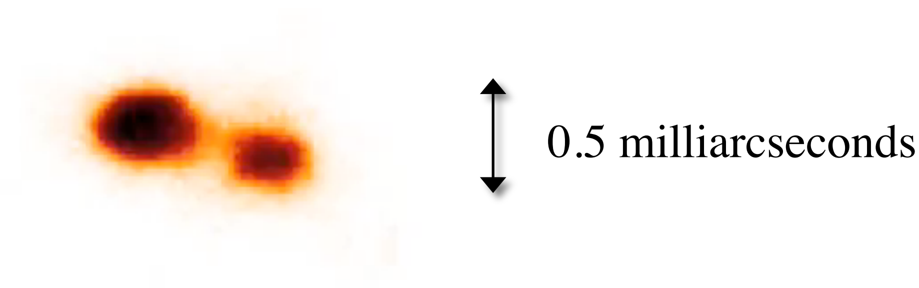
Imaging Stars and Planets with the CHARA Interferometer



Ming Zhao
JPL

Collaborators: John D. Monnier (U. Michigan)
Theo ten Brummalaar, Douglas Gies (CHARA),
Ettore Pedretti, Nathalie Thureau (Univ. of St. Andrews)

Stars - big or small?

- The nearest star: α Cen (A)

  R = 1.23 R_{sun} , D = 1.34 pc

  Angular size = 4.3 milliarcseconds

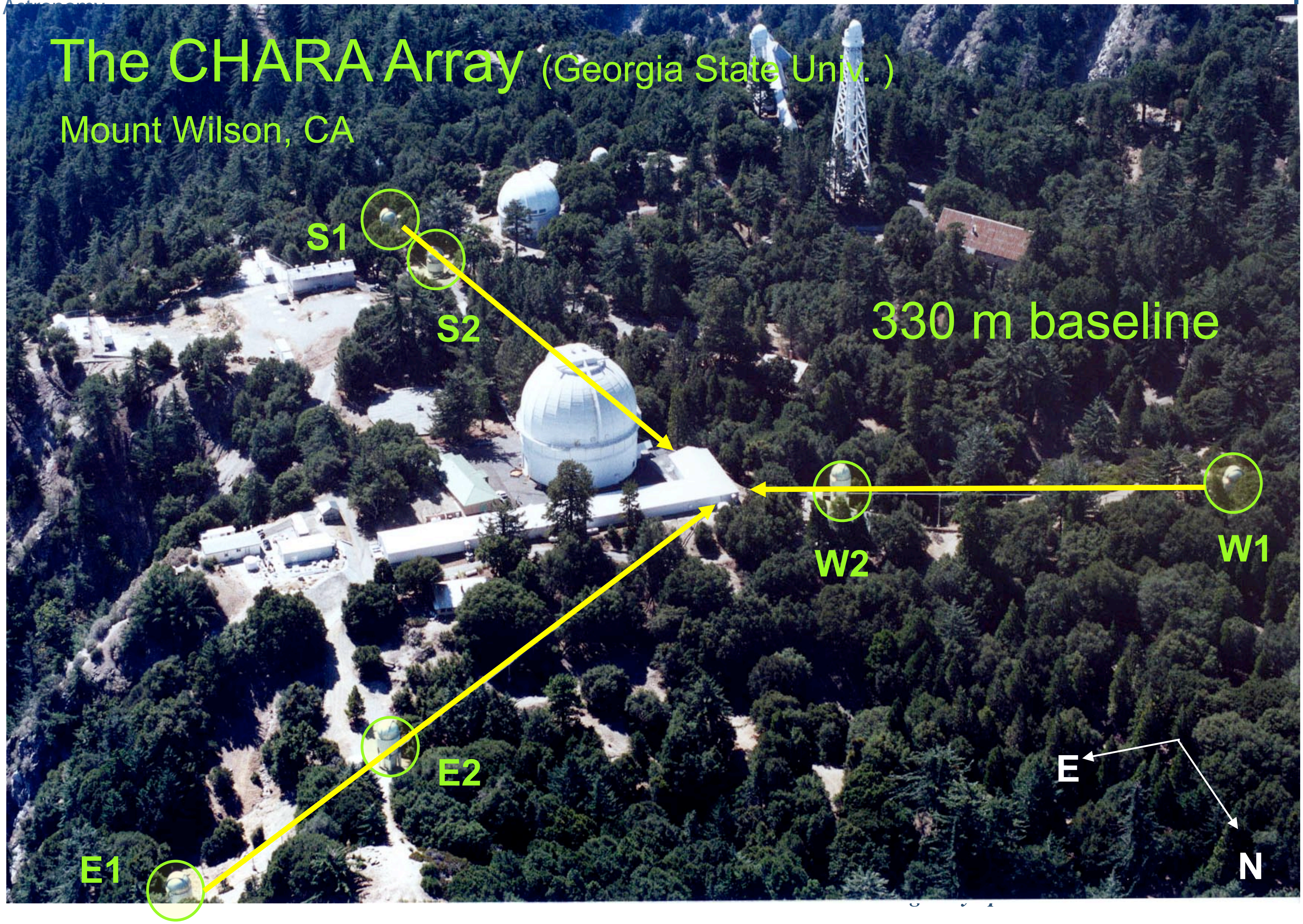
- The brightest star: Sirius (A)

  R = 1.71 Rsun, D = 2.64 pc

  Angular size = 3.0 milliarcseconds

Observatory	Wavelength	Diameter Or Baseline	Angular Resolution
Hubble Space Telescope	500 nm	2.4m	43 milli-arcsecond
Keck Observatory	1.65 micron	10 m	34 milli-arcsecond

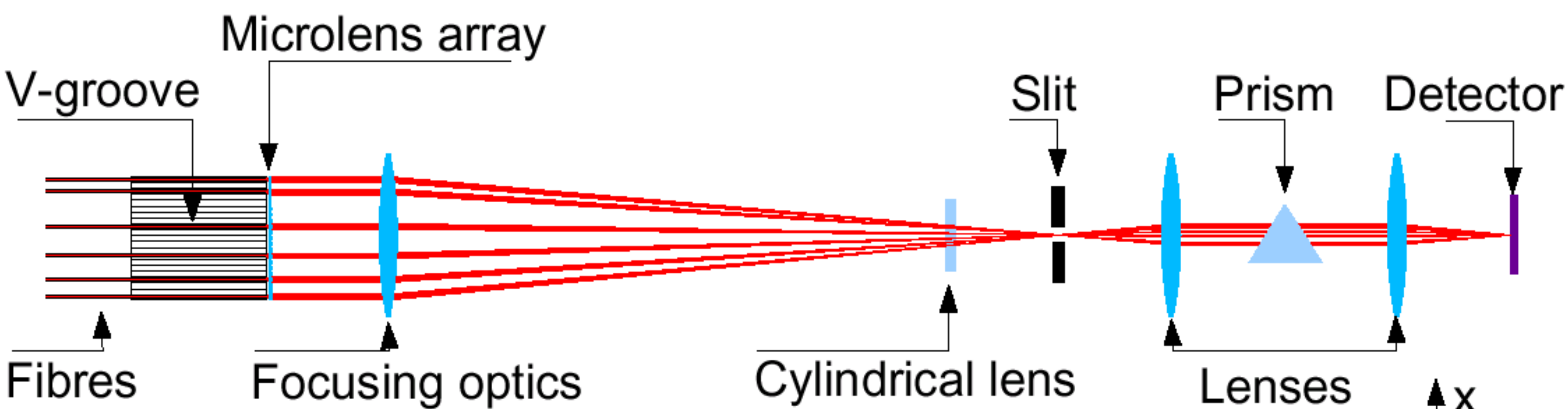
1 milliarcsecond at 1.65 micron => 340 m ! (λ/D)


The CHARA Array (Georgia State Univ.)
Mount Wilson, CA
330 m baseline
S1
S2
W2
W1
E2
E1
E
N

MIRC: Michigan Infrared Combiner

Basic Capabilities:

1) Designed for *imaging* -- currently combines 4 telescopes at once
2) 1.5-2.4 micron wavelength coverage
   (in this talk, all results are H band, 1.65 microns)
3) Spectral modes: R~40,150,400



(Monnier et al. 2004)

CHARA+MIRC can image and provide new science to :

- Stars - rapid rotators, spotty stars, etc.
- Binaries - interacting systems
- Circumstellar disks - YSO disks,
  Be star disks
- Hot Jupiter systems

Imaging Stellar Surfaces: Resolving Rapid Rotation

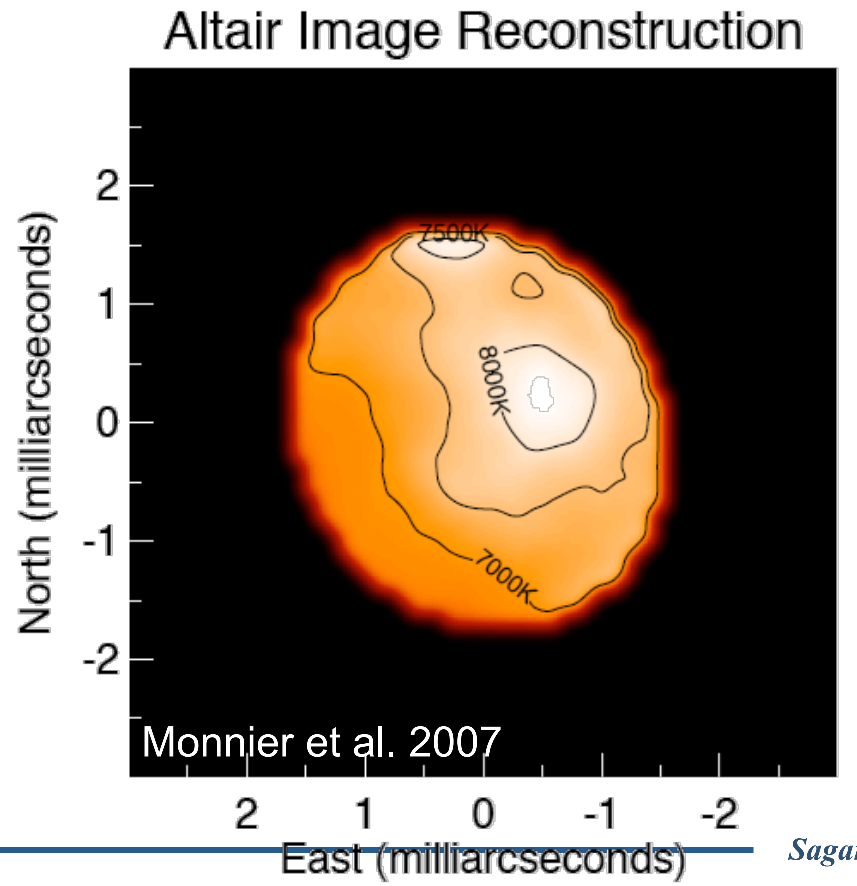
- Rapid rotation of hot stars is expected to
  - Distort stellar photosphere
  - Cause "gravity darkening" along the stellar equator (von Zeipel 1924)
  - Modify interior angular momentum and differential rotation
- Importance in many areas
  - Rotation-induced mixing causing observed abundance anomalies (Pinsonneault 1997)
  - Alters H-R diagram and Mass-Luminosity relation (Maeder & Maynet 2000)
  - Affects circum-stellar environments
  - Link to Gamma Ray Burst progenitors

Imaging

- All previous results were based on model-fitting of interferometry data with a few baselines
- Basic model of Von Zeipel (1924ab)
  - Big assumptions: solid body rotation, point gravity, simplistic radiative transfer model for outer layers
- Hydro models suggest non-solid body rotation, e.g., differential rotation, meridional flows
  - Jackson et al. 2004; MacGregor 2007; Espinosa Lara & Rieutard 2007
- “Model-Independent” imaging with CHARA-MIRC can test wide class of models

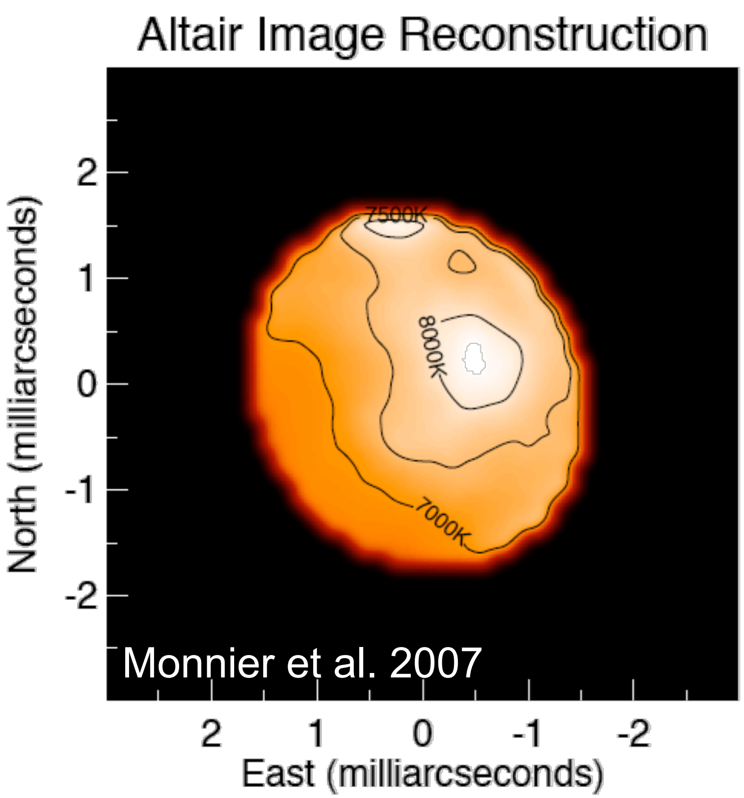
First image of a main-sequence star
(besides the Sun…)

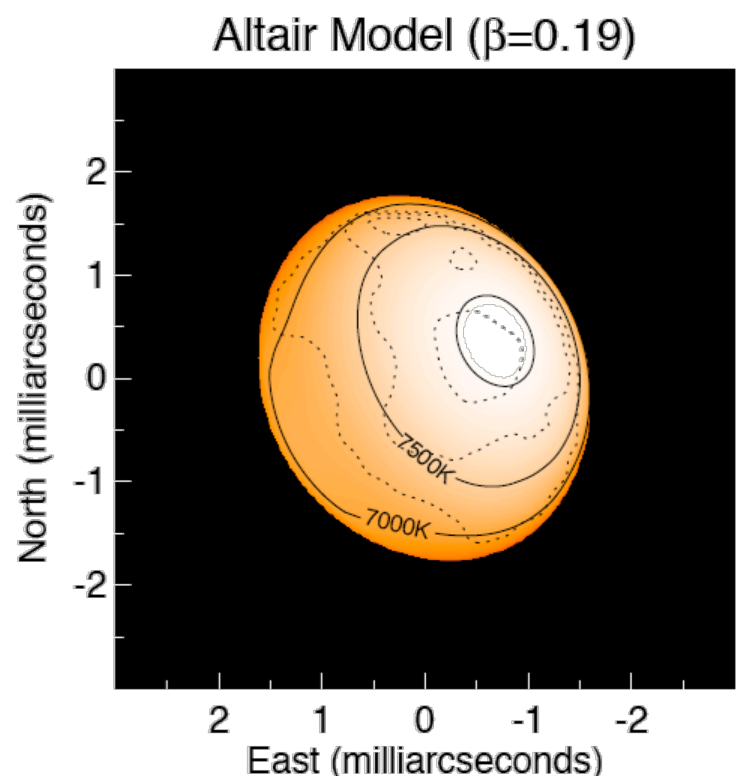
- Altair (α Aql, V=0.7)
  - Nearby hot star (d=5.1pc, A7V, T=7850 K)
  - Rapidly rotating (v sin i = 240 km/s, ~90% breakup)



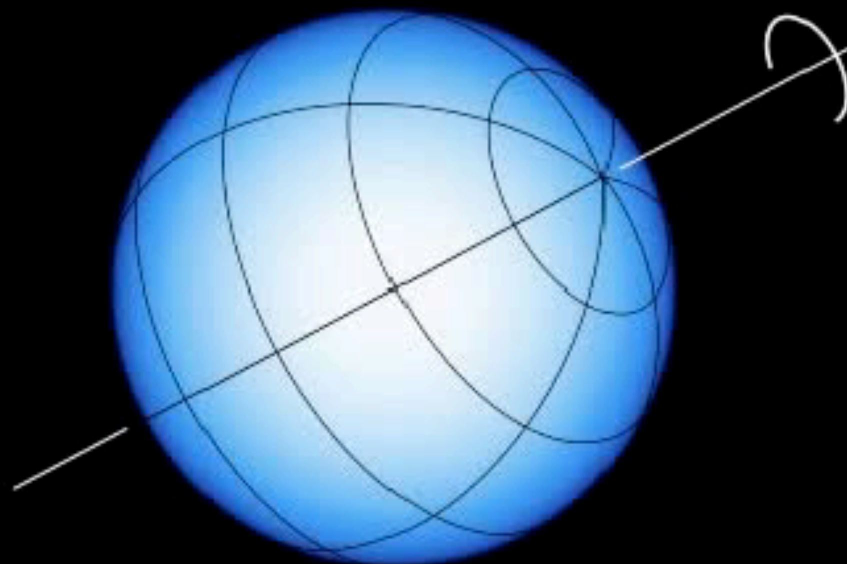
Modeling Altair

- Construct 3D sphere + apply von Zeipel model ($T \propto g^{\beta}$) + Kurucz limb darkening
- Fast algorithm: more accurate, faster





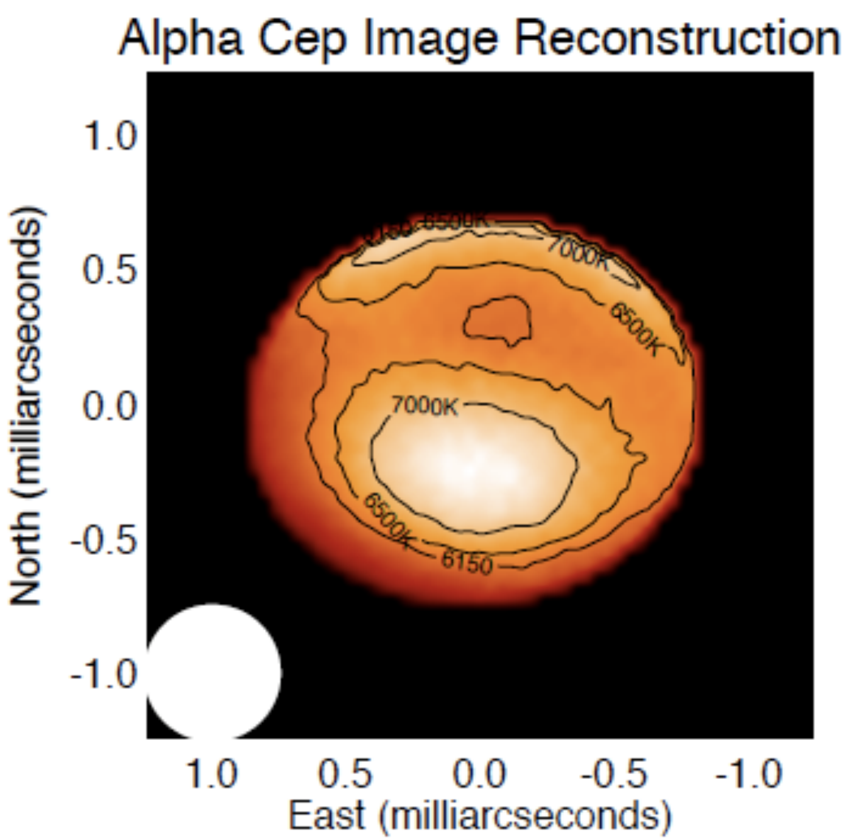
Model of a fast-spinning star

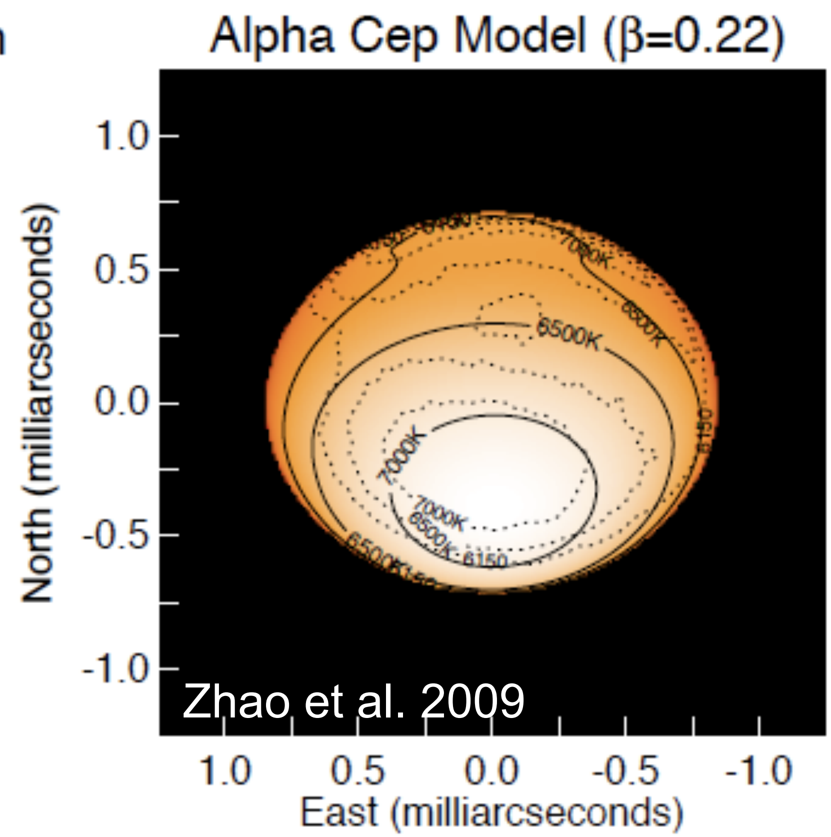


0.1 revolutions/day

More Results: Alderamin (α Cep)

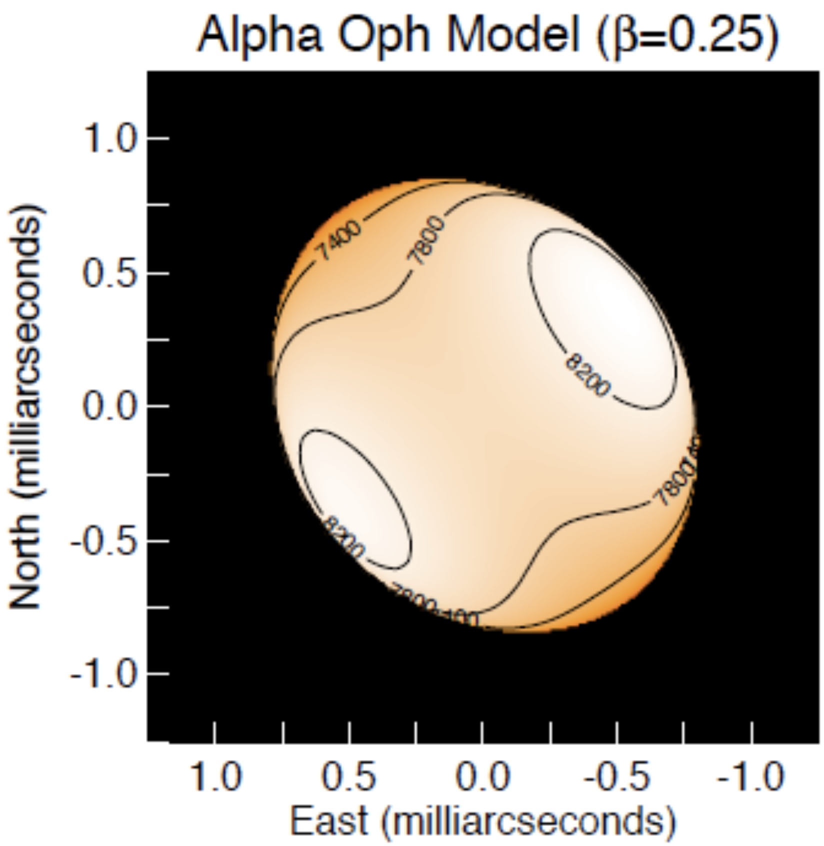
- A7 IV-V, D = 15pc
- ~93% of break-up, 12.46 hrs/cyc
- R_eq/R_pol = 1.26
- T_pol - T_eq = 2000K



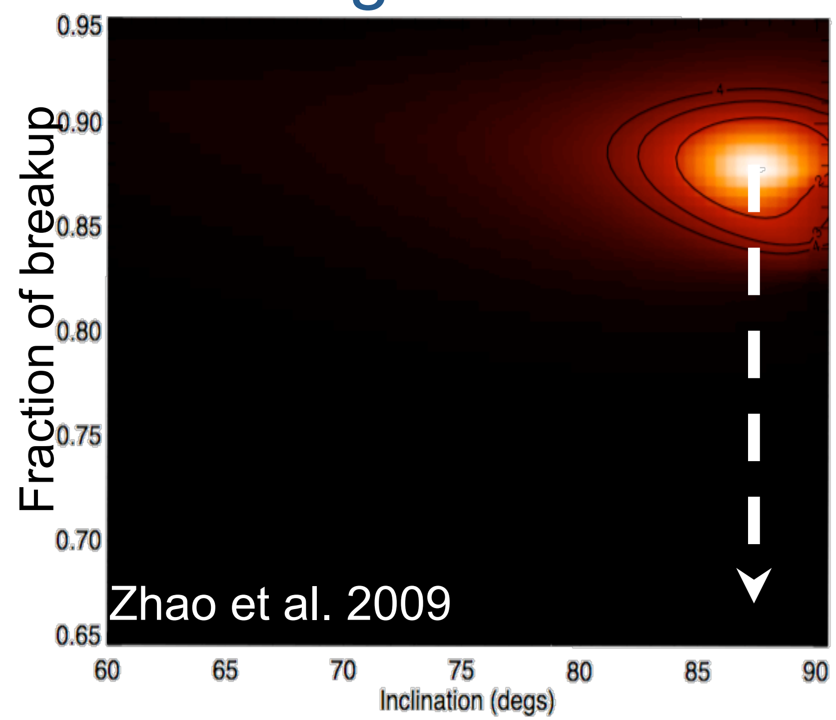


More Results: Rasalhague (α Oph)

- A5IV, d = 14pc
- ~ 89% break-up, 14.6 hrs/cyc
- T_pol -T_eq = 1850 K
- R_eq/R_pol = 1.20



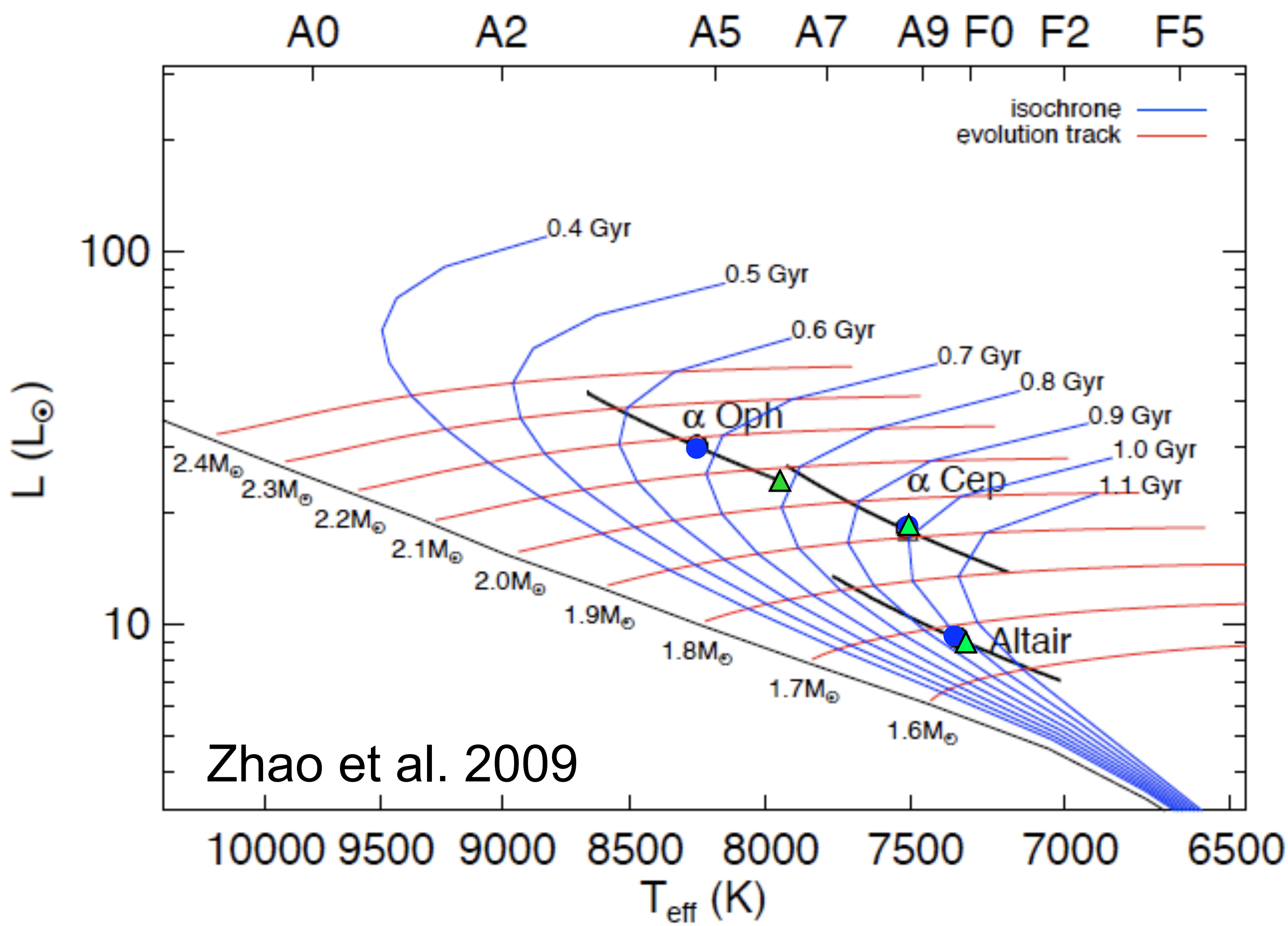
An edge-on rotator!



Scrutinizing von Zeipel Theory

- Our models prefer non-standard von Zeipel law
- Models show that the polar areas of the stars are radiative and equatorial areas might be convective
  - Other evidence: both stars have strong chromosphere activity
- Images show that equator is cooler than expected
  - Differential Rotation?
  - Spectral line analysis underway

True HR Diagram

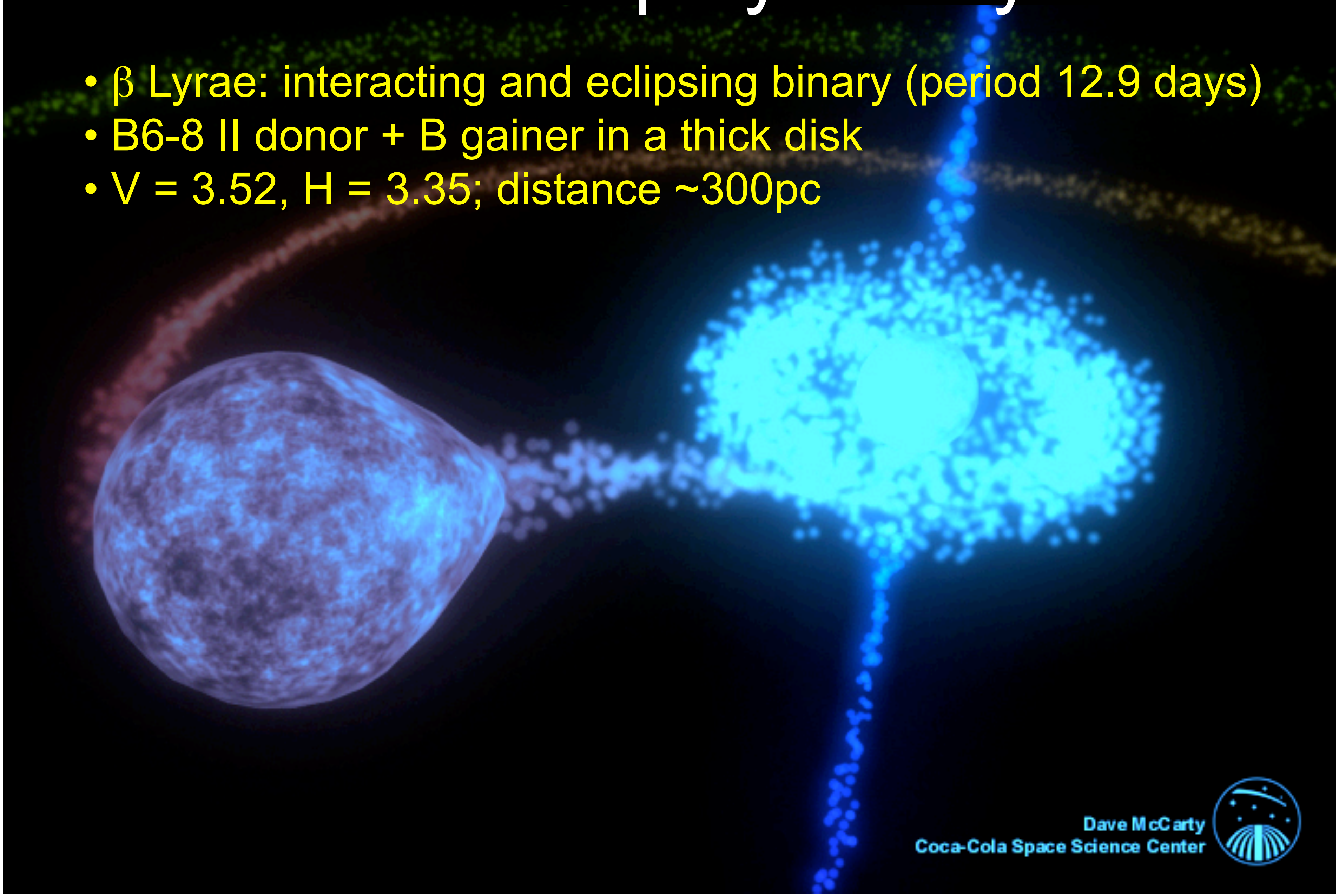


More Results: 7 rapid rotators in total

Star	Spectral Type
Regulus (α Leo)	B8IV
Vega (α Lyr)	A0V
Denebola (β Leo)	A3V
Rasalhague (α Oph)	A5IV
Altair (α Aql)	A7V
Alderamin (α Cep)	A7IV-V
Caph (β Cas)	F2 IV

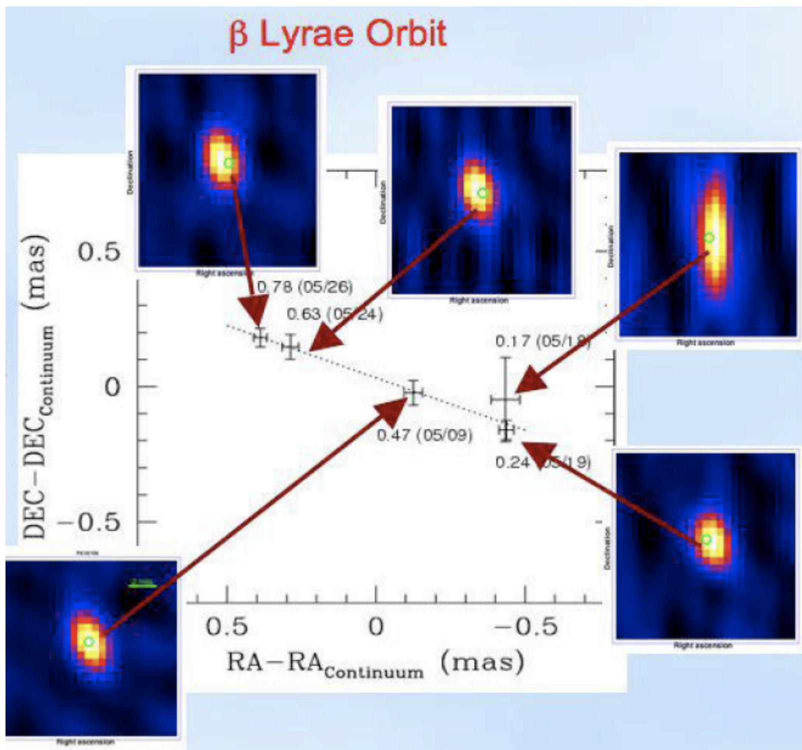
A well-known “β Lyrae” system:

- β Lyrae: interacting and eclipsing binary (period 12.9 days)
- B6-8 II donor + B gainer in a thick disk
- V = 3.52, H = 3.35; distance ~300pc



Previous Studies on Beta Lyrae

- Mostly light curves
- NPOI imaging of Hα emission region



(Hutter et al. 2008)

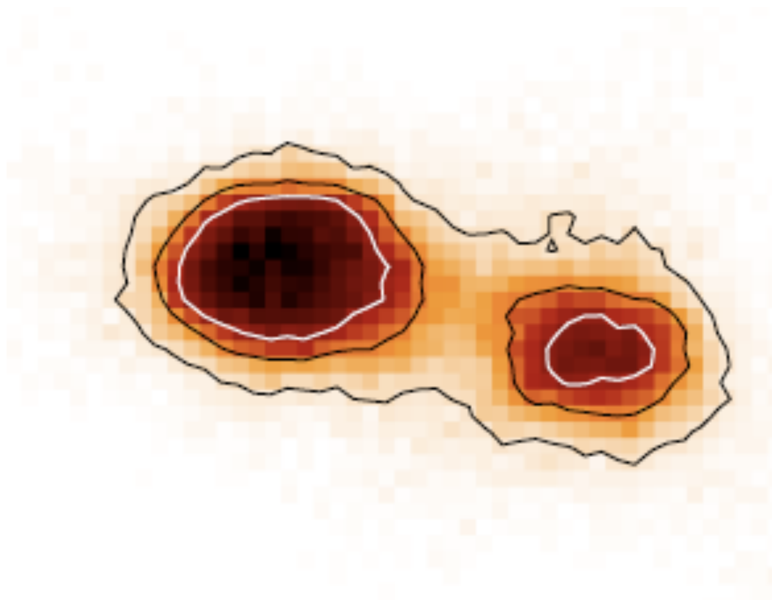
Previous Studies on Beta Lyrae

- Mostly light curves
- NPOI imaging of Hα emission region

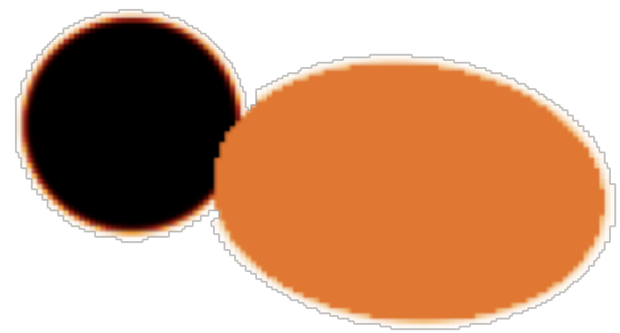
However, components unresolved,
no astrometric orbit available

First imaging of the 12.9-day eclipsing binary Beta Lyrae

CHARA-MIRC Image



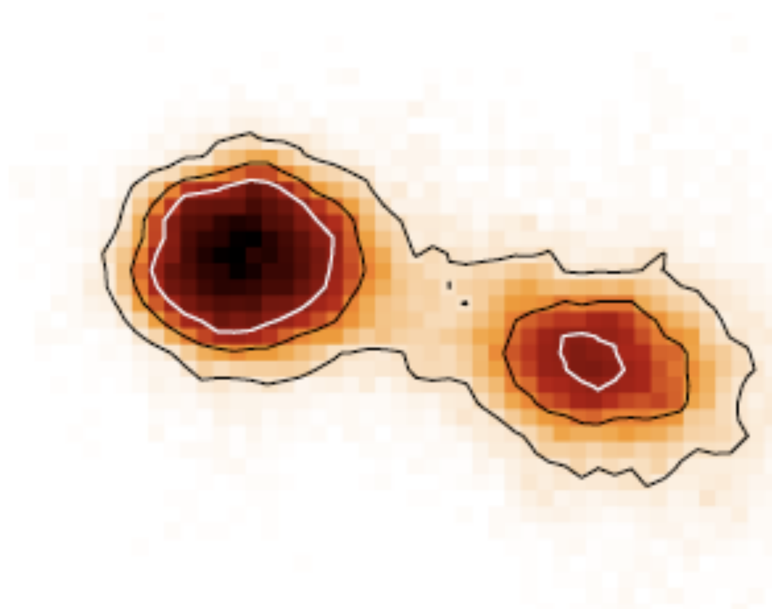
Model



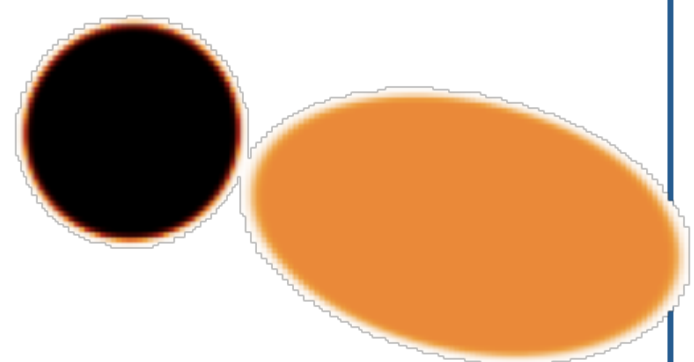
Phase = 0.132

First imaging of the 12.9-day eclipsing binary Beta Lyrae

CHARA-MIRC Image



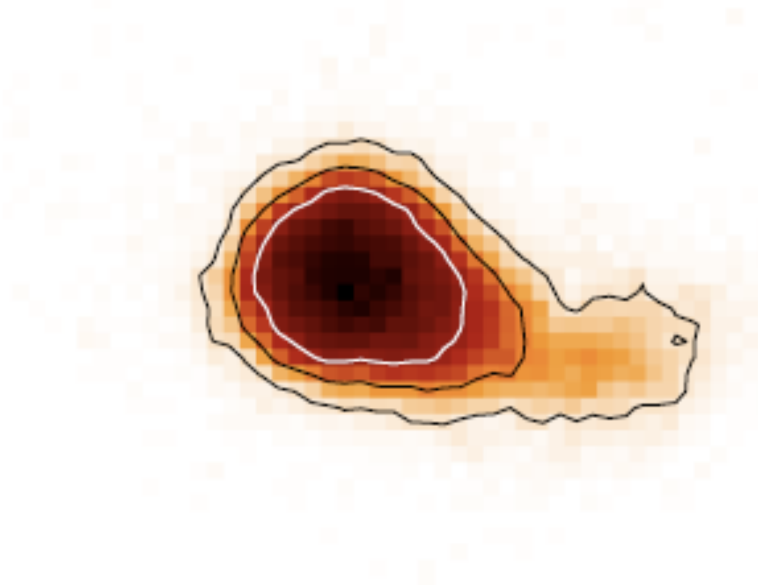
Model



Phase = 0.210

First imaging of the 12.9-day eclipsing binary Beta Lyrae

CHARA-MIRC Image

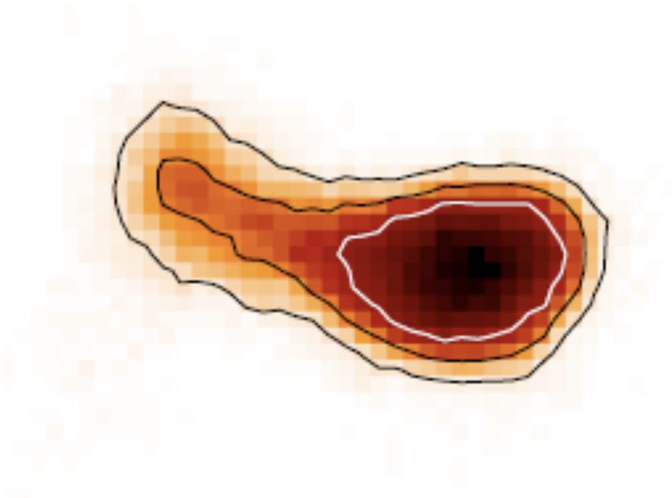


Model

Phase = 0.438

First imaging of the 12.9-day eclipsing binary Beta Lyrae

CHARA-MIRC Image

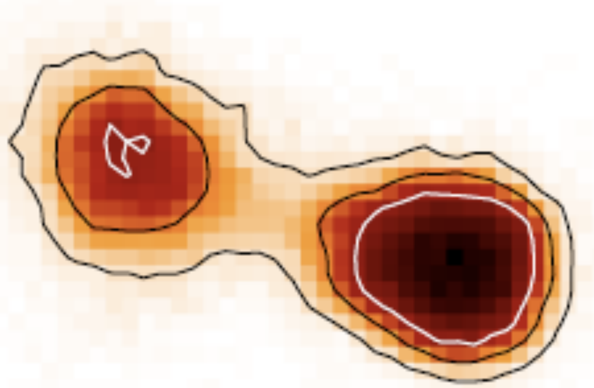


Model

Phase = 0.595

First imaging of the 12.9-day eclipsing binary Beta Lyrae

CHARA-MIRC Image



0.5 mas

Model

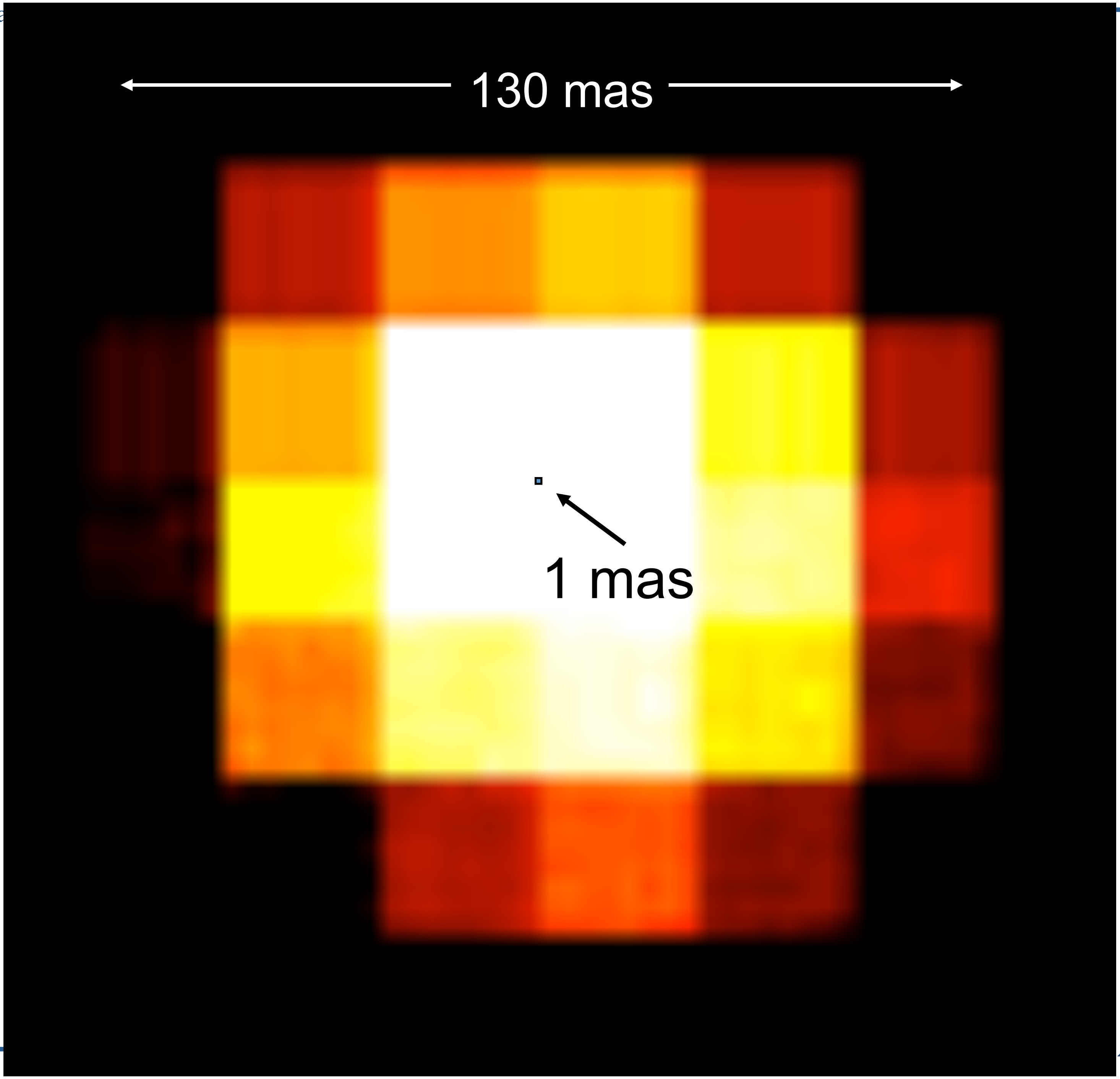
1 mas

Phase = 0.828

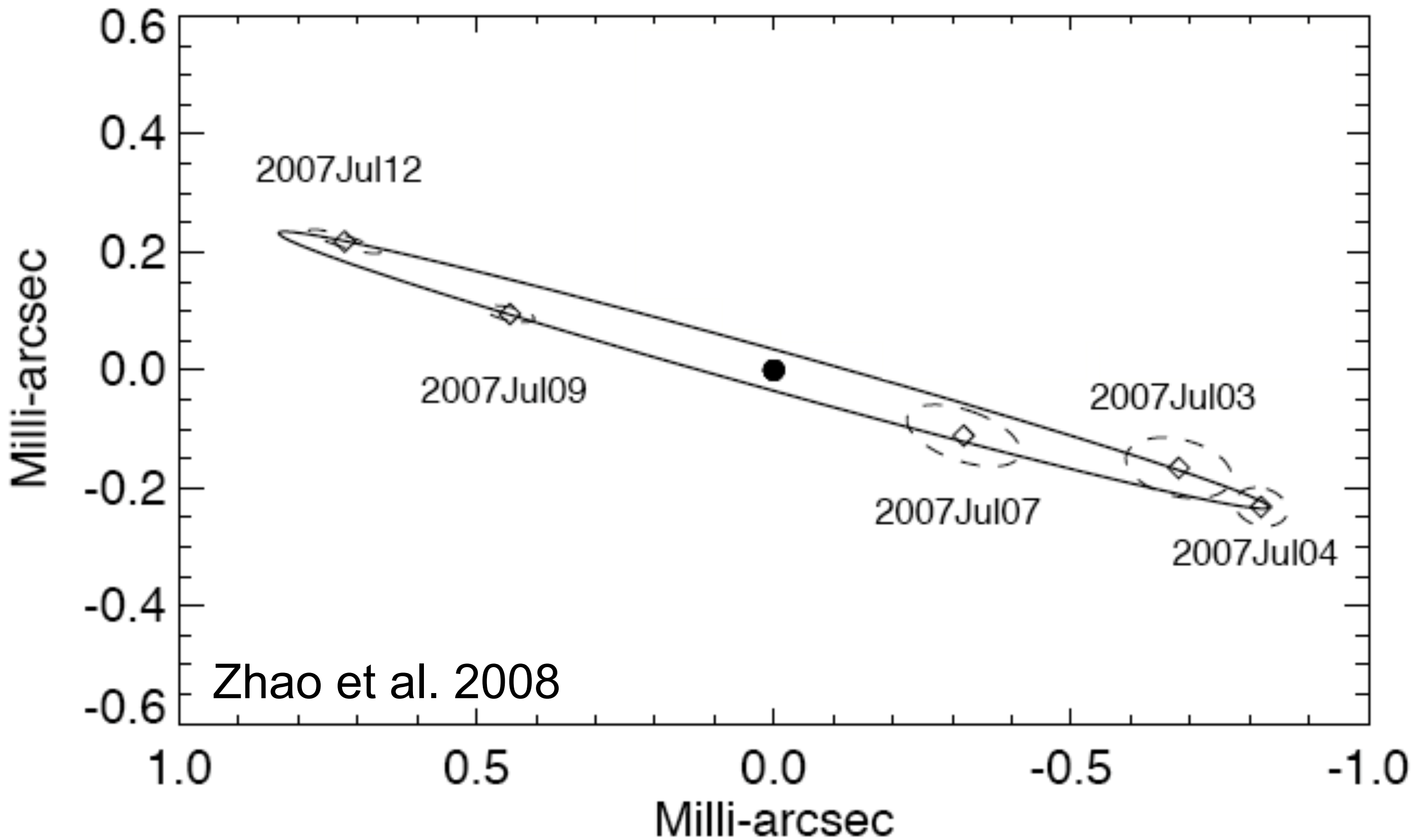
Zhao et al. 2008

First imaging of the 12.9-day eclipsing binary Beta Lyrae

Zhao et al. 2008

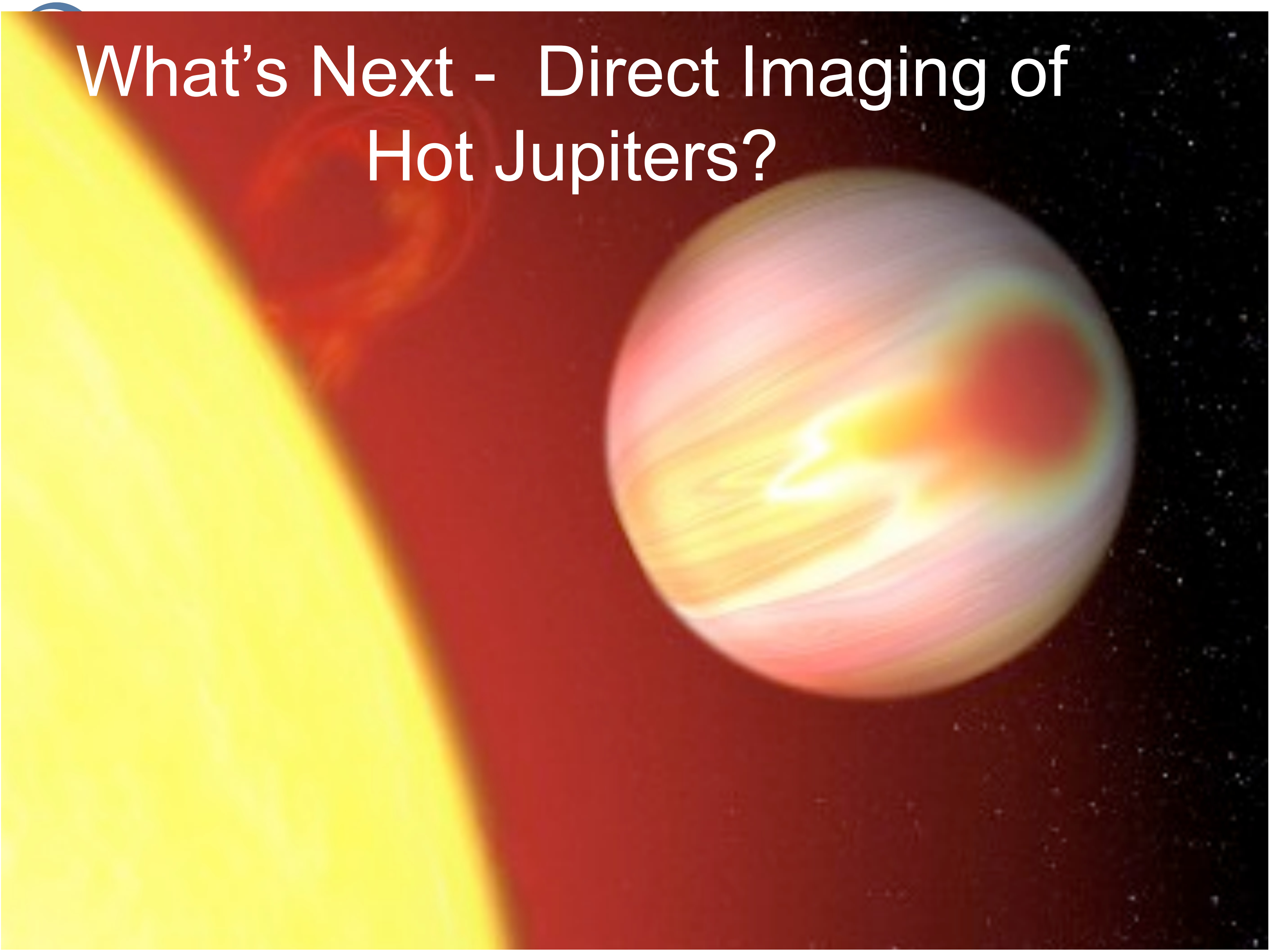

130 mas
1 mas

First Astrometric Orbit for β Lyr



- Orbit: $i \sim 92$ degs
- Mass: $M_{donor} = 12.8 +/- 0.3\ M_{sun}$; $M_{gainer} = 2.8 +/- 0.2\ M_{sun}$

What’s Next - Direct Imaging of Hot Jupiters?

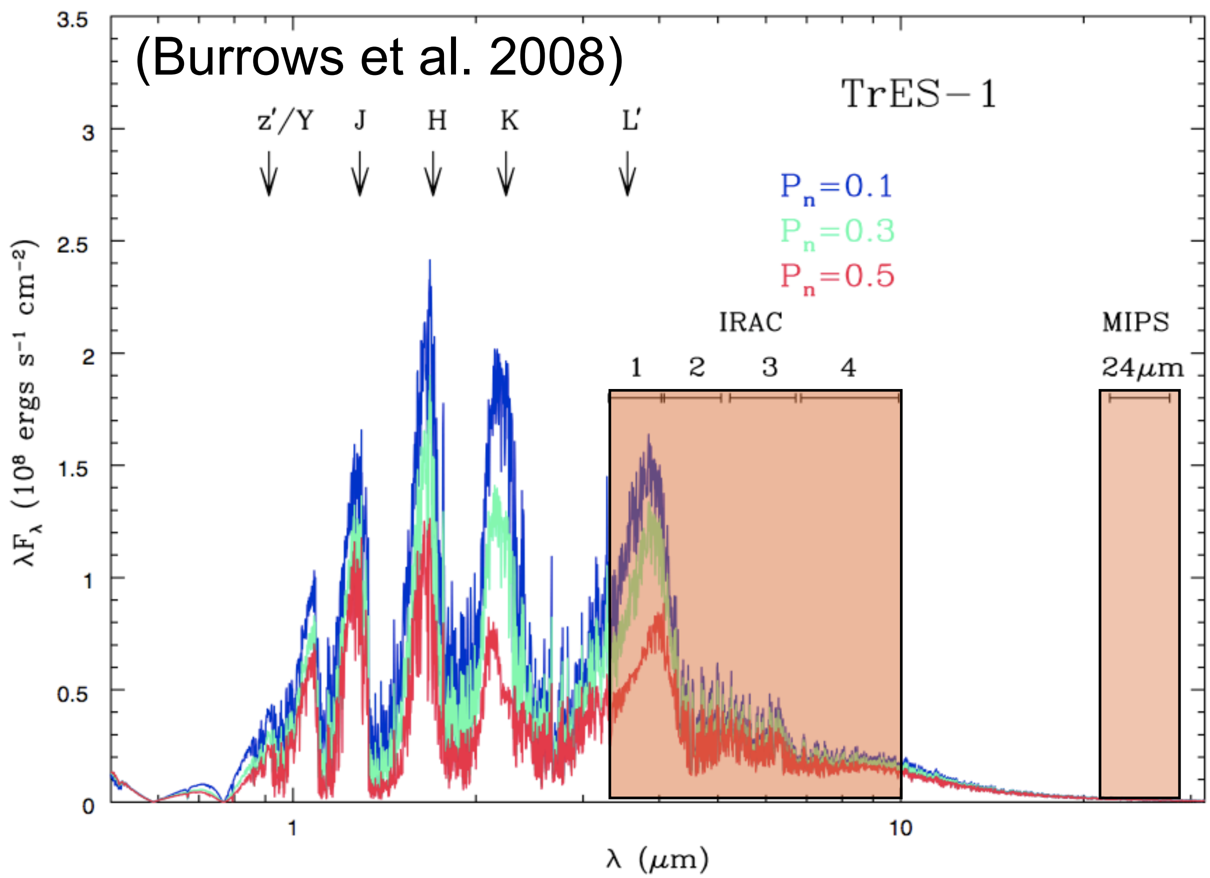


What can interferometry add to the science of hot Jupiters?

1). Spectral information in the near-IR

- Estimate global energy budget of hot Jupiters

• IRAC and MIPS cover only a small fraction of SED



What can interferometry add to the science of hot Jupiters?

1). Spectral information in the near-IR
   - Estimate global energy budget of hot Jupiters

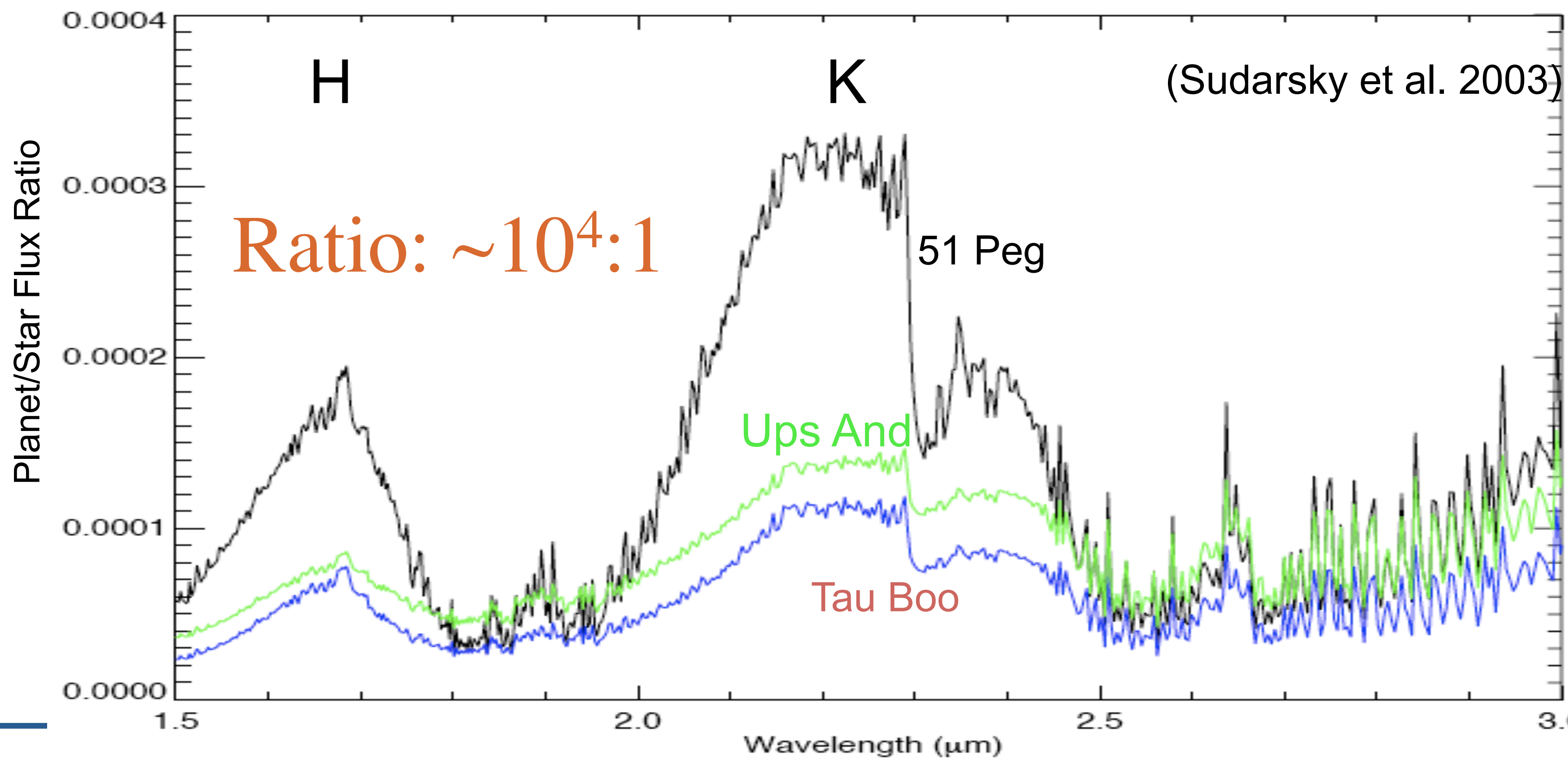
2). Day/night flux variation and flux calibration for non-transiting hot Jupiters
   - Break down model degeneracy

3). Obtain inclination and determine accurate mass for non-transiting hot Jupiters
   - Interferometers can see hot Jupiter systems as high contrast binaries

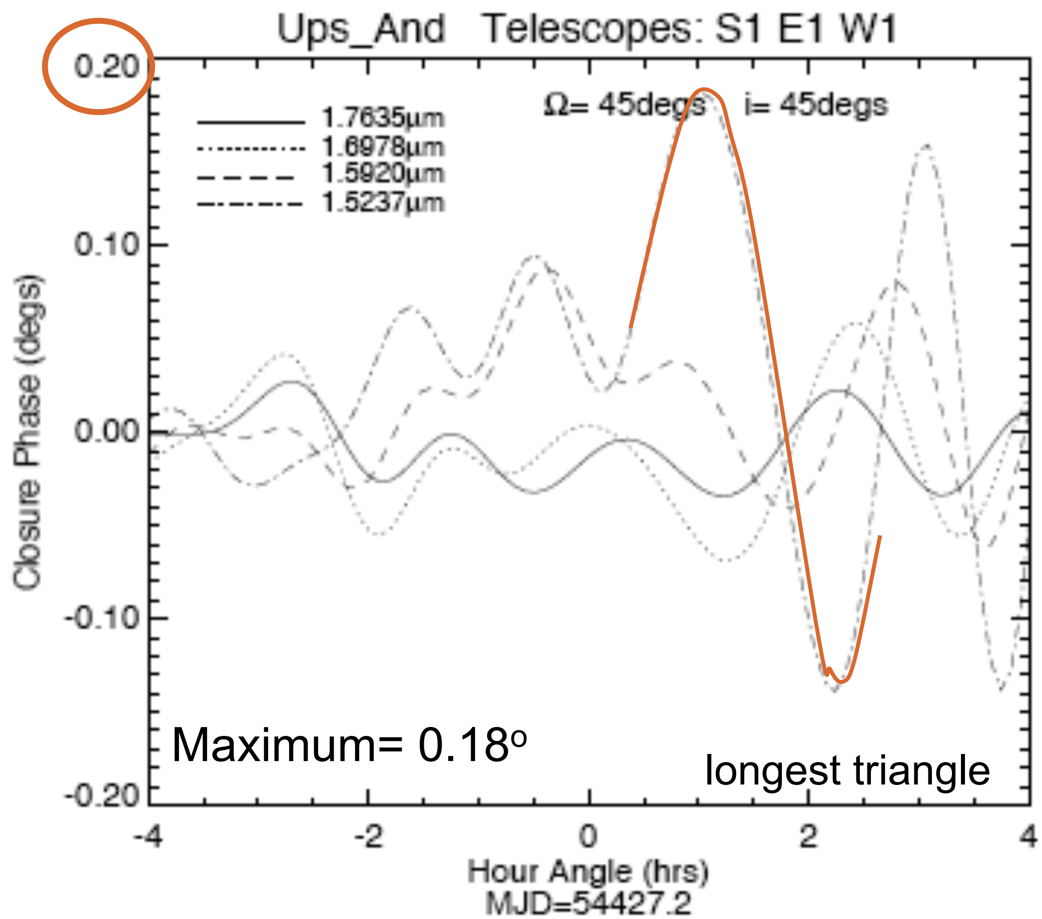
Best Candidates

Table 1. Hot Jupiter candidates for CHARA-MIRC

Star Name	Dist. pc	H mag	K mag	Period day	e	Semimajor axis AU	(mas)	T_0 JD	R_* mas
υ And	13.5	2.957	2.859	4.6170	0.034	0.059	(4.42)	2450088.64	0.569
τ Boo	15.6	3.546	3.507	3.3128	0.018	0.049	(3.13)	2451653.968	0.45
51 Peg	15.4	4.234	3.911	4.2310	0.01	0.051	(3.31)	2450203.947	0.35

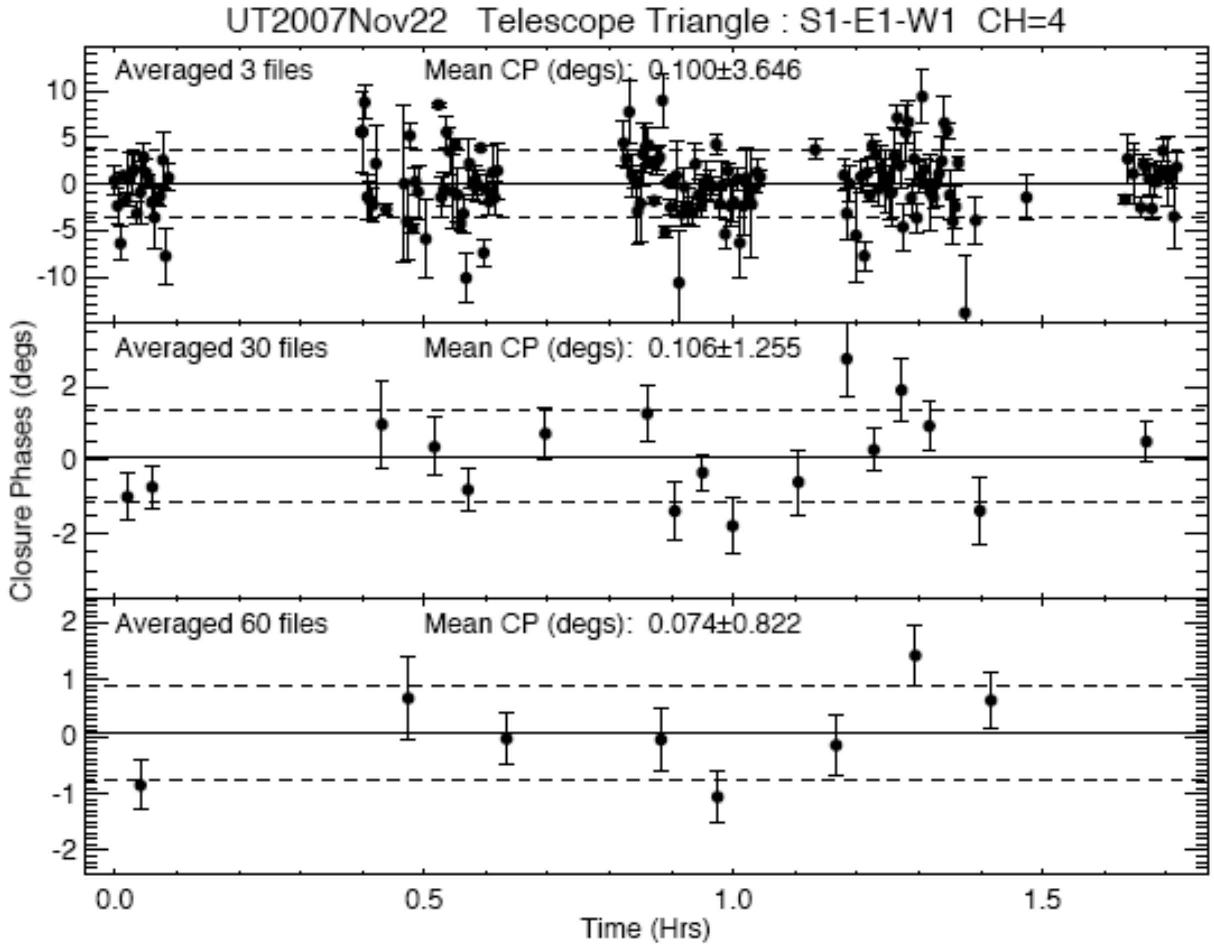


Closure phase simulation



Precision requirement: < 0.18º for the highest resolution channel

Observation of υ And



Need 6x S/N for 3σ detection!

Improvements

- Analysis Method:

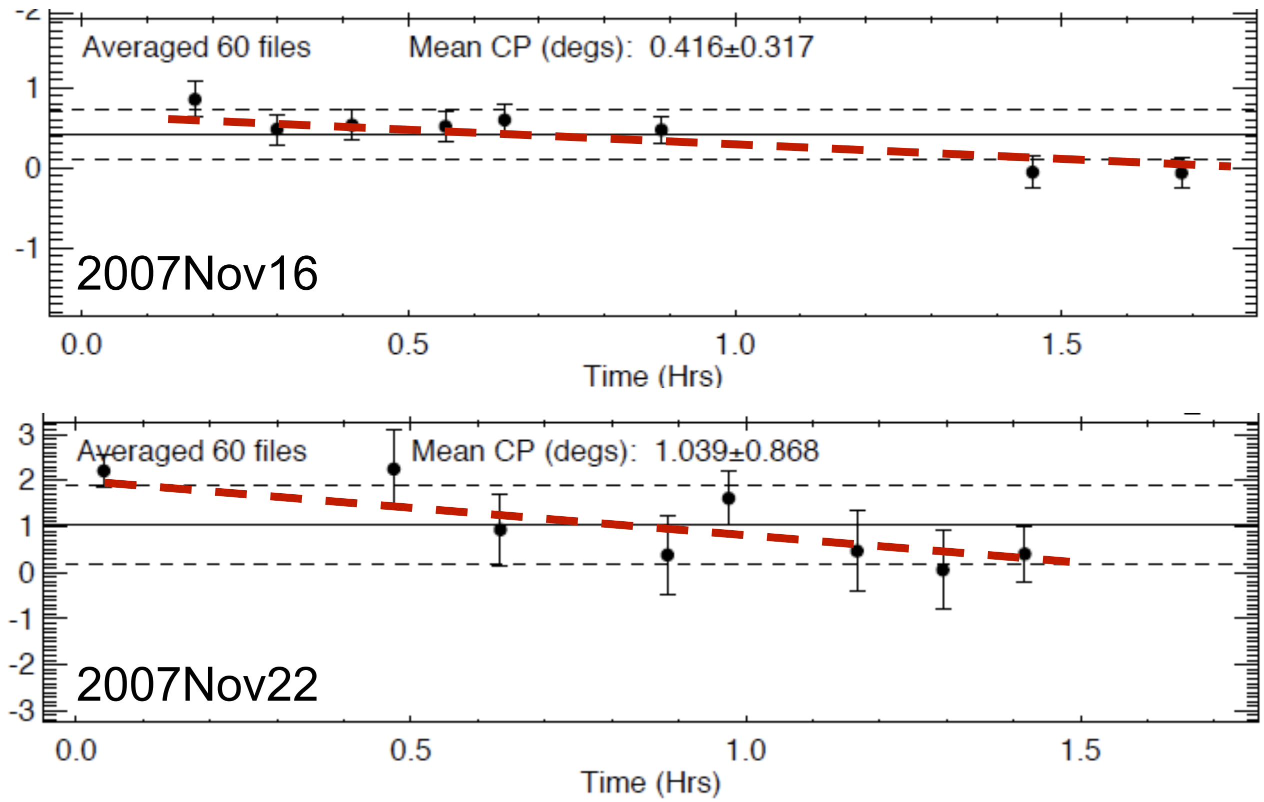
  - Orbital parameters: i, Ω
  - Day/night flux variation: amplitude, phase
  - Closure phase offset

$\Rightarrow$ Combined solution of multiple channels and nights

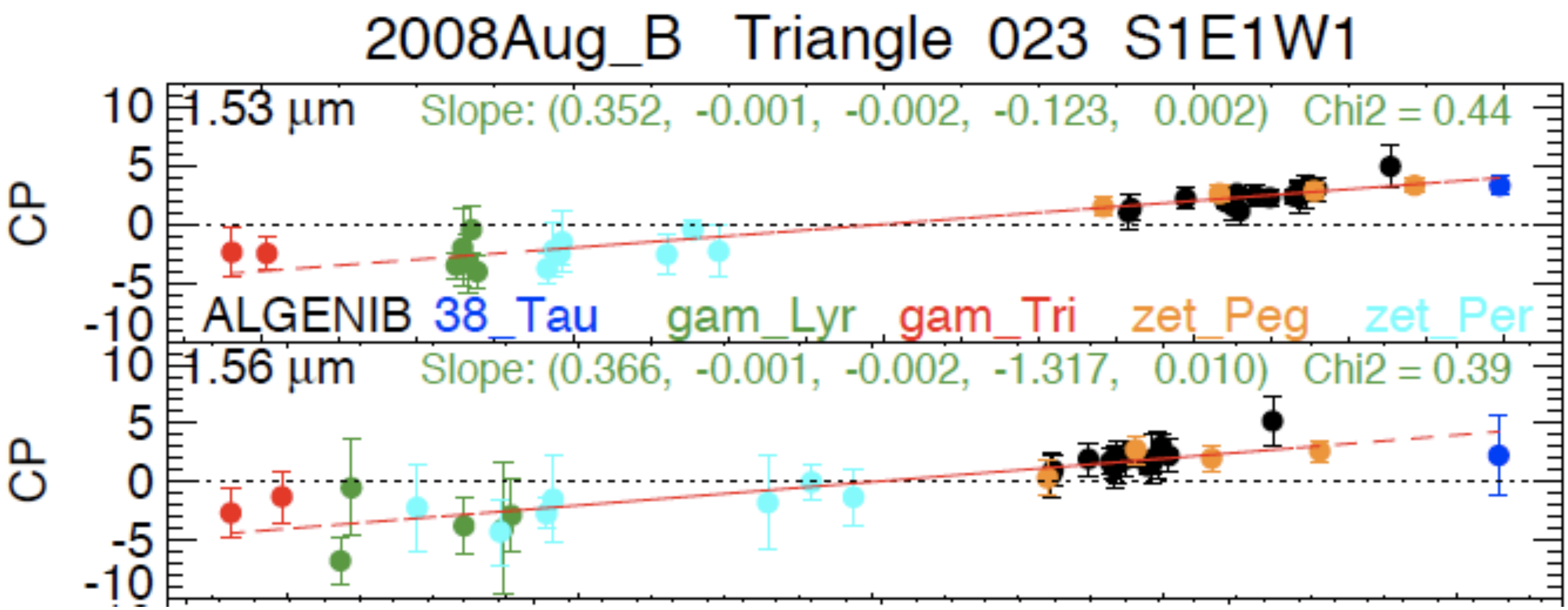
Improvements

- Calibration:
  - closure phase drifts due to polarization or dispersion (under investigation)

Drifts in closure phase

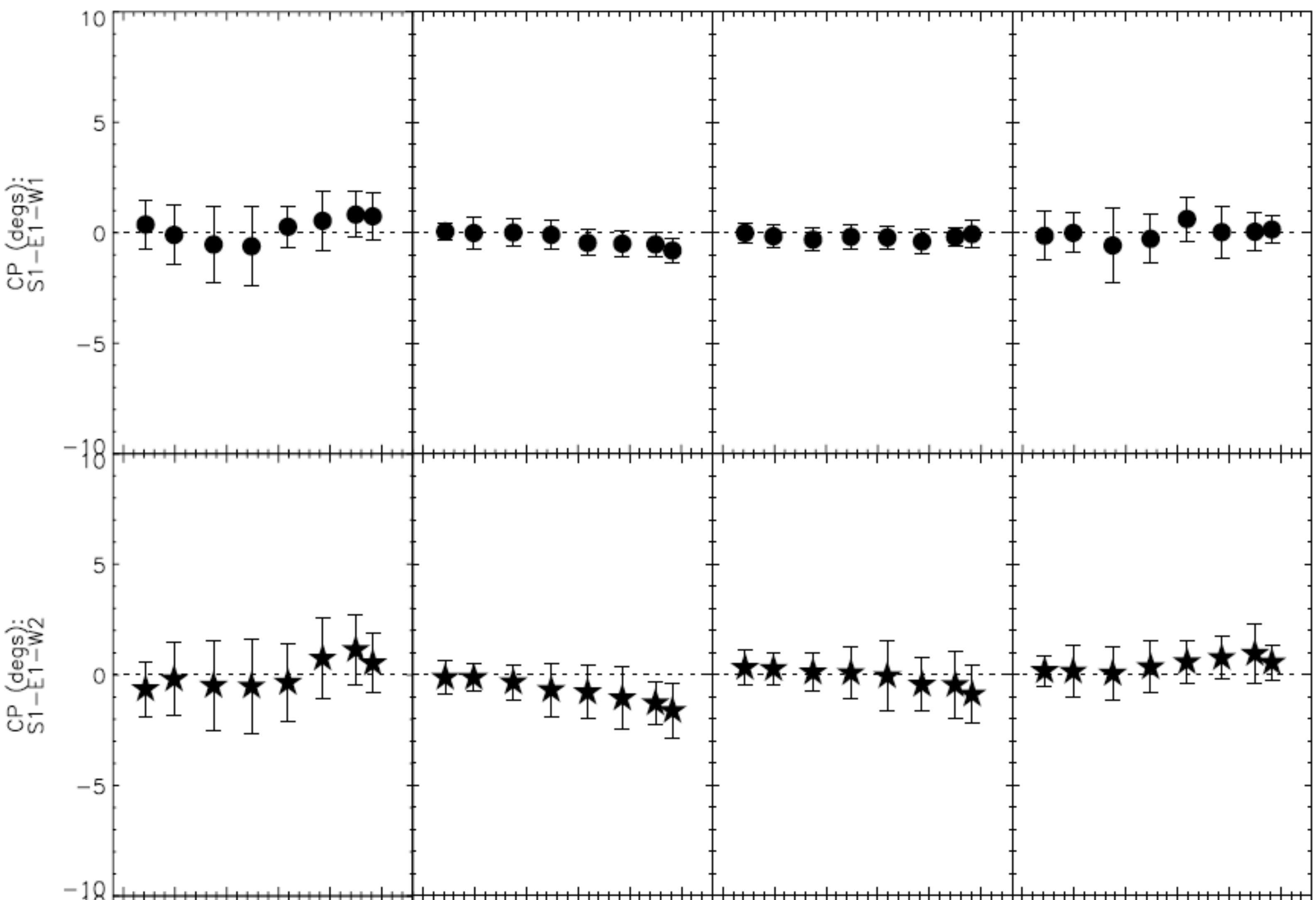


Closure phase as a quadratic surface function of Altitude and Azimuth

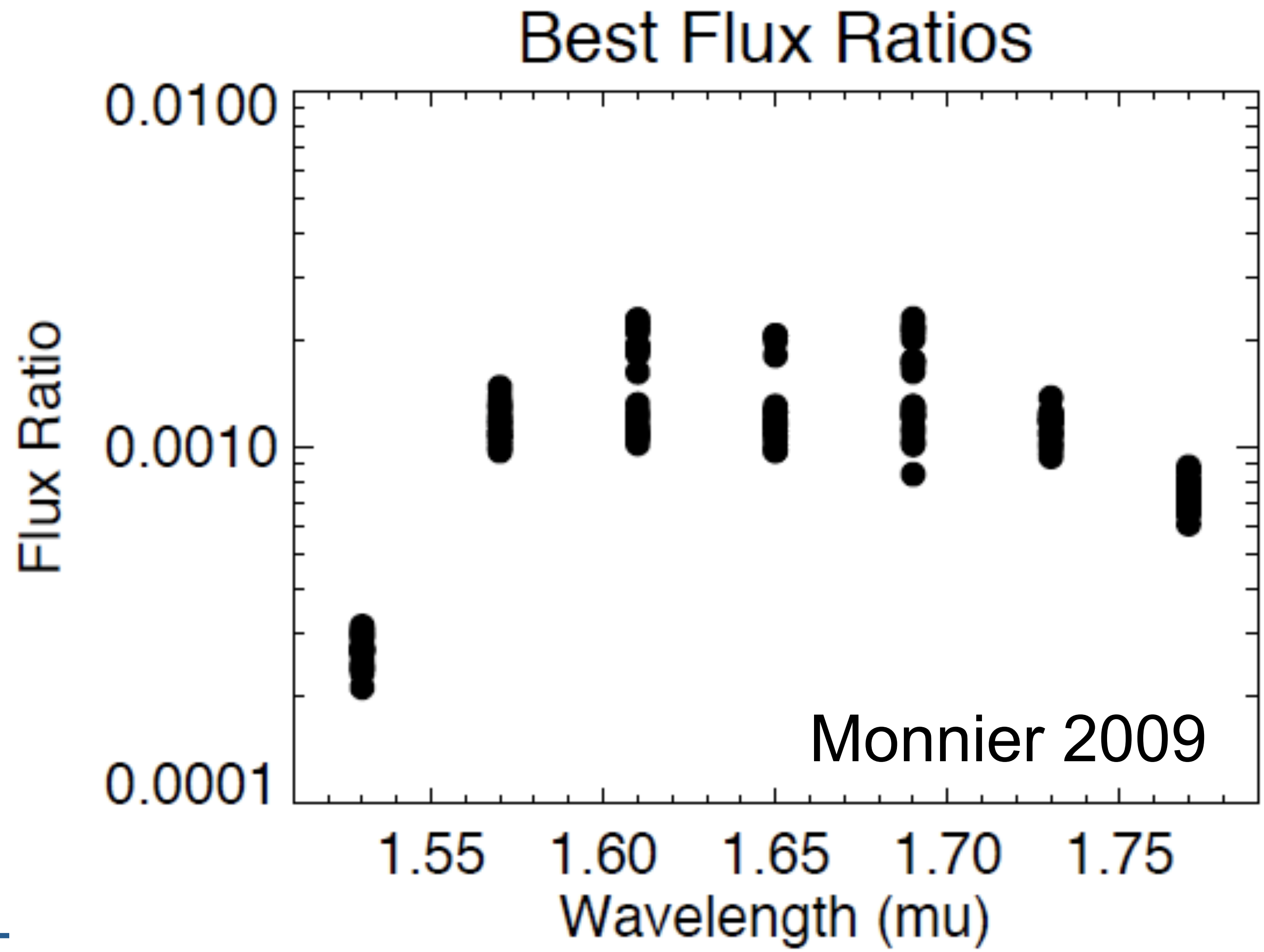


$$a1*AZ + a2*AZ^2 + a3*AZ*Alt + a4*Alt + a5*Alt^2$$

After new calibration



Preliminary upper limit for Ups And



Improvements

- Throughput
- Efficiency
- Noise Regime
- Calibration
- Data analysis

All improvements add together:
$\Rightarrow$ 6x - 10x S/N

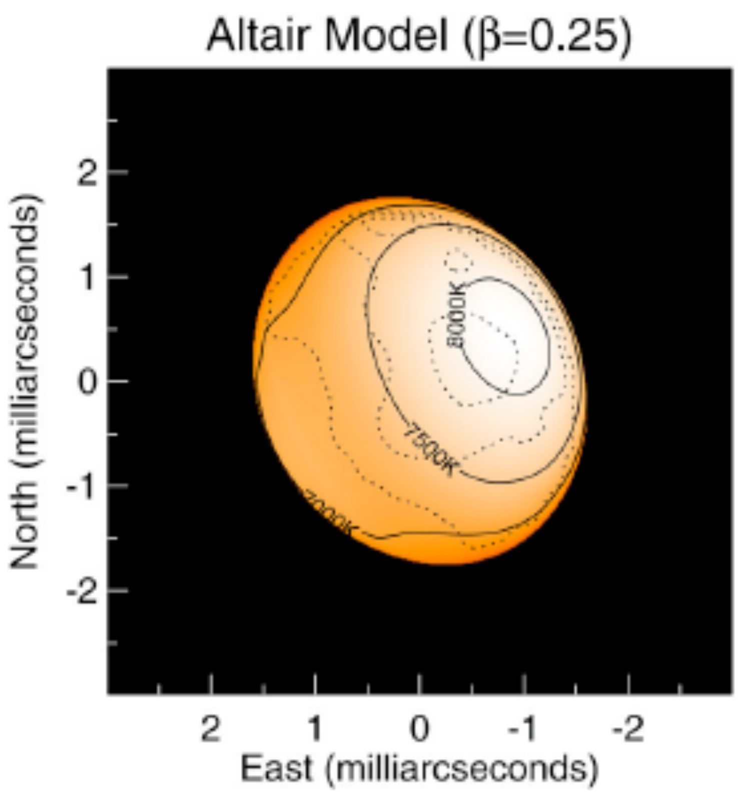
Summary

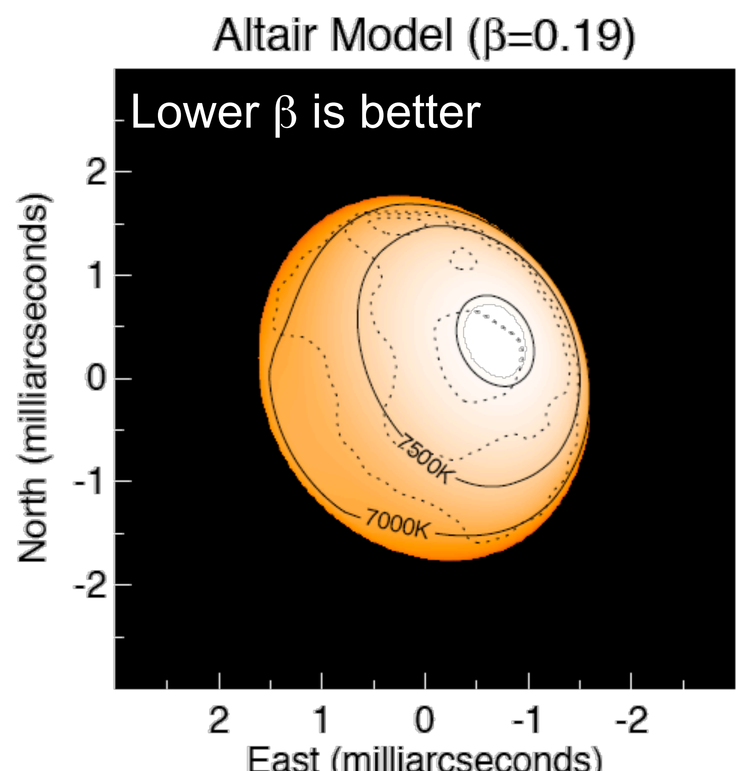
- First images of main sequence stars besides Sun
  - Temperatures not consistent with von Zeipel law, suggesting differential rotation
  - Interferometry combined with spectroscopy can weigh stars in new way
  - Knowledge of geometry will allow precise calibration of upper main sequence for first time
- Interacting binaries now accessible
  - Physics of accretion disks in close binaries
- Directly detecting hot Jupiters underway!

Backup slides

Modeling Altair

- Construct 3D sphere + apply Roche- von Zeipel model ($T \propto g^{\beta}$) + Kurucz limb darkening
- Fast algorithm: more accurate, faster



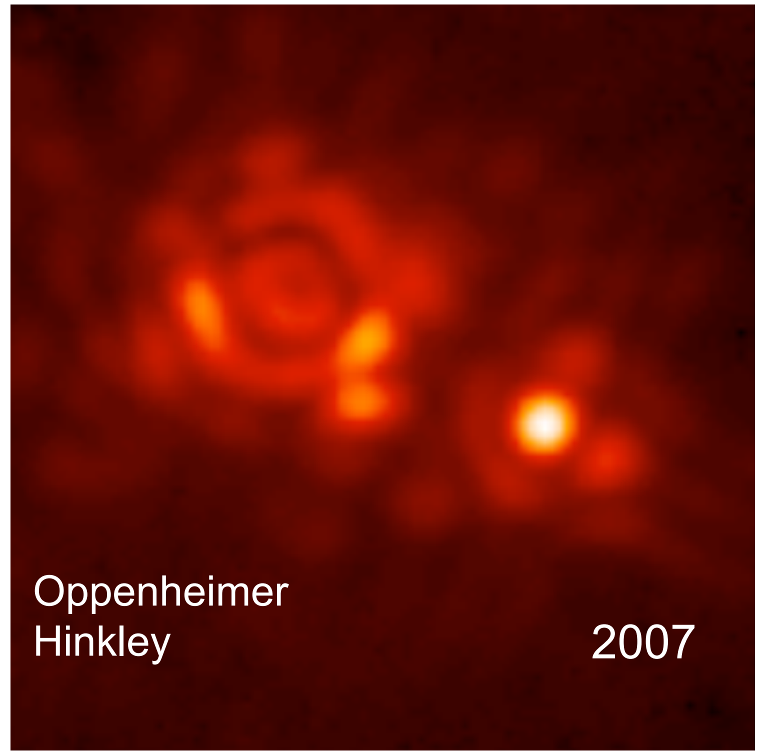


New Method to Measure Mass of Single Star

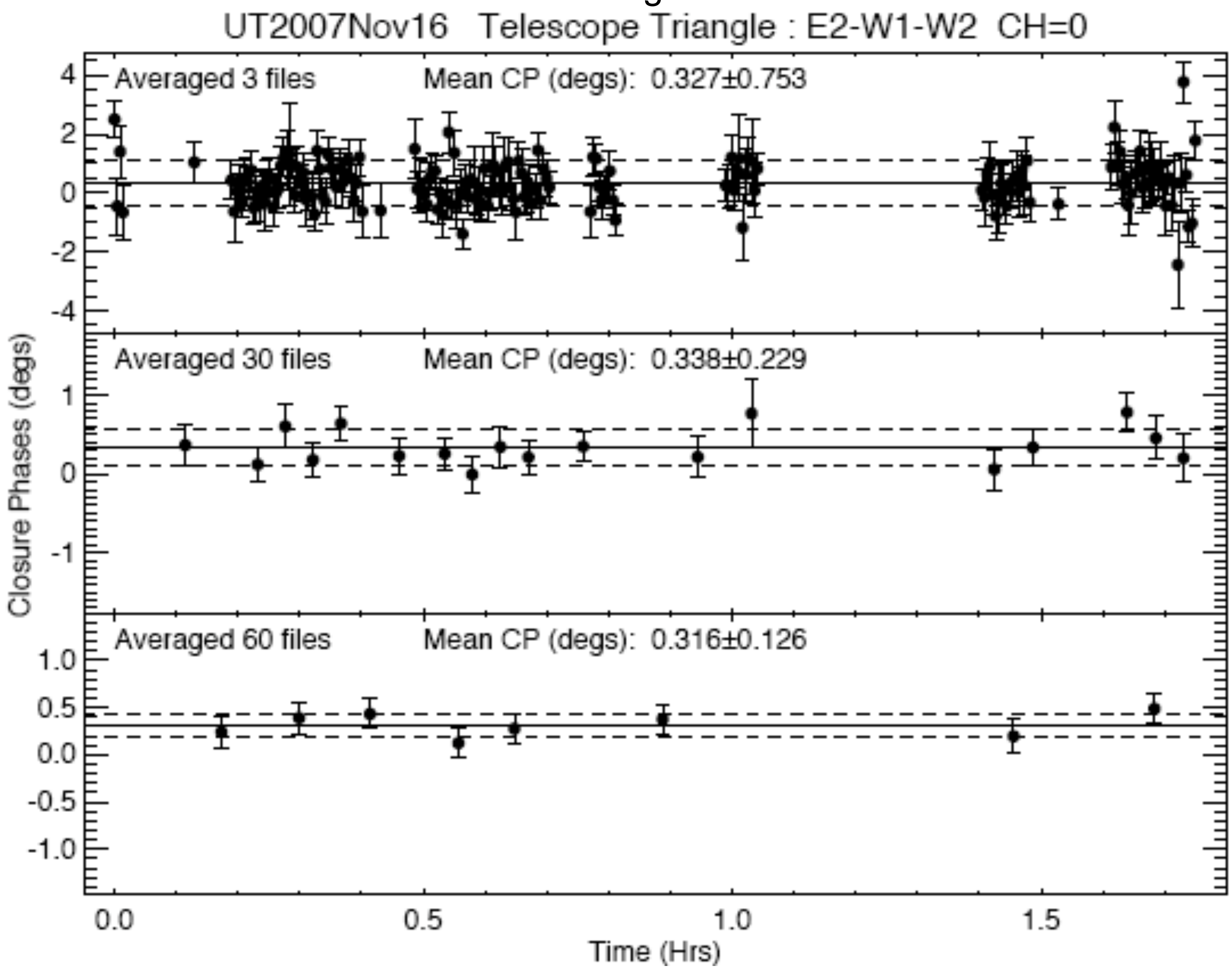
- Interferometer measures star's oblateness & inclination angle
  - This distortion does not tell us the stellar mass directly
- Spectroscopy can determine projected surface velocities (v sin i)
- Together: we can measure the mass of the star
  - Depends on some assumptions, such as uniform internal rotation, and proper model of spectral line profiles

Test Case: Rasalhague (α Oph)

- A well-known binary
  - Gatewood et al. 2005 determine primary mass 2.8 +/- 0.2 Msun
- Interferometer-determined geometry and v sini suggests lower mass ~2.1 Msun
- New AO imaging will determine precise mass as a check of the Oblateness Method
  - Work in progress..

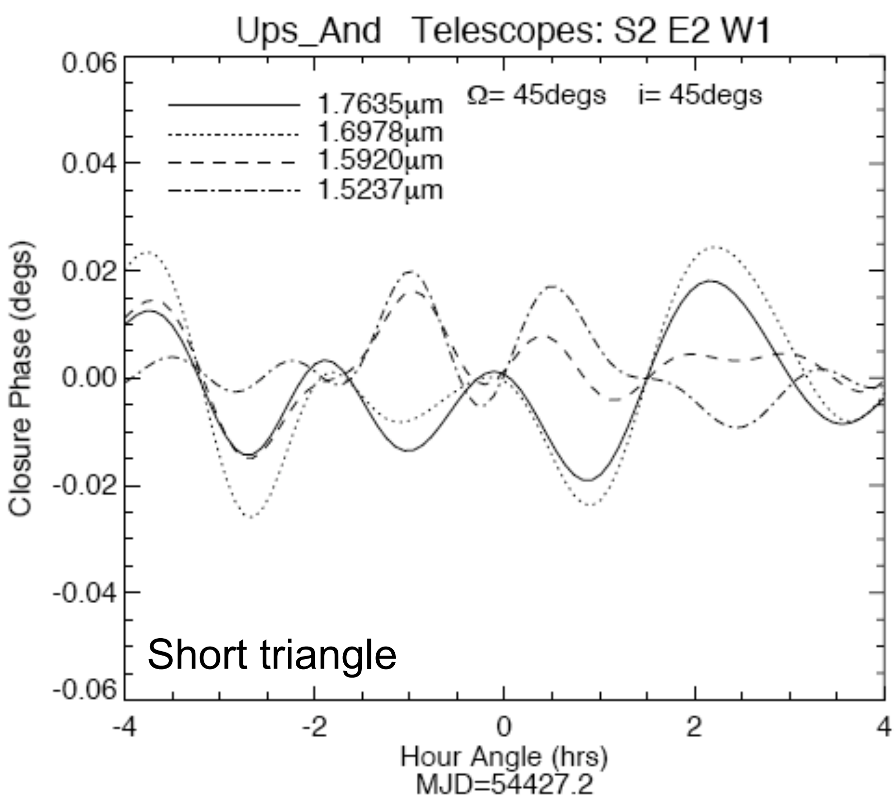


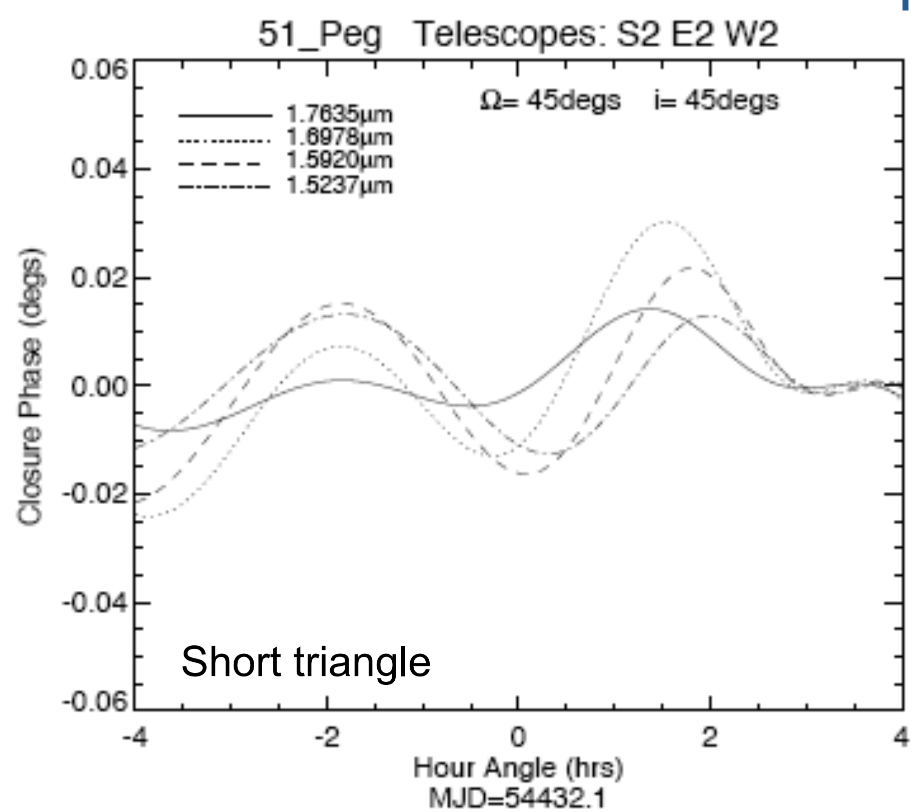
Short triangle ~ 0.8 mas resolution



Averaging the whole 1.7 hours=> 0.045°

Closure phase simulation





Maximum= 0.02°

Maximum= 0.03°

Precision requirement: < 0.02° for the highest resolution channel

Altair

Parameters	β Fixed	β Free
Inclination (degs)	62.7 ± 1.6	56.8 ± 2.2
Position Angle (degs)	-61.7 ± 1.2	-61.9 ± 1.0
T_{pole} (K)	8650 ± 150	8370 ± 140
R_{pole} ($R_\odot$)	1.662 ± 0.005	1.632 ± 0.011
(mas)	1.503 ± 0.005	1.476 ± 0.010
T_{eq} (K)	6790 ± 110	6810 ± 70
R_{eq} ($R_\odot$)	2.023 ± 0.011	2.029 ± 0.009
(mas)	1.830 ± 0.010	1.835 ± 0.008
ω	0.902 ± 0.005	0.924 ± 0.005
β	0.25 (Fixed)	0.188 ± 0.011
Model V Mag	0.765	0.765
Model H Mag	0.221	0.217
Model v sin i (km/s)	241	239
Reduced χ^2:		
Total	1.81	1.35
Closure Phase	2.16	1.70
Vis^2	1.50	1.09
Triple Amp	2.12	1.58

Rasalhague

Table 1: Best-fit parameters for Alp Oph

Parameters	Standard model ($\beta = 0.25$)
Inclination (degs)	87.70 ± 0.43
Position Angle (degs)	-53.88 ± 1.23
T_{pol} (K)	9300 ± 150
R_{pol} ($R_{\odot}$)	2.390 ± 0.014
T_{eq} (K)	7460 ± 100
R_{eq} ($R_{\odot}$)	2.871 ± 0.020
ω	0.885 ± 0.011
Model V Magnitude	2.086
Model H Magnitude	1.66
Model v $sini$ (km/s)	275
Total χ^2_ν	0.91
CP χ^2_ν	1.33
Vis^2 χ^2_ν	0.72
T3amp χ^2_ν	0.81

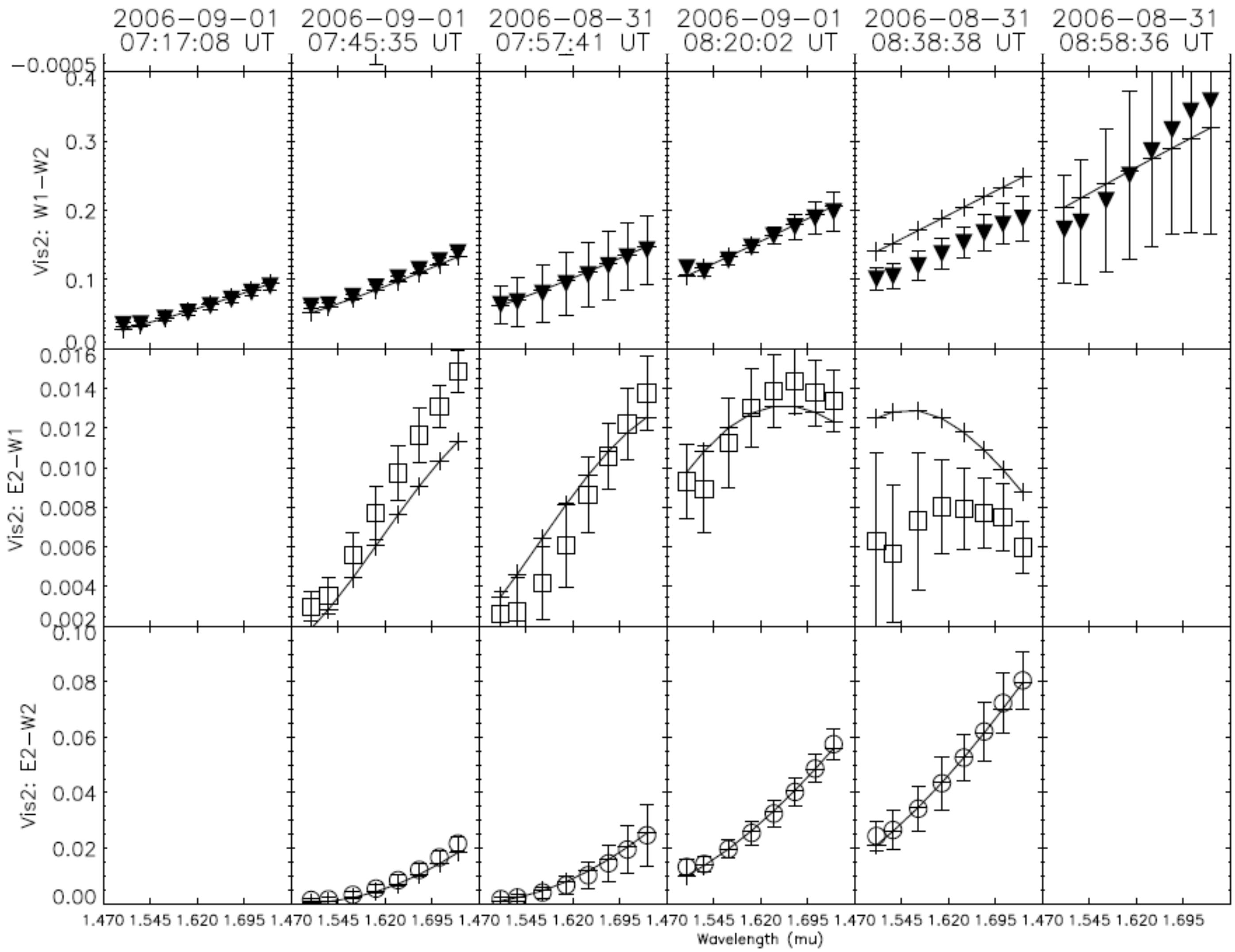
[a] V magnitude from literature: 2.086 ± 0.003

[b] H magnitude from Literature: 1.66 ± 0.03

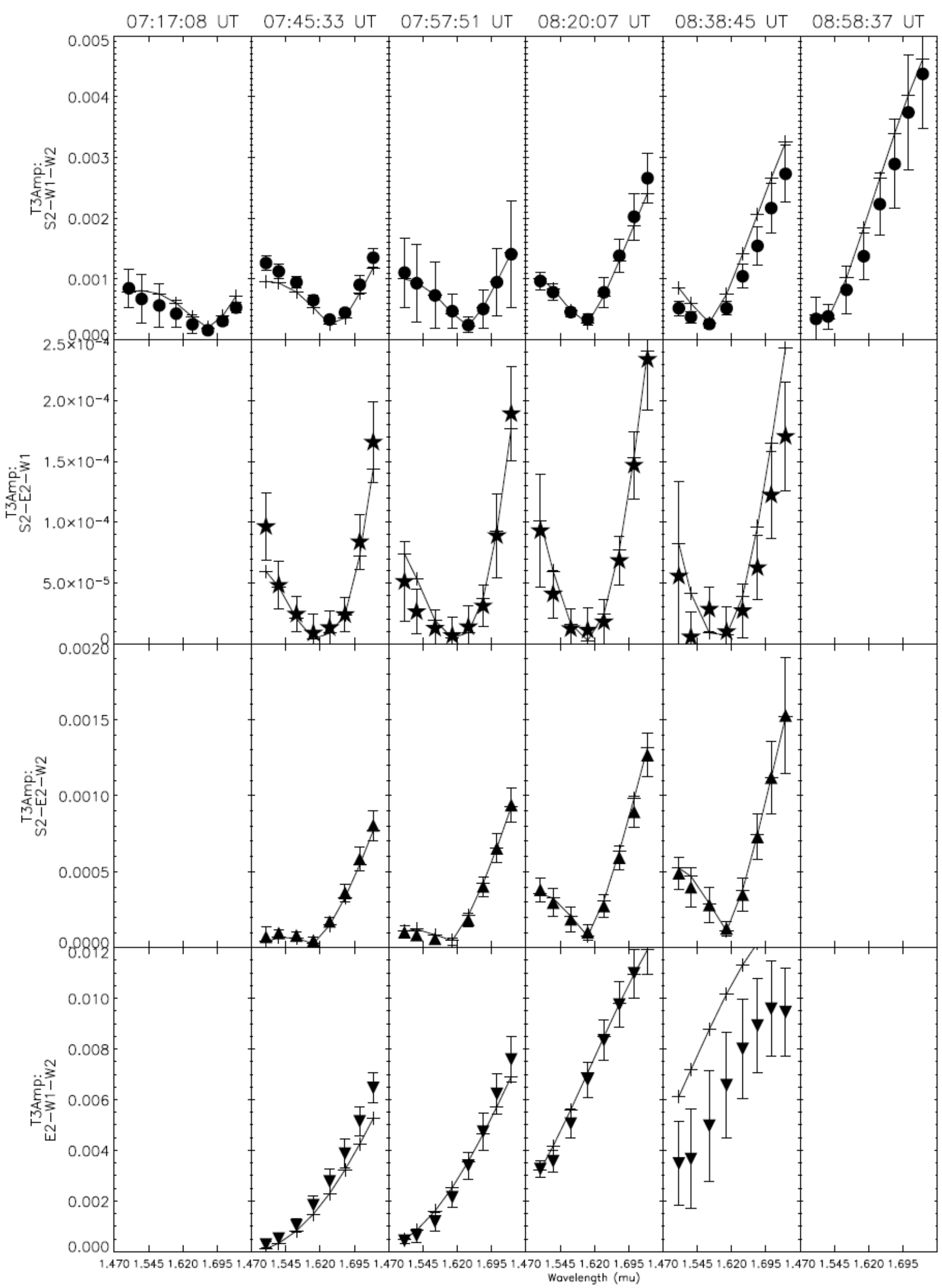
Alderamin

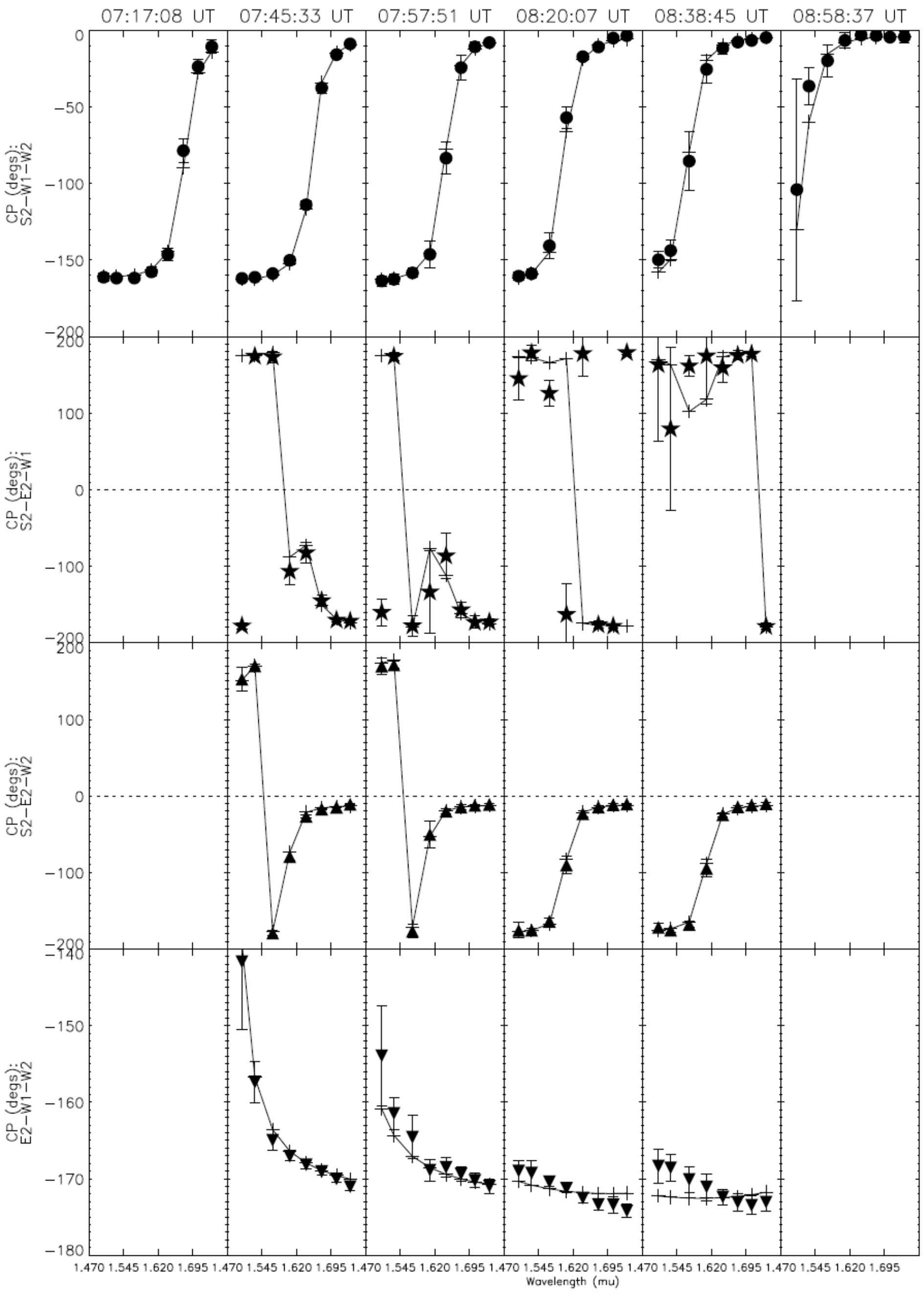
Table 3.3. Best-fit and physical parameters of α Cep

Model Parameters	Standard ($\beta = 0.25$)	Non-standard (β-free)*
Inclination (degs)	64.91 ± 4.11	55.70 ± 6.23
Position Angle (degs)	-178.26± 4.10	-178.84 ± 4.28
T_{pol} (K)	8863± 260	8588 ± 300
R_{pol} ($R_\odot$)	2.199 ± 0.035	2.162 ± 0.036
T_{eq} (K)	6707 ± 200	6574 ± 200
R_{eq} ($R_\odot$)	2.739± 0.040	2.740 ± 0.044
ω	0.926 ± 0.018	0.941 ±0.020
β	0.25 (fixed)	0.216± 0.021
Model V Magnitude[a]	2.45	2.45
Model H Magnitude[b]	1.92	1.91
Model v sin i (km/s)	237	225
Total χ^2_ν	1.21	1.18
Vis^2 χ^2_ν	0.79	0.80
CP χ^2_ν	1.43	1.27
T3amp χ^2_ν	1.71	1.76
Other Physical Parameters		
True $T_{eff}(K)$	7690 ± 150	7510 ± 160
True Luminosity ($L_\odot$)	20.1 ± 1.6	18.1 ± 1.8
Apparent $T_{eff}(K)$	-	7510
Apparent Luminosity ($L_\odot$)	-	17.9
Mass ($M_\odot$)[c]	-	1.92 ± 0.04
Age (Gyrs)[c]	-	0.99 ± 0.07
$[Fe/H]$[d]	0.09	
Distance (pc)[e]	14.96	

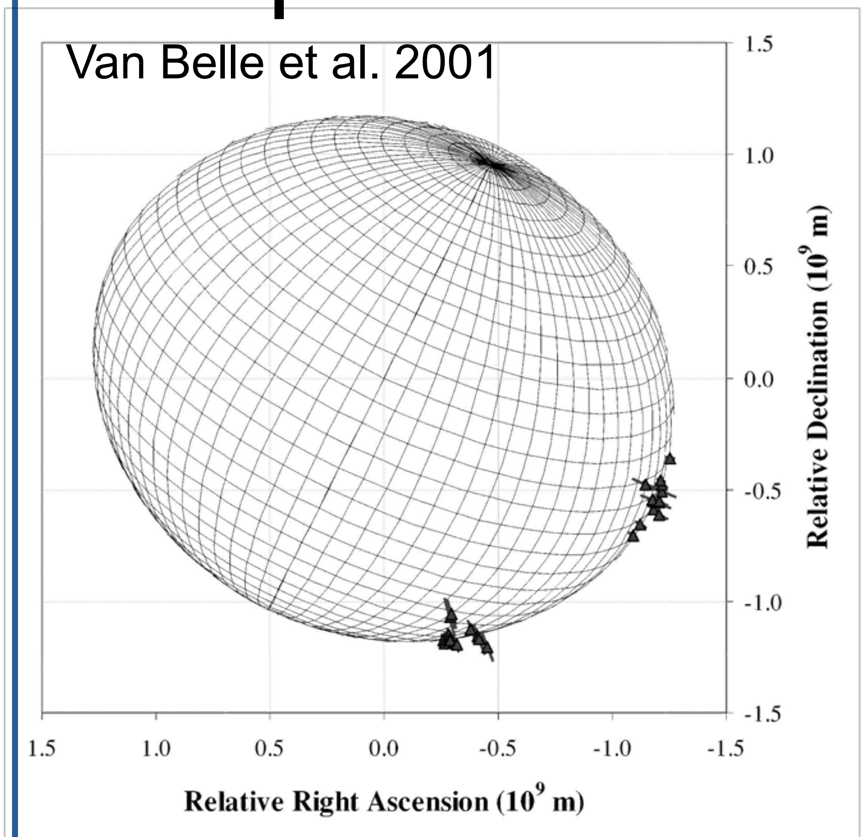

2006−09−01 07:17:08 UT
2006−09−01 07:45:35 UT
2006−08−31 07:57:41 UT
2006−09−01 08:20:02 UT
2006−08−31 08:38:38 UT
2006−08−31 08:58:36 UT
Vis2: W1−W2
Vis2: E2−W1
Vis2: E2−W2
Wavelength (mu)
1.470 1.545 1.620 1.695

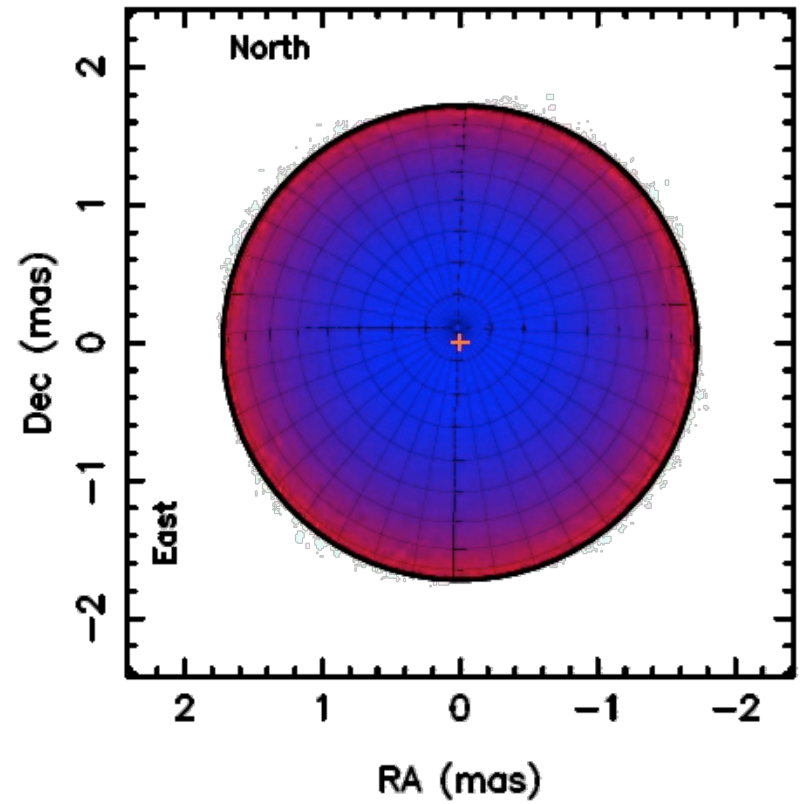
Imaging Stars a




07:17:08 UT
07:45:33 UT
07:57:51 UT
08:20:07 UT
08:38:45 UT
08:58:37 UT
CP (degs): S2−W1−W2
CP (degs): S2−E2−W1
CP (degs): S2−E2−W2
CP (degs): E2−W1−W2
Wavelength (mu)

Rapid Rotation with Interferometry





- First measurement: Altair (α Aql) by Van Belle et al. 2001
- 14% longer in one direction than another

- Vega rotating at ~91% of breakup
  - NPOI (Peterson et al 2005)
  - CHARA (**Aufdenberg** et al 2006)