CHARA Community Workshop:

Milliarcsecond Astronomy with the CHARA Array

Gail Schaefer

The CHARA Array of
Georgia State University

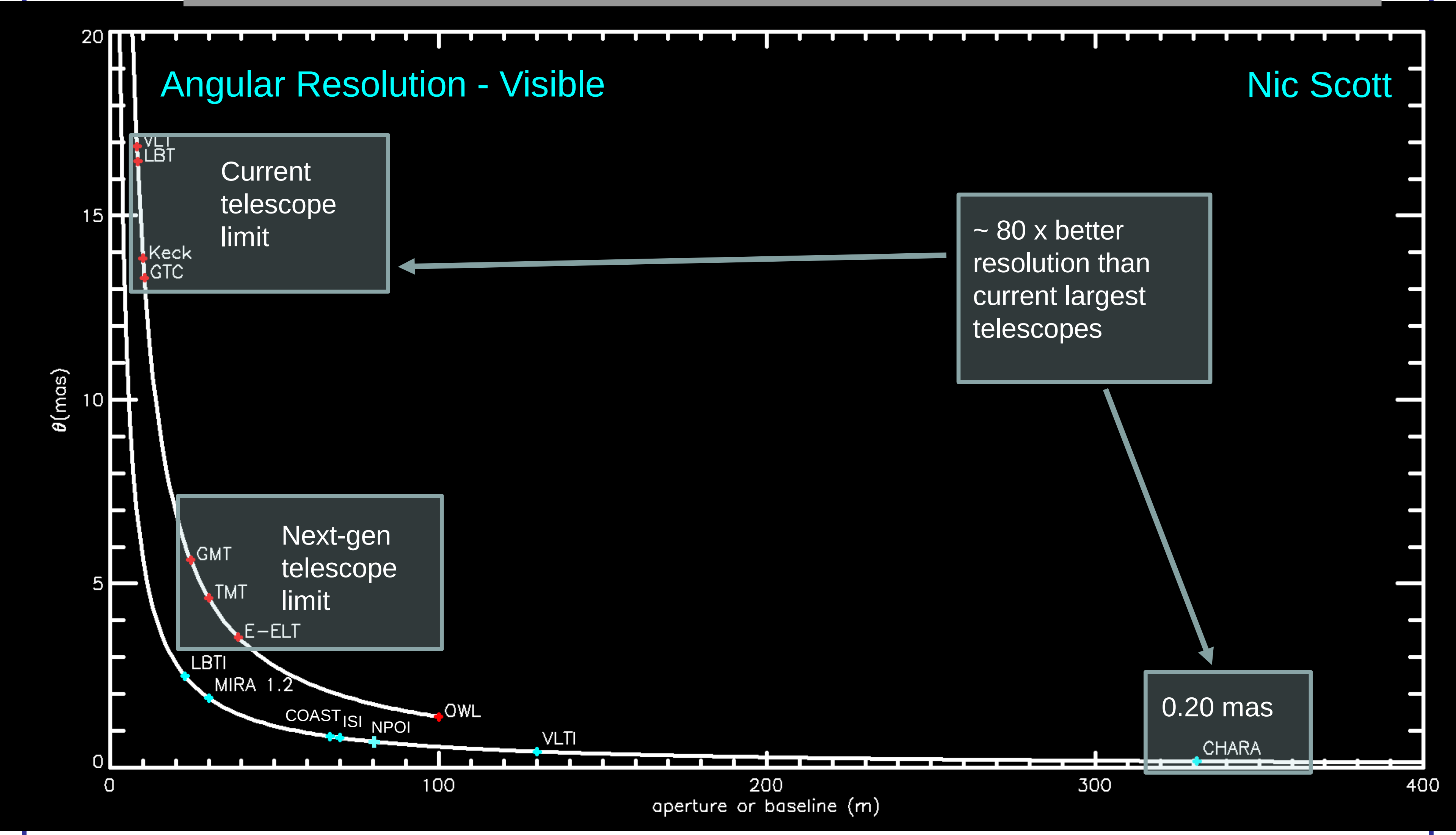
Mount Wilson, CA

CHARA Community Workshop

Schedule		
Stellar Astrophysics at High Angular Resolution	Gail Schaefer	2:00 – 2:45 pm
Overview of the CHARA Array and Applying for Time	Douglas Gies	2:45 – 3:30 pm
Break		
Planning Observations and Software Tools (laptops)	Gail Schaefer	3:45 – 4:30 pm
Open Discussion	All	4:30 – 5:00 pm

Thanks to William Cochran and Kelly Quinney for hosting us!

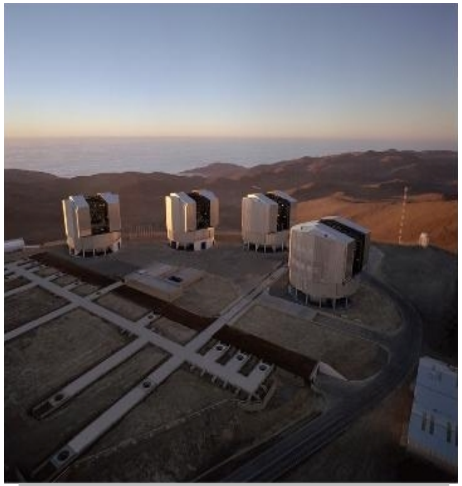
Angular Resolution



Long Baseline Optical/Infrared Interferometers

CHARA Array - Mount Wilson, CA

NPOI - Anderson Mesa, AZ

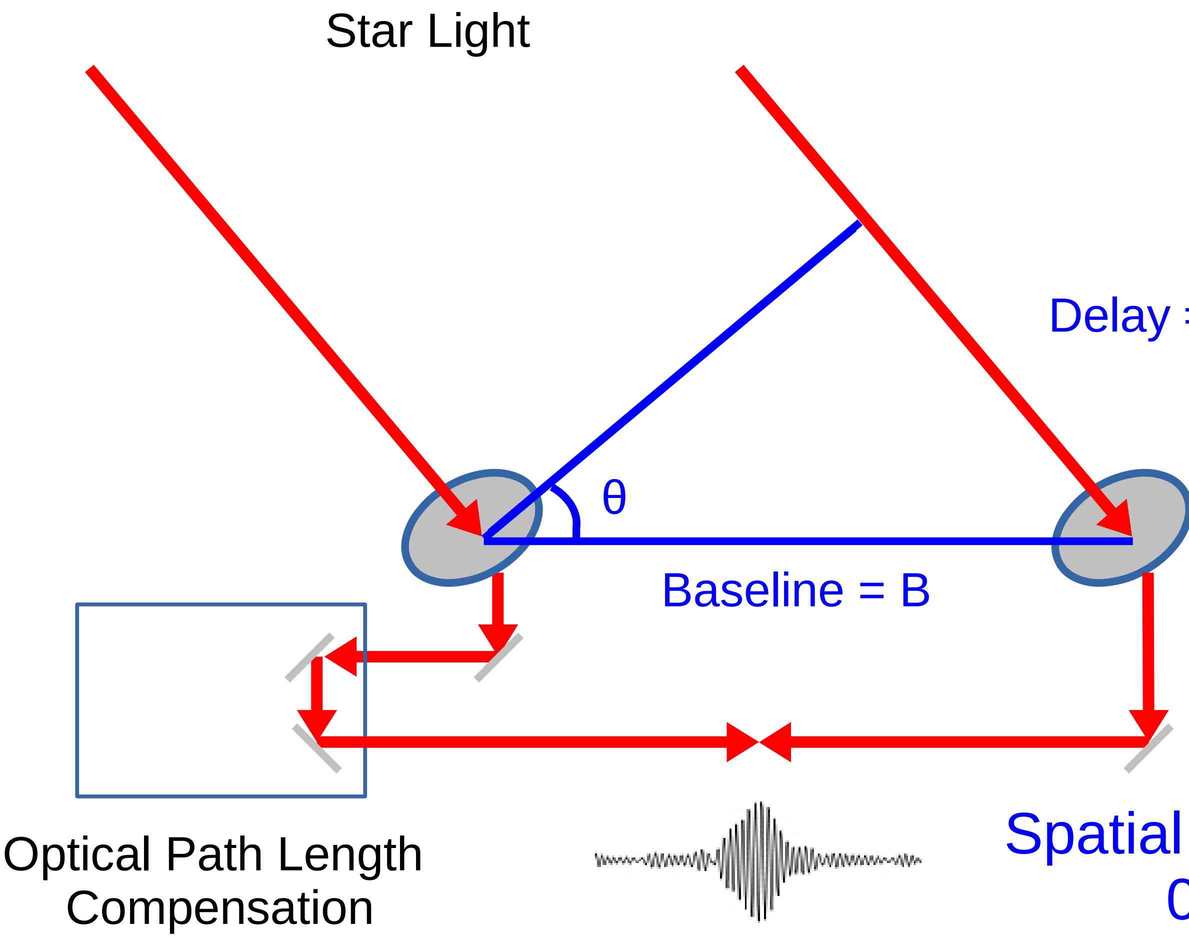


VLTI - Paranal, Chile

MROI - Magdalena Ridge, NM
(under construction)

Principles of Interferometry

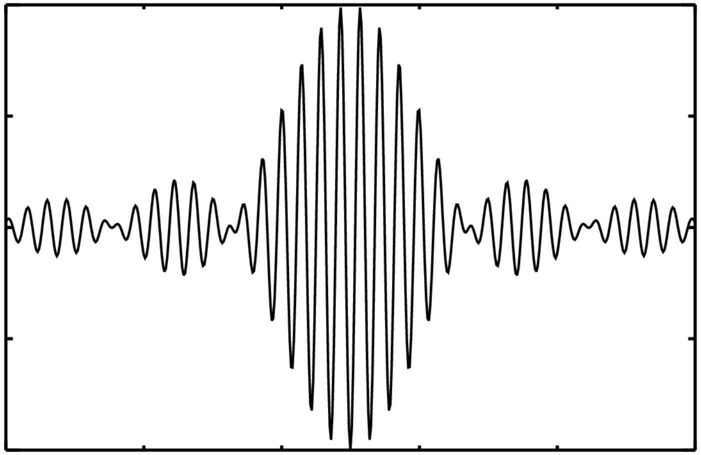
Interferometer



Spatial Resolution:
0.5 λ/B

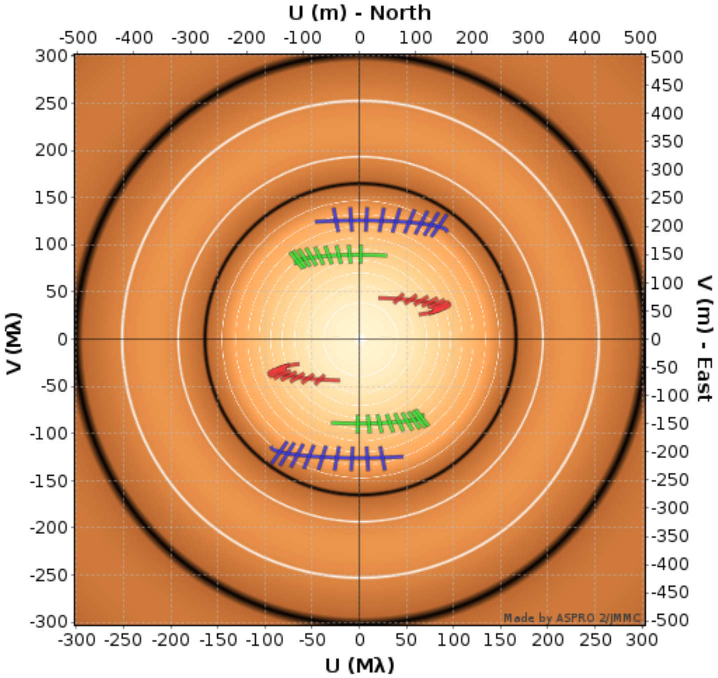
Resolution ~ 0.5 mas for 300 meter baseline in the H-band (1.6 μm)

Fringe Visibility



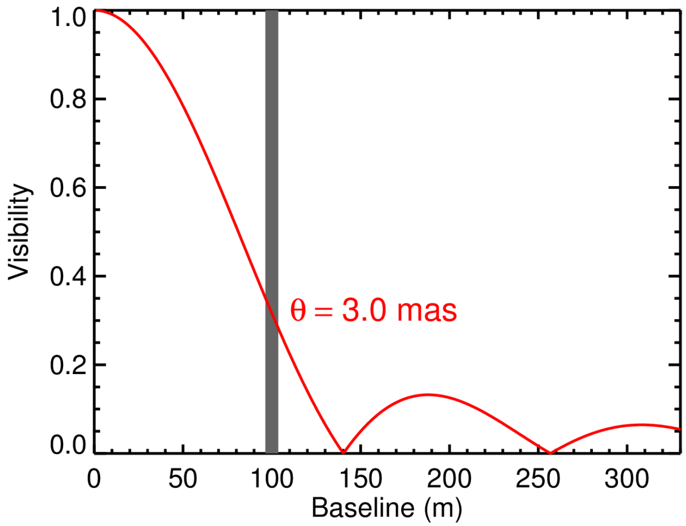
- Amplitude of fringes = Visibility
  - Point Source: V = 1.0
  - Resolved source: loss of coherence reduces fringe visibility
  - Measures the size and geometry of source

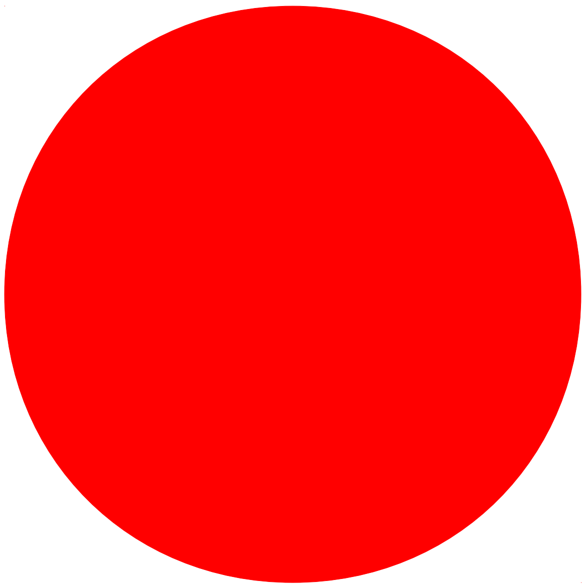
Fringe Visibility



- 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

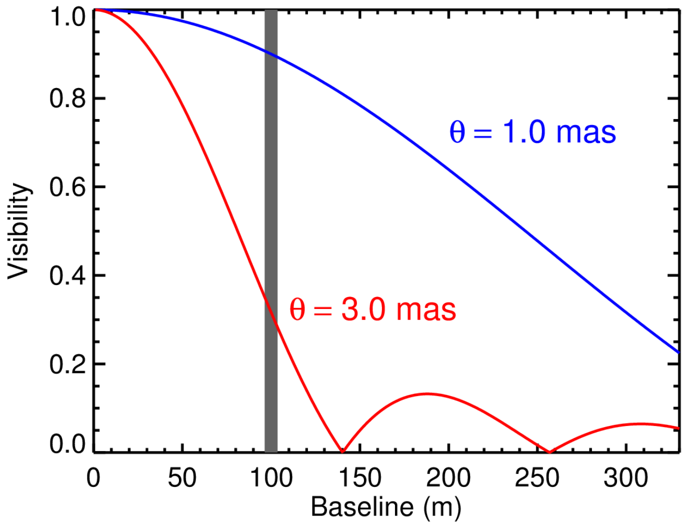
Angular Diameters

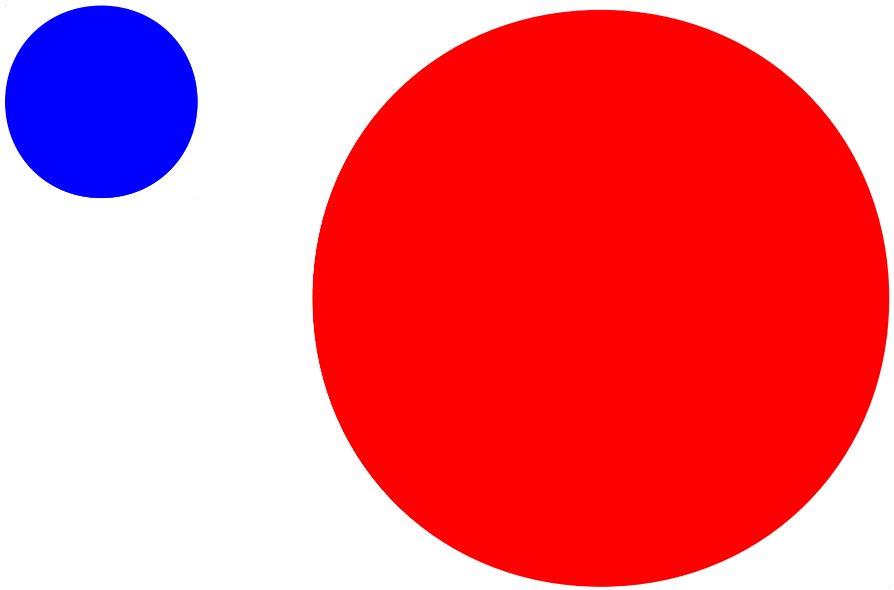




- Visibility amplitude
  - size and structure of source

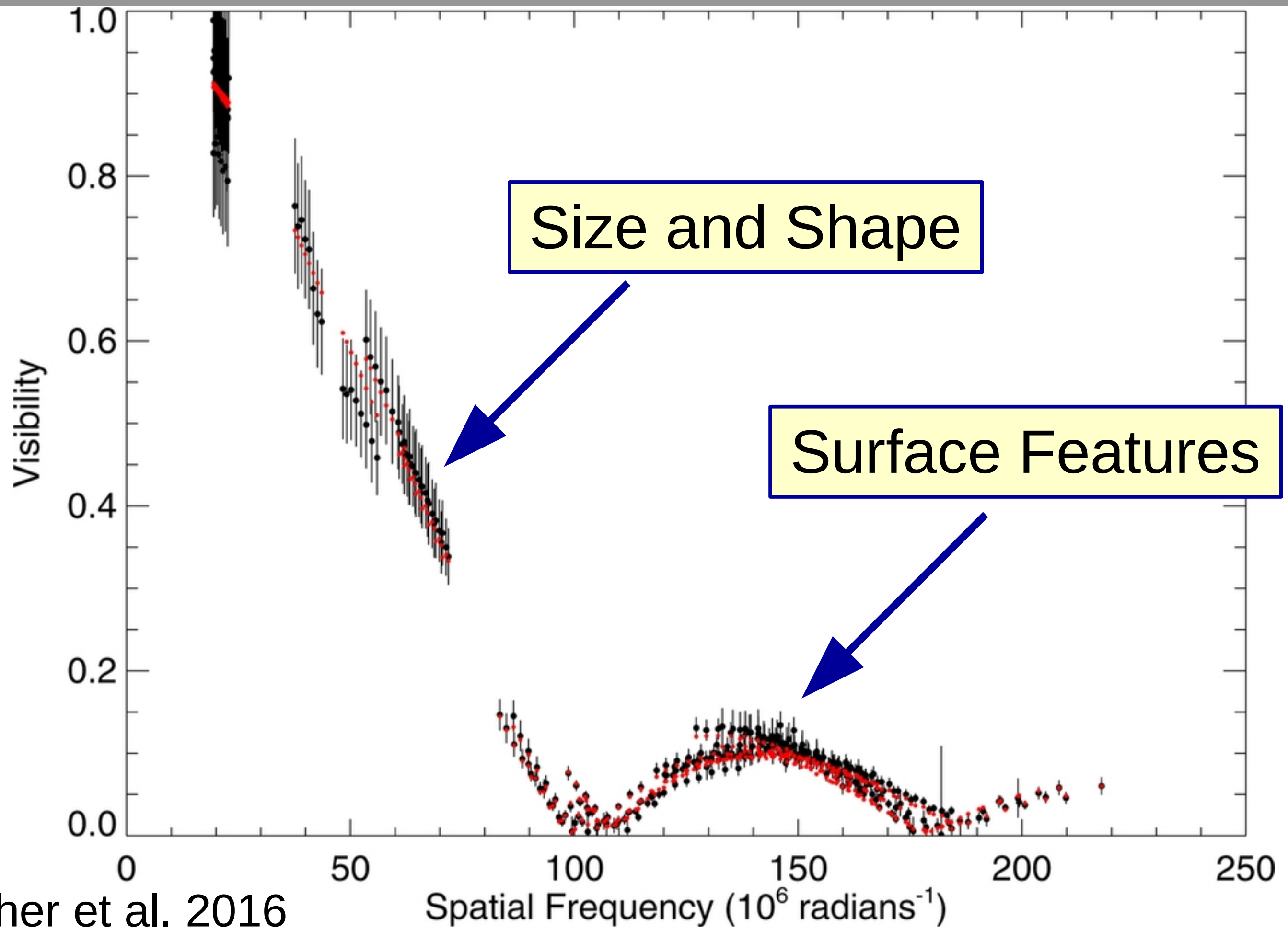
Angular Diameters





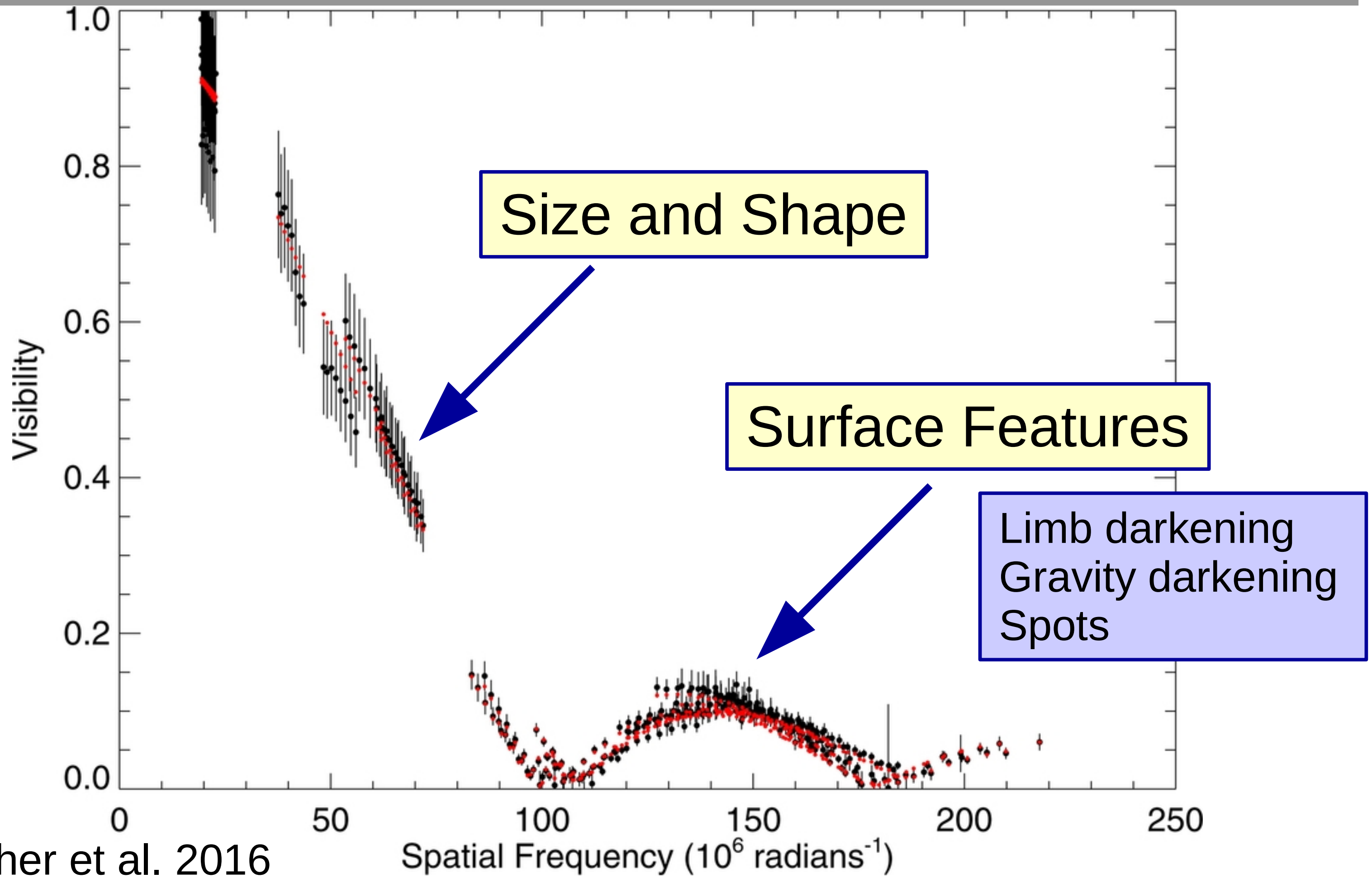
- Visibility amplitude
  - size and structure of source

Surface Features



Roettenbacher et al. 2016

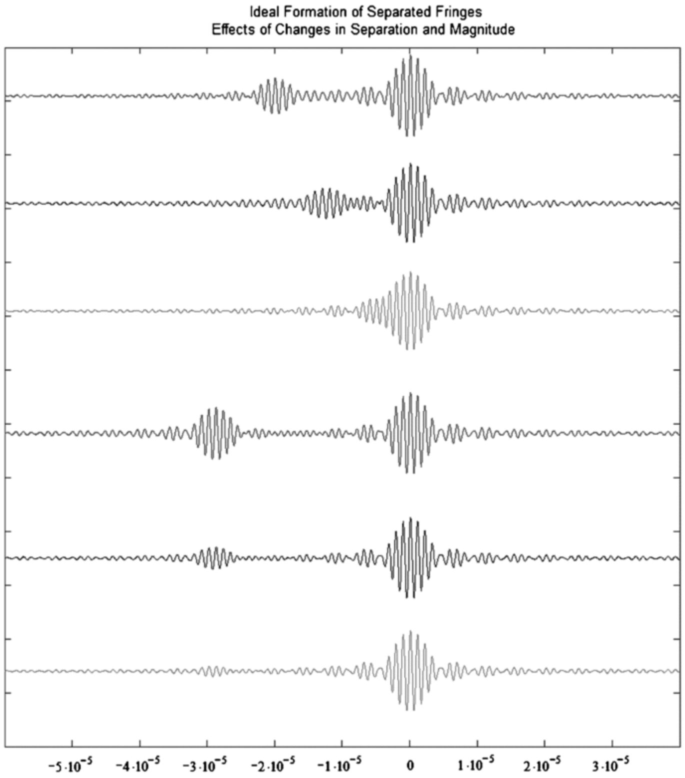
Surface Features



Roettenbacher et al. 2016

Binary Stars

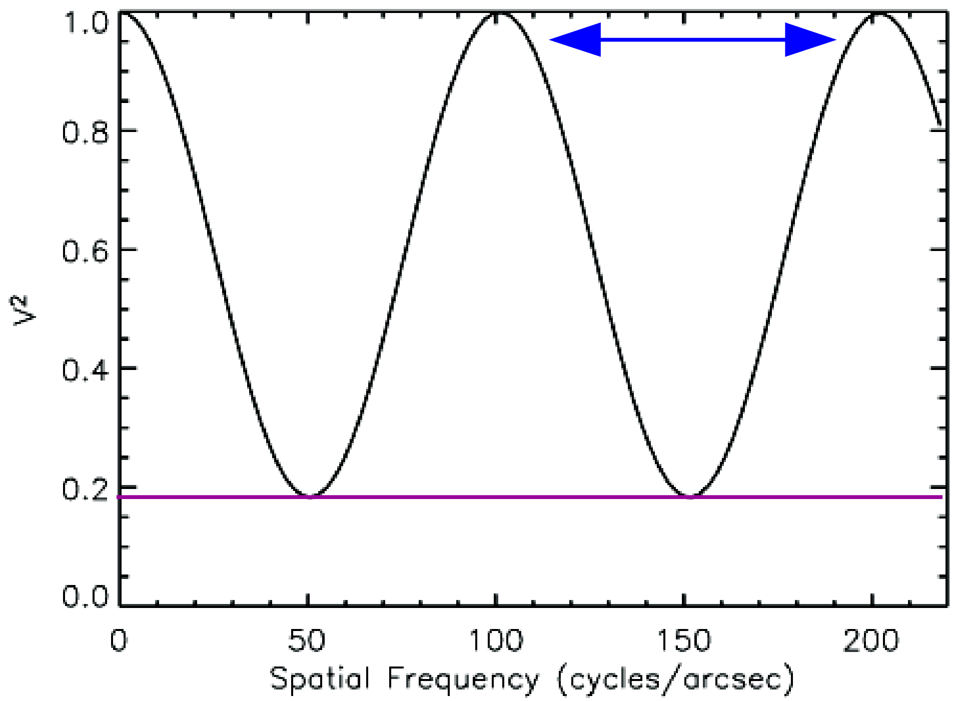
Separated Fringe Packet Binaries



Farrington et al. (2010)

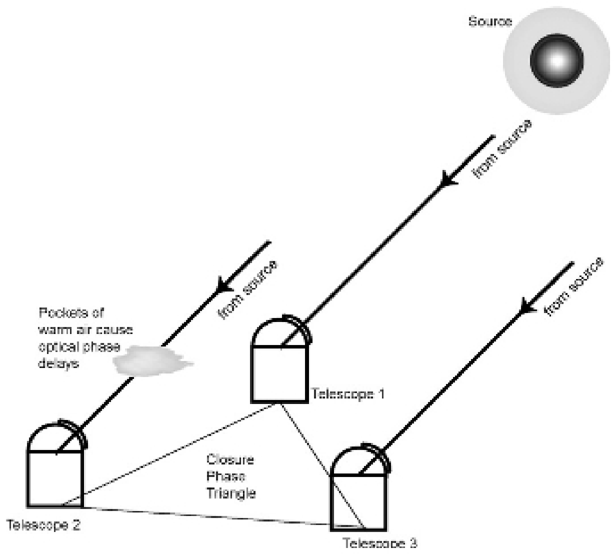
Binary Stars

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

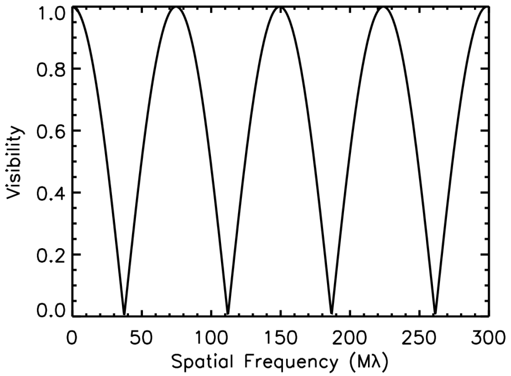


Monnier, “Phases in Interferometry” 2007, New Ast Rev, 51, 604

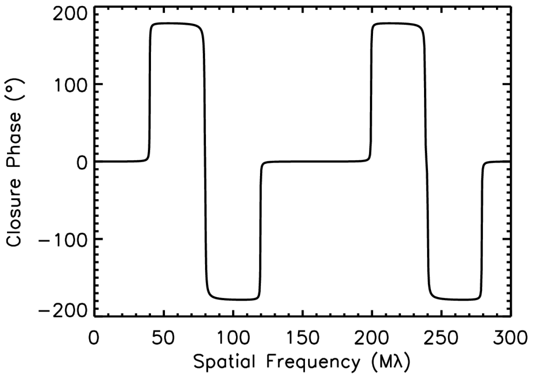
- Atmosphere corrupts phase information at vis/IR wavelengths
- Closure phase (3 or more telescopes):
  - $CP = \Phi_{12} + \Phi_{23} + \Phi_{31}$
- Cancels atmospheric effects
- Point symmetric object will have closure phase of 0° or 180°
- Measures asymmetries in source distribution

Binary Stars

Visibility (S1-E1)



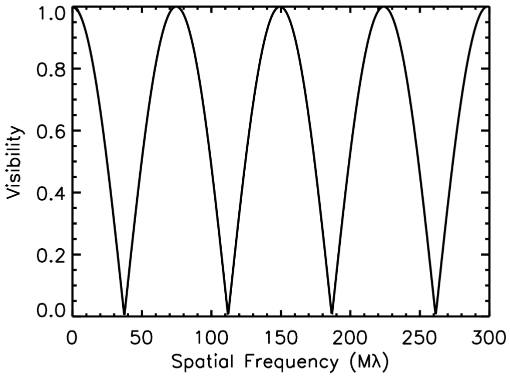
Closure Phase (S1-E1-W1)

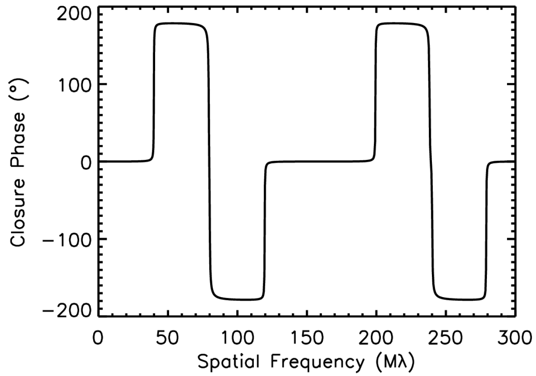


Flux ratio = 0.99

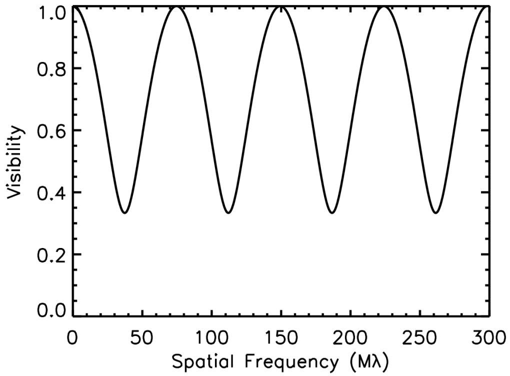
Binary Stars

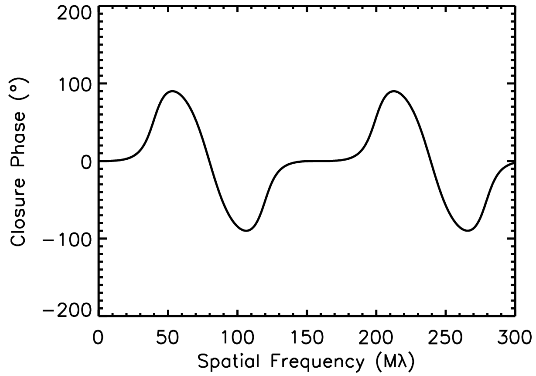
Visibility (S1-E1) | Closure Phase (S1-E1-W1)





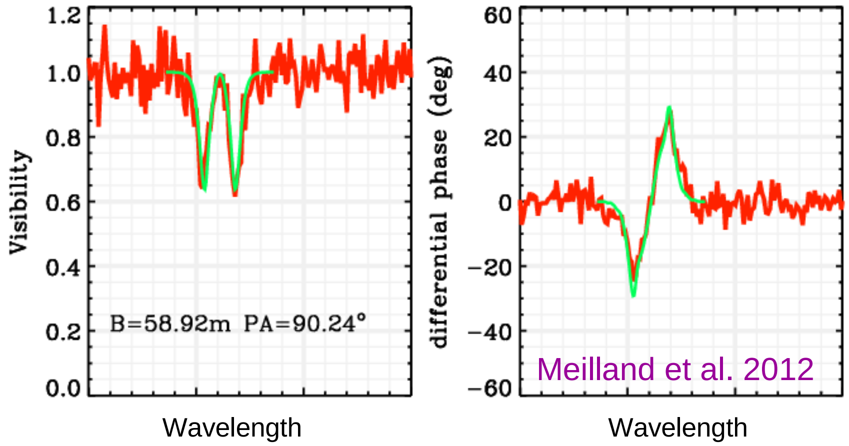
Flux ratio = 0.99





Flux ratio = 0.50

Differential Visibilities and Phases



- Spectrally dispersed interferometry
  - emission lines (BrG, Hα)
  - 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

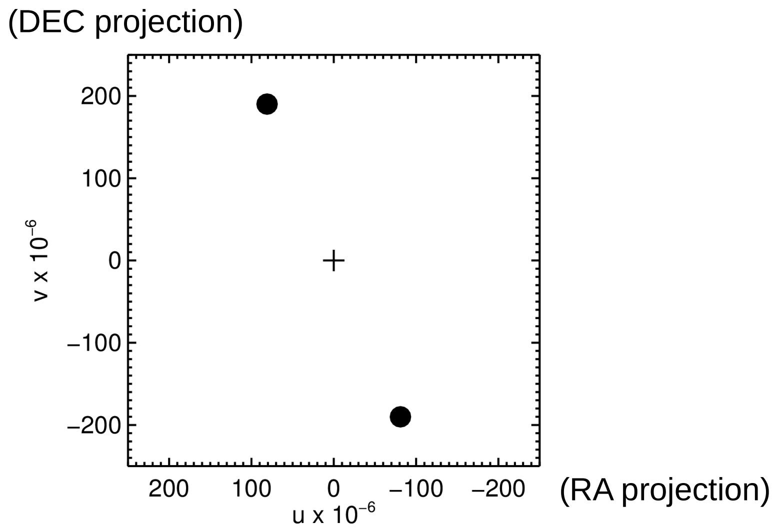
- Visibility amplitude
  - size and structure of source
- Closure phase
  - asymmetries in source distribution
- Differential visibilities and phases
  - emission lines
  - velocity structure

UV Coverage

Spatial Frequency:

$u = B_x/\lambda$

$v = B_y/\lambda$



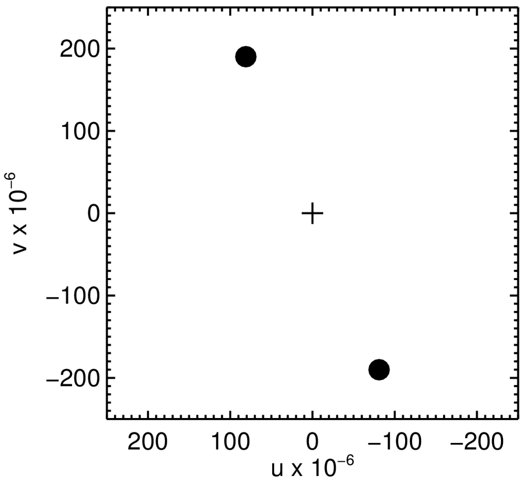
- Interferometer baseline projected on to plane of sky

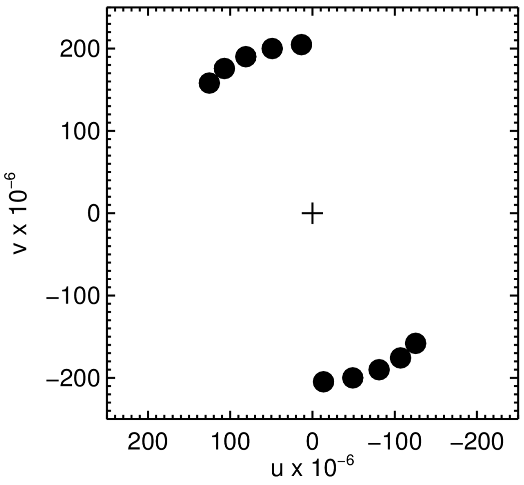
UV Coverage

Spatial Frequency:

$u = B_x/\lambda$

$v = B_y/\lambda$

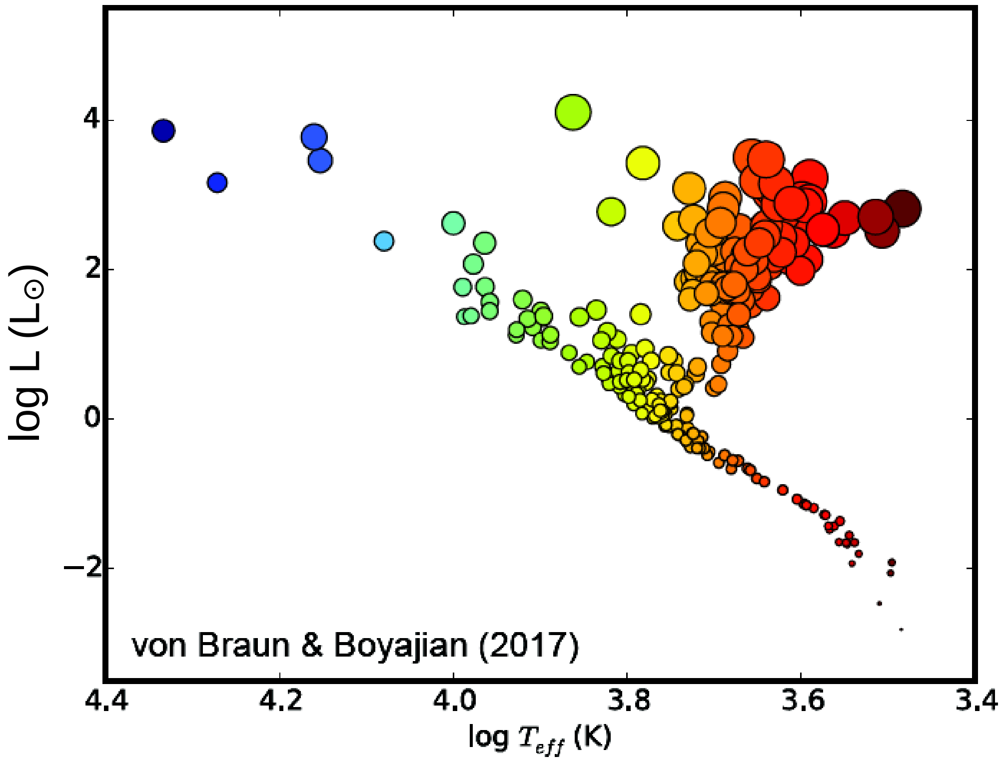




- Interferometer baseline projected on to plane of sky
- Position angle and projected baseline length will change as the earth rotates

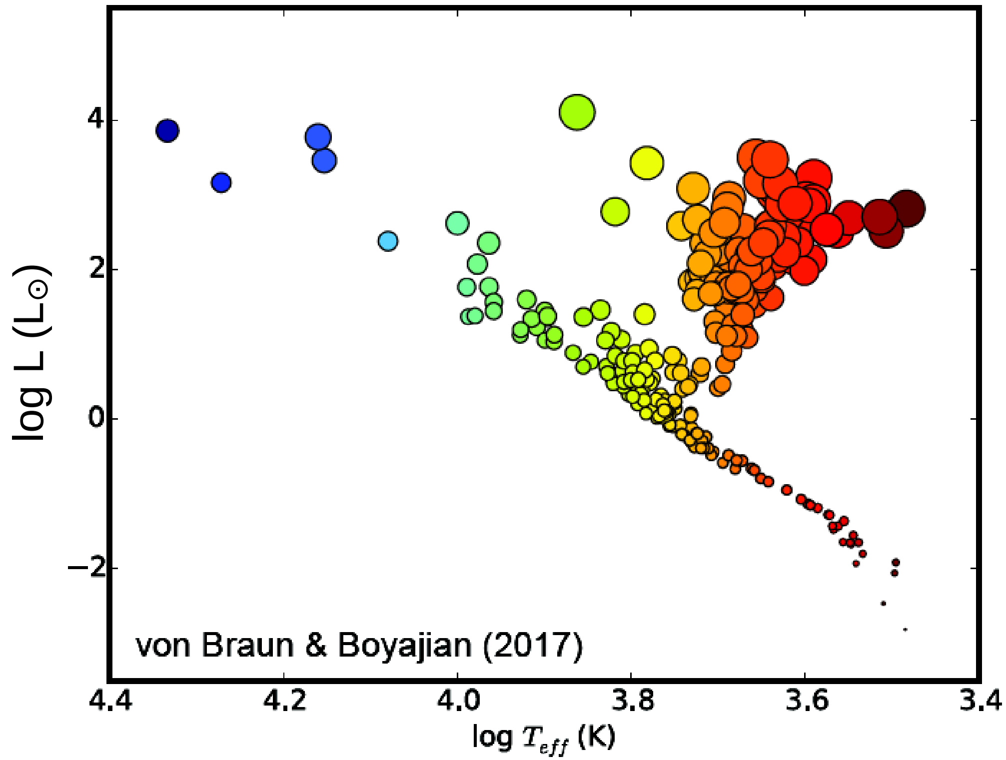
Science at High Angular Resolution

Stellar Diameters

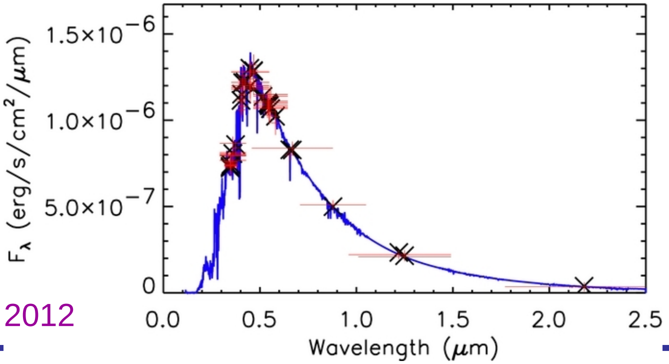


- Empirical HRD
- ~ 290 stars, σ_θ < 5%
- Angular diameter + parallax
  - Linear radius

Stellar Diameters

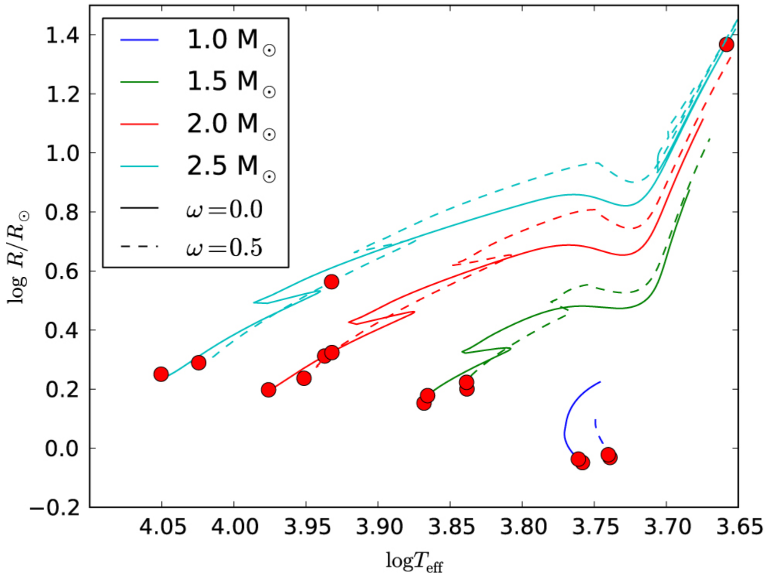


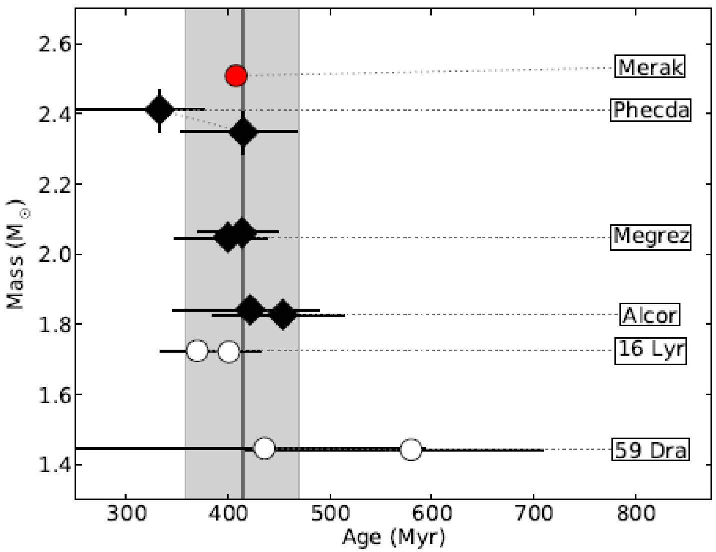
- Empirical HRD
- ~ 290 stars, σ_θ < 5%
- Angular diameter + parallax
  - Linear radius
- Effective Temperature
  - $F_{bol} = \frac{1}{4}\theta^2 \sigma T^4$



Boyajian et al. 2012

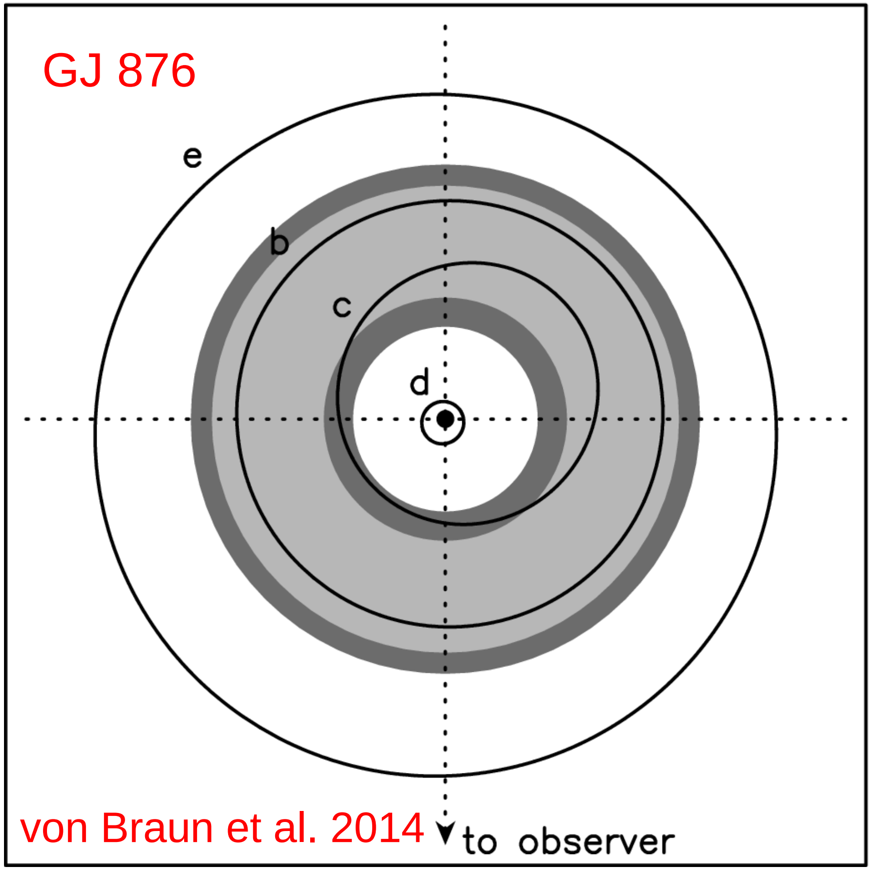
Stellar Ages





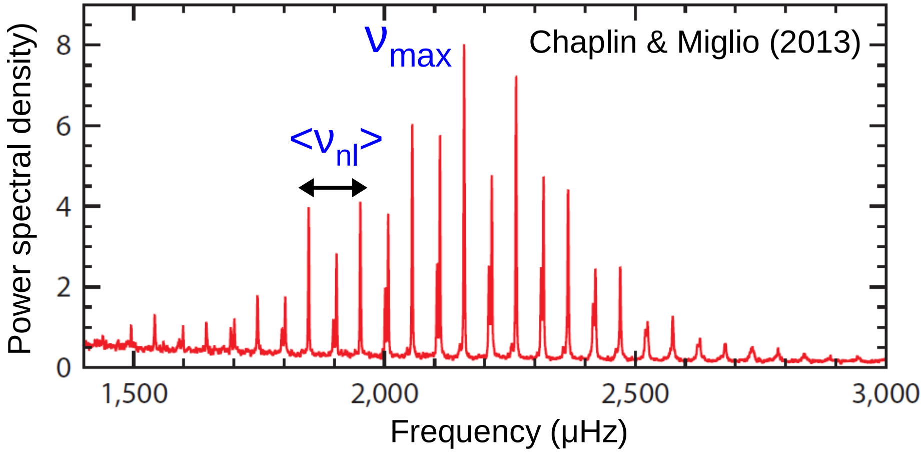
- Comparison of R, T_{eff}, L with evolutionary models
  - Masses and ages of stars
- Age of the Ursa Major moving group: 414 ± 23 Myr
  - Diameters of A-stars (Jones et al. 2015)

Exoplanet Host Stars



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

Asteroseismology

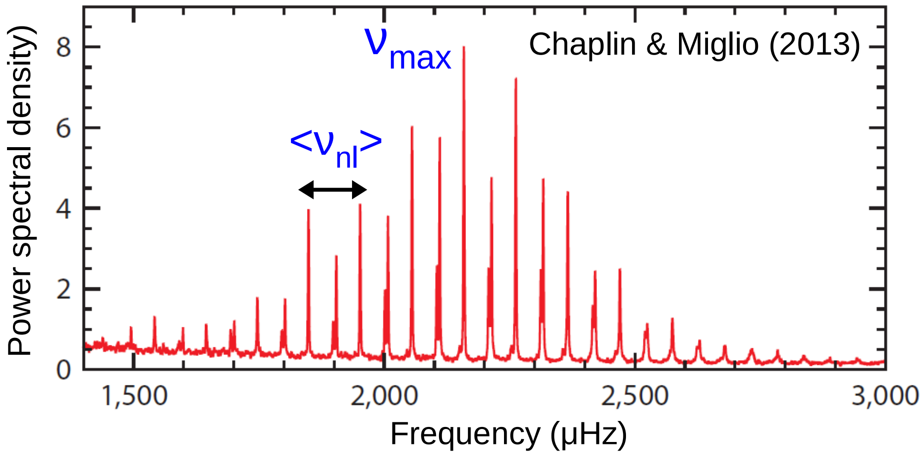


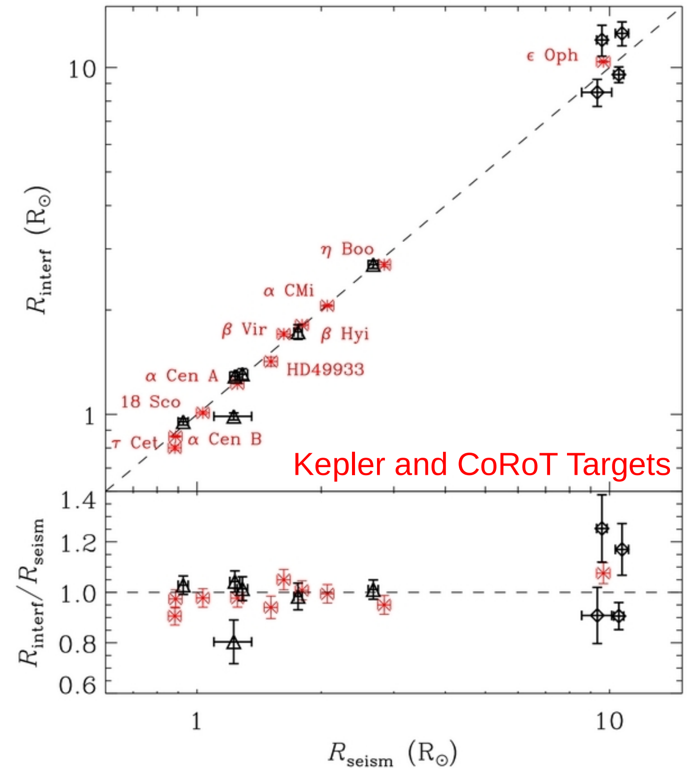
Mass, radius, mean density, and surface gravity (need Teff)

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

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

Asteroseismology





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

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

$\langle\nu_{nl}\rangle \propto \langle\rho\rangle^{0.5}$

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)

Asteroseismology: Transiting Exoplanet Survey Satellite

- TESS Input Catalog
  - 596 million objects
  - 200,000 – 400,000 selected for high cadence
- Two-year mission
- Launched on April 18, 2018

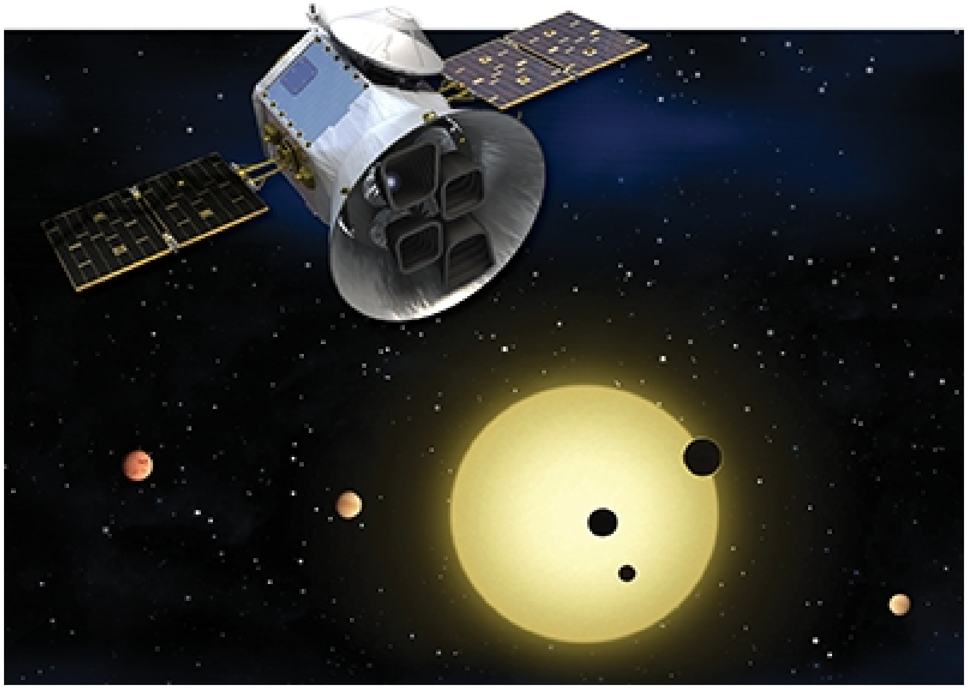
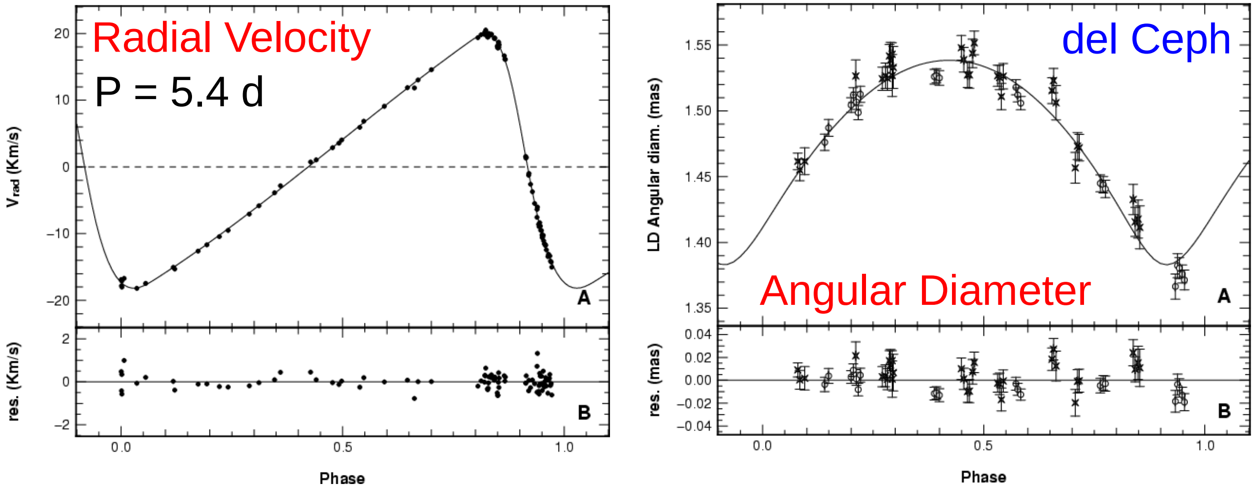


Image credit: NASA

- V < 7 mag
  - 4,864 stars resolvable (θ > 0.2 mas)
- V < 8 mag
  - 13,922 stars resolvable (θ > 0.2 mas)

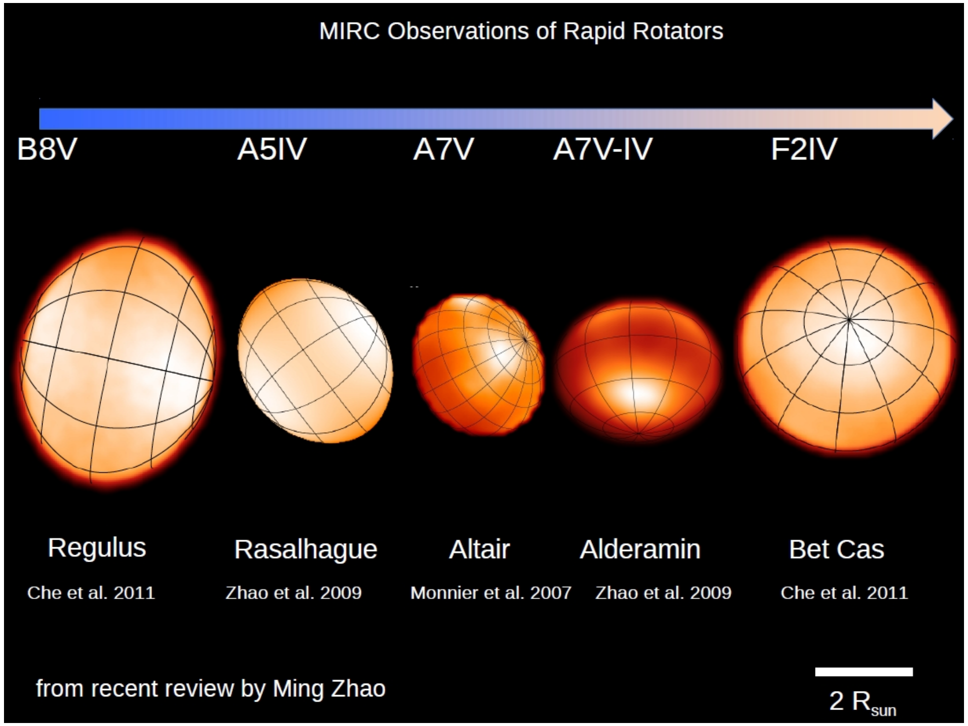
Cepheids



Merand et al 2005

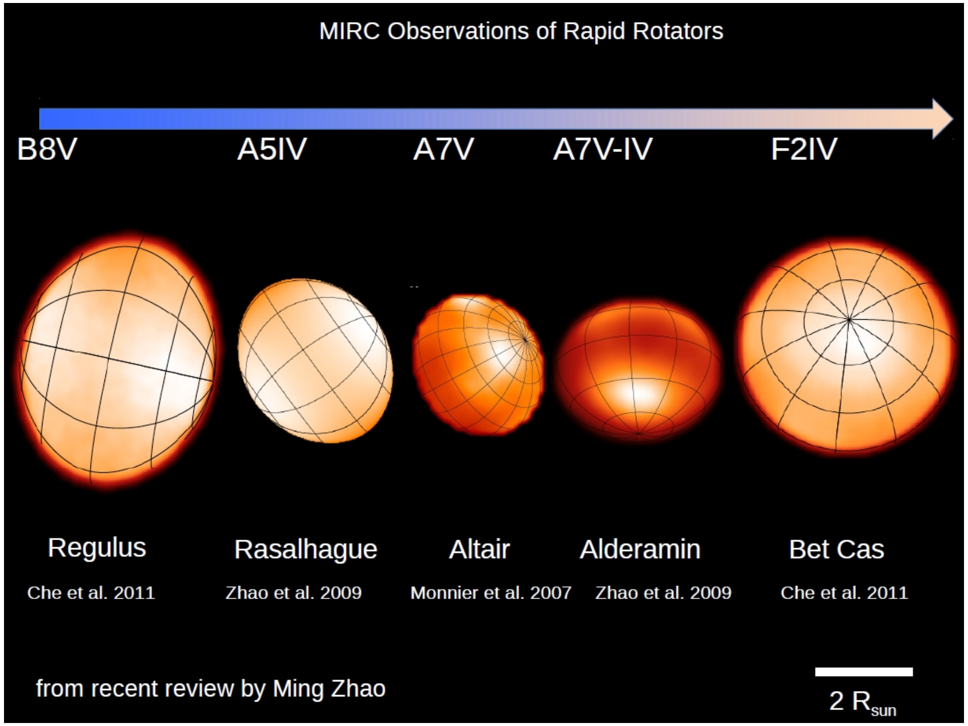
- Radial velocity and angular diameter variation over pulsational phase
- Calibration of Baade-Wesselink technique - pulsation parallaxes
- Simultaneously fit photometry, spectroscopy, interferometry (Merand et al. 2015)
  - Mitigate systematics in projection factor
  - 2% accuracy on radius and distance

Rapid Rotators

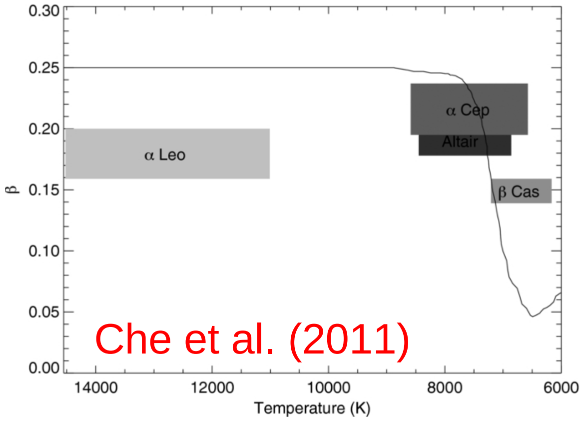


- Oblateness
- Gravity darkening
  - $T_{eff} \sim g^{\beta}$

Rapid Rotators



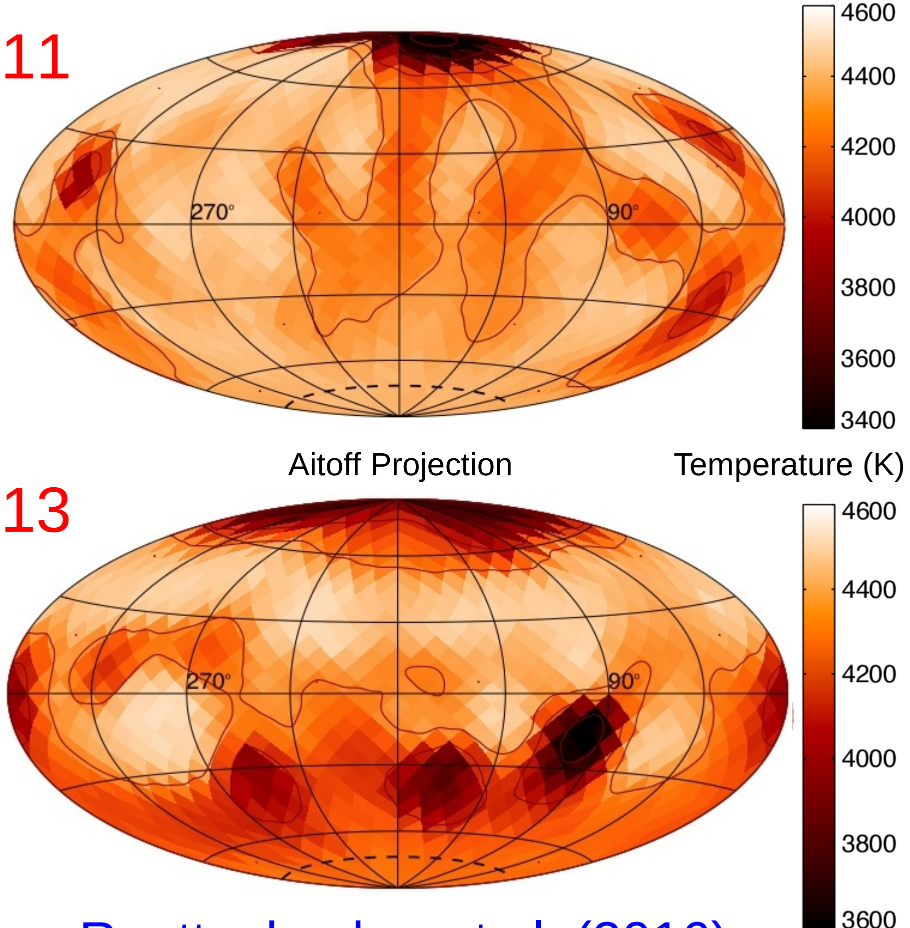
- Oblateness
- Gravity darkening
  - $T_{eff} \sim g^{\beta}$
  - von Zeipel model: $\beta = 0.25$
  - empirically derived $\beta = 0.19$



Spotted Stars

2011

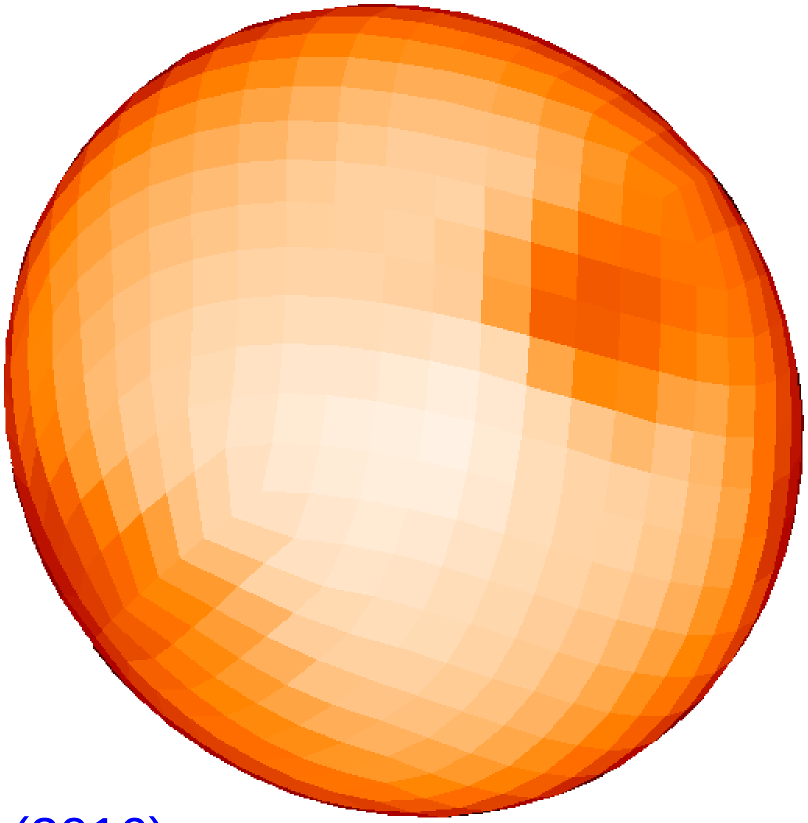
2013



Roettenbacher et al. (2016)

- 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

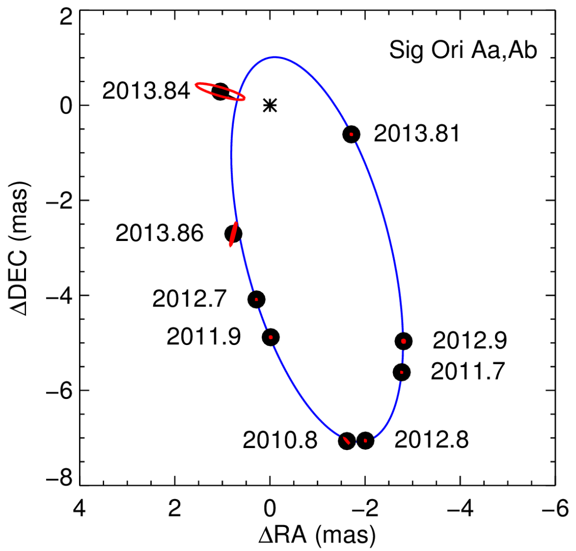
Spotted Stars



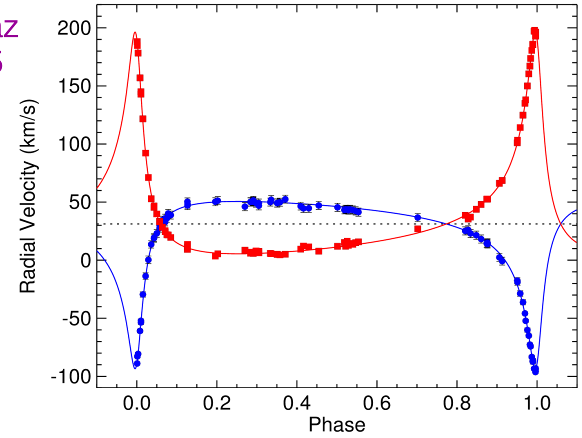
Roettenbacher et al. (2016)

Binary Stars:
Orbits and Dynamical Masses

Schaefer et al. 2016



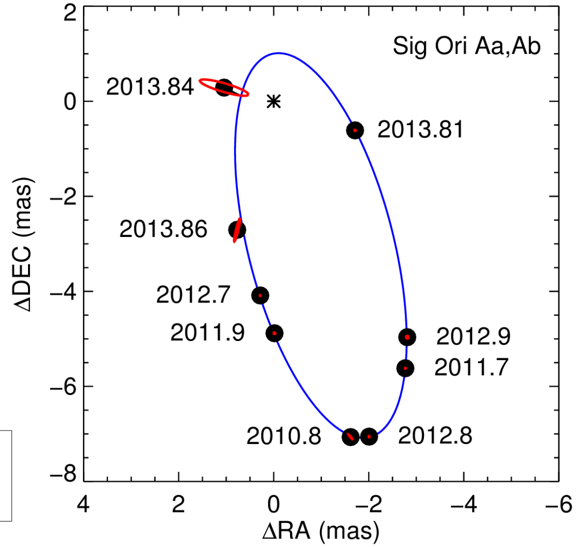
Simon-Diaz et al. 2015



- Spatially resolved orbits of spectroscopic binaries
  - Masses and distances to 1-3% precision

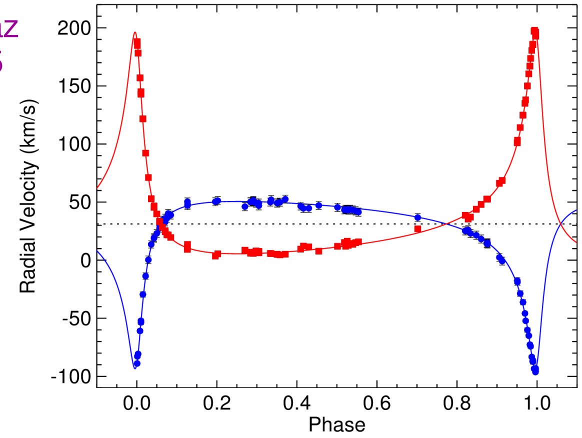
Binary Stars:
Orbits and Dynamical Masses

Schaefer et al. 2016



P = 143 d
a = 4.3 mas

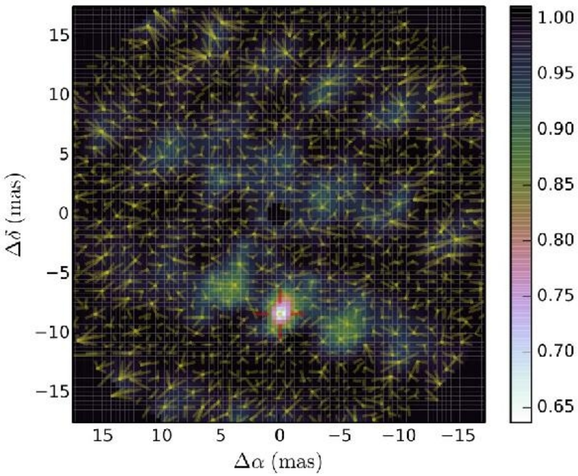
Simon-Diaz et al. 2015

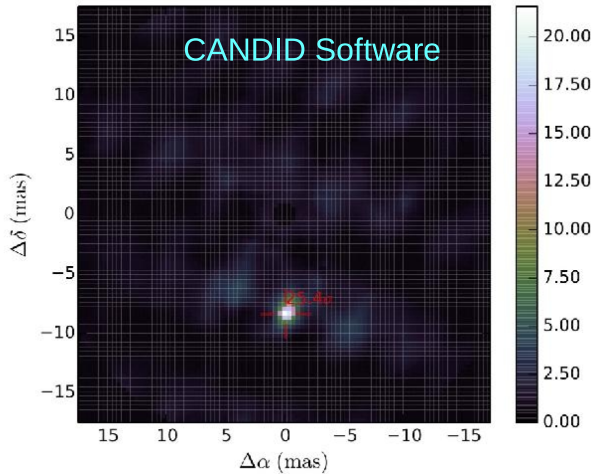


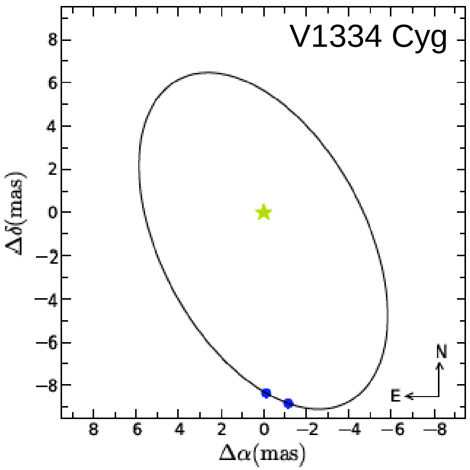
- Spatially resolved orbits of spectroscopic binaries
  - Masses and distances to 1-3% precision
- O-Star Triple sigma Orionis
  - $M_{Aa} = 16.99 \pm 0.20\ M_\odot$
  - $M_{Ab} = 12.81 \pm 0.18\ M_\odot$
  - $d = 387.5 \pm 1.3$ pc
  - Distance to sigma Orionis cluster

    Schaefer et al. 2016

High Contrast Binaries







- High contrast companions
  - Separations 0.5 - 50 mas
  - ΔH < 6 mag
  - Cepheids companions - Gallenne et al. 2013, 2015
  - RS CVn companions - Roettenbacher et al. 2015a, 2015b

Interacting Binaries

Beta Lyrae

P = 13 days
a = 0.87 mas

Zhao et al. (2008)

- Mass donor is elongated – detection of photospheric distortion due to Roche lobe filling
- Thick disk around mass gainer - elongated

Interacting Binaries

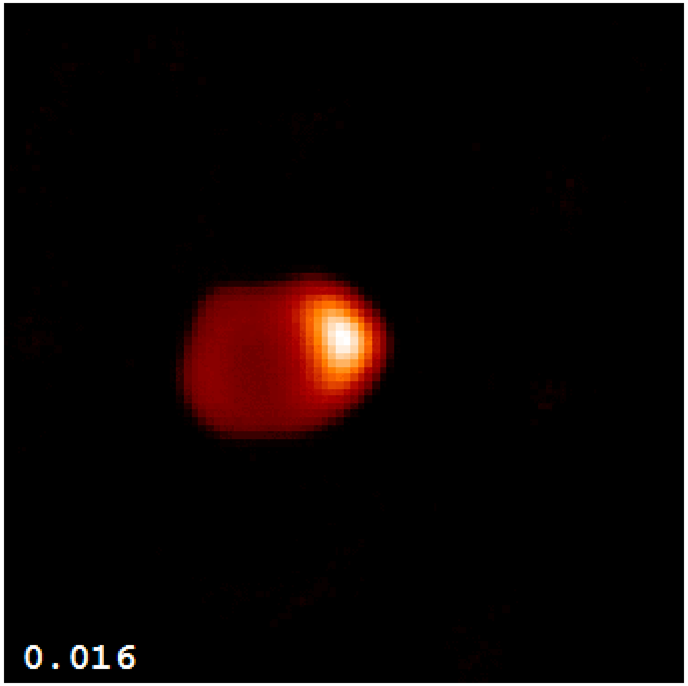
Beta Lyrae

P = 13 days
a = 0.87 mas

Zhao et al. (2008)

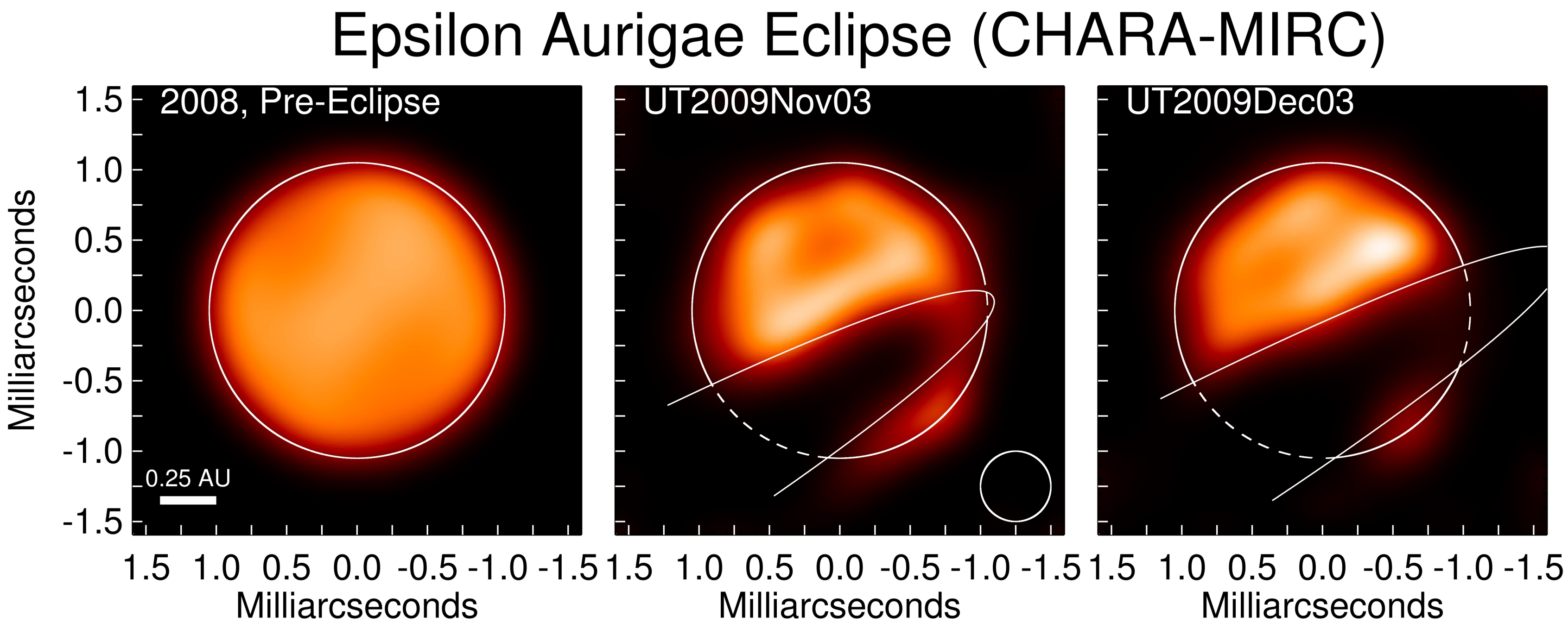
Algol

P = 2.9 days
a = 2.2 mas



Baron et al. (2012)

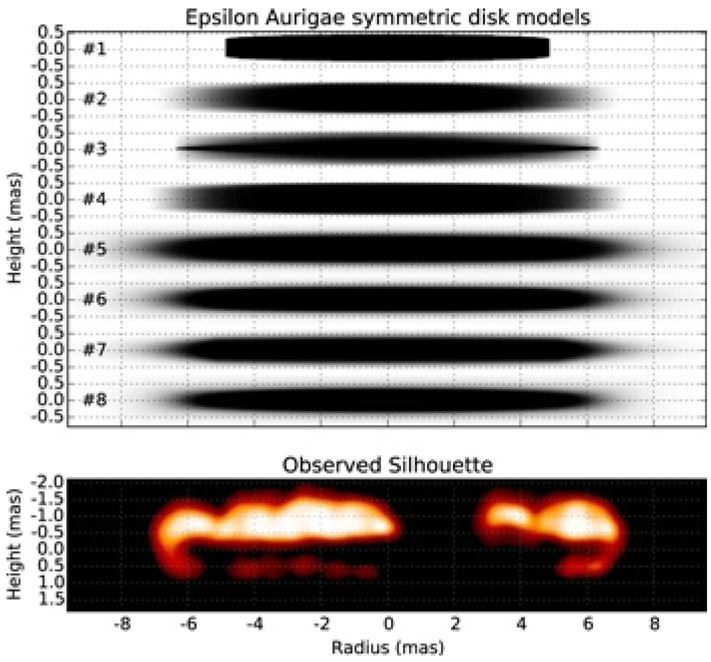
Transiting Disk: Epsilon Aurigae

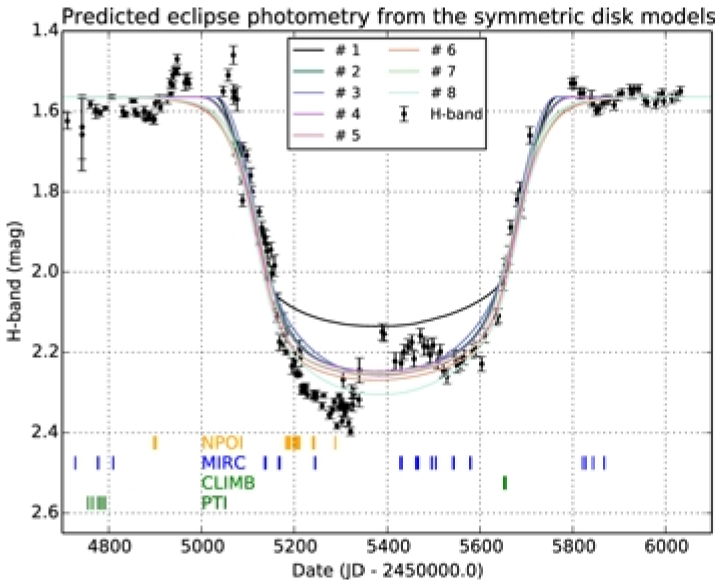


Limb-Darkened Disk:
θ_{LDD} = 2.22 ± 0.09 mas
μ_{LDD} = 0.50 ± 0.26

Kloppenborg et al. (2010)

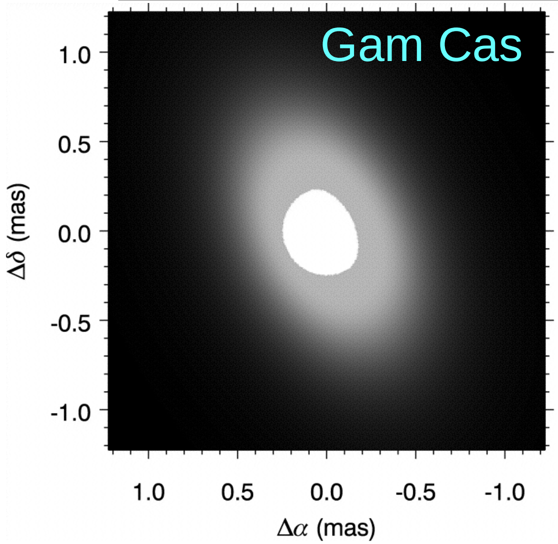
Transiting Disk: Epsilon Aurigae

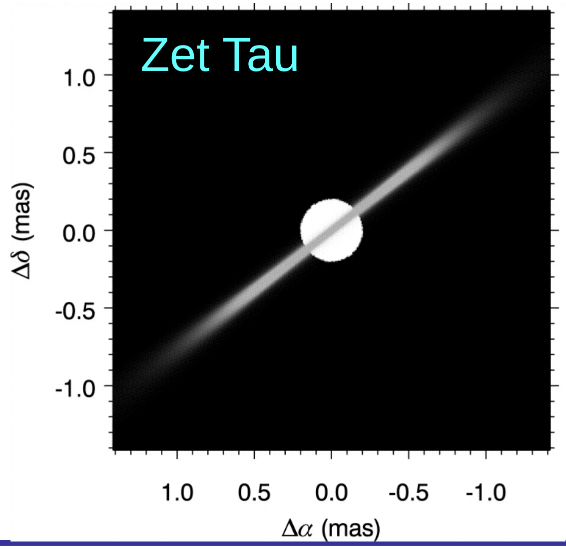




Kloppenborg et al. (2015)

Be Stars

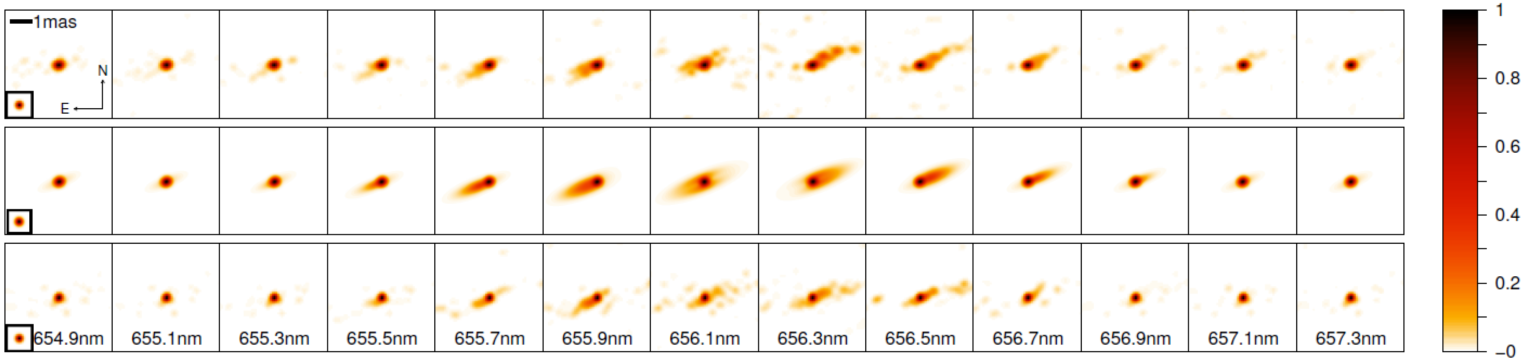


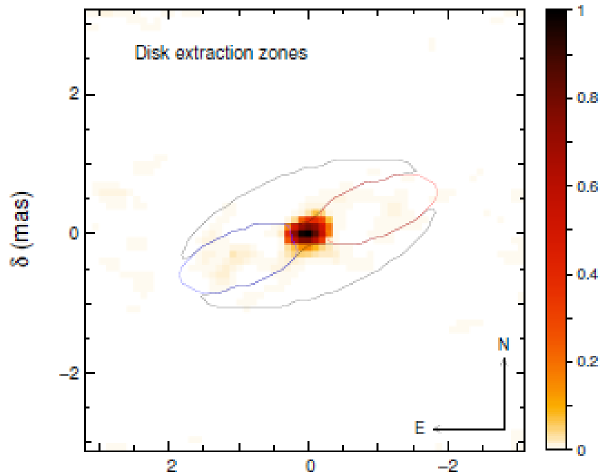


- Rapidly rotating B-type stars that eject gas into a circumstellar disk
- Geometry and physical structure of disks
- Kinematics
- Size vs. wavelength
- Investigate variability over time

Gies et al. (2007)

Kinematics of Be Star Disks

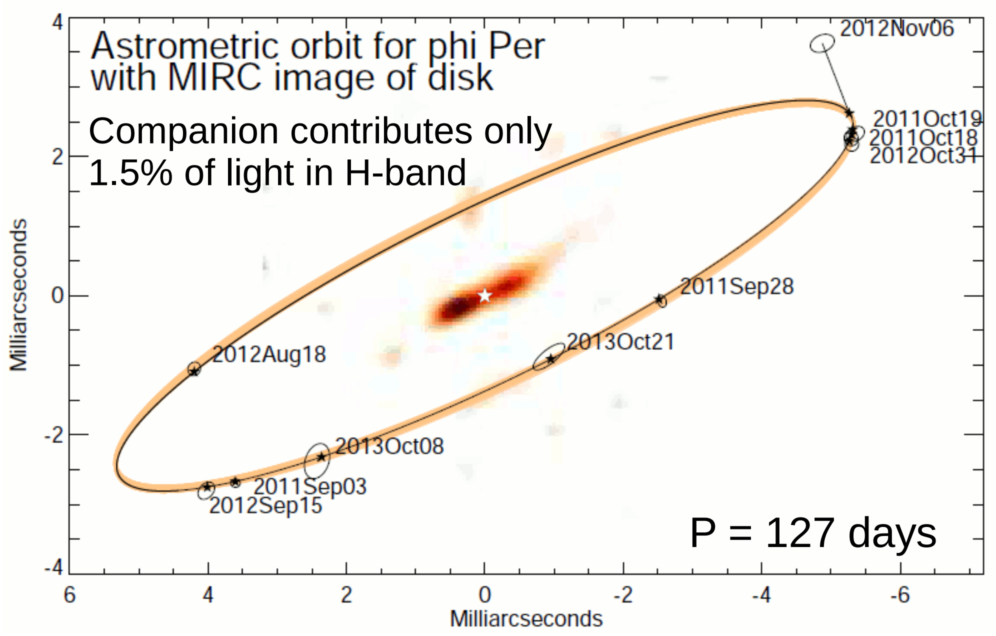




Mourard et al. 2015

Binarity in Be Stars

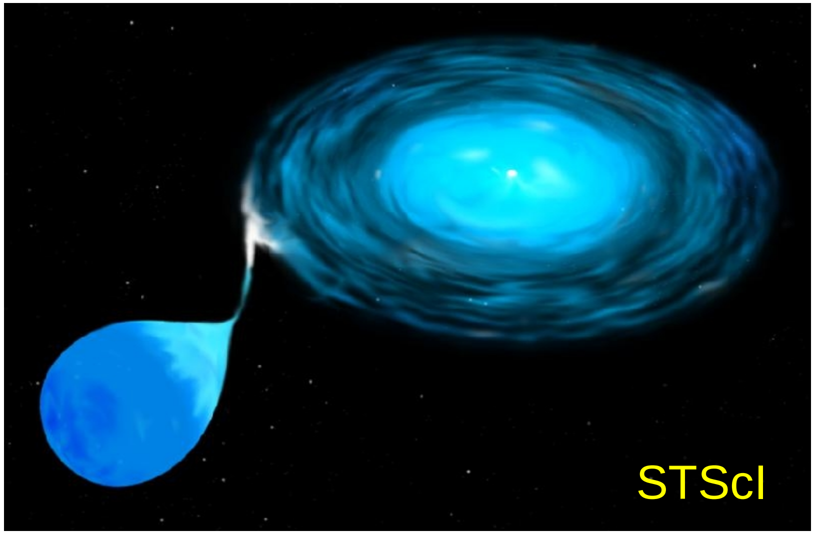
- Role of binarity in Be stars – past mass transfer events?
  - Spun up secondary orbiting stripped down remnant companion (neutron star, white dwarf, helium star)
  - High contrast at close separations



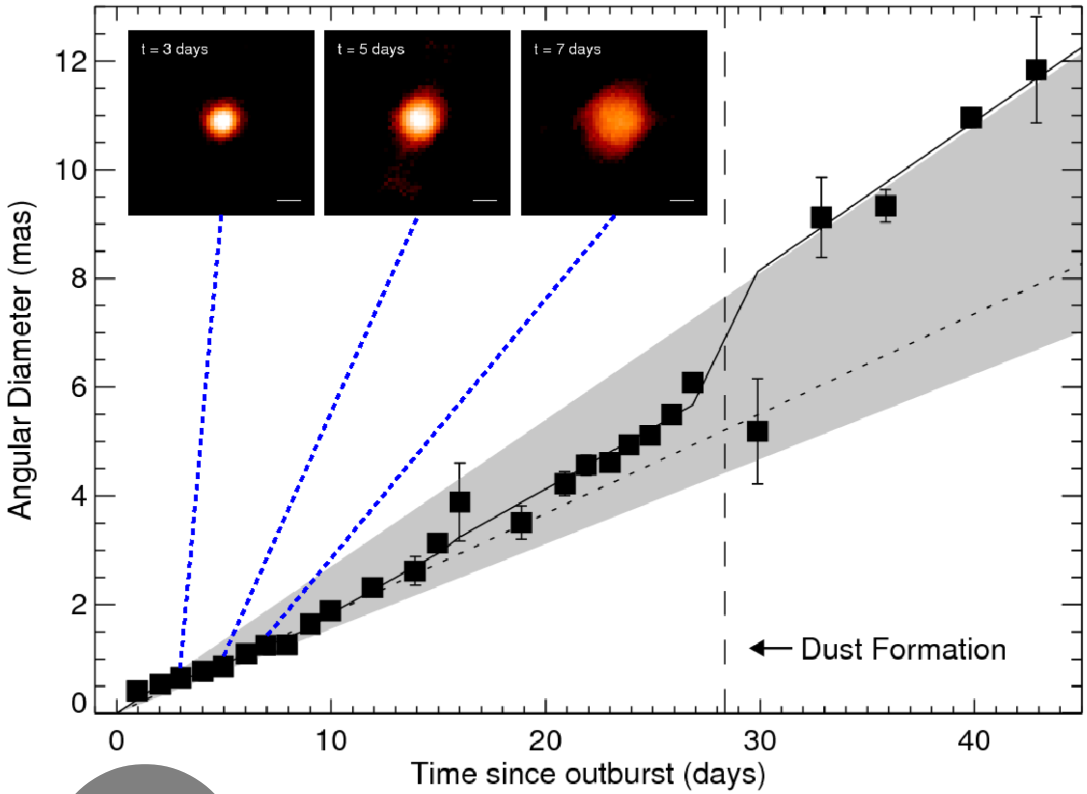
Mourard et al. (2015)

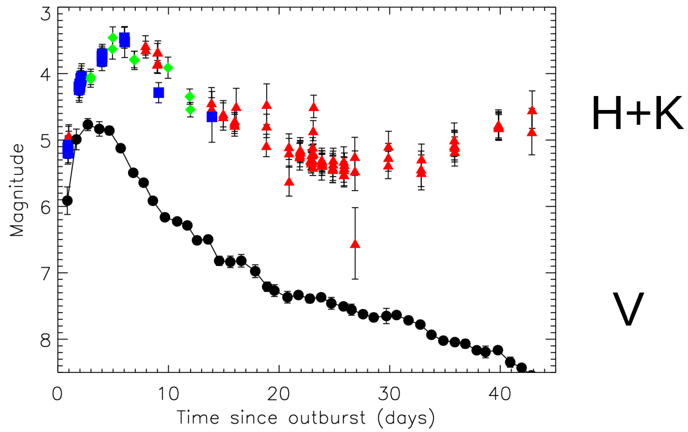
Classical Nova

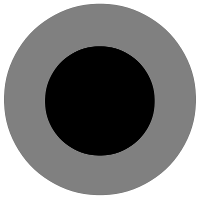
- Material from close binary companion accretes onto surface of white dwarf
- When pressure and temperature of accreted material reach a critical level, ignites in a thermonuclear runaway
- Expansion velocities of 500 – 3000 km/s



Nova Delphini 2013





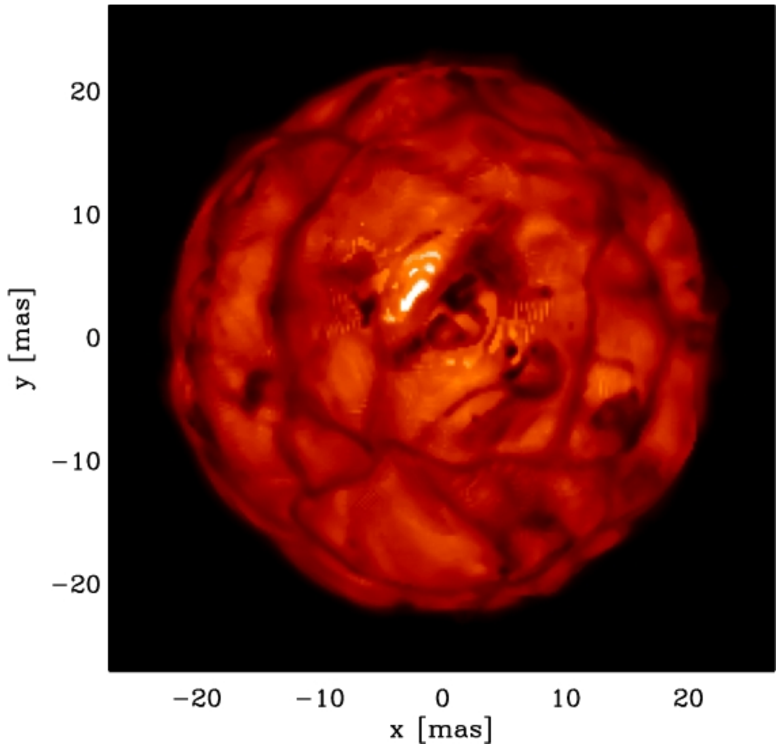


Schaefer et al. 2014

- 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

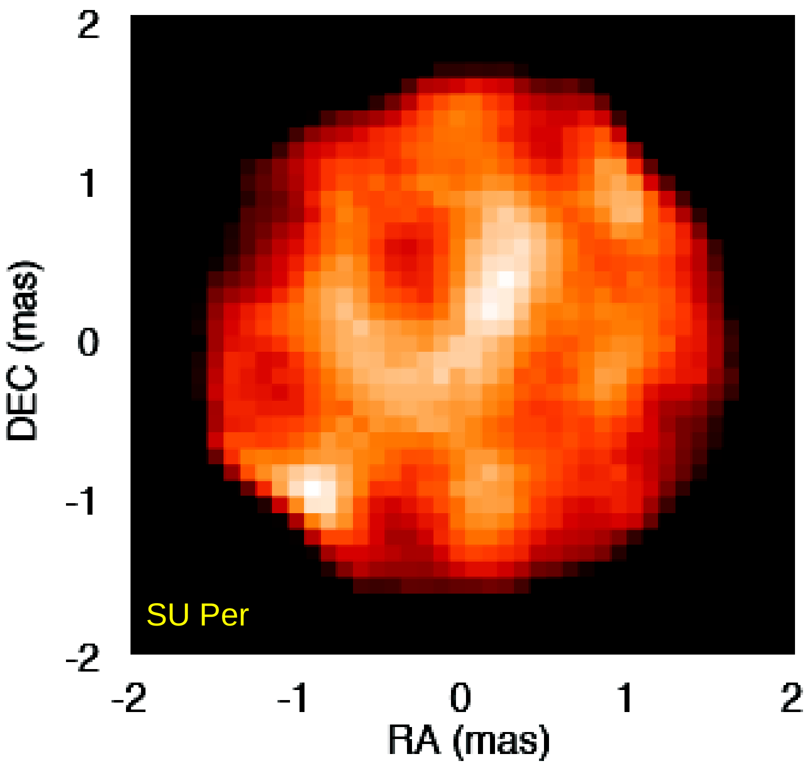
Stellar Convection

Model of Convection for Red Supergiant



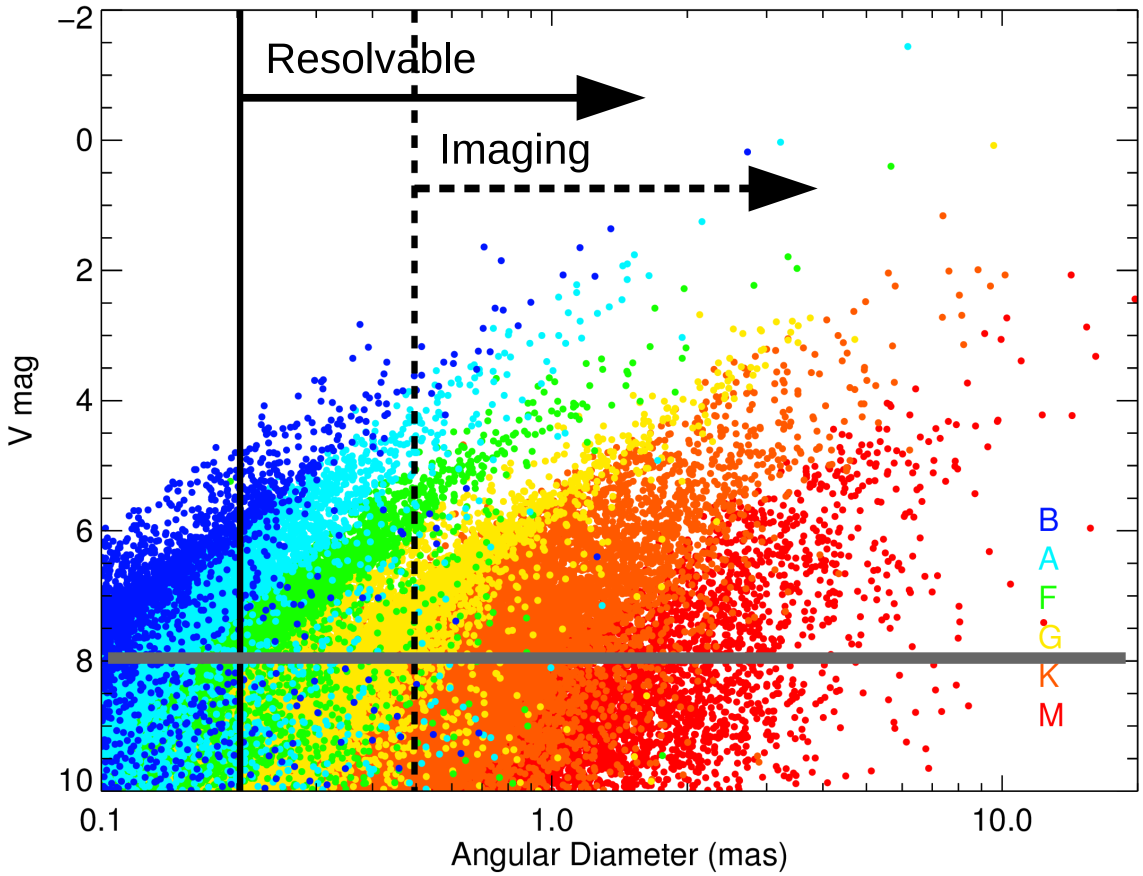
Chiavassa et al. (2010)

CHARA Image of SU Per



Norris et al. (in prep)

Looking Toward the Future...



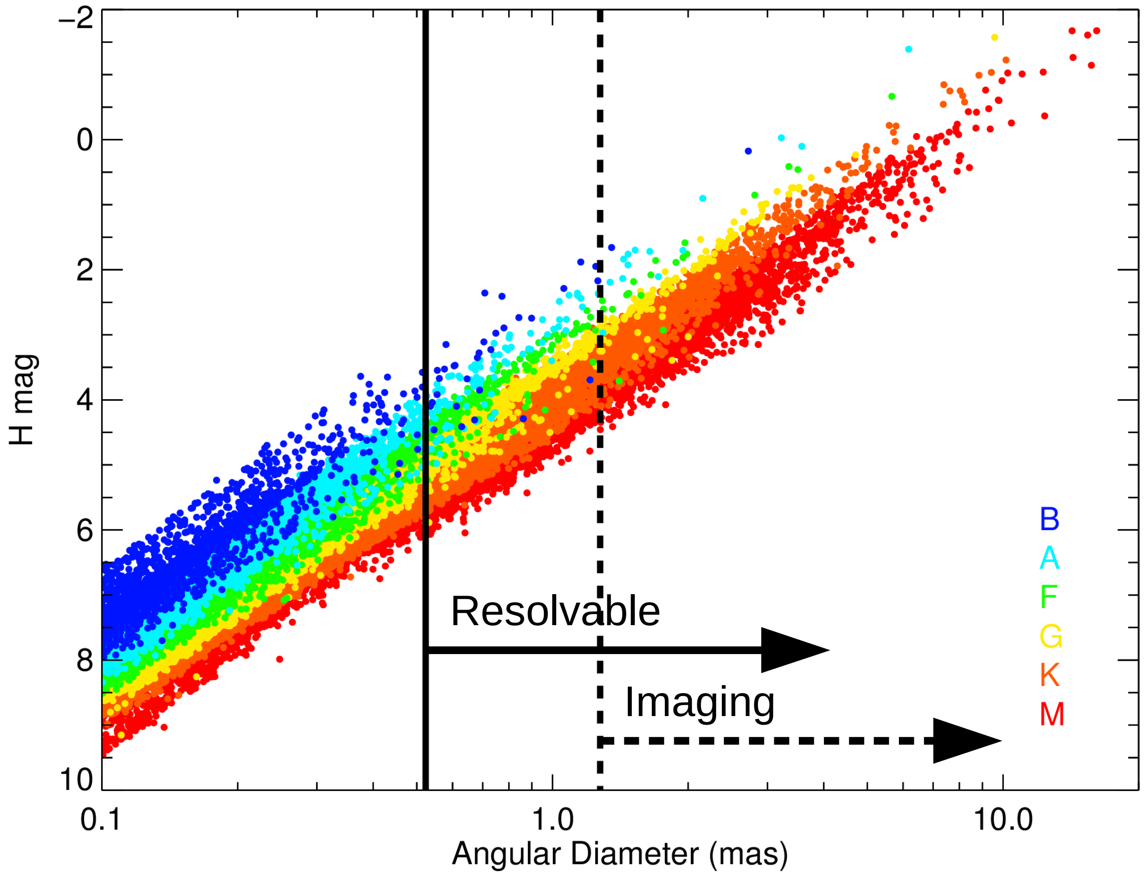
JMMC Stellar Diameter Catalog

DEC > -20°
V < 8 mag
θ > 0.2 mas

Nstar = 18,147

Imaging = 9,781

Looking Toward the Future…



JMMC Stellar Diameter Catalog

DEC > -20°
H < 8 mag
θ > 0.5 mas

Nstar = 19,116

Imaging = 3,558

Summary

- CHARA Array can resolve sizes of stars across the HR Diagram
- Improving our understanding of stellar structure and evolution
  - Stellar radius, effective temperature, dynamical masses
  - Limb darkening, gravity darkening
  - Rotation
  - Starspots
  - Mass loss
  - Convection
- Community access time
  - 50 nights available per year
  - NOAO proposals due in September and March