Zooming in on the Stars with the CHARA Array

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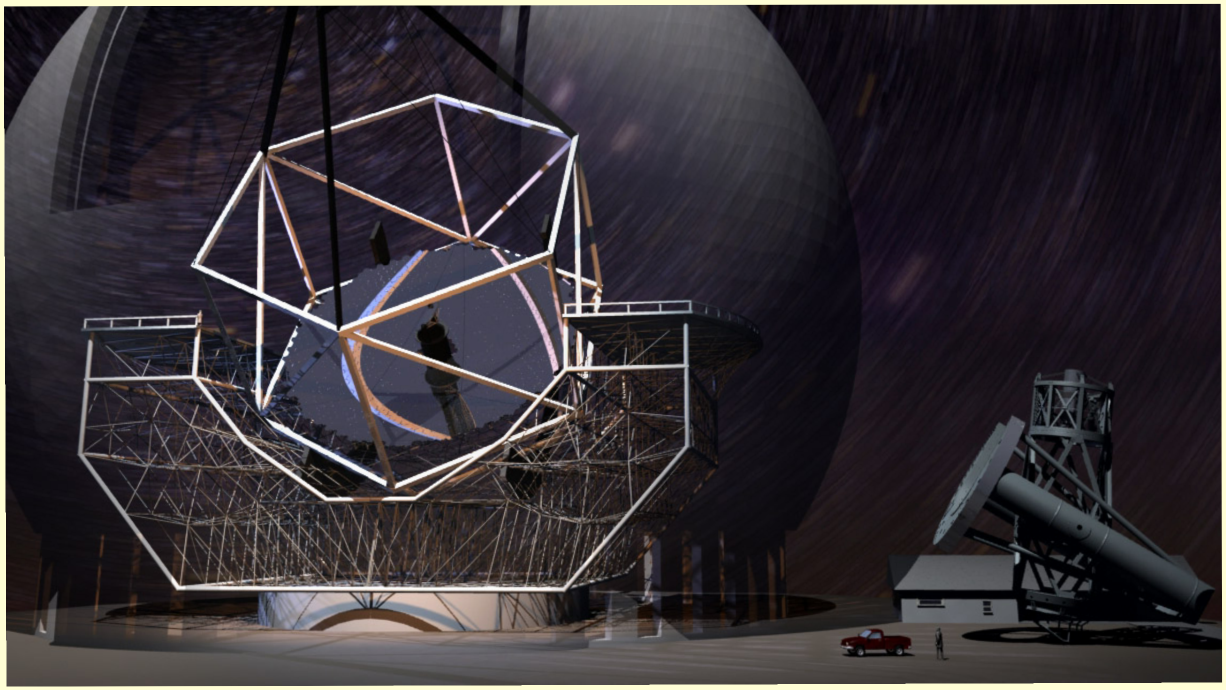
Cosmic Trails #2 on Board the Nieuw Amsterdam

Why We Build Larger & Larger Telescopes I. Light Gathering Power

- Light Gathering Power goes as the *area* of the light collecting mirror thus LGP is proportional to *aperture*^{2}
- Eg. The 200-inch Hale telescope has a million times the LGP of the human eye.



The proposed "Thirty Meter Telescope" will have 36 times the LGP of the Hale Telescope

Why We Build Larger & Larger Telescopes II. Angular Resolution

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- Resolution improves in direct proportion to the diameter of a telescope mirror. So, if you want to see something twice as clearly, you need to double the size of your telescope

\$\$\$\$

- Okay, so why not look at spots on nearby stars like the sun?

\$\$\$\$

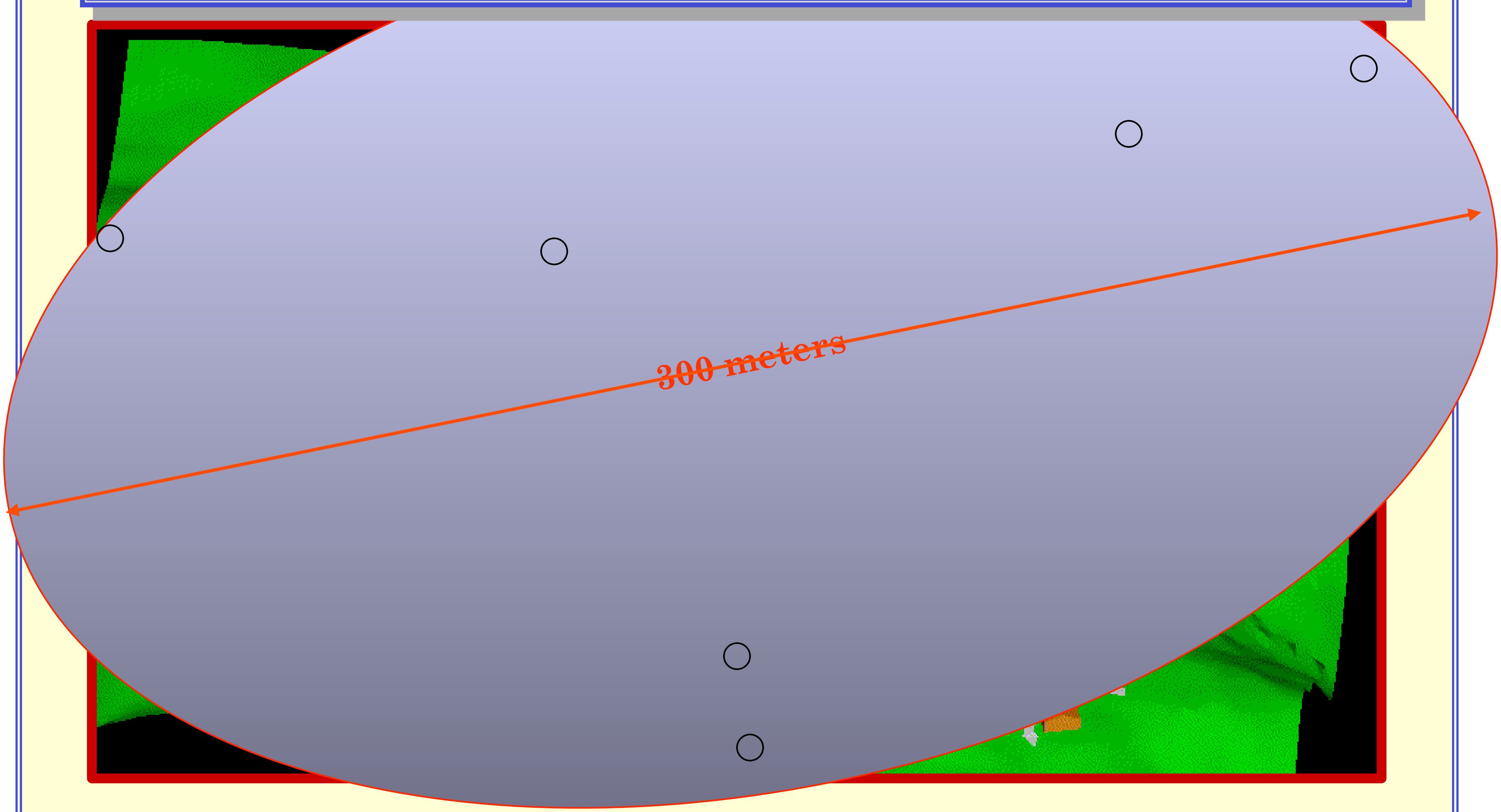
The sun seen from a distance of 20 parsecs has an angular diameter of about 0.0005 arcseconds (That's about the size of a button from 10,000 miles away!)

\$\$\$\$

No big deal, just build a telescope 10 times larger than the TMT!!!

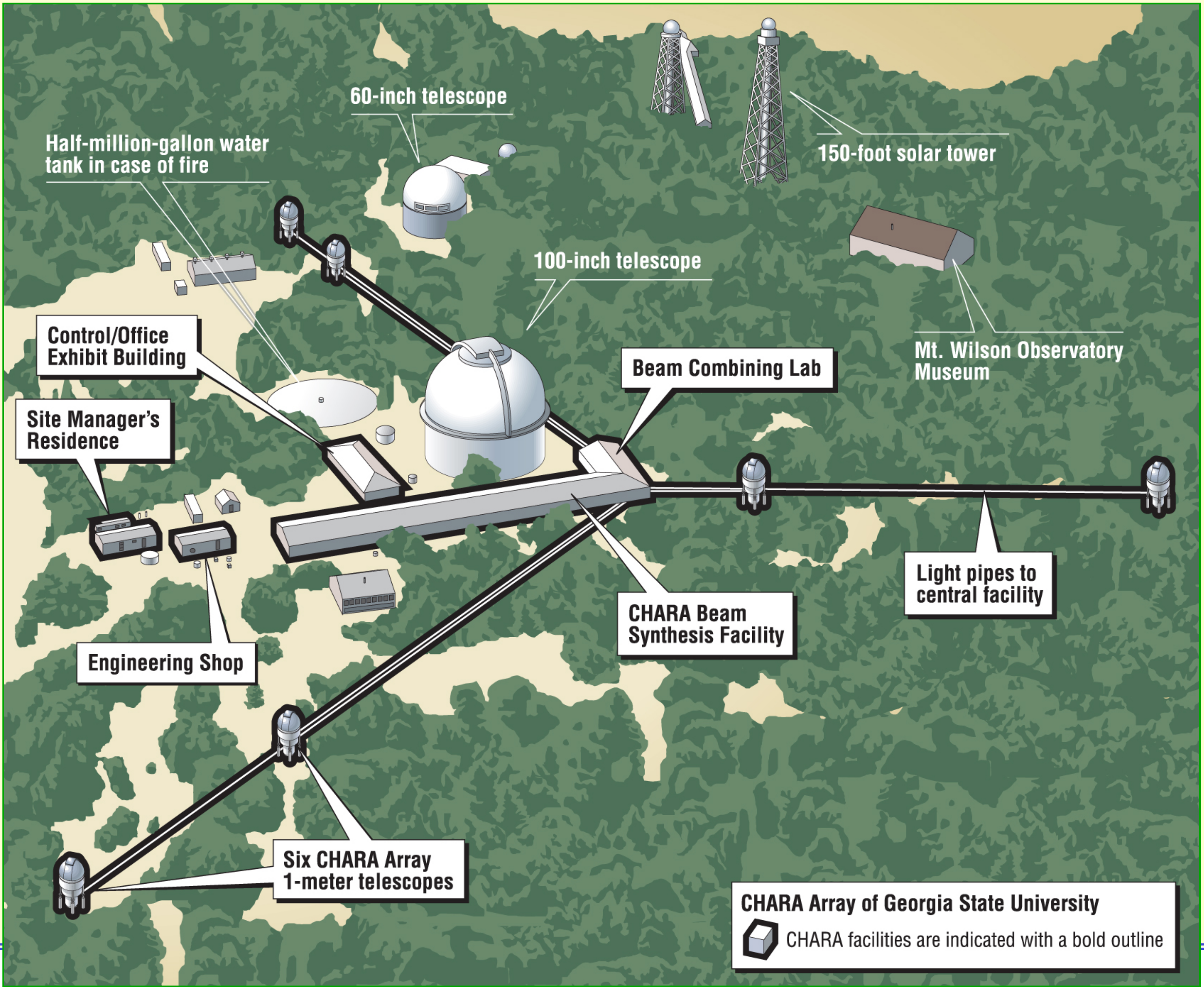
\$\$\$\$

Not Enough $$ - Then just cheat!



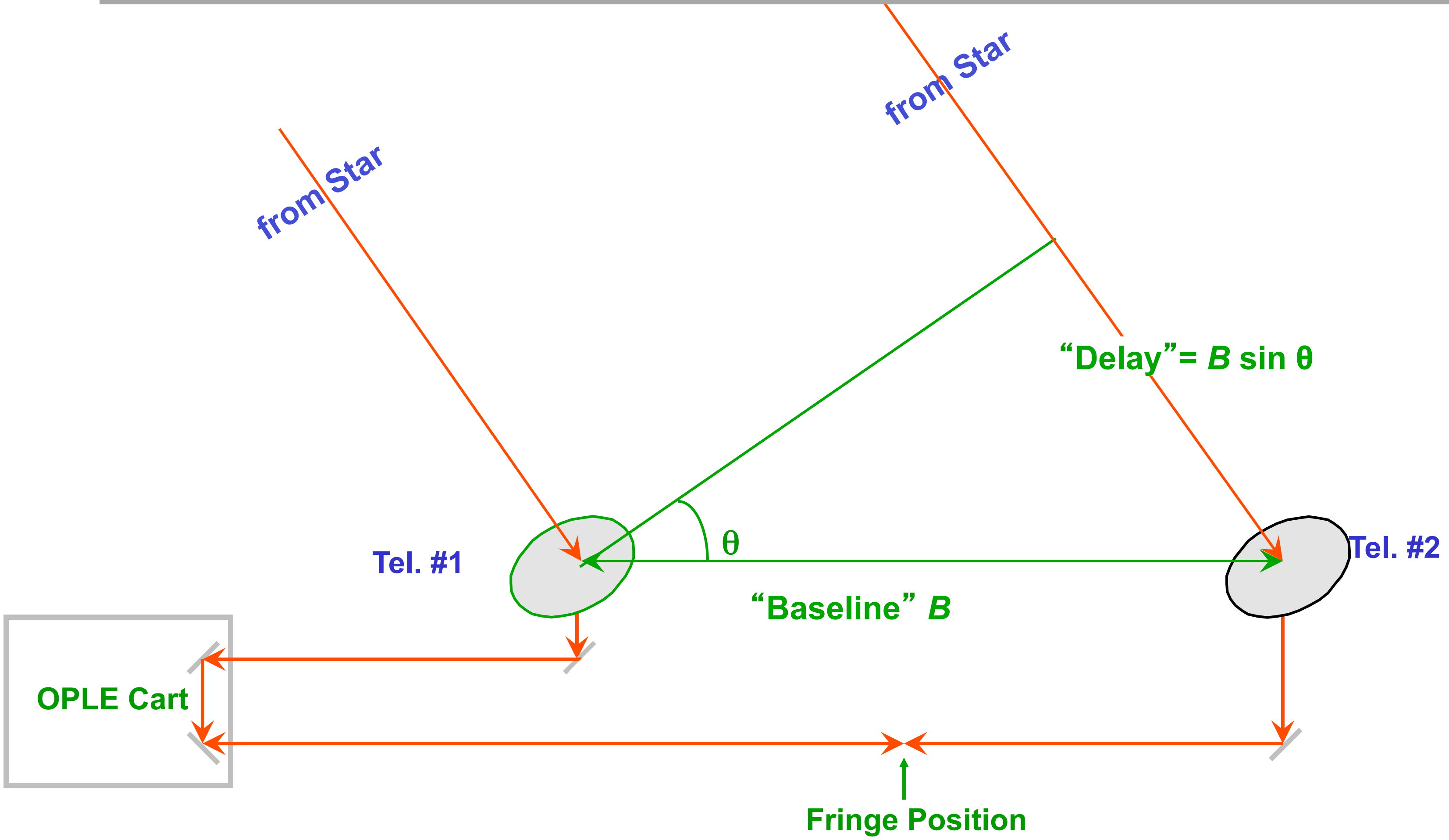
Mount Wilson Observatory

Angeles National Forest, Los Angeles County, California, Elev. 5712 ft

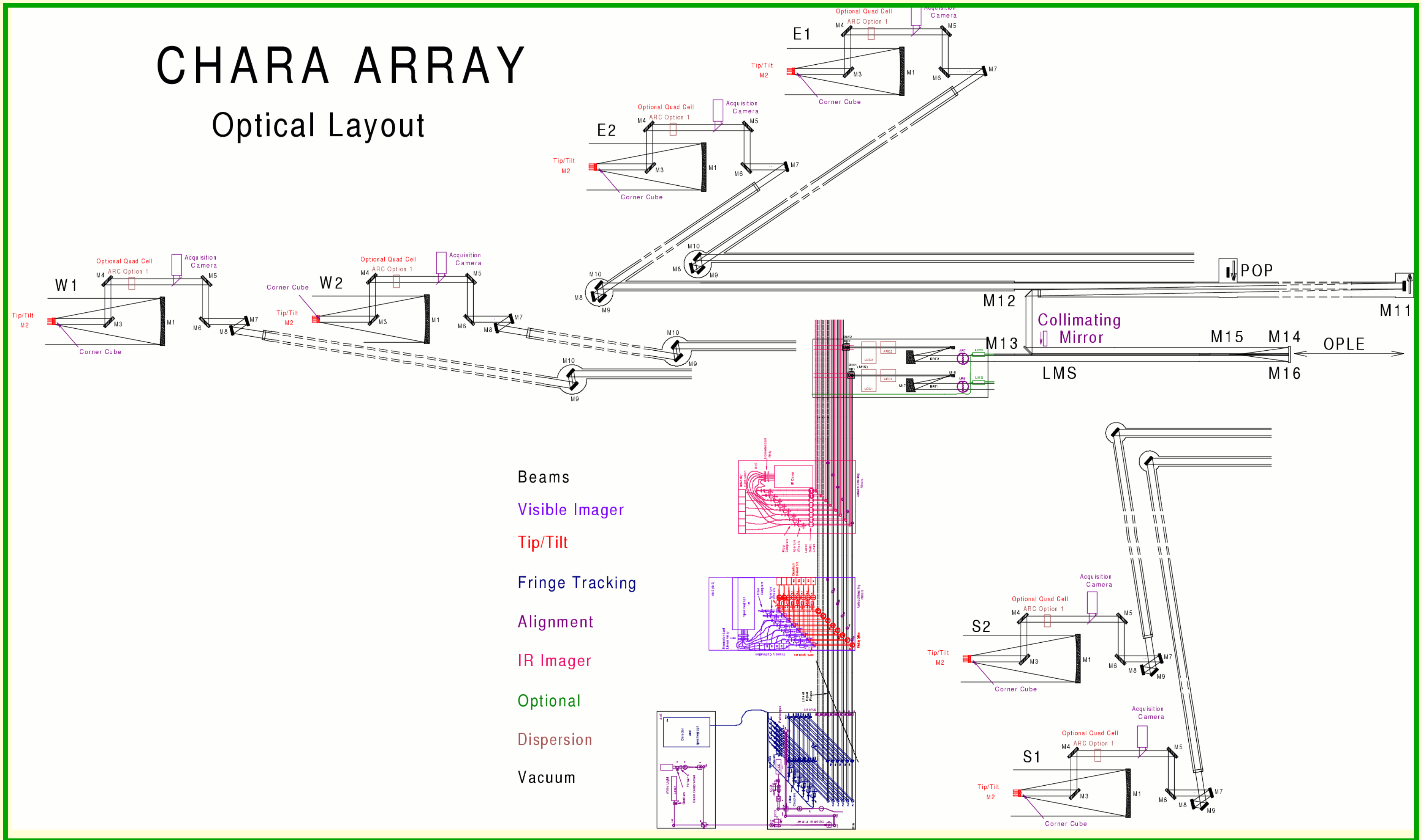


A “Simple” Long-Baseline Interferometer

Delay Compensator Must Match Paths to Within 1 micron



The Actual Layout of the CHARA Array



CHARA Overview

- Y-shaped Array Configuration
  - 15 baselines from 31 to 331 meters
  - World's longest baselines => world's highest resolution
- Six 1.0-meter Collecting Telescopes
  - Can accommodate 2 more telescopes
  - Adaptive optics retrofit currently being pursued
- Dual Operating Wavelength Regimes
  - Visible (470 - 800 nm => 0.15 mas limiting resolution)
  - Near infrared (2.0 - 2.5 microns => 0.6 mas limiting resolution)
- Science Emphasis on Fundamental Stellar Parameters
  - Sizes, shapes, distances, temperatures, masses & luminosities
- Located on Historic Mount Wilson, California
  - Ground broken 1996
  - First fringes 1999
  - Routine operations initiated 2005
  - First optical imaging 2007
- 50 refereed science papers since July 2005

Telescope Enclosures

In Their Opened and Closed Configurations

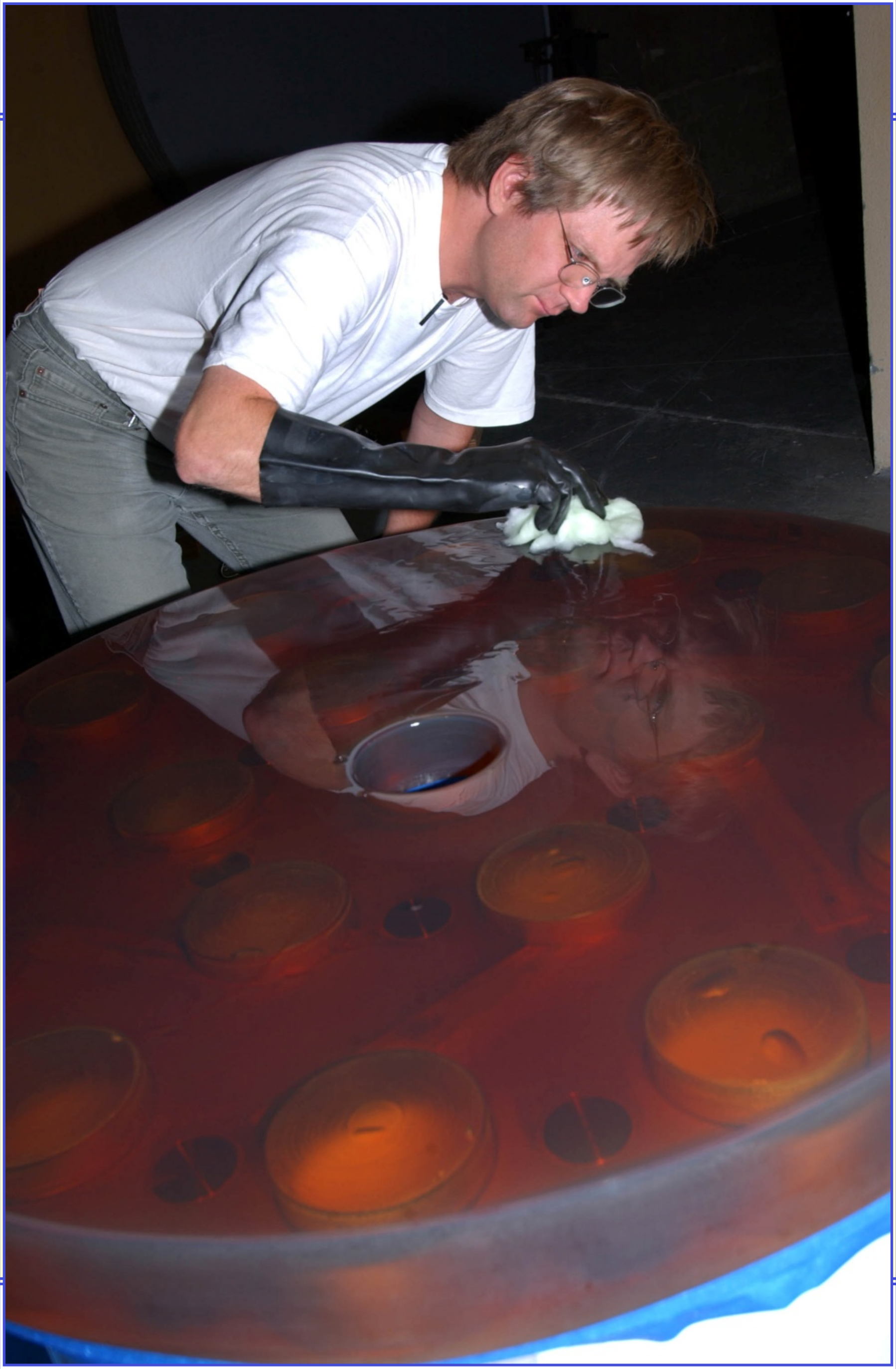
Telescopes

CAD by Laszlo Sturma

Photo by Steve Golde

Telescope Optics

Nils Turner prepping one of the 1-meter telescope primary mirrors for recoating in the 100-inch telescope vacuum chamber.



Vacuum Light Tubes I.

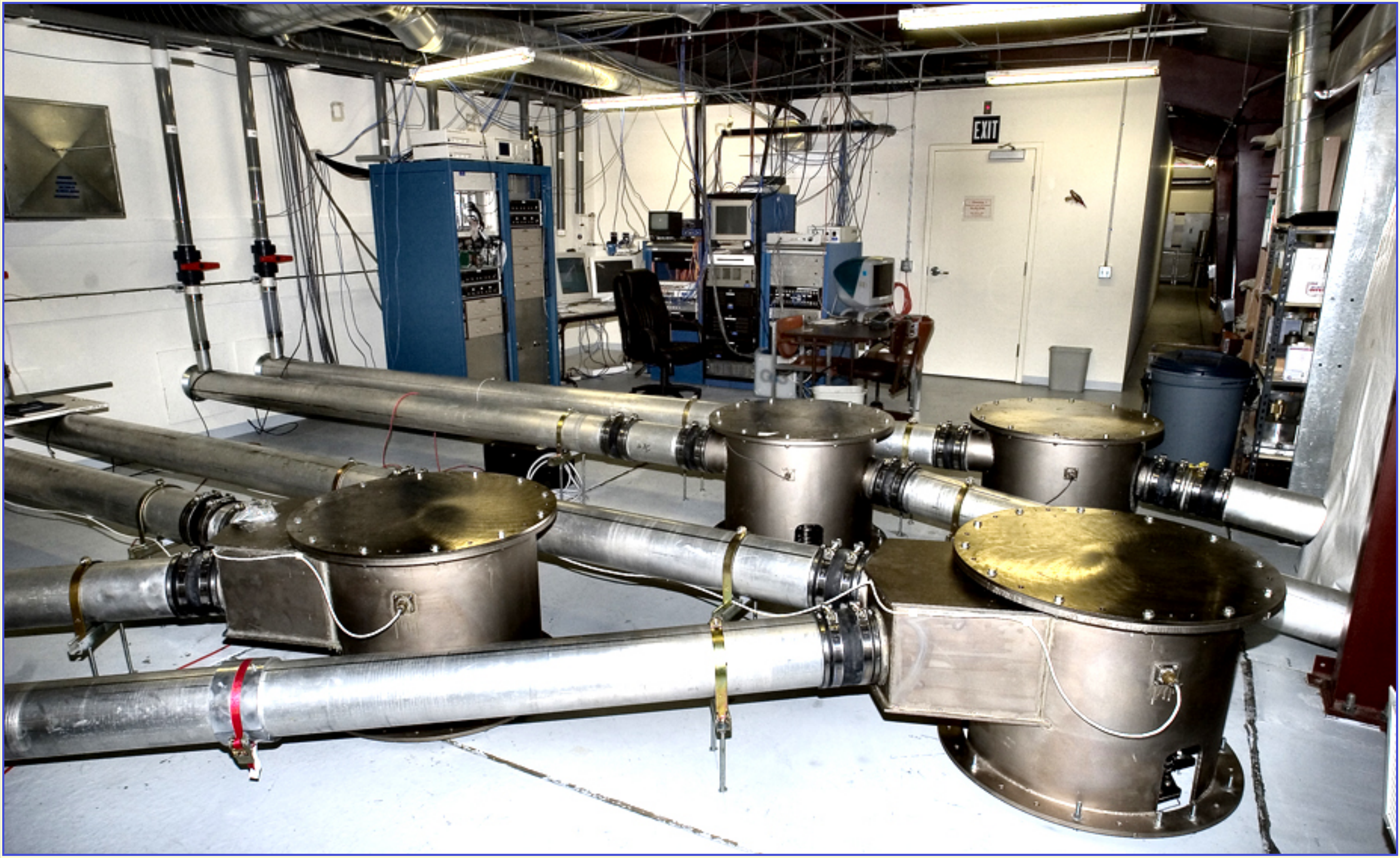
Feed Light from Each Telescope to the Central Lab

Vacuum Light Tubes II.

Tubes from the Three Arms of the Array

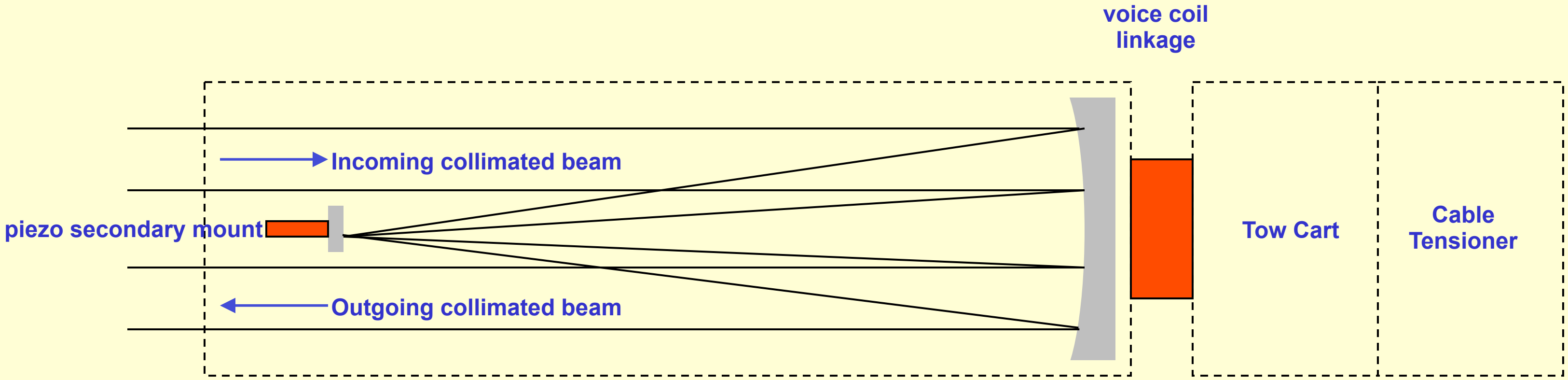
Vacuum Turning Boxes

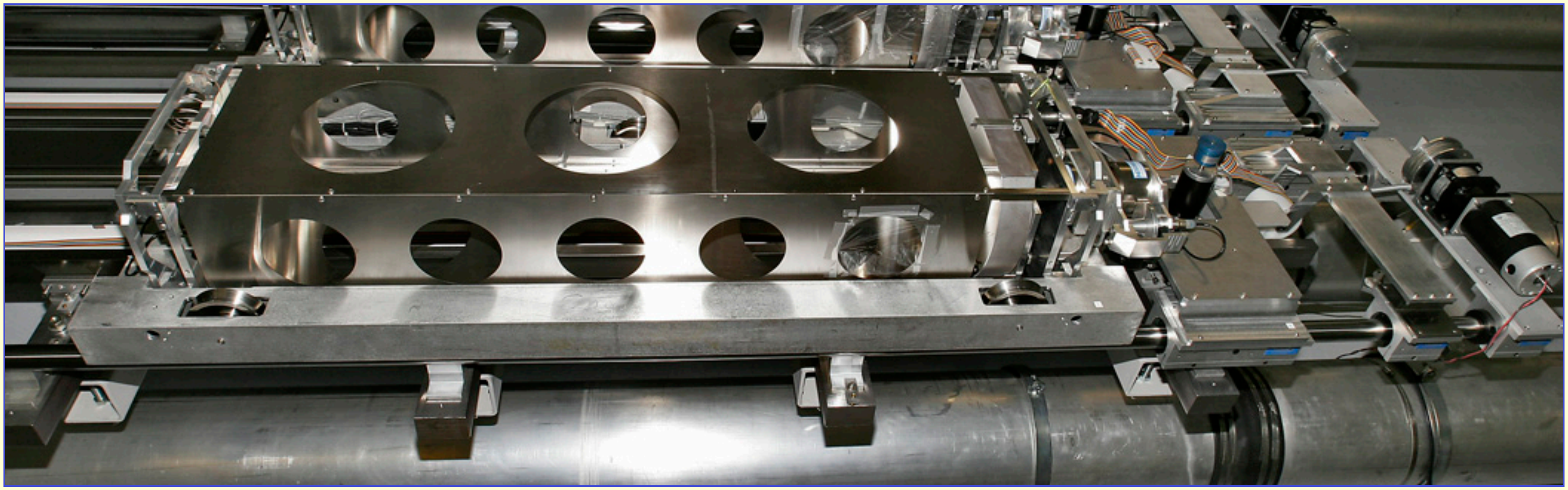
Make 6 Lines Parallel while Preserving Polarizations



OPLE Carts

Catseye Optical System in a Nested Servo Provide ~10 nm Correction





OPLE Carts

Provide Continuously Variable Path Length Compensation

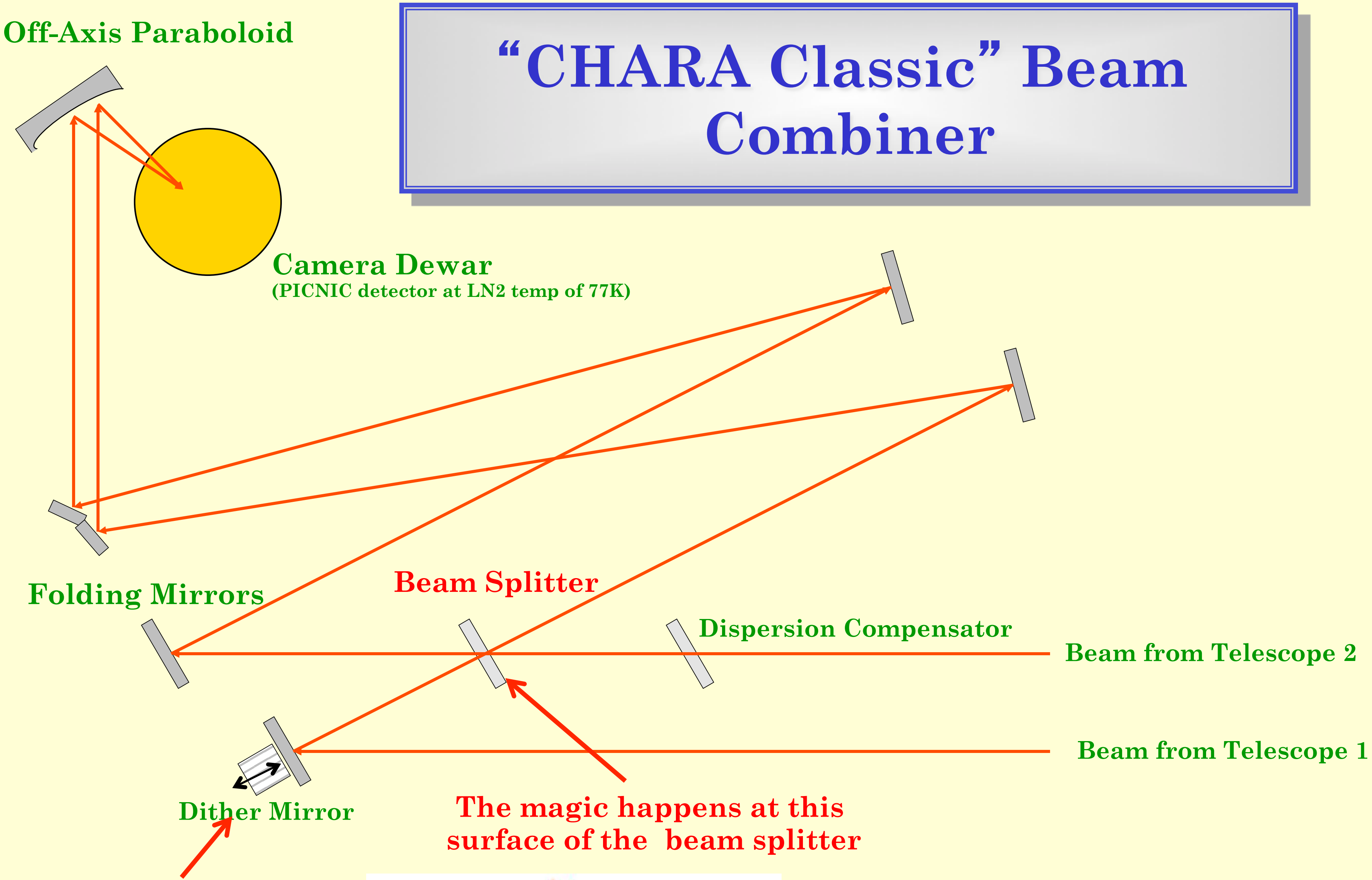
Beam Management Subsystems

Separate Visible from Infrared and "Massage" Light Beams

Beam Combining Tables

Accommodate five beam combiners, and tip/tilt, alignment, and fringe tracking subsystems

“CHARA Classic” Beam Combiner



Off-Axis Paraboloid

Camera Dewar
(PICNIC detector at LN2 temp of 77K)

Folding Mirrors

Beam Splitter

Dispersion Compensator

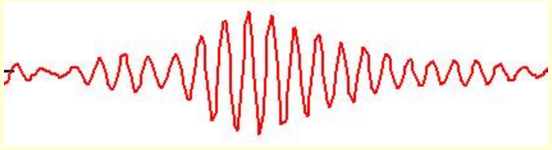
Beam from Telescope 2

Beam from Telescope 1

Dither Mirror

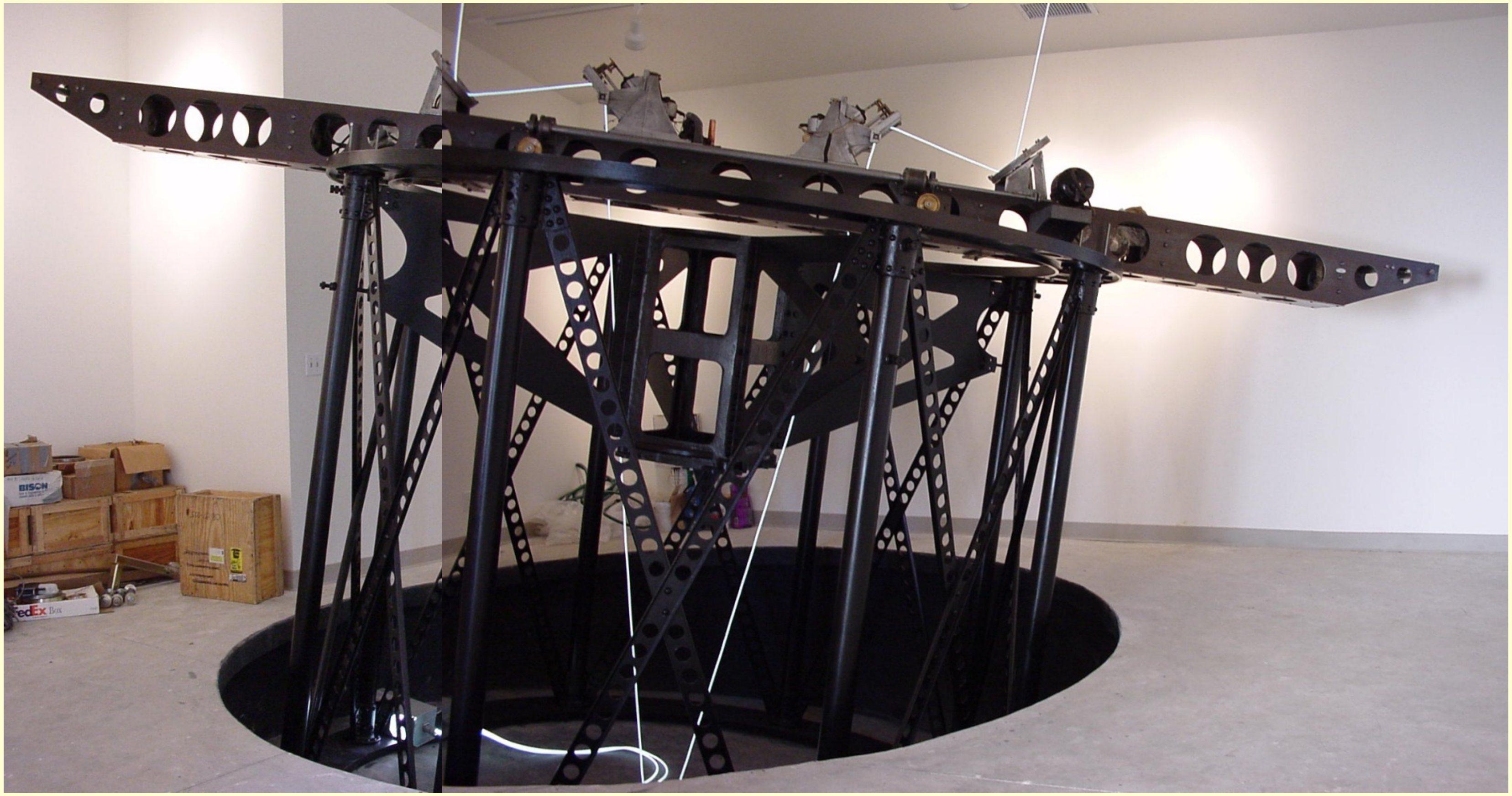
The magic happens at this surface of the beam splitter

As the dither mirror scans through perfect path matching



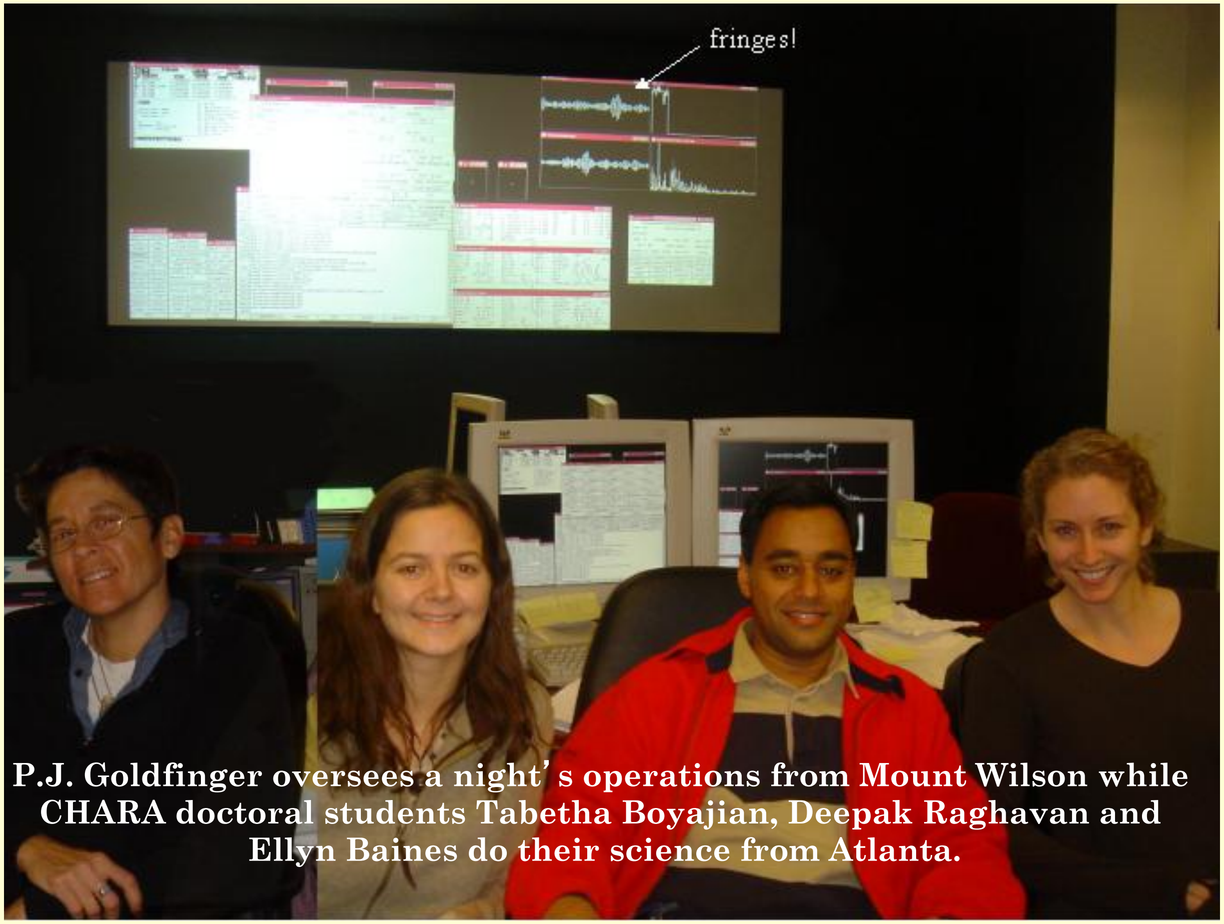
An interference fringe is formed!

Control/Office Bldg & Exhibit Hall



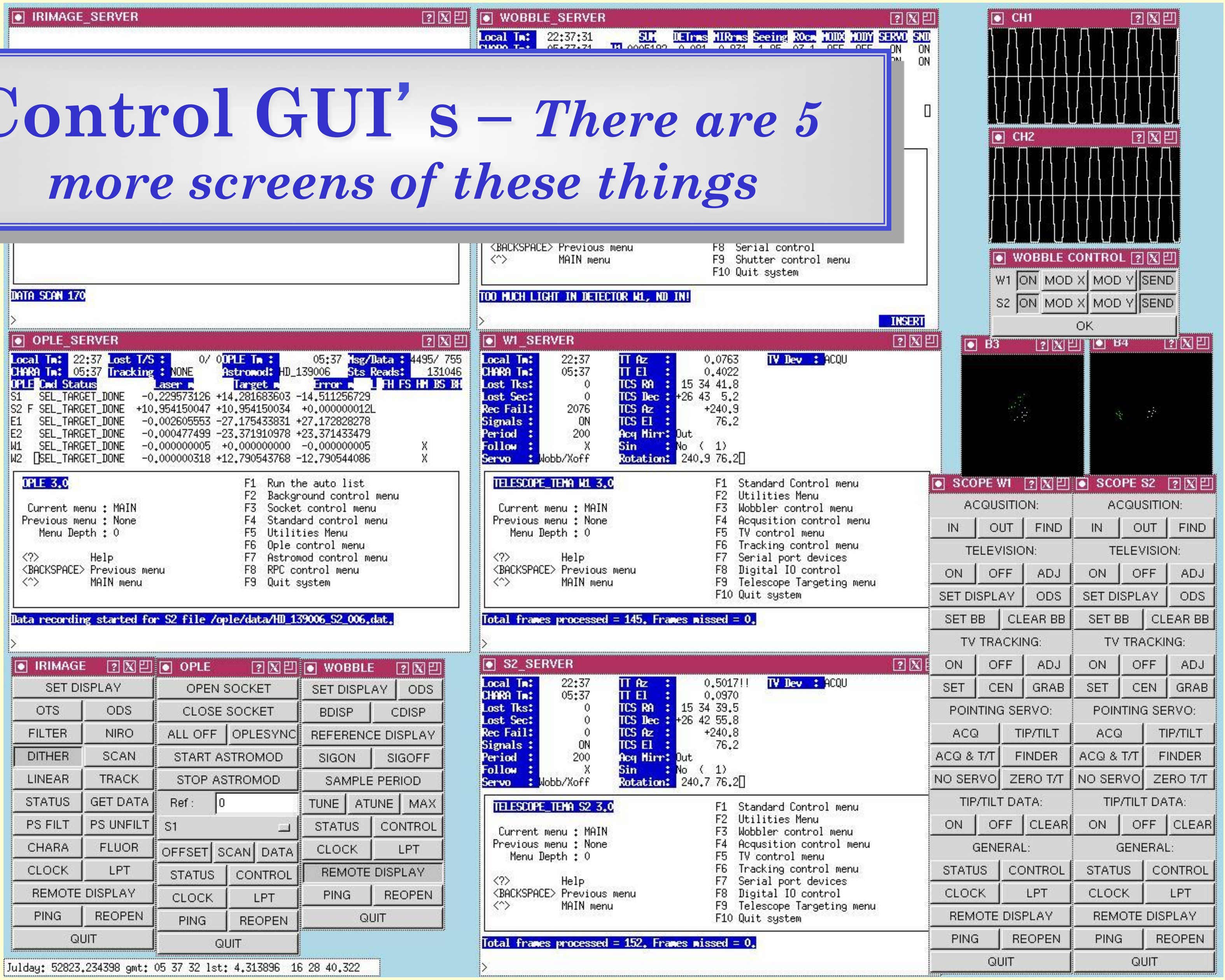
Remotely Operable From Atlanta

and also by members of the CHARA Collaboration in Paris, Nice, Sydney and Ann Arbor



P.J. Goldfinger oversees a night's operations from Mount Wilson while CHARA doctoral students Tabetha Boyajian, Deepak Raghavan and Ellyn Baines do their science from Atlanta.

Control GUI' s – *There are 5 more screens of these things*



IRIMAGE_SERVER

```
DATA SCAN 170
>
```

WOBBLE_SERVER

```
Local Tm:   22:37:31         SUM   DETrms  MIRrms  Seeing  R0cm  MODX  MODY  SERVO  SND
                                                                              ON     ON
                                                                                     ON

<BACKSPACE> Previous menu              F8  Serial control
<^>         MAIN menu                  F9  Shutter control menu
                                       F10 Quit system

TOO MUCH LIGHT IN DETECTOR W1, ND IN!
>                                                                          INSERT
```

OPLE_SERVER

```
Local Tm:  22:37 Lost T/S :      0/ 0OPLE Tm :       05:37 Msg/Data : 4495/ 755
CHARA Tm:  05:37 Tracking : NONE     Astromod: HD_139006   Sts Reads:     131046
OPLE Cmd Status            Laser        Target        Error      L FH FS HM BS BH
S1   SEL_TARGET_DONE   -0.229573126 +14.281683603 -14.511256729
S2 F SEL_TARGET_DONE  +10.954150047 +10.954150034  +0.000000012L
E1   SEL_TARGET_DONE   -0.002605553 -27.175433831 +27.172828278
E2   SEL_TARGET_DONE   -0.000477499 -23.371910978 +23.371433479
W1   SEL_TARGET_DONE   -0.000000005  +0.000000000  -0.000000005          X
W2  SEL_TARGET_DONE   -0.000000318 +12.790543768 -12.790544086          X

OPLE 3.0                               F1  Run the auto list
                                       F2  Background control menu
 Current menu : MAIN                   F3  Socket control menu
Previous menu : None                   F4  Standard control menu
   Menu Depth : 0                      F5  Utilities Menu
                                       F6  Ople control menu
<?>         Help                       F7  Astromod control menu
<BACKSPACE> Previous menu              F8  RPC control menu
<^>         MAIN menu                  F9  Quit system

Data recording started for S2 file /ople/data/HD_139006_S2_006.dat.
>
```

W1_SERVER

```
Local Tm:      22:37    TT Az    :       0.0763    TV Dev  : ACQU
CHARA Tm:      05:37    TT El    :       0.4022
Lost Tks:          0    TCS RA   :  15 34 41.8
Lost Sec:          0    TCS Dec  : +26 43  5.2
Rec Fail:       2076    TCS Az   :      +240.9
Signals :         ON    TCS El   :        76.2
Period  :        200    Acq Mirr: Out
Follow  :          X    Sin      : No  (  1)
Servo   : Wobb/Xoff     Rotation:  240.9 76.2

TELESCOPE_TEMA W1 3.0                  F1  Standard Control menu
                                       F2  Utilities Menu
 Current menu : MAIN                   F3  Wobbler control menu
Previous menu : None                   F4  Acqusition control menu
   Menu Depth : 0                      F5  TV control menu
                                       F6  Tracking control menu
<?>         Help                       F7  Serial port devices
<BACKSPACE> Previous menu              F8  Digital IO control
<^>         MAIN menu                  F9  Telescope Targeting menu
                                       F10 Quit system

Total frames processed = 145. Frames missed = 0.
>
```

S2_SERVER

```
Local Tm:      22:37    TT Az    :       0.5017!!  TV Dev  : ACQU
CHARA Tm:      05:37    TT El    :       0.0970
Lost Tks:          0    TCS RA   :  15 34 39.5
Lost Sec:          0    TCS Dec  : +26 42 55.8
Rec Fail:          0    TCS Az   :      +240.8
Signals :         ON    TCS El   :        76.2
Period  :        200    Acq Mirr: Out
Follow  :          X    Sin      : No  (  1)
Servo   : Wobb/Xoff     Rotation:  240.7 76.2

TELESCOPE_TEMA S2 3.0                  F1  Standard Control menu
                                       F2  Utilities Menu
 Current menu : MAIN                   F3  Wobbler control menu
Previous menu : None                   F4  Acqusition control menu
   Menu Depth : 0                      F5  TV control menu
                                       F6  Tracking control menu
<?>         Help                       F7  Serial port devices
<BACKSPACE> Previous menu              F8  Digital IO control
<^>         MAIN menu                  F9  Telescope Targeting menu
                                       F10 Quit system

Total frames processed = 152. Frames missed = 0.
>
```

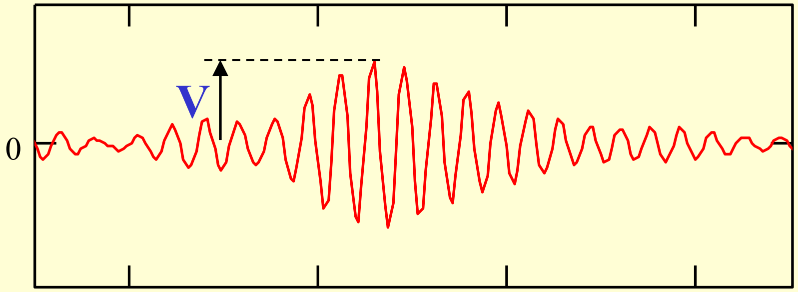
OPLE Ref : 0

```
Julday: 52823.234398 gmt: 05 37 32 lst: 4.313896  16 28 40.322
```

Visibility Amplitude of Single & Binary Stars

The basic observable quantity of an interferometer

$$V^2(b) = (1+\beta)^{-2} \{\beta^2 V_1^2(b) + V_2^2(b) + 2\beta V_1(b) V_2(b) \cos[2\pi b \lambda^{-1} \rho \cos\psi]\}$$



where:

b = projected baseline length,

$\beta = 10^{0.4\Delta m}$,

λ = wavelength of observed bandpass,

ρ = angular separation of the binary,

ψ = projection angle of binary star vector onto baseline vector,

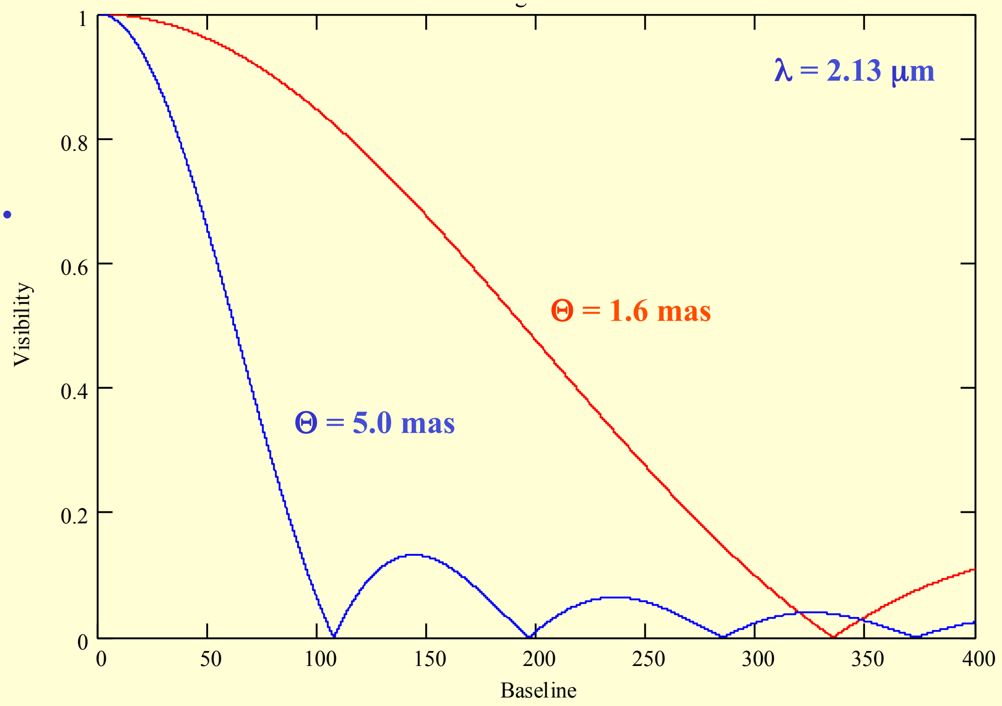
$V_{1,2}$ are the visibilities arising from the component angular diameters $\Theta_{1,2}$ where $V_{1,2}(b) = 2[J_1(\pi\Theta_{1,2} b/\lambda)]/(\pi\Theta_{1,2} b/\lambda)$

Measuring a Star's Diameter

The visibility arising from the angular diameter of each component is:

$$V(b) = 2[J_1(\pi\Theta b/\lambda)]/(\pi\Theta b/\lambda)$$

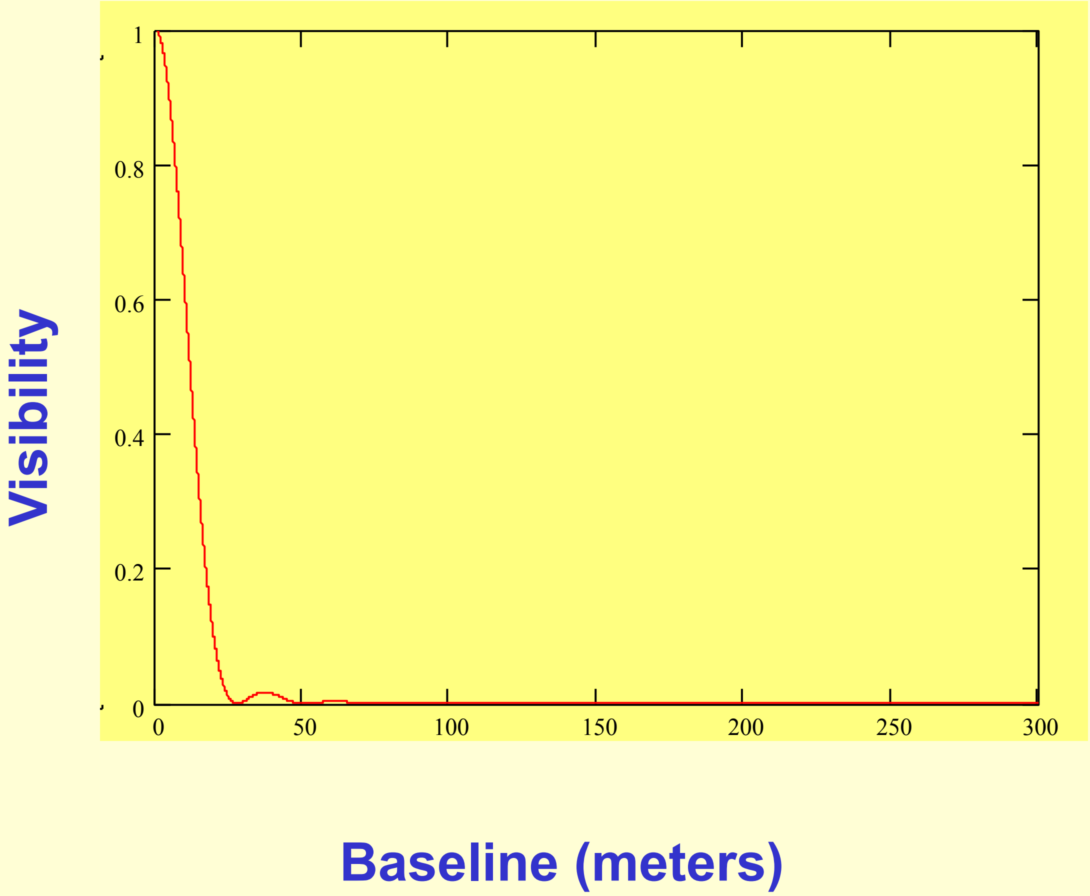
where Θ is the angular diameter (in radians), b is the baseline, and λ is the effective wavelength of the observed spectral pass band. J_1 is the first order Bessel function.



Before we do such fits, we must derive actual visibilities from what we measure with an interferometer. This involves a straightforward calibration process using other stars.

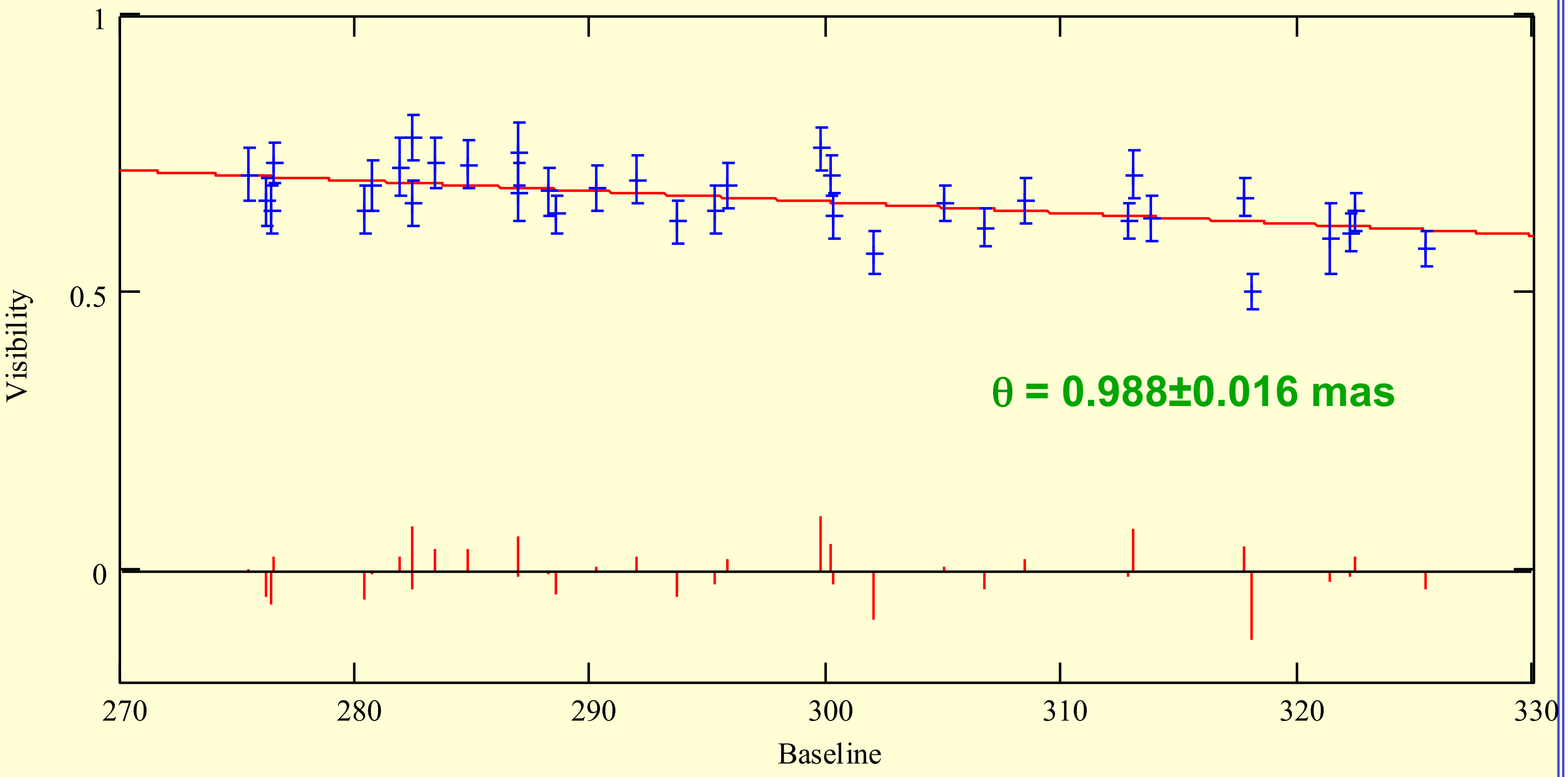
Effect of Increasing Angular Diameter θ

θ = *5.0 mas*



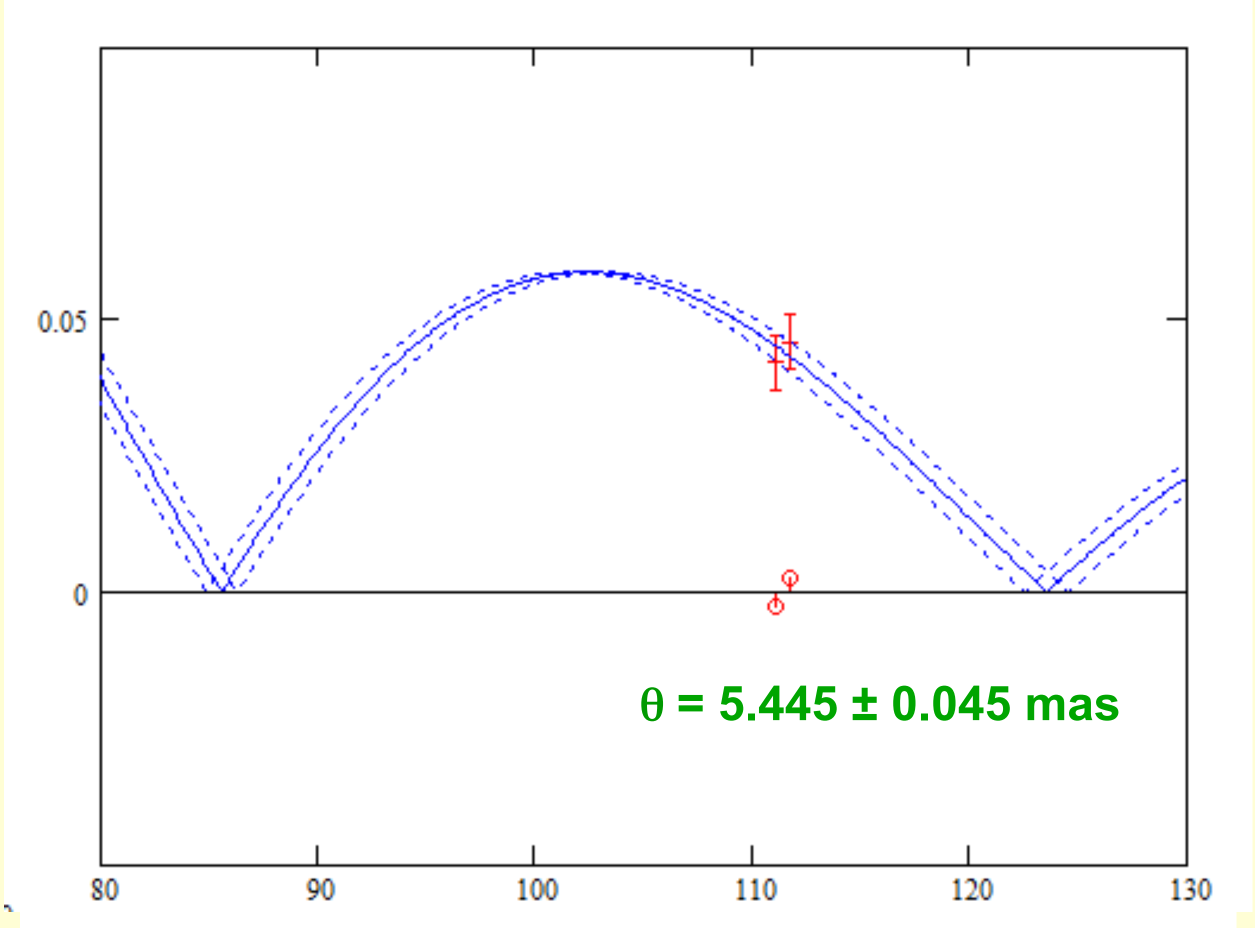
An Example Angular Diameter Fit

A smallish star – GJ 752A (Ross 652)

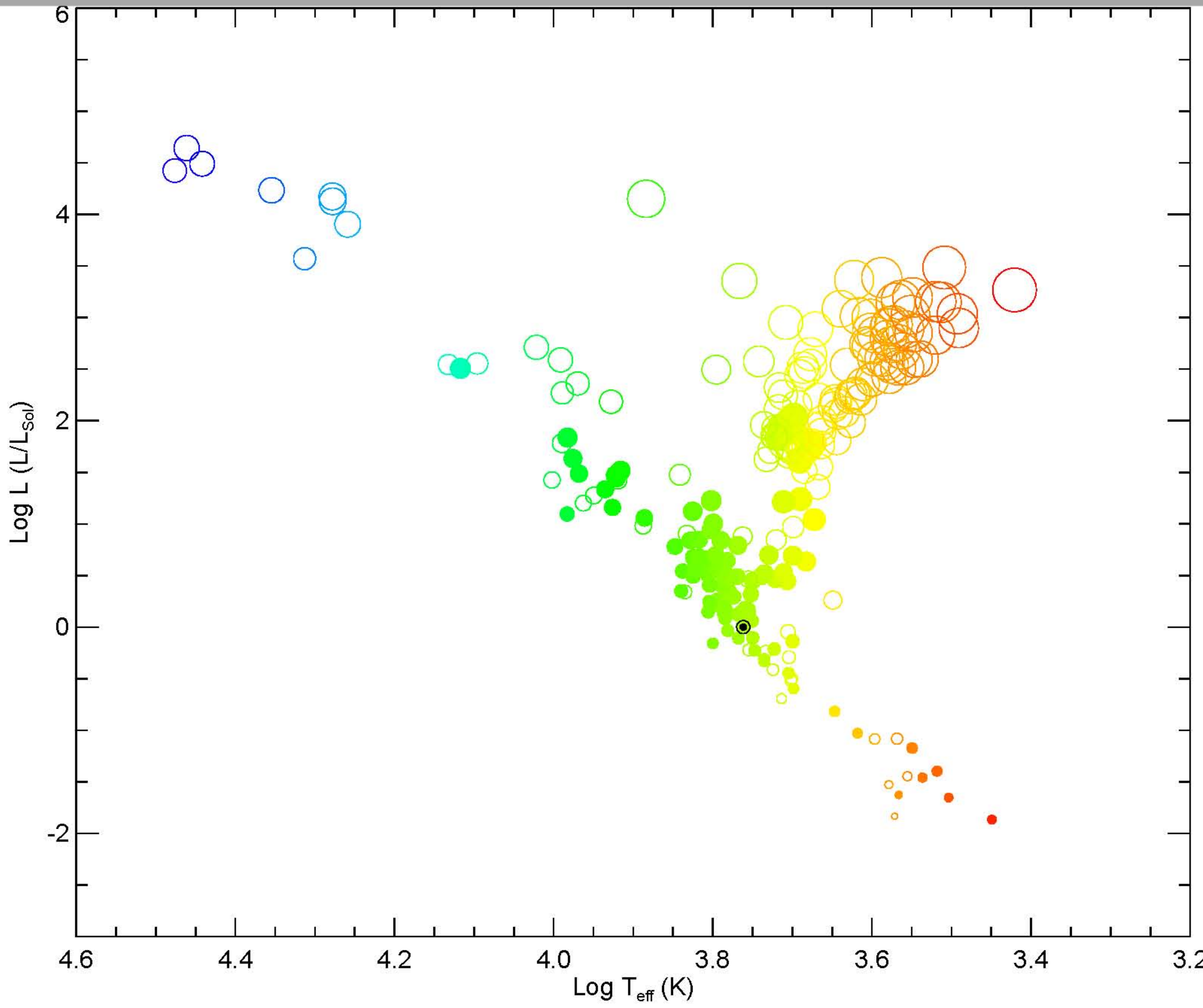


An Example Angular Diameter Fit

A largish star – Procyon (α Canis Minoris)

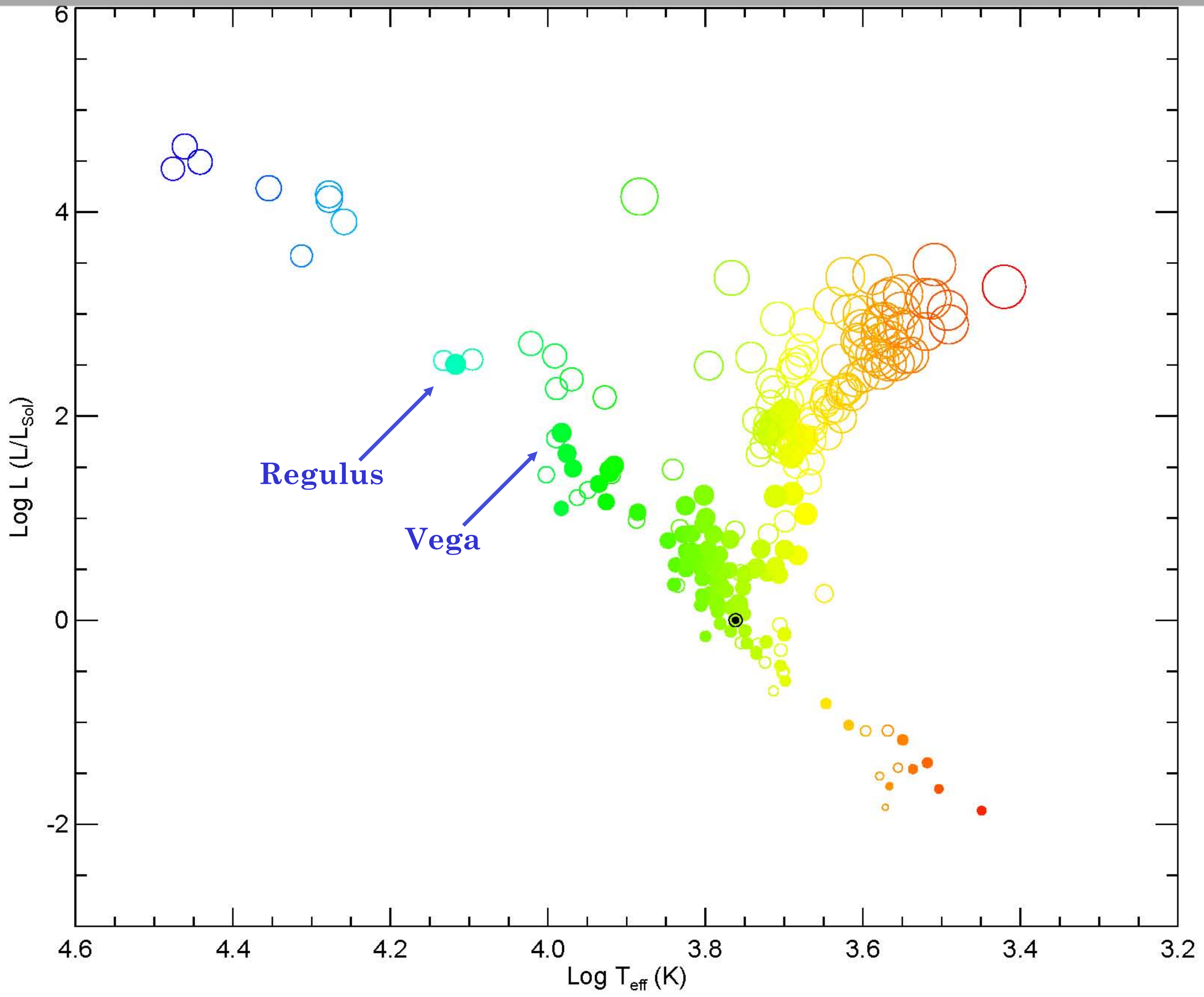


An Interferometric HR Diagram



Rapidly Rotating Stars

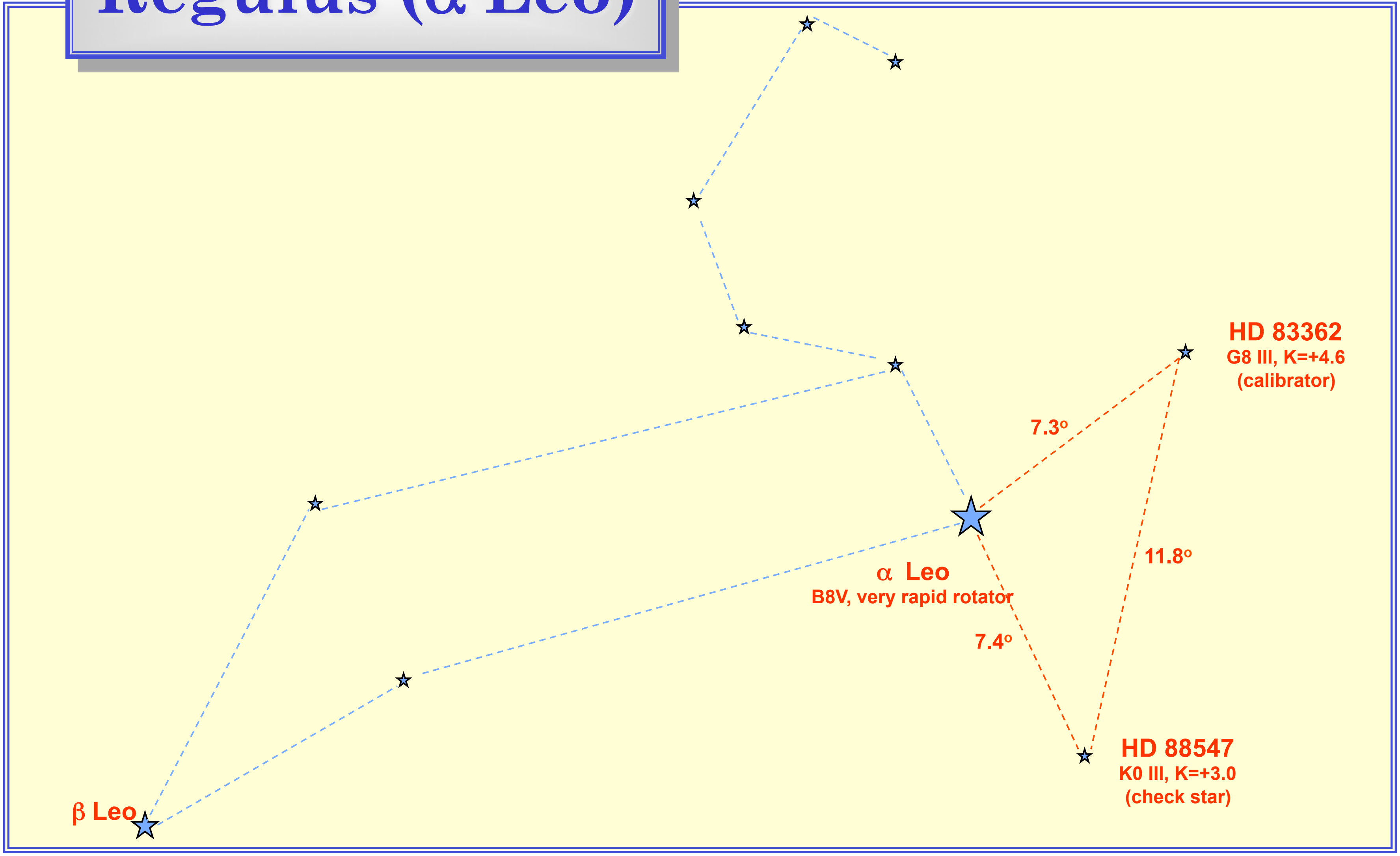
α Leonis and α Lyrae



Regulus

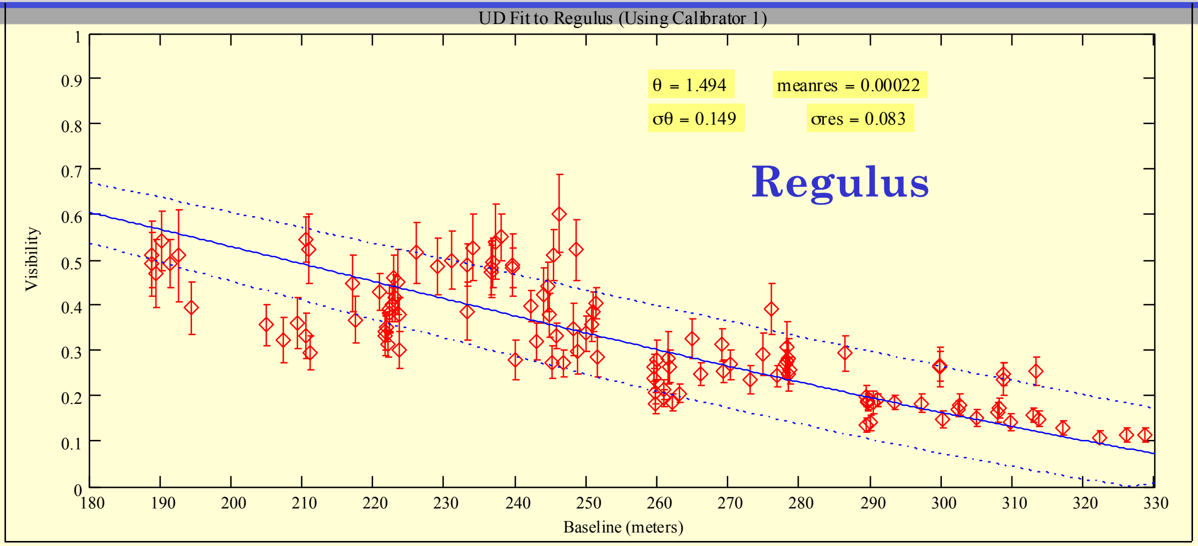
Vega

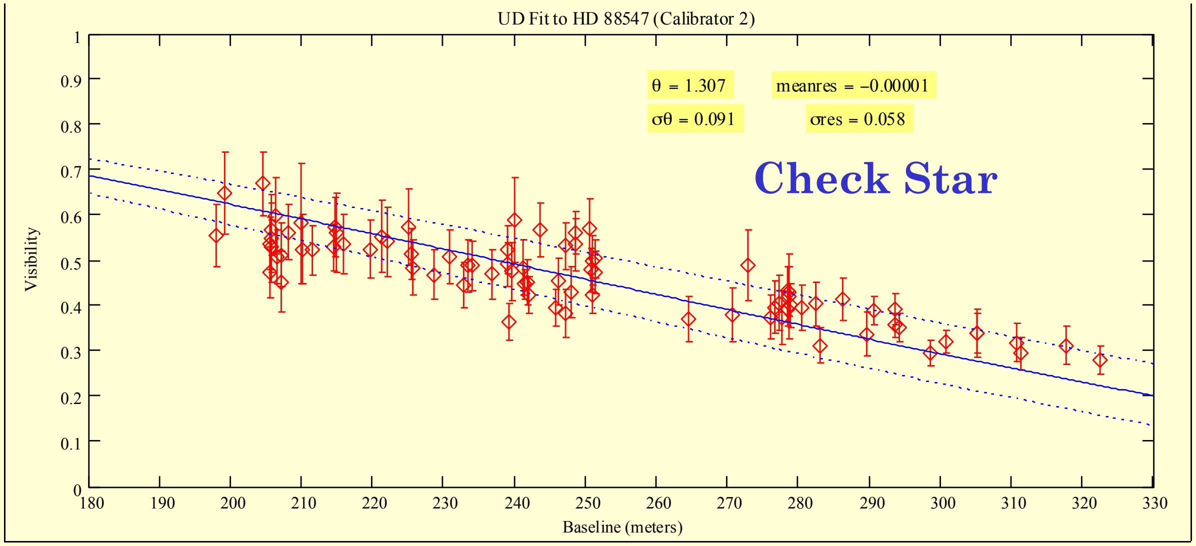
Regulus (α Leo)



Regulus Visibilities & Diameter Fit

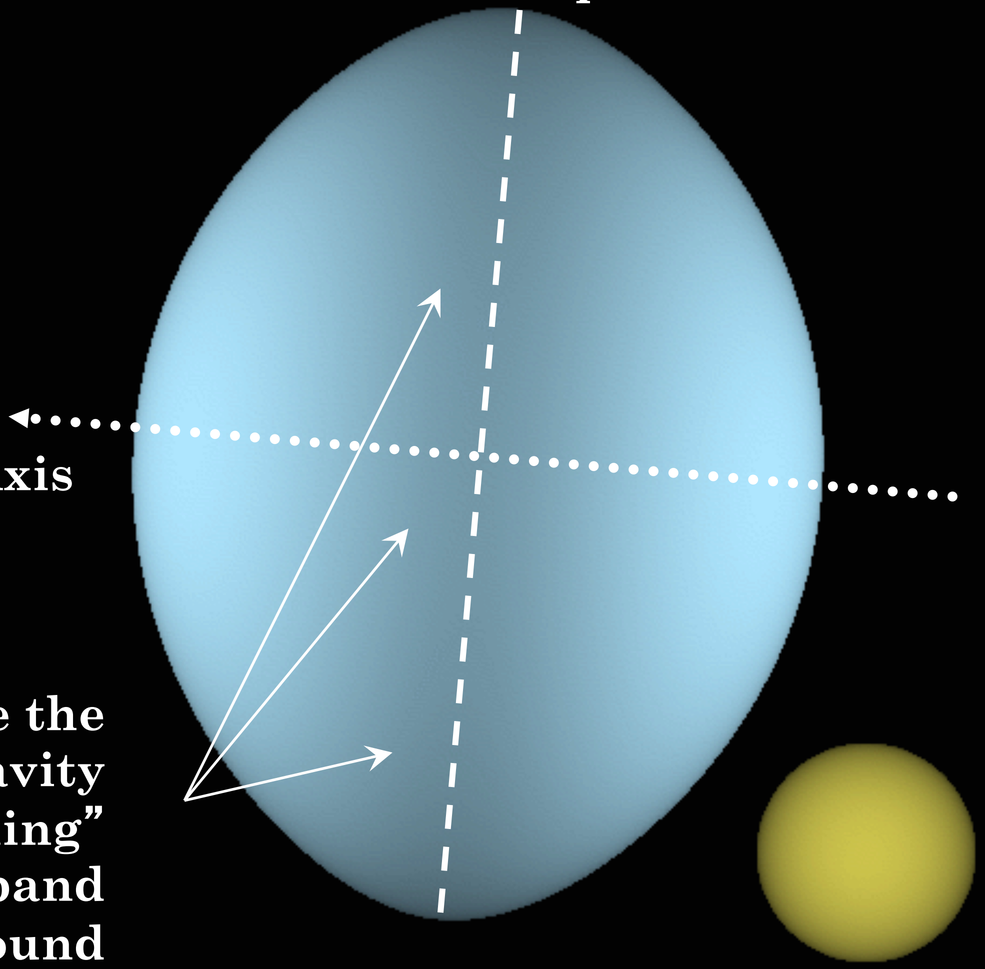
Regulus clearly isn't round





Regulus & the Sun

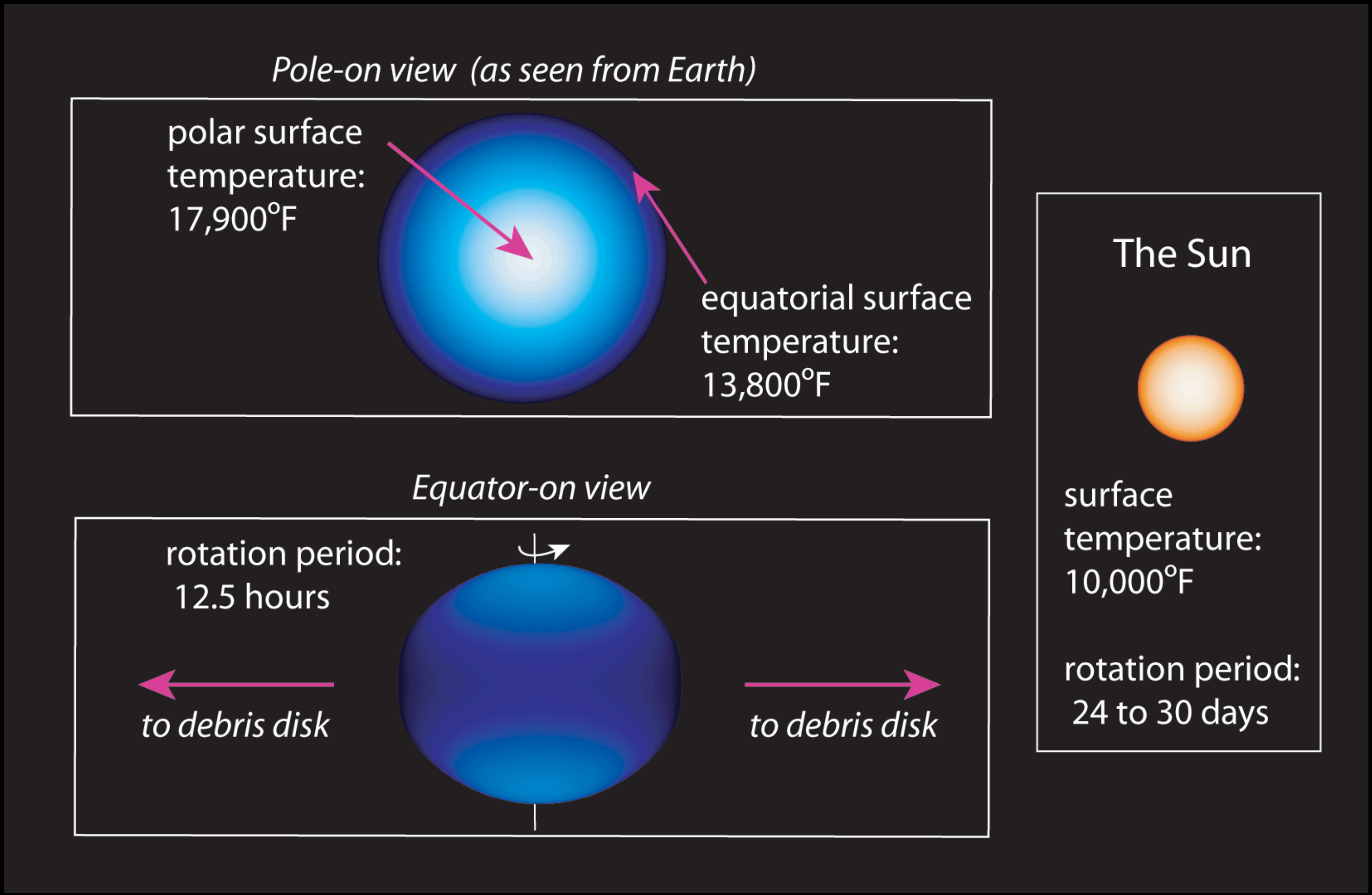
CHARA's First Refereeed Science Paper



The Sun rotates about its spin axis once every 24 days. Regulus rotates once every 16 hours.

Note the "Gravity Darkening" band around equator.

Vega – A Pole-on Rapid Rotator



Pole-on view (as seen from Earth)

polar surface
temperature:
17,900°F

equatorial surface
temperature:
13,800°F

Equator-on view

rotation period:
12.5 hours

to debris disk

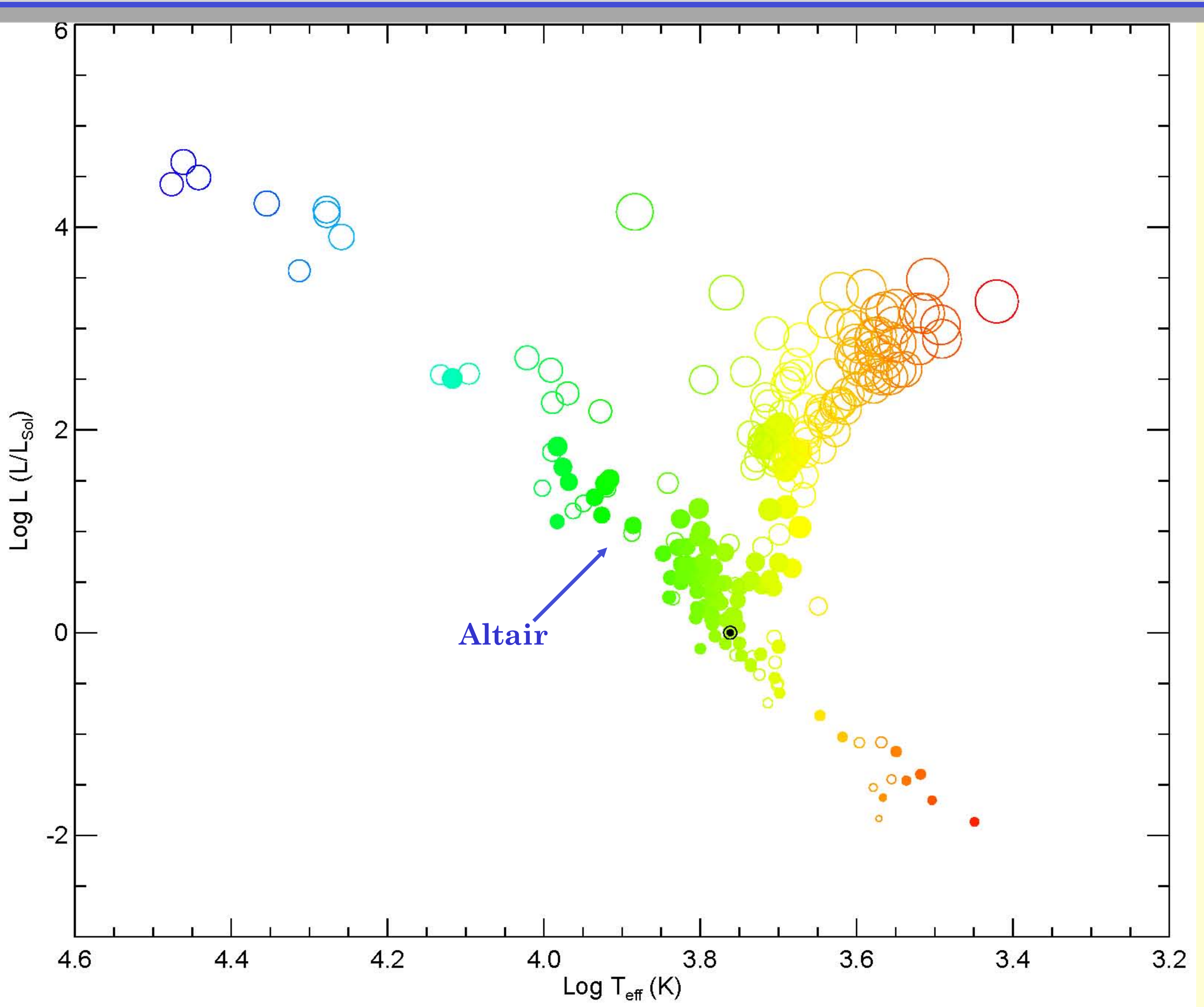
to debris disk

The Sun

surface
temperature:
10,000°F

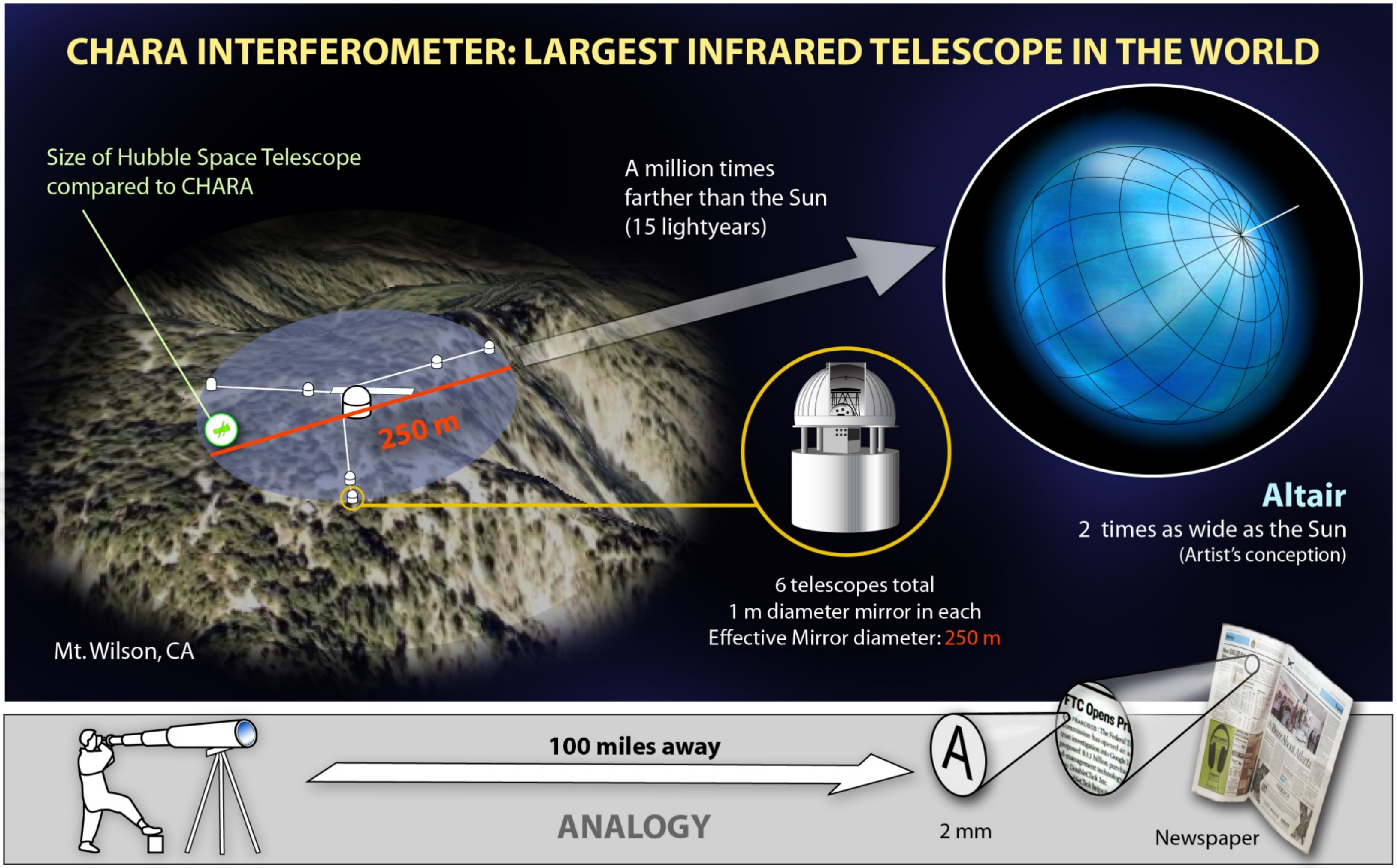
rotation period:
24 to 30 days

Imaging α Aquilae (Altair)



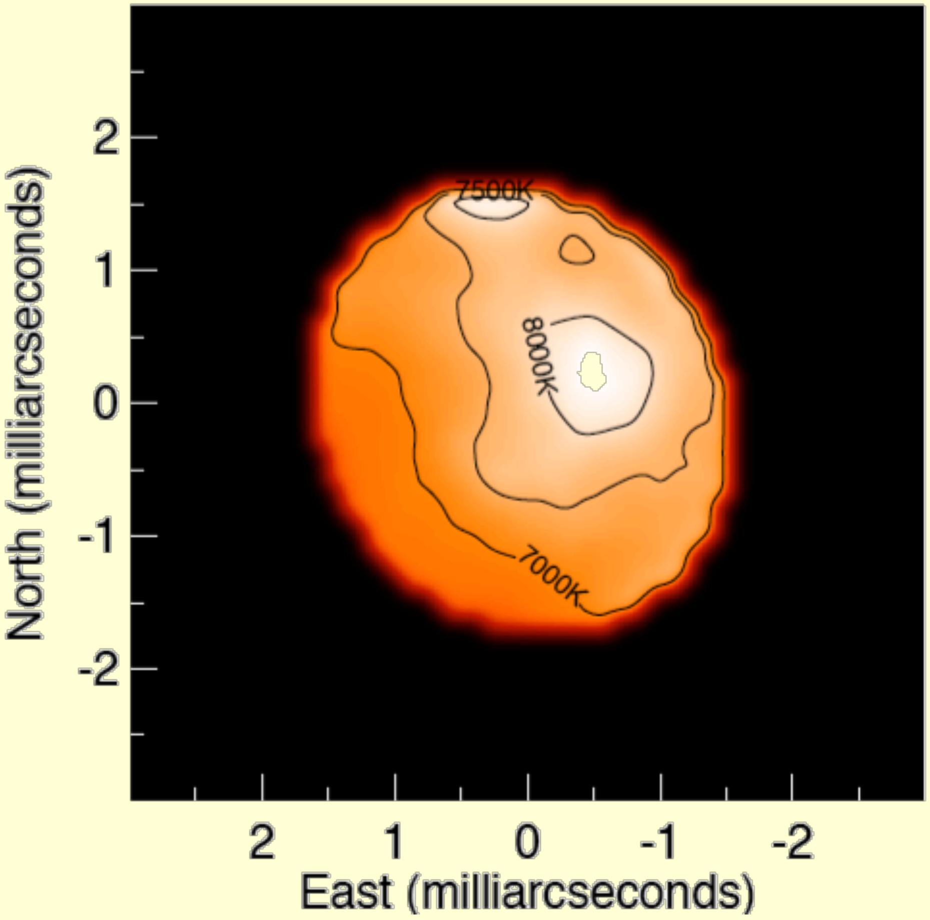
The Rapid Rotator Altair

The first image ever made of another sunlike star



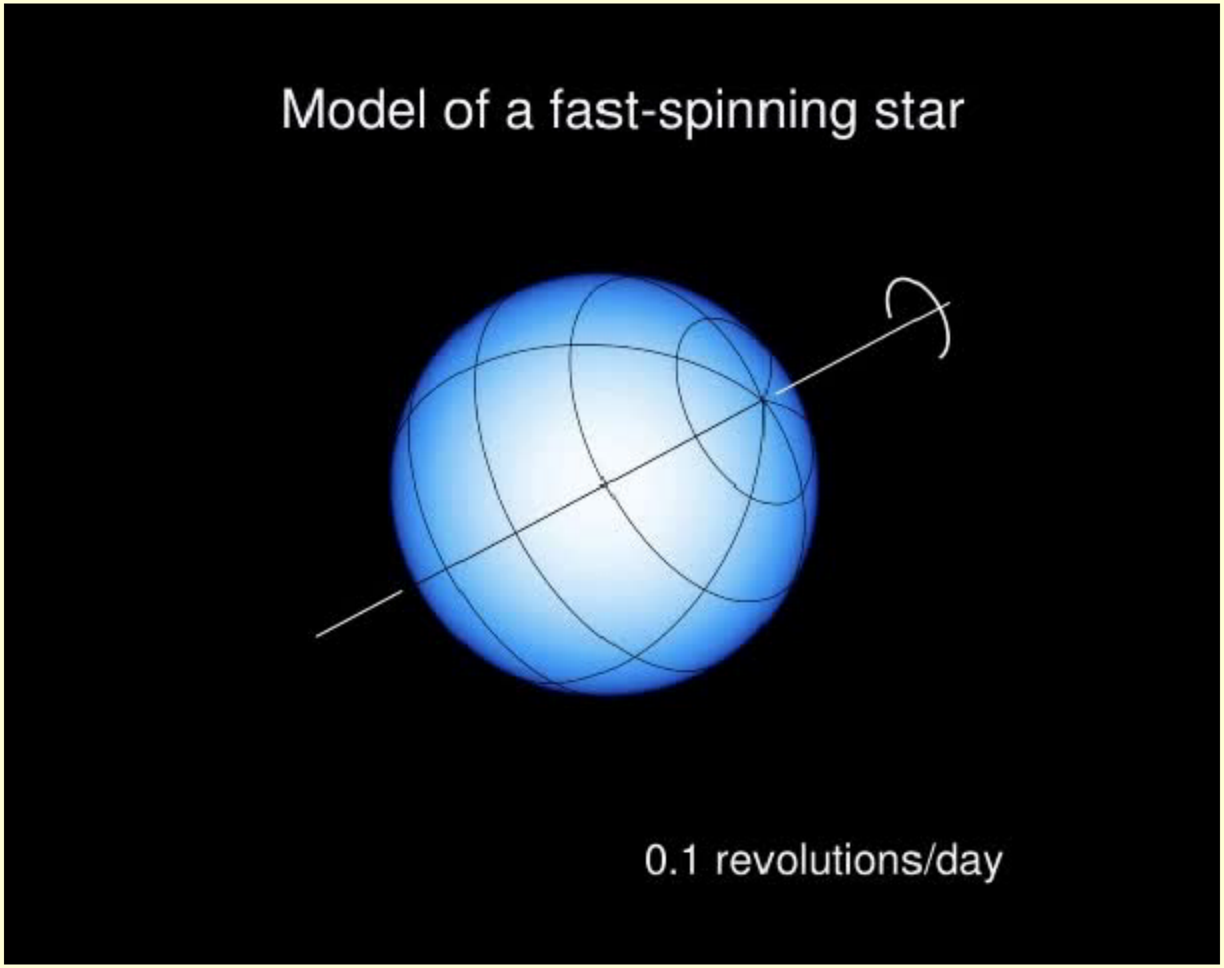
The Rapid Rotator Altair

The first image ever made of another sunlike star



The Rapid Rotator Altair

The first image ever made of another sunlike star



Comparison of Image with Standard Model

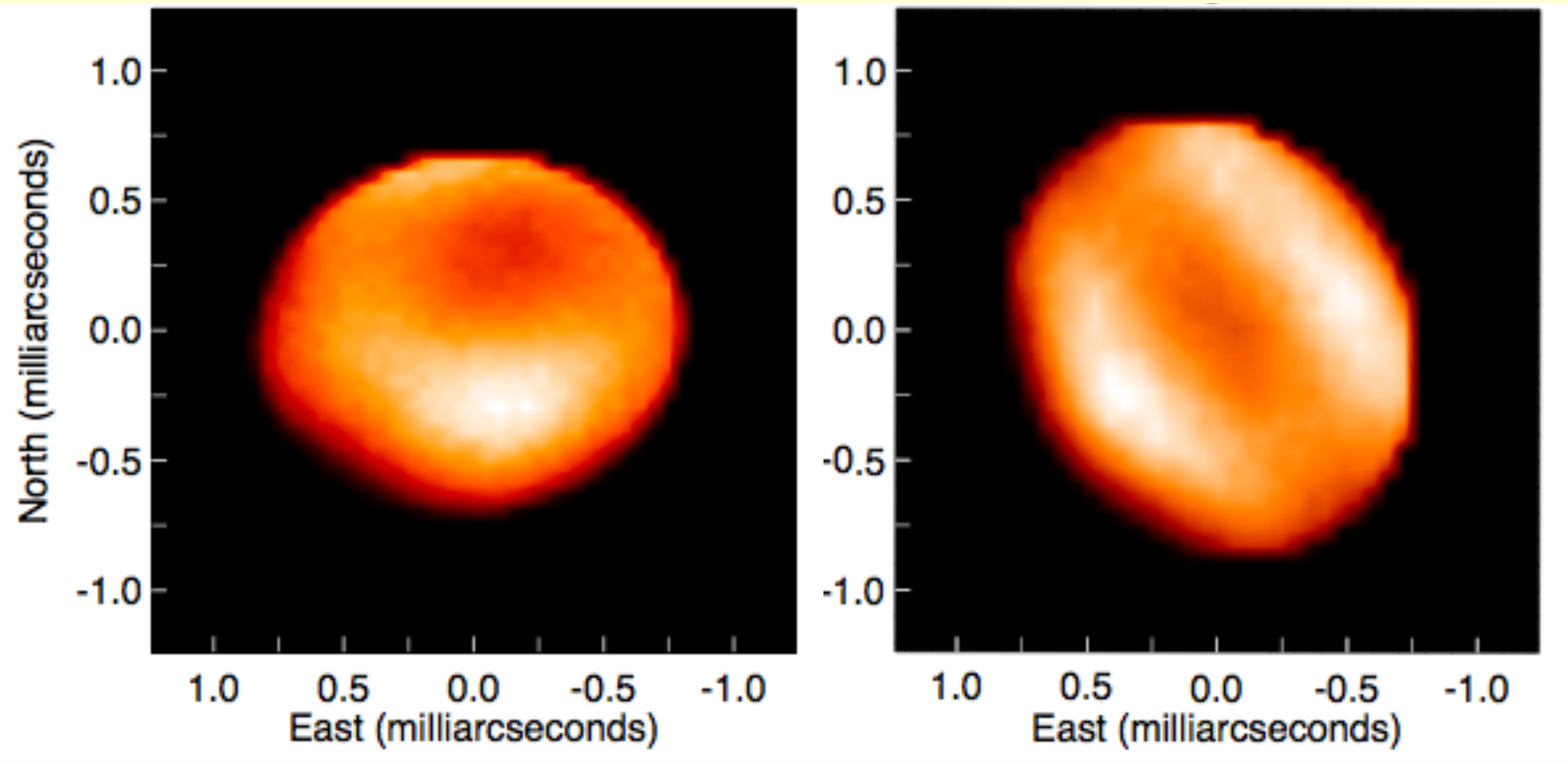
- Altair (Alp Aql, V=0.7)
  - Nearby hot star (d = 5.1pc, Spectral Type A7V, T = 7850 K)
  - Rapidly rotating (v sin i = 240 km/s, ~90% breakup)
  - 22% longer in one dimension than other (Van Belle et al. 2001)
  - Equator is ~1600 K cooler and ~35% less bright than pole)

- Ideal test of Von Zeipel Theory of gravity darkening
  - Assumptions: solid body rotation, point gravity
  - Centrifugal distortion will cause oblateness
  - Equatorial "gravity darkening": hot pole looks like bright spot

- Equatorial gravity darkening we see is greater than predicted by this theory

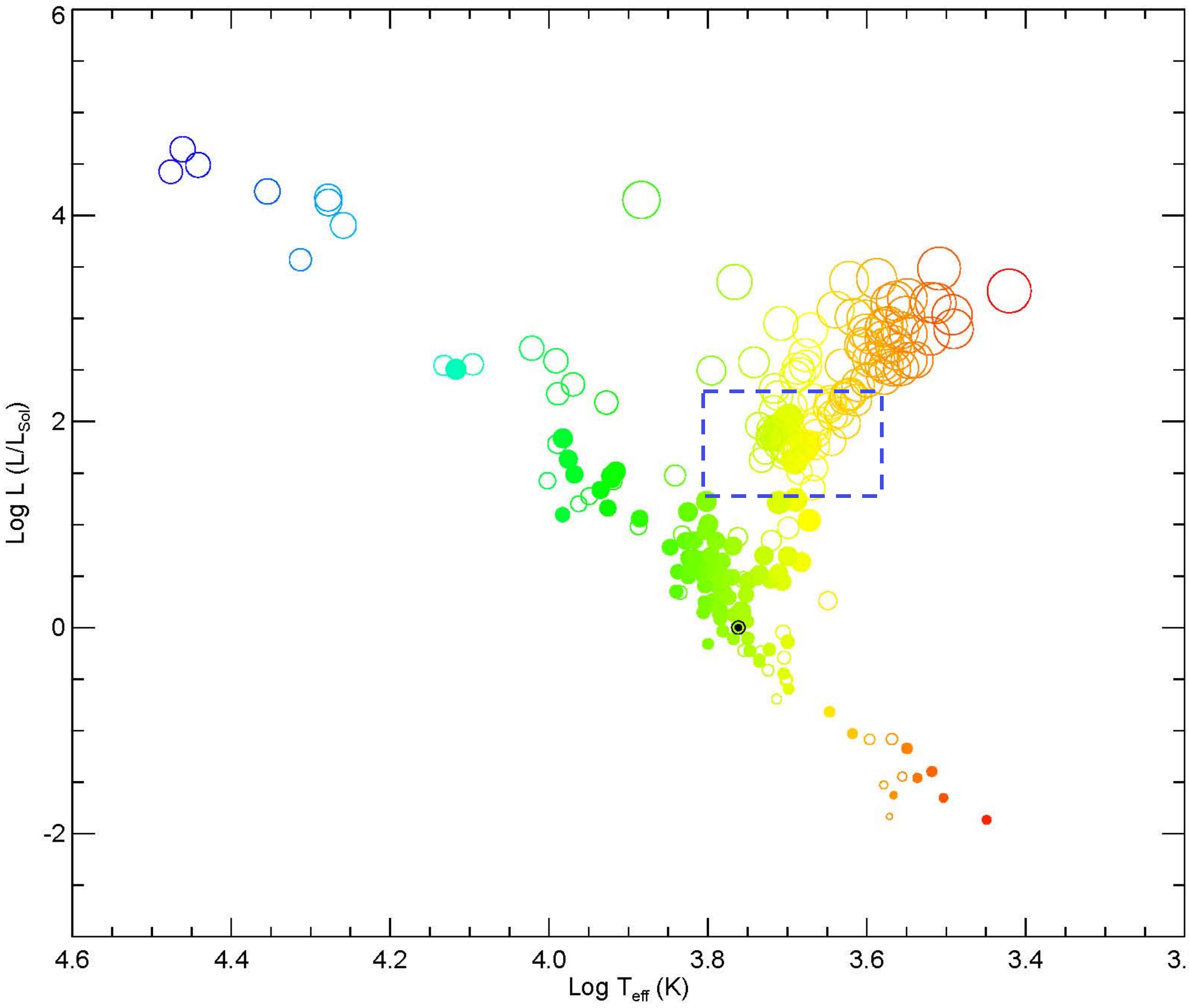
There's More! – α Cep & α Oph

aka Alderamin & Ras Alhague

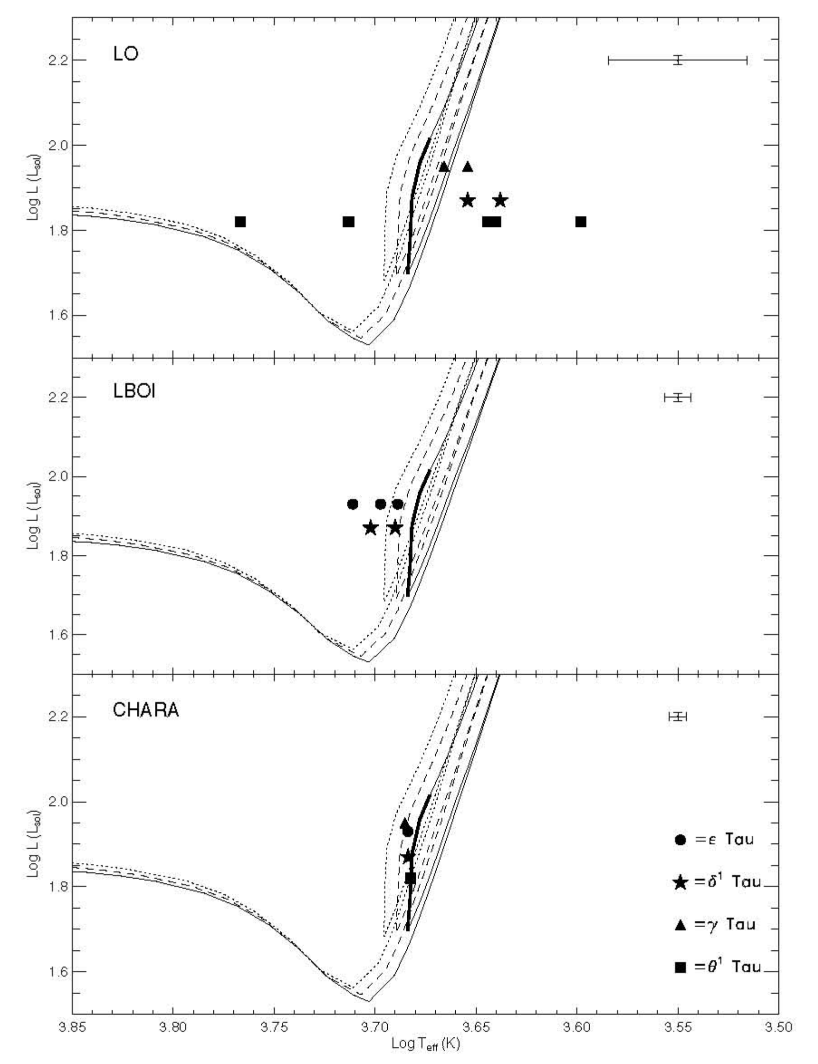


Red Giants in the Hyades

Known Cluster Age is an Asset in Modeling



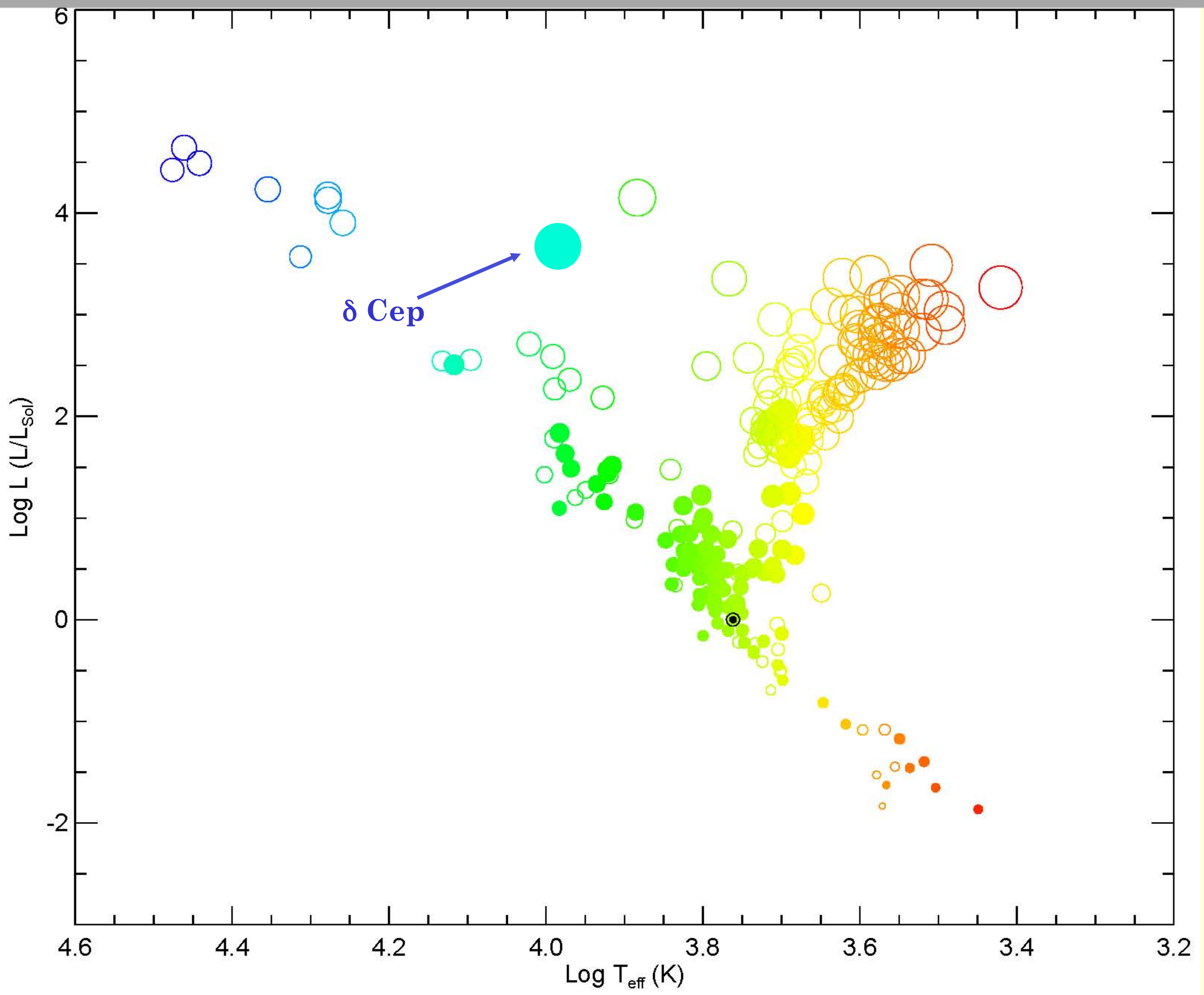
Red Giants in the Hyades



625 Myr isochrones with slightly varying heavy element abundances for existing and new results for Hyades giants.

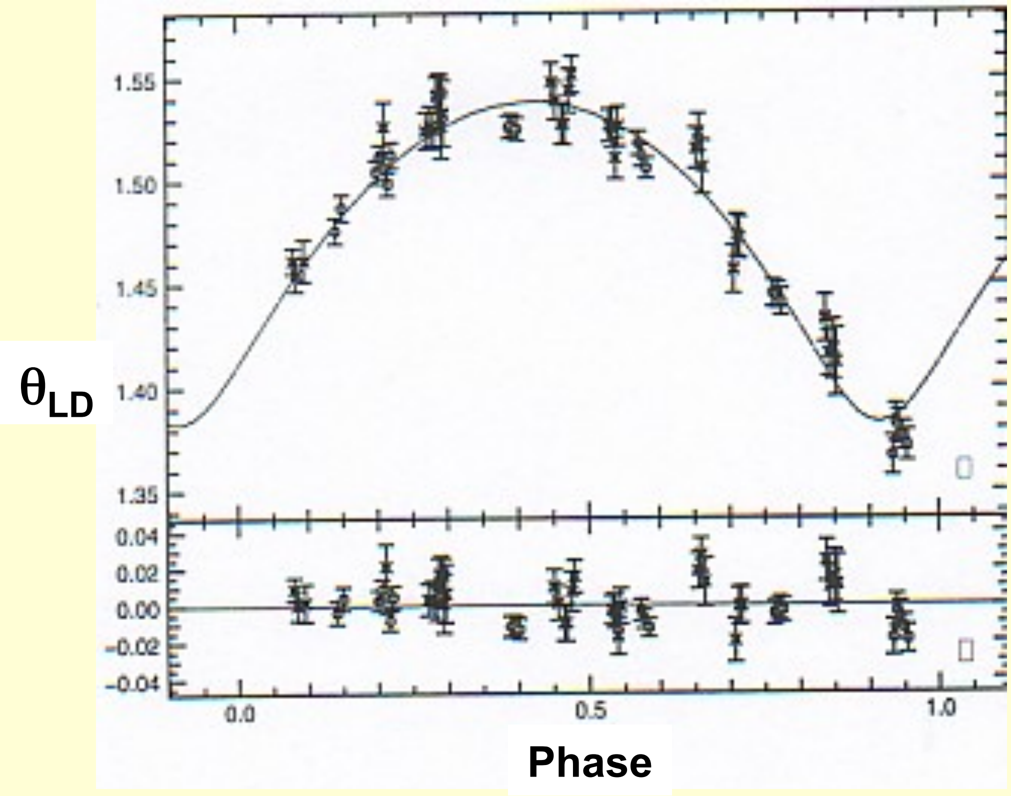
CHARA values show the stars sitting pretty on the "Red Giant Clump."

δ Cephei – Prototype of the Classical Cepheids



δ Cephei – P Factor Determination

Mérand et al. A&A 2005



The angular diameter with phase is shown following the adjustment of the p-factor in order to follow the radial velocity fit (solid line).

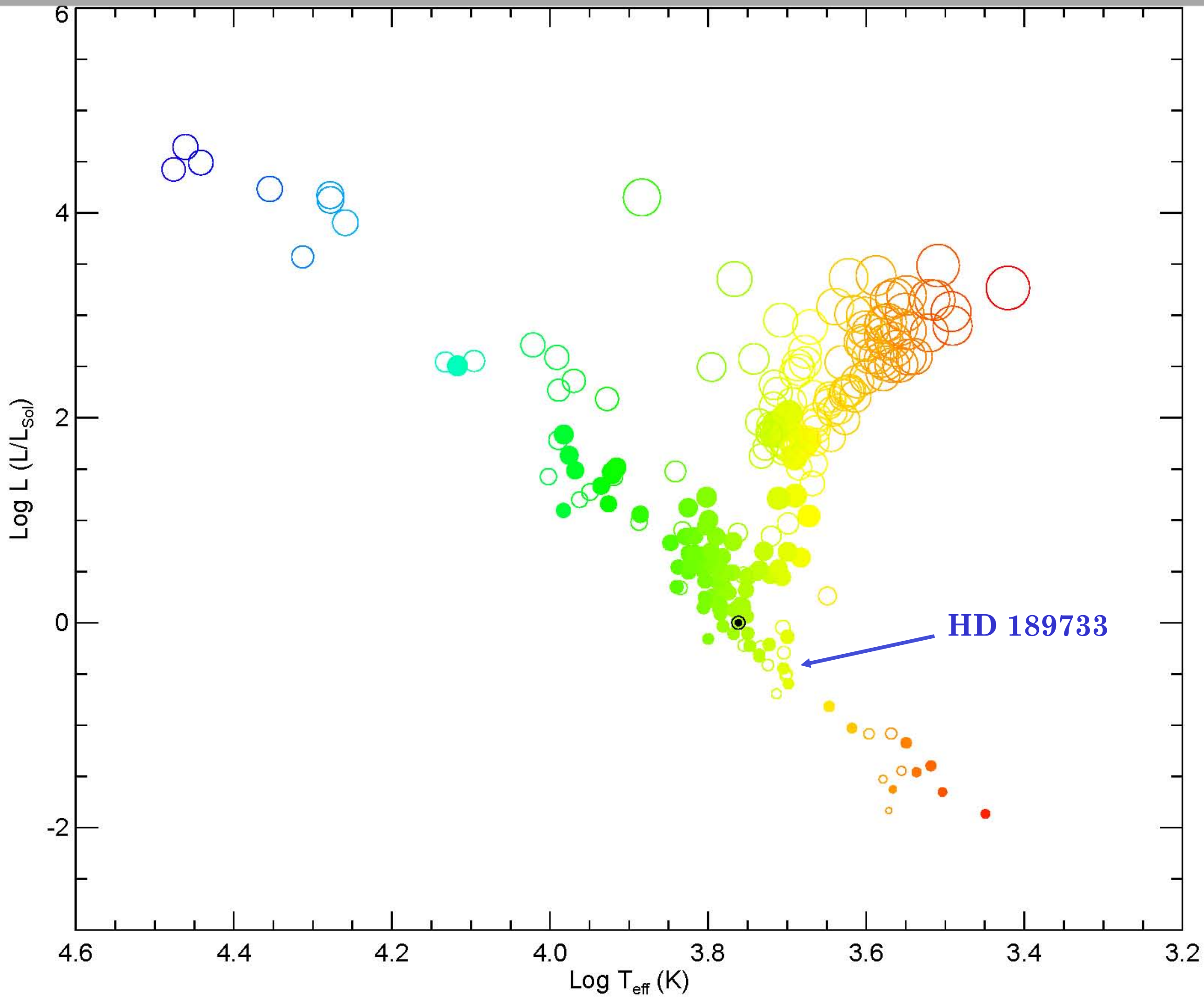
Θ_{mean} = 1.475±0.004 mas

corresponding to

R_{star} = 43.3±1.7 R_{sun}

Exoplanet Host Star Diameters

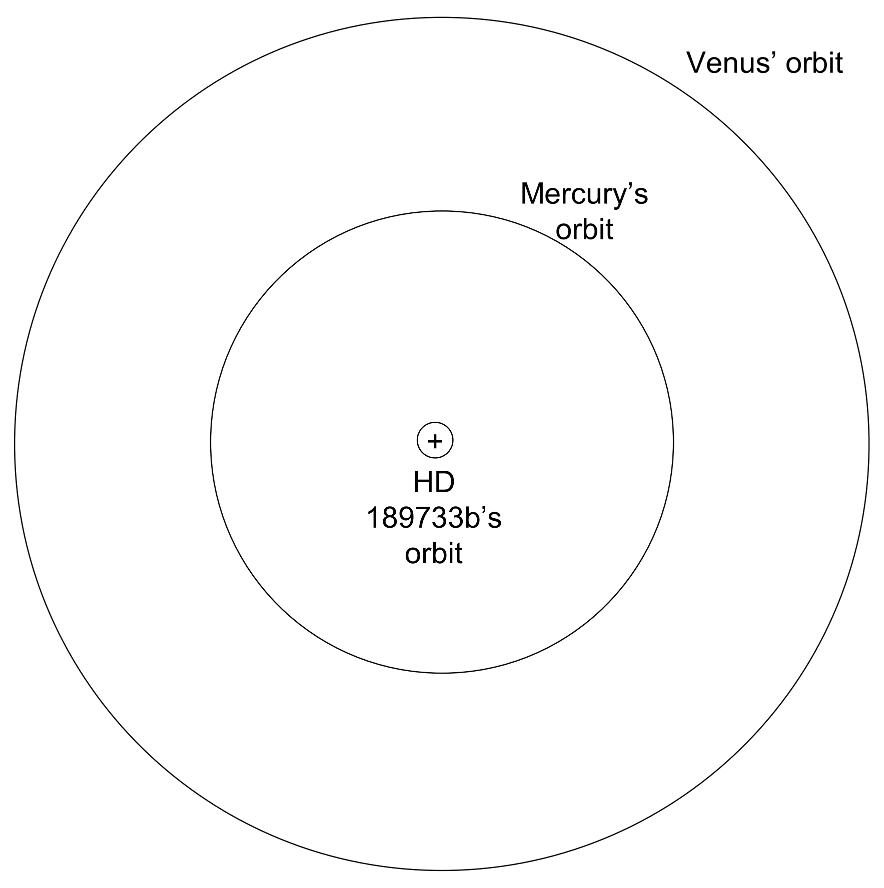
Transiting Exoplanet HD 189733 b



HD 189733

The Exoplanet Orbiting HD 189733 I.

A "Hot Jupiter"



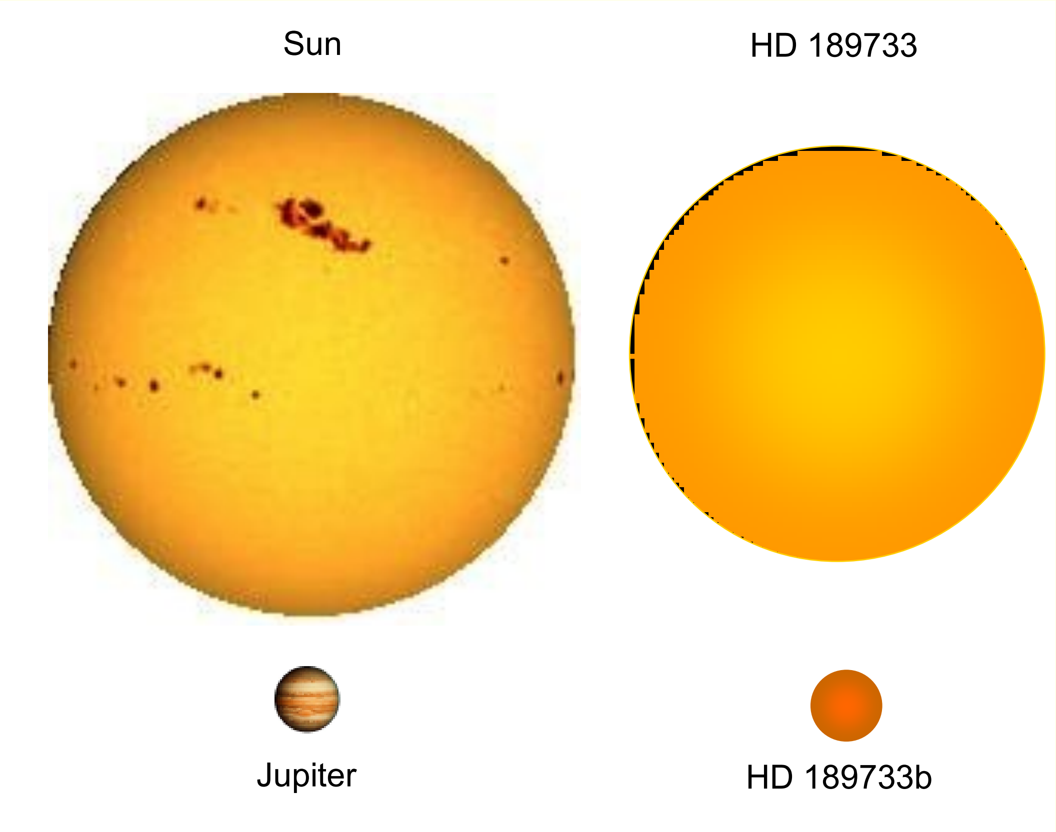
This planet orbits once every 2.2 days with an orbital plane that is nearly in our line of sight.

Thus, the planet transits the star and produces a small decline in the star's brightness equivalent to an eclipsing binary star system.

By measuring the size of the star, we get the size of the planet.

The Exoplanet Orbiting HD 189733 II.

Baines et al. ApJ 2007.



Ellyn Baines found an angular diameter for the star of 0.00038 arc seconds, one of the smallest yet measured.

This means the planet, which was known to be about 17% the diameter of the star, is about 20% larger than Jupiter.

The planet has a density of about 0.75 gm/cm^3, similar to Saturn.

This is the first direct measurement of the diameter of an exoplanet

The HR 8799 Exoplanet System

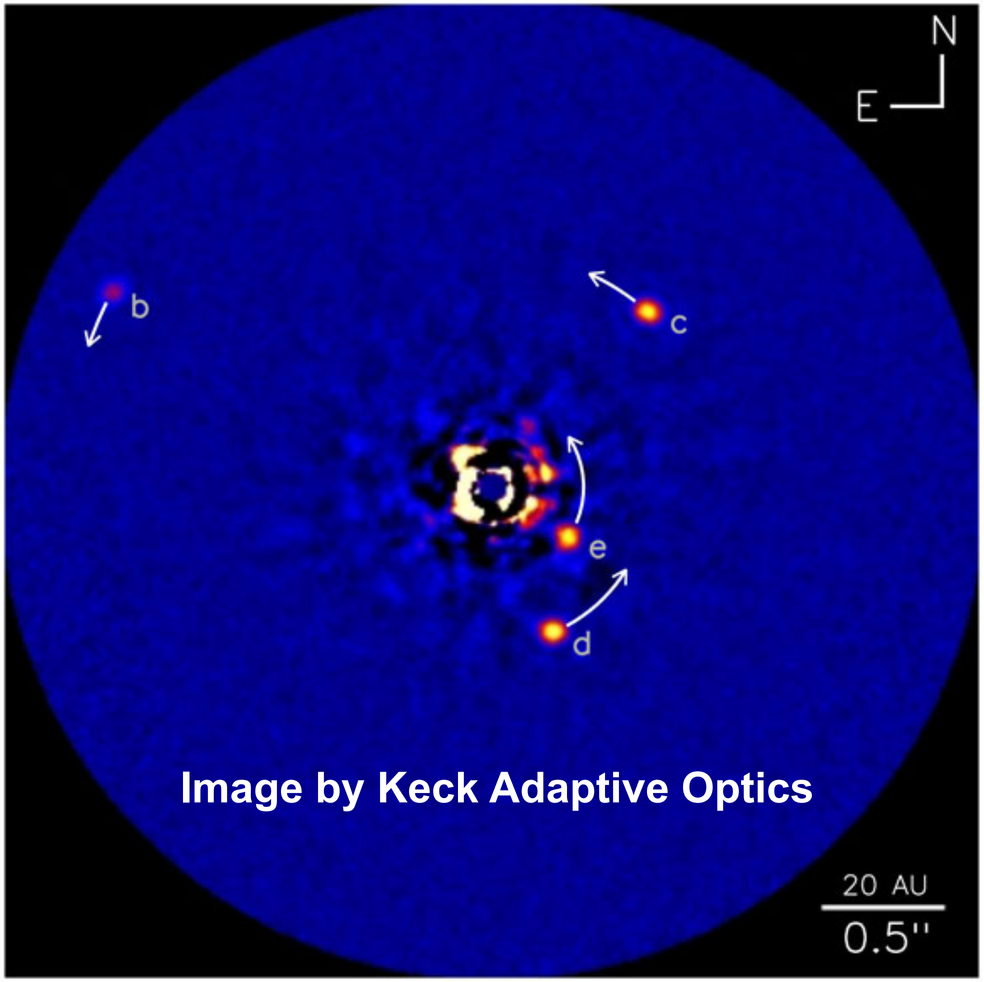
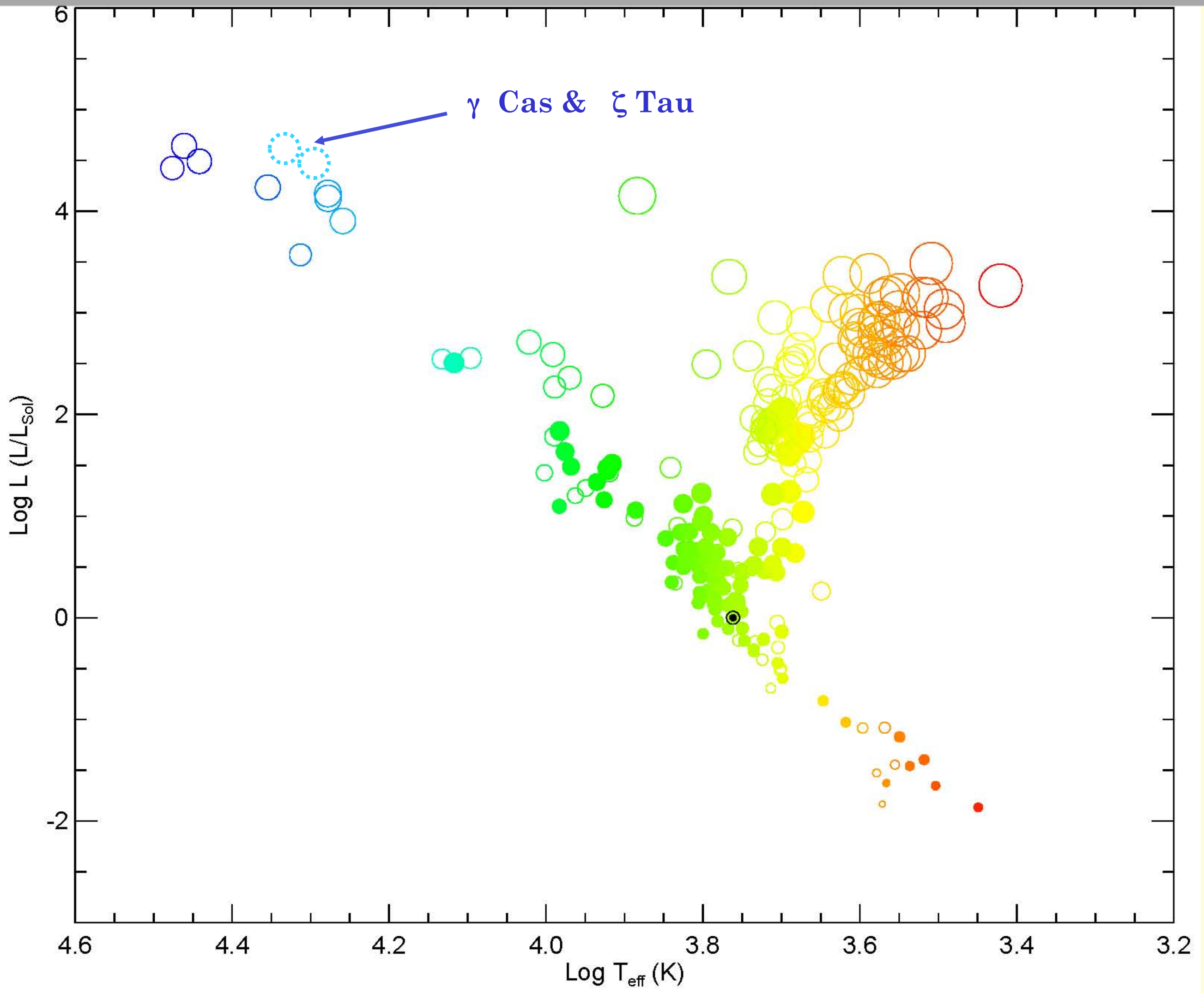


Image by Keck Adaptive Optics

New CHARA observations of the host star’s diameter have led to its placement on the HR diagram in a position suggesting that it is much older than thought and that the “planets” may instead be brown dwarfs.

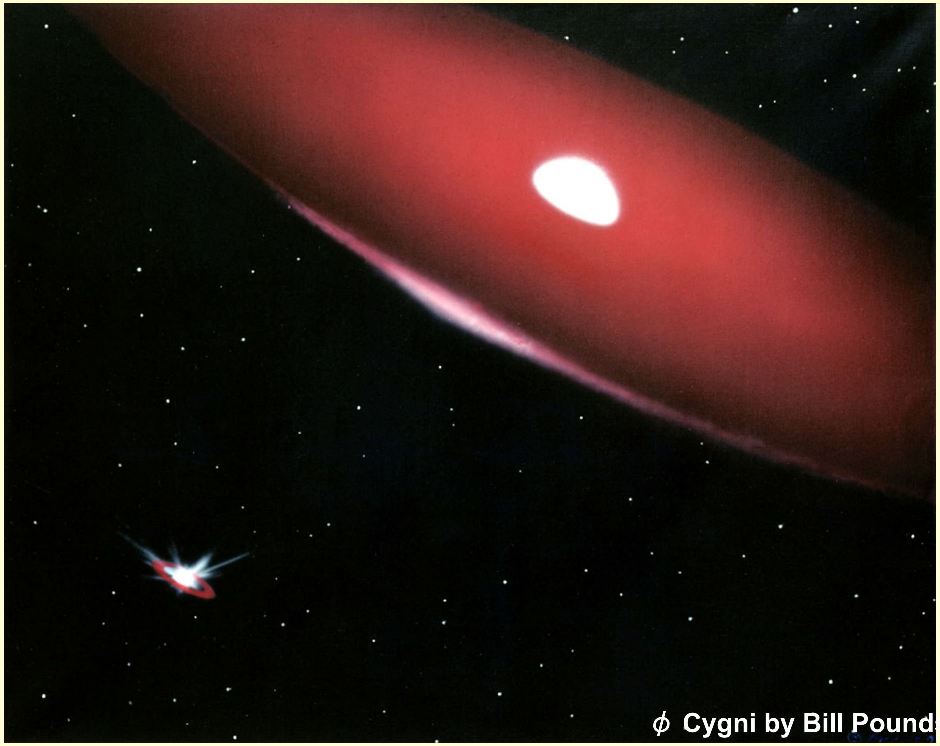
Hot Stars With Disk

The "Be" Stars γ Cas and ζ Tau



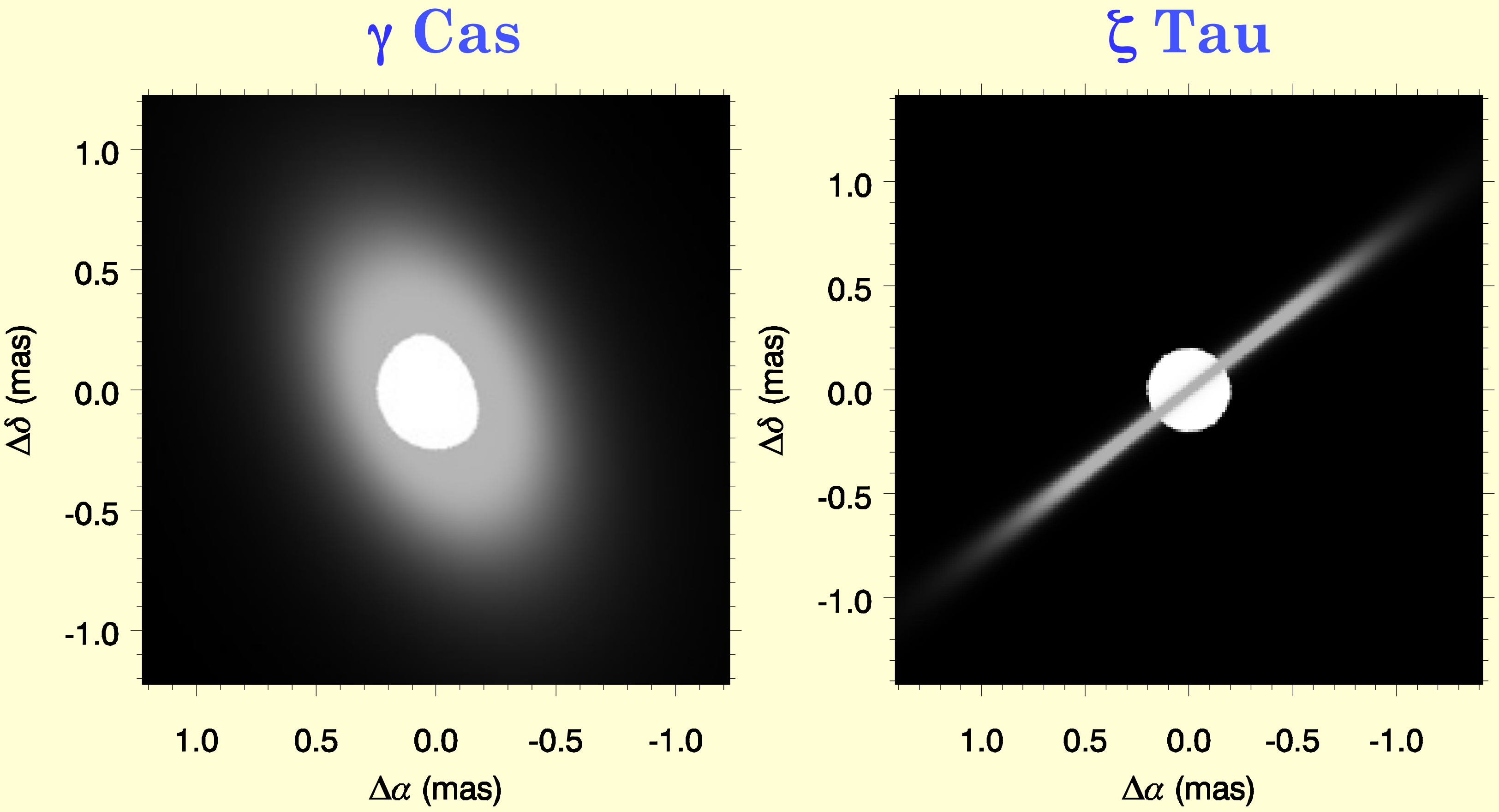
Be Star Properties

- 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
- Variable on timescales of days to decades

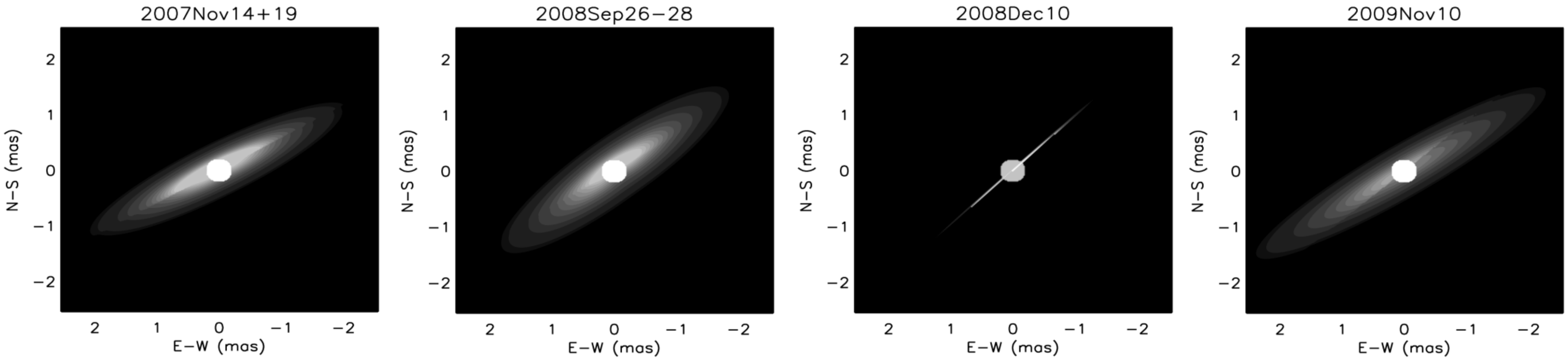


ϕ Cygni by Bill Pounds

Disks Around “Be” Stars

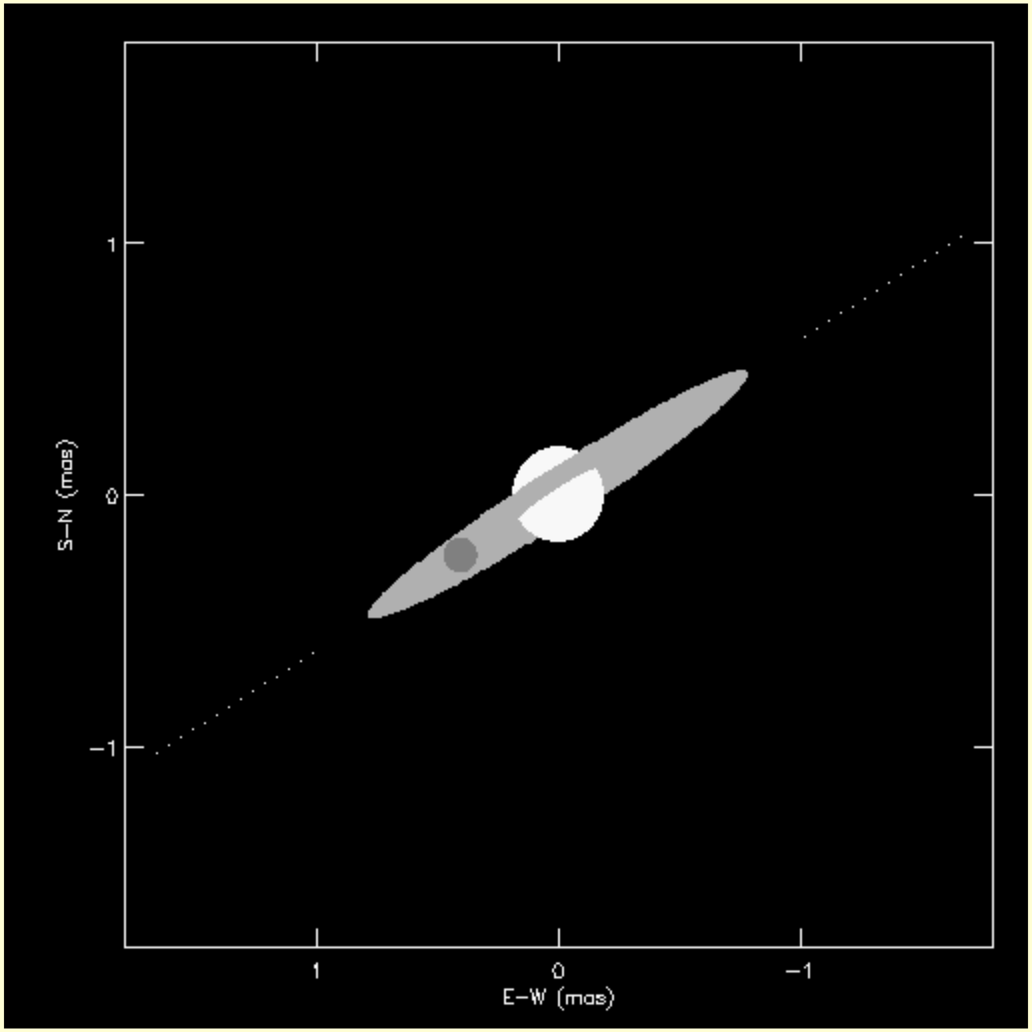


Geometric Models of ζ Tauri



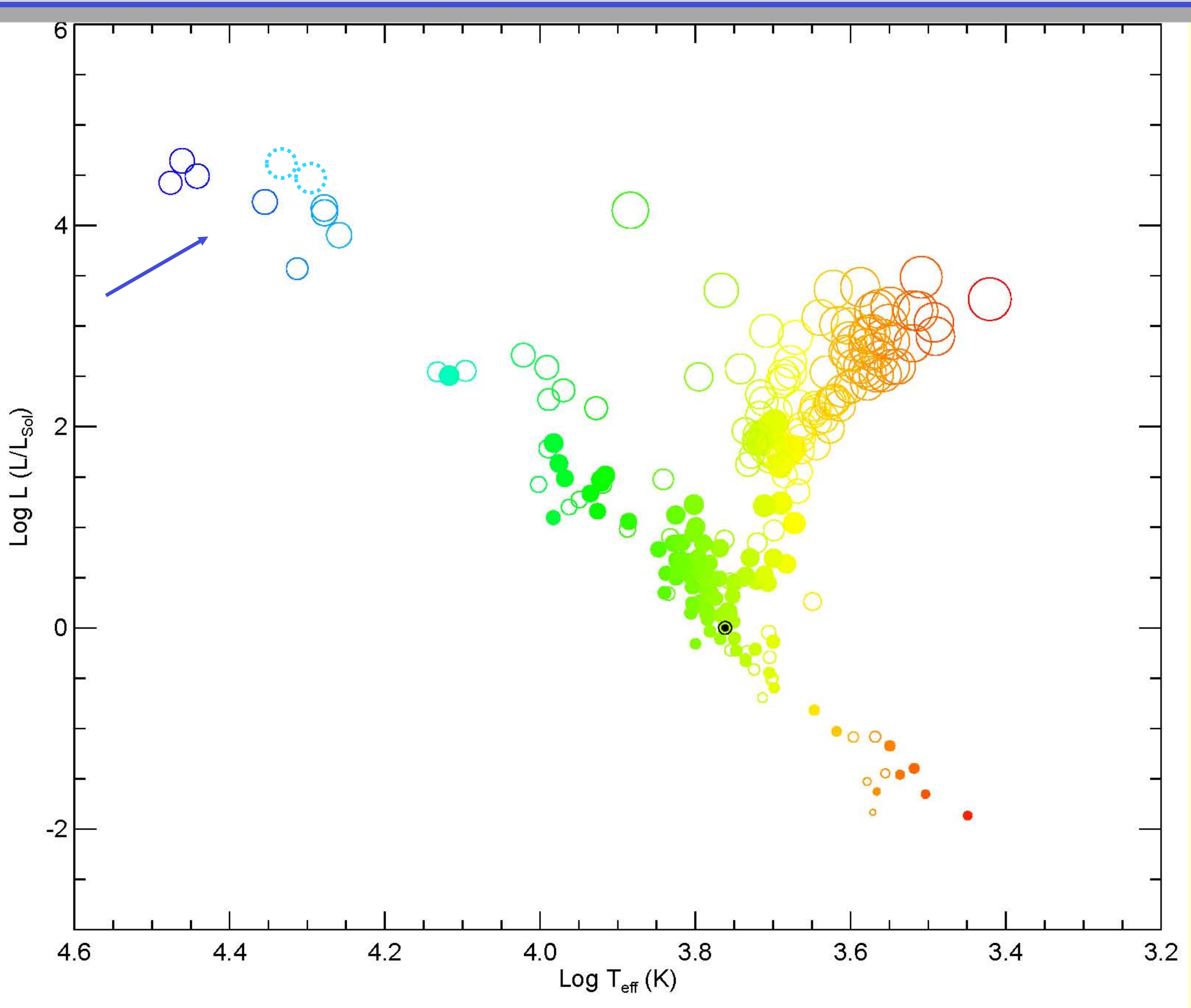
- Major Axis ~ 1.8 mas in radius
- On average, the central star contributes ~half the infrared light
- Apparent change in position angle of the major axis of 10-15°

ζ Tauri Disk Appears to be Precessing!



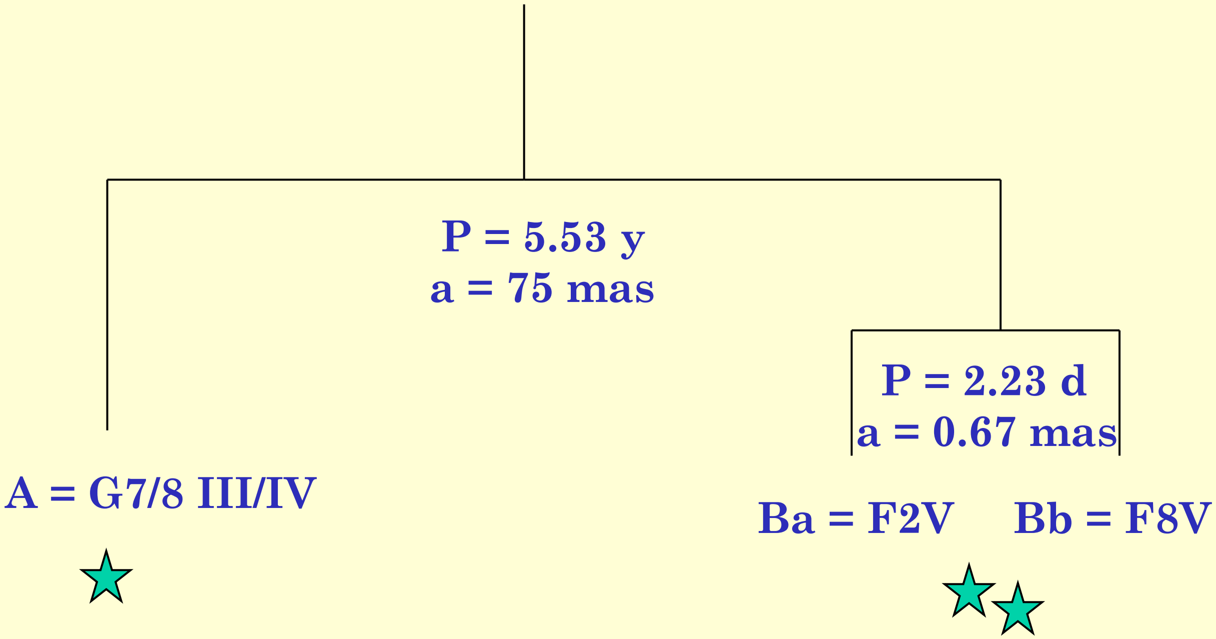
Binary Star Studies

They're all over the map!



HD 157482 (V819 Her)

A Hierarchical Triple System



P = 5.53 y
a = 75 mas

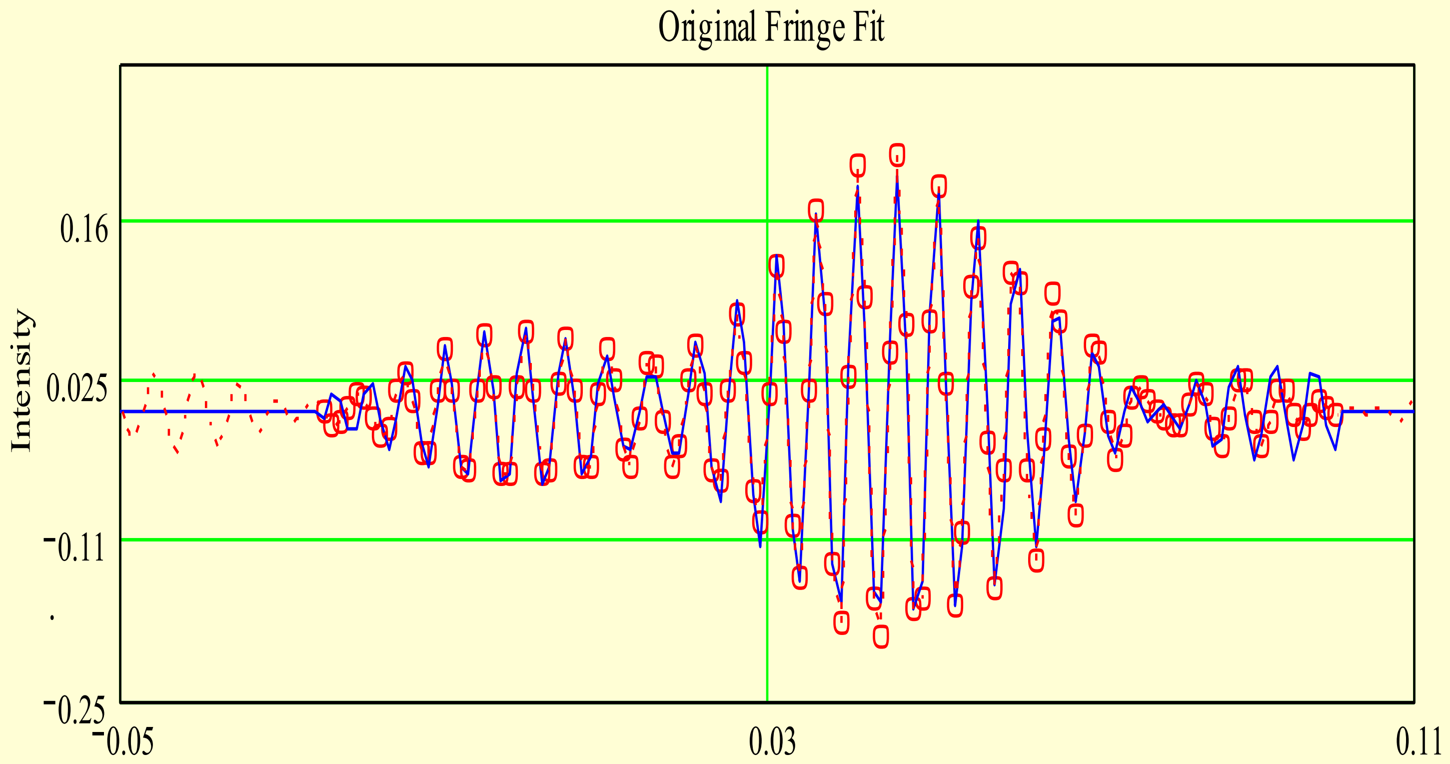
P = 2.23 d
a = 0.67 mas

A = G7/8 III/IV

Ba = F2V

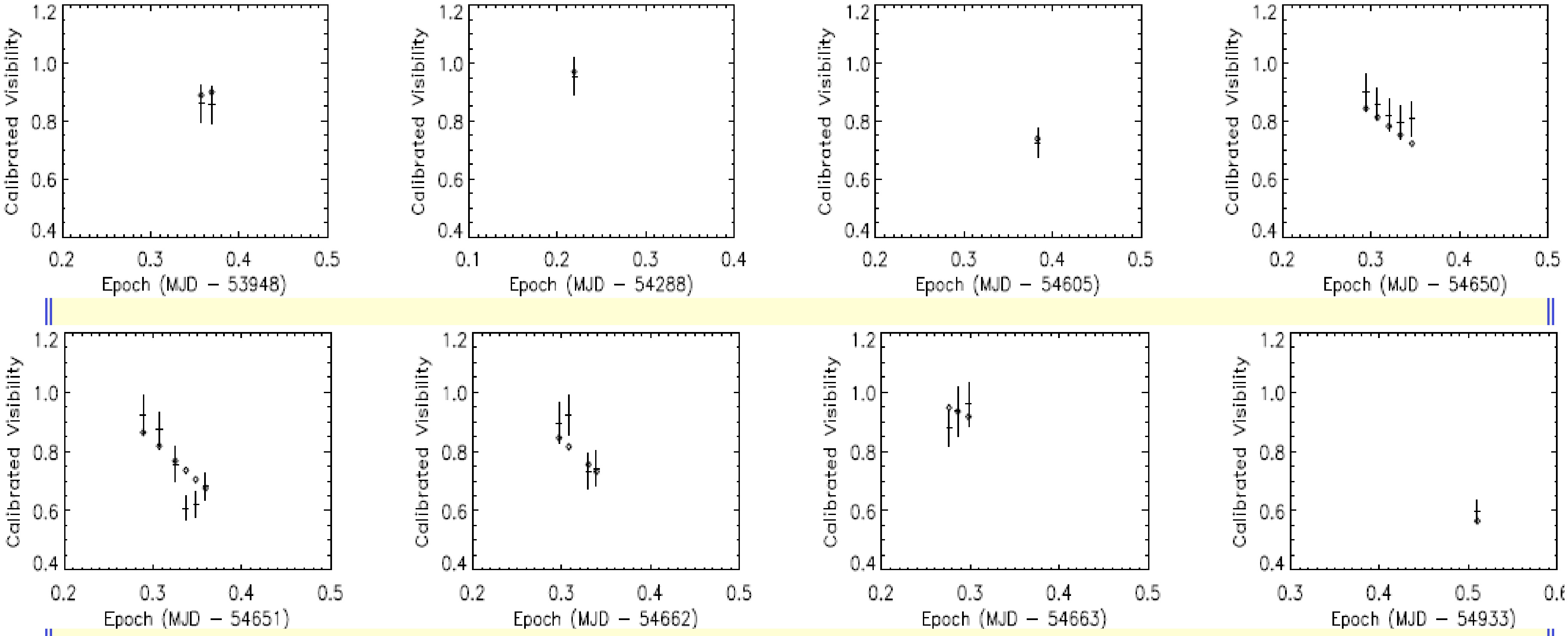
Bb = F8V

“Separated” Fringe Packets


Original Fringe Fit

HD 157482 (V819 Her)

Orbital Fit to Visibilities



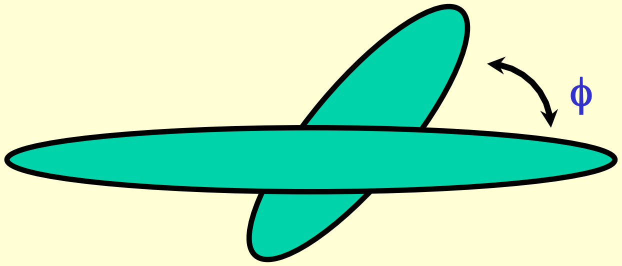
Points represent 3-4 data sets averaged together

Mutual Inclination

- Mutual inclination is the angle between planes of the wide orbit and the close orbit

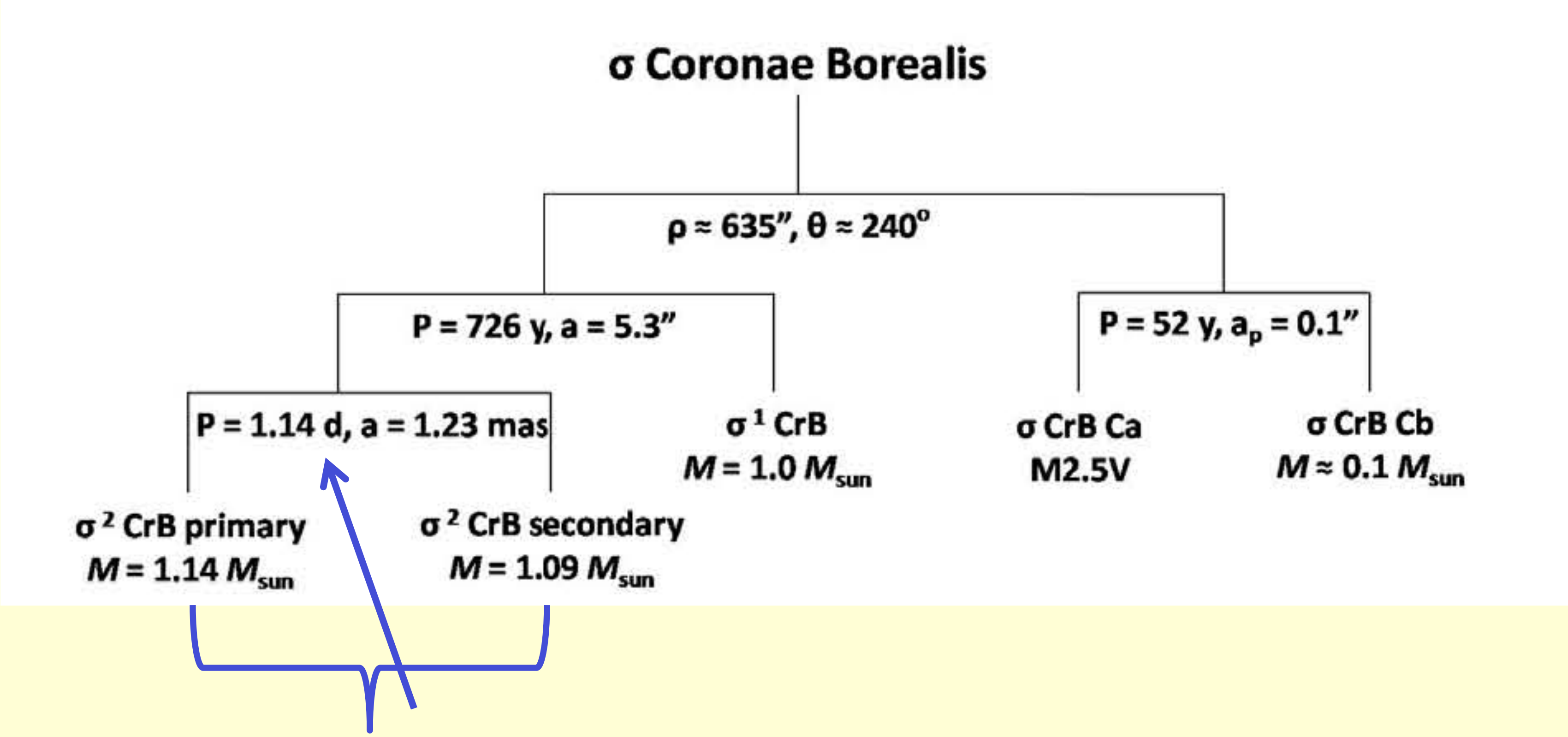
$$\cos \phi = \cos i_{\mathrm{Close}} \cos i_{\mathrm{Wide}} + \sin i_{\mathrm{Close}} \sin i_{\mathrm{Wide}} \cos (\Omega_{\mathrm{Wide}} - \Omega_{\mathrm{Close}})$$

$$= 33.5^{\circ} \pm 5.5^{\circ}$$



- This suggests a very energetic formation process within a highly oblate gas cloud.

Resolved Spectroscopic Binary



σ Coronae Borealis

$\rho \approx 635''$, $\theta \approx 240^{\circ}$

P = 726 y, a = 5.3″

P = 52 y, $a_p = 0.1''$

P = 1.14 d, a = 1.23 mas

σ^1 CrB
$M = 1.0\ M_{sun}$

σ CrB Ca
M2.5V

σ CrB Cb
$M \approx 0.1\ M_{sun}$

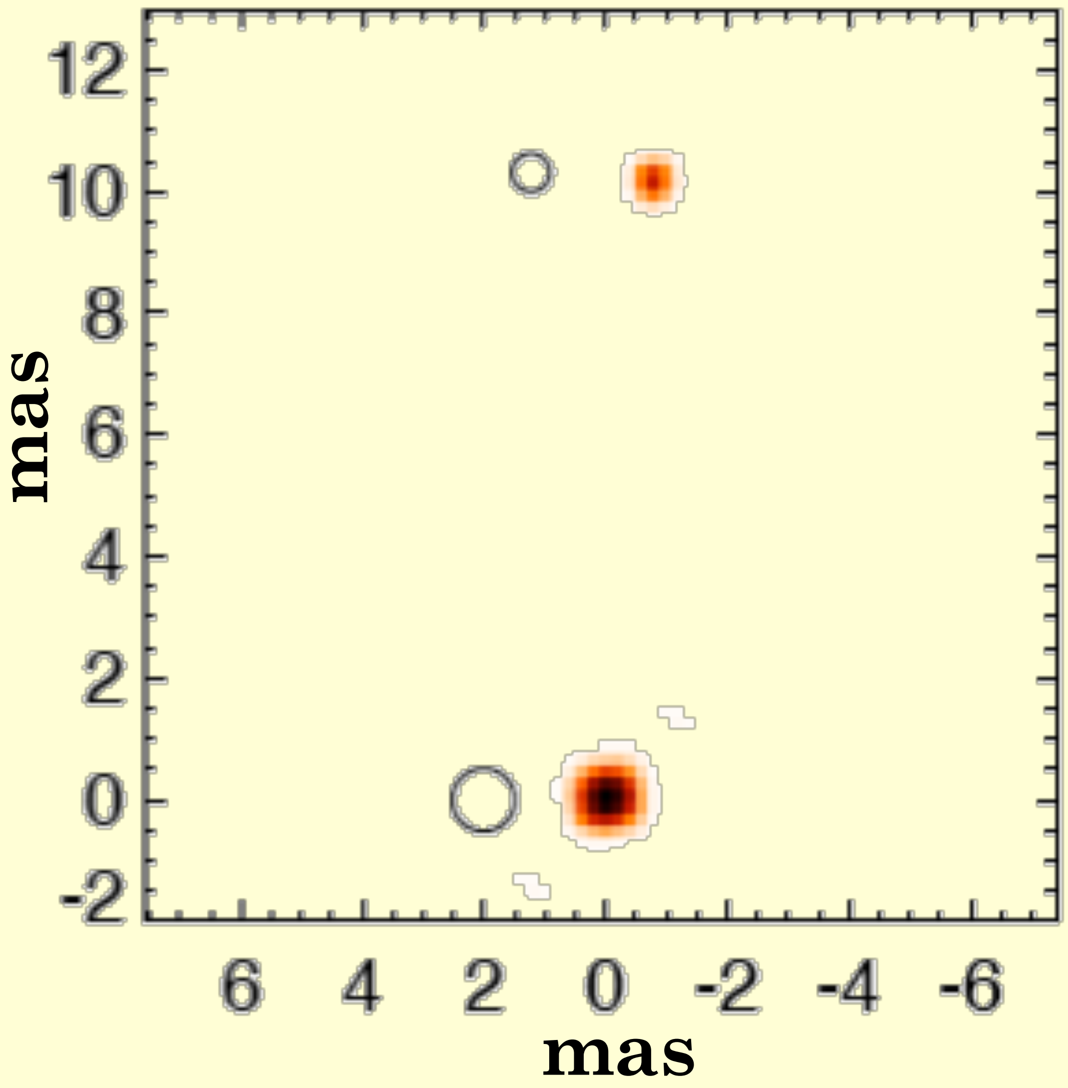
σ^2 CrB primary
$M = 1.14\ M_{sun}$

σ^2 CrB secondary
$M = 1.09\ M_{sun}$

Shortest-period binary
ever resolved

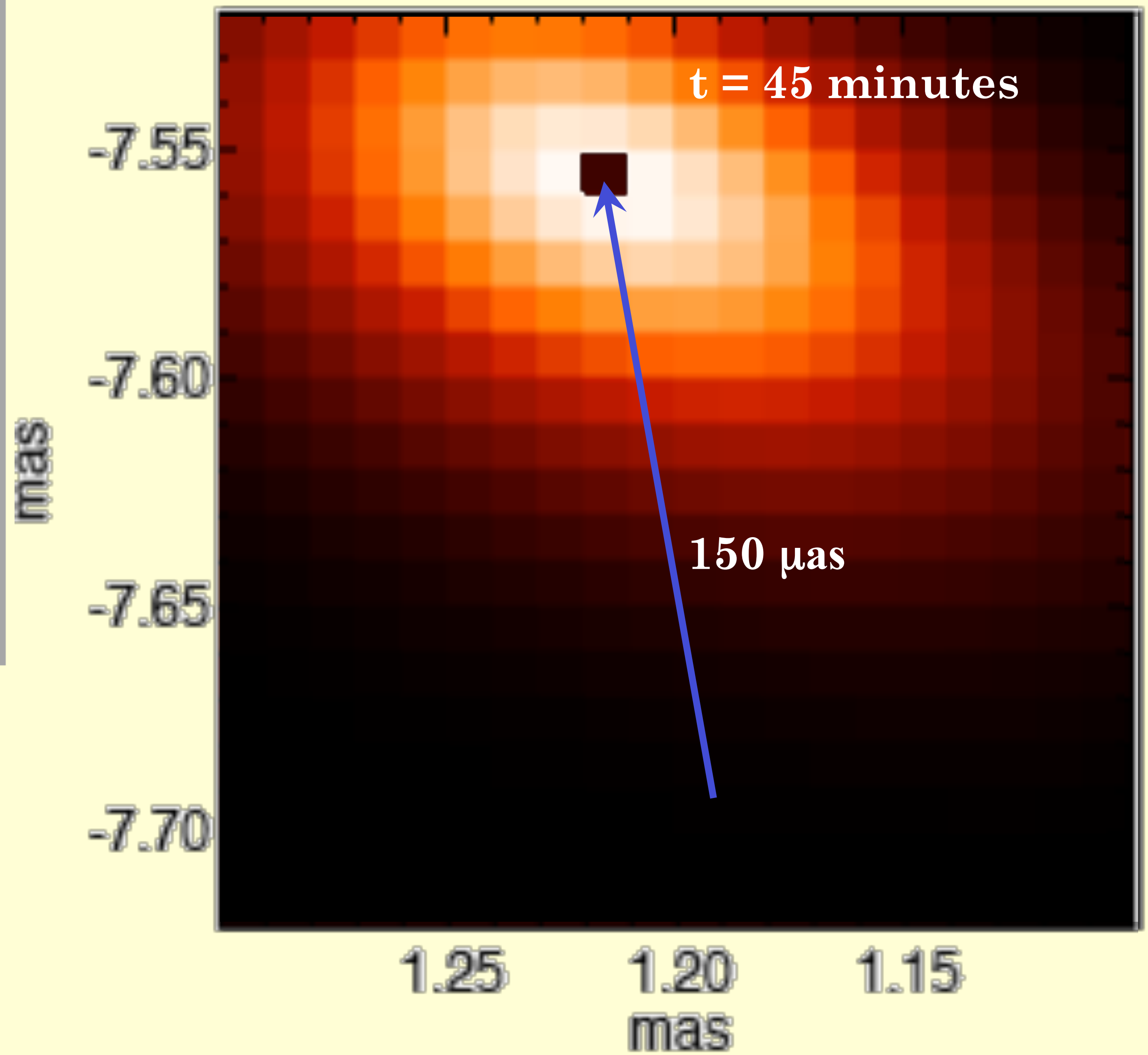
CHARA/MIRC Imaging Demonstration

10.2-day Spectroscopic Binary ι Peg



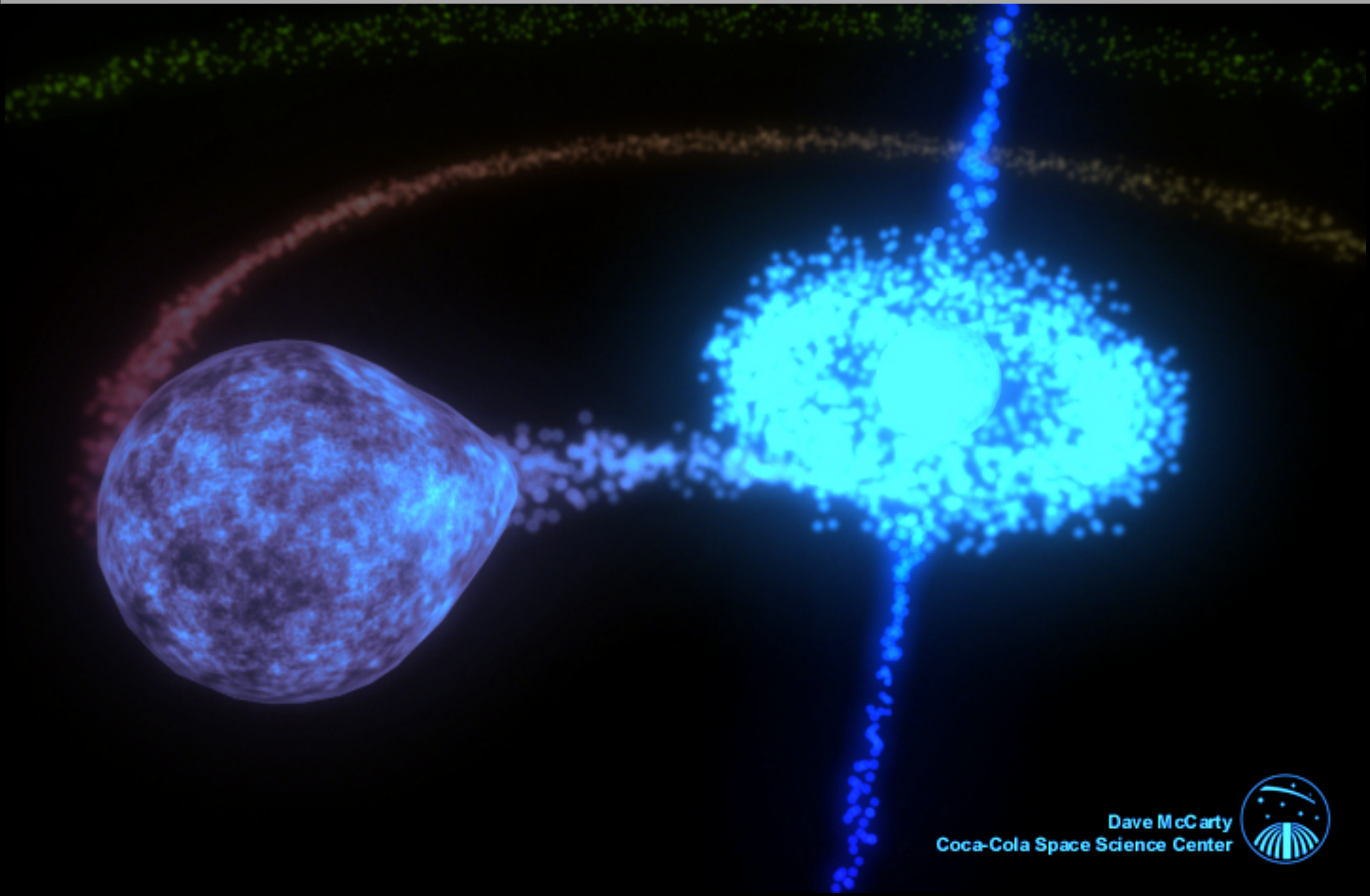
Predicted orientation and diameters are shown offset from the image of the binary star.

ι Peg Companion Motion Through 1° of Orbital Phase



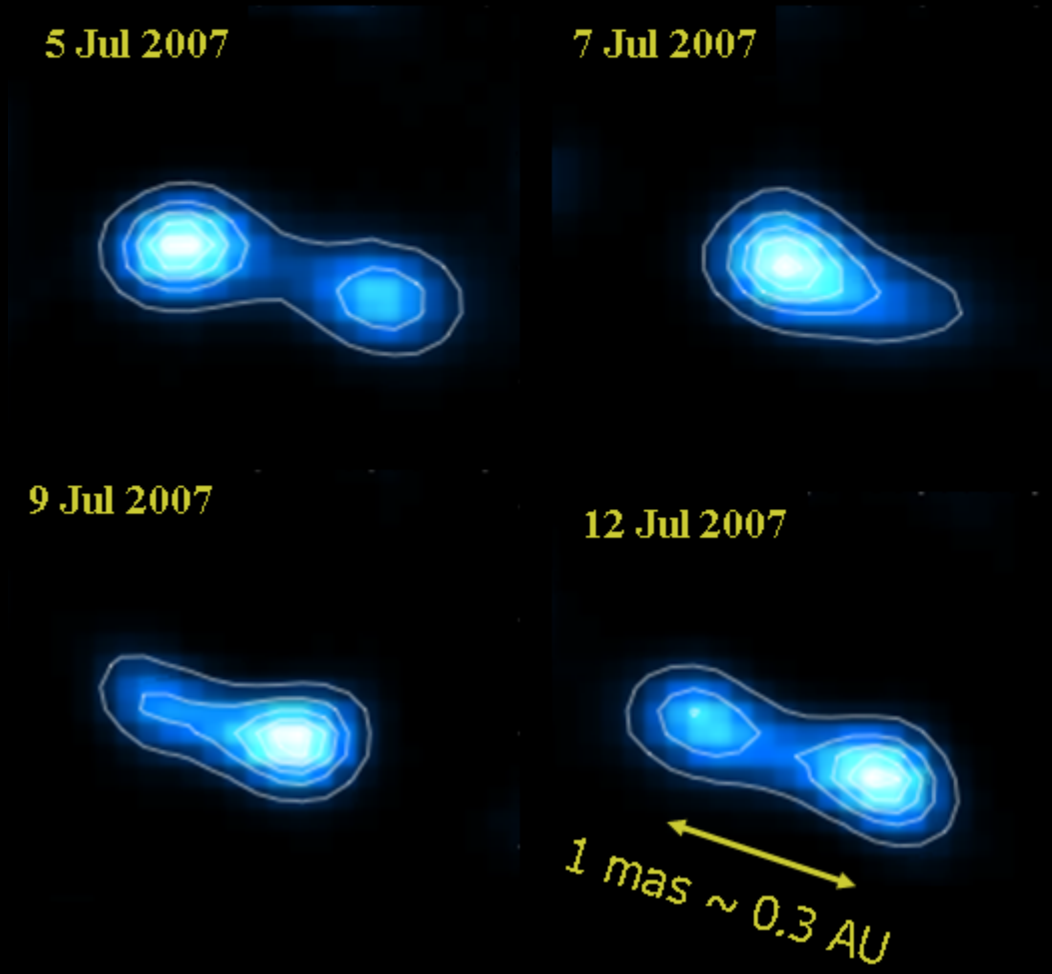
β Lyrae – B7 V + A8 V w/ P = 12.0 days

Prototype Mass Transfer Eclipsing/Spectroscopic Binary



Dave McCarty
Coca-Cola Space Science Center

β Lyrae – First Images Ever of an Eclipsing Binary

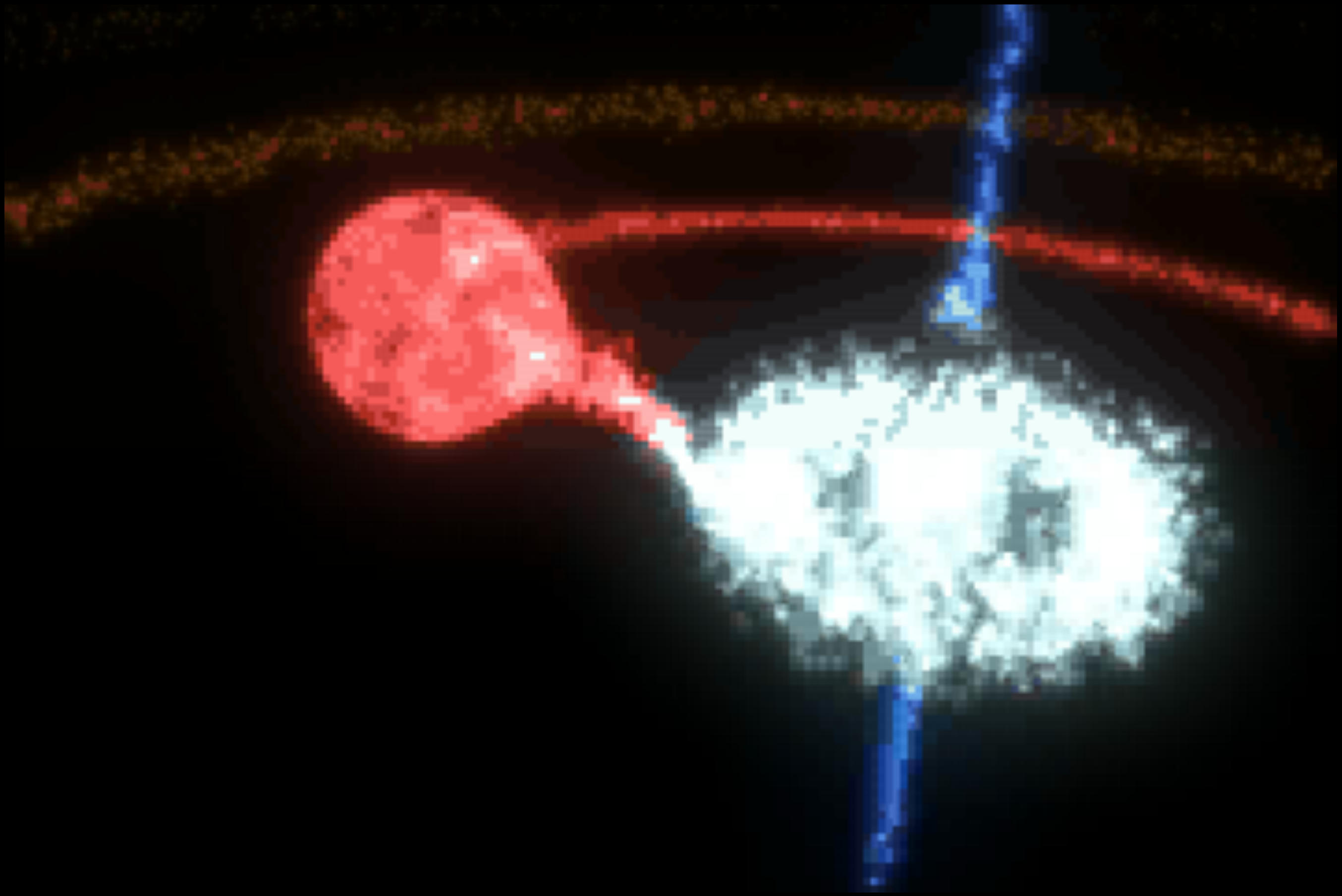


Four images are consistent with model and show hints of mass exchange.

Model of
Linnell *et al.*
1988

β Lyrae – A Simulation

Dave McCarty, Coca Cola Space Science Center



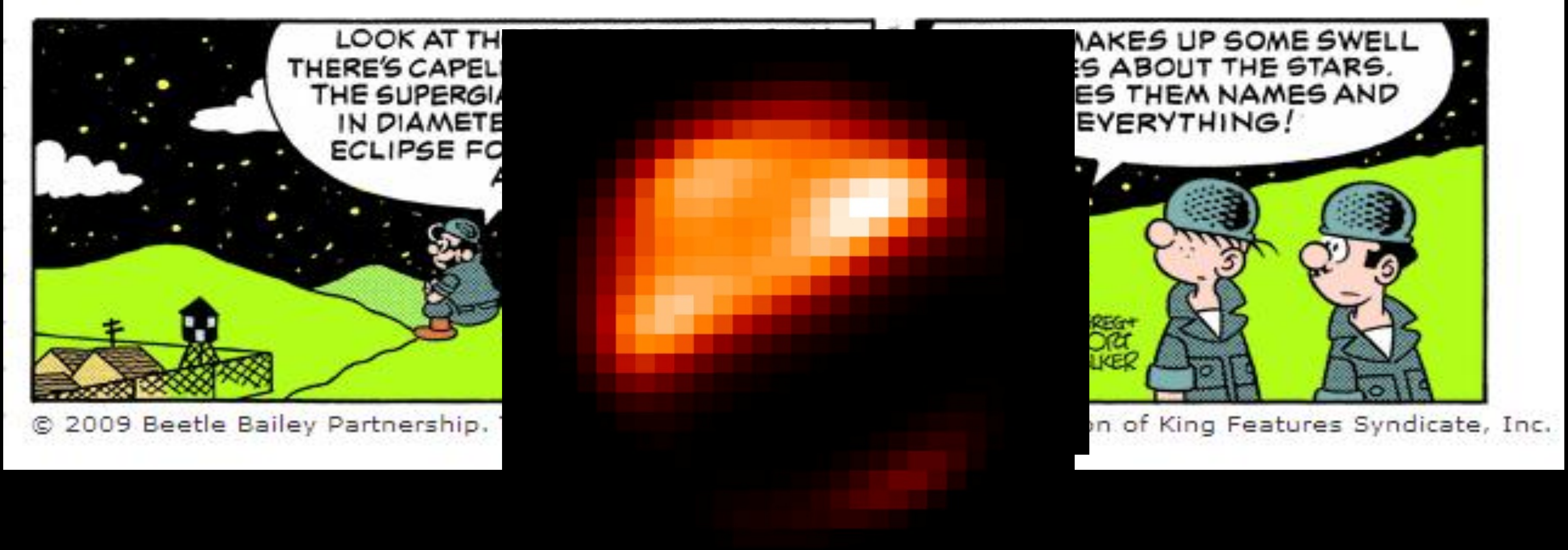
β Lyrae – The Movie!

From CHARA/MIRC Imagery

betlyr.mov

ε Aurigae – Imaging the Eclipse

New imagery appeared in Nature Letters, *April 8, 2010*



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