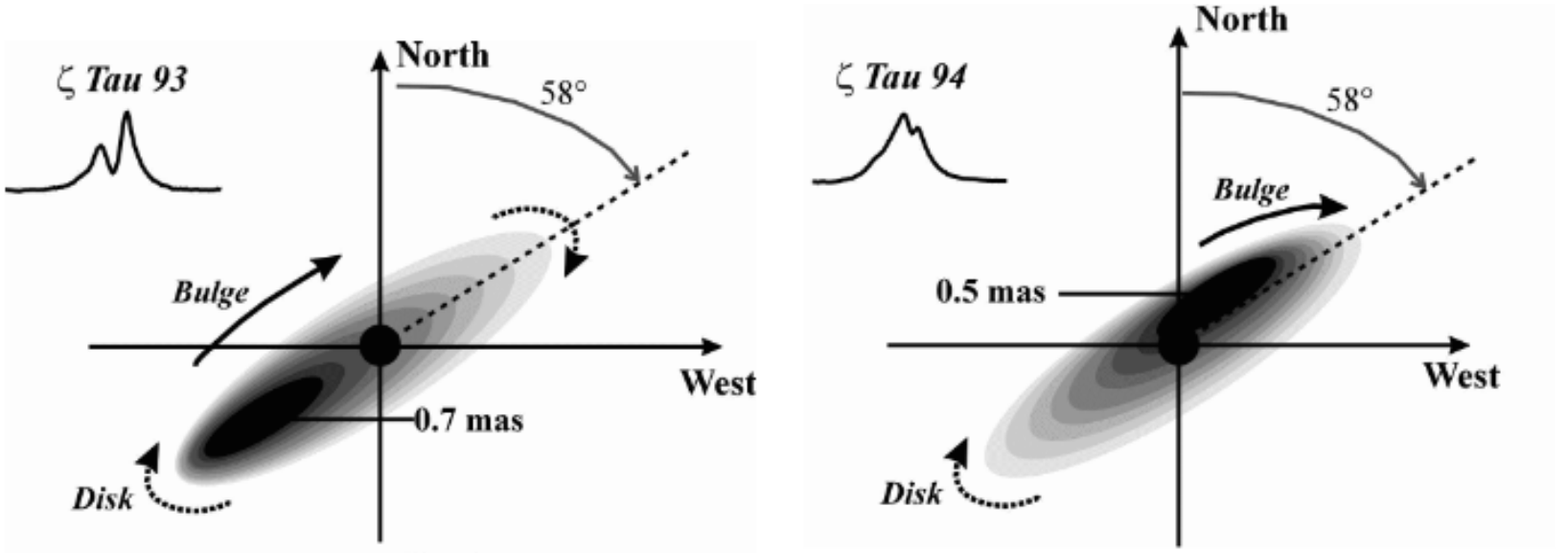
Stefl et al. 2009



Hanuschik et al. 1995

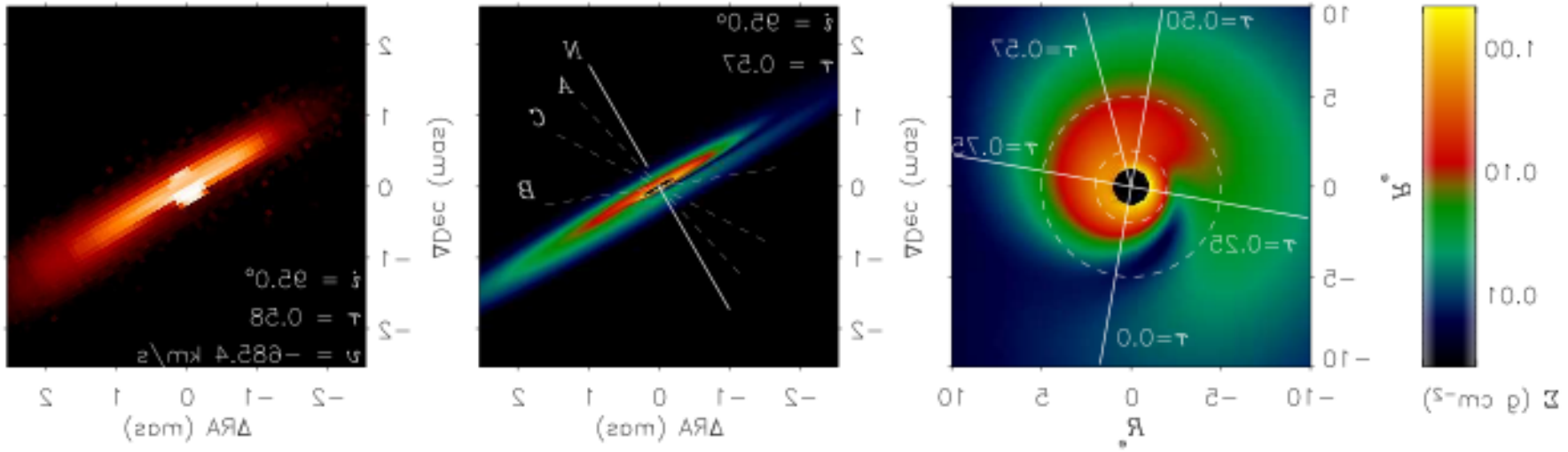
Density wave enhancement

Asymmetries in the Disk of Zeta Tau



- Asymmetry detected in differential phases
- Shift in position of bulge in disk
- GI2T - Vakili et al. 1998

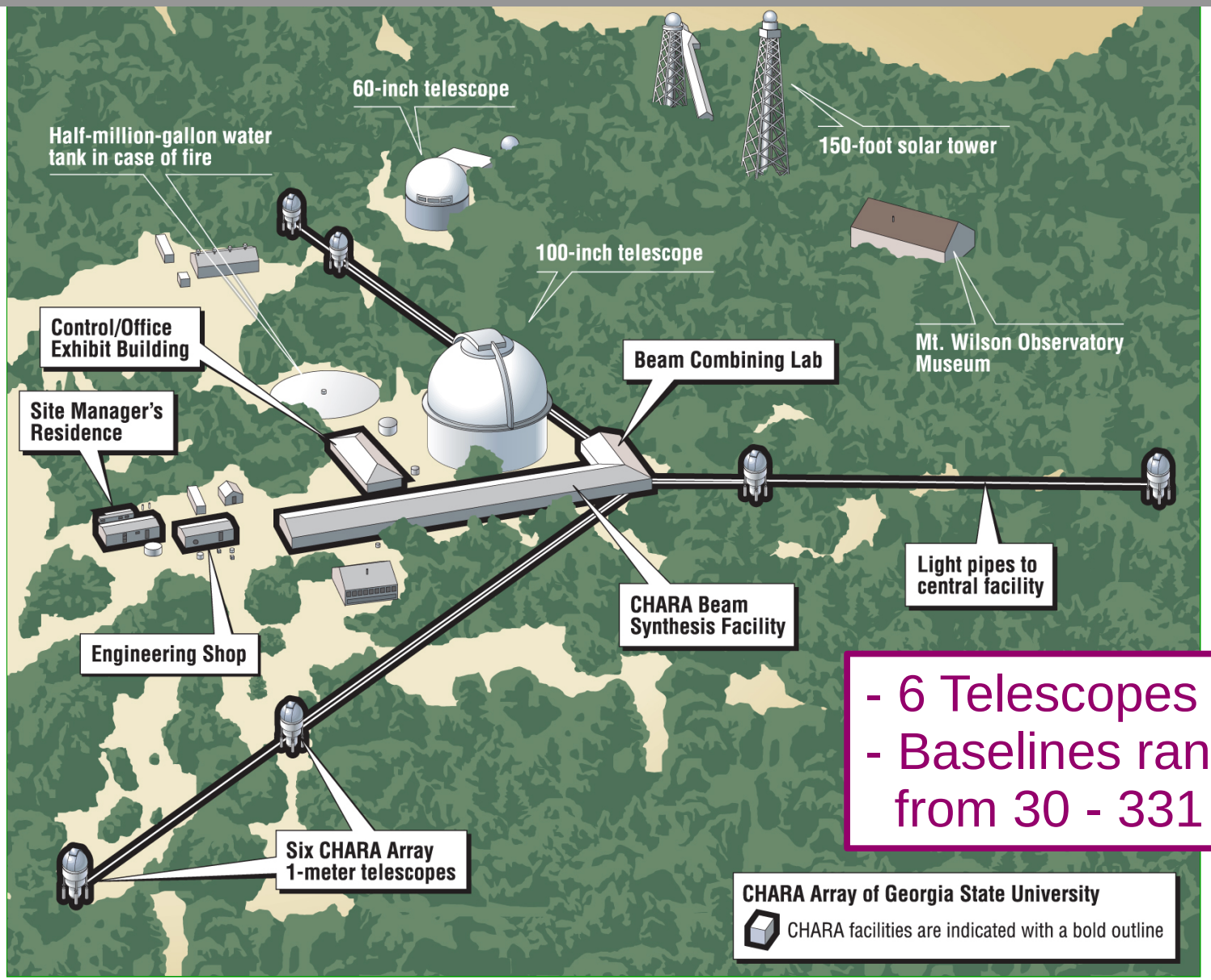
Asymmetries in the Disk of Zeta Tau



- Asymmetry consistent with oscillation pattern created by one-armed spiral in disk
- Visibilities and differential phases - VLTI AMBER
- Stefl et al. 2009, Carciofi et al. 2009

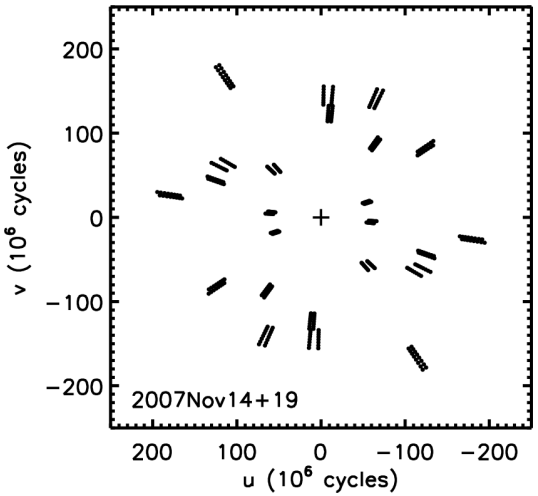
Long-term Monitoring of Be Star Disks using the MIRC Beam Combiner at the CHARA Array

The CHARA Array
Mount Wilson Observatory

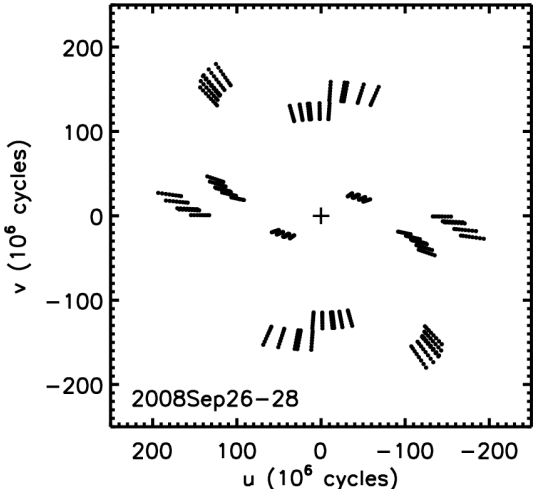


- 6 Telescopes
- Baselines ranging from 30 - 331 meters

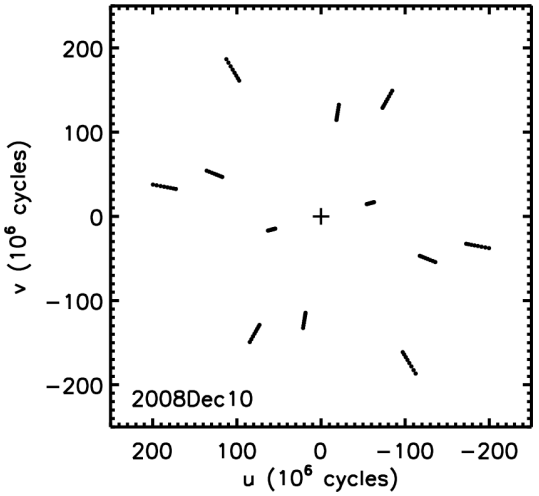
Example uv coverage of Zeta Tau MIRC Observations 2007-2009



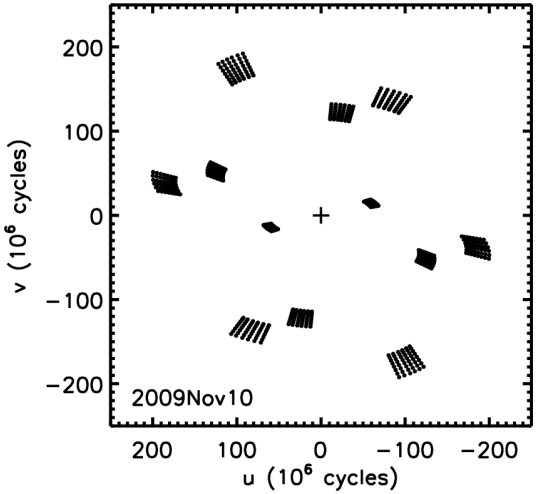
2007Nov
S2E2W1W2
S1E1W1W2



2008Sep
S1E1W1W2

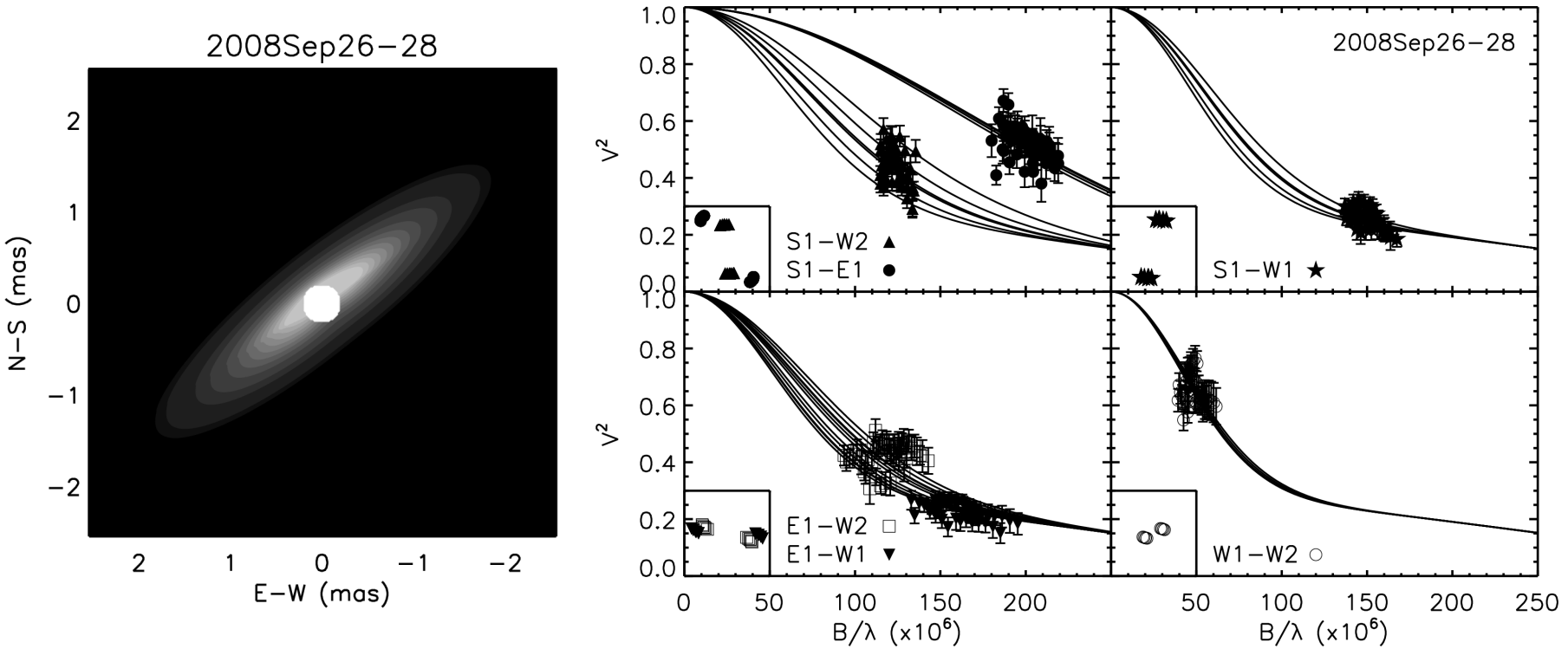


2008Dec
S1E1W1W2



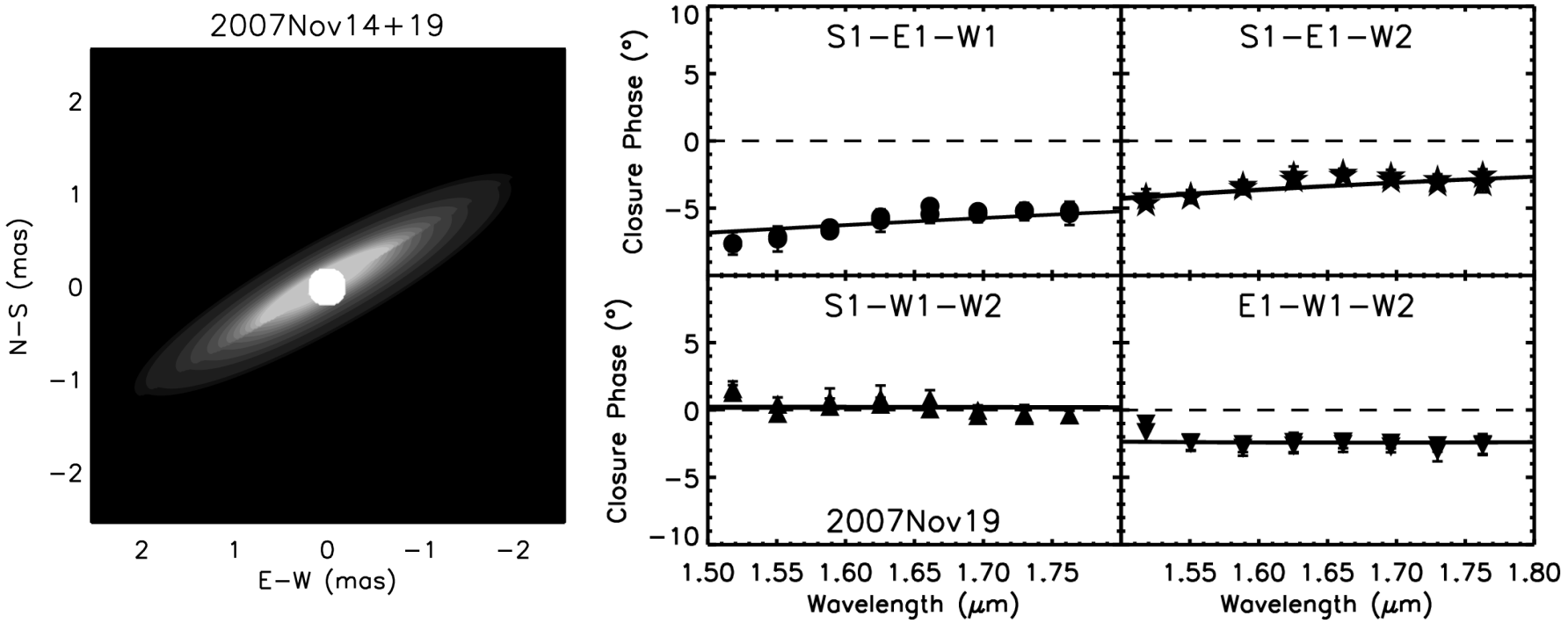
2009Nov
S1E1W1W2

Zeta Tau: MIRC Visibilities



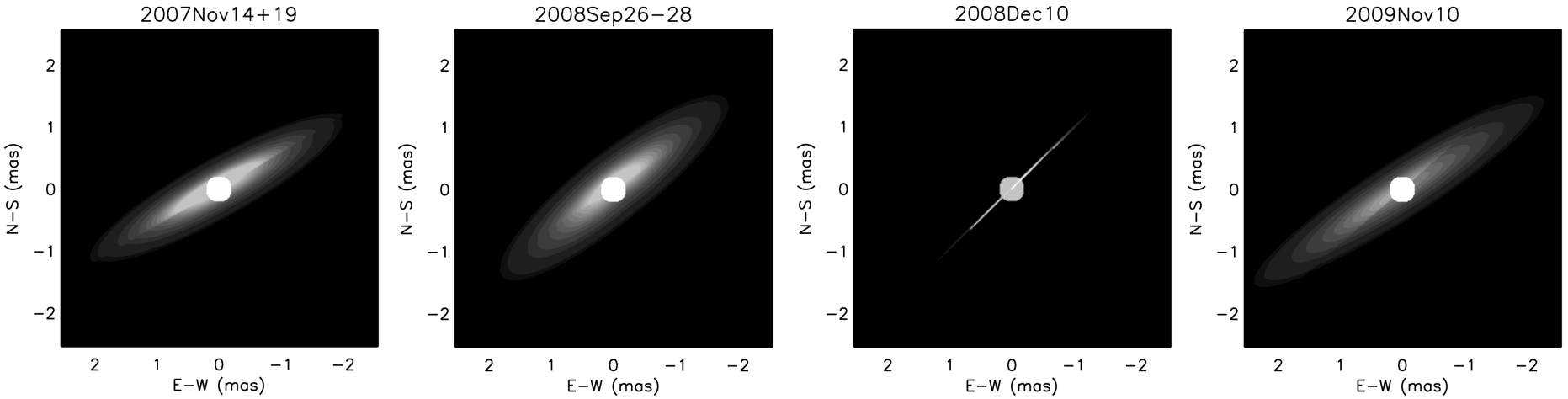
Elliptical shape and orientation of Zeta Tau disk

Zeta Tau: Non-zero Closure Phases



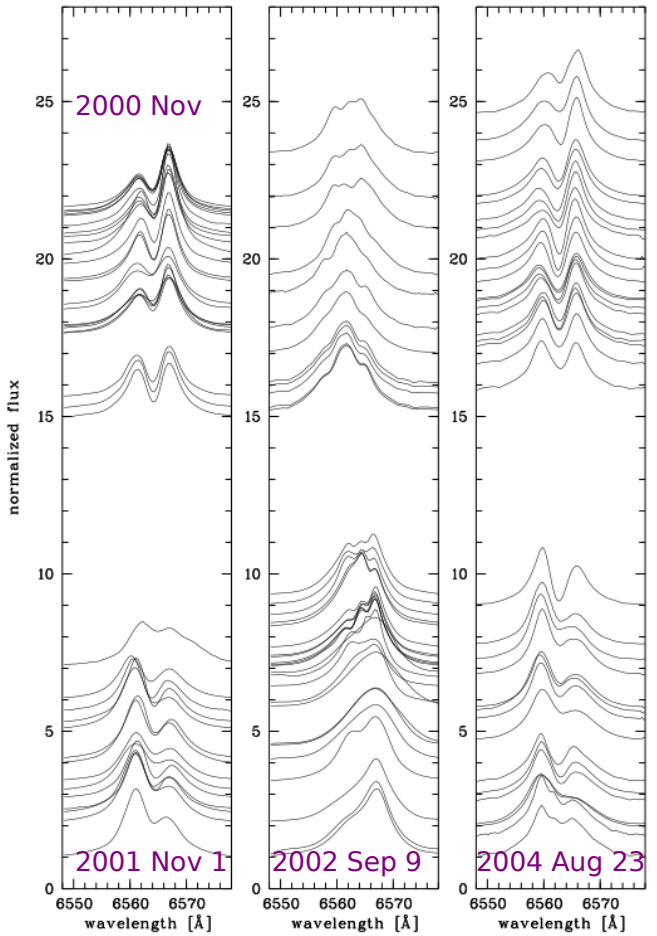
Asymmetry in the light distribution of Zeta Tau

Geometric Models of Zeta Tau



- FWHM Major Axis ~ 1.8 mas
- On average, the central star contributes ~ 55% of the light in the H-band (41% in the K-band)
- Change in position angle of the major axis of 10-15°
- Motion of the asymmetry

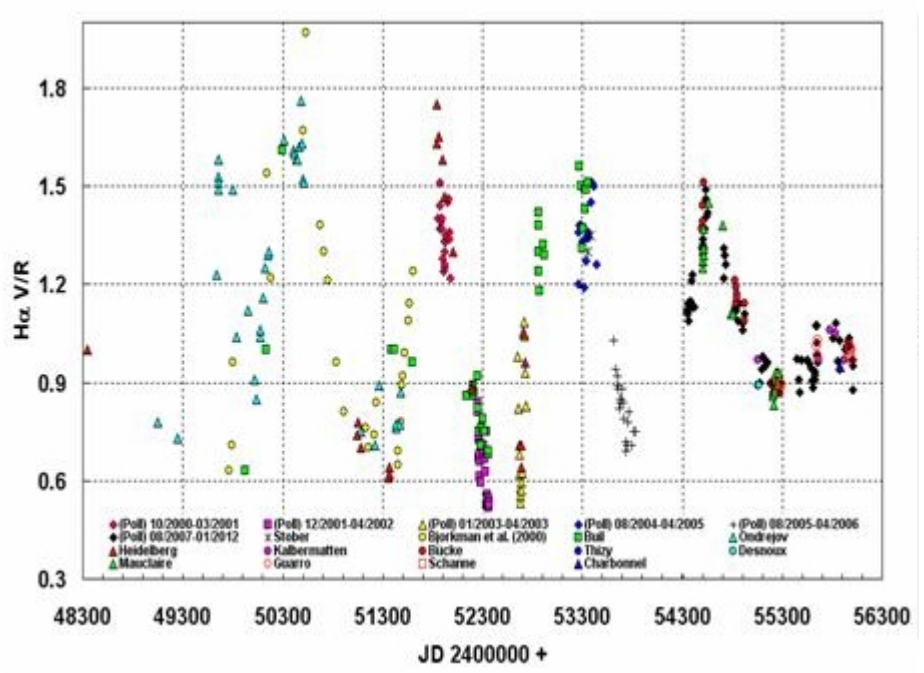
Zeta Tau: Hα Profile Variability



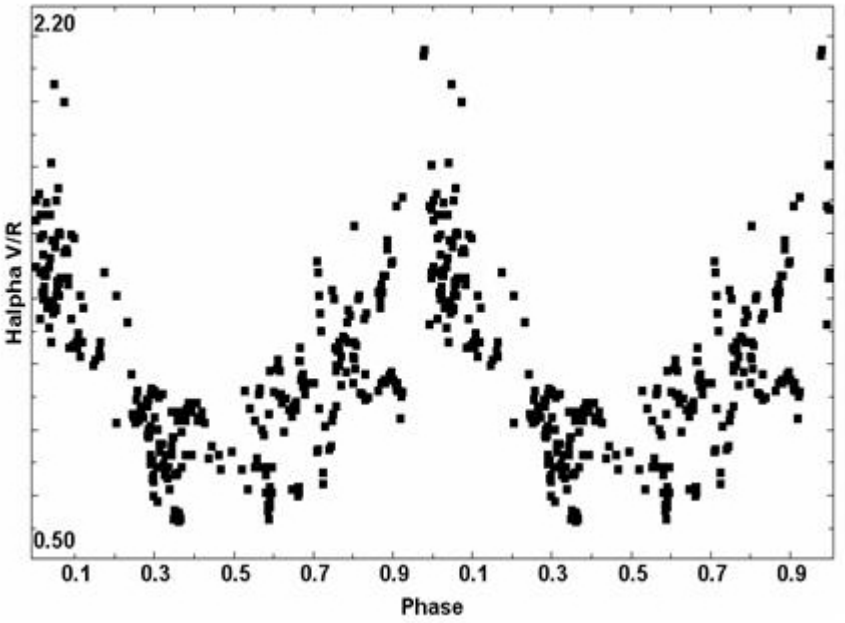
Pollmann & Rivinius 2008

Zeta Tau: Hα Profile Variability

1995 2012

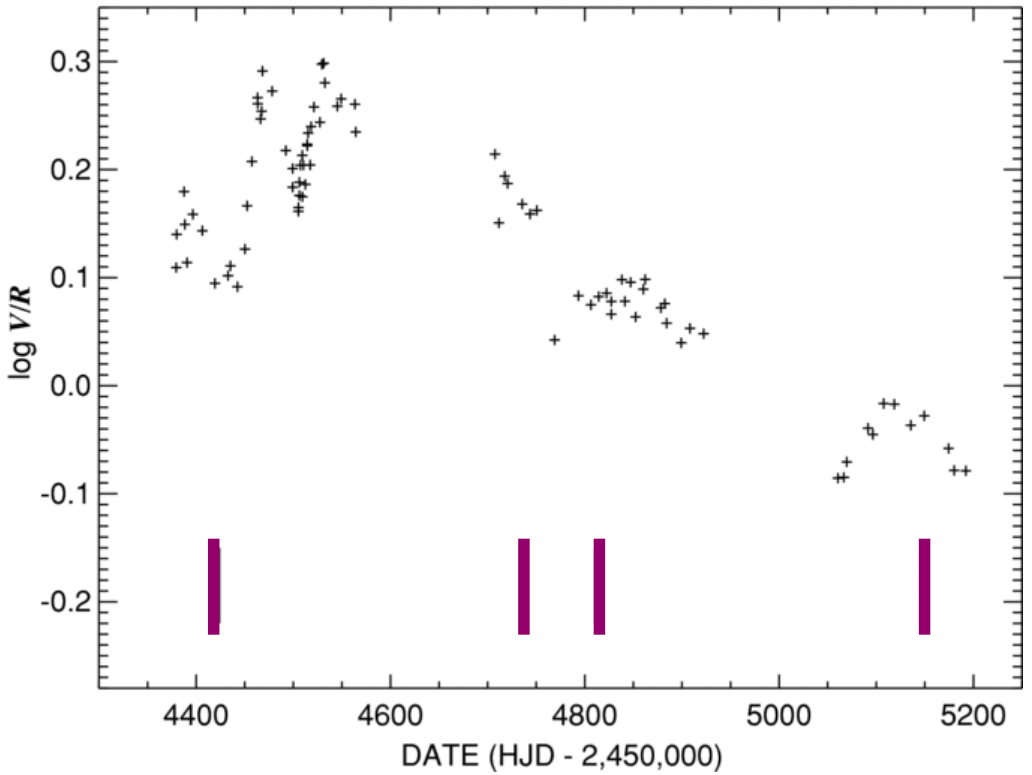


Period: 1428 days



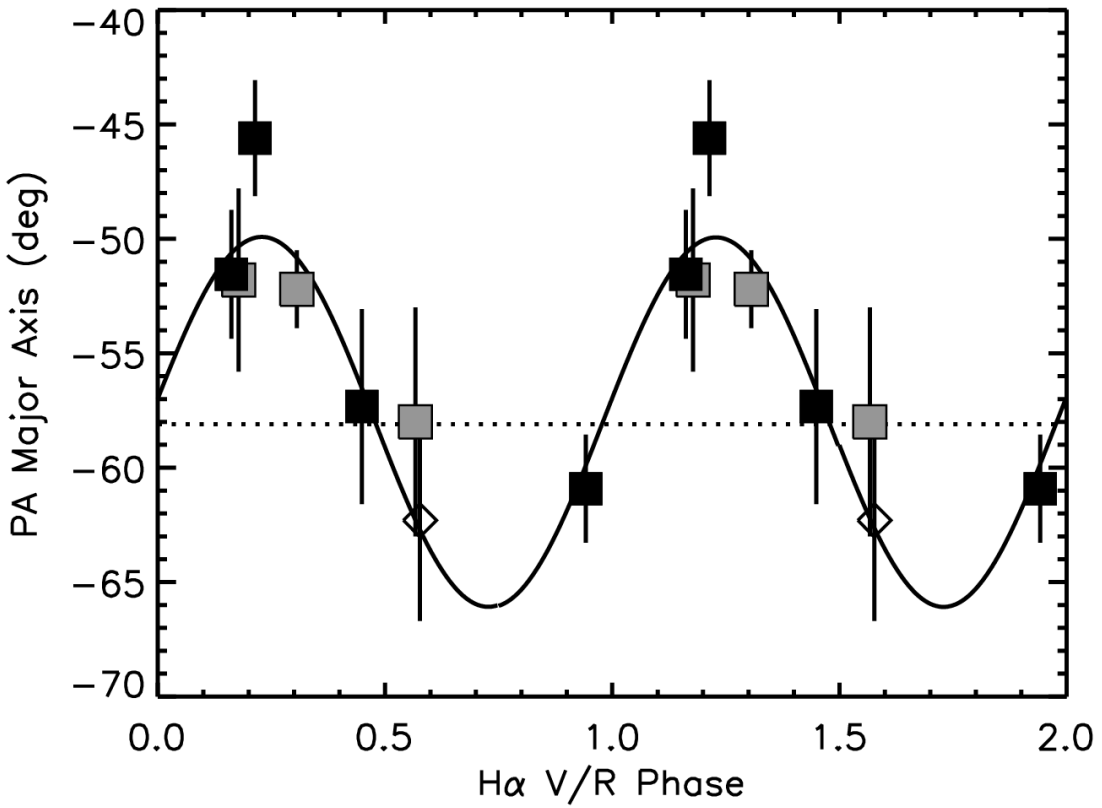
E. Pollmann 2012

V/R Variation Continued Through Time Space of MIRC Observations



Schaefer et al. 2010

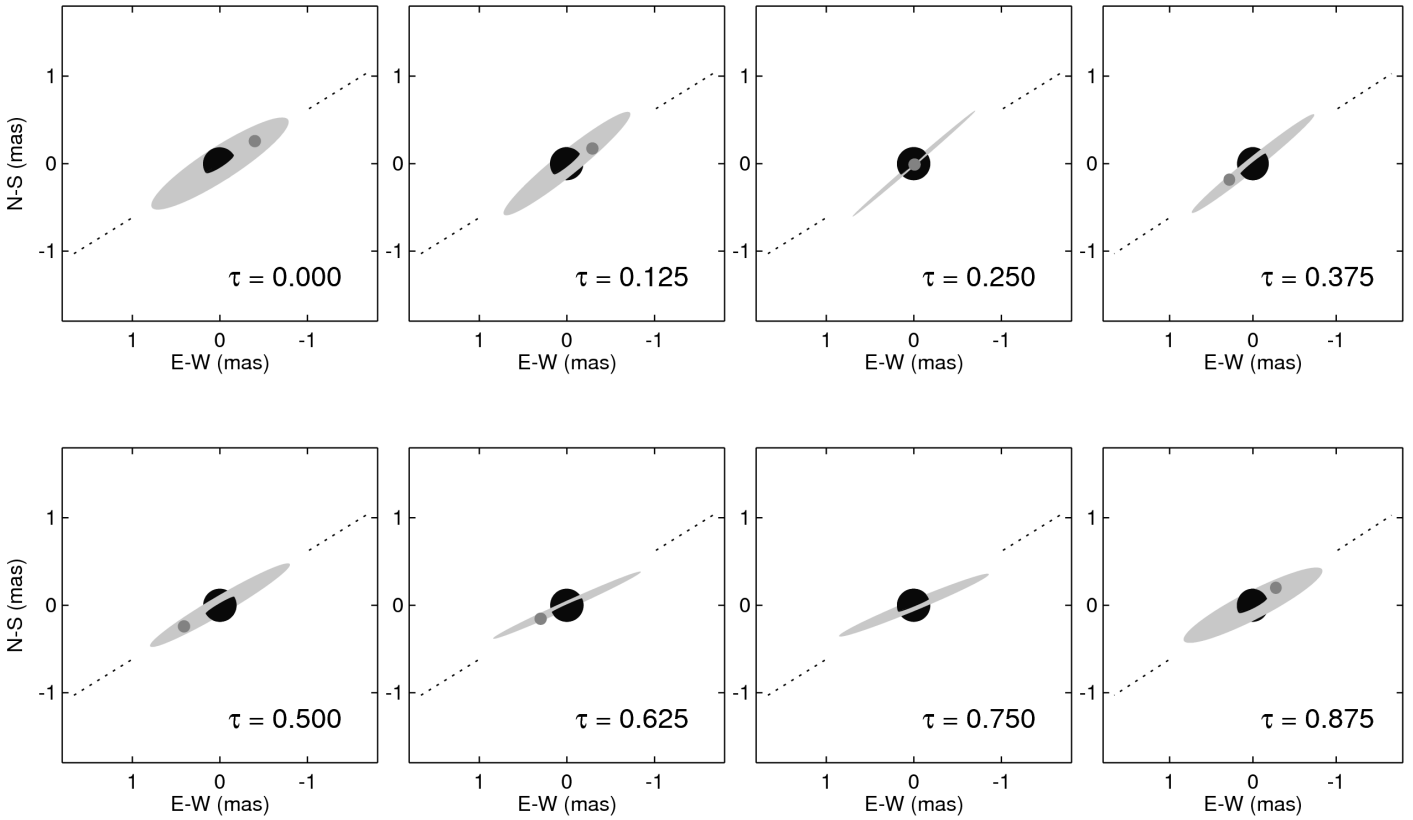
Disk Position Ange vs Hα V/R Phase



Mean position angle: -58.0° ± 1.4°
Semi-amplitude: 8.1° ± 1.7°
Maximum occurs at τ = 0.23 ± 0.03

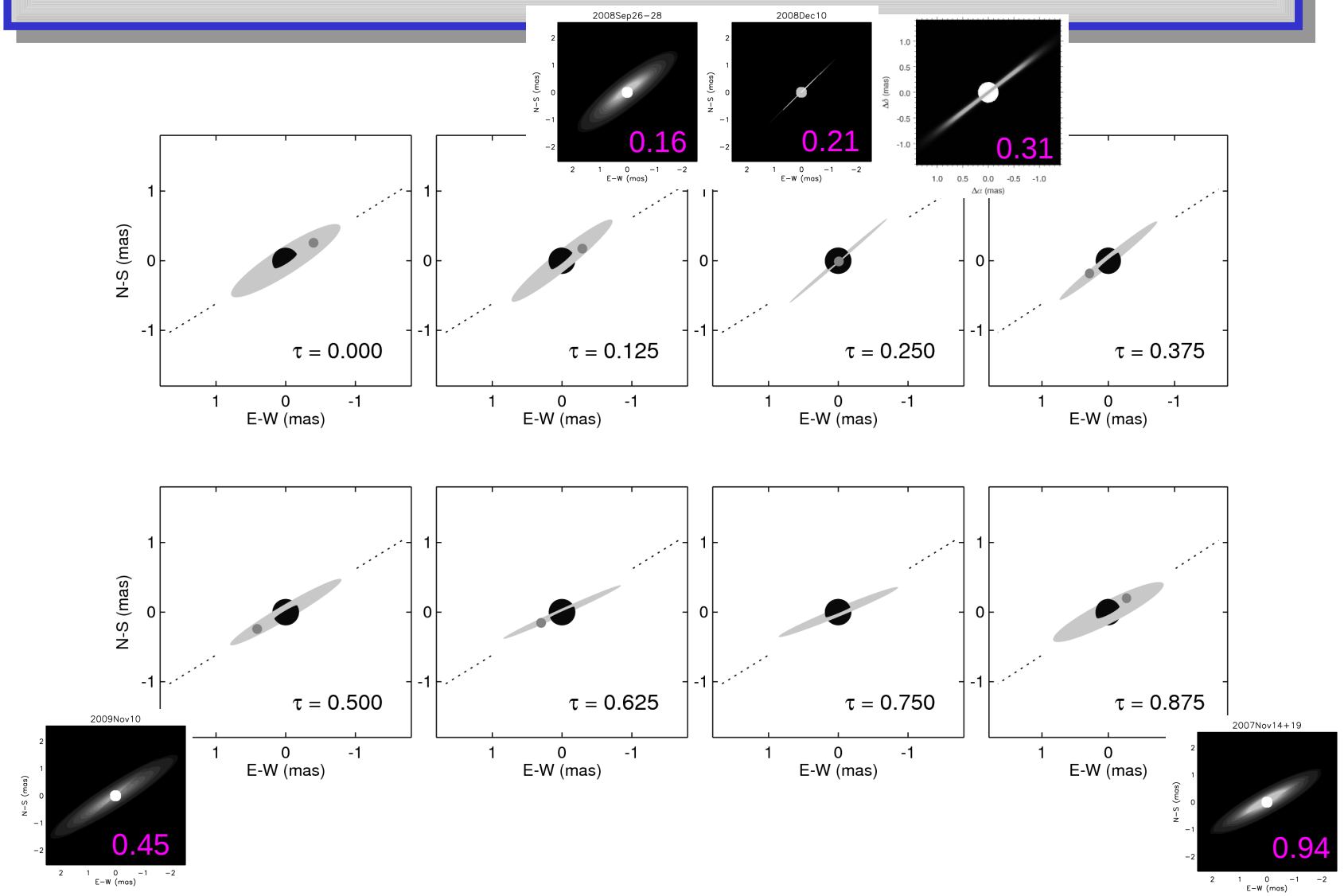
Mean position angle from linear polarization: -58.1° ± 1.2°
(McDavid 1999; Stefl et al. 2009)

Zeta Tau: Disk Precession?



Tilt of disk associated with one-armed spiral density enhancement

Zeta Tau: Disk Precession?

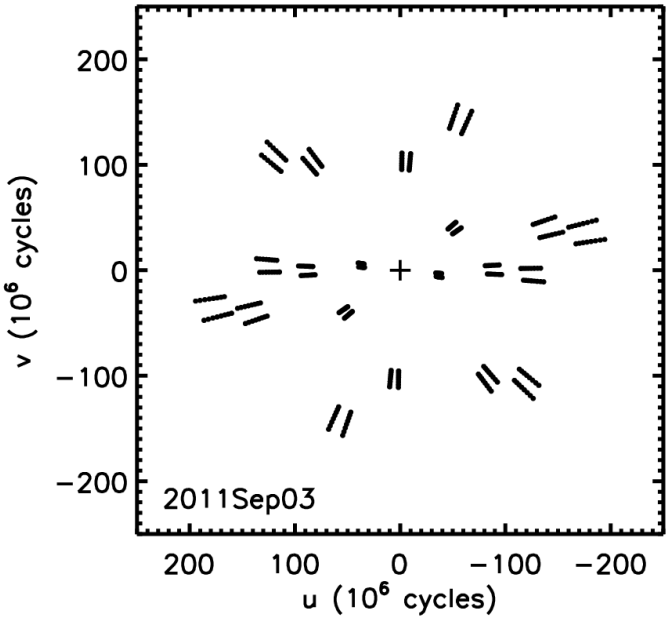


Small Scale Asymmetries:

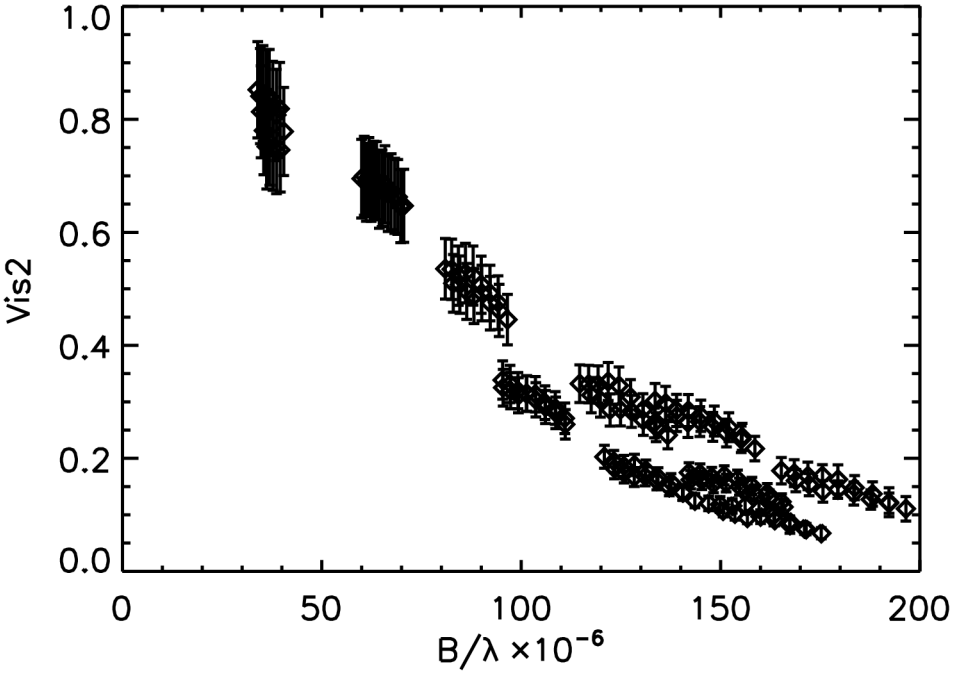
Shadowing of the Central Star

Gam Cas - Visibilities

Telescope Coverage

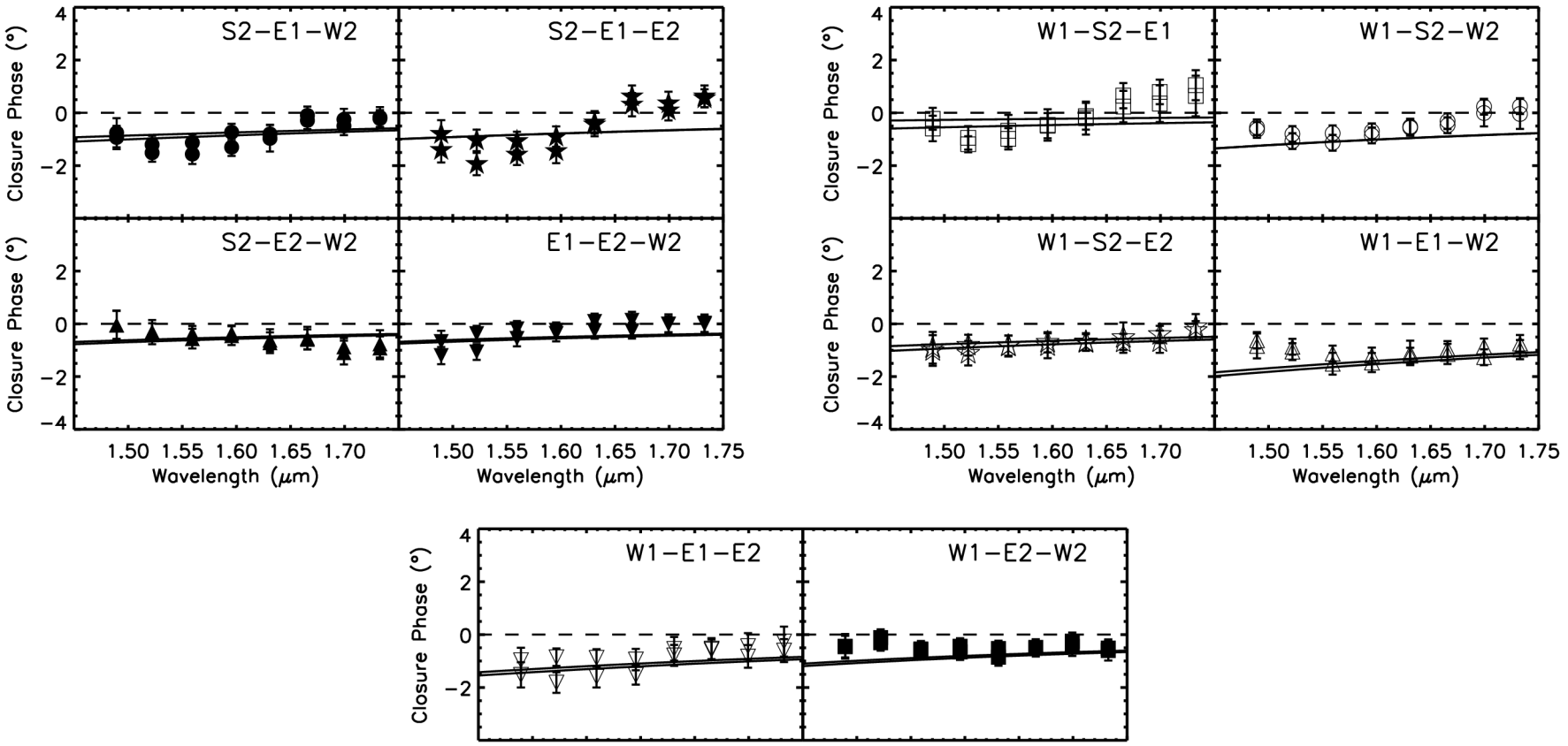


Visibilities



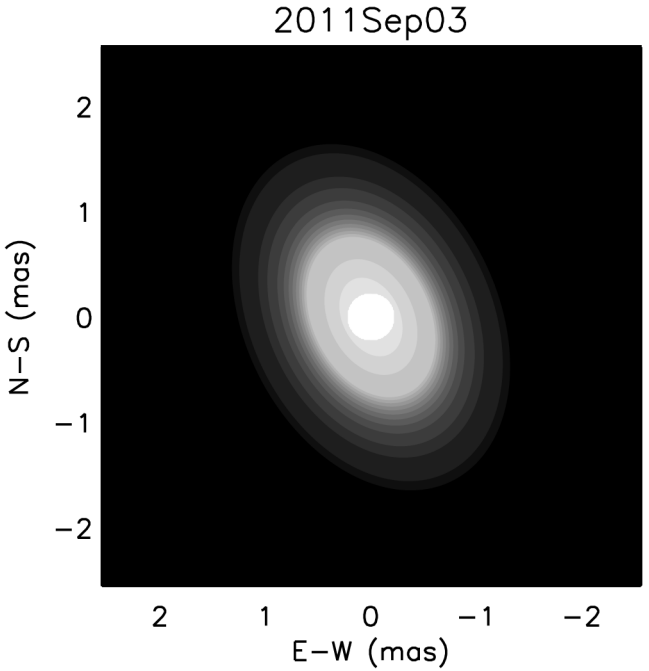
MIRC - H-band data from 2011 Sept 3

Gam Cas - Closure Phases



MIRC - H-band data from 2011 Sept 3

Geometric Model of Gam Cas

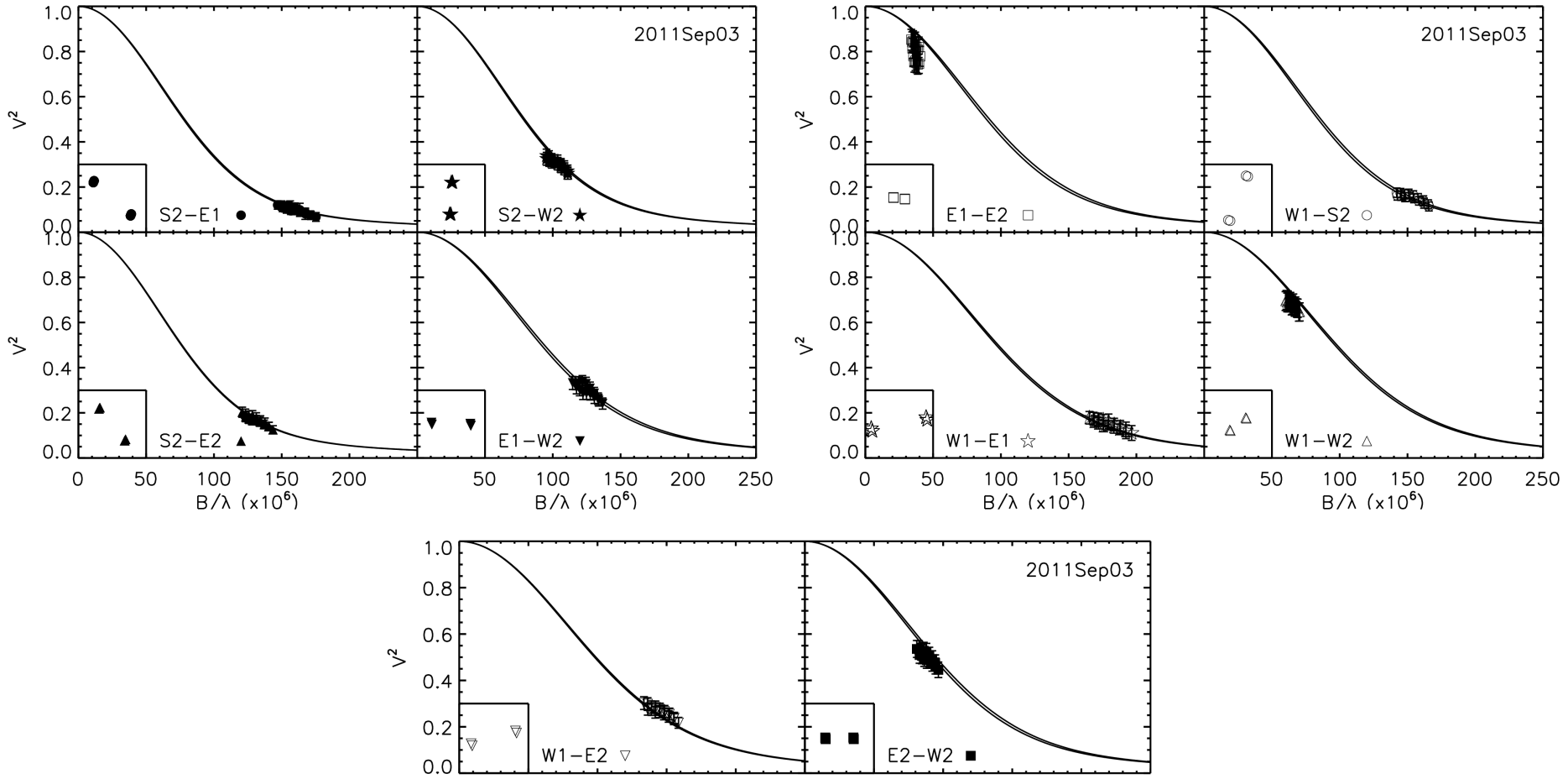


- Uniform circular disk star
- Elliptical Gaussian disk

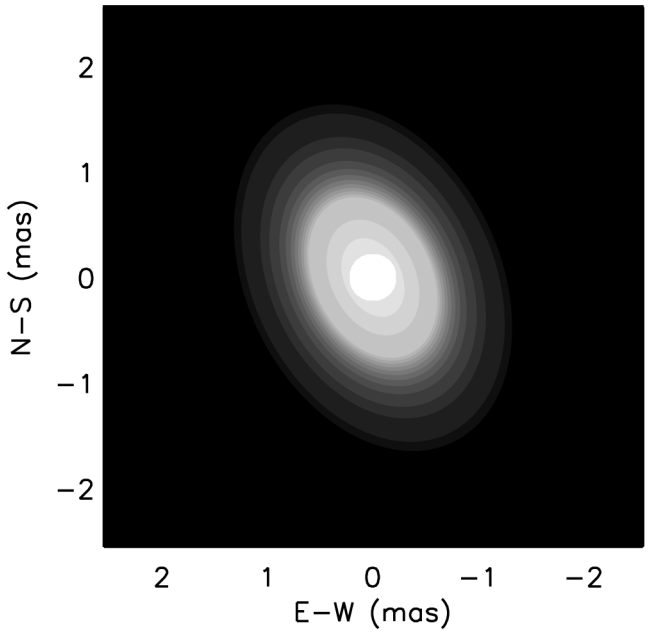
Fix stellar diameter: 0.44 mas

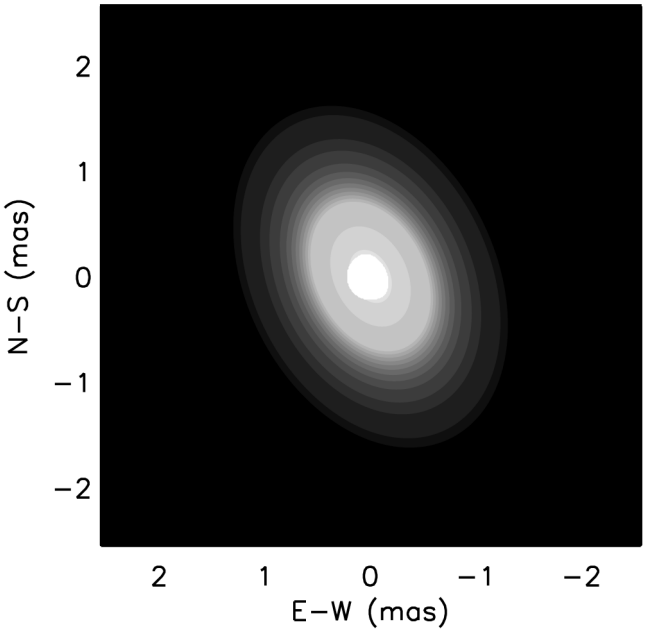
Model Parameters:
Disk major axis: 1.02 mas
Disk minor axis: 0.76 mas
Position angle: 204.3º
63% light from disk
37% light from star

Fit to Visibilities: Gam Cas



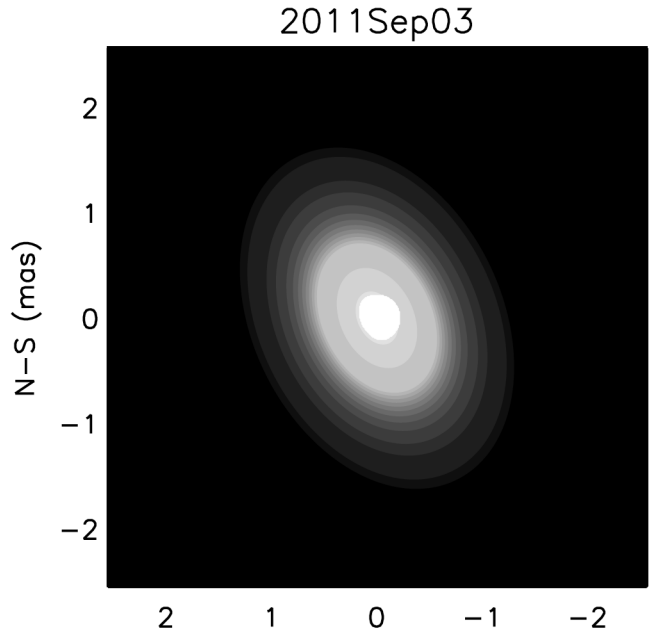
Small Scale Asymmetries in Light Distribution





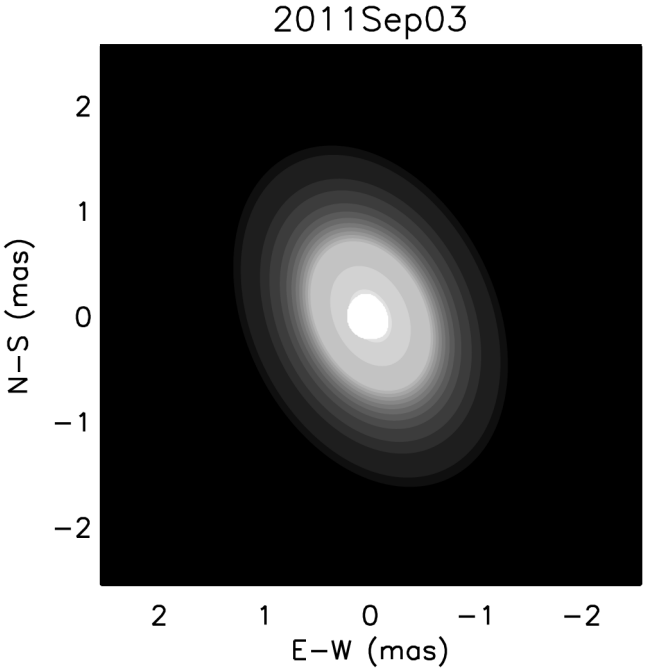
- Uniform disk star
- Elliptical Gaussian disk

- Star partially shaded by disk



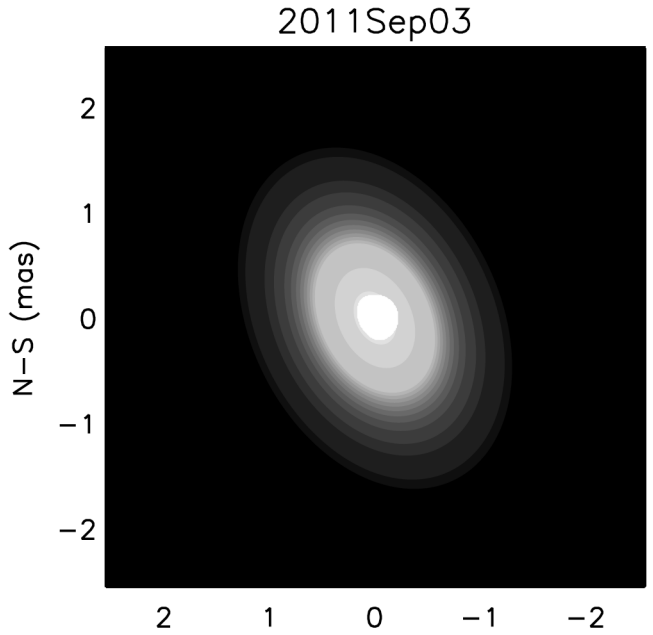
Bottom of star shaded by disk

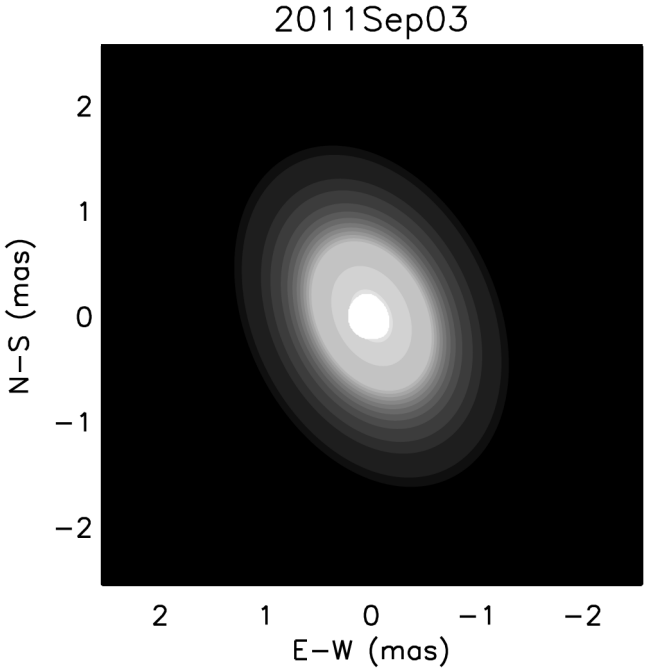
Can we measure the difference?

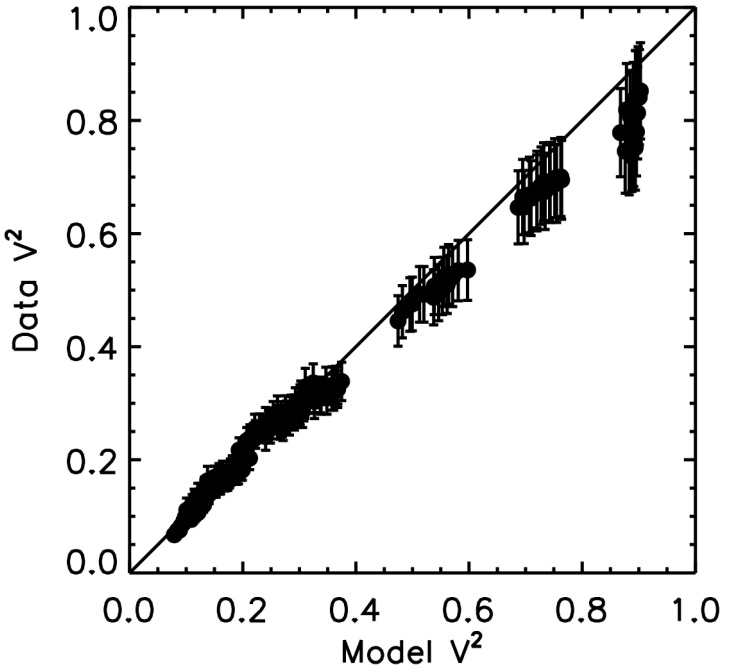


Top of star shaded by disk

Visibilities

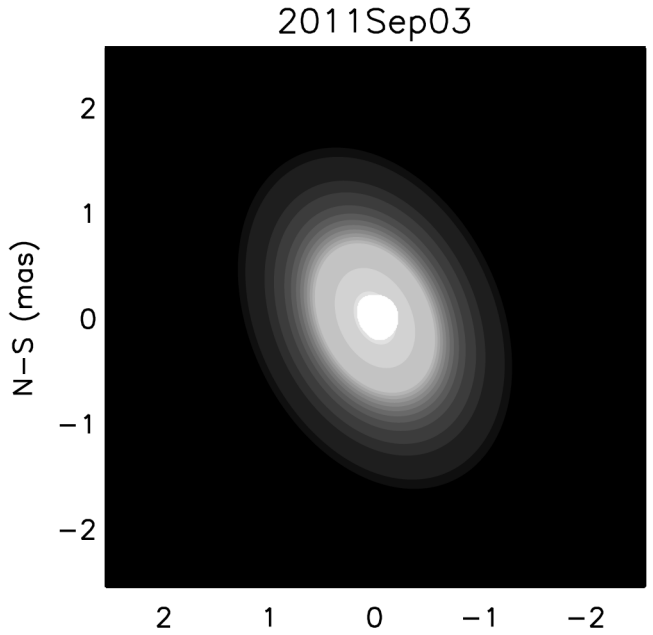


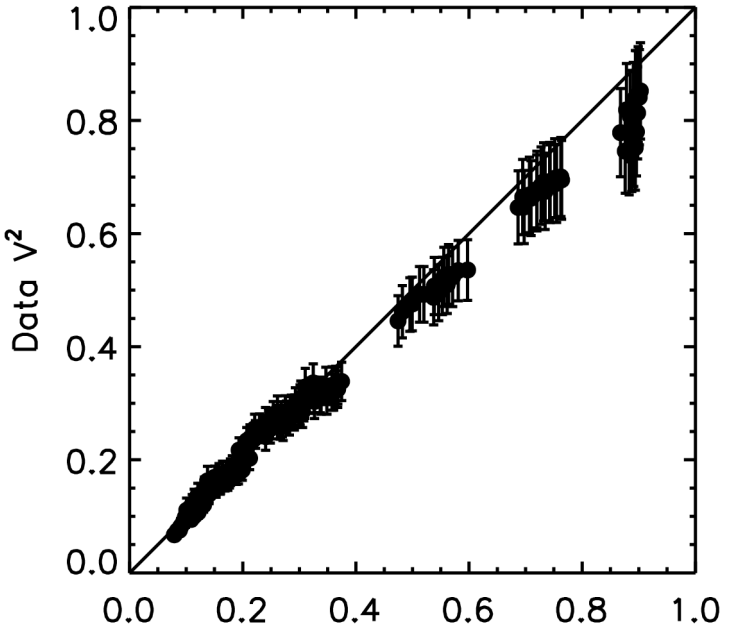




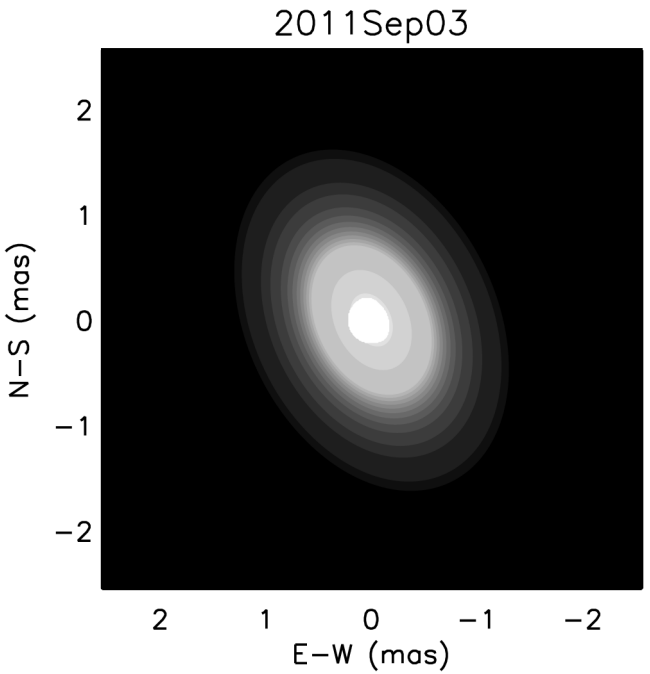
$\chi_\nu^2=0.6$

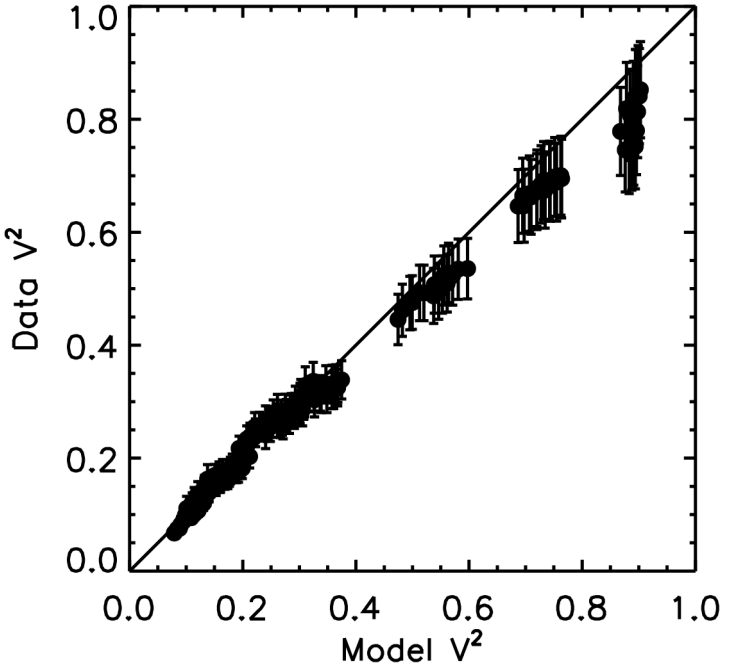
Visibilities





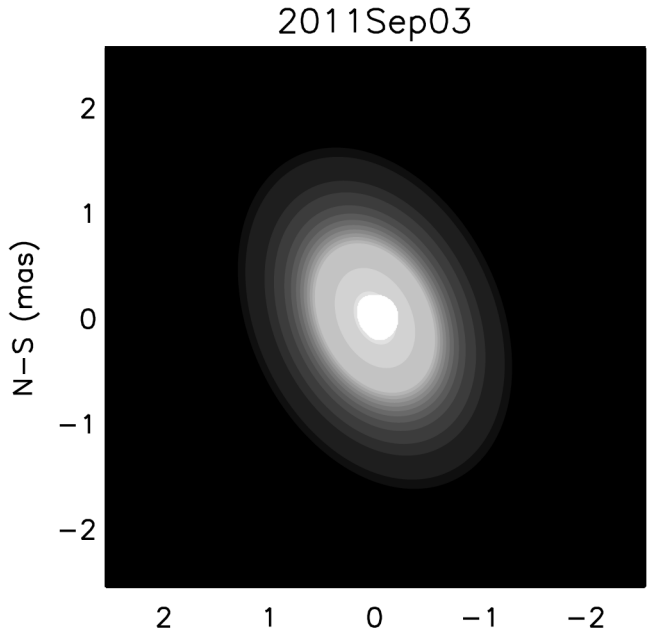
χ_ν^2=0.6

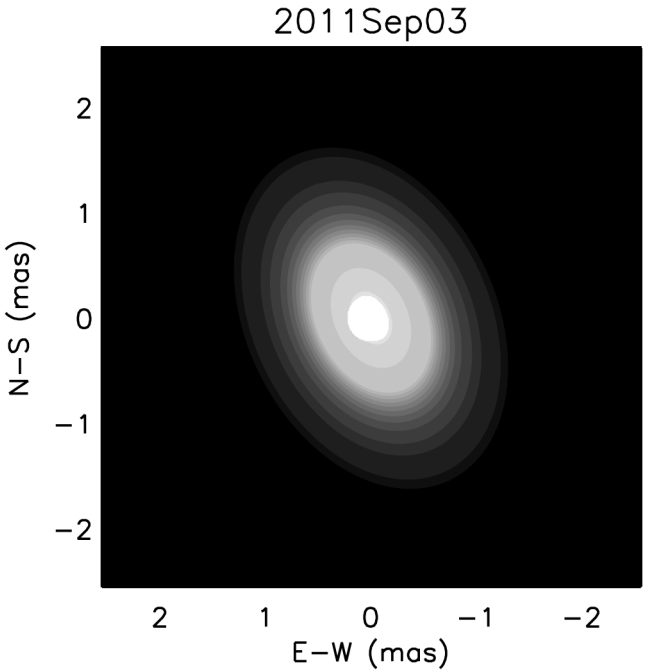


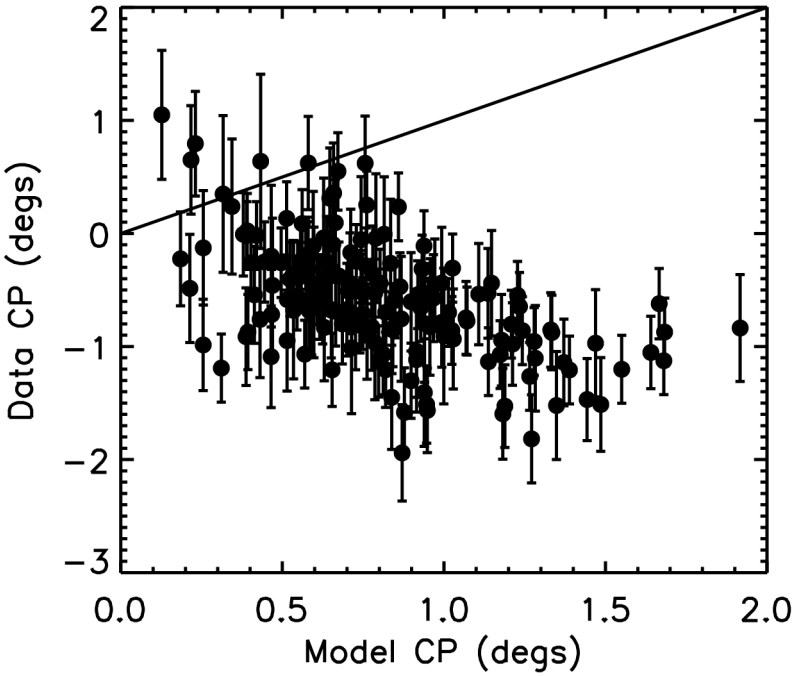


χ_ν^2=0.6

Closure Phases

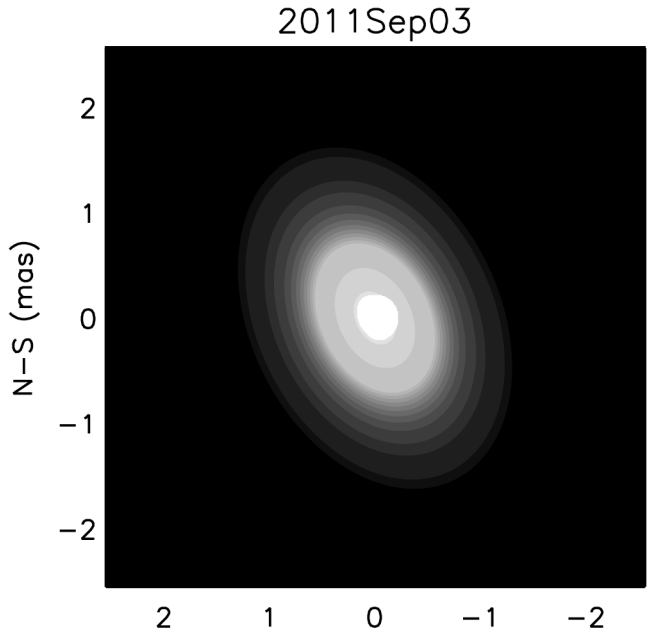


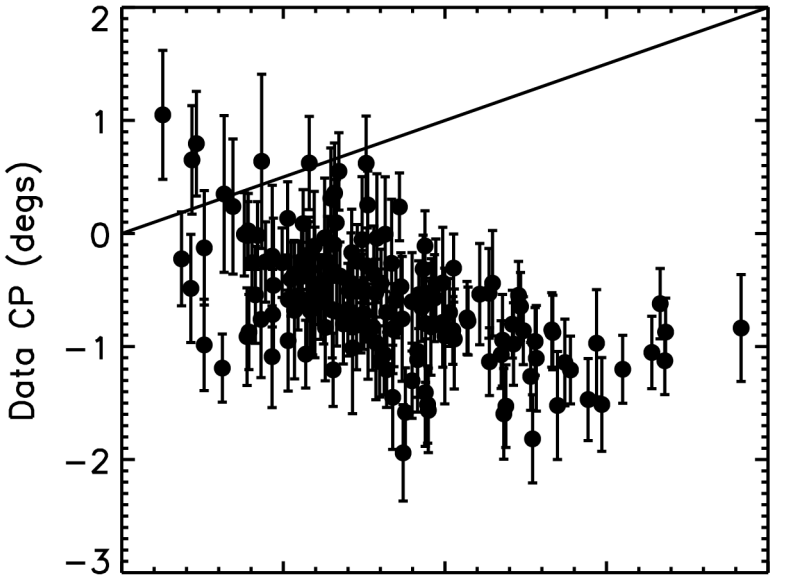




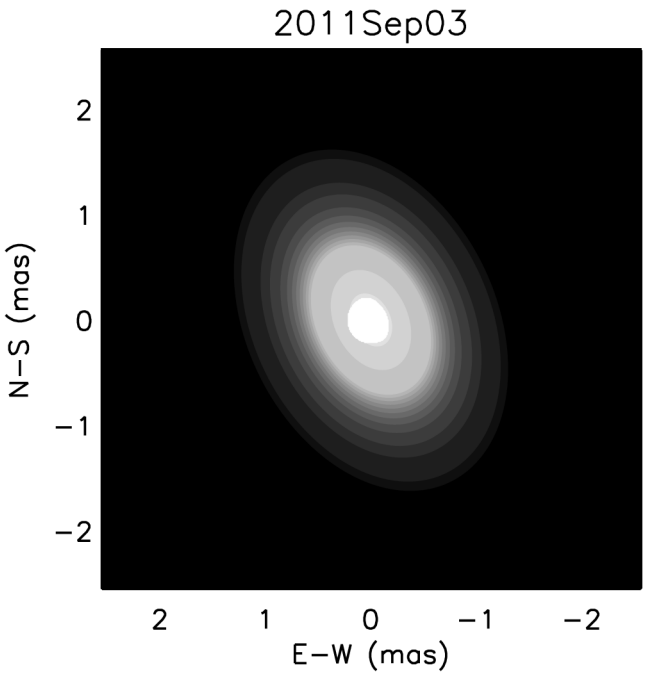
χ_ν^2=20.4

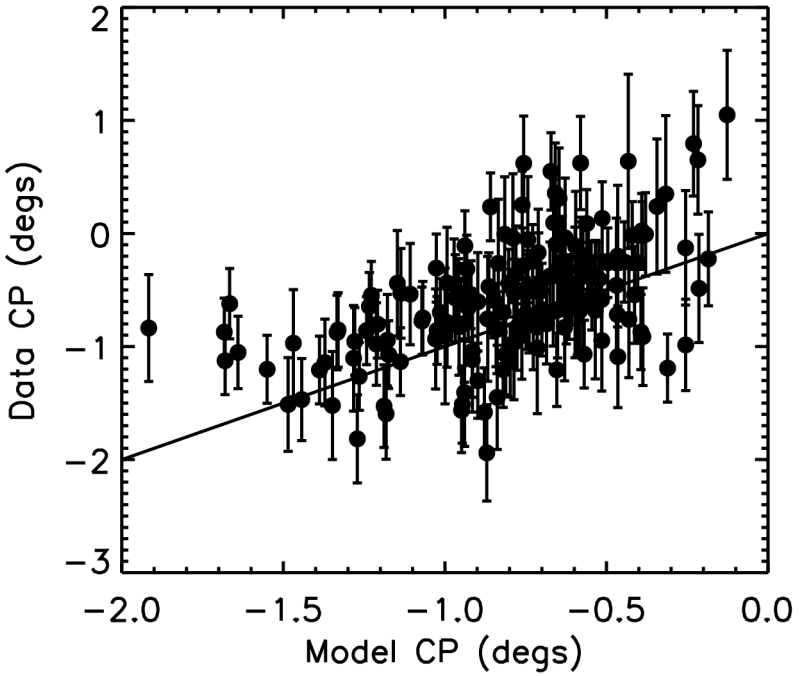
Closure Phases





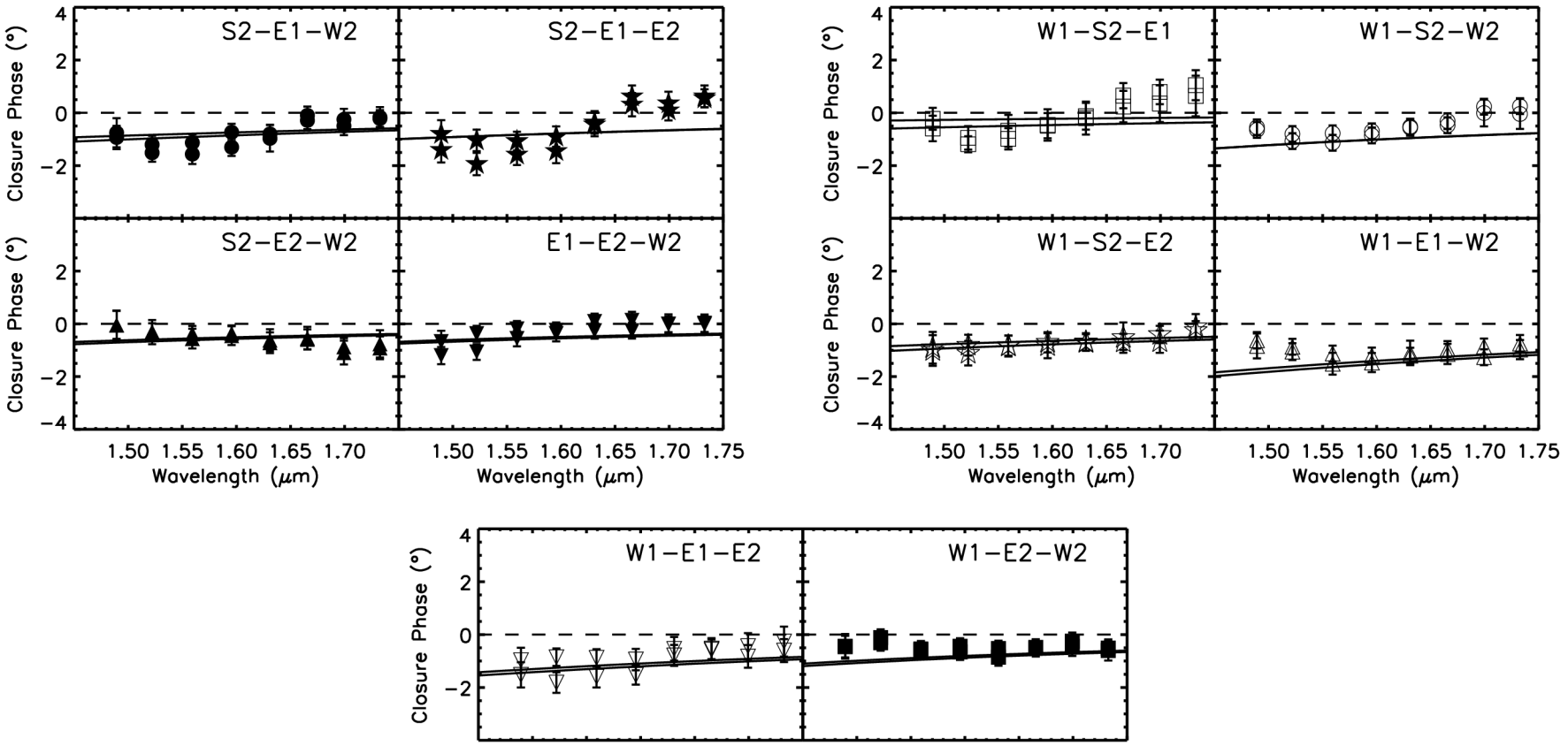
χ_ν^2=20.4





χ_ν^2=1.8

Gam Cas - Closure Phases



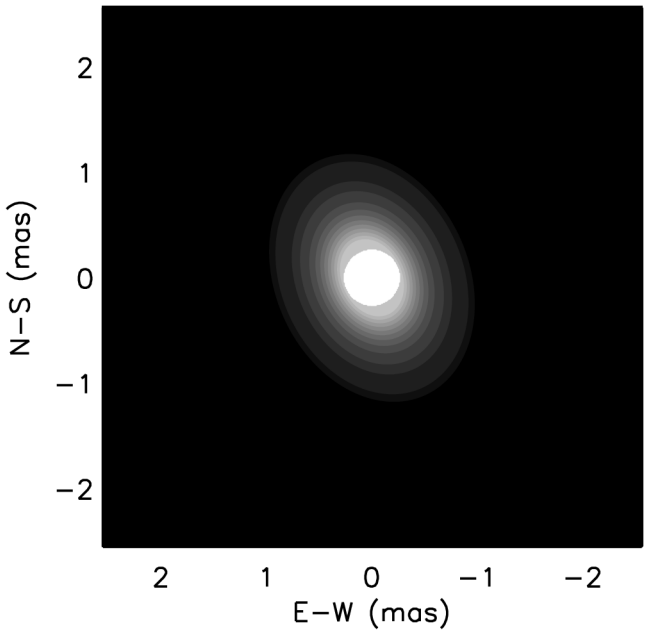
MIRC - H-band data from 2011 Sept 3

Image Reconstructions of

Be Star Disks

Image Reconstruction: Gam Cas

Geometric Model



MACIM Image

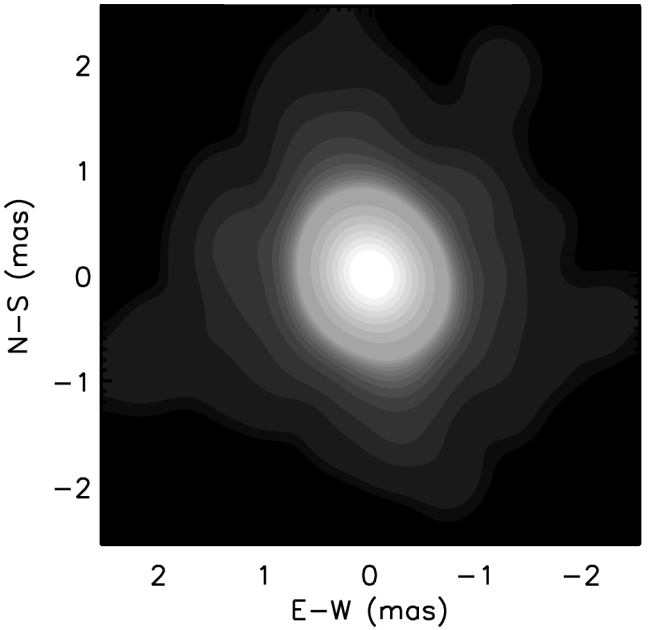
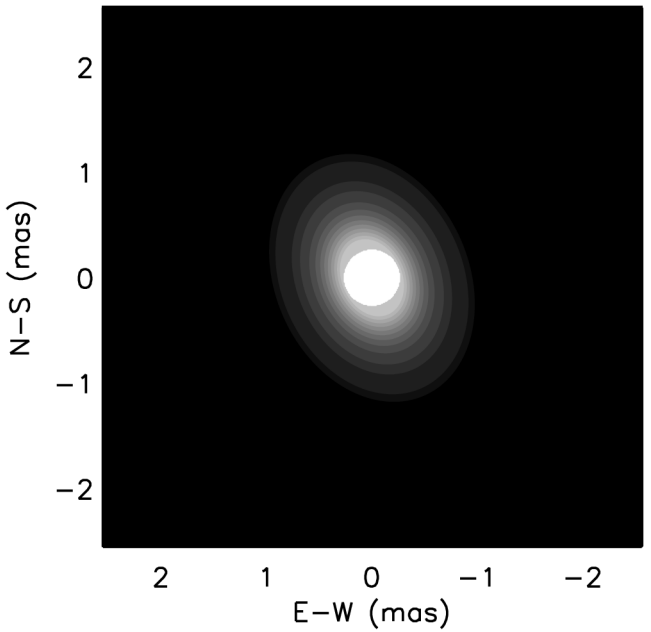
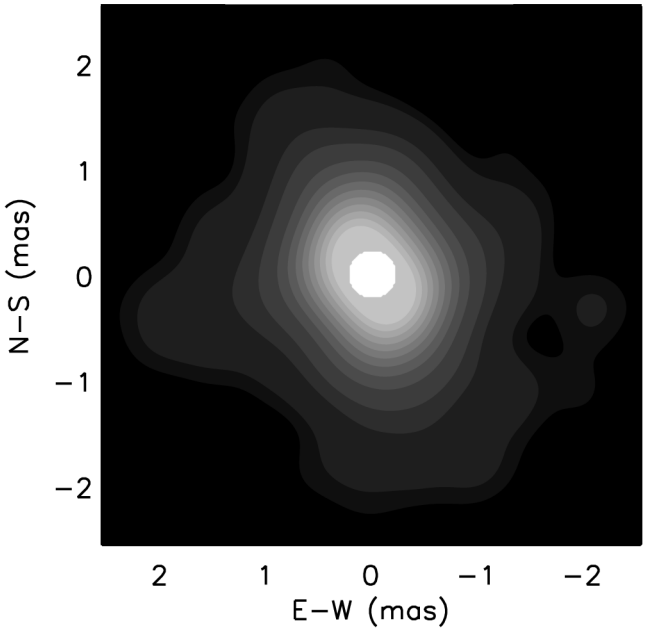


Image Reconstruction: Gam Cas

Geometric Model



MACIM Image



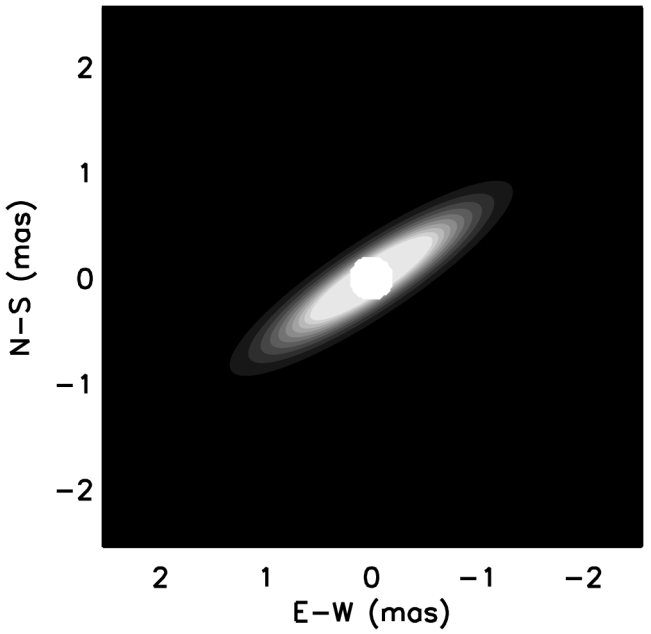
Reconstruct image while fitting for uniform disk star

MACIM + Model Fitting

- cd ~/Workshop/Software/macim
- Options for model fitting:
  - modelcode_ud.c
  - modelcode_im.c
- cp modelcode_ud.c modelcode.c
- make
- macim datafile.oifits -s 0.1 -w 50 -P p0 p1 -S s0 s1
  - p0, p1: % flux in UD disk, UD diameter
  - step sizes in flux and diameter (set to 0 to fix)

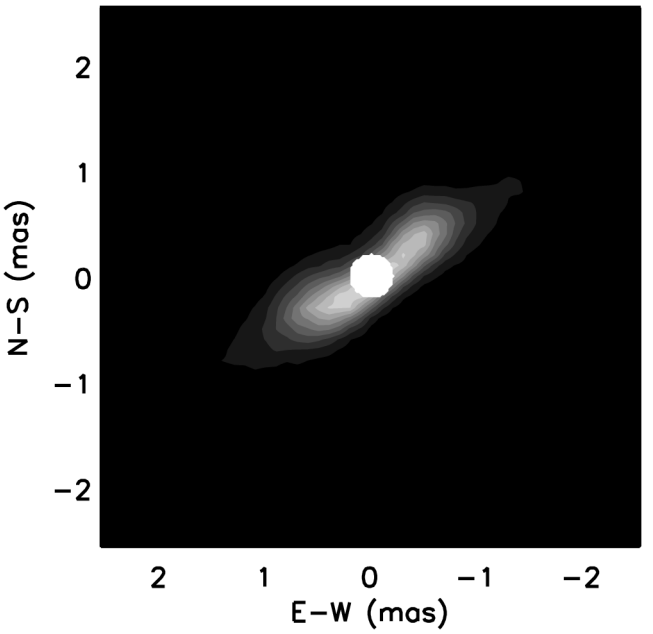
Image Reconstruction: Zeta Tau

Geometric Model



Combined data set from 2007 to 2009

MACIM Image



- Fit star as uniform disk
- Use elliptical Gaussian as prior to reconstruct disk

Challenges with Imaging Be Stars

- Goal: describe outward motion of gas and density enhancements through the disk over time
- Boundary between star and disk
  - model fitting: point source or uniform disk star
  - rapidly rotating central star?
- Overall shape and orientation of reconstructed disk is consistent with modeling
- Difficult to reconstruct small asymmetries in diffuse disk emission reliably
  - need good uv-coverage
  - include gaussian prior?
  - regularizer?

The End

Zeta Tau: Disk Precession?

- Disks of Be stars may develop a spiral density wave that precesses prograde with the disk rotation.
- Theoretical work by Ogilvie (2008) and Oktariani & Okazaki (2009) suggest that there is significant vertical motion associated with the spiral arm that might assume the form of a tilted disk. If so, perhaps this tilt precesses with the one-armed oscillation mode.
- Martin et al. (2011) - transitions between shell and Be stars may suggest a warped, precessing disk. Torque from binary companion may cause oscillations in disk mass and inclination.
- Previous evidence for precession in Be star disks
  - Hummel 1998 (Gam Cas, 59 Cyg) - emission line widths
  - Hirata 2007 (Pleione) - intrinsic polarization, Hα emission

What About the Polarization angle?

- Intrinsic polarization angle has remained remarkably stable over the last decade (McDavid 1999; Stefl et al. 2009)
- No evidence of changes as large as those seen in the interferometric data

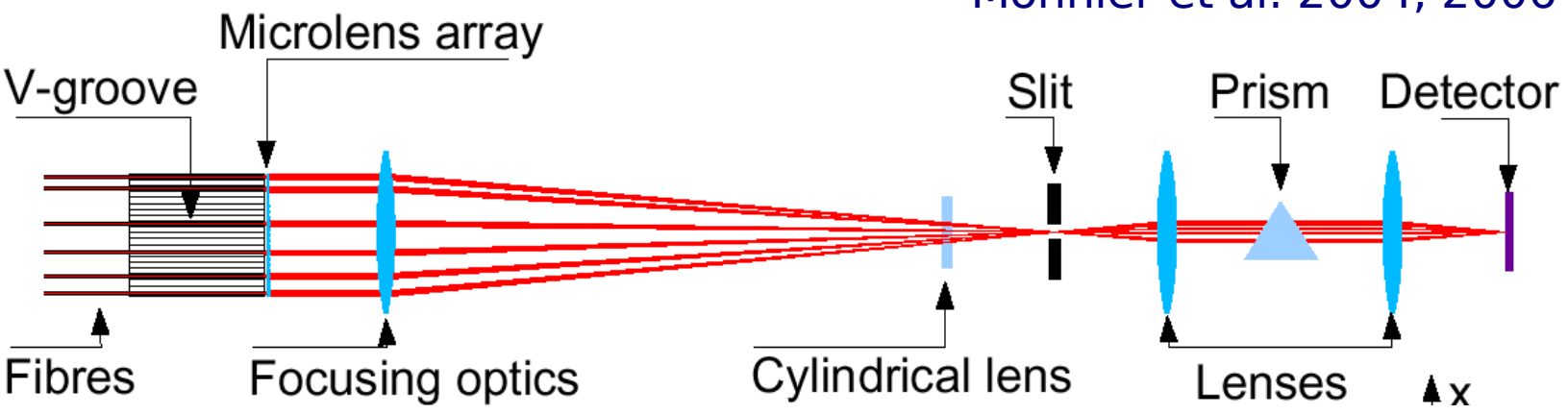
Is There a Resolution?

- Polarization probes scattering radiation from the innermost part of the disk where it is probably co-aligned with stellar equator (source of ejected material)
- Tilt associated with larger scale structure of spiral oscillation in disk – measured by interferometry

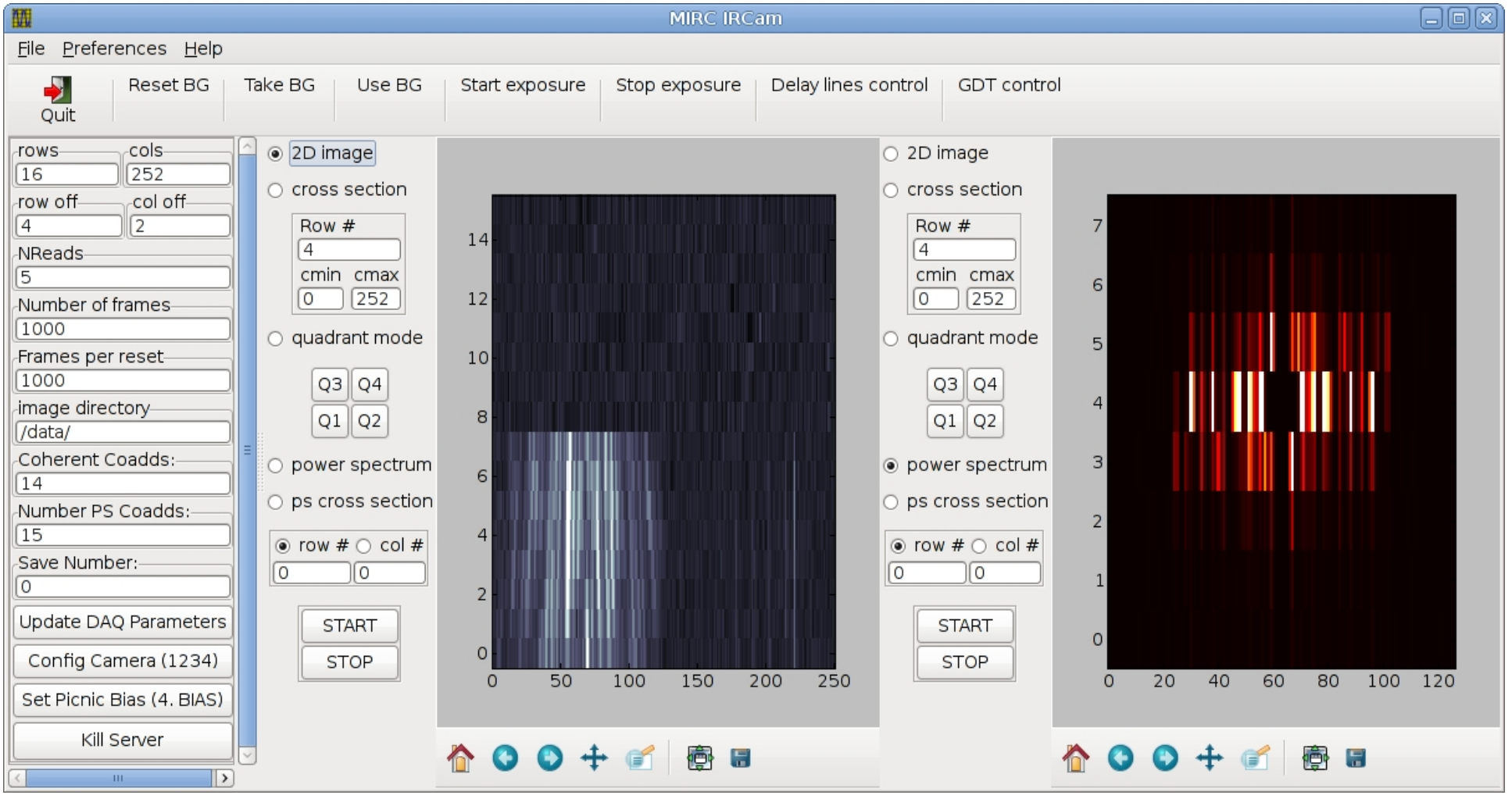
Michigan Infrared Combiner: MIRC

- Designed for imaging
  - Combines light from 6 telescopes simultaneously
  - 15 visibilities and 20 closure phases
- 8 spectral channels across the H- band (λ = 1.6 μm)

Monnier et al. 2004, 2006

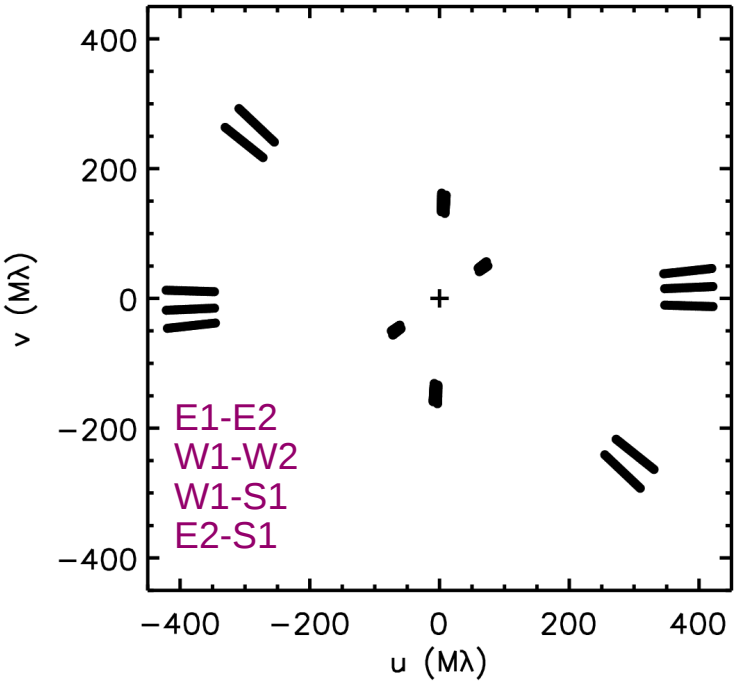


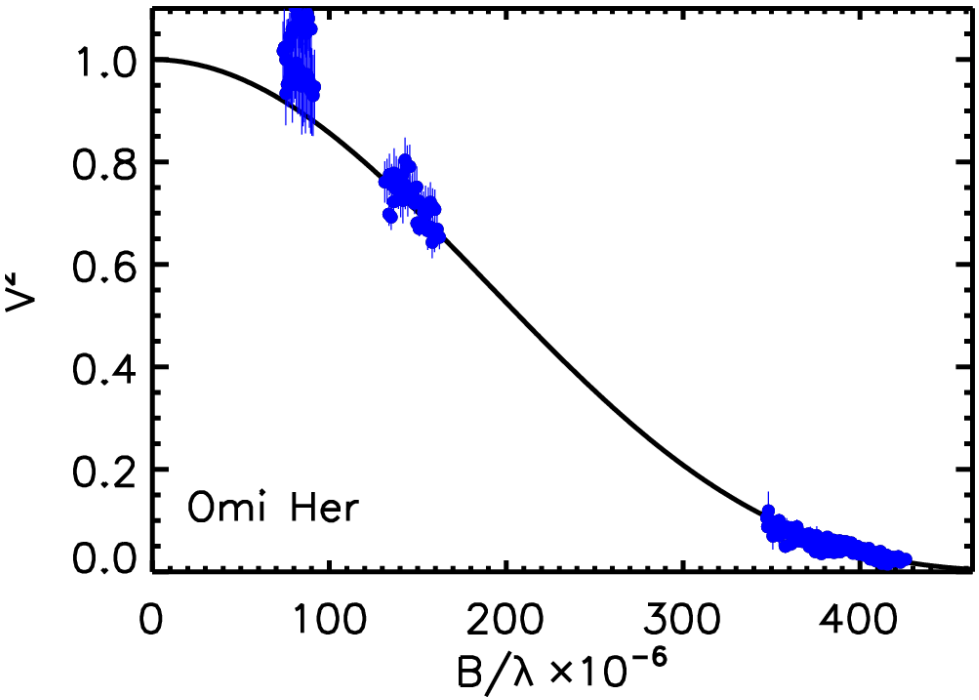
MIRC


MIRC IRCam
File Preferences Help
Quit
Reset BG
Take BG
Use BG
Start exposure
Stop exposure
Delay lines control
GDT control
rows 16
cols 252
row off 4
col off 2
NReads 5
Number of frames 1000
Frames per reset 1000
image directory /data/
Coherent Coadds: 14
Number PS Coadds: 15
Save Number: 0
Update DAQ Parameters
Config Camera (1234)
Set Picnic Bias (4, BIAS)
Kill Server
2D image
cross section
Row # 4
cmin 0 cmax 252
quadrant mode
Q3 Q4
Q1 Q2
power spectrum
ps cross section
row # col # 0 0
START
STOP
2D image
cross section
Row # 4
cmin 0 cmax 252
quadrant mode
Q3 Q4
Q1 Q2
power spectrum
ps cross section
row # col # 0 0
START
STOP

PAVO - Omi Her

2011 Aug 10-12



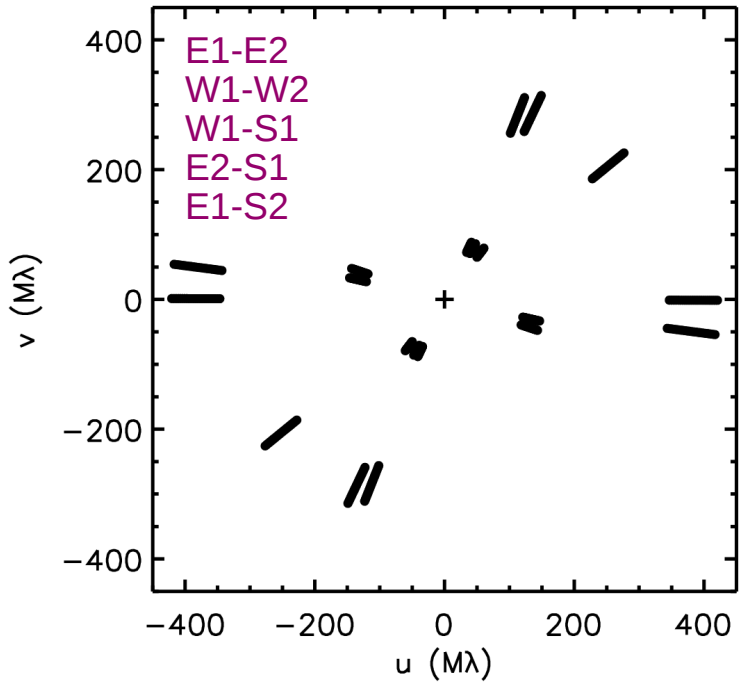


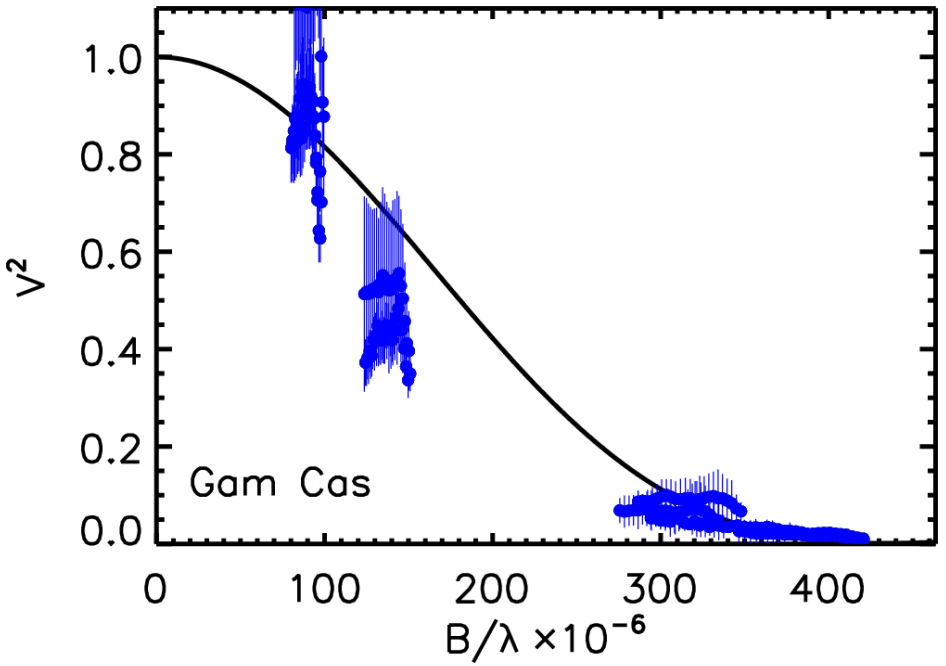
Stellar Diameter = 0.527 mas

Agrees with SED diameter of 0.52 mas (Y. Touhami)

PAVO - Gam Cas

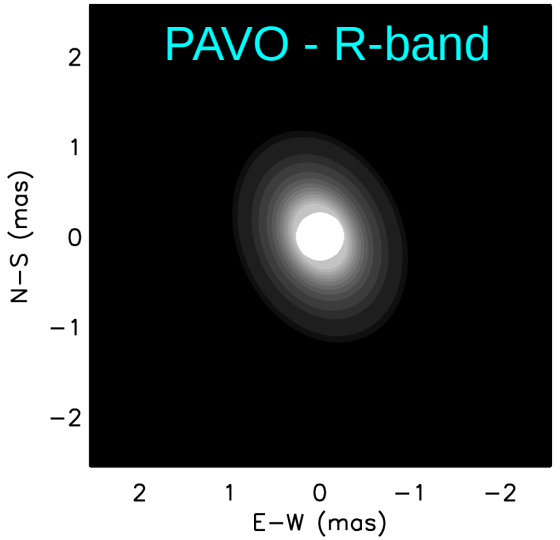
2011 Aug 10-12

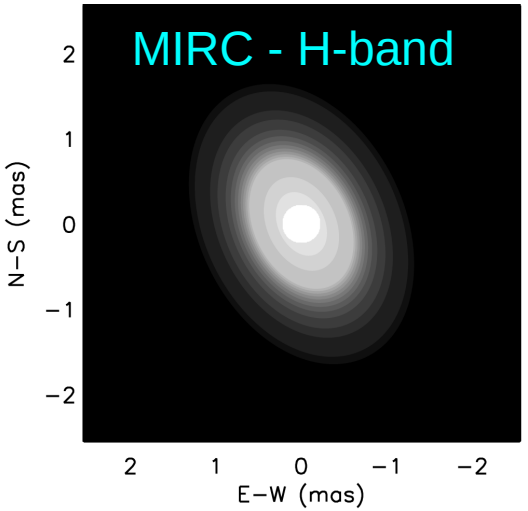


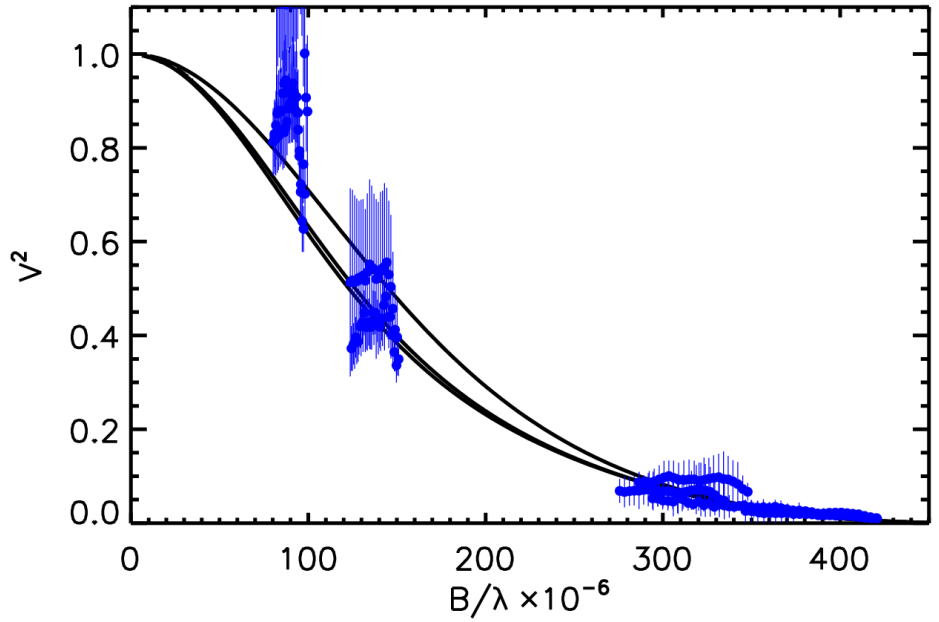


Disk Contribution?

PAVO - Gam Cas

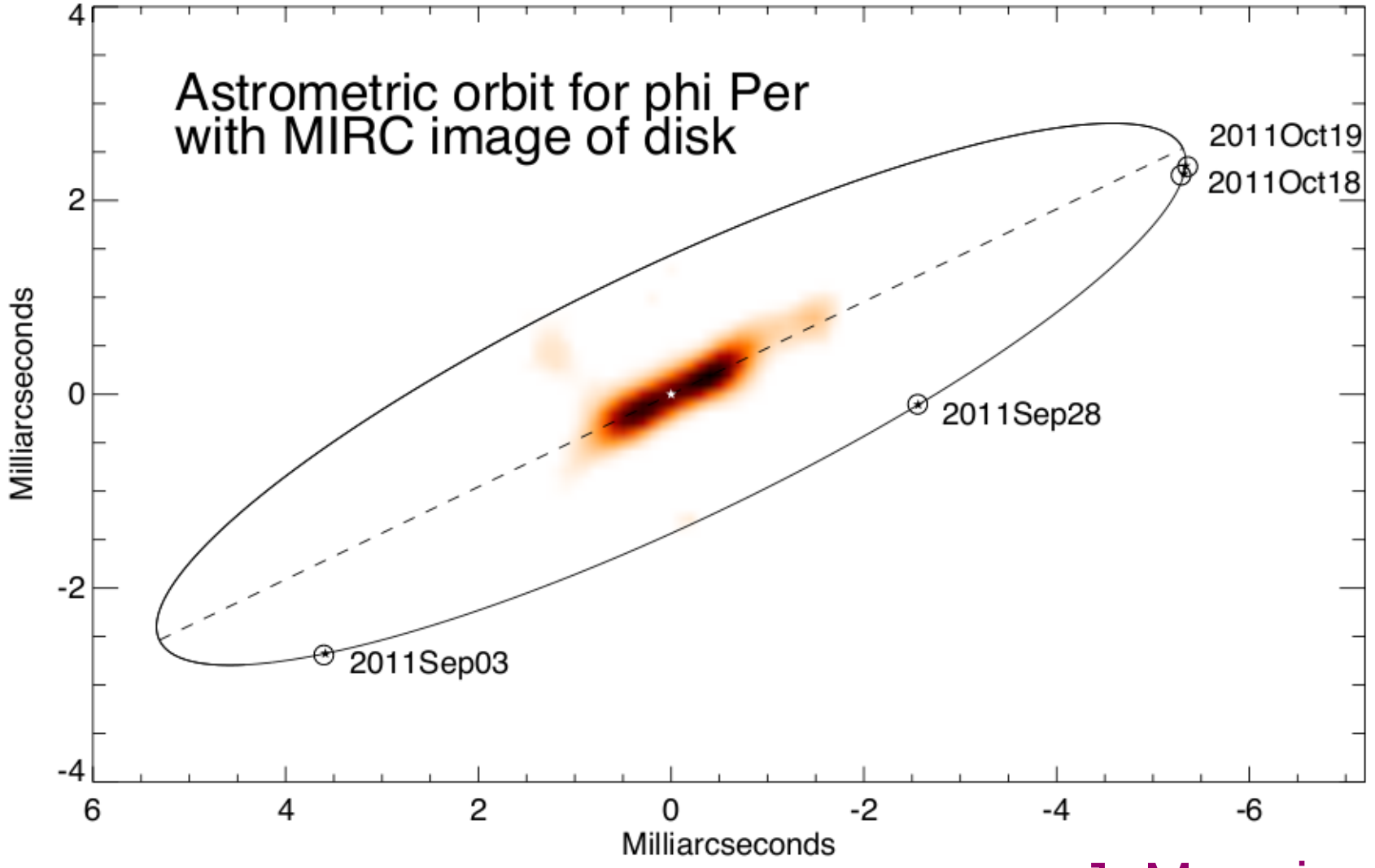






- Fix position angle and axis ratio based on infrared models
- Star diameter: 0.52 mas
- Disk FWHM: 0.84 mas
- 37% of light from disk
- Degeneracy between star/disk size and flux

Gam Cas: Binary Companion



J. Monnier