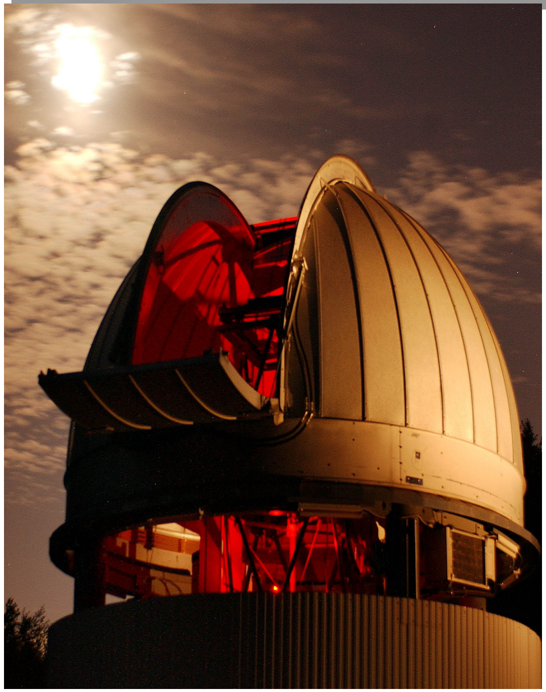
Principles of Interferometry and Science Results at the CHARA Array



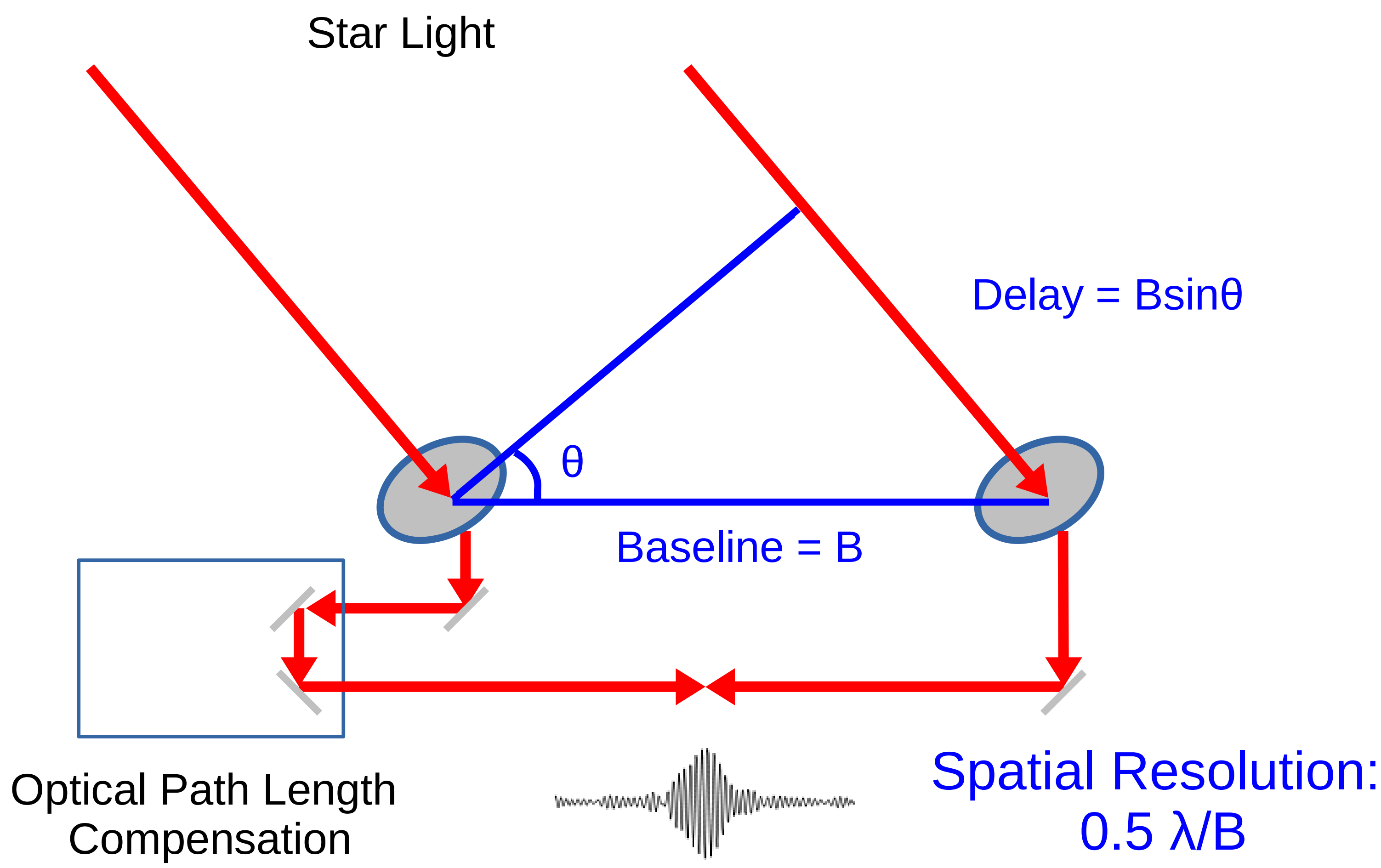
Gail Schaefer

The CHARA Array of Georgia State University

Mount Wilson, CA

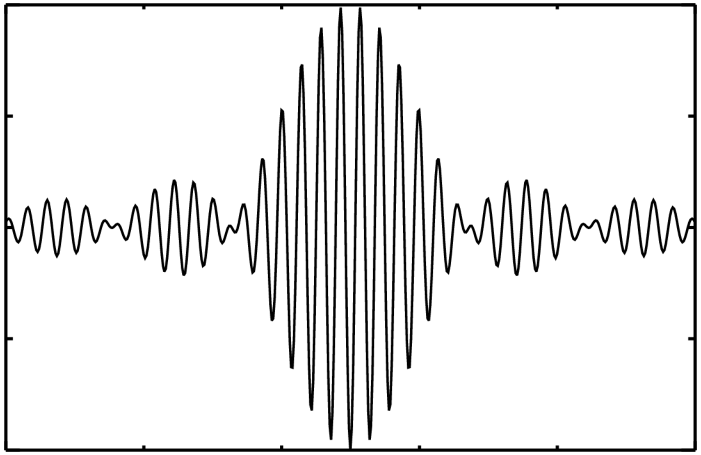
Principles of Interferometry

Interferometer



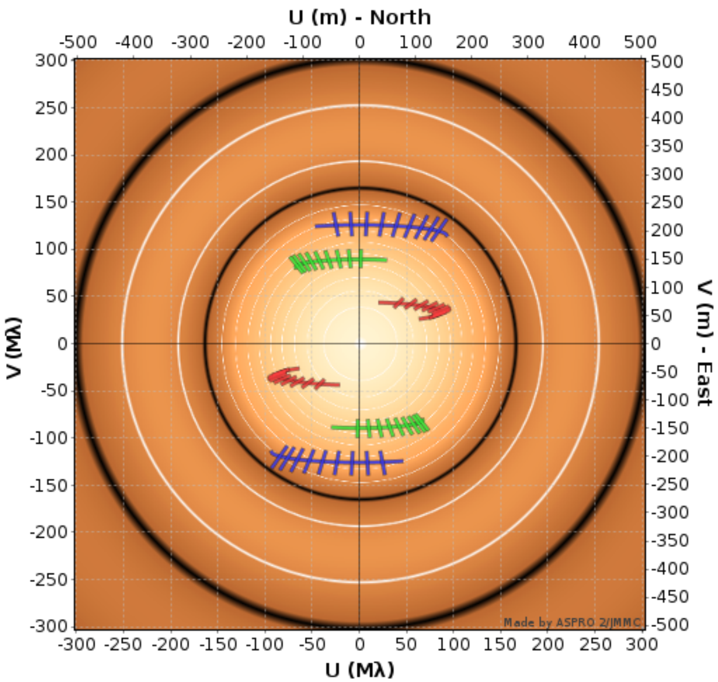
Resolution ~ 0.5 mas for 300 meter baseline in the H-band (1.6 μm)

Fringe Visibility



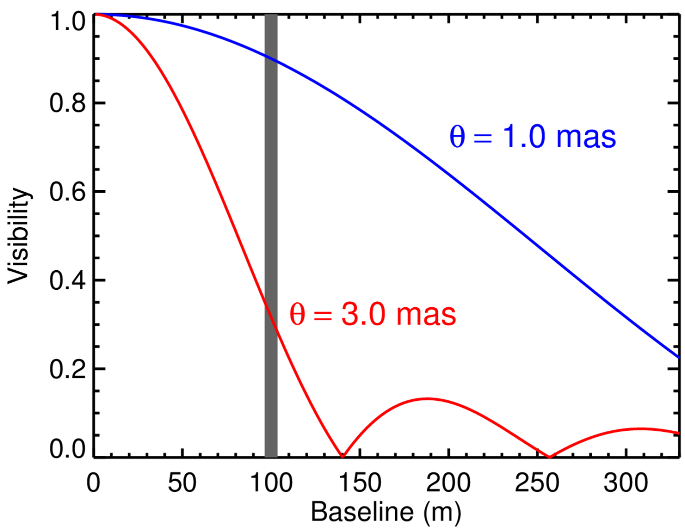
- Amplitude of fringes = Visibility
  - Point Source: V = 1.0
  - Resolved source: loss of coherence reduces fringe visibility
  - Measures the size and geometry of source

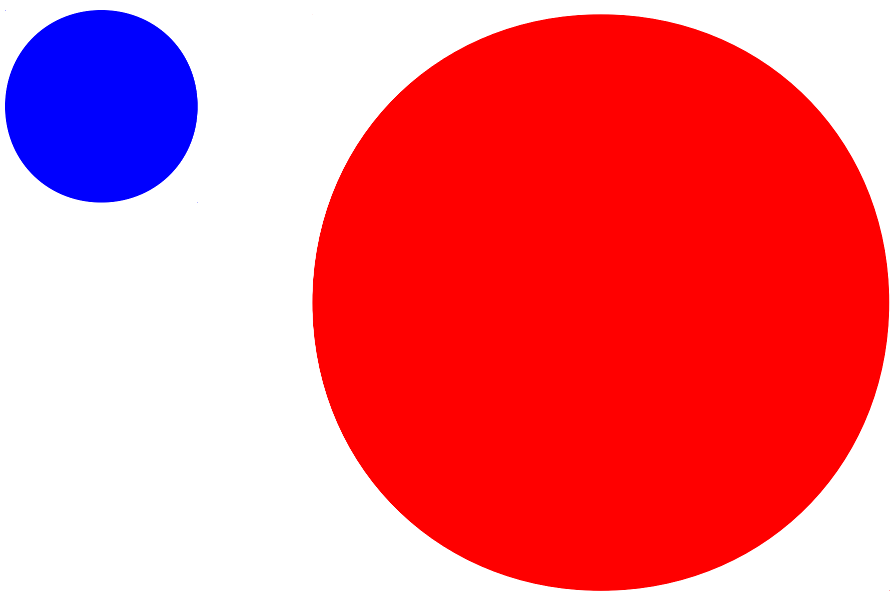
Fringe Visibility



- The visibility is the Fourier Transform of the brightness distribution
- Analytic functions for simple geometries
- Berger & Segransan "Introduction to visibility modeling" 2007, New Ast Rev, 51, 576

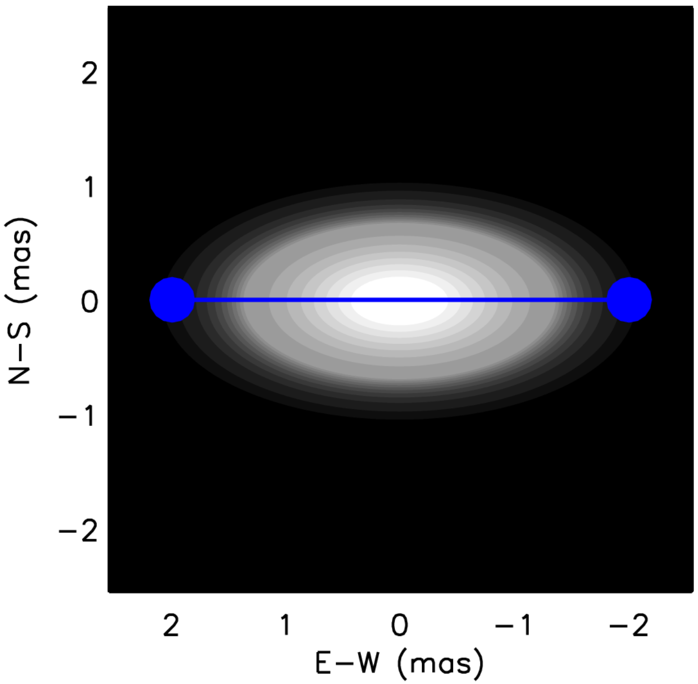
Angular Diameters

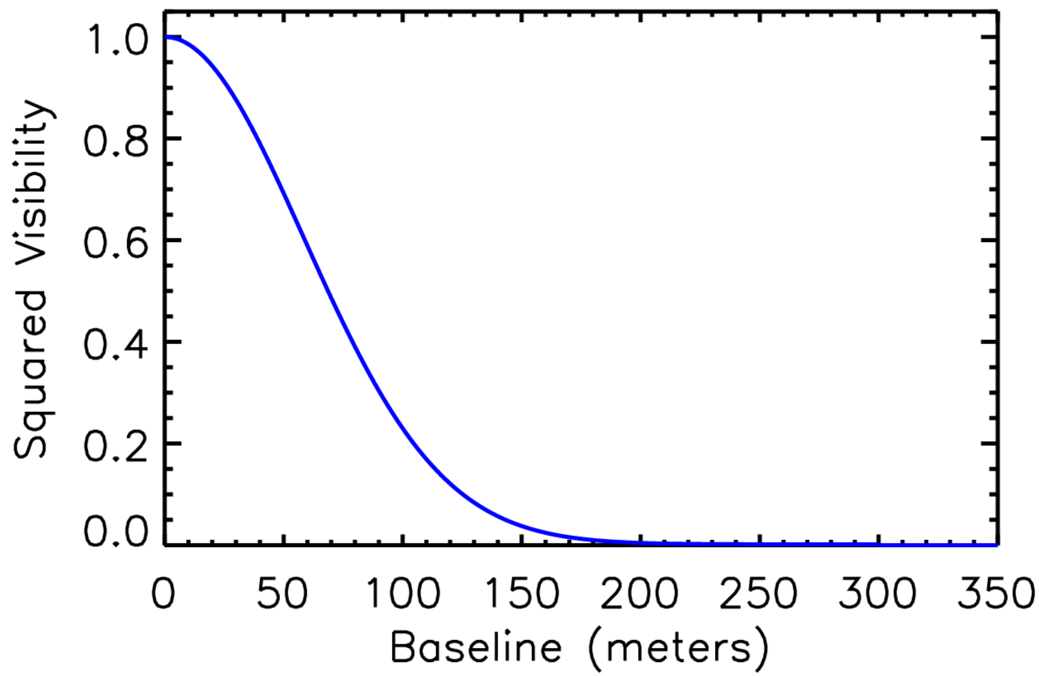




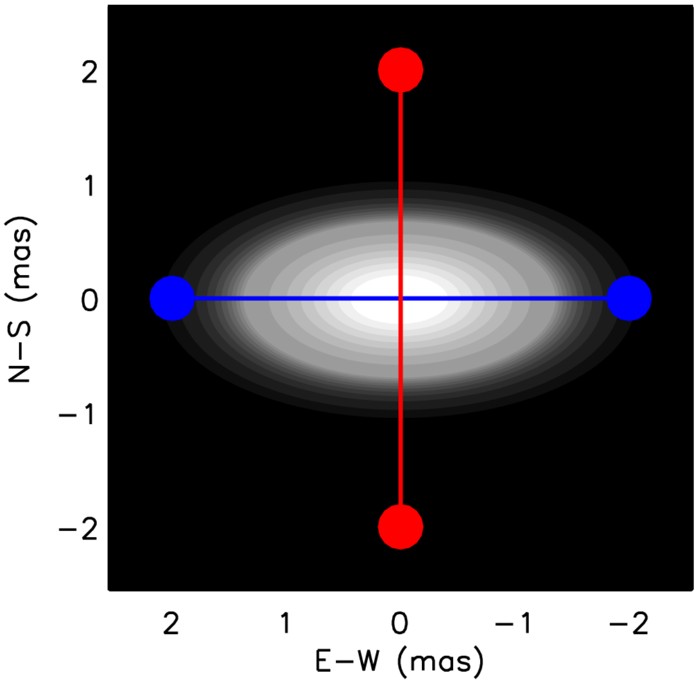
- Visibility amplitude
  - size and structure of source

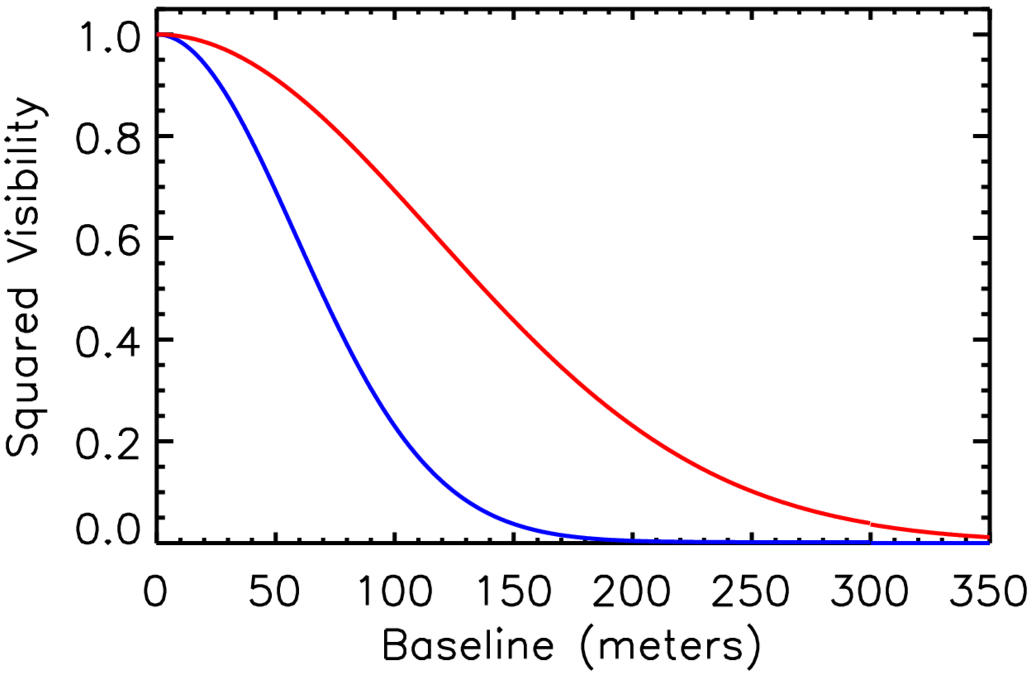
Elliptical Disk



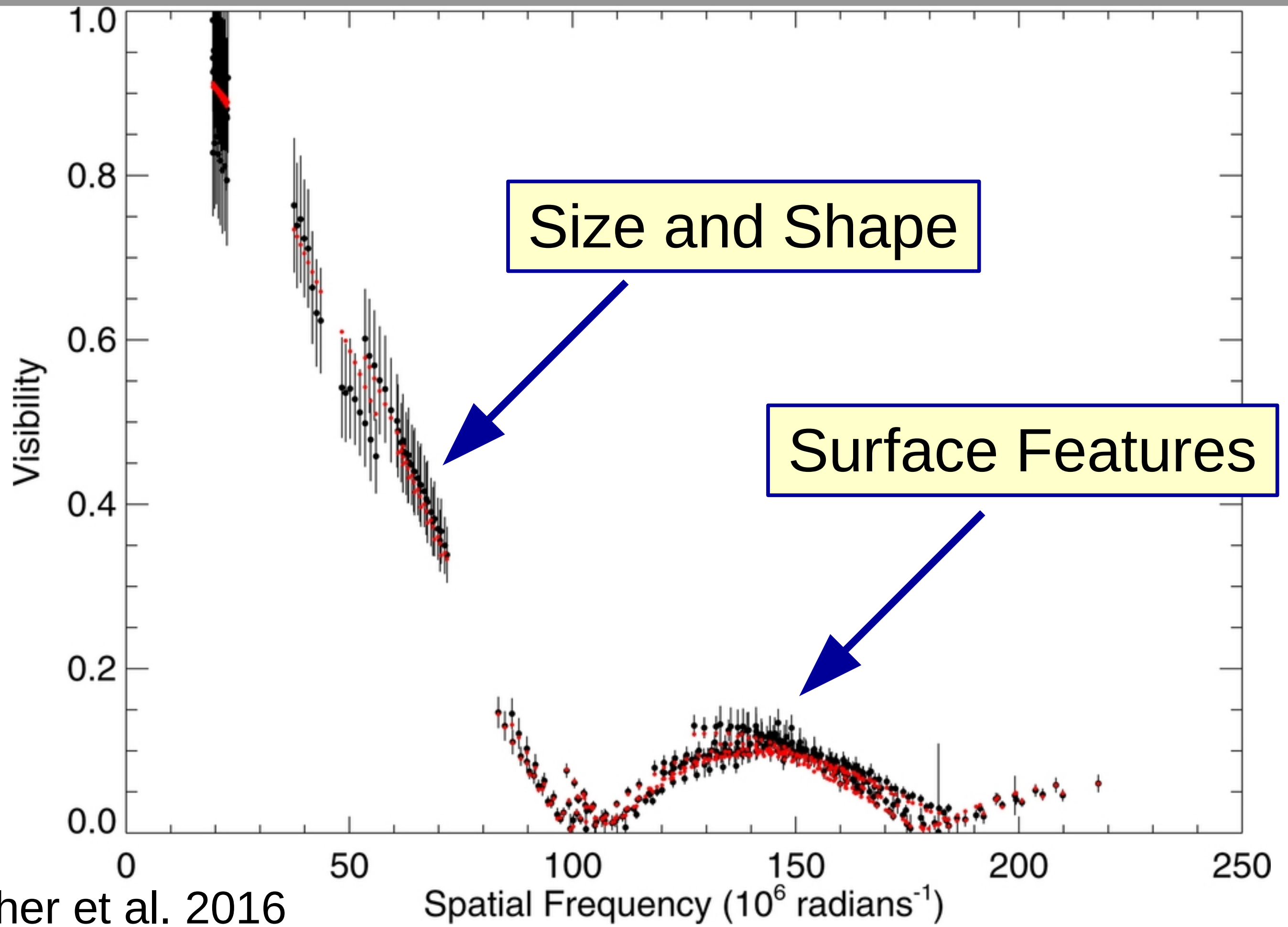


Elliptical Disk



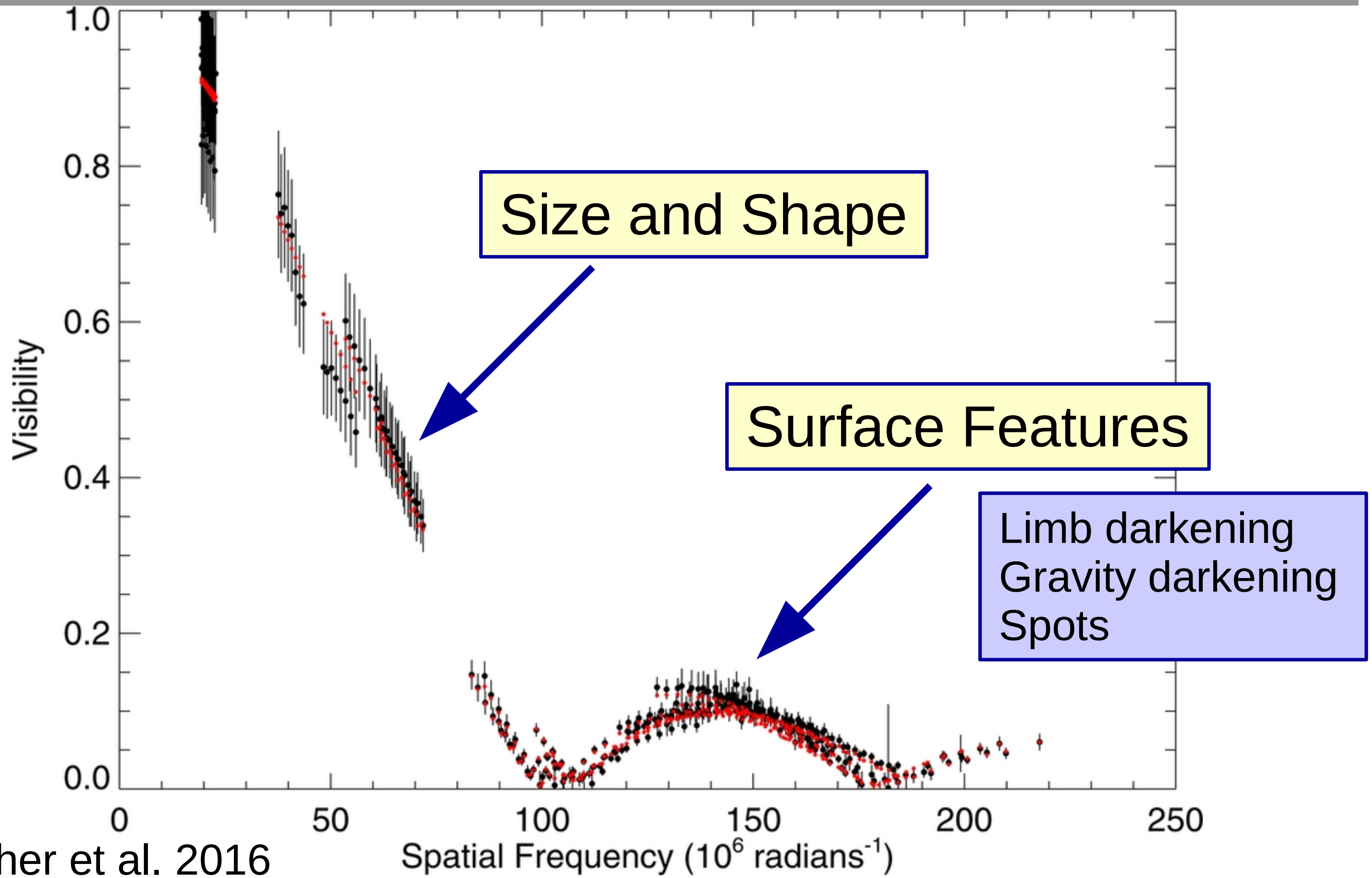


Surface Features



Roettenbacher et al. 2016

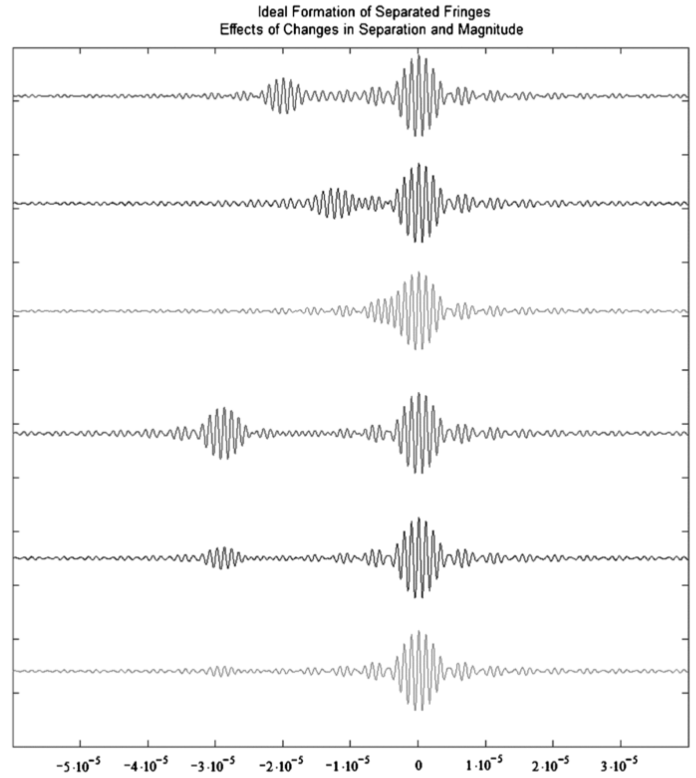
Surface Features



Roettenbacher et al. 2016

Binary Stars

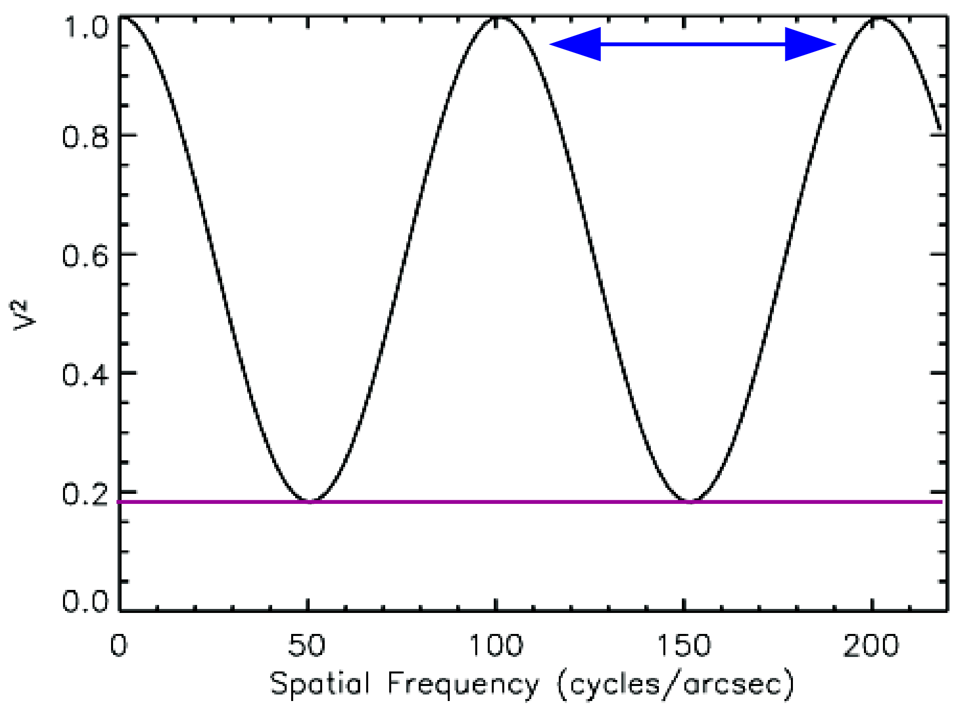
Separated Fringe Packet Binaries



Farrington et al. (2010)

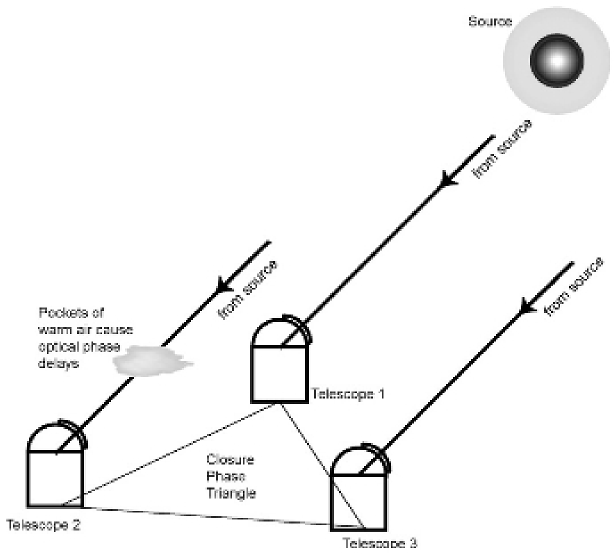
Binary Stars

Visibility Modulation



- Fringe packets for the two components overlap
- Fringe visibility varies periodically
  - binary separation
- Minimum in curve
  - flux ratio = $\frac{1-V_{min}}{1+V_{min}}$

Closure Phase

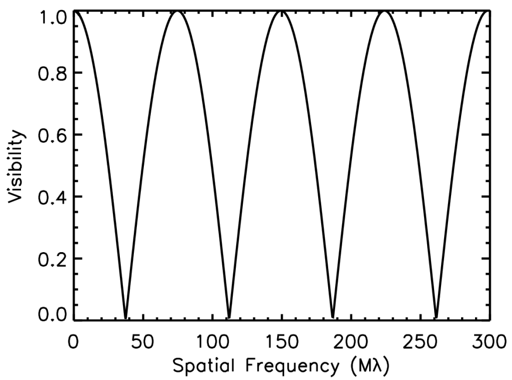


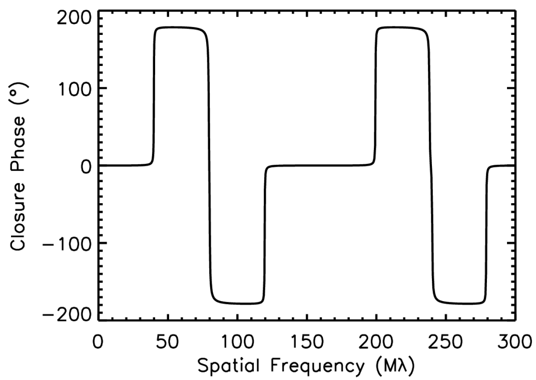
Monnier, "Phases in Interferometry" 2007, New Ast Rev, 51, 604

- Atmosphere corrupts phase information at vis/IR wavelengths
- Closure phase (3 or more telescopes):
  - $CP = \Phi_{12} + \Phi_{23} + \Phi_{31}$
- Cancels atmospheric effects
- Point symmetric object will have closure phase of 0° or 180°
- Measures asymmetries in source distribution

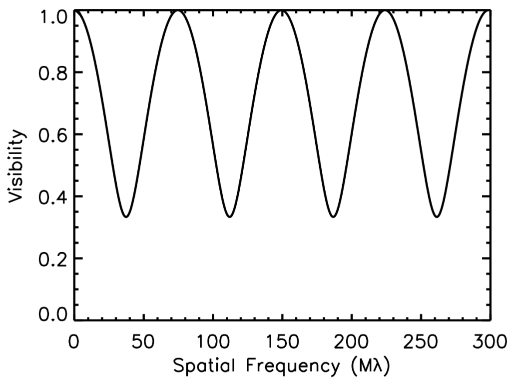
Binary Stars

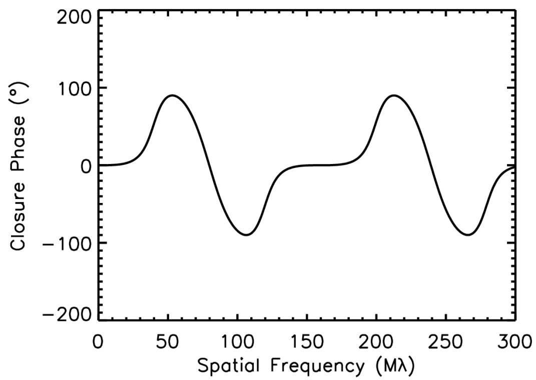
Visibility (S1-E1)   Closure Phase (S1-E1-W1)





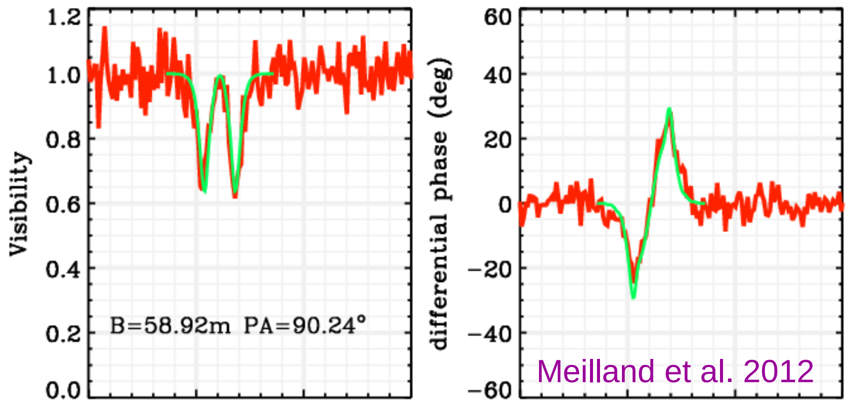
Flux ratio = 0.99





Flux ratio = 0.50

Differential Visibilities and Phases



- Spectrally dispersed interferometry
  - emission lines (BrG, Ha)
  - velocity structure

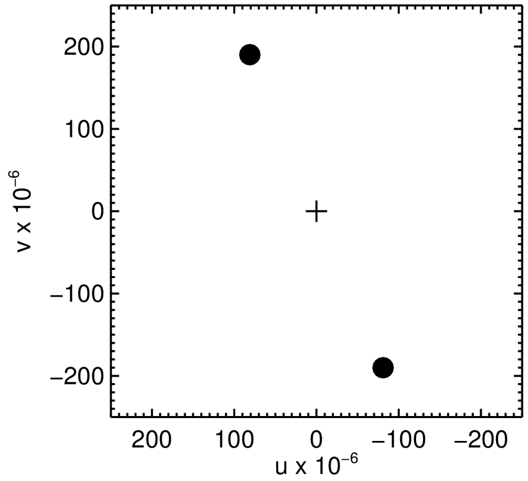
- Drop in visibility across emission line
  - variation in size and flux ratio between star and disk
- “S” shaped profile in differential phase
  - photo-center shift across wavelength channels

Interferometric Observables

- Visibility amplitude
  - size and structure of source
- Closure phase
  - asymmetries in source distribution
- Differential visibilities and phases
  - emission lines
  - velocity structure

UV Coverage

$u = B_x/\lambda$
$v = B_y/\lambda$

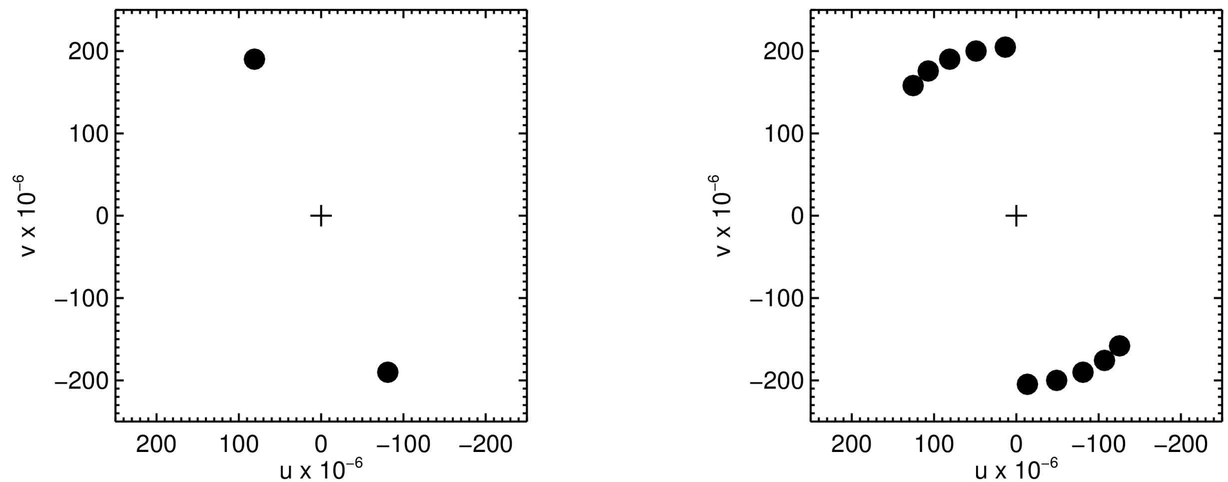


- Inteferometer baseline projected on to plane of sky
- Position angle and projected baseline length will change as the earth rotates

UV Coverage

$u = B_x/\lambda$

$v = B_y/\lambda$



- Inteferometer baseline projected on to plane of sky
- Position angle and projected baseline length will change as the earth rotates

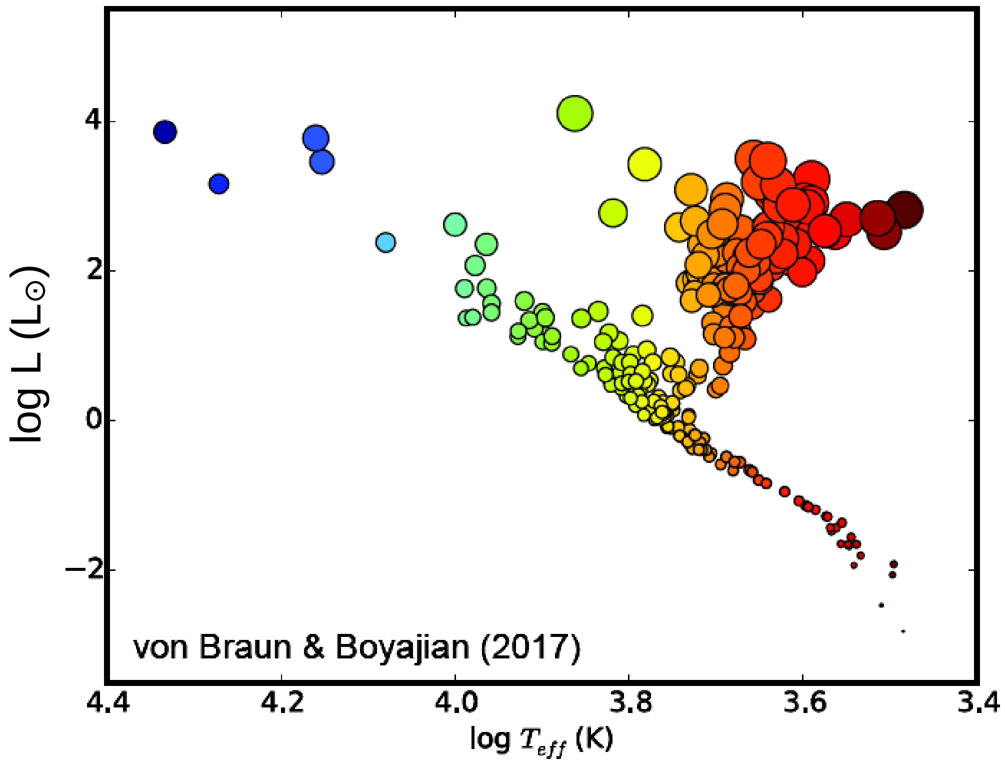
Science Review:

Recent Results at the CHARA Array

Outline

- Stellar Astrophysics
  - Stellar Diameters
  - Rapid Rotation
  - Spotted Stars
- Binary Stars
  - Orbits
  - High Contrast Binaries
  - Interacting Binaries
- Circumstellar Disks
  - Be Stars
  - Young Stellar Objects
- Variable Stars
  - Cepheids
  - Nova Explosions

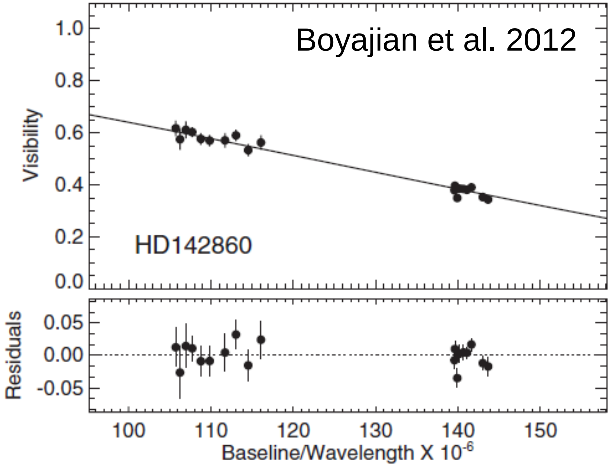
Stellar Diameters



- Empirical HRD
- ~ 290 stars
- σ_θ < 5%
- Derive empirical color-temperature relations

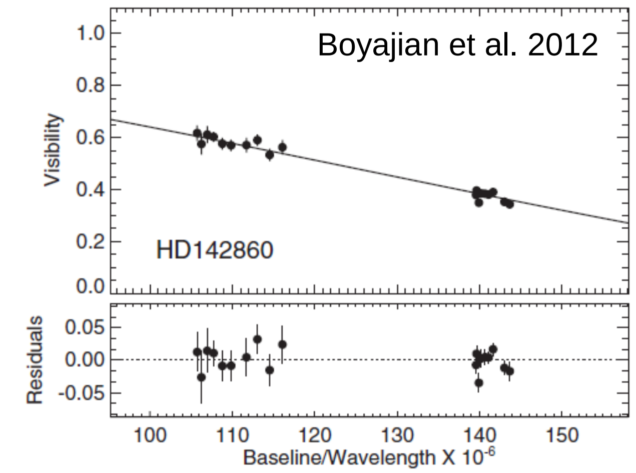
Fundamental Stellar Parameters

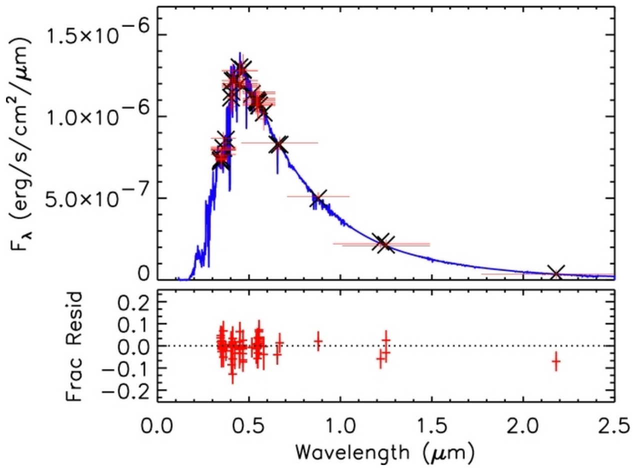
- Angular diameter + parallax
  - Linear radius



Fundamental Stellar Parameters

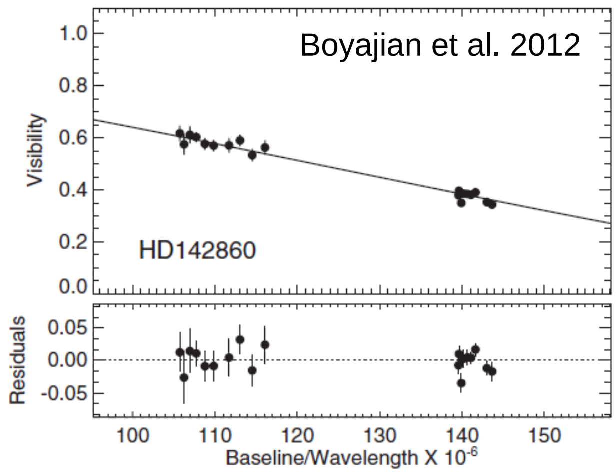
- Angular diameter + parallax
  - Linear radius
- Spectral Energy Distribution
  - Bolometric flux

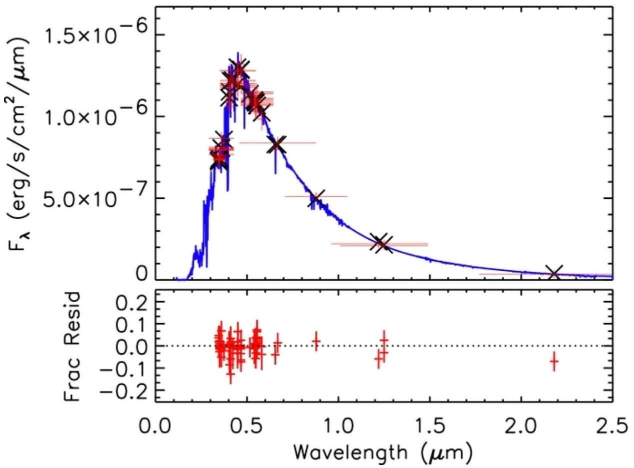




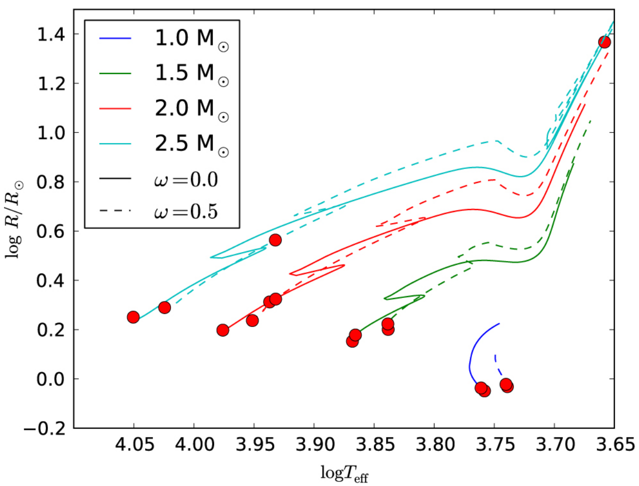
Fundamental Stellar Parameters

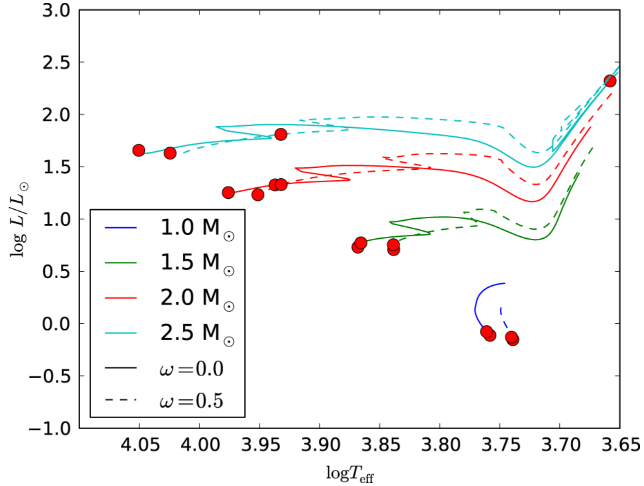
- Angular diameter + parallax
  - Linear radius
- Spectral Energy Distribution
  - Bolometric flux
- Effective Temperature
  - $F_{bol} = \frac{1}{4} \theta^2 \sigma T^4$



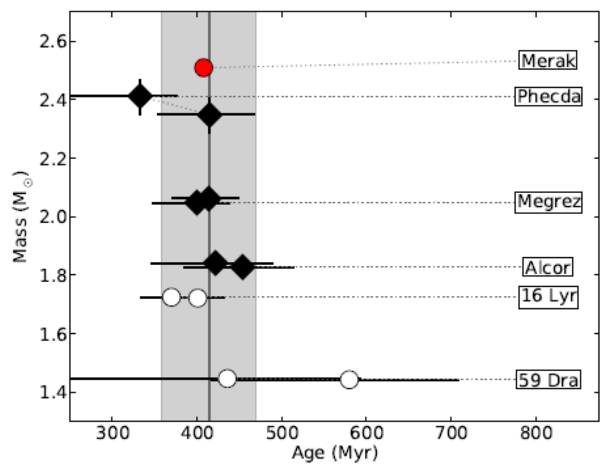


Ages of Stars





- Diameters of 7 A-type stars in Ursa Major moving group
- Compare with evolutionary models that include rotation (mass, age)
- Age = 414 ± 23 Myr
- Jones et al. 2015



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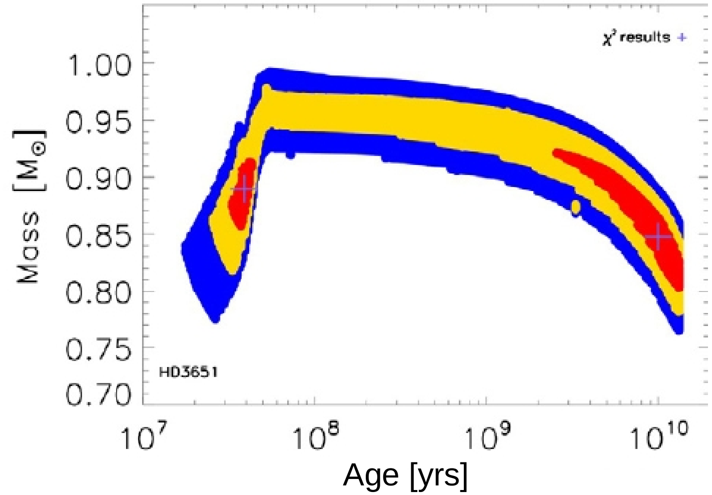
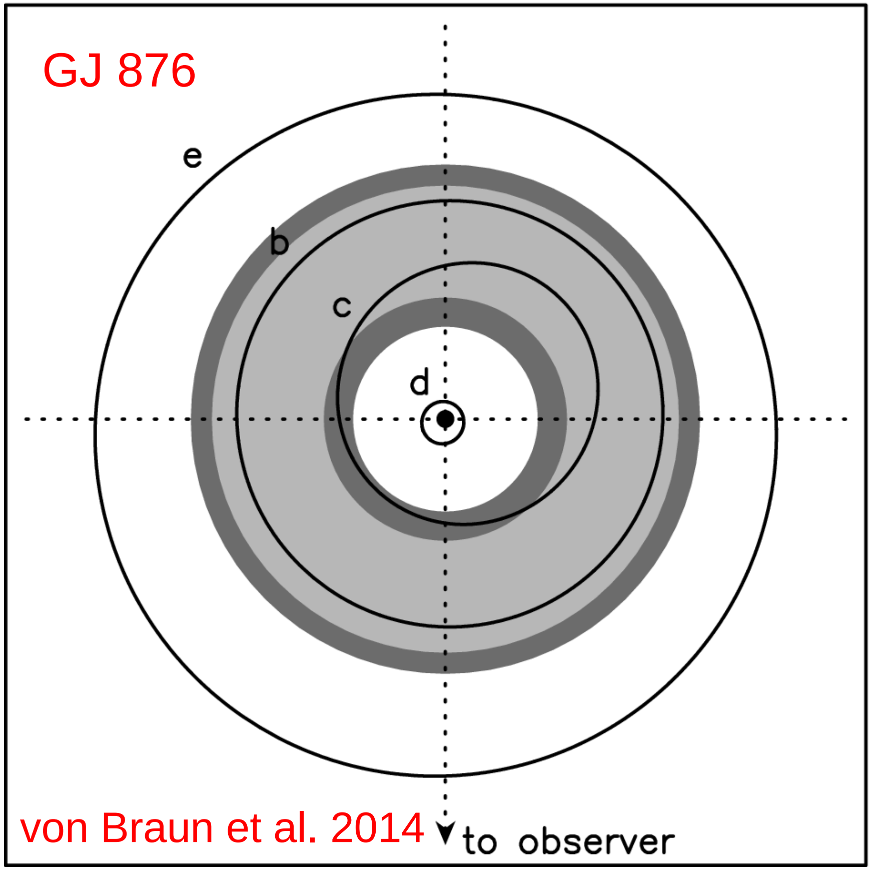
Ages of Stars



Ligi et al. 2016

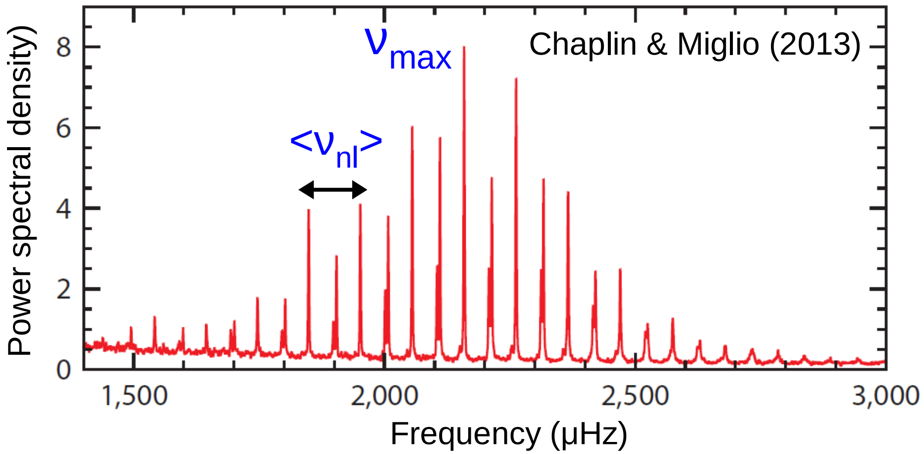
- Diameters of 18 bright exoplanet host stars and candidates
- Compare (R, Teff) with evolutionary tracks to compute mass and age estimates
- Typically, two distinct solutions (old and young age)

Exoplanet Host Stars



- Size of habitable zones
  - L, Teff
- Age and mass of host star
- Physical parameters of planets
  - Radius of transiting planets

Asteroseismology

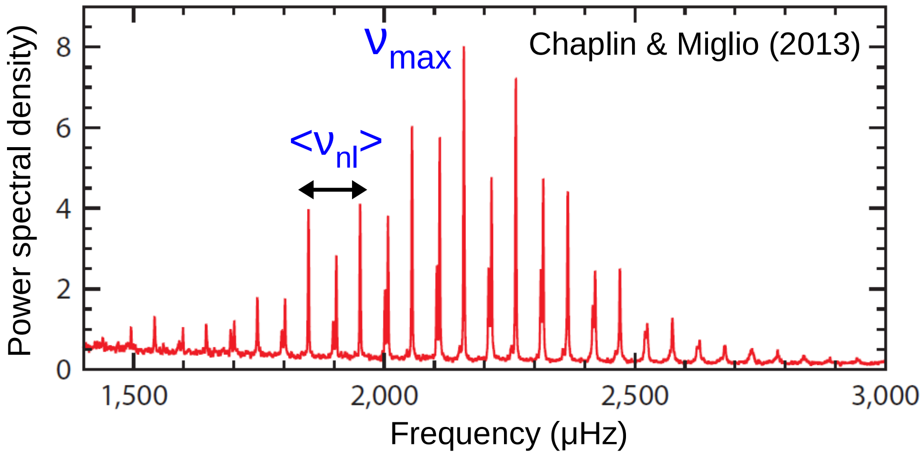


Mass, radius, mean density, and surface gravity (need Teff)

$\nu_{max} \propto (M / R^2)\ (T_{eff})^{-0.5}$
$<\nu_{nl}> \propto <\rho>^{0.5}$

Oscillation power spectrum
$<\nu_{nl}>$: frequency separation of modes
ν_{max}: frequency of maximum power

Asteroseismology



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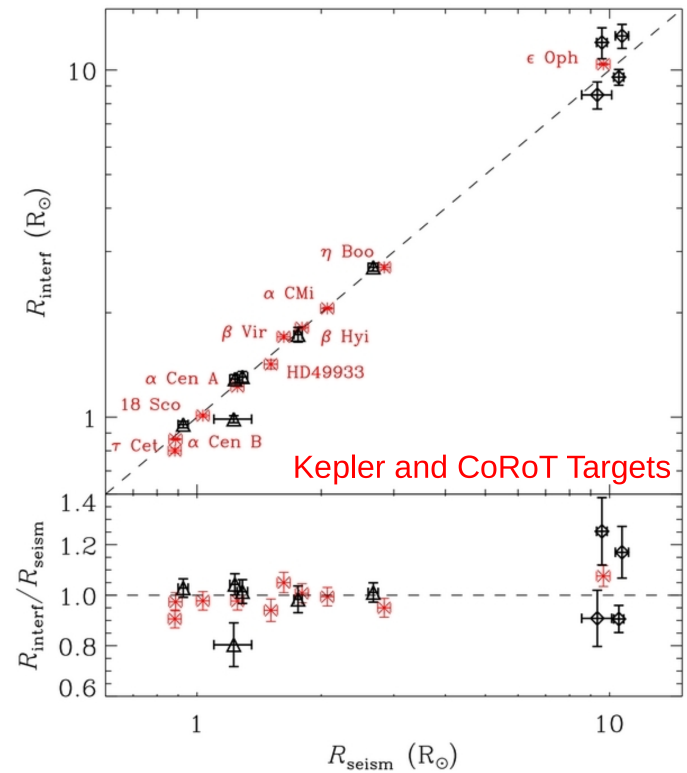
Oscillation power spectrum

$\langle \nu_{nl} \rangle$: frequency separation of modes

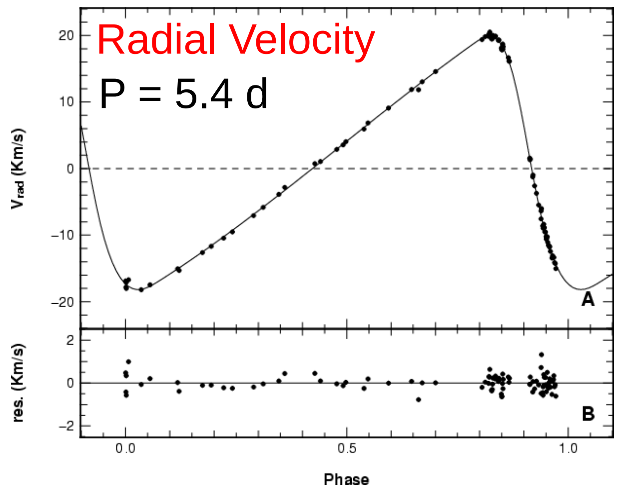
ν_{max}: frequency of maximum power

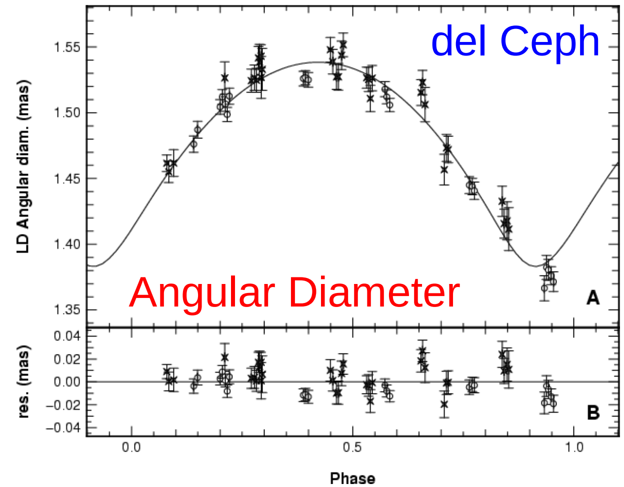


Test asteroseismic scaling relations for main sequence stars

Huber et al. (2012)

Cepheids

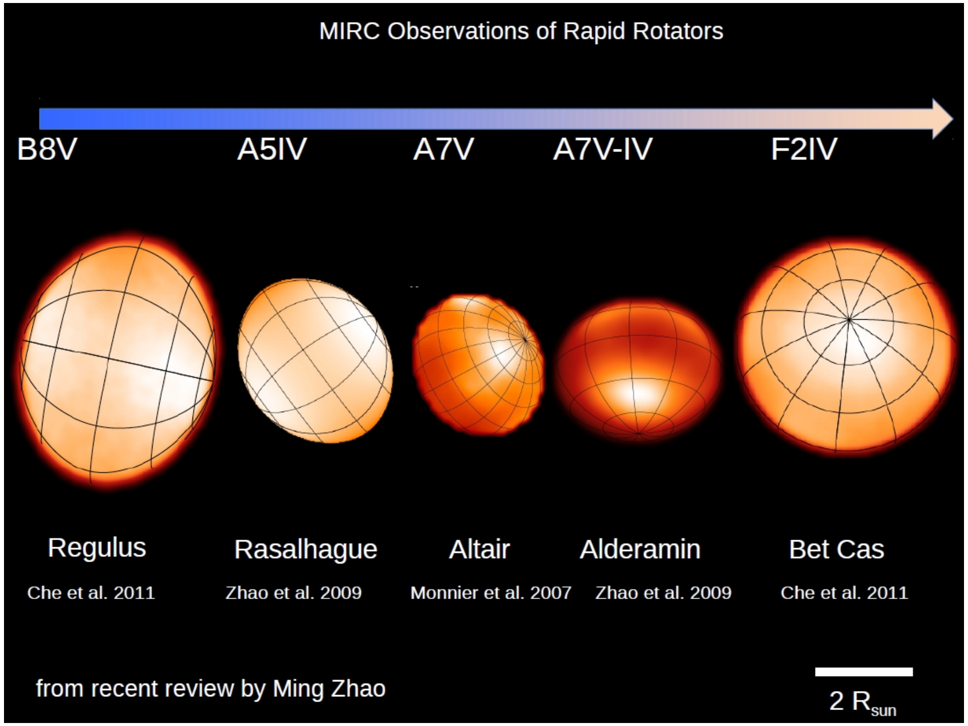




Merand et al 2005

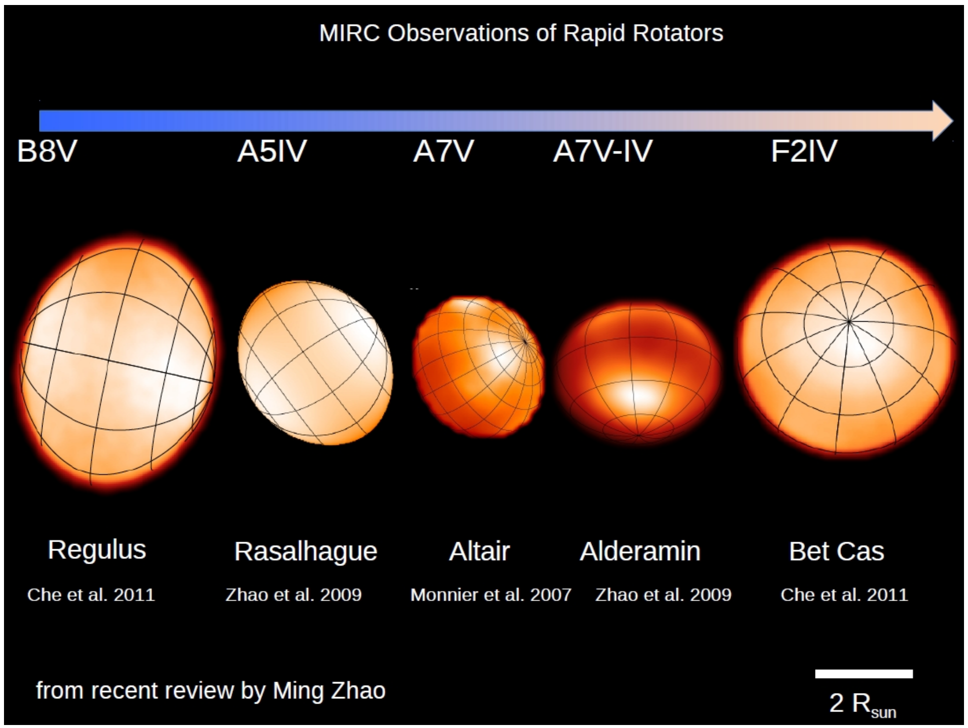
- Radial velocity and angular diameter variation over pulsational phase
- Calibration of Baade-Wesselink technique - pulsation parallaxes
- Simultaneously fit photometry, spectroscopy, interferometry (Merand et al. 2015)
  - Mitigate systematics in projection factor
  - 2% accuracy on radius and distance

Rapid Rotators

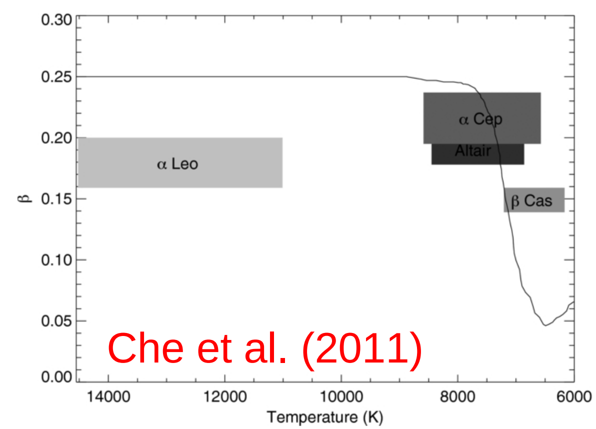


- Oblateness
- Gravity darkening
  - $T_{eff} \sim g^{\beta}$

Rapid Rotators

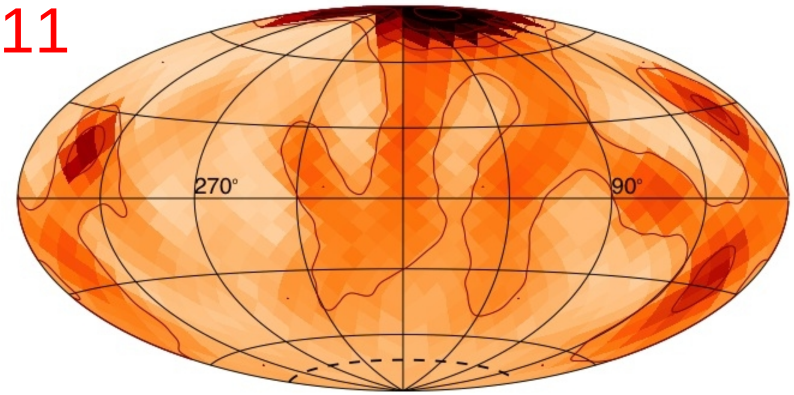


- Oblateness
- Gravity darkening
  - $T_{eff} \sim g^{\beta}$
  - von Zeipel model: β = 0.25
  - empirically derived β = 0.19

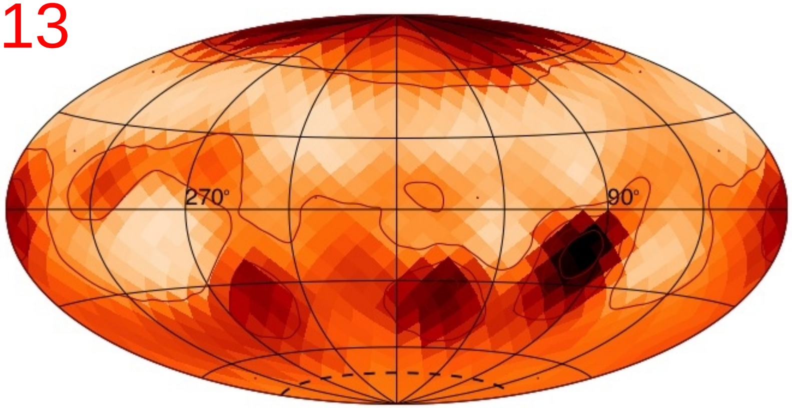


Spotted Stars

2011



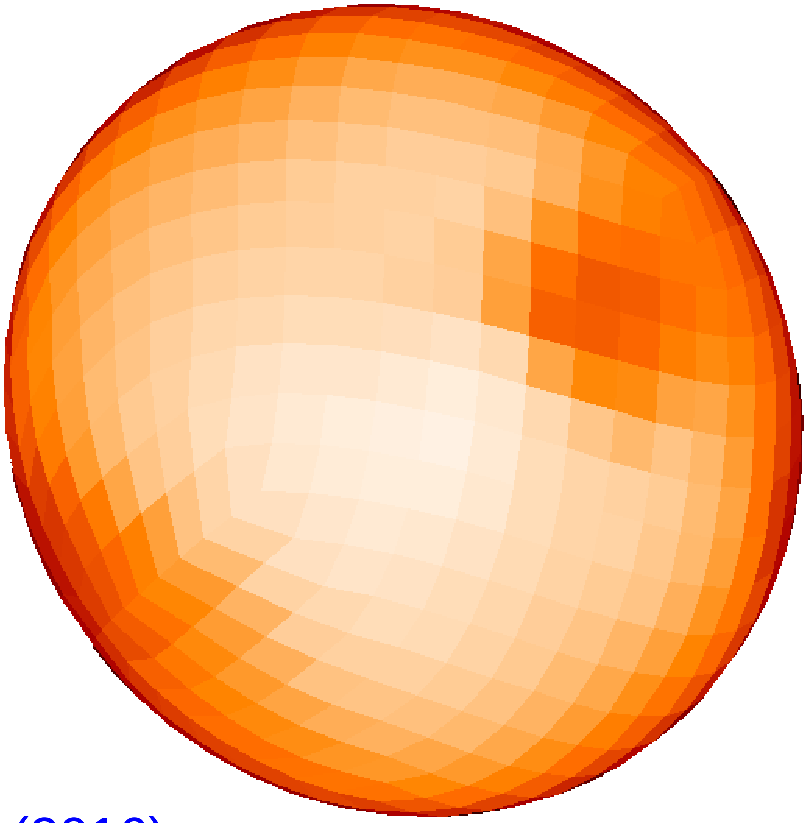
2013



- Magnetically active star zeta Andromedae
- Rotation Period: 18 days
- θ = 2.502 ± 0.008 mas
- Direct confirmation of persistent polar spot
- Transient lower latitude spots
- Can't be explained by solar dynamo

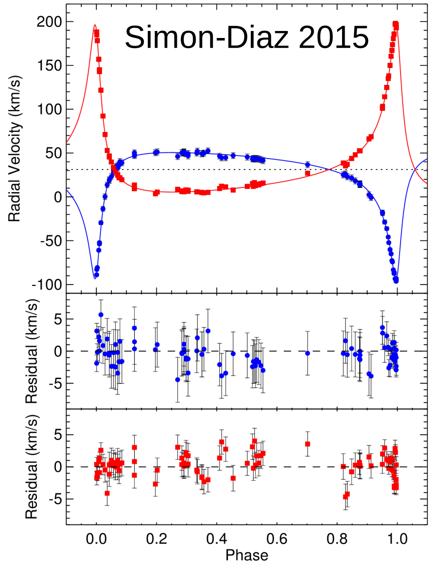
Roettenbacher et al. (2016)

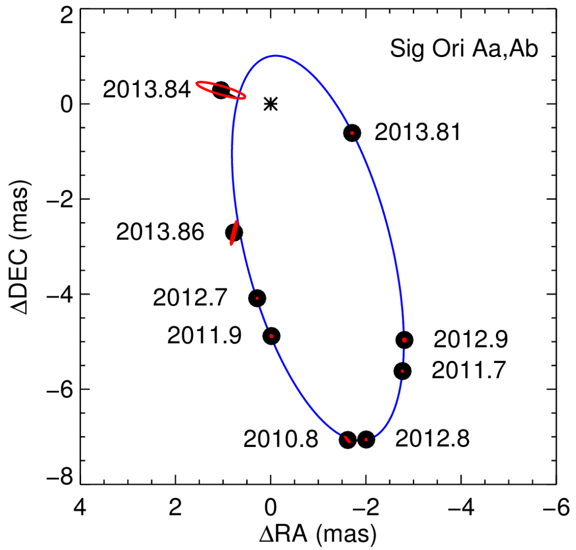
Spotted Stars



Roettenbacher et al. (2016)

O-Star Triple
Sigma Orionis



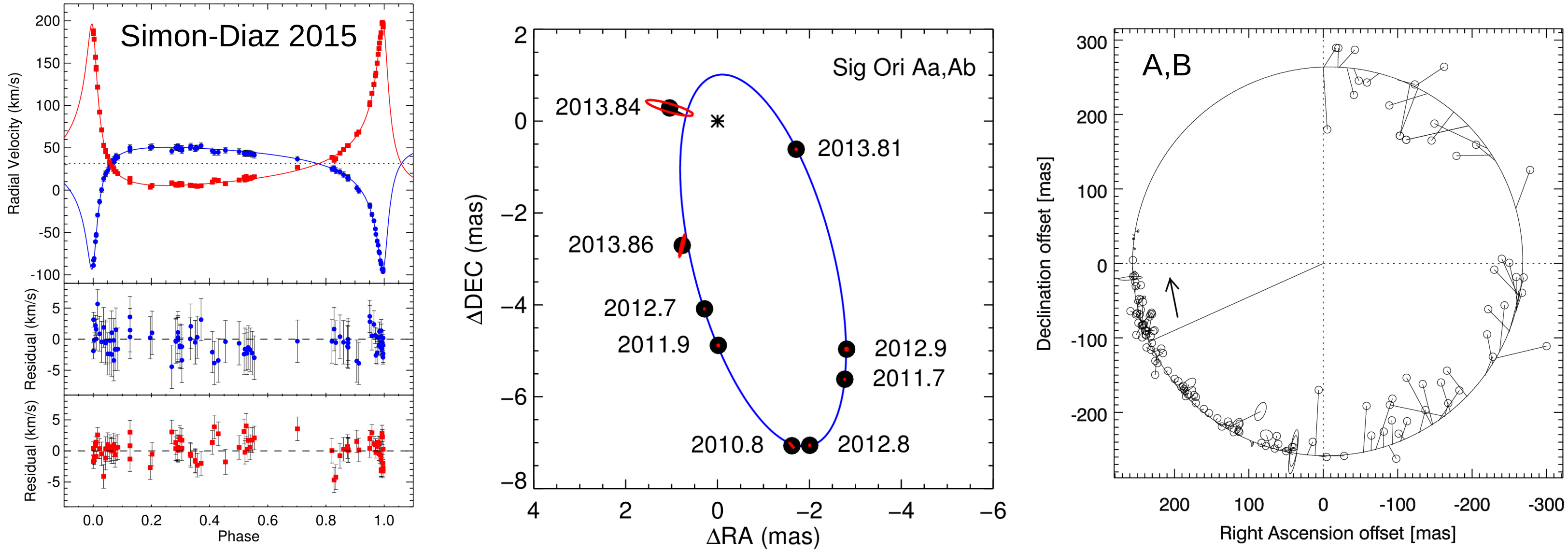


Schaefer et al. 2016

- Dynamical masses for O-stars
- Distance to sigma Orionis cluster

MAa = 16.99 ± 0.20 $M_\odot$
MAb = 12.81 ± 0.18 $M_\odot$
d = 387.5 ± 1.3 pc

O-Star Triple Sigma Orionis



Schaefer et al. 2016

MAa = 16.99 ± 0.20 $M_\odot$
MAb = 12.81 ± 0.18 $M_\odot$
d = 387.5 ± 1.3 pc

- Dynamical masses for O-stars
- Distance to sigma Orionis cluster
- Inner and outer orbits are not co-planar (120 – 127 deg)

Interacting Binaries

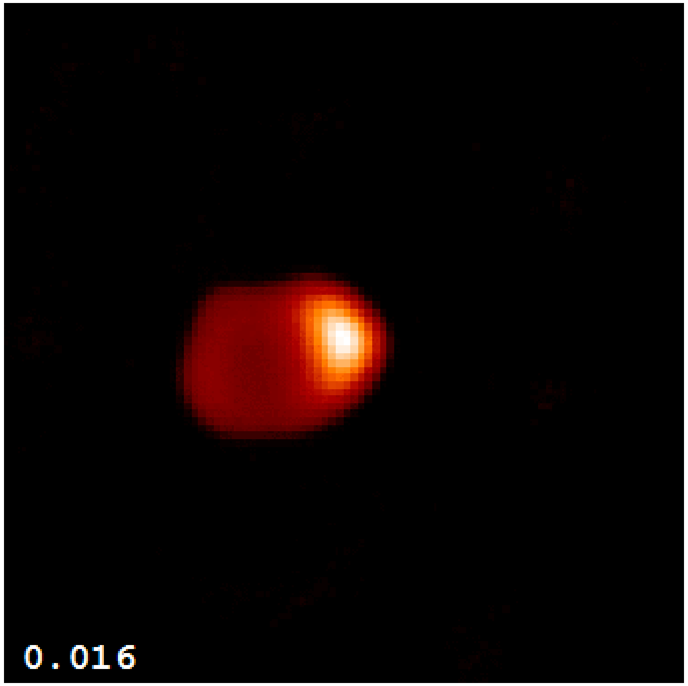
Beta Lyrae

P = 13 days
a = 0.87 mas

Zhao et al. (2008)

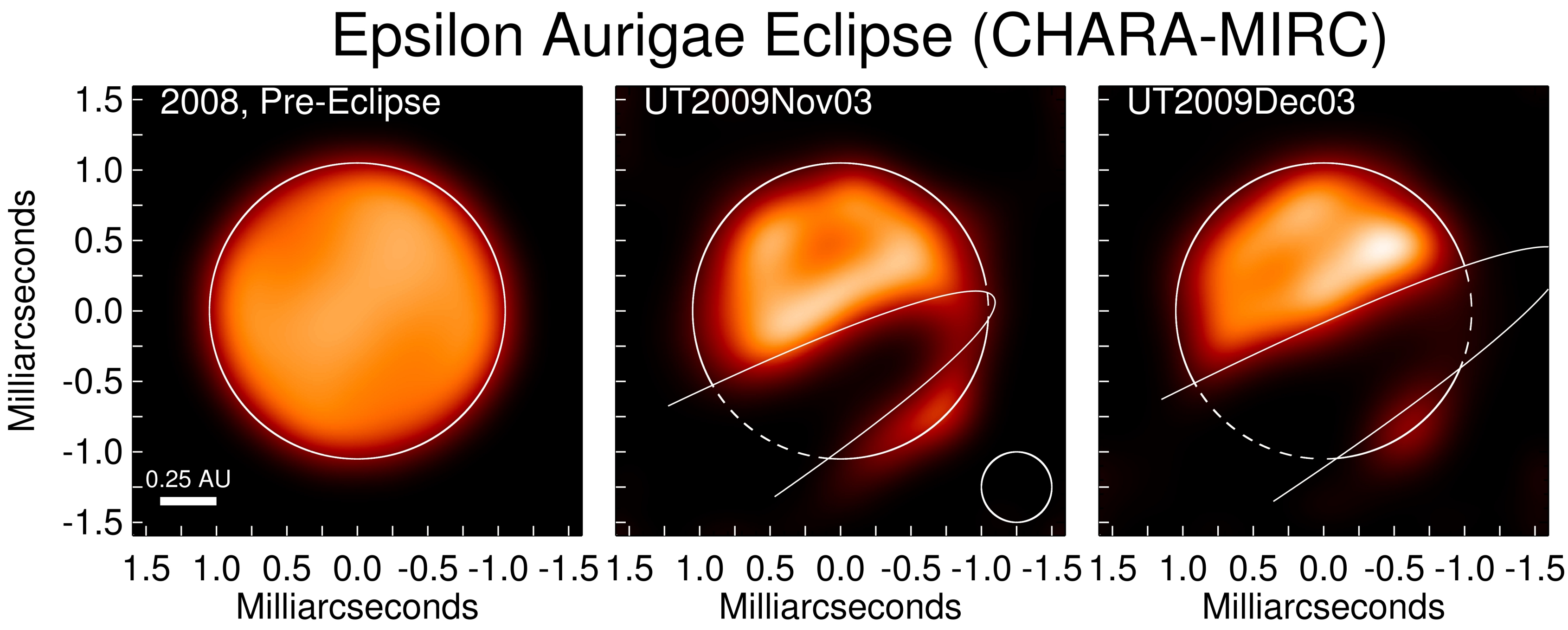
Algol

P = 2.9 days
a = 2.2 mas



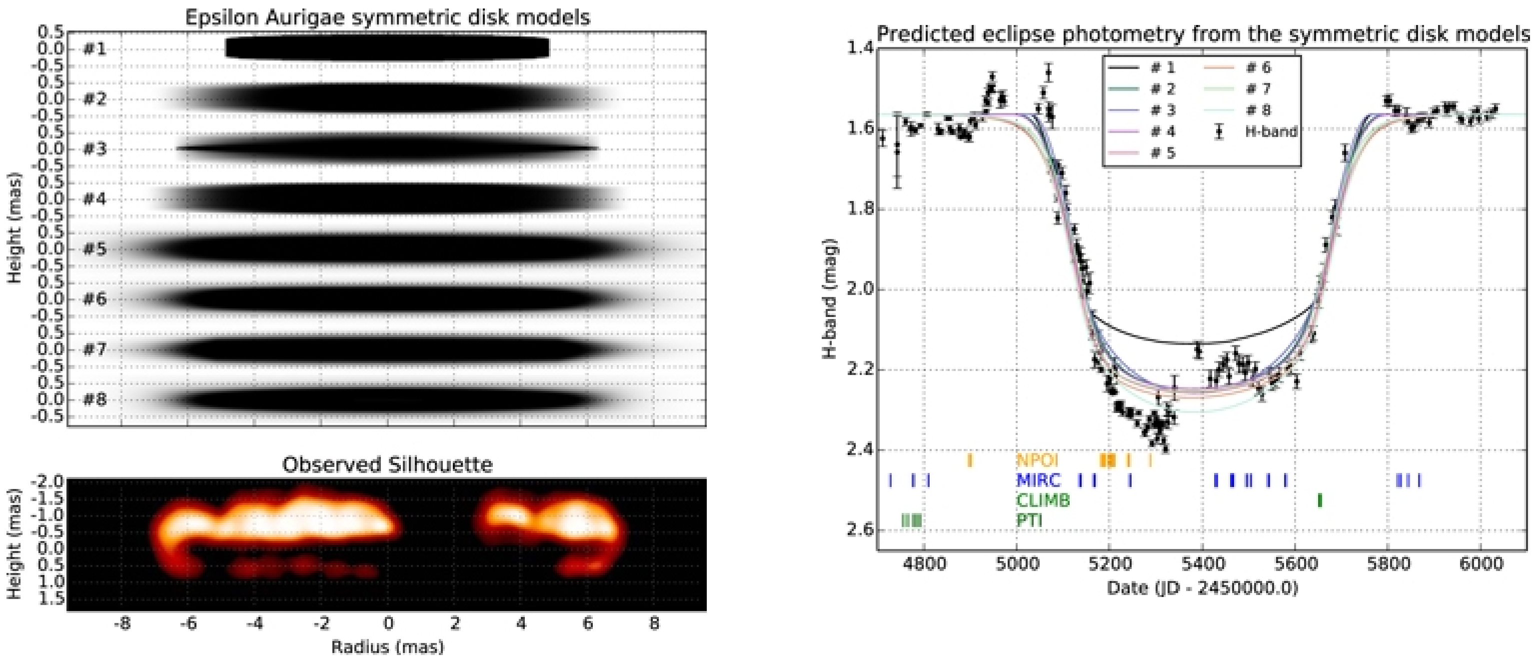
Baron et al. (2012)

Transiting Disk: Epsilon Aurigae



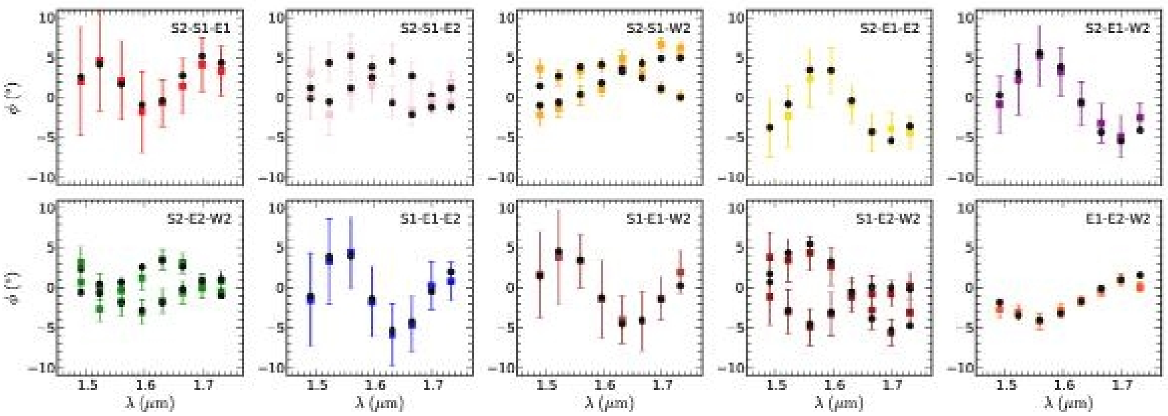
Kloppenborg et al. (2010)

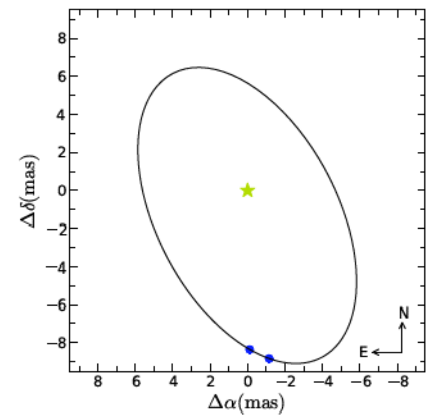
Transiting Disk: Epsilon Aurigae

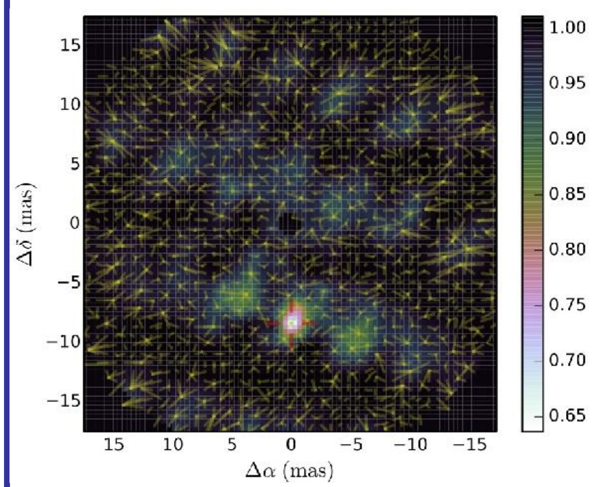


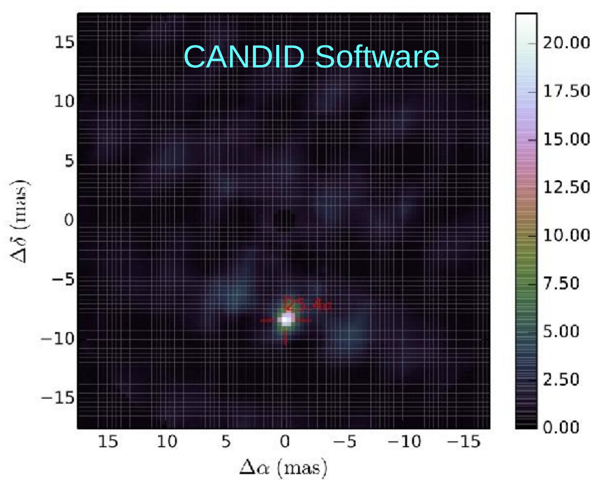
Kloppenborg et al. (2015)

High Contrast Binaries





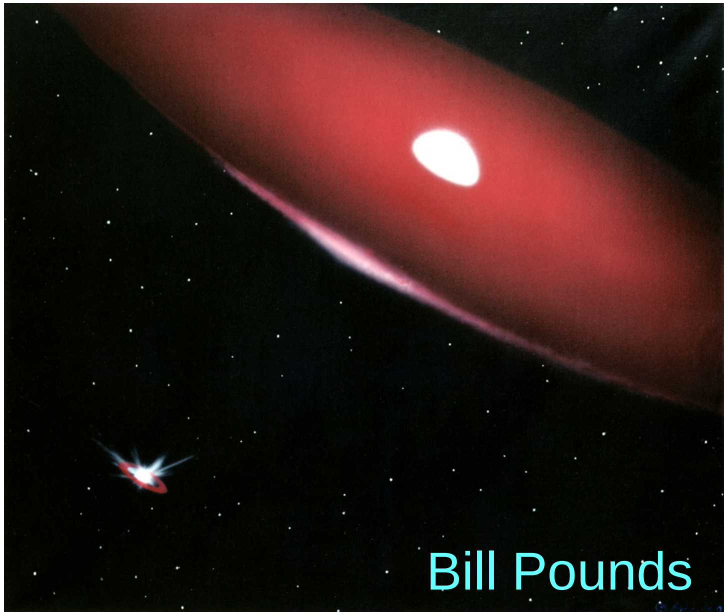




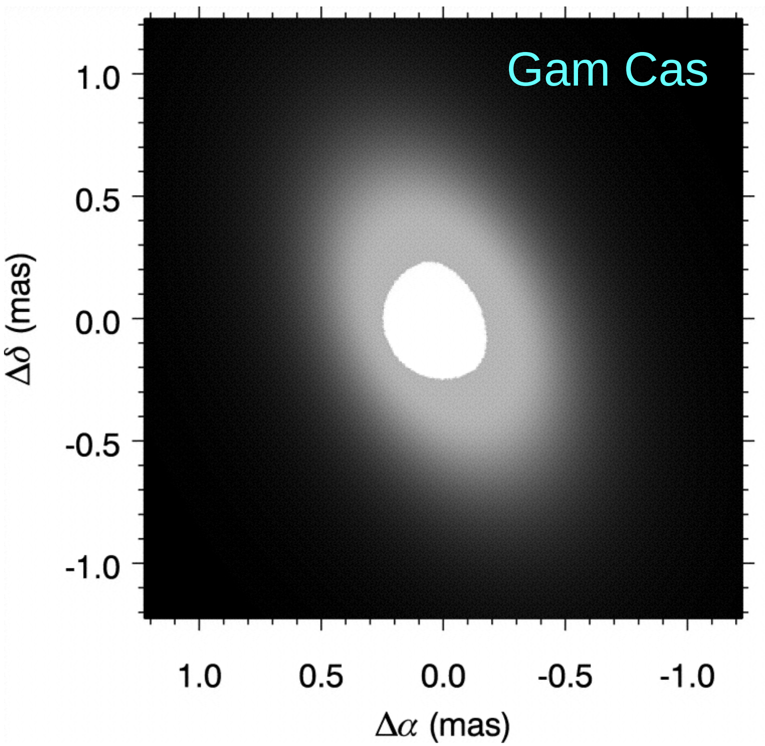
- Cepheid V1334 Cyg
- P = 5 yr
- Companion contributes 3.1% of flux
- Gallenne et al. (2013,2015)

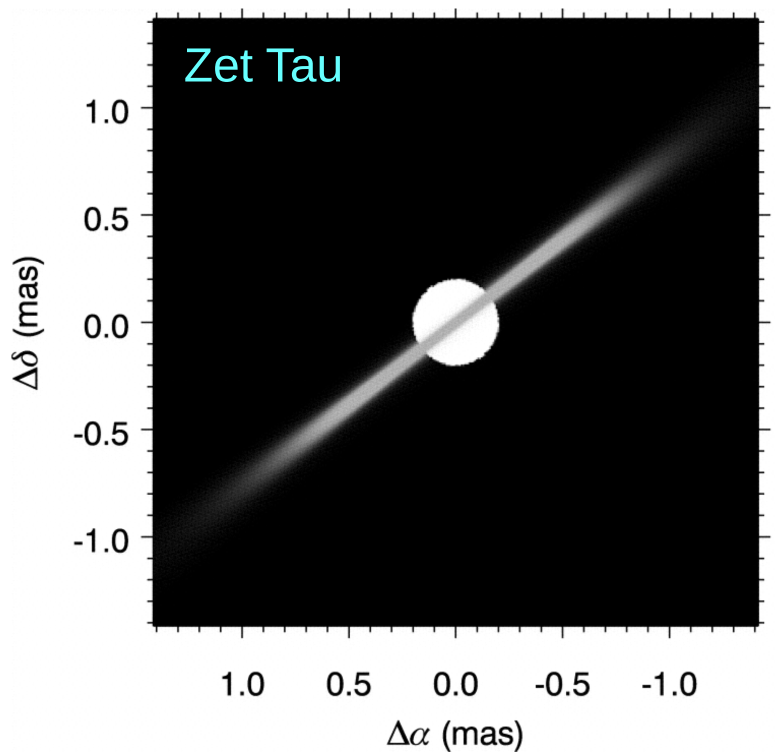
Be Stars

- Rapidly rotating B-type stars that eject gas into a circumstellar disk
- Evidence for the disks
  - Rotationally broadened emission lines
  - IR excess
  - Linear polarization
  - Spatially resolved through interferometry
- Variable on time-scales of days to decades



Be Stars

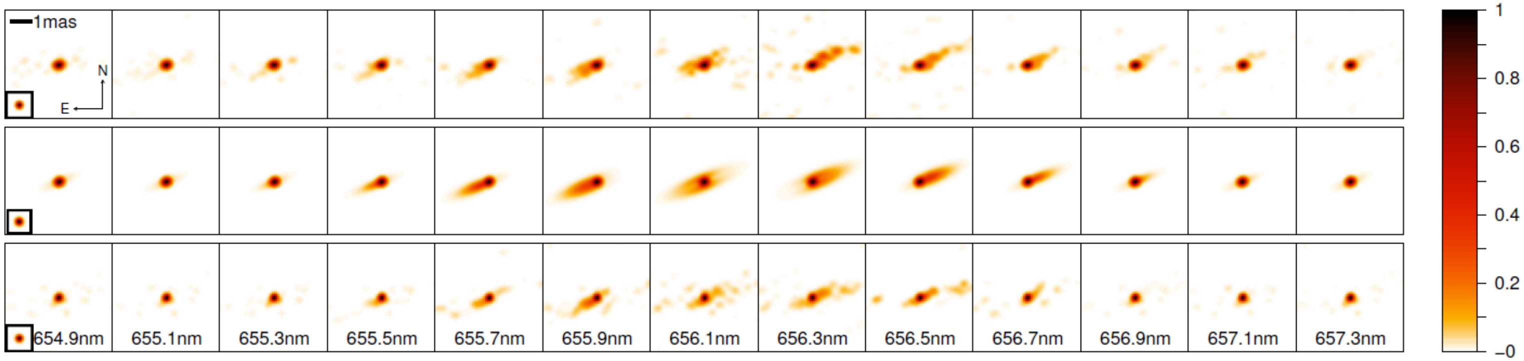


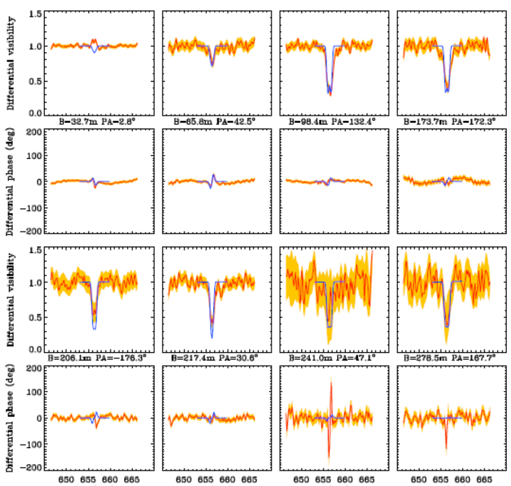


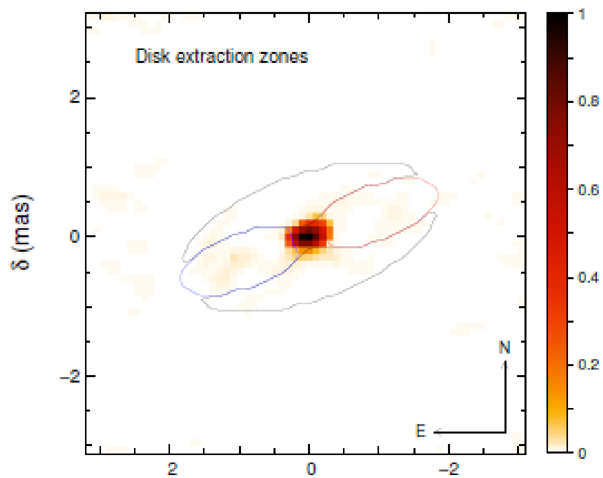
Geometry and physical structure of disks

Gies et al. (2007)

Kinematic Model
Be Stars



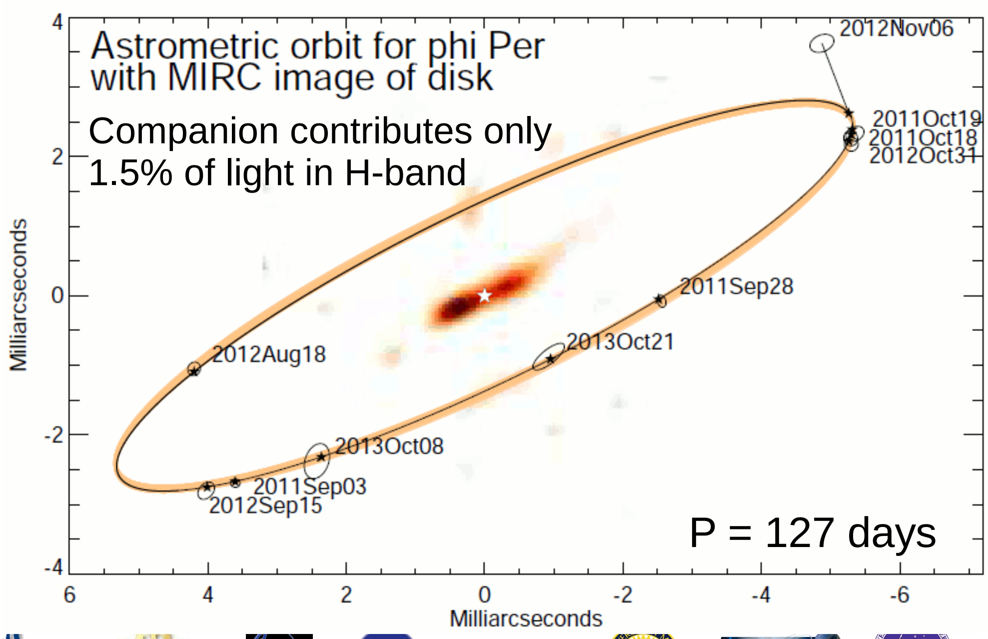




Mourard et al. 2015

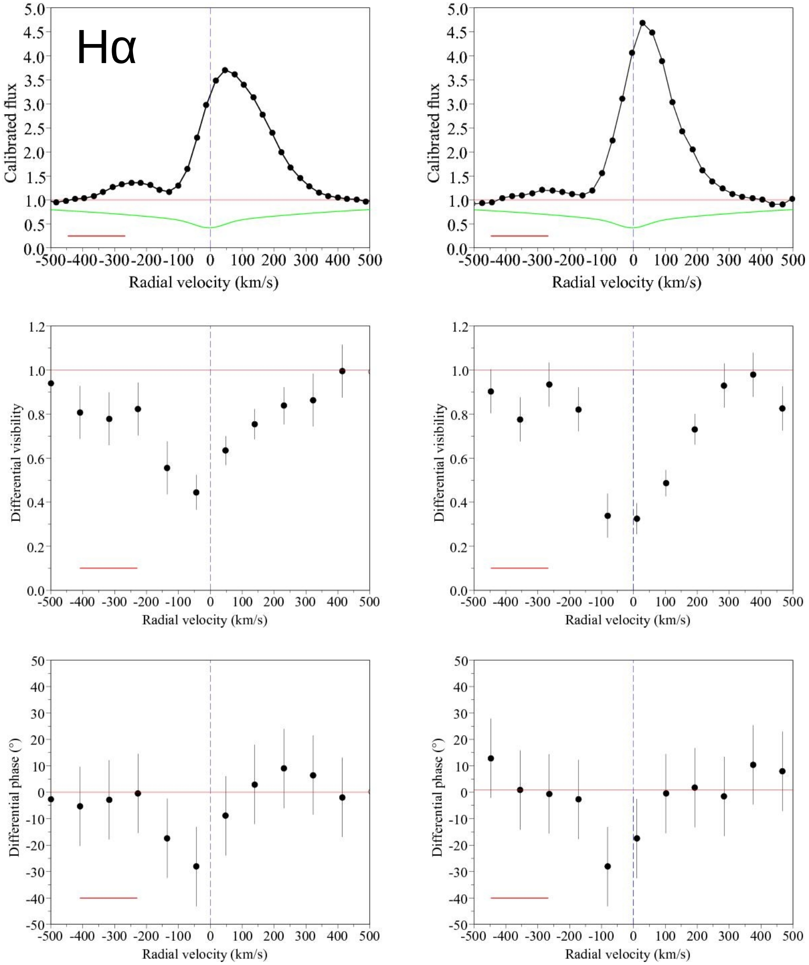
Binarity in Be Stars

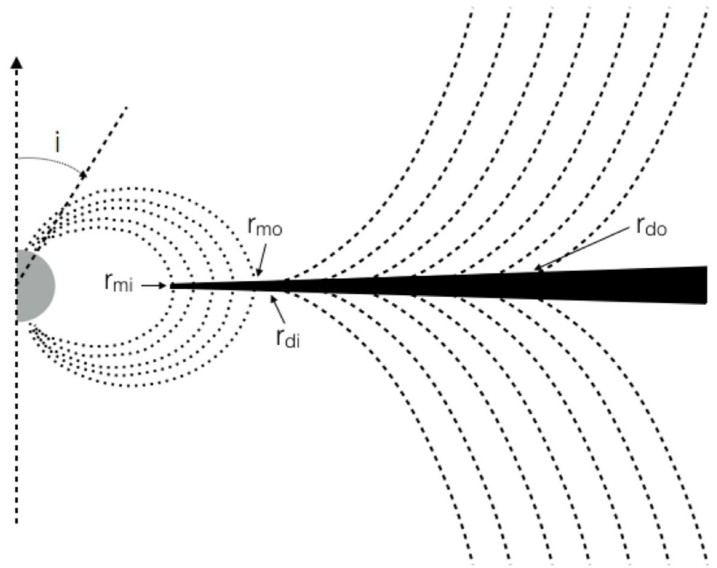
- Role of binarity in Be stars – past mass transfer events?
  - Spun up secondary orbiting stripped down remnant companion (neutron star, white dwarf, helium star)
  - High contrast at close separations



Mourard et al. (2015)

Disk wind in AB Aurigae

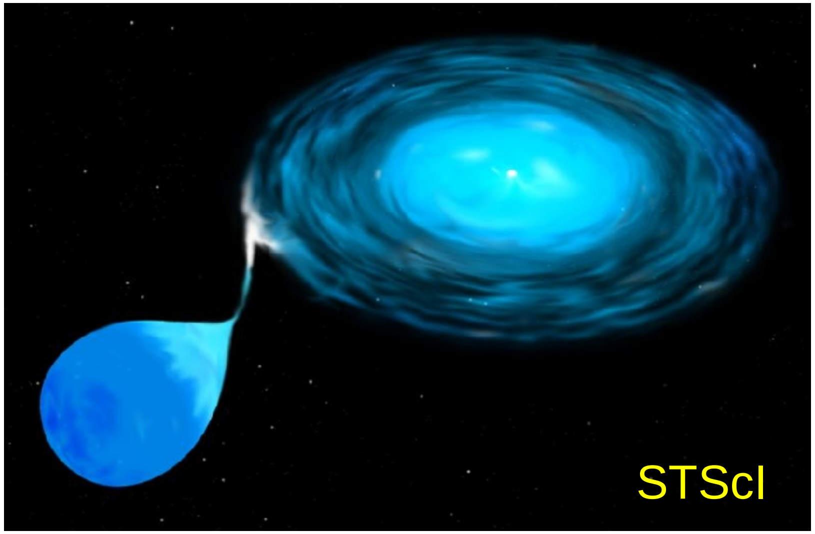




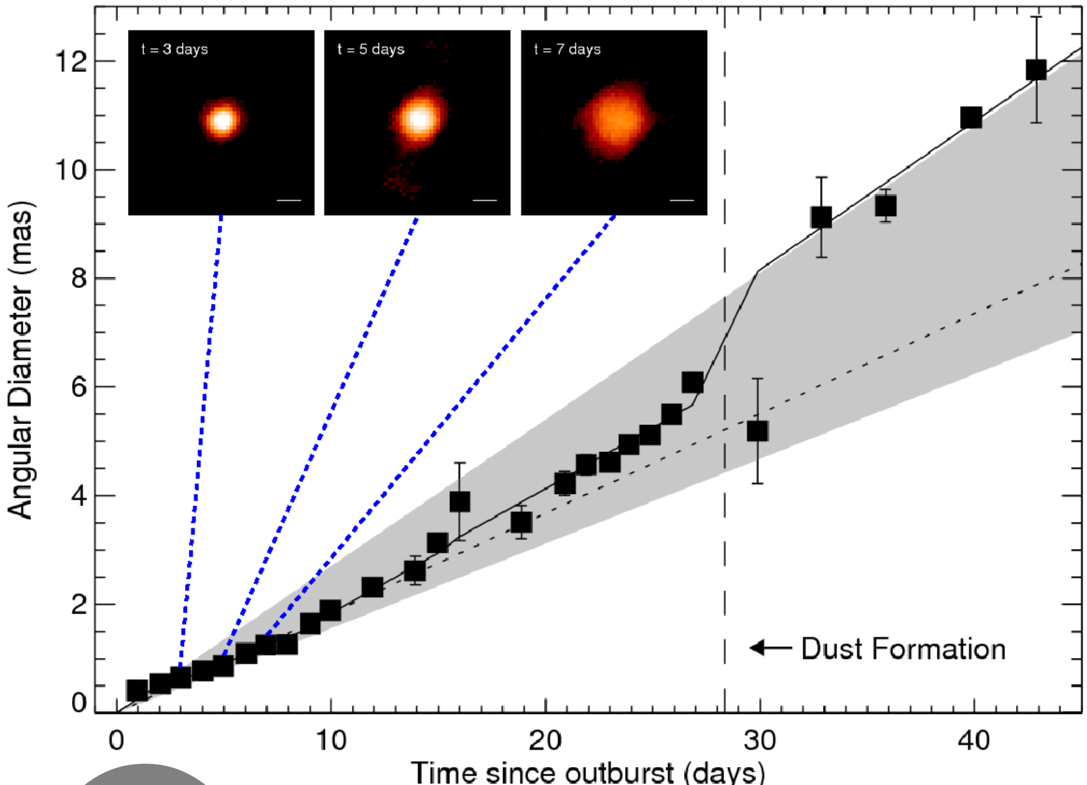
- Resolve Hα formation region in young accreting intermediate mass star
- Bulk of Hα forms in disk wind from innermost regions (0.05 – 0.15 AU)
- Perraut et al. (2016)

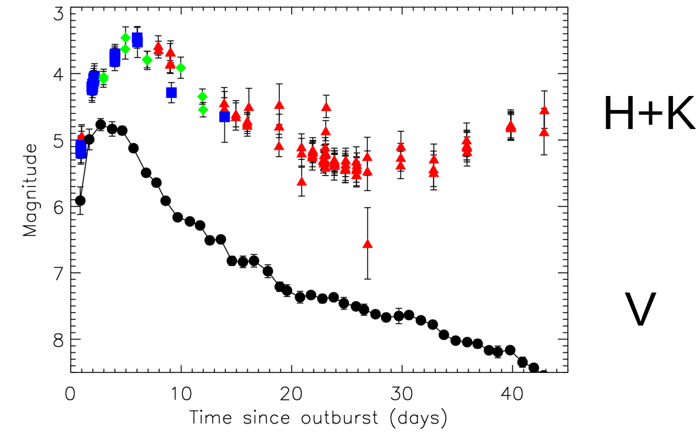
Classical Nova

- Material from close binary companion accretes onto surface of white dwarf
- When pressure and temperature of accreted material reach a critcal level, ignites in a thermonuclear runaway
- Expansion velocities of 500 – 3000 km/s

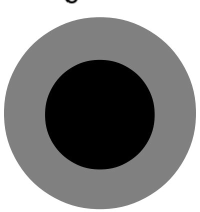


Nova Delphini 2013





- Changes in apparent expansion – optically thick core surrounded by diffuse envelope that cools over time
- Geometric distance (4.5 kpc)
- Asymmetric shape detected as early as t = 2 days



Schaefer et al. 2014

Summary

- Exciting science opportunities
  - 148 refereed papers and counting
- AO + updated detectors + community input
- Many more years of productive science programs in the future