Modeling the Disk of Zeta Tau Using MIRC

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Outline

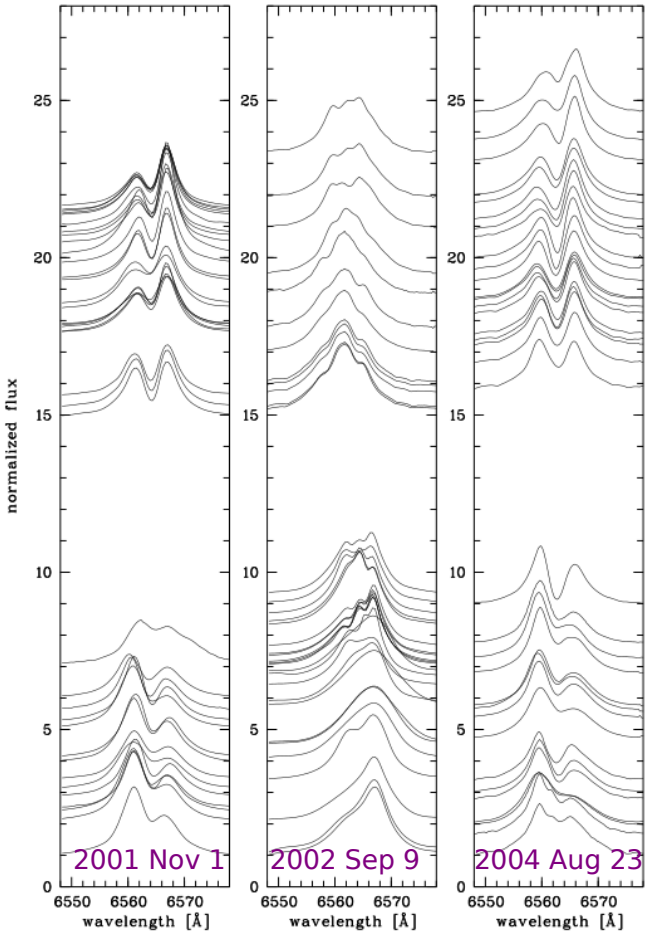
- Be star properties and variability
- Previous interferometric observations of Zeta Tau
- Asymmetries measured in Be star disks
- MIRC observations of Zeta Tau

Be Star Properties

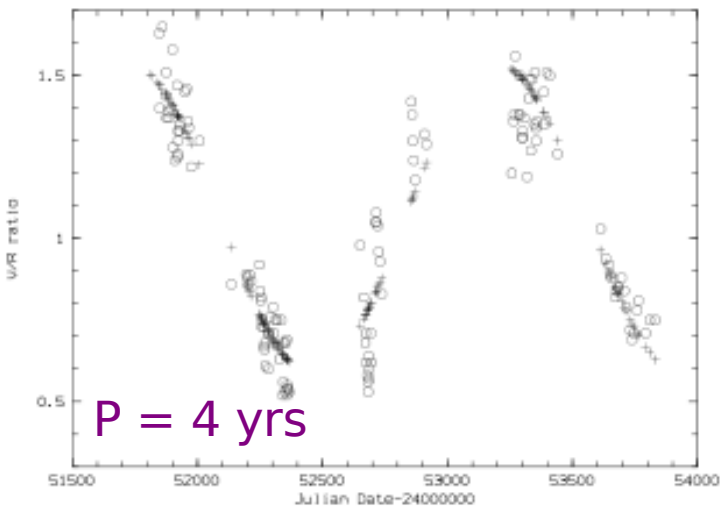
- Rapidly rotating B-type stars that eject gas into a circumstellar disk
- Evidence for disks observed in Hα emission lines, IR excess flux, linear polarization (e.g. Porter & Rivinius 2003)
- Variable on timescales of days to decades

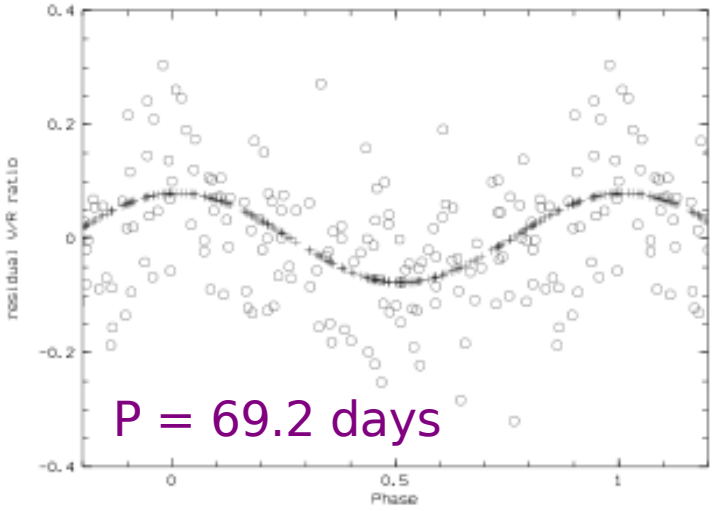
Hα Profile Variability

- Pollmann & Rivinius 2008
- Hα profiles measured from late 2000 to early 2006 for Zeta Tau
- Vertical offset proportional to time
- Variable V/R ratio
- Complicated triple-peak profiles too



V/R Ratio Variability



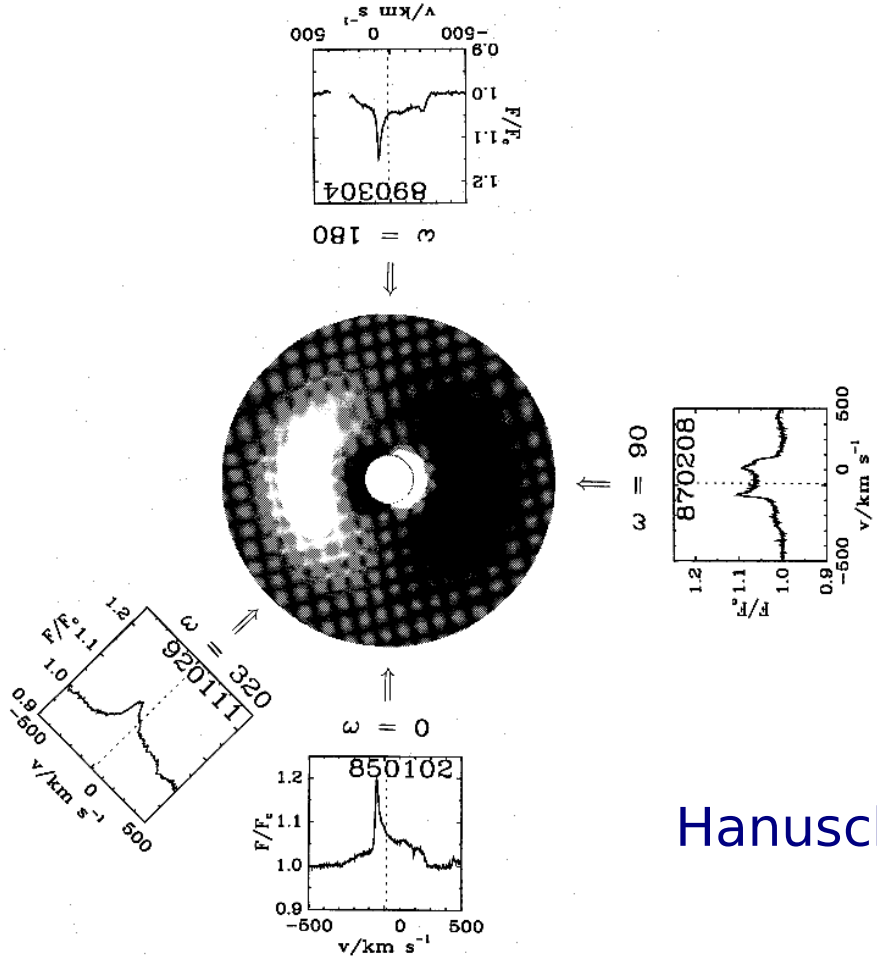


Pollmann & Rivinius 2008, Zeta Tau

One-armed Oscillations in Be Star Disks

- Elliptical ring/disk in Keplerian rotation (Struve 1931)
  - to explain broad double-peaked emission line profiles
- Perturbations in disk create spiral density waves
- One-armed low frequency density waves (m=1) in geometrically thin, nearly Keplerian disk
  - Kato 1983, Okazaki 1991
  - Explains long-term V/R variations
  - Reproduces timescales of years to decades

One-armed Oscillations



Hanuschik et al. 1995

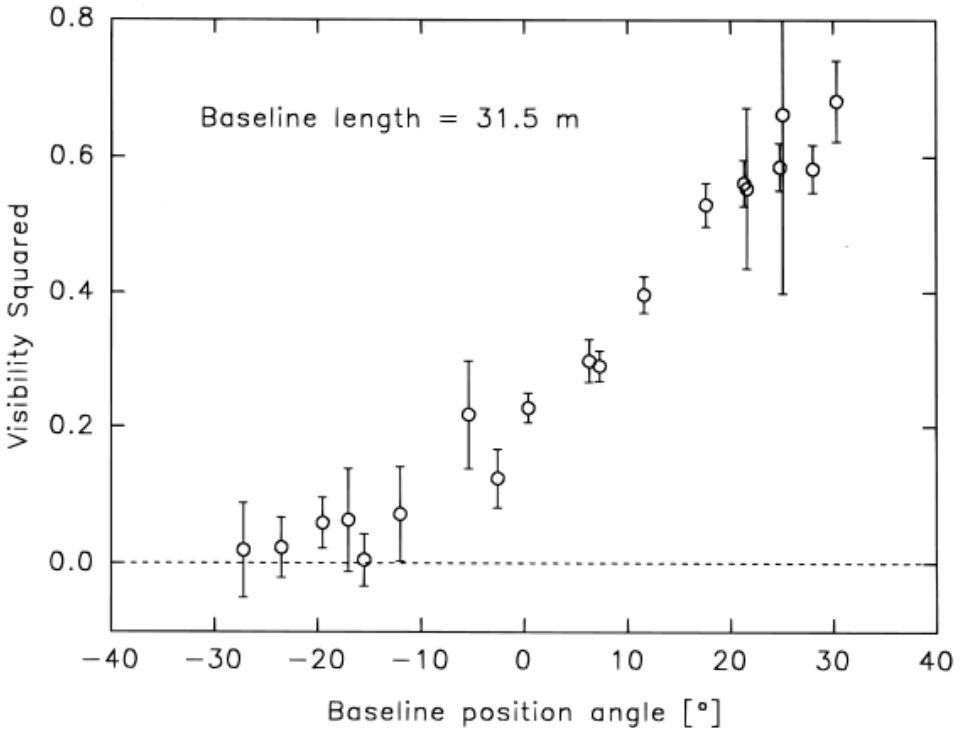
Fig. 16. Distorted part of the density field, σ_1 (as taken from Okazaki 1991), and observed Fe II λ5317 profiles of δ Cen, plotted at approximate angles $\omega = 0°, 90°, 180°, 320°$ corresponding to the mutual orientation of the observer and the precessing nodal line of σ_1. Particles in the disk rotate counterclockwise. Dark areas denote $\sigma_1 < 0$, bright ones $\sigma_1 > 0$

Properties of Zeta Tau

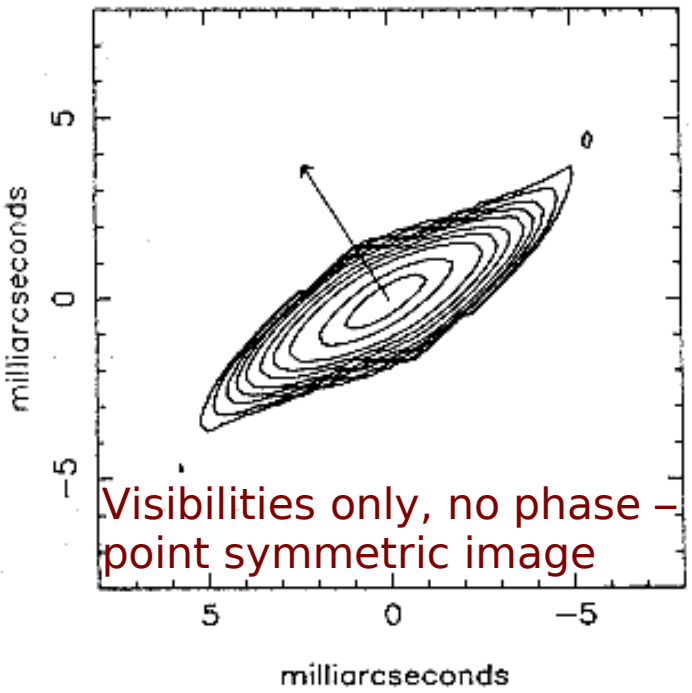
- One of the brightest Be stars (V=3.0)
- B2 IIIe
- Parallax 7.82 mas (128 pc)
- Vsini = 320 km/s
- Single-lined spectroscopic binary with a period of 132 days
  - Companion expected to be ~ 5 mag fainter

Elliptical Disk of Zeta Tau (non-circular)

- Quirrenbach et al. 1997
- Mark III Interferometer
- 4-32 m baselines, Hα
- Fit elliptical Gaussian
- Semi-major axis of 4.53 mas

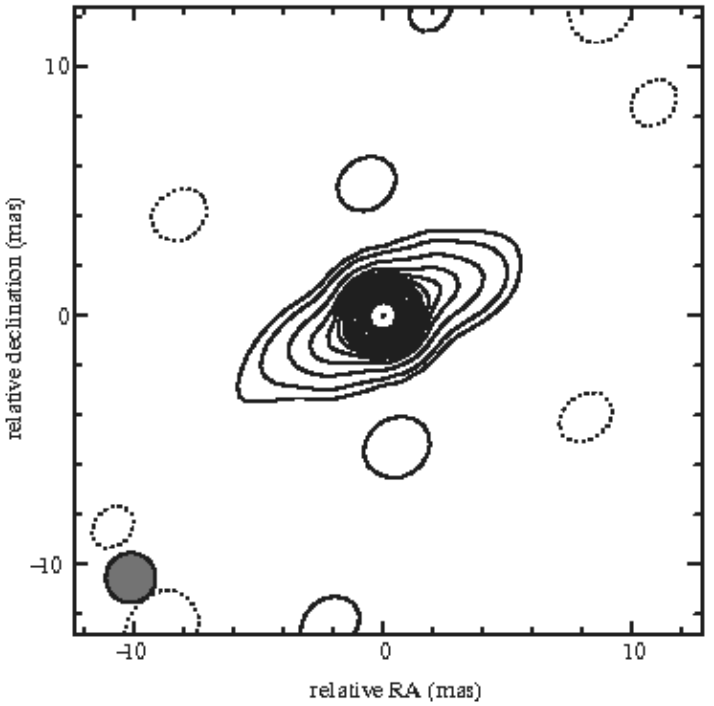


First Image Reconstructions of Zeta Tau



Visibilities only, no phase – point symmetric image

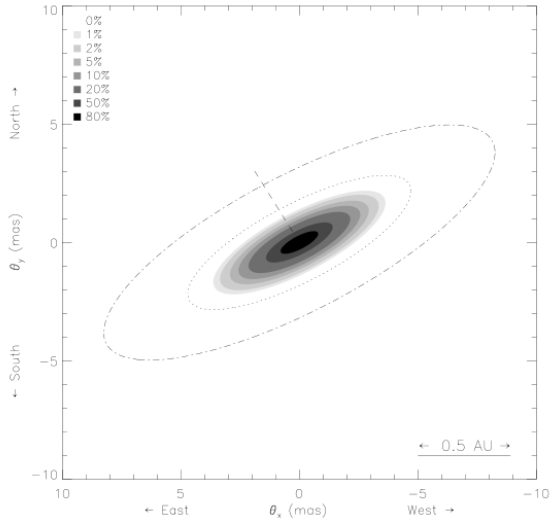
Quirrenbach et al. 1994
Mark III: 3-32 m baselines
Maximum entropy map

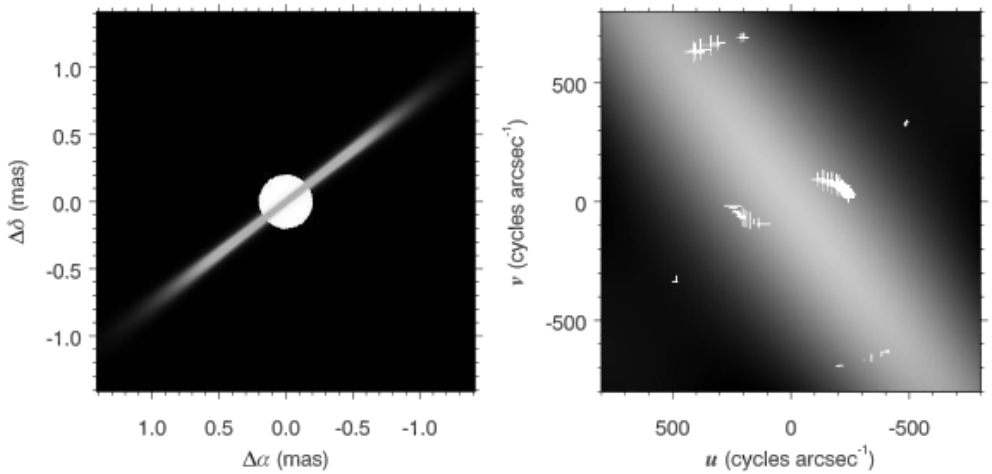


Baldwin & Haniff 2002
COAST – 50 m baseline

More Interferometric Observations of Zeta Tau Tau Disk

- Tycner et al. 2004
  - NPOI
- Elliptical Gaussian
  - 3.14 mas at Hα

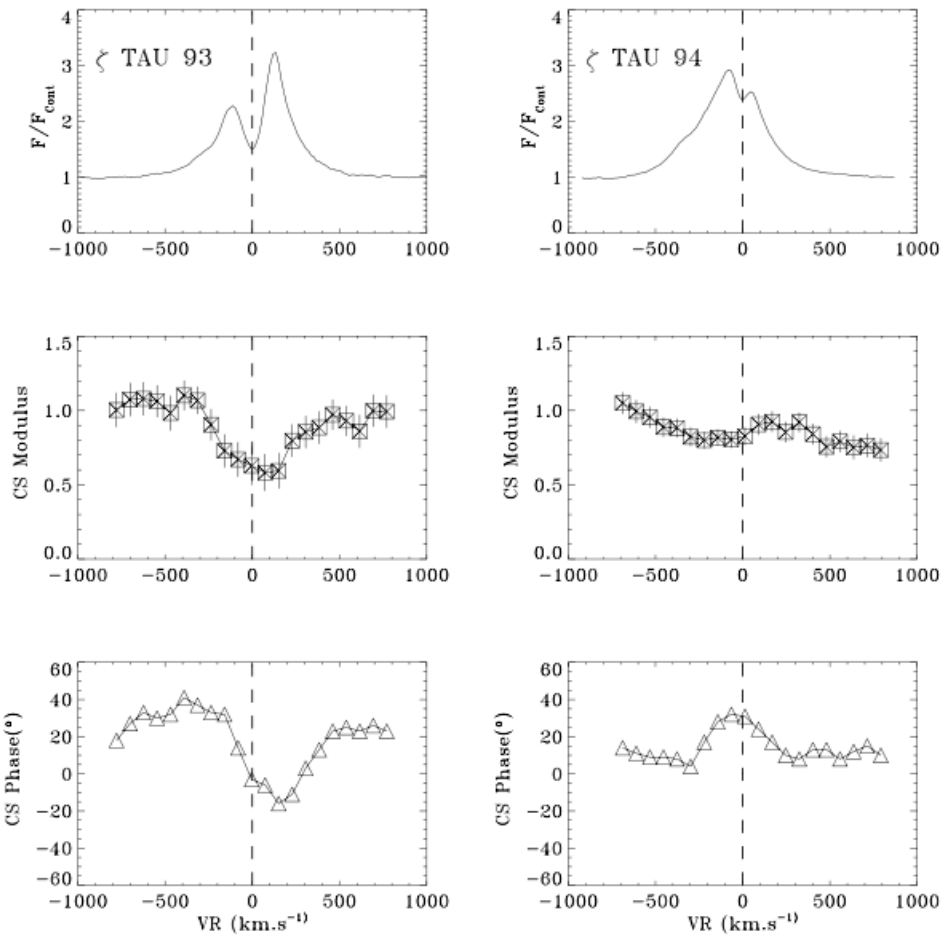




- Gies et al. 2007
  - CHARA Classic
- Model of isothermal disk in Keplerian rotation
- 1.99 mas at K

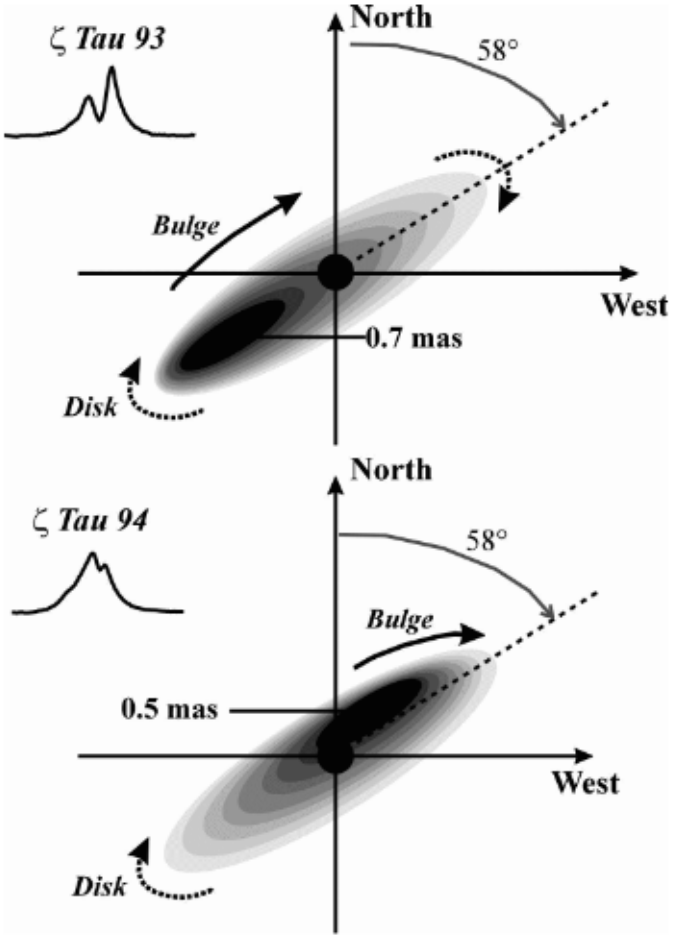
Asymmetry detected in the Disk of Zeta Tau Using Interferometry

- Vakili et al. 1998
- GI2T
  - 15-28 m baselines
- Differential phases and visibilities across the Hα line (relative to the continuum)
- Change in sign of phase indicates a shift in position



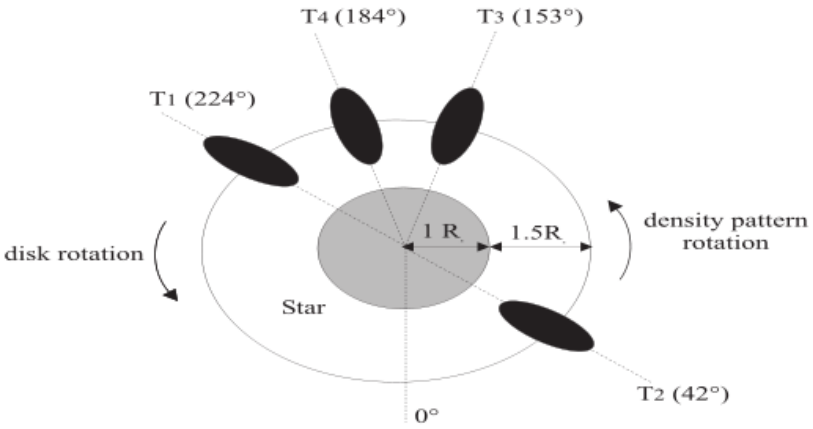
Asymmetry detected in the Disk of Zeta Tau Using Interferometry

- Vakili et al. 1998
- Assume orientation and size of disk from Quirrenbach et al. 1997
- Differential phases vs. Doppler shift provide location of bulge within the disk
- Consistent with one-armed spiral oscillation in disk
  - Prograde motion



Asymmetries in γ Cas

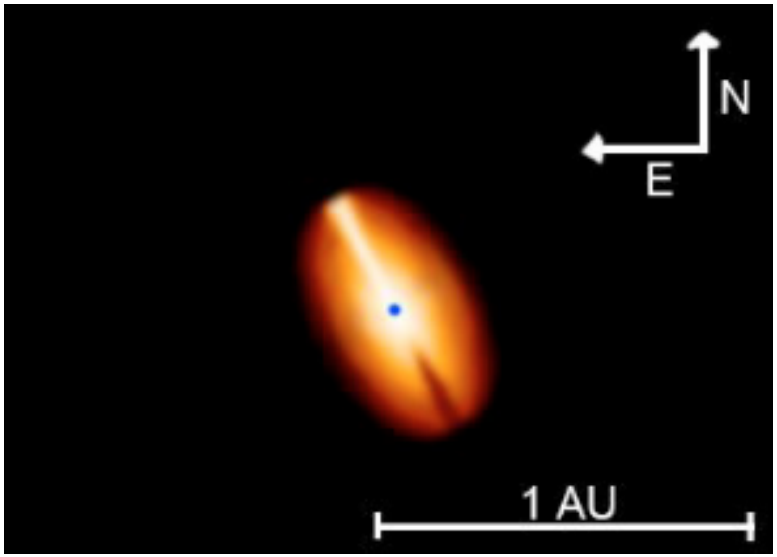
- Berio et al. 1999
- GI2T Interferometer
  - 20-51 m baselines
- High spatial resolution data across Hα line reveals asymmetric variations correlated with V/R variations of Hα profile
- Agrees with one-armed oscillation precessing in equatorial disk



High density pattern in γ Cas equatorial disk

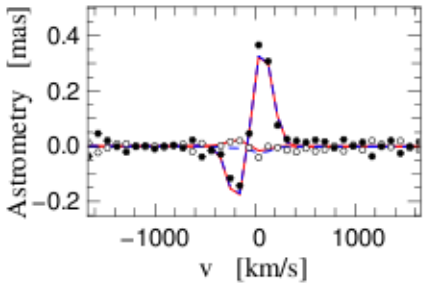
Asymmetries in κ CMa

- Meilland et al. 2007
- VLTI/AMBER
  - 43, 59, 81 m baselines
- Differential phases and visibilities across Brγ line
- Keplerian rotating disk
- Radiative wind model modified to introduce a longitudinal dependence of envelope density

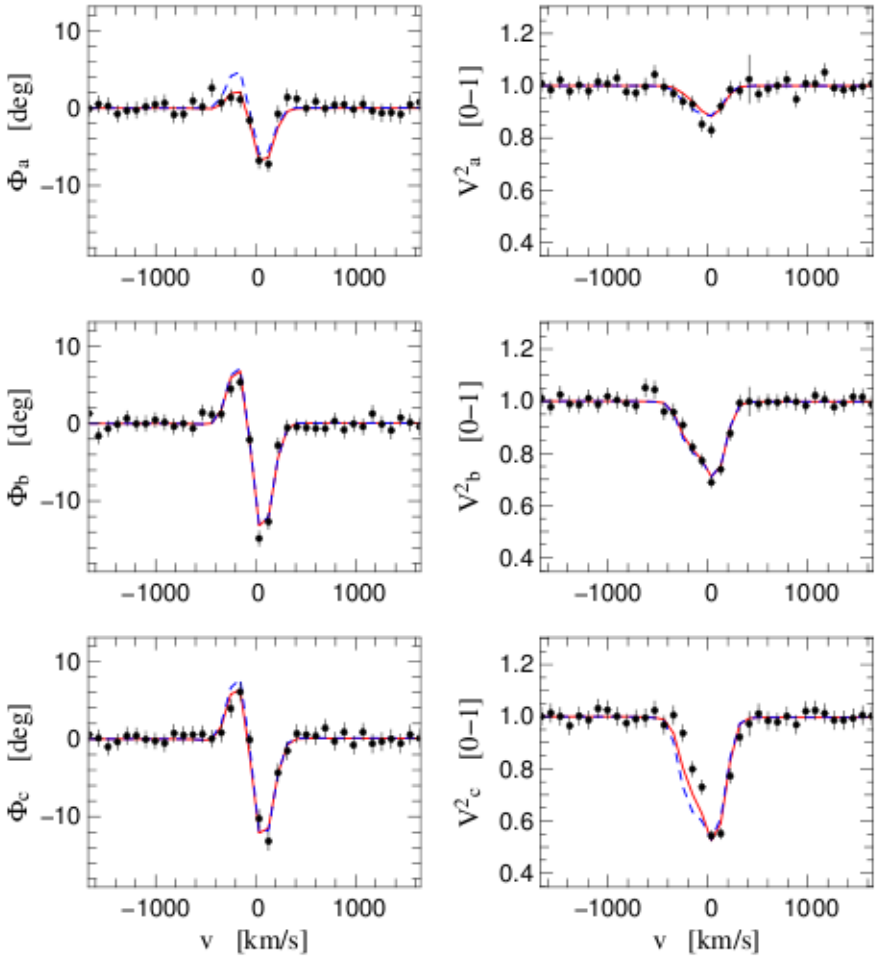


Asymmetries in Zeta Tau

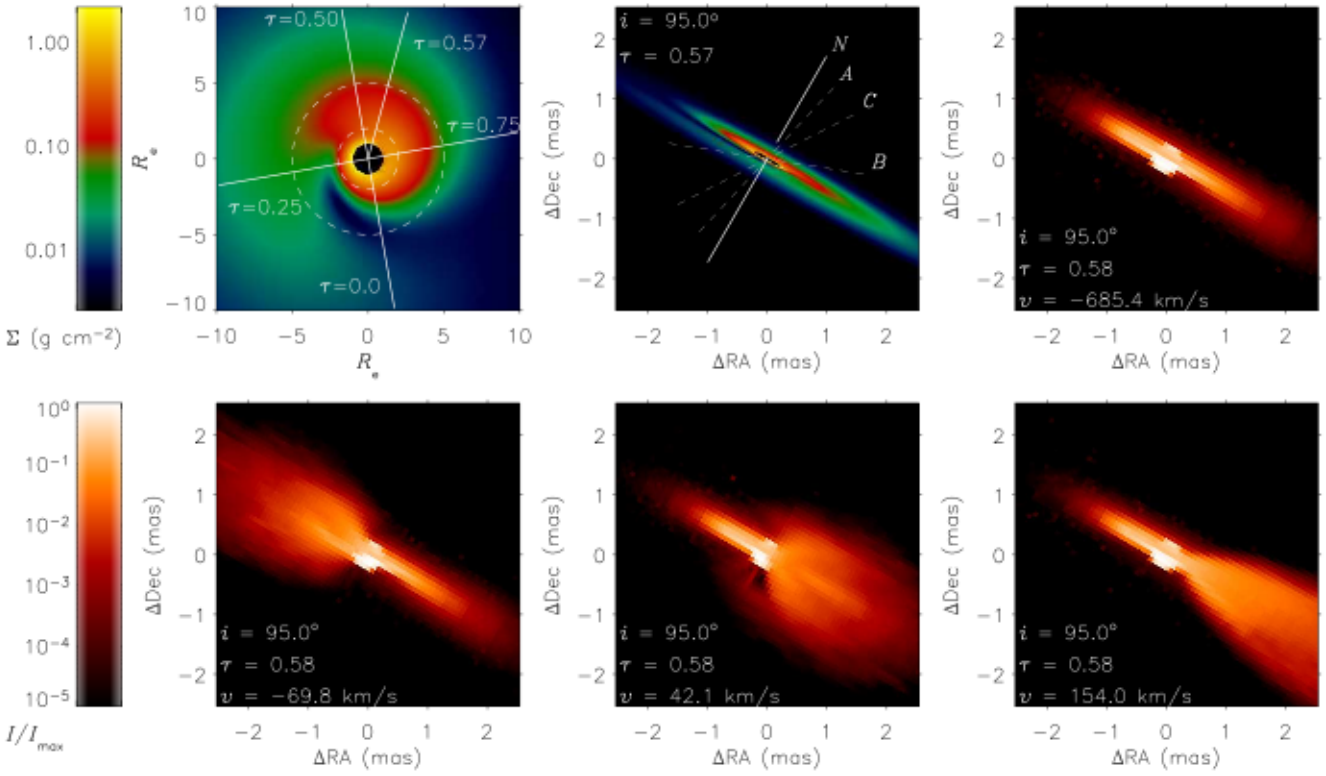
- Carciofi et al. 2009
- VLTI/Amber
- 93, 53, 130 m baselines
- Differential phases and visibilities vs. Doppler shift velocity (Brγ)
- Astrometric shift of photocenter



Differential Phases | Visibilities



Modeling – density waves



- Carciofi et al. 2009
- Consistent with one-armed spiral oscillation model

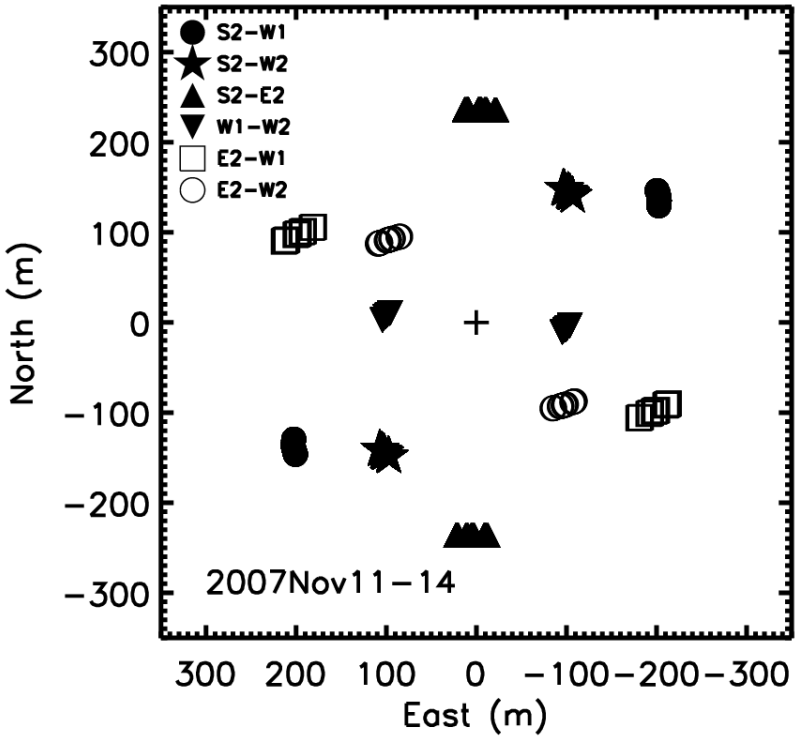
MIRC Observations of Zeta Tau

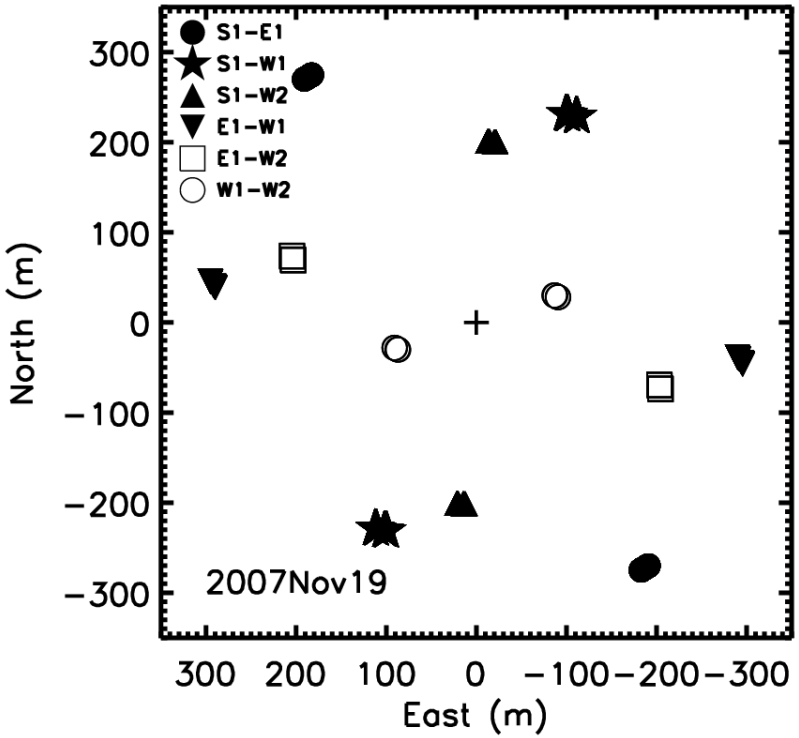
- Goal: Multi-year monitoring campaign to measure asymmetric features in the disk and follow motions of disk enhancements

Observing Log

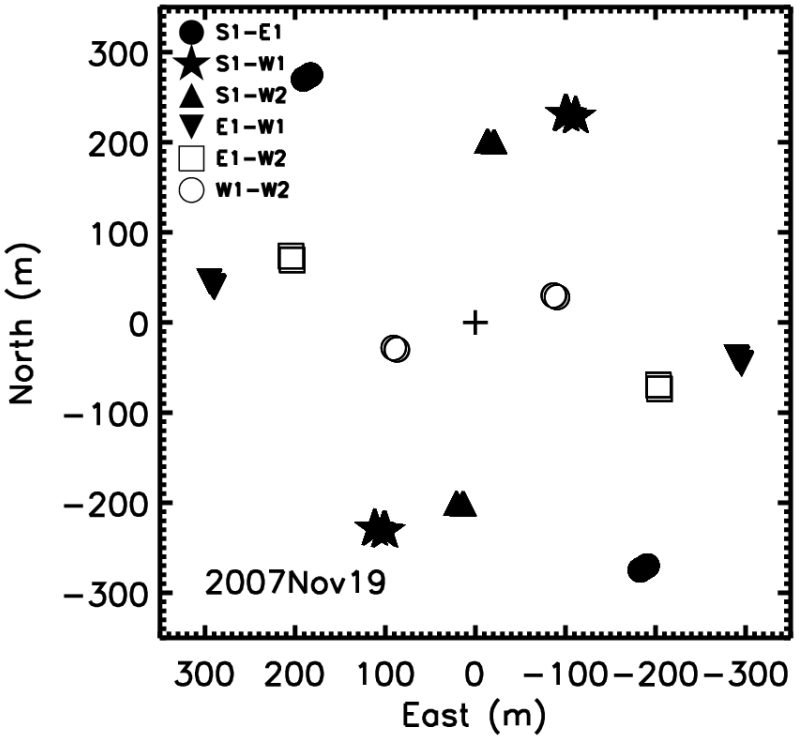
UT Date	Configuration	Baselines	Calibrators
2007 Nov 11	S2-E2-W1-W2	108-248 m	ζPer
2007 Nov 13	S2 E2 W1 W2	108-248 m	σCyg, ζPer
2007 Nov 14	S2 E2 W1 W2	108-248 m	σCyg, ζPer
2007 Nov 19	S1 E1 W1 W2	108-331 m	ζPer, 10Aur
2008 Sep 26	S1 E1 W1 W2	108-331 m	ζPer, θGem

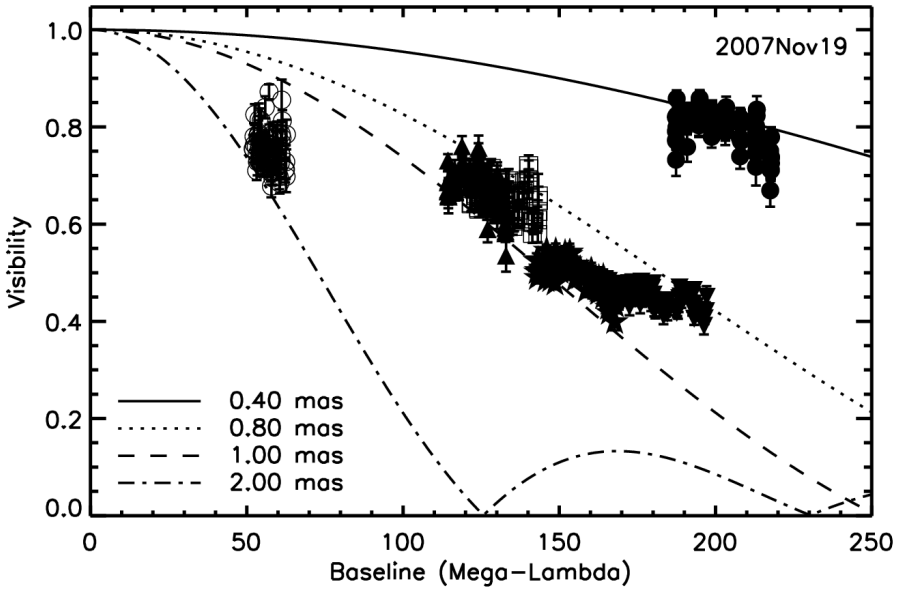
UV Coverage


S2-W1
S2-W2
S2-E2
W1-W2
E2-W1
E2-W2
2007Nov11-14
North (m)
East (m)
300
200
100
0
-100
-200
-300


S1-E1
S1-W1
S1-W2
E1-W1
E1-W2
W1-W2
2007Nov19
North (m)
East (m)
300
200
100
0
-100
-200
-300

MIRC Visibilities

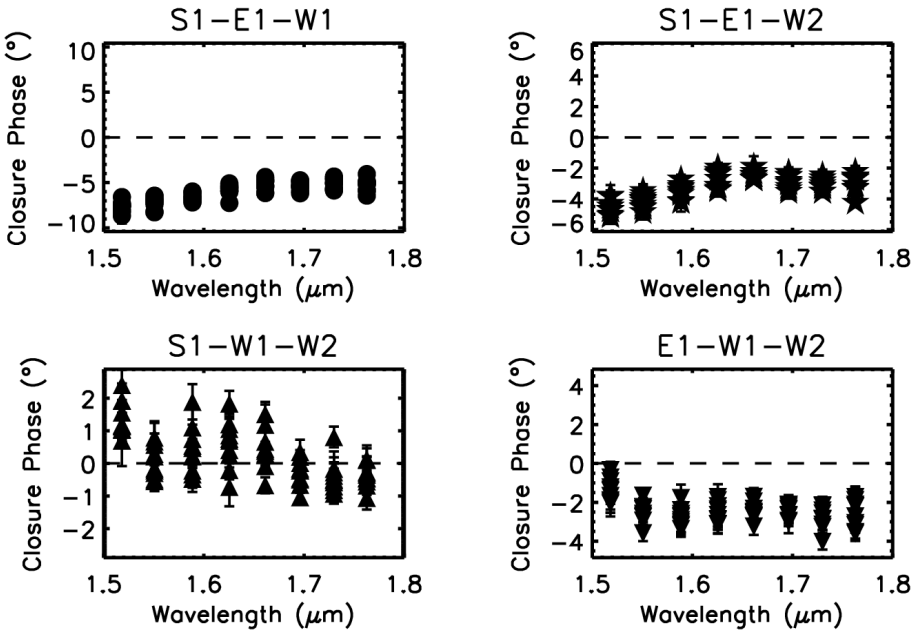




- 6 baselines
- 8 spectral channels
- Elliptical shape of Zeta Tau disk

MIRC Closure Phases

- Closure phases on four closed triangles
- Non-zero closure phases indicate and asymmetry in the disk

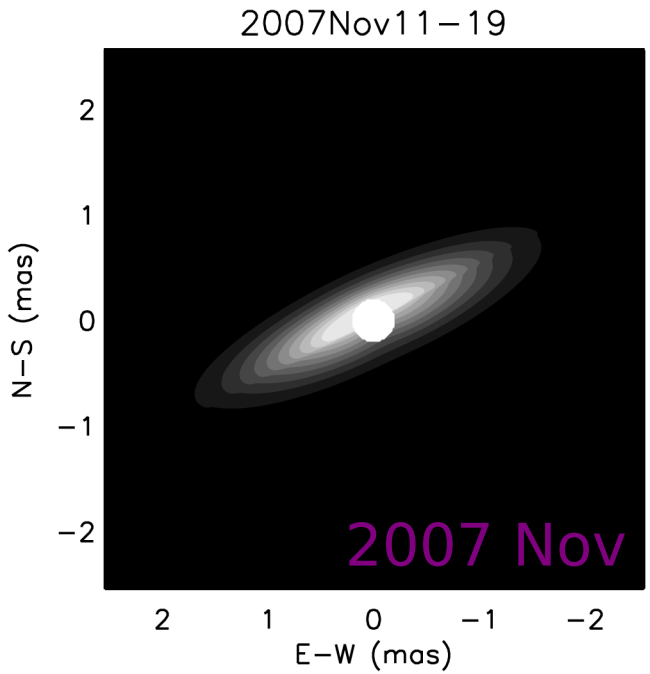


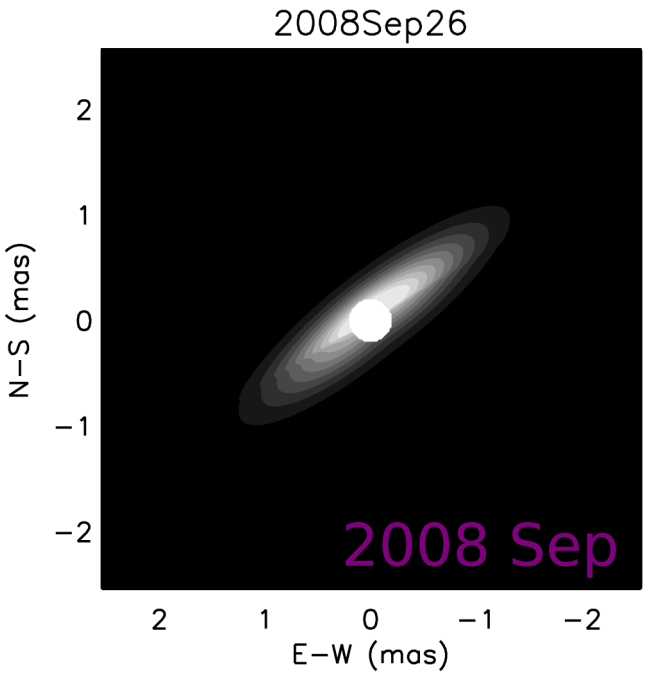
Geometric Modeling of Zeta Tau

Skewed Elliptical Gaussian

- Central star with fixed uniform diameter of 0.38 mas
- Elliptical Gaussian disk modulated as a function of azimuth by a sinusoid (e.g. Monnier et al. 2006)

Skewed Elliptical Gaussian

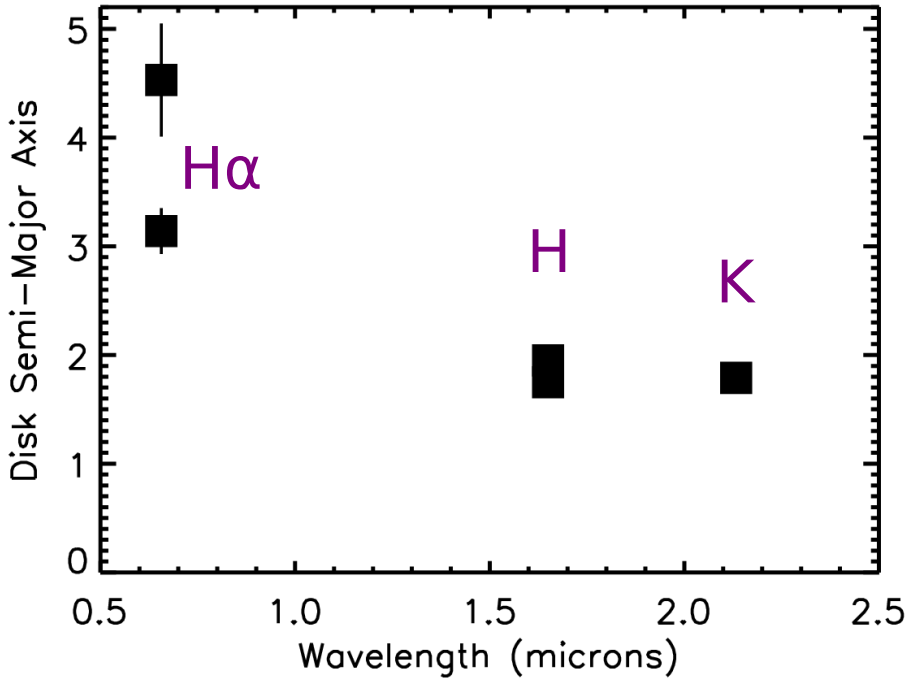




- Asymmetry lies along minor axis of disk
- Major axis of 1.95 mas at H
- Axis ratio of 0.26

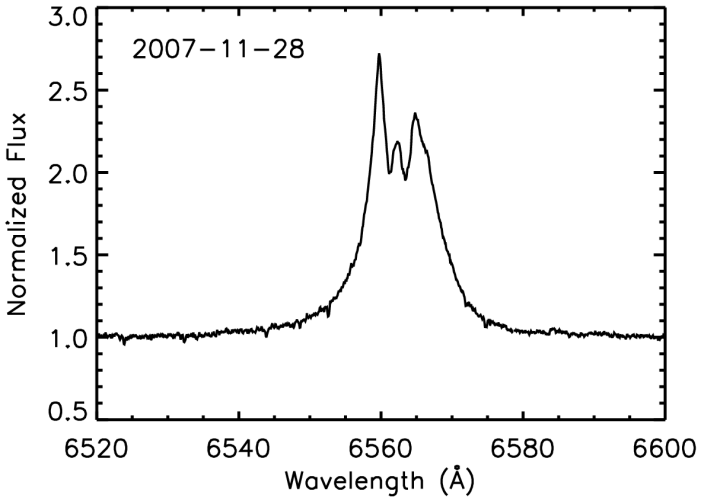
- ~10° change in PA of major axis
- Major axis of 1.75 mas at H
- Axis ratio of 0.25

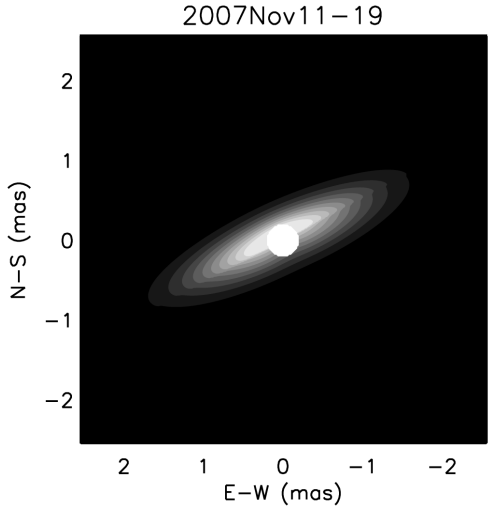
Disk Size vs. Wavelength

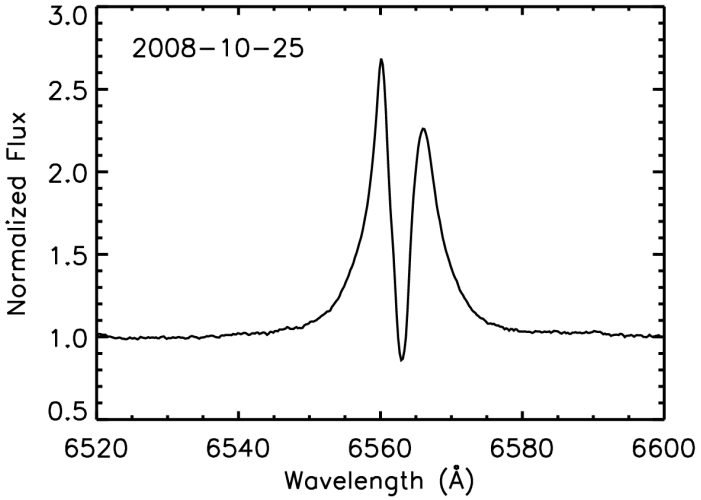


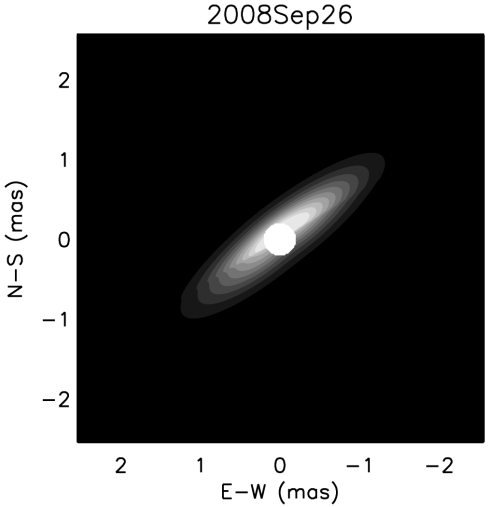
- Smaller disk size than measured in Hα (e.g. Quirrenbach et al. 1994, Tycner et al. 2004)

Comparison with Hα Spectroscopy







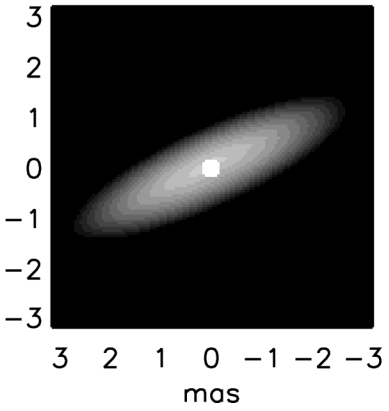


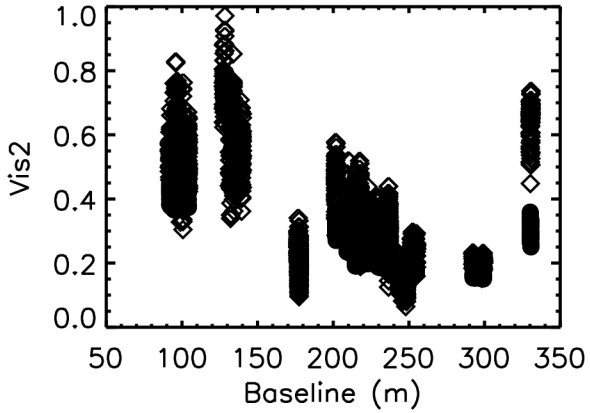
Future Work

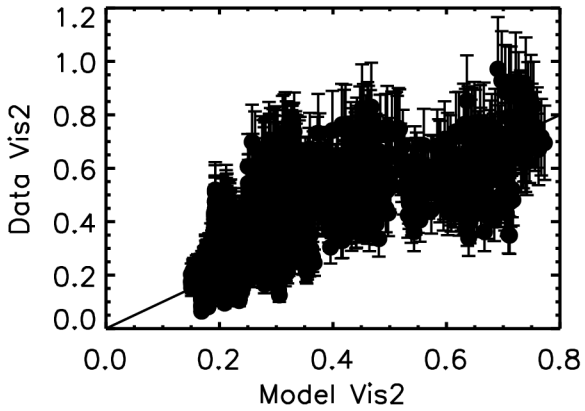
- Interferometric coverage in Hα (NPOI), K'-band (CHARA), Brγ (VLTI/AMBER), H-band (CHARA/MIRC)
- Follow motion of asymmetric features as they propagate through disk
- Synthesize results on asymmetries measured through interferometry and spectroscopy
- Compare with theoretical models such as one-armed oscillations in disks

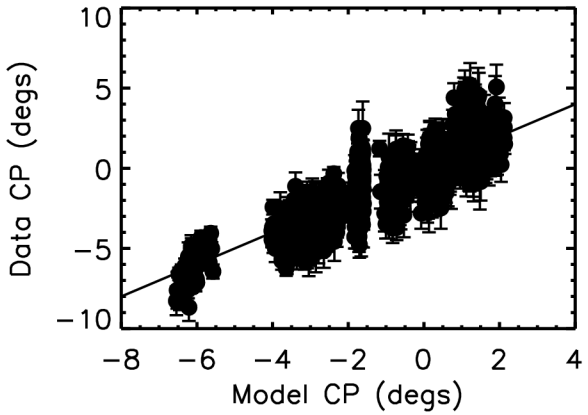
The End

2007 Nov 11-19 Residuals

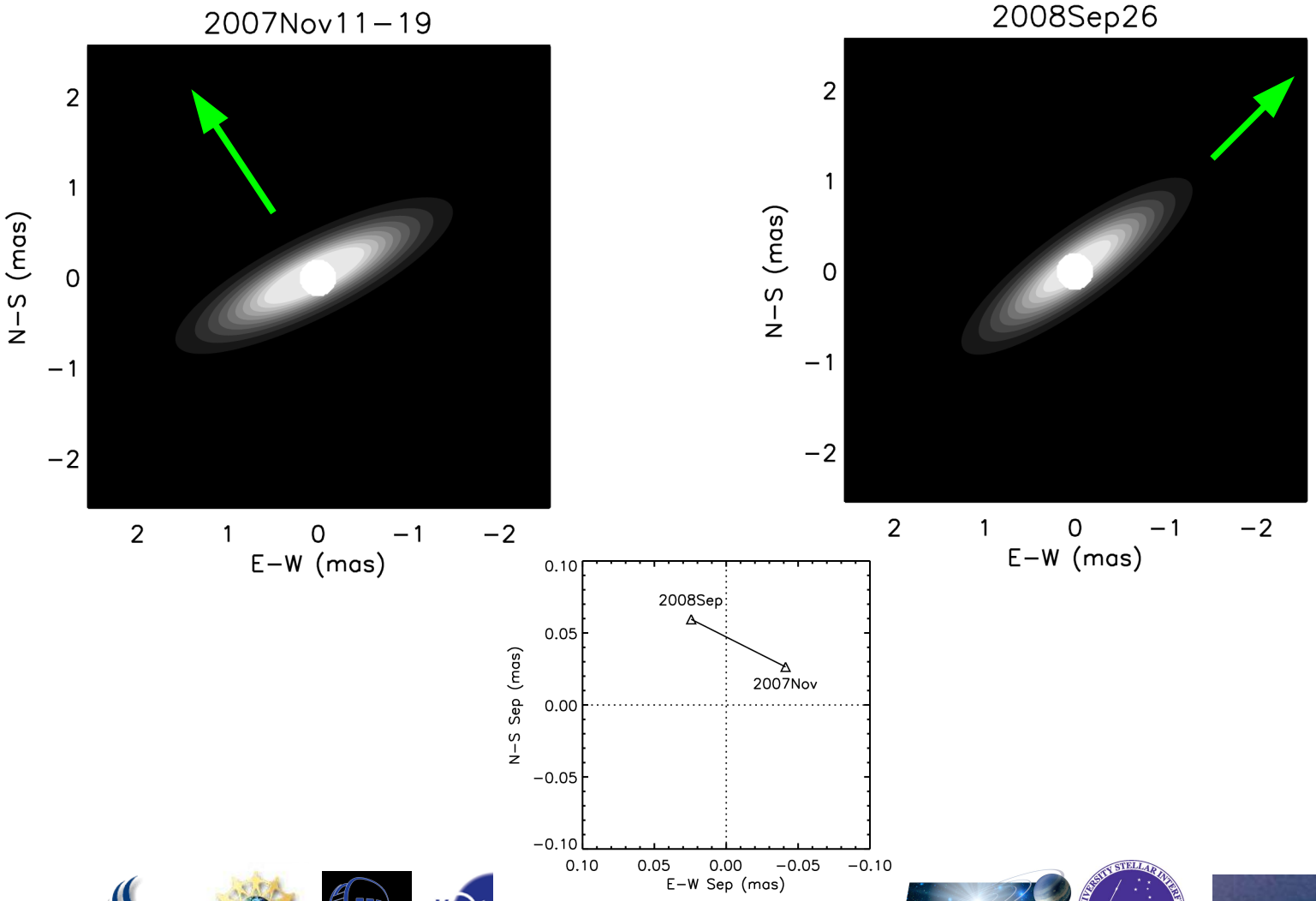




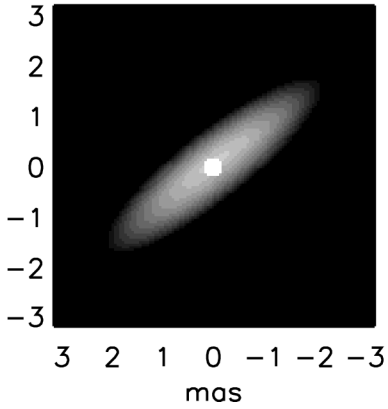


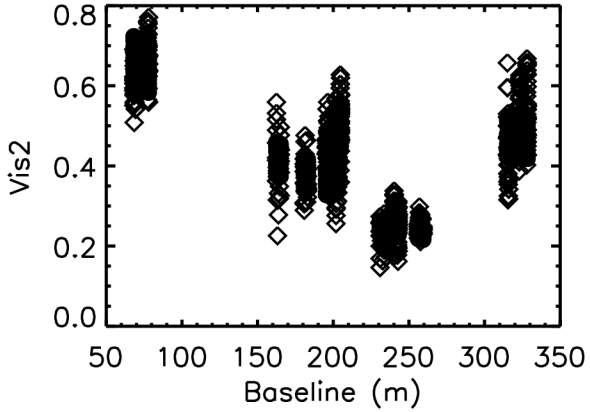


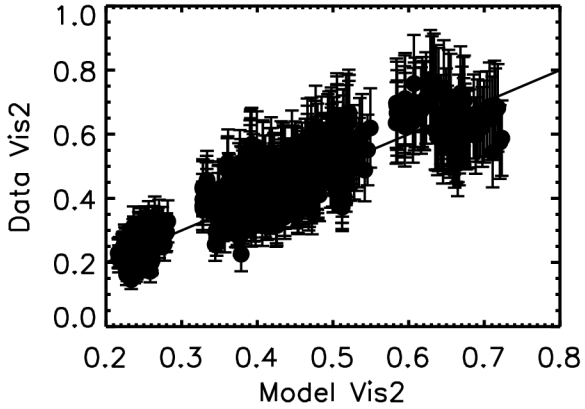
Off-centered Elliptical Gaussian

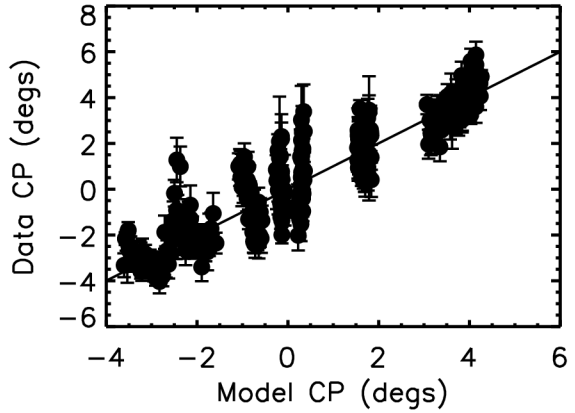


2008 Sept 26 Residuals









Comparison