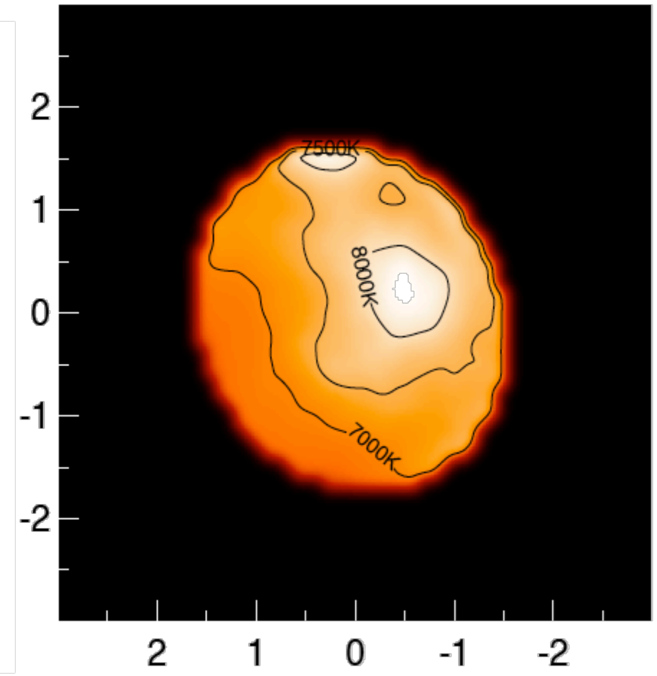
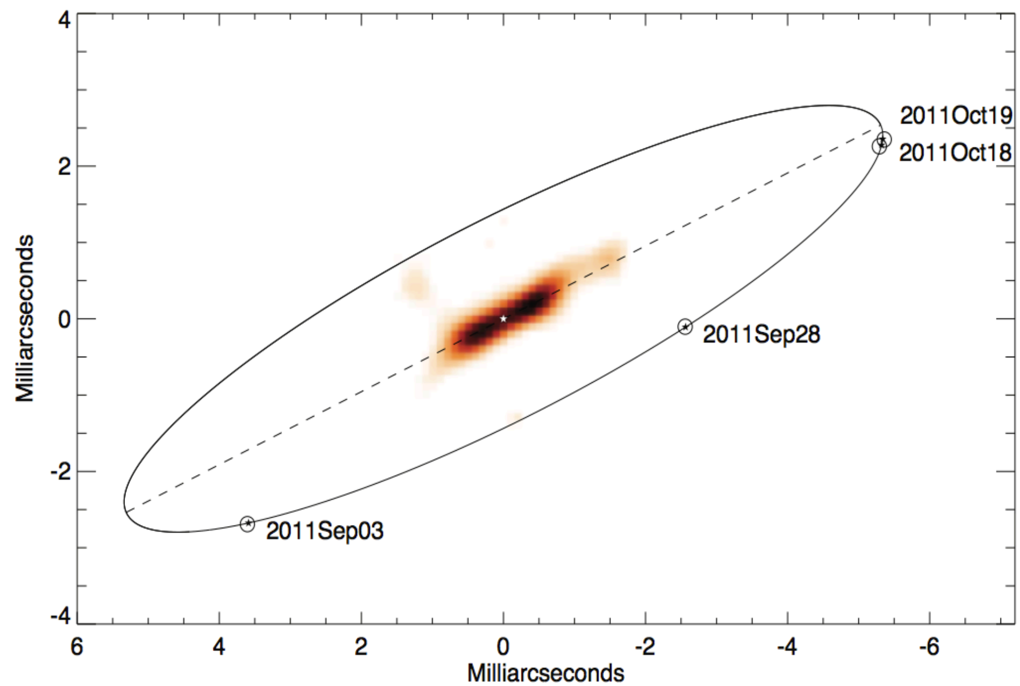
Infrared Interferometric Imaging of (Massive) Stars and Circumstellar Disks





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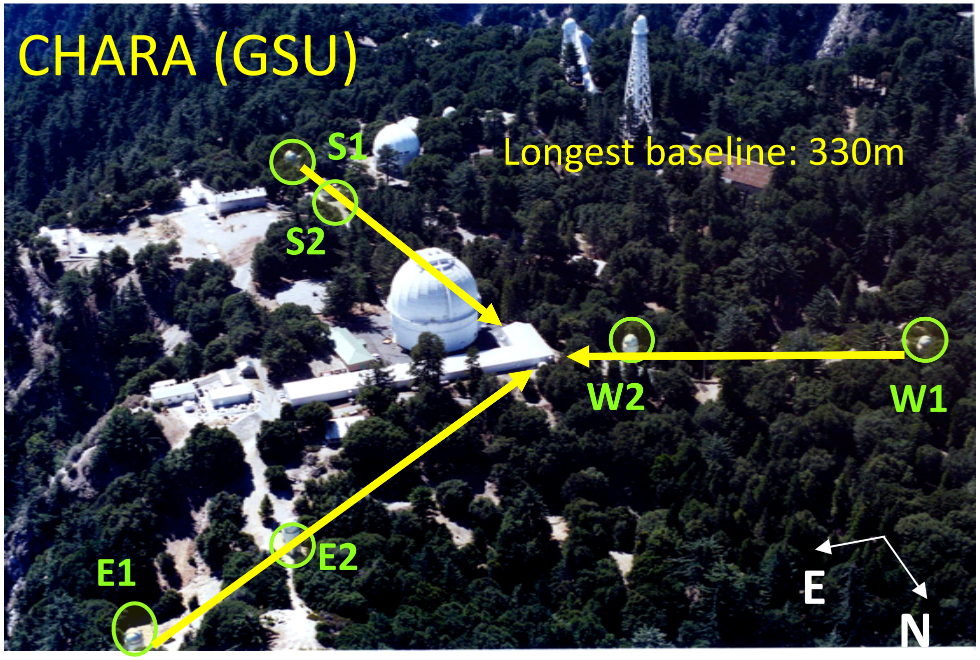
Outline

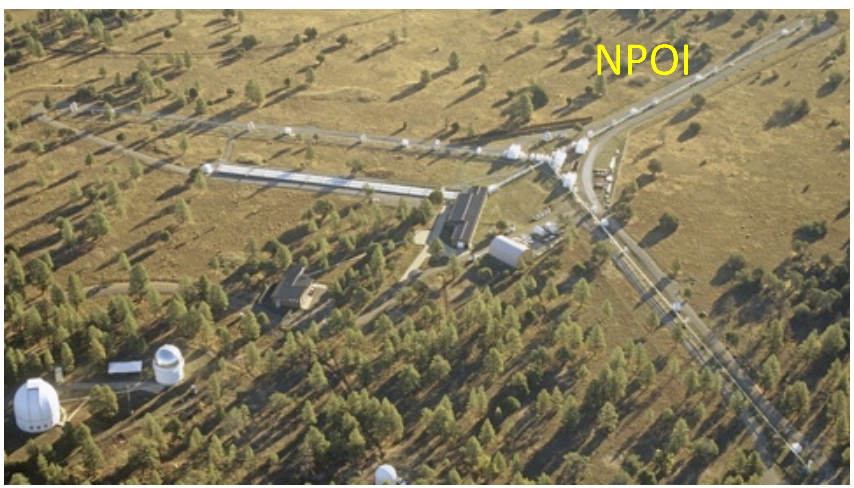
- Introduction
  - Massive stars in optical interferometric context
- Interferometers
- Case study
  - Rapid rotators
  - Be stars
  - Multi-object systems
- Summary and future

Interferometric View of Massive Stars

- Why interferometry? High angular resolution.
- Strong Doppler-broadening lines
  - Rapidly rotating
- Circumstellar disks: accretion and decretion disks
  - YSO, Be stars
- Multi-object systems: binary, triplet
- Spotty stars

Interferometers





The VLT Array on the Paranal Mountain

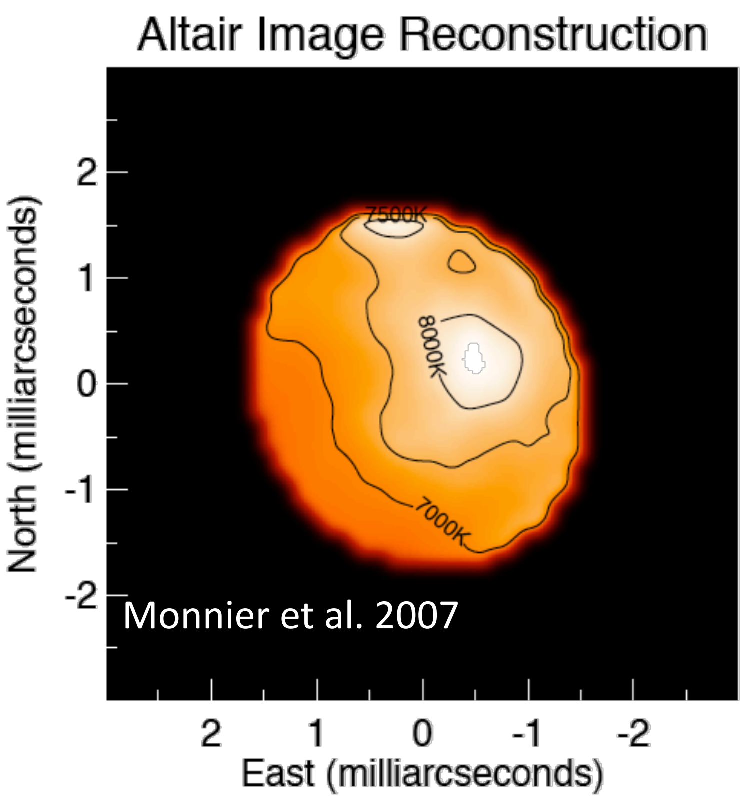
Introduction to MIRC

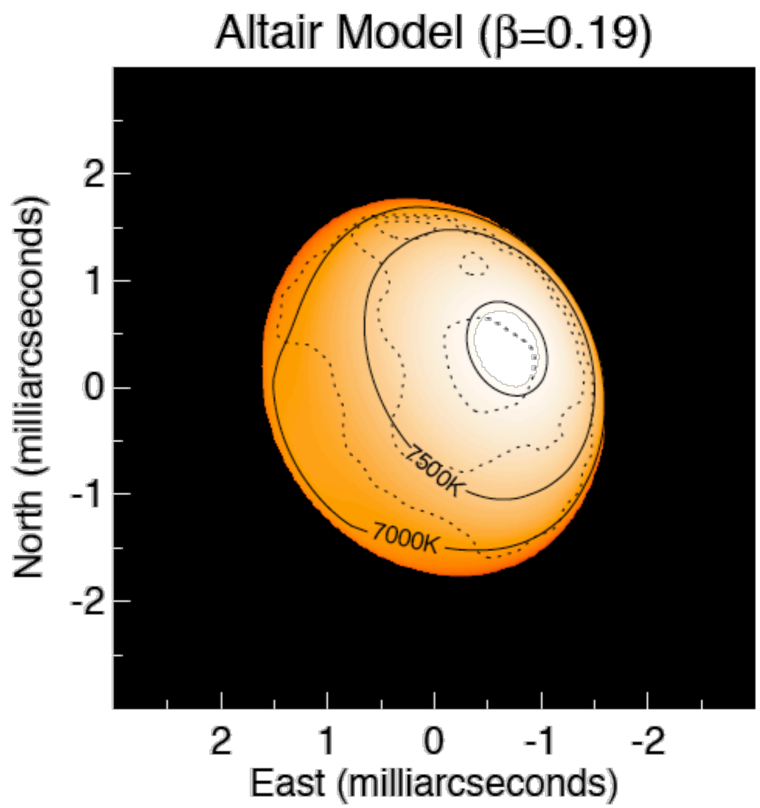
- Michigan InfraRed Combiner (MIRC) at the CHARA array
  - Near infrared, H, K band
  - Spectral resolution, R ~ 45, 150, 450
  - Image-plane all-in-one combiner
  - Single-mode fibers to filter out atmosphere turbulence
  - Photometric Channels subsystem for better data quality
  - Designed and constructed by John Monnier and his group at University of Michigan
  - Science goals: rapid rotators (e.g. Monnier et al 2007), binaries (e.g. Zhao et al 2008), Be stars (e.g. Schaefer et al 2010), exoplanets (e.g. Zhao et al 2011), YSOs.

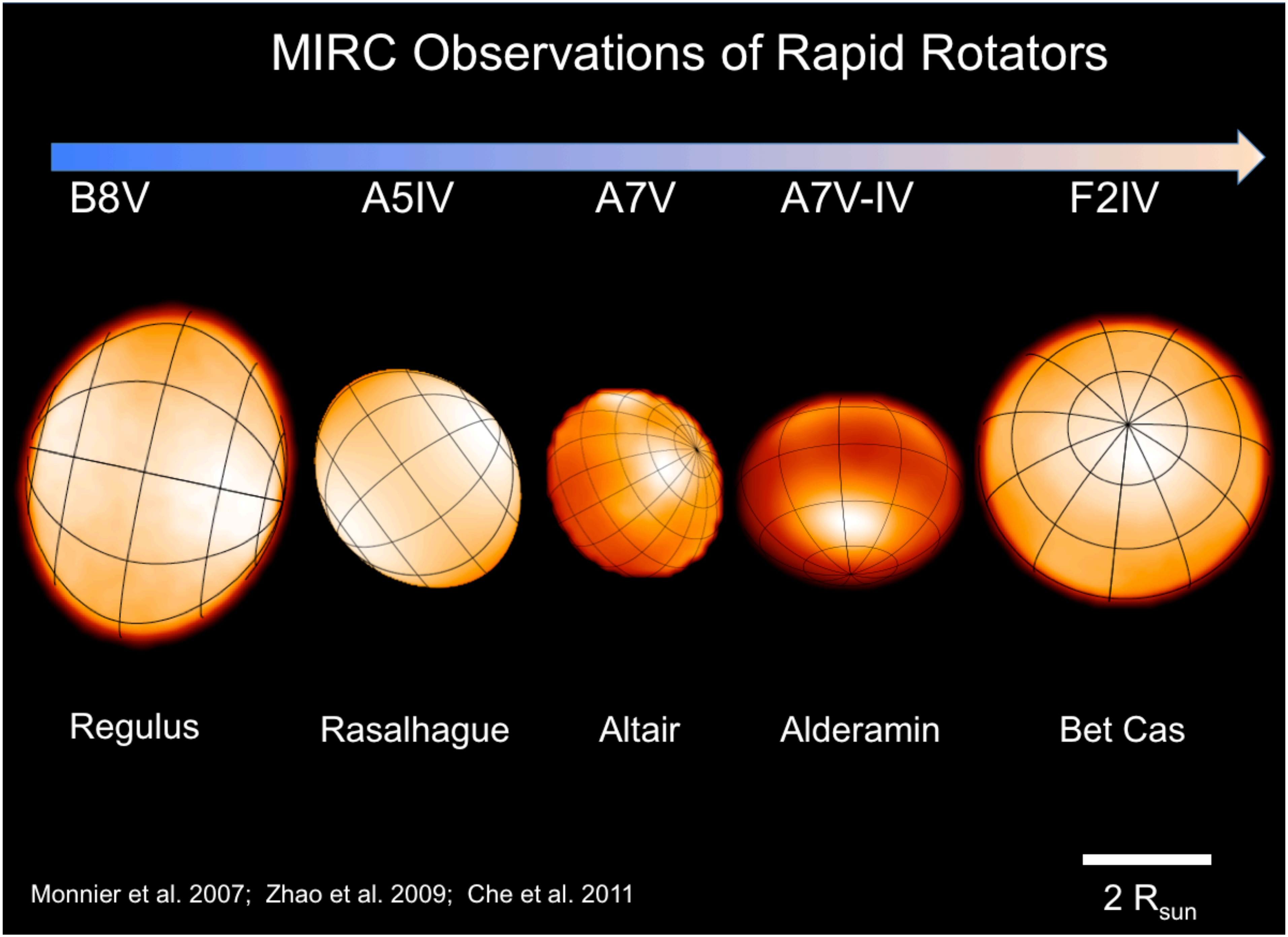
First 6-beam infrared combiner. Imaging!

First Image of a Main Sequence Star Beyond the Solar System

- Altair (α Aql, V=0.7)
  - Imaging algorithm: MACIM (Ireland et al. 2006)
  - Rigid rotation model (Aufdenberg et al 2006) fitting shows the star is rotating at ~90% breakup speed







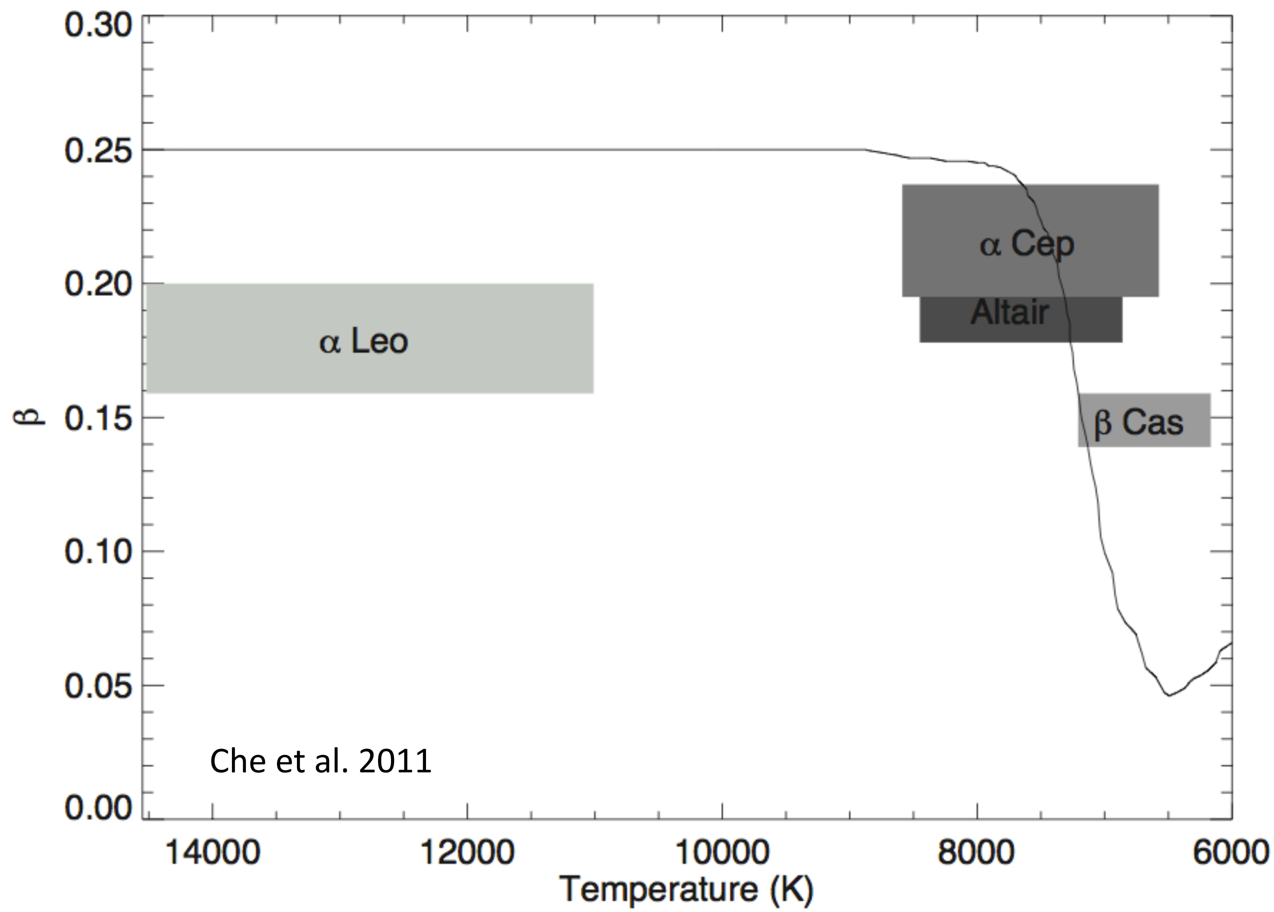
MIRC Observations of Rapid Rotators
B8V
A5IV
A7V
A7V-IV
F2IV
Regulus
Rasalhague
Altair
Alderamin
Bet Cas
Monnier et al. 2007; Zhao et al. 2009; Che et al. 2011
2 R_{sun}

von Zeipel Theory

T ~ g^{β}, where β = 0.25 for radiative envelope and 0.08 (Lucy, 1967) for convective envelope

Claret (2000) calculates β as a function of temperature

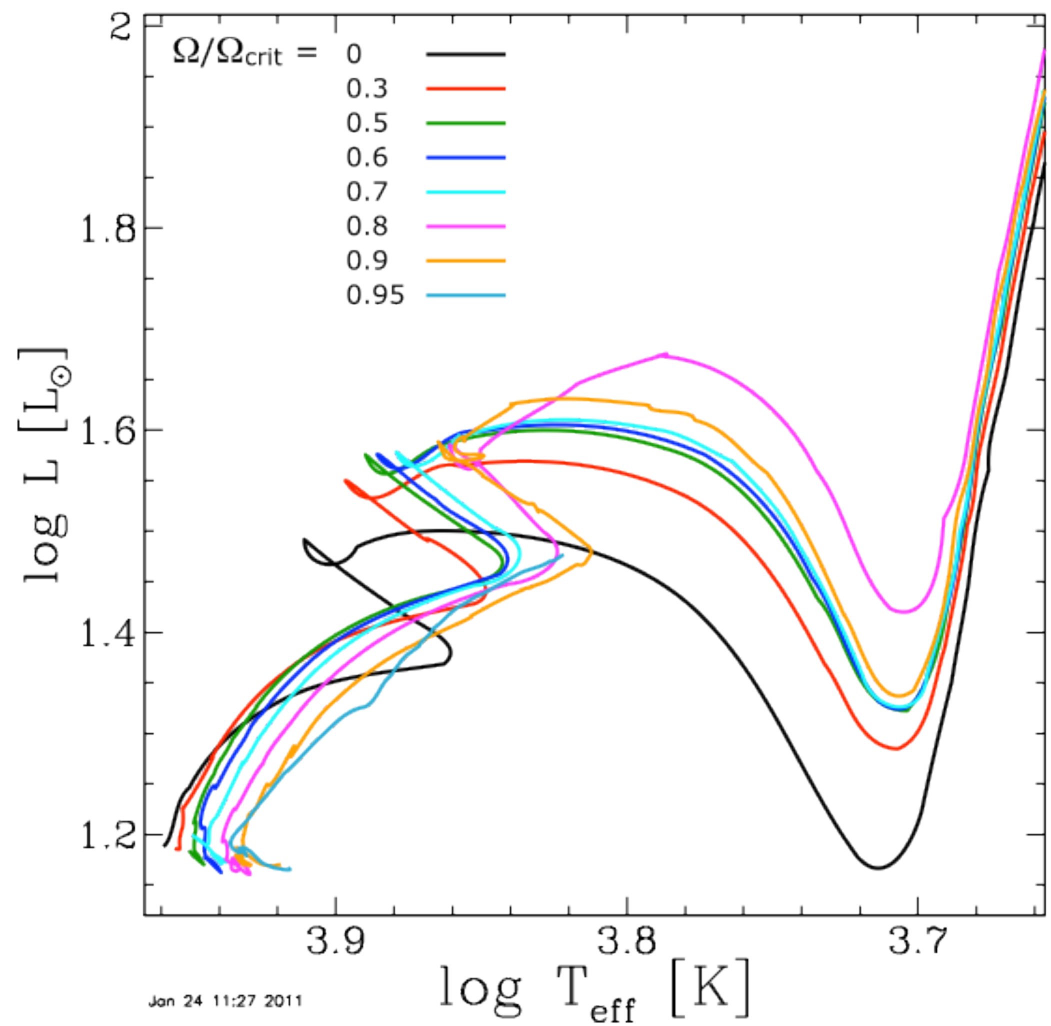
Our results of α Leo show a lower β than expected



Evolution tracks of rotators

- Rigid rotation model, vsini measurements

  ---> stellar mass
- Test evolution models of rotators

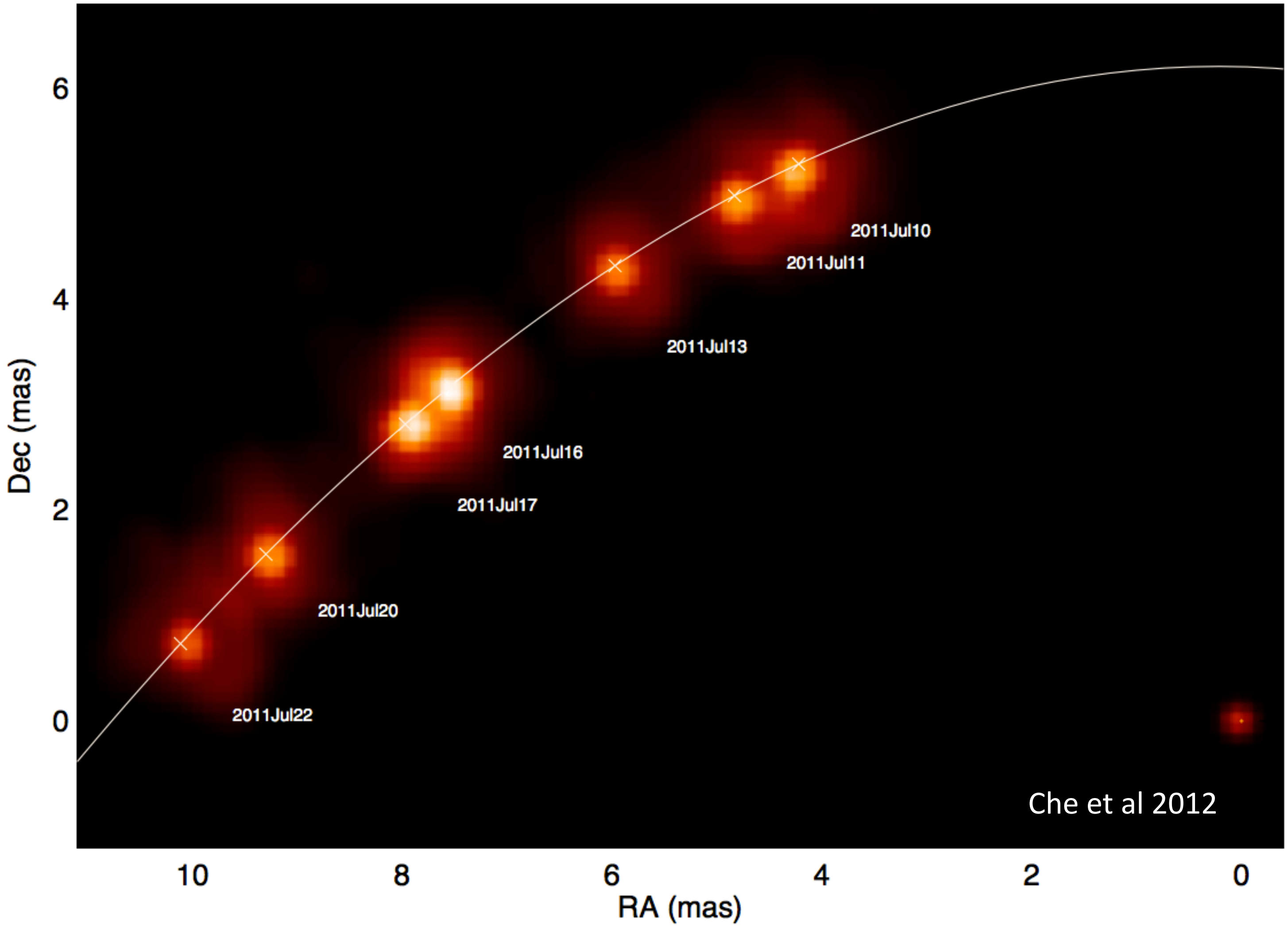


(Private communication with Sylvia Ekstrom)

Main Sequence Be Stars

- Be stars are generally fast rotators (Meilland et al. 2011)
- Vulnerable to many instabilities to eject material into orbit
- Interferometry can resolve disk structure and intensity distribution, and study disk formation and variability.

Imaging Results on Del Sco

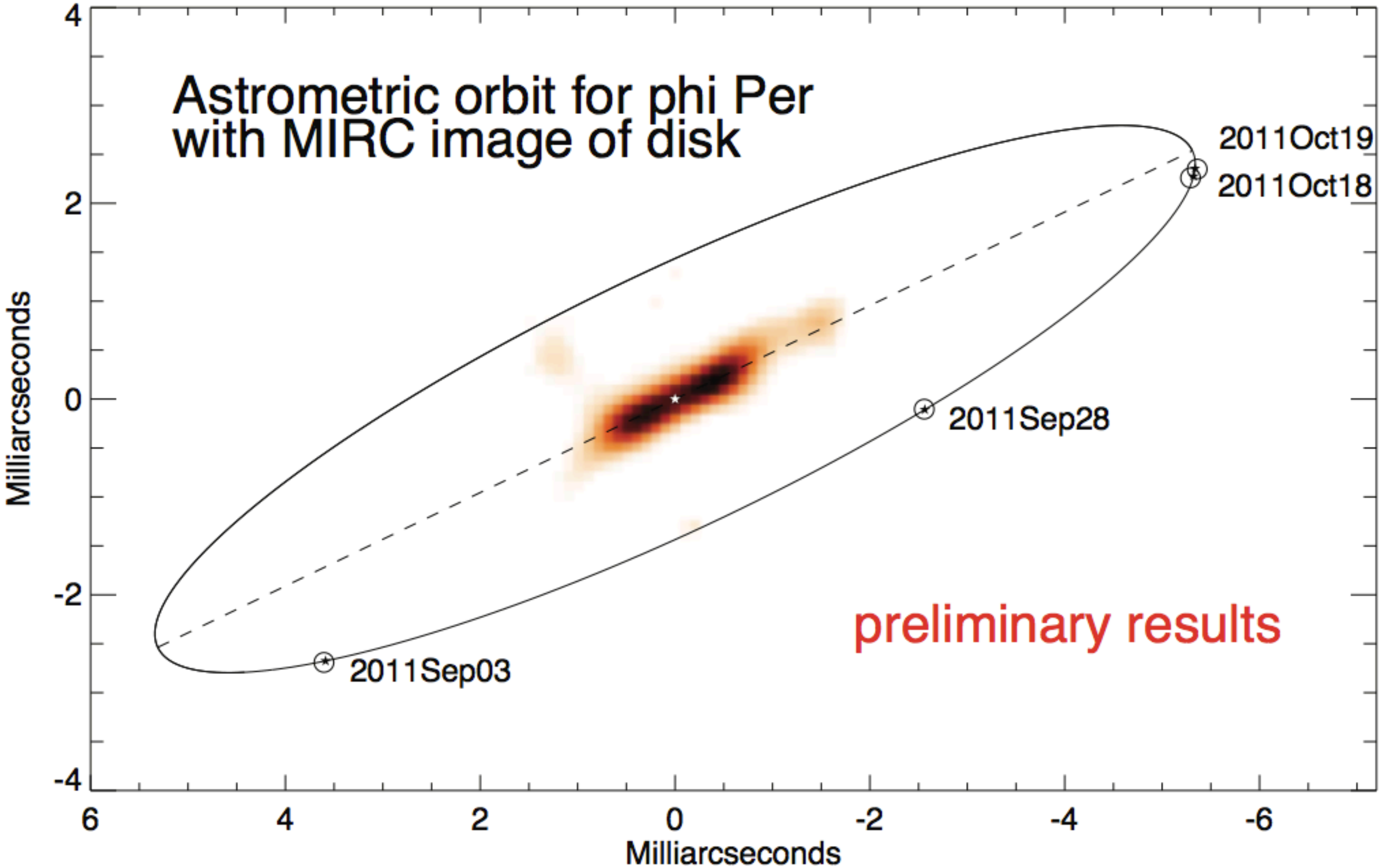


- Del Sco:
  - •Be binary
  - •High eccentricity
  - •Periastron in July 2011
  - •Disk formation due to Secondary passage?

- Del Sco observed on 7 nights from 2011 July 10th to 22nd

- The flux contribution from the disk is consistent through 7 nights, implying no on-going material outflow

Imaging Results on Phi Per



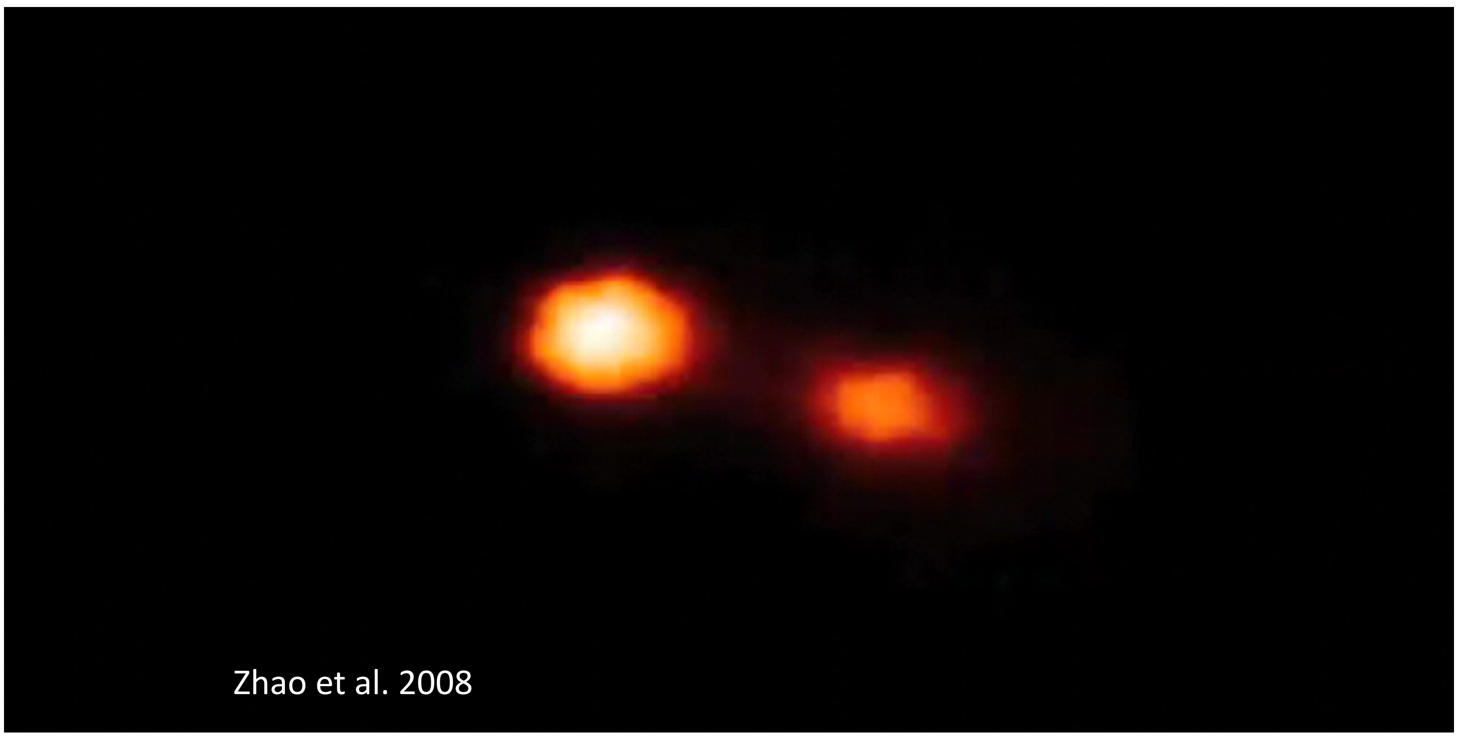
Provided by John Monnier

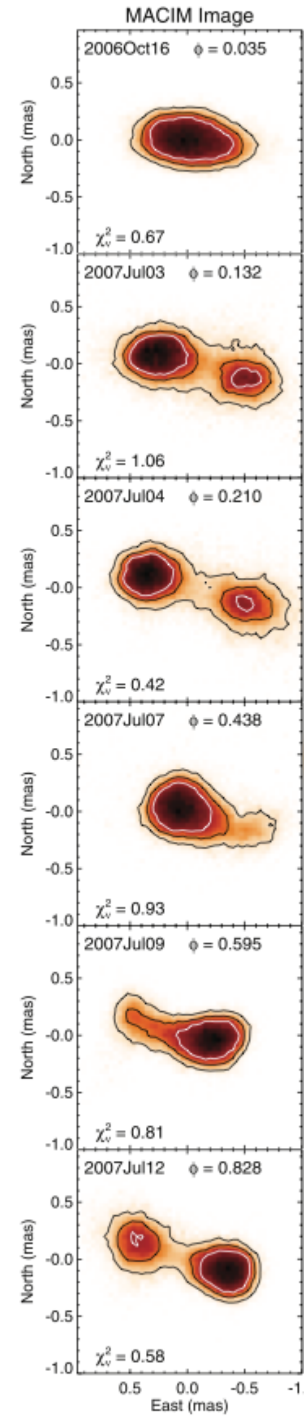
Multi-object Systems

- Most massive stars are not single.
- Interferometry can resolve the orbits
- Interferometry can resolve the stellar surfaces; Roche lobe filling, stellar spots

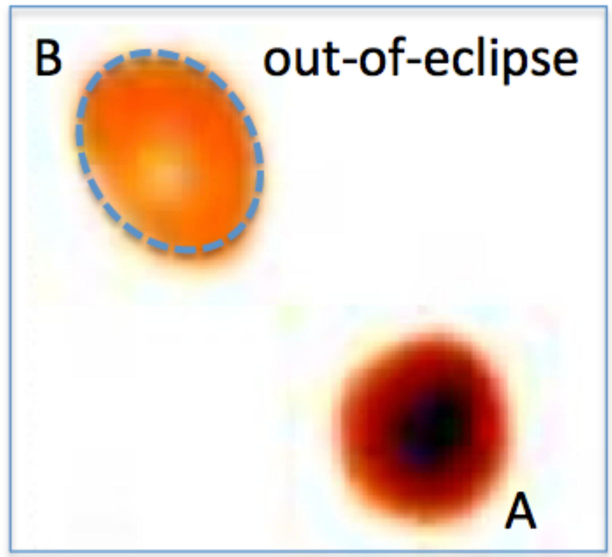
β Lyr

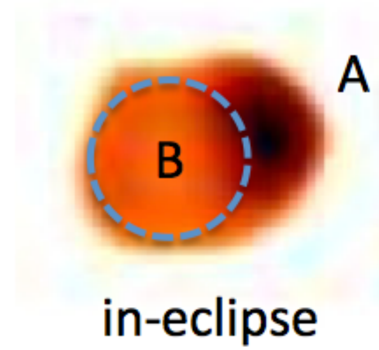
Binary, B stars, the donor is a Roche lobe filling mass-losing star
Edge-on orbit with ~13 days period

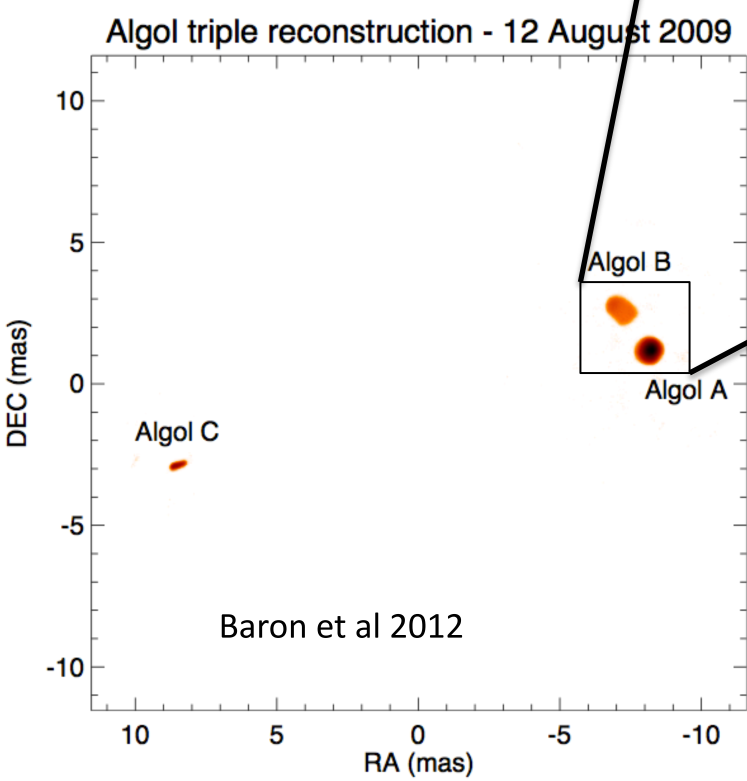

Zhao et al. 2008



Algol

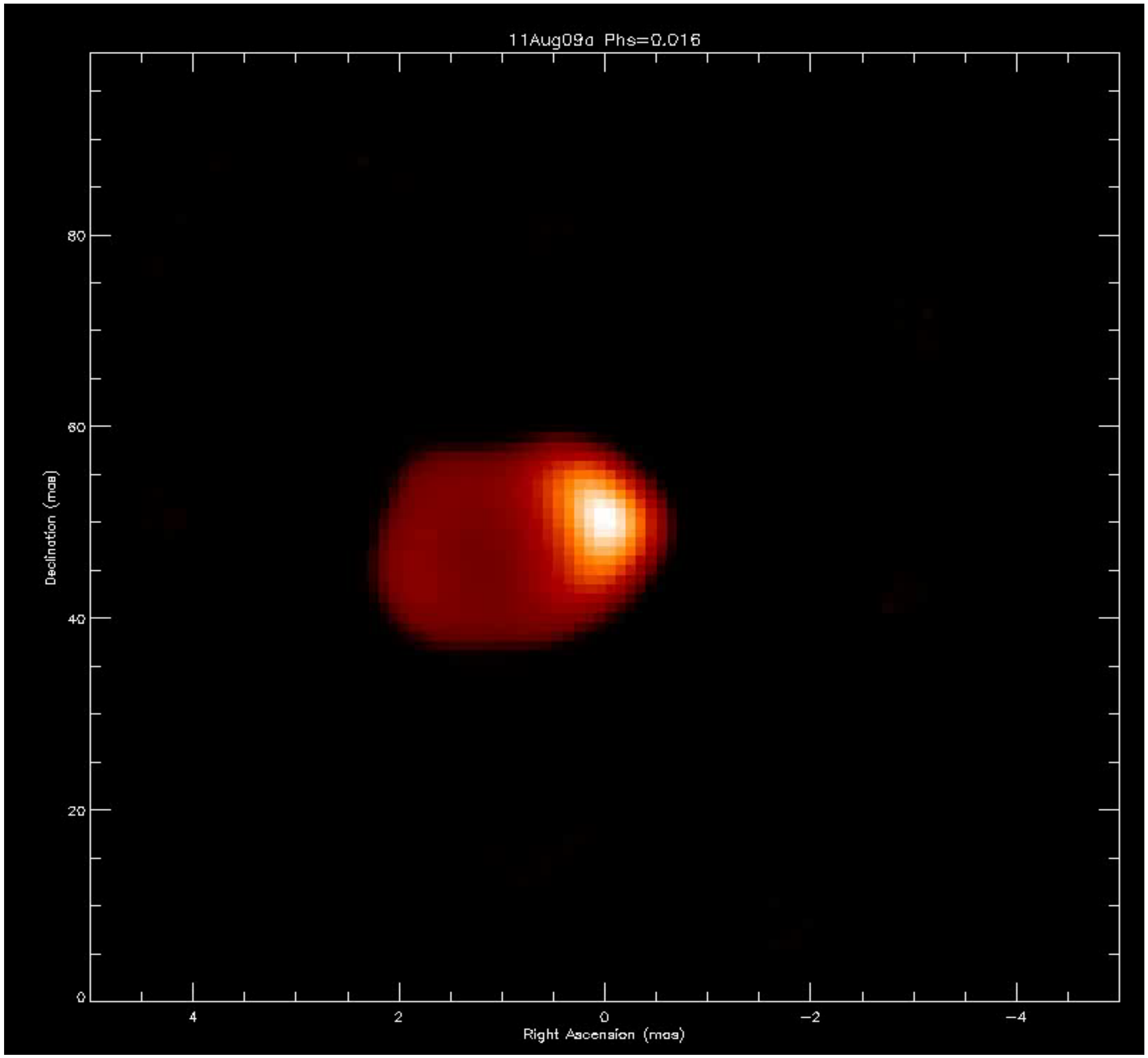






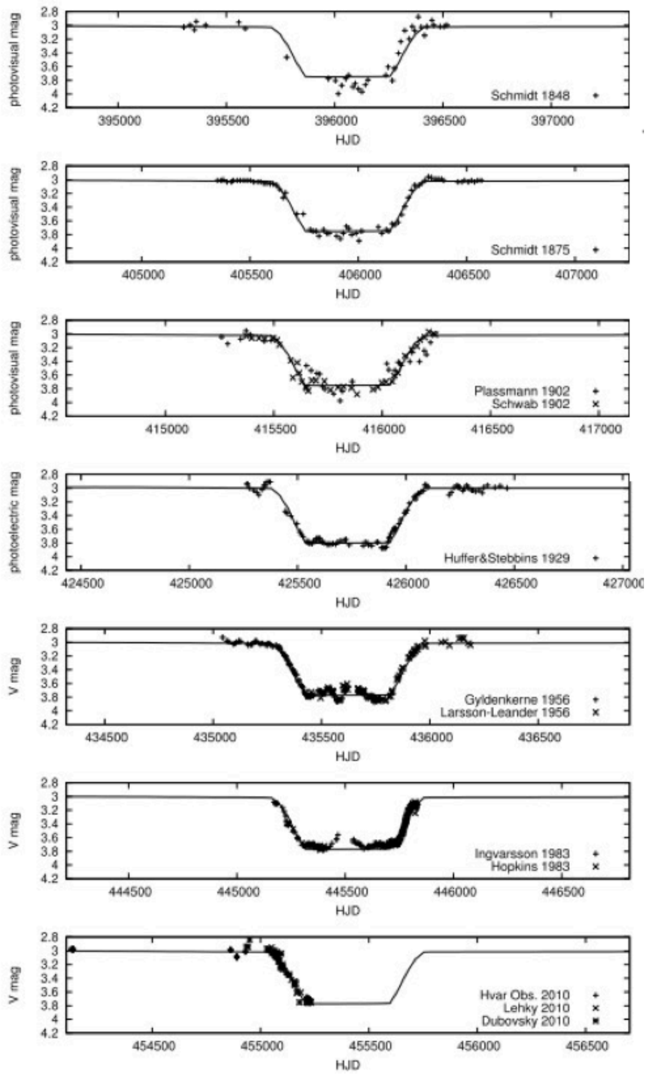
Triple star system
Inner eclipsing binary
the orbits of B and C components
are perpendicular

Inner Binary of Algol



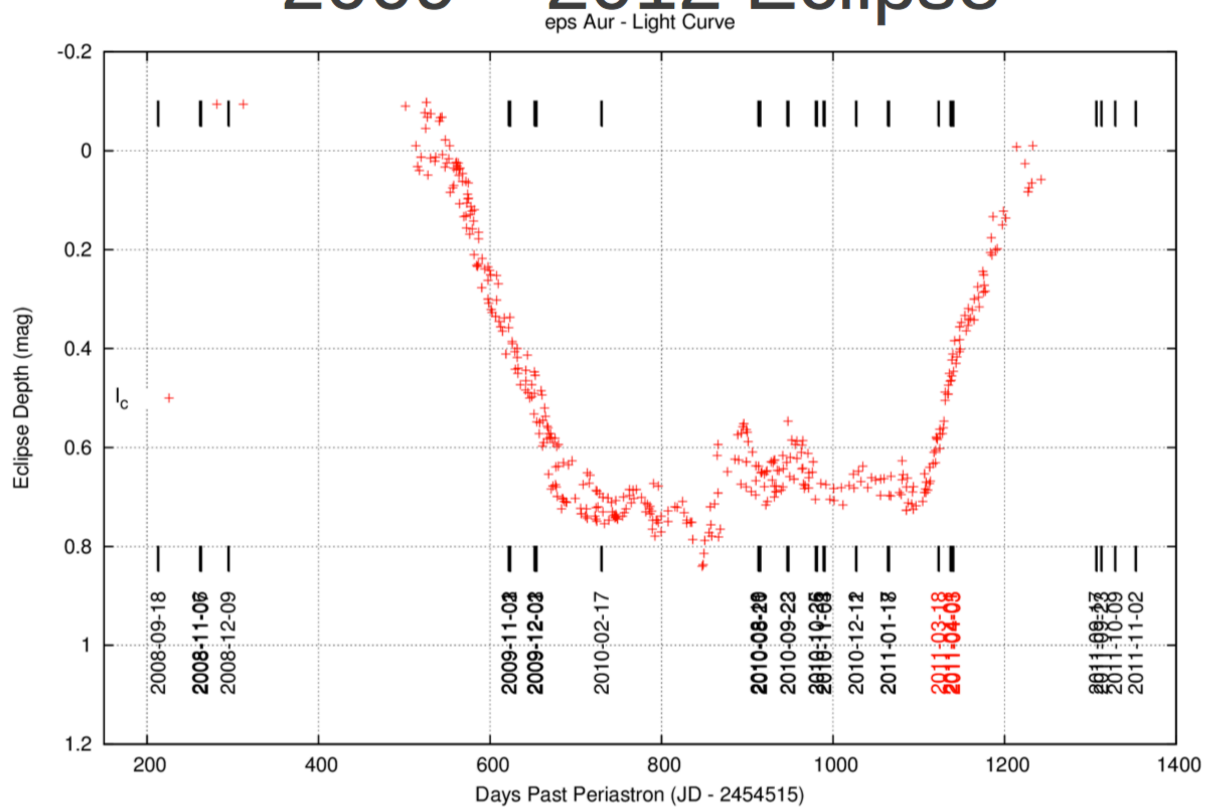
Baron et al 2012

ε Aur

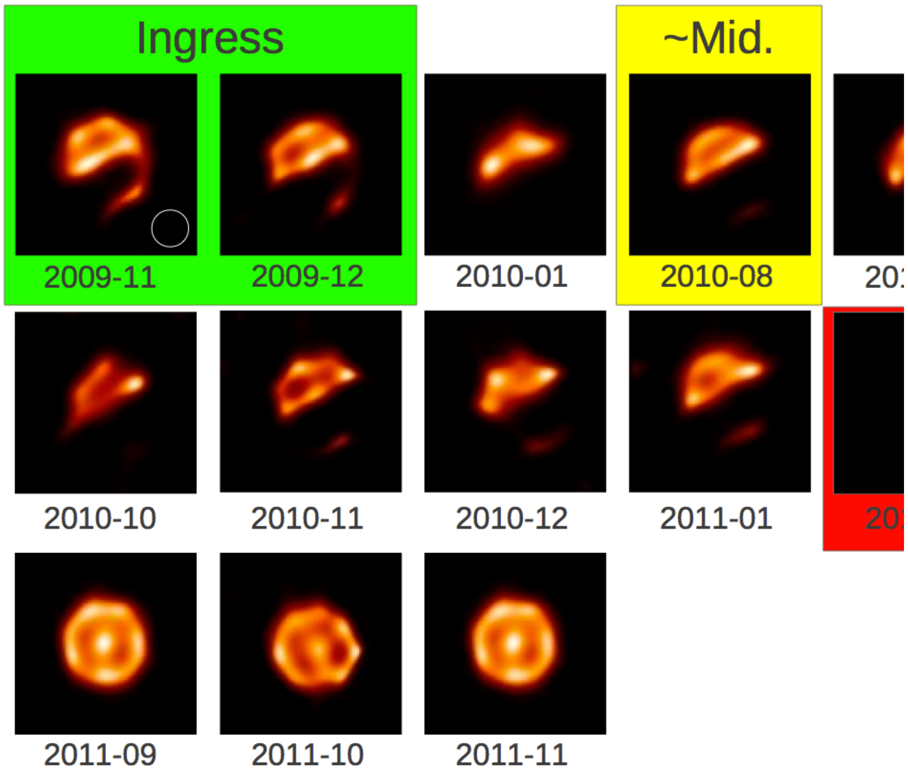


Single line spectroscopic eclipsing binary that undergoes a 50% dimming every 27 years

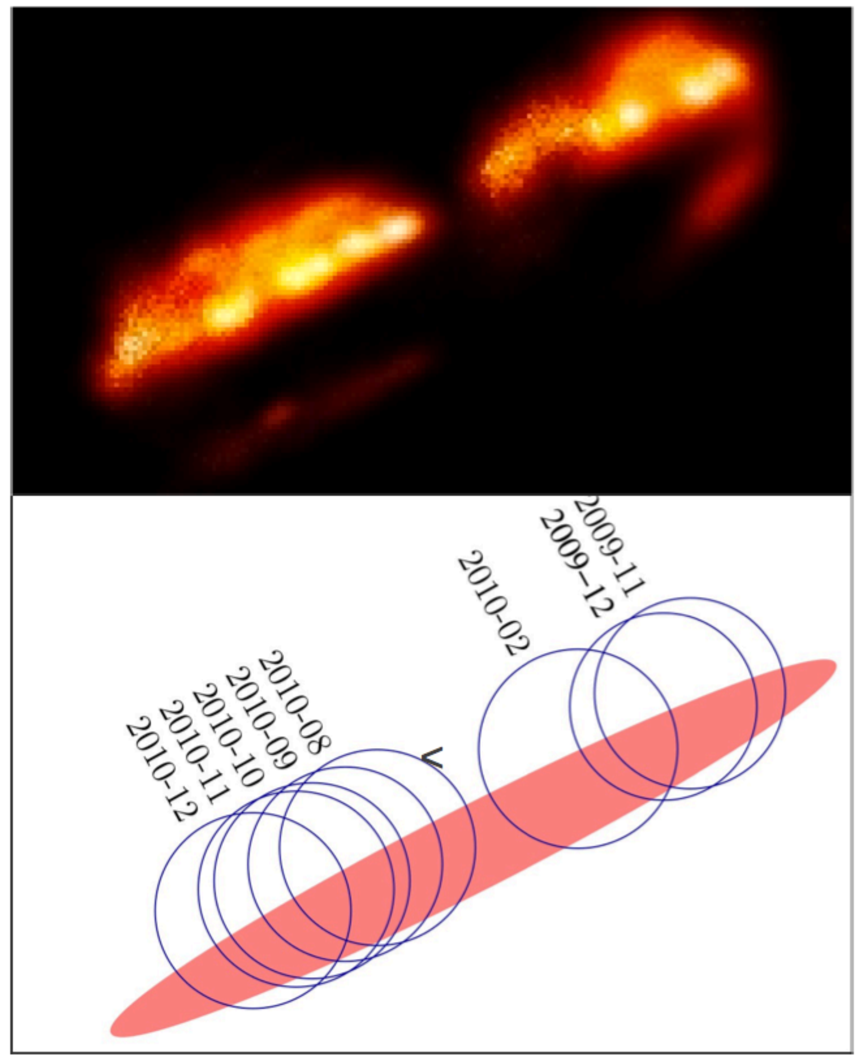
2009 – 2012 Eclipse



ε Aur



The Disk's Silhouette



Ingress images in Kloppenborg et al
(2010, Nature)
Remaining figures to appear in Kloppenborg et al
(2012, in prep)

Summary and Future

- Current optical Interferometers can achieve sub-milliarcsecond angular resolution, able to resolve nearby stellar systems, providing a unique view of how massive stars form and evolve
- Great uv coverage allows CHARA/MIRC to image stellar system without assuming any physical models
- One new on-going project is to image stellar spots to study chromosphere activities.
- Another promising project is to image YSOs after two major upgrades to CHARA/MIRC to improve the system sensitivity.
- 4/5D imaging algorithms are under development