(Long-Baseline)
Interferometric Measurements of Binary Stars

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Outline

- Introduction:
  - Why study binary stars (with an interferometer)…
  - What kinds of binary star measurements are interesting
  - What kinds of binary stars are best suited to interferometry
- History of Interferometric Binary Star Measurements:
  - Classical imaging
  - Speckle
  - Long-baseline interferometry
- How Do Interferometers Measure Binary Stars
  - Visibility model
  - Interpretation
- Case Study: HD 195987
  - Why is the system interesting
  - Measurements & integrated orbit modeling
- What Next?
- Summary

Why Study Binary Stars?

Don't try to teach a pig to sing…it doesn't work, and it annoys the pig!

- Multiplicity (binary) is a pervasive phenomenon:
  - Multiplicity's role in the star formation process
    - Most stars likely form in multiple associations
  - Multiplicity's role in the field:
    - Two out of three solar-like stars have a stellar companion (DM91)
  - Multiplicity's role in stellar evolution:
    - The cornucopia of interacting binary stars
- Binary star interactions are SIMPLE, allowing insight into the properties of the components
  - Mass (through physical orbit)
  - Radius
  - Luminosity (through photometry, physical & angular orbit)

The Historical Lexicon of Binary Stars

- Eclipsing Binaries
  - Systems aligned so that components occlude each other (constrains inclination)
  - (By phase-space arguments) highly likely to be close => short-period
- Spectroscopic Binaries
  - Systems whose kinematics and component properties yield detectable component radial velocity variations
  - SB1 – single-lined binaries
  - SB2 – double-lined binaries
  - Most (essentially all) eclipsing binaries are spectroscopic binaries
    - Combination directly yields masses, radii, *less* directly luminosity
- Visual Binaries
  - Systems whose components can be resolved into two distinct sources…
    - …Allowing astrometry
    - Motion in time yields orientation of orbit (inclination)
    - Combined with SB2 => masses, distance (luminosity)

What Kinds of Binary *Information* is Interesting?

- Multiplicity statistics
- Orbit characteristics statistics

  as remnants of the formation process
- Component properties
  - Mass, Radius, Luminosity (the “big” three)
  - Elemental Abundance

    critical to place M, R, L in proper context
  - Rotation

    as tracer of tidal interaction & internal convective structure
- Distance (“orbital parallax”)

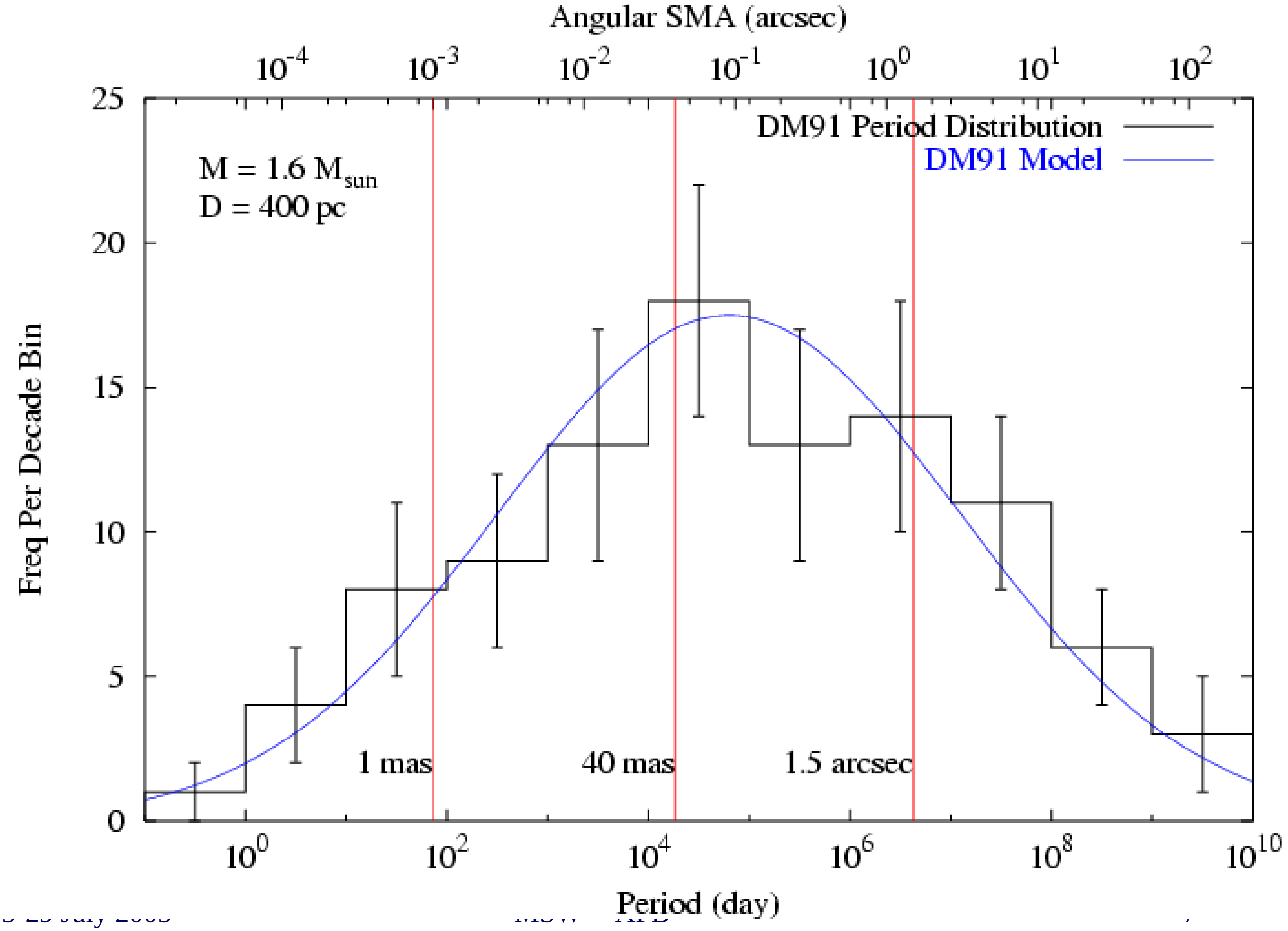
  for direct & indirect luminosity calibration
- Age

  using binary systems as chronometers

What Kinds of Binary *Measurements* are Interesting?

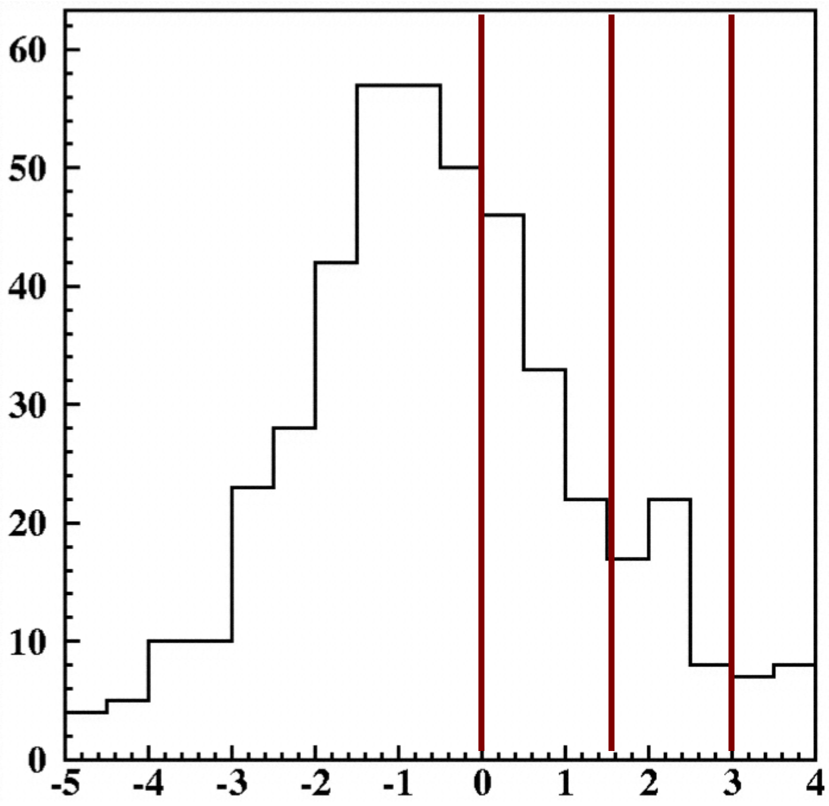
- Photometry
  - System and/or component brightness → luminosity
  - Detection and measurements of binary eclipses
  - Tracer of stellar rotation period
- "Imaging" (i.e. real imaging, speckle, interferometery)
  - Inference of association
  - Astrometry
    - "Absolute" (relative to some "quasi-inertial" fiducials)
    - "Relative" (two components relative to each other)
- Spectroscopy
  - Astrophysics of components
  - "Velocimetry" – gauging the line-of-sight motions of components

What Binaries are Suitable for

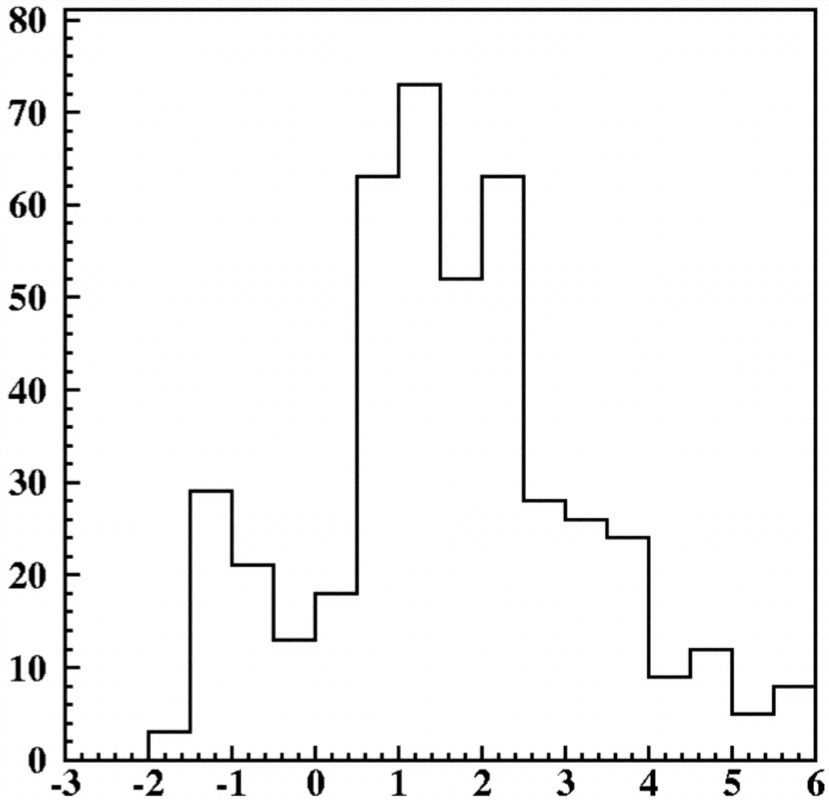


Known Spectroscopic Binary Distributions

From Taylor, Harvin, and McAlister 2003



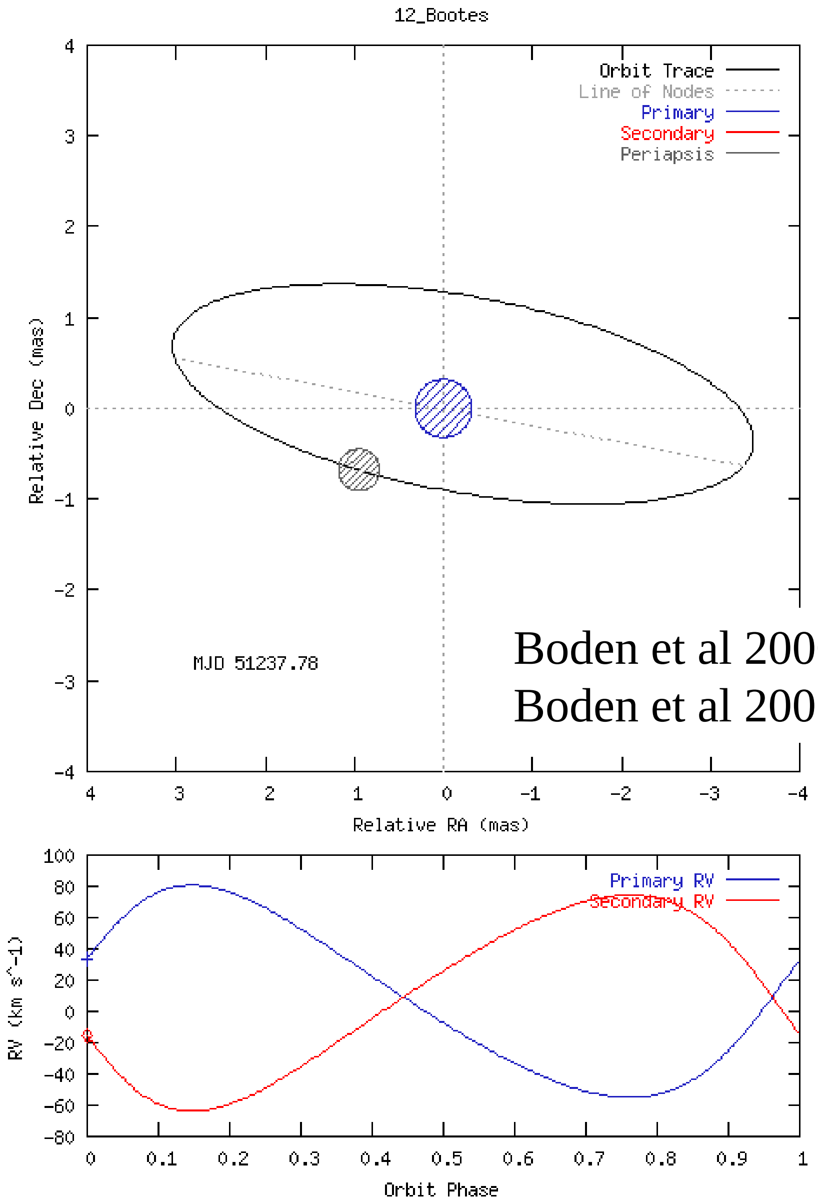
Log Greater Nodal Sep (mas)



Log Period (d)

“The Deal” with Binary Star Studies

- In (essentially) all cases, observational objective is to determine “physical orbit” (physical dimensions, orientation), this provides component masses
- Eclipsing systems provide that with spectroscopy (“spectroscopic orbit”) & photometry (inclination)
- Non-eclipsing systems require integrating the “visual orbit” to determine system orientation
- Ratio of physical and angular scales (e.g. semi-major axis) yields direct system distance (duh)



Boden et al 2000
Boden et al 2005

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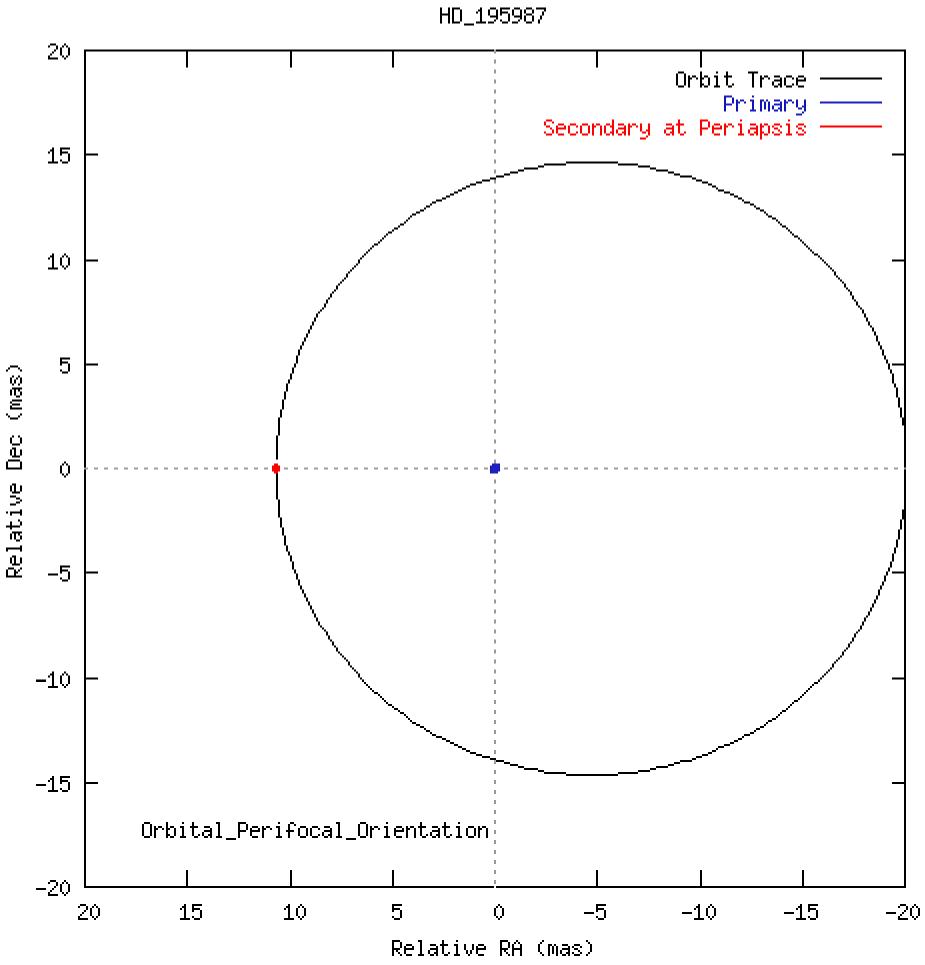
- Why?

Describing Binary Systems

- (By definition) binary systems have *Primary* (A) and *Secondary* (B) components
- We describe binary kinematics with *orbital elements*
  - Four elements (a, e, P, T_0) describe motion in the orbital plane
  - Three elements (Euler angles, i, Ω, ω) define orbital plane orientation
  - Three elements (K_A, K_B, γ) describe rates projected onto the line-of-sight
- Additional parameters may describe component properties
  - Diameters (θ_A, θ_B)
  - Intensity ratio ($r = B / A$)



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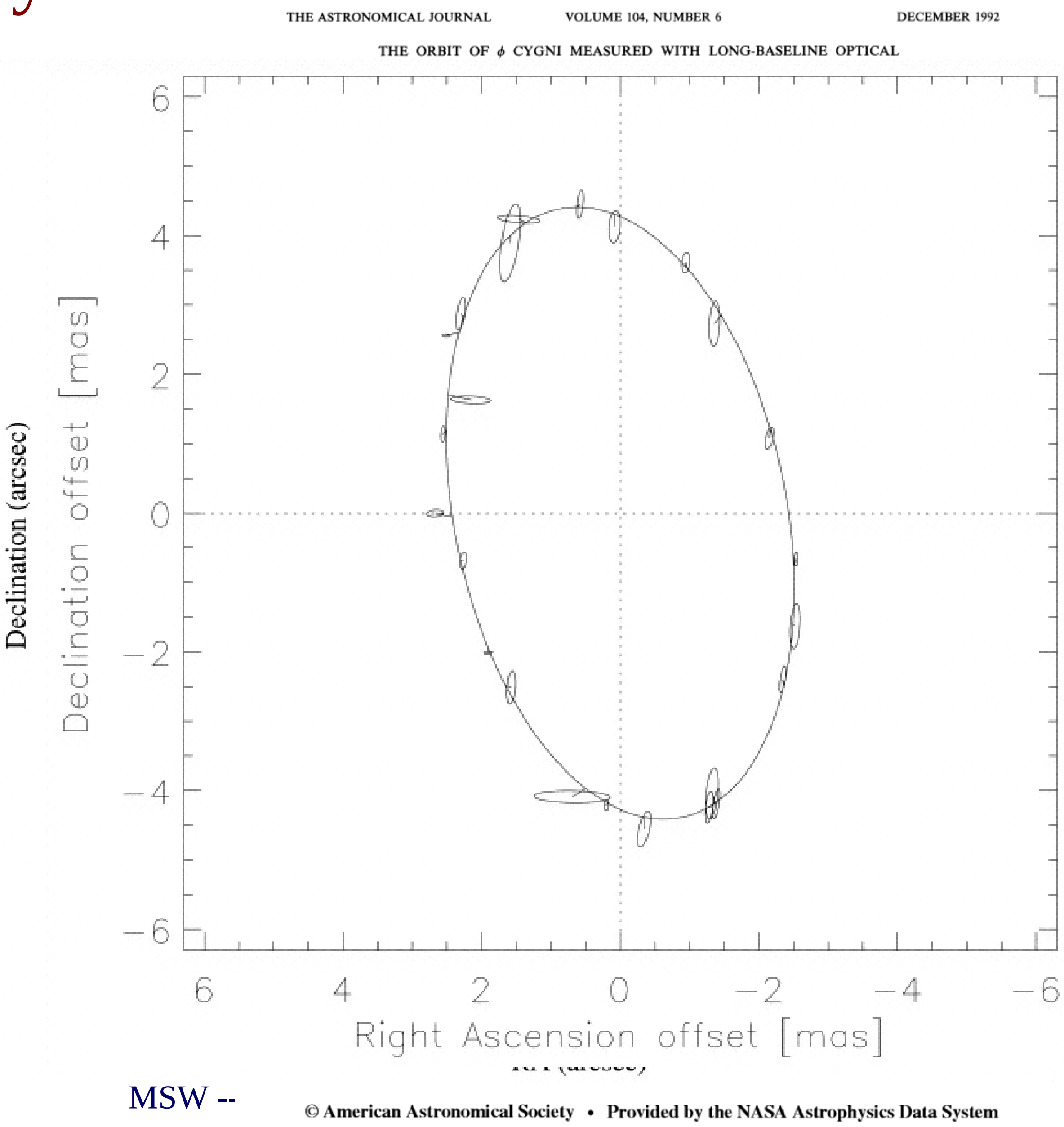
Historical Binary Studi
Interferometers

- Classical imaging/
- Speckle
- Long-baseline inte
  - Capella with Mt W
  - α Vir with intensit
  - Mark III
  - HST FGS
  - NPOI
  - PTI
  - SUSI
  - KI
  - CHARA



THE ASTRONOMICAL JOURNAL VOLUME 104, NUMBER 6 DECEMBER 1992

THE ORBIT OF ϕ CYGNI MEASURED WITH LONG-BASELINE OPTICAL

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What Does Interferometric Binary Data Look Like: A "Typical" Night of PTI V^2 Data...

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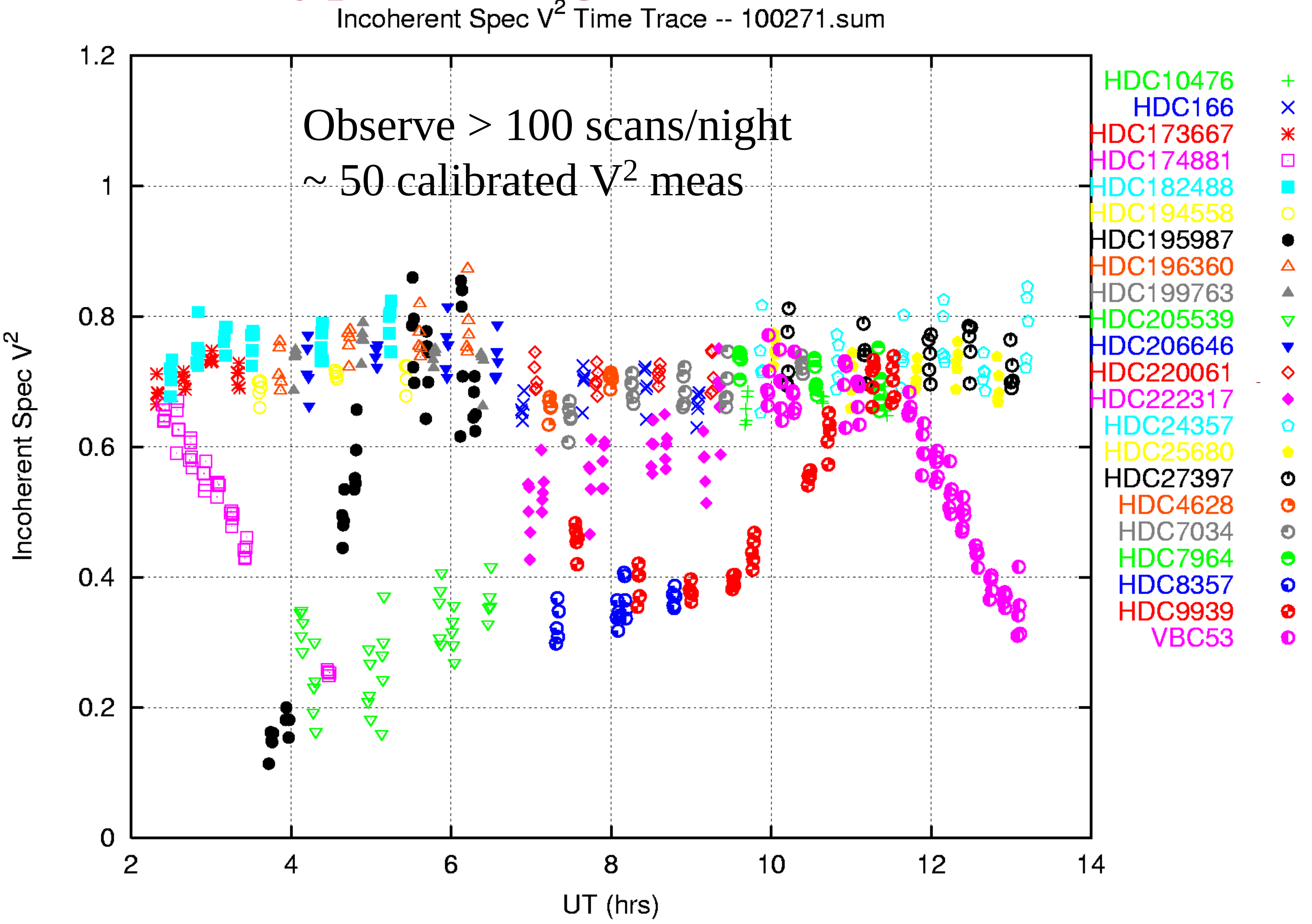


Observe > 100 scans/night

~ 50 calibrated V^2 meas

Long-Baseline Interferometry Observables

- (L-B) Interferometers provide visual (i.e. astrometric) information on binary stars
- Interferometric visibility as proxy for relative component astrometry

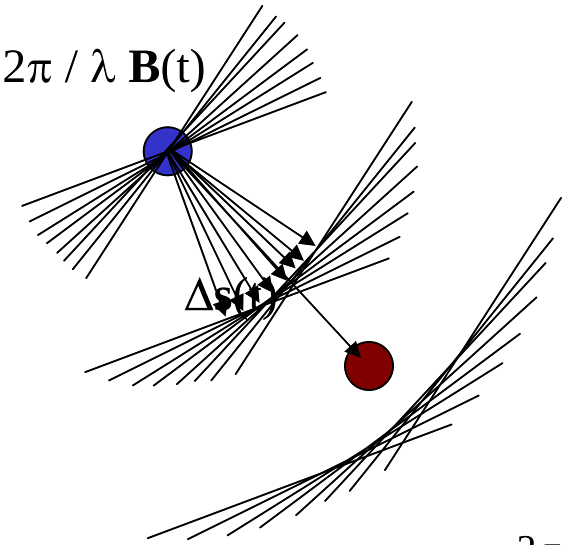
$$V_{binary} = \frac{P_A V_A + P_B V_B}{P_A + P_B} = e^{-2\pi i(u\alpha_1 + v\beta_1)} \frac{|V_A| + r|V_B| e^{-2\pi i(u\Delta\alpha + v\Delta\beta)}}{1+r}$$

$$V_{binary}^2 = V_{binary}^* V_{binary} = \frac{|V_A|^2 + r^2|V_B|^2 + 2r|V_A||V_B|\cos(2\pi(u\Delta\alpha + v\Delta\beta))}{(1+r)^2}$$

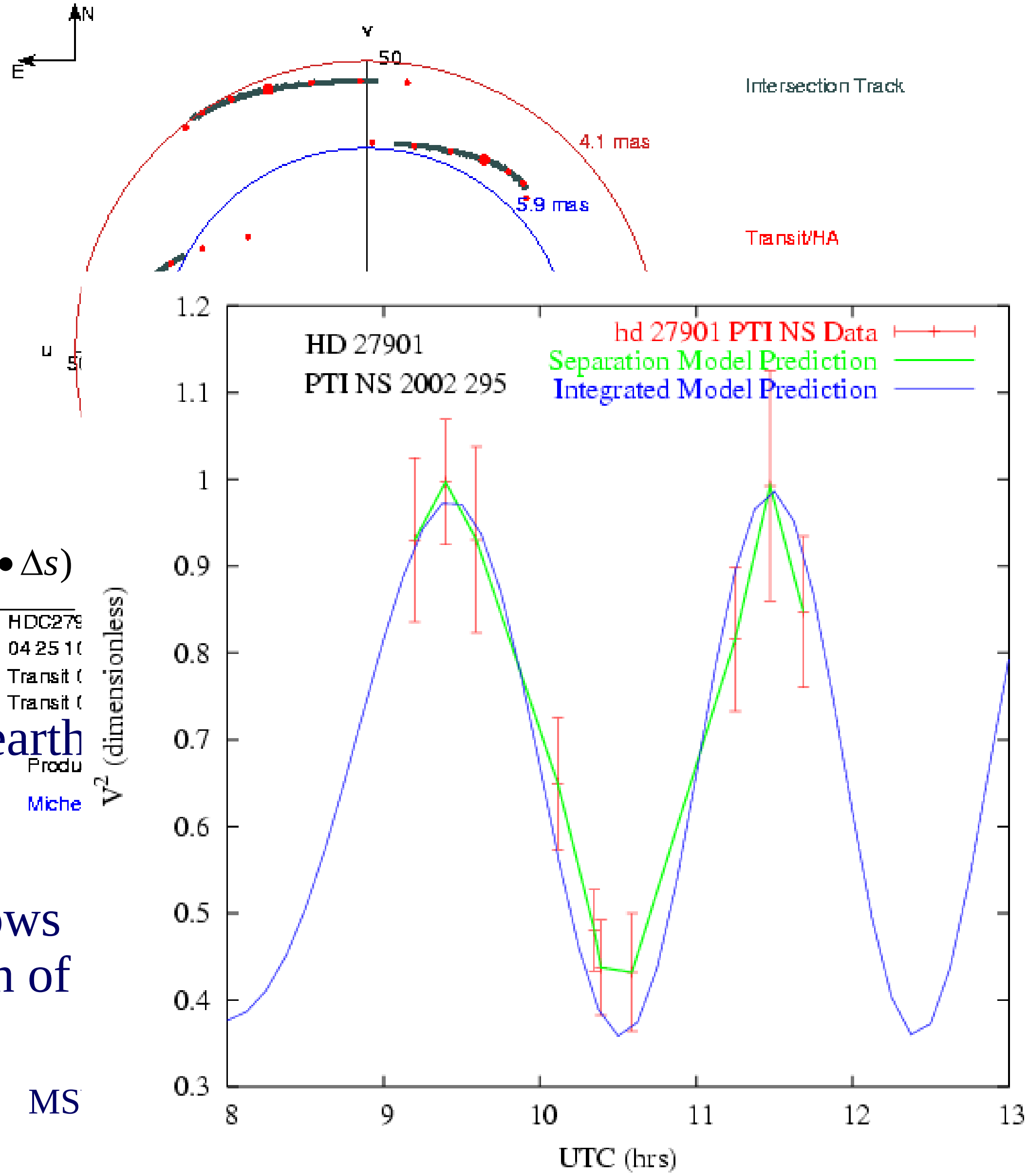
$$= \frac{|V_A|^2 + r^2|V_B|^2 + 2r|V_A||V_B|\cos(\frac{2\pi}{\lambda} B \bullet \Delta s)}{(1+r)^2}$$

Δs – relative separation r – relative intensity ***B*** – baseline

Separation Vector Modeling



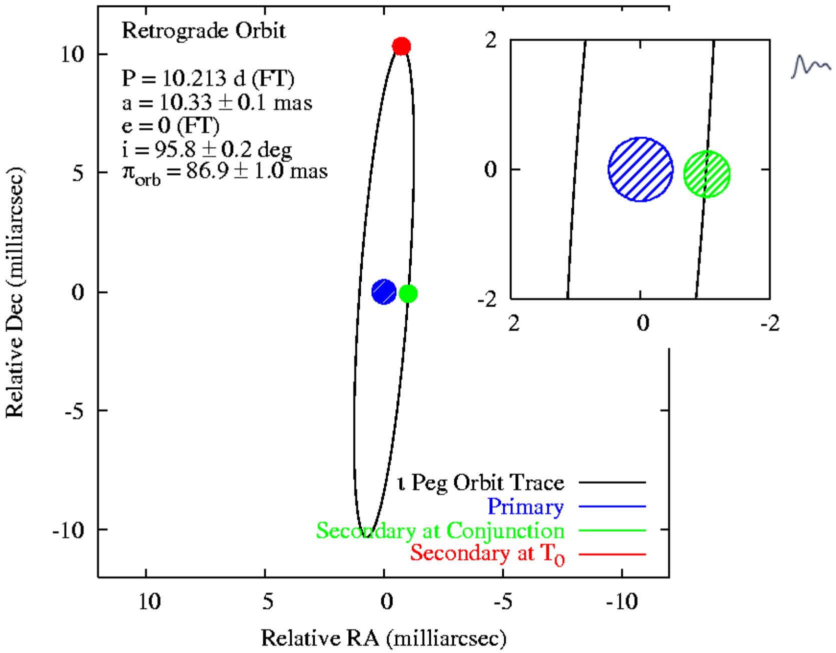
$$V_{binary}^{2} = \frac{|V_A|^2 + r^2|V_B|^2 + 2r|V_A||V_B|\cos(\frac{2\pi}{\lambda} B \bullet \Delta s)}{(1+r)^2}$$

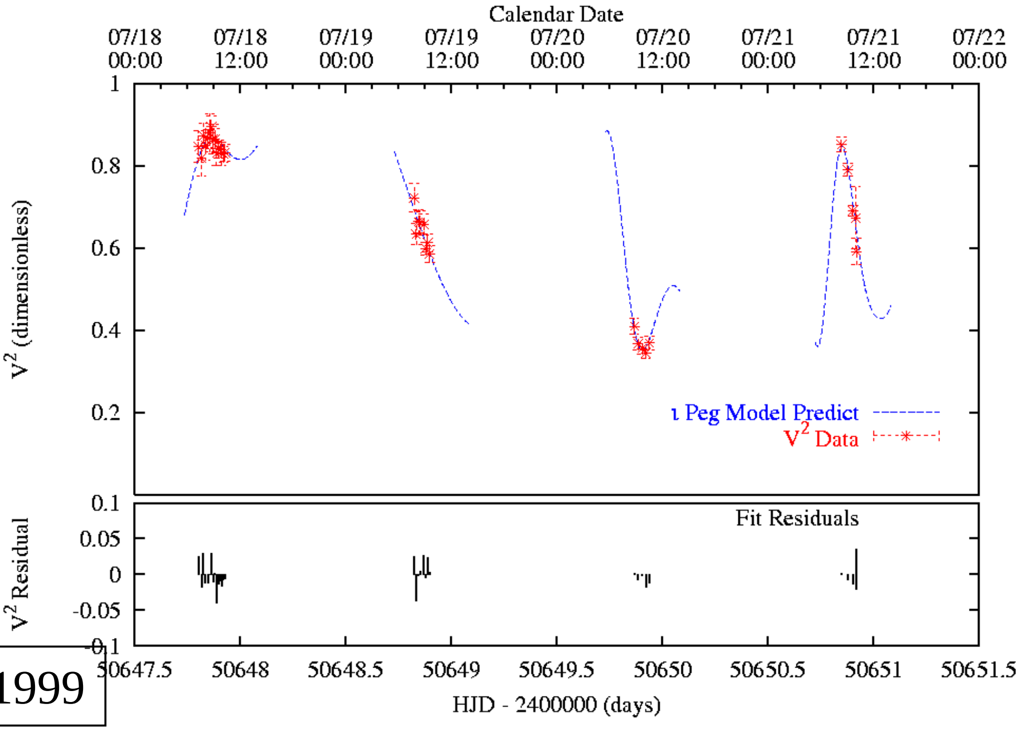


- Projected baseline motion (earth rotation) varies relative geometry
- This geometry variation allows (straightforward!) estimation of binary separation

Integrated Modeling I

- Separation vector modeling works in many cases, but breaks down when:
  - System is marginally resolved, providing little visibility evolution on a given night
  - Few data points are available on given night
  - System moves appreciably during night
- Solution: integrated modeling – estimating orbit directly from visibilities (just like RV Orbit modeling)
- This is what (essentially) everyone in the business does



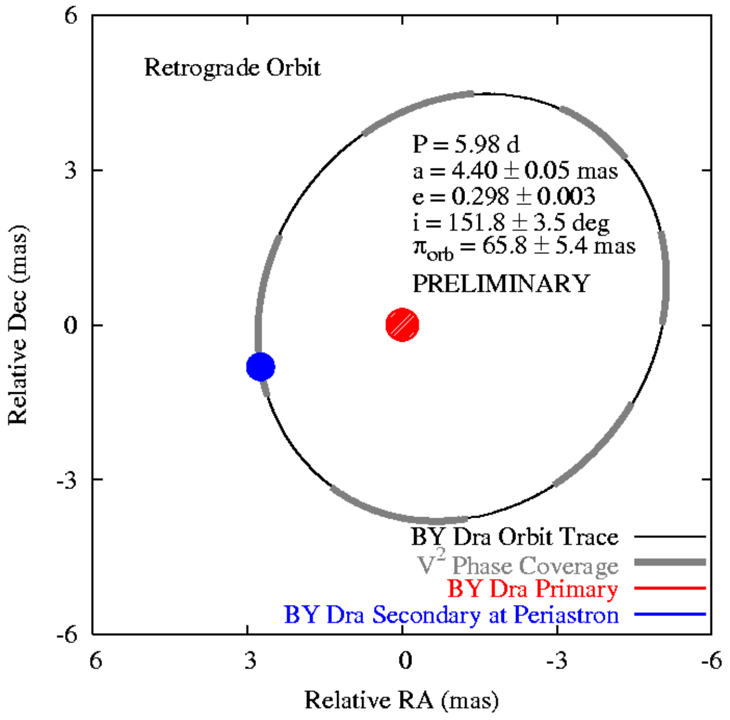


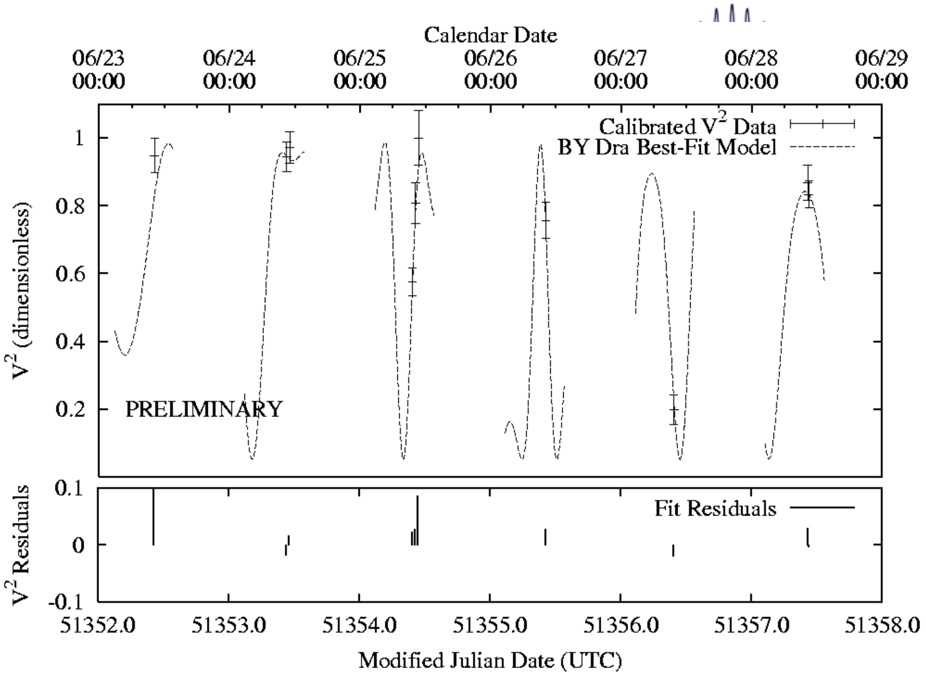
Boden et al 1999

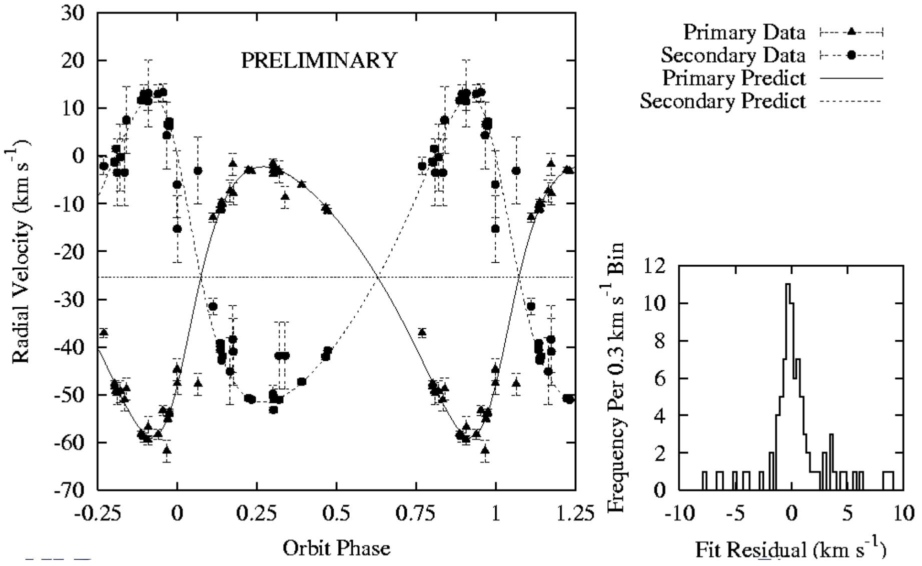
Integrated Modeling II

- While you're at it, you might as well also directly integrate with RV measurements

Boden & Lane 2000







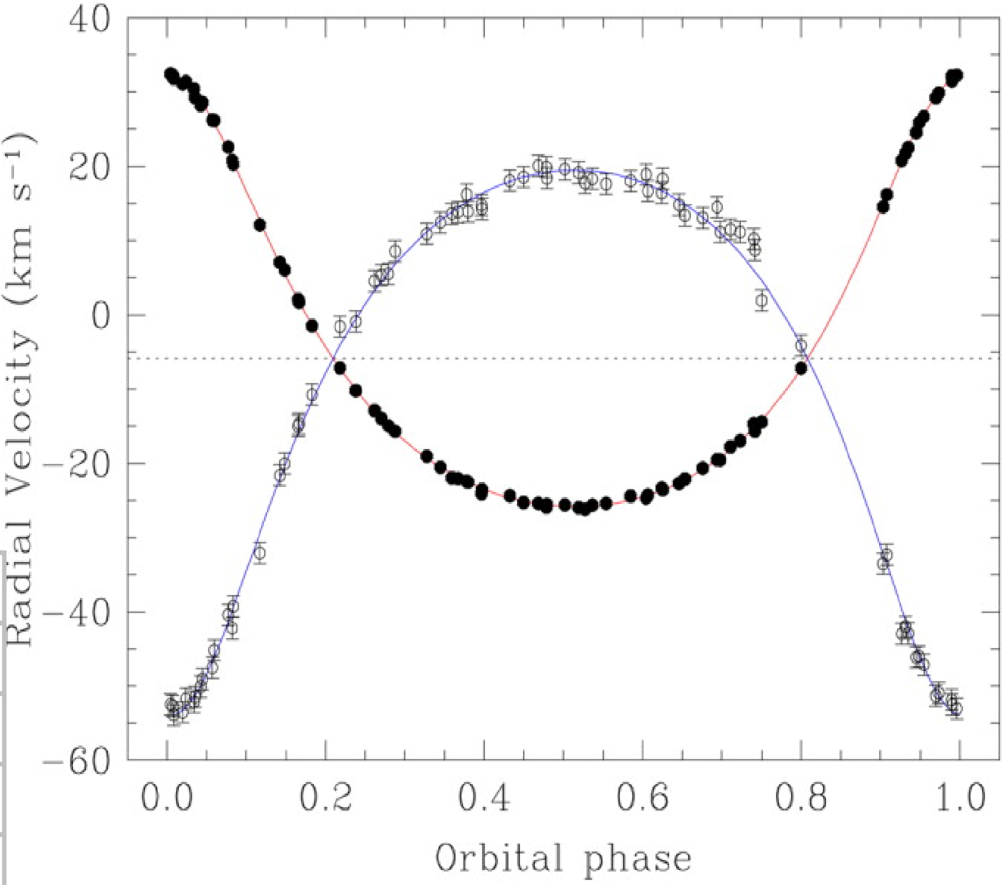
Case Study: HD 195987

- HD 195987 is a modestly low-metallicity ([Fe/H] ~ -0.5) double-lined spectroscopic binary (SB2)
- (Essentially) no eclipsing system constraints for metal-poor stellar models
- RV Orbit determine as part of Carney-Latham high-proper-motion survey
- Long-term velocity monitoring CfA
- Visibility orbit from PTI circa 1999
- Integrated orbit solution (Torres et al 2002)
- First (precision) O/IR interferometric solution for “metallicly-challenged” system

HD 195987 RV Orbit

- Modest eccentricity (*e*~0.3) double-lined orbit
- 0.1 contrast ratio in the visible – TODCOR extraction of RV lines
- 73 double-lined measurements

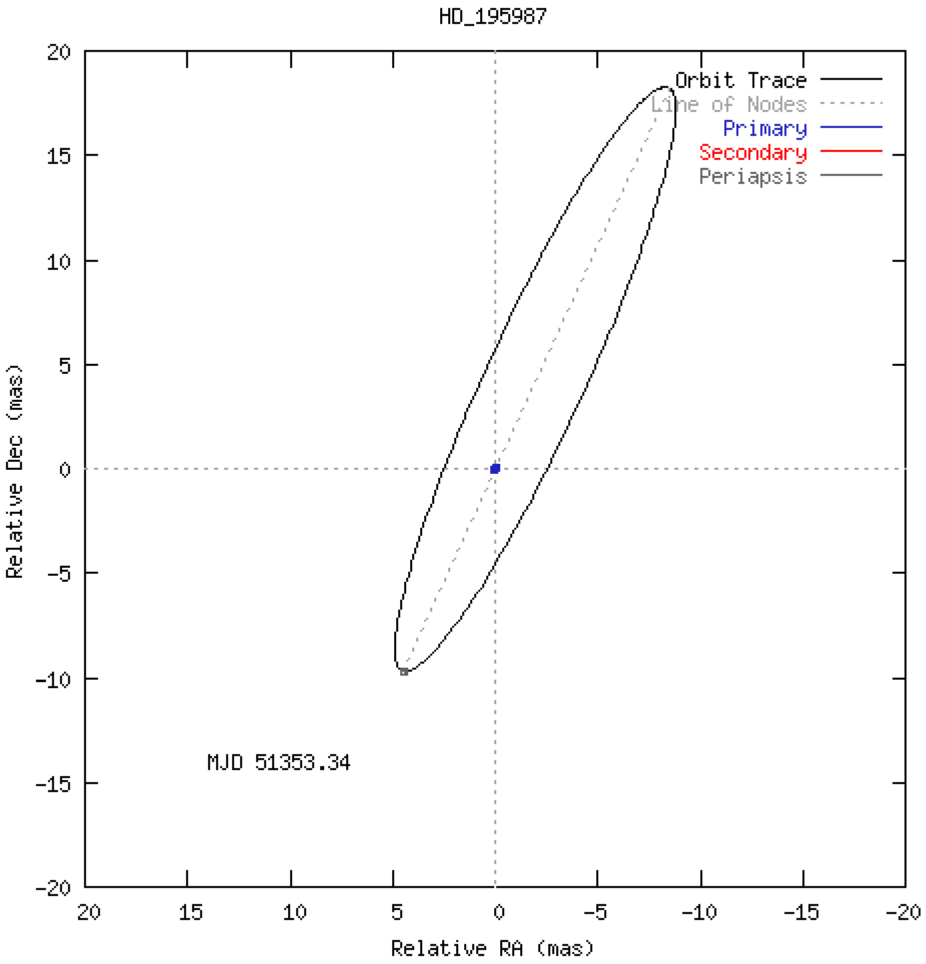
T0 (d)	49404.825 ± 0.045
e	0.3103 ± 0.0018
γ	-5.867 ± 0.038
KA	28.944 ± 0.046
KB	36.73 ± 0.21
ω	357.03 ± 0.35

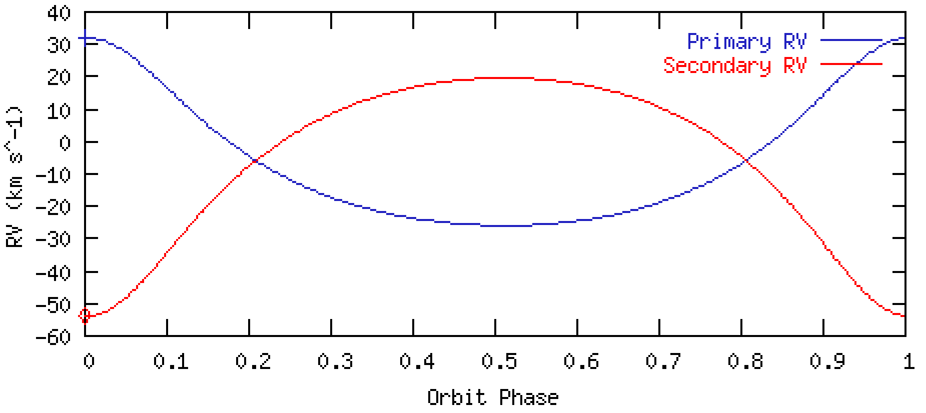


HD 195987 Physical Orbit

- Simultaneous solution to both RV and PTI visibility data
- Complementary information about "mutual" elements (P, T_0, *e*, ω)

P	57.32178 ± 0.00029
T0	51353.813 ± 0.038
γ	-5.841 ± 0.037
KA	28.929 ± 0.046
KB	36.72 ± 0.21
a	15.378 ± 0.027
e	0.30626 ± 0.00057
i	99.364 ± 0.080
Ω	334.960 ± 0.070
ω	357.40 ± 0.29





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HD 195987 System Parameters

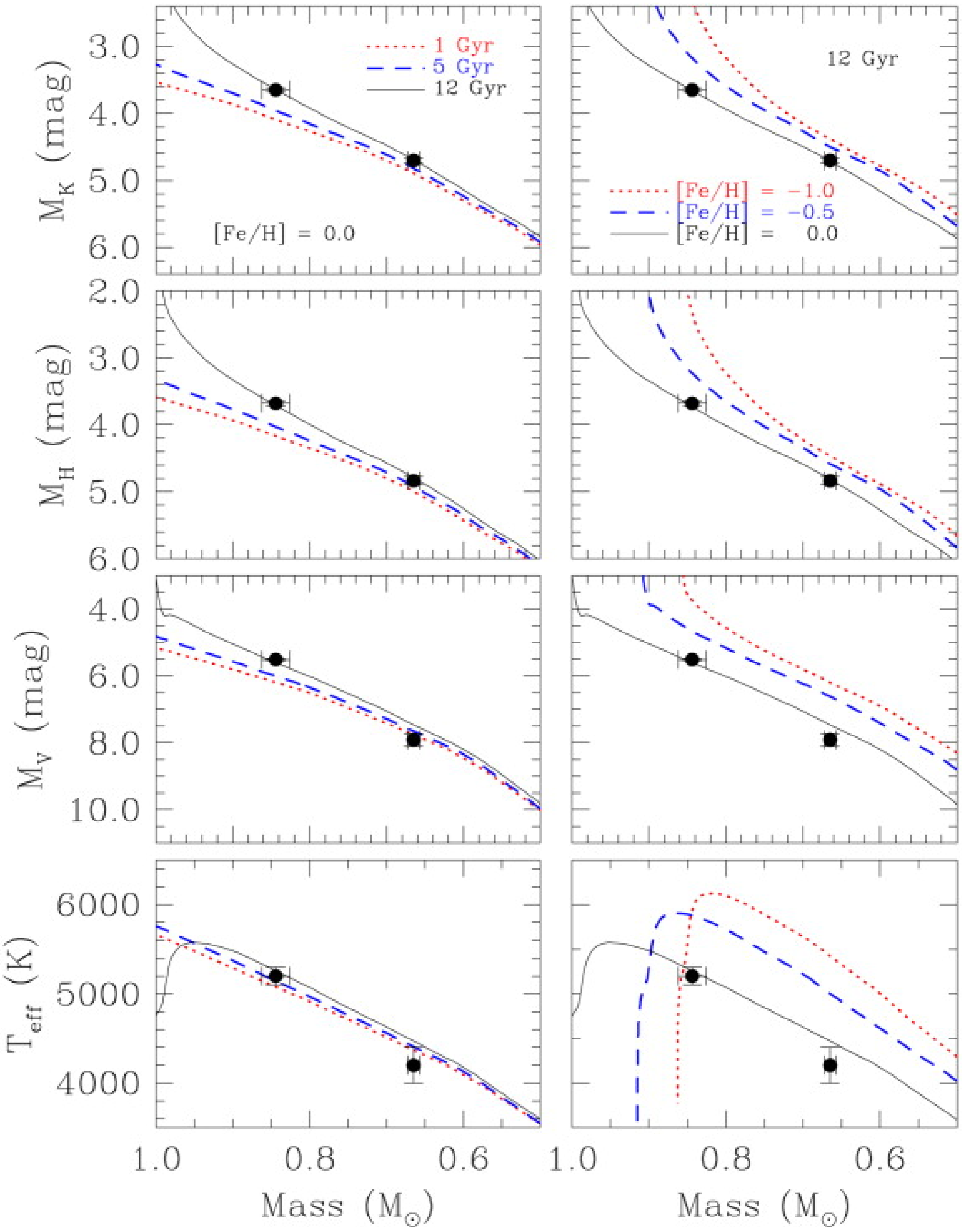
2% Primary Mass,
1% Secondary Mass

Parameter	Primary	Secondary
Mass (M)..	0.844 ± 0.018	0.6650 ± 0.0079
Teff (K)...	5200 ± 100	4200 ± 200
oPlx (mas)	46.08 ± 0.27	
Dist (pc)...	21.70 ± 0.13	
MV (mag).	5.511 ± 0.028	7.91 ± 0.19
MH (mag)	3.679 ± 0.037	4.835 ± 0.059
MK (mag)	3.646 ± 0.033	4.702 ± 0.034
V-K (mag)	1.865 ± 0.039	3.21 ± 0.19

Factor of two
better than Hipparcos

HD 195987 Stellar Model Comparisons

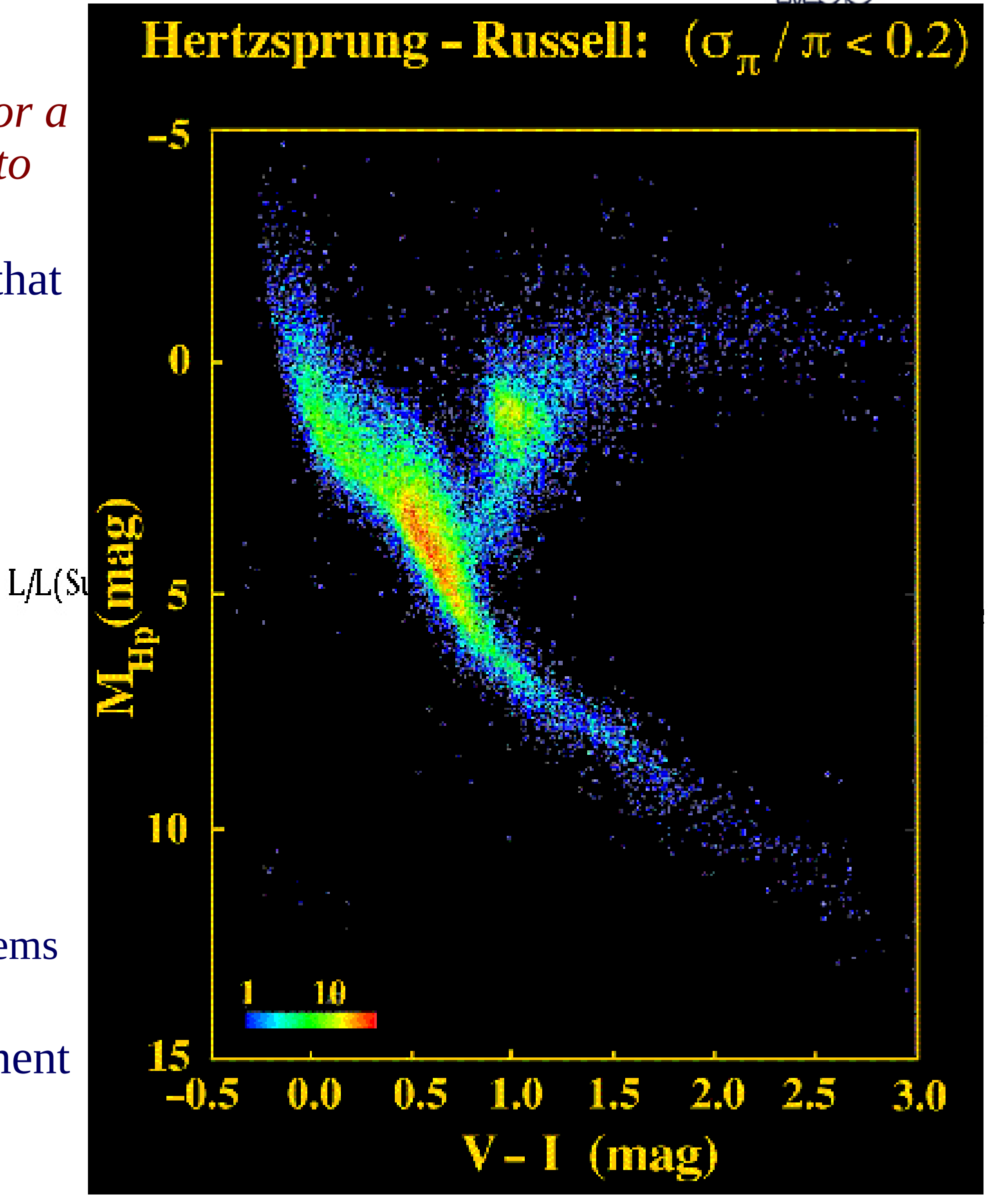
- Having determined *precision* component parameters, it's time to test stellar models!
- No single set of models do a perfect job of predicting HD195987 component parameters
- This is how an observationalist defines progress…



What Now?

We've been doing this binary thing for a while, what is there possibly left to do?

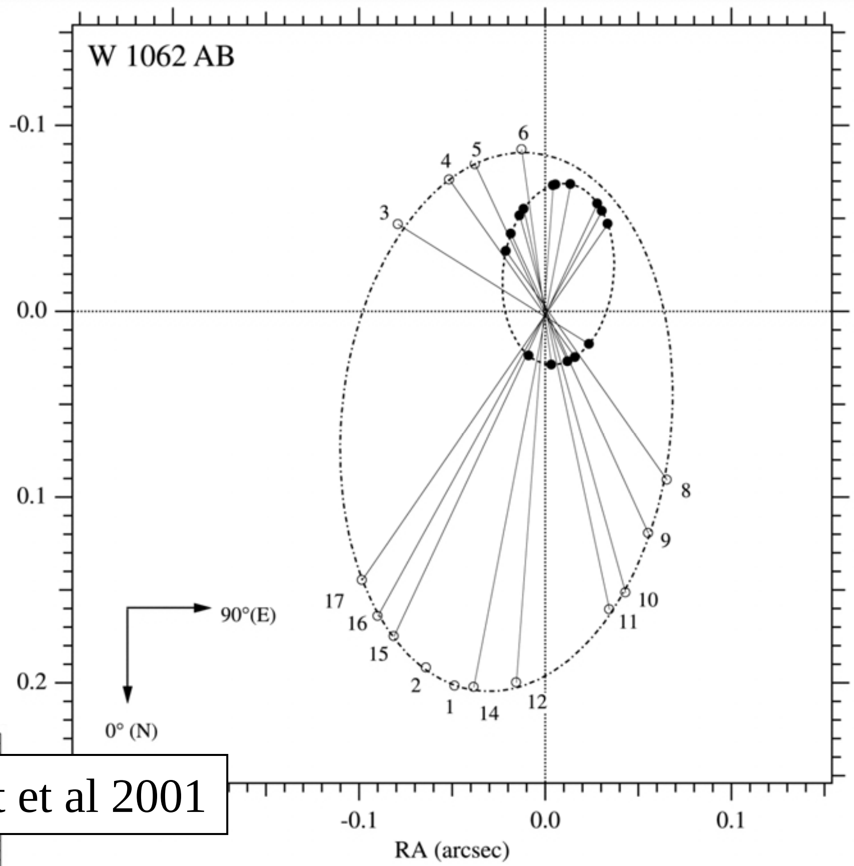
- Component parameters for stars that are not well covered by eclipsing systems
    - Low-mass stars
    - Subgiant & Giant stars
    - Pre-main sequence stars
    - Metal-poor & metal-rich stars
- Systems where there's "extra" physics
    - Tidal interaction & angular momentum evolution
    - Interacting systems
    - Higher-order (hierarchical) systems
- Systems where there is science beyond/in addition to the component properties
    - e.g. Cluster distances and ages



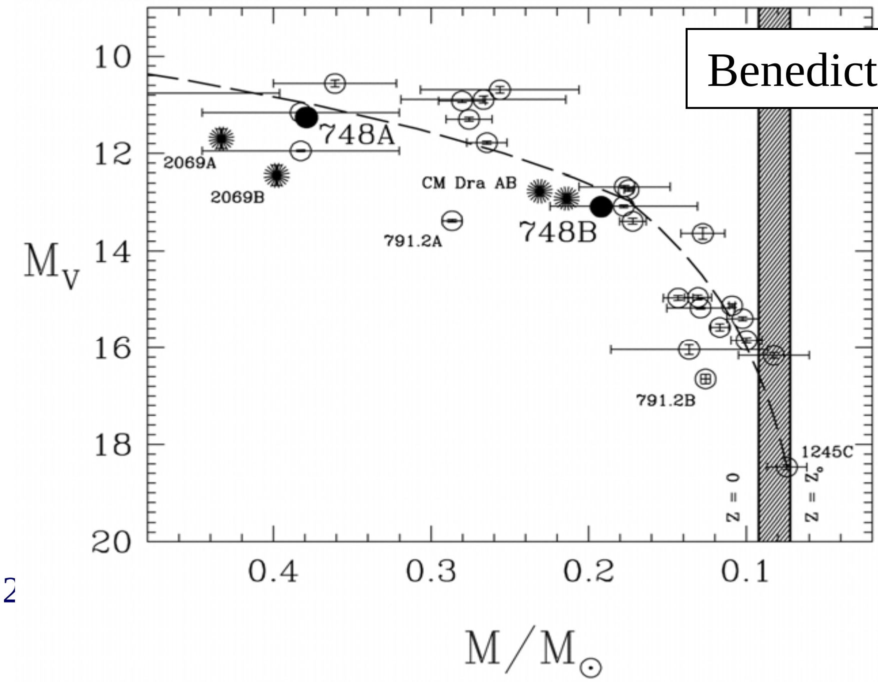
Credit: Hipparcos Web Site

Low-Mass Stars

- Nature is inordinately fond of M-stars, yet few high-precision mass/luminosity determinations made among such stars
- System are difficult primarily because they are dim & elemental abundances hard to measure



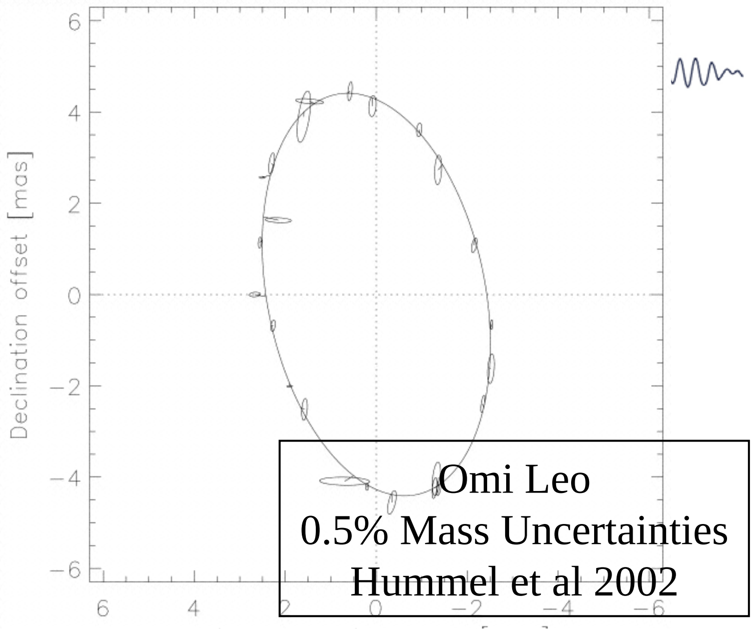
Benedict et al 2001



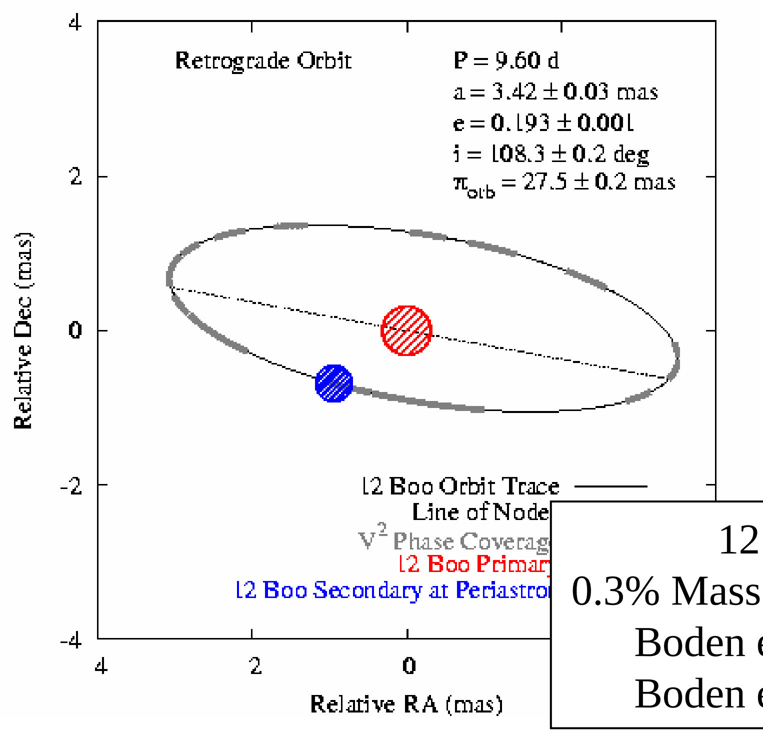
- The sensitivity of HST FGS make such low-mass systems the (nearly) unique purview of FGS
- With an HST servicing mission appearing more likely, prospects for additional work in this area appear good

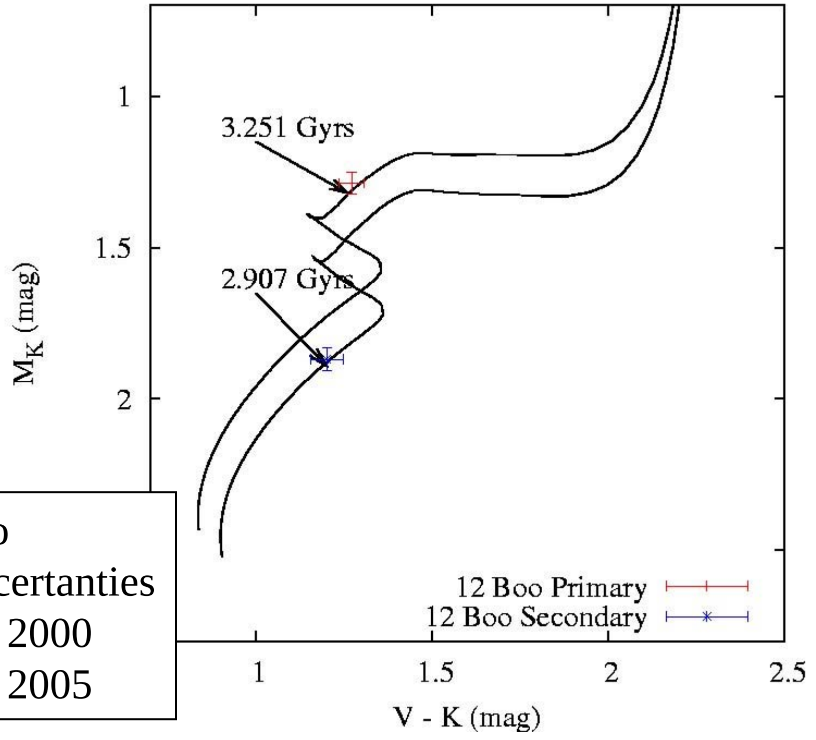
Evolved Stars

- Surprisingly few high-precision tests exist of stars off the main sequence…
    - 12 Boo
    - Omi Leo
- But some more are on the way…



Omi Leo
0.5% Mass Uncertainties
Hummel et al 2002

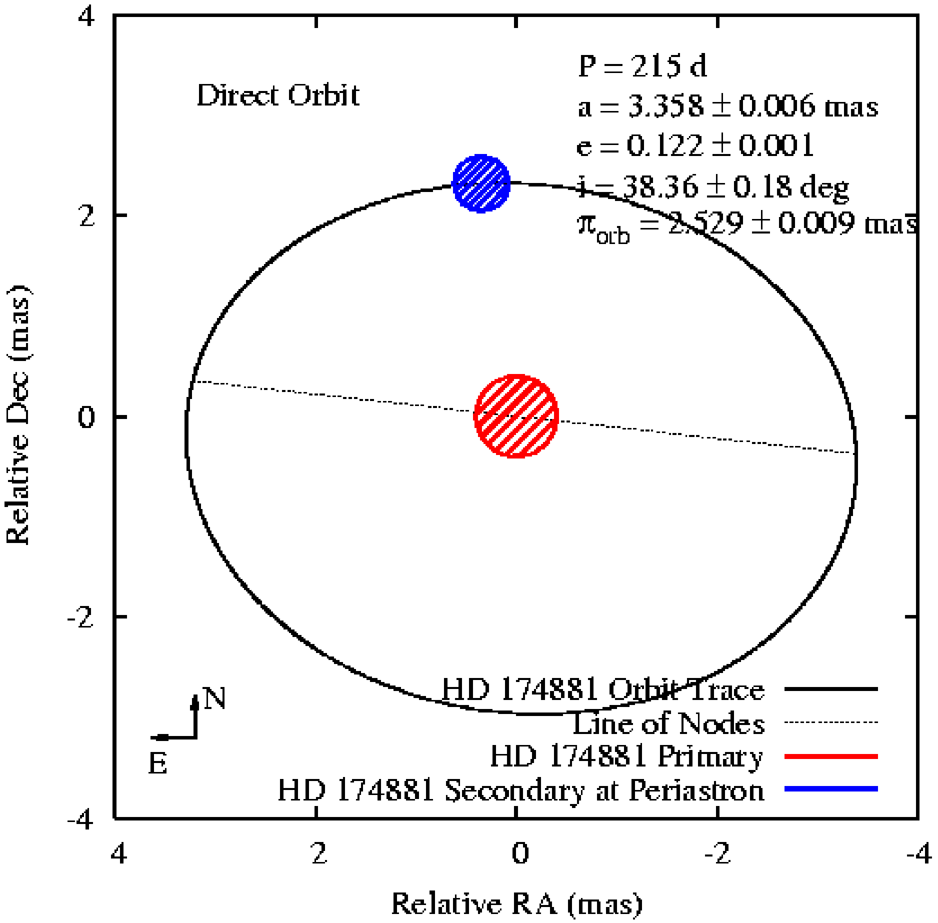




12 Boo
0.3% Mass Uncertanties
Boden et al 2000
Boden et al 2005

HD 174881

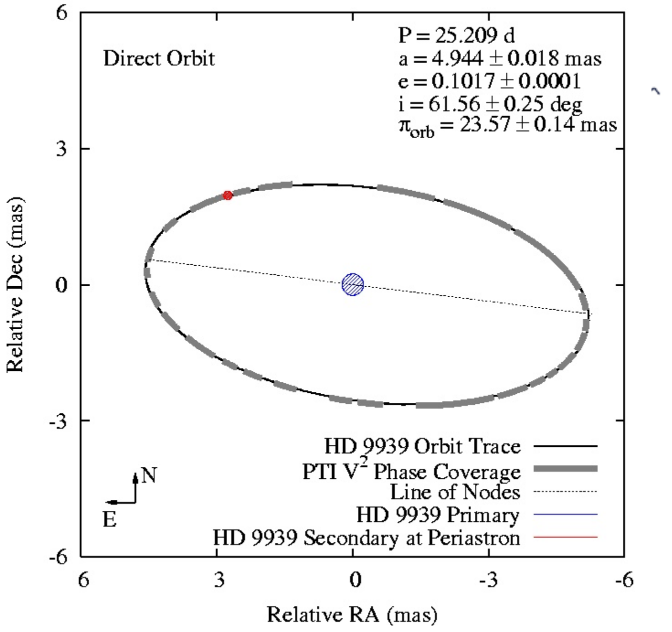
- HD 174881 is a pair of bona-fide post He-flash giants
- Secondary (lower-mass component) is larger, brighter, and cooler than primary
  - Primary envelope loss
- First-of-a-kind precision measurement of a He-burning giant core

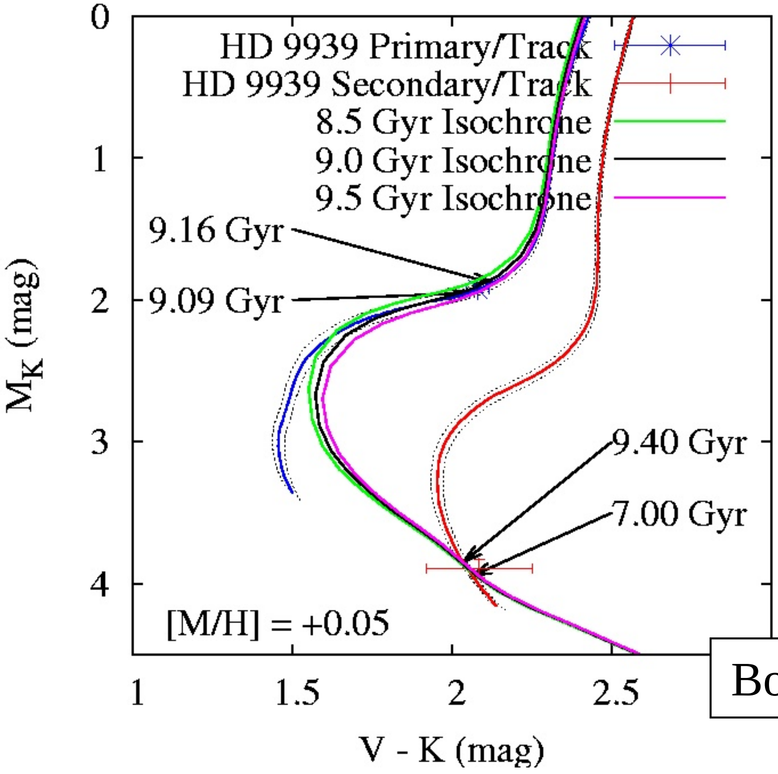


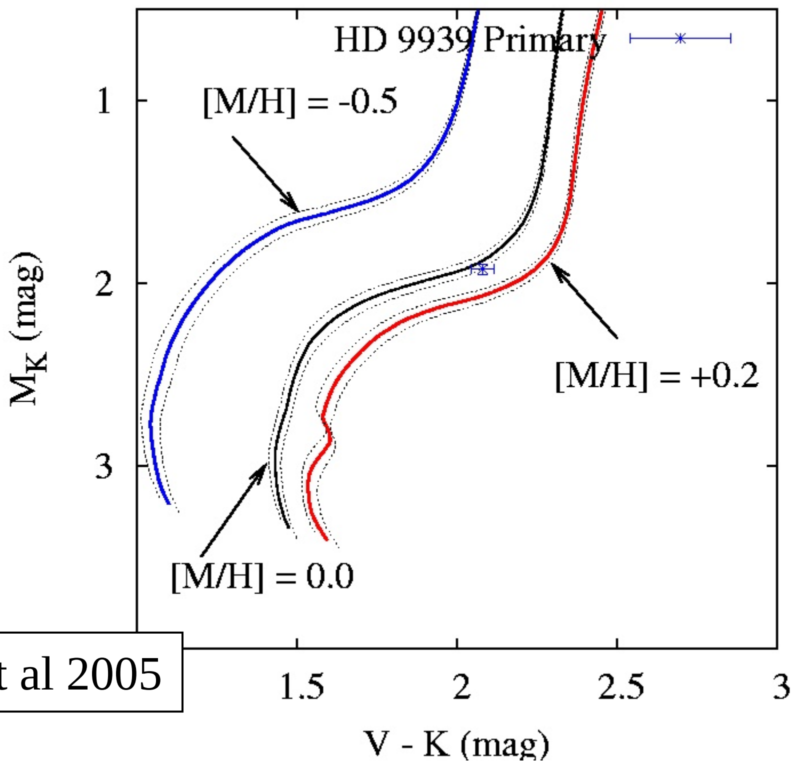
Torres & Boden 2005
(in prep)

Chronometry: HD 9939

- Kinematically selected "metal-poor" system (Carney & Latham sample)
- System is actually slightly super-solar(!)
- Primary dead in H-gap => system age very well determined (9.1 +/- 0.25 Gyr)
- Challenges <u>some</u> notions of age/metallicity relations



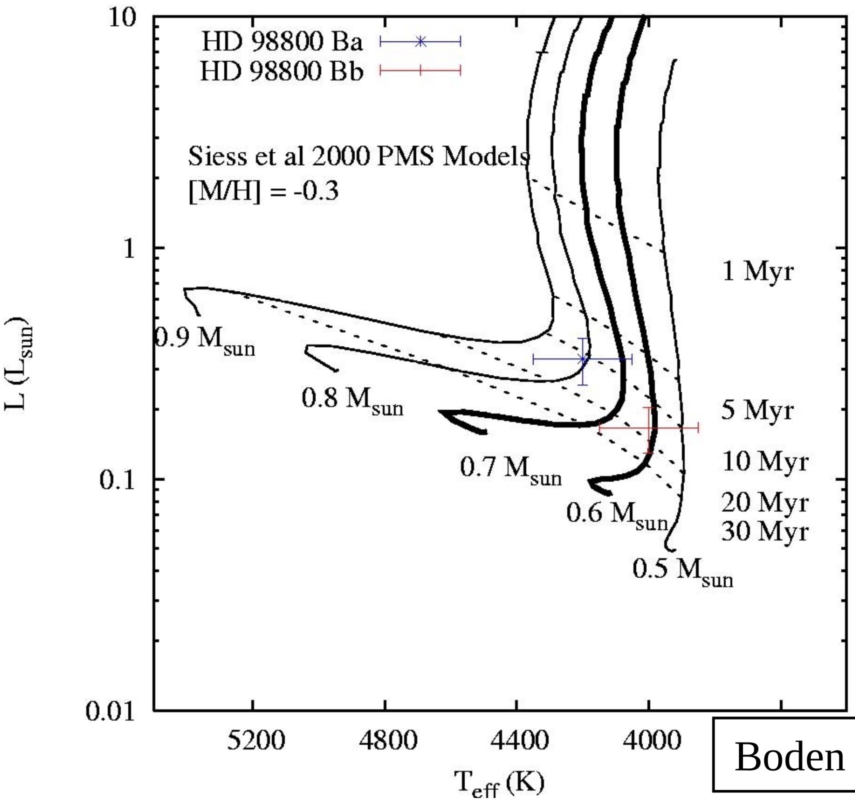


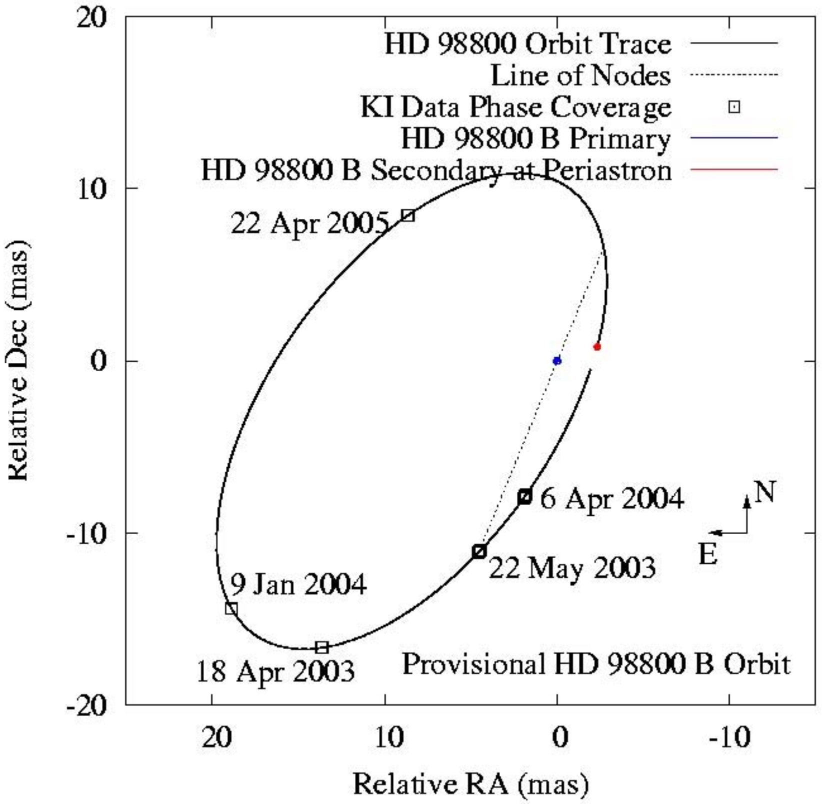


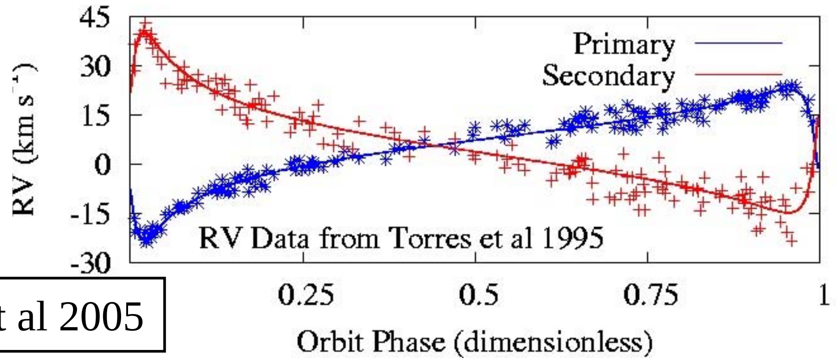
Boden et al 2005

PMS Binary HD 98800 B

- HD 98800 is PMS quad system with two SBs; B is an SB2 with 315d period & mid-IR excess
- Physical orbit estimated with KI V^2, HST FGS, & RV data; yielding dynamical masses of two low-mass PMS components
- Suggestion that HD 98800 (& TW Hya stars) have sub-solar metallicity







Boden et al 2005

Short Period Systems: Tidal Interactions

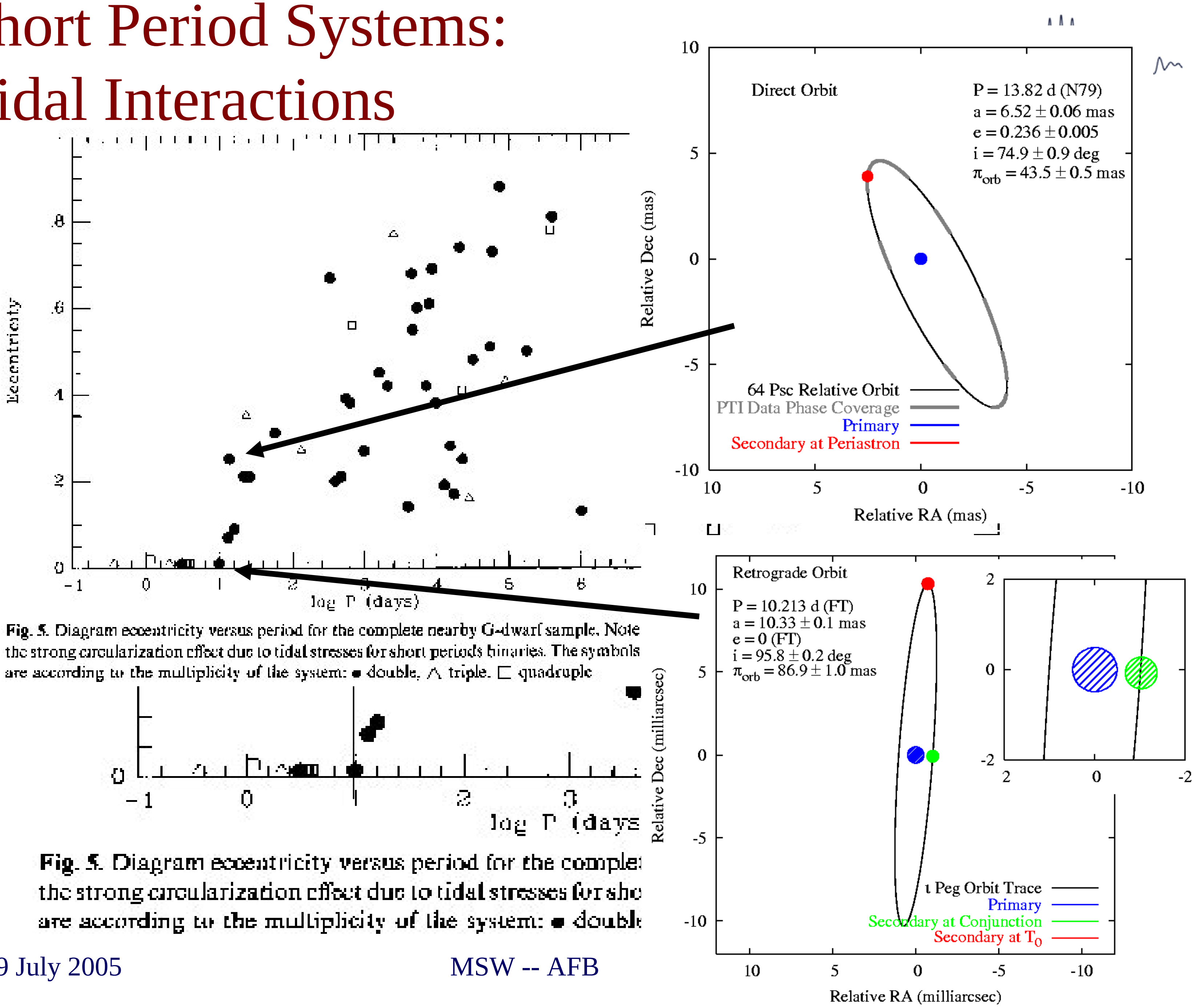
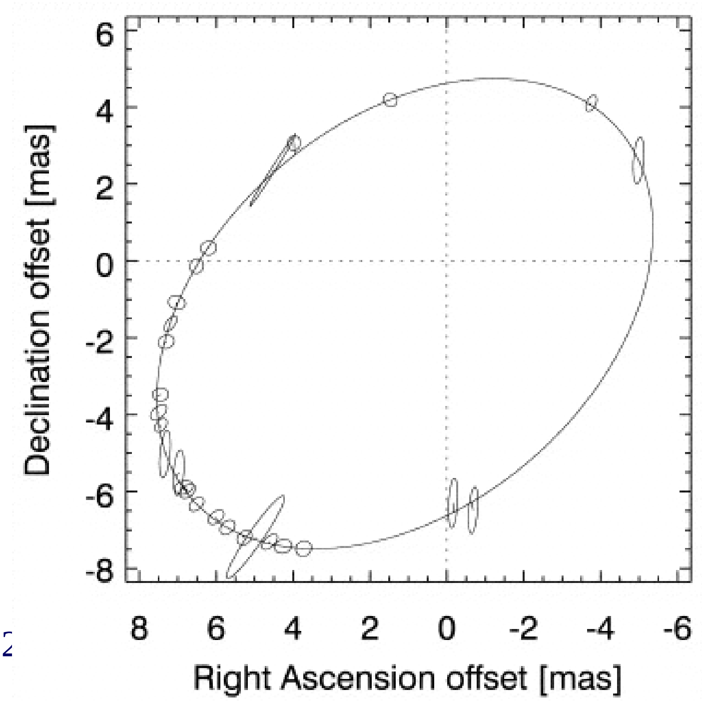


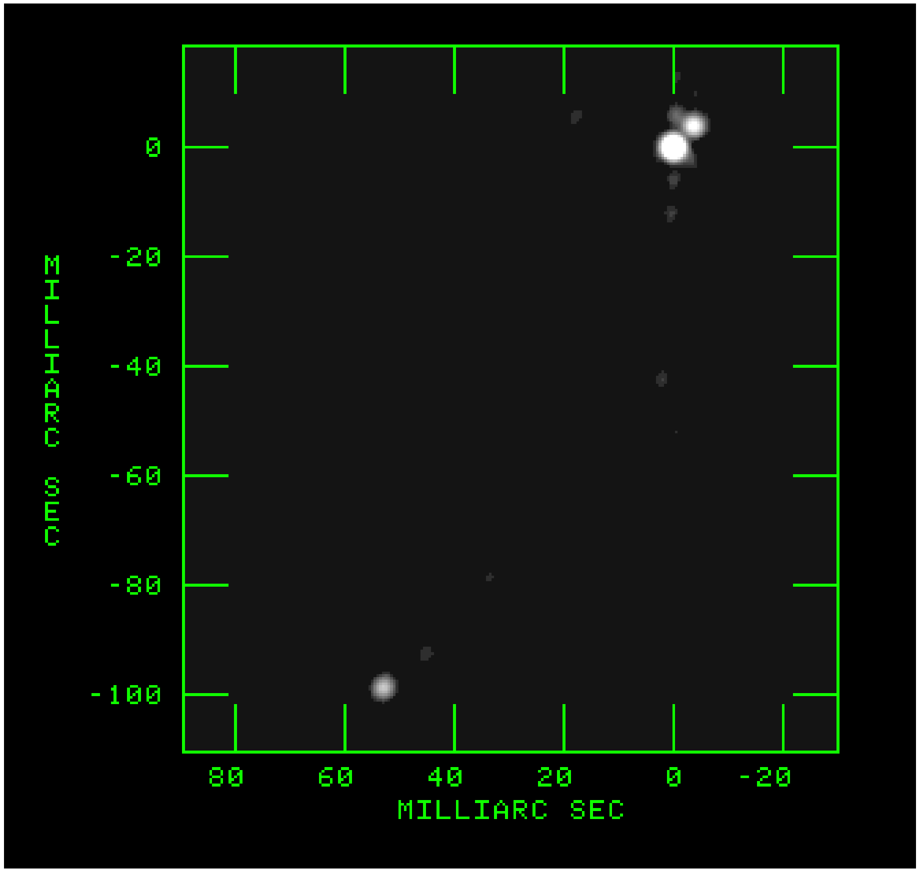
Fig. 5. Diagram eccentricity versus period for the complete nearby G-dwarf sample. Note the strong circularization effect due to tidal stresses for short periods binaries. The symbols are according to the multiplicity of the system: ● double, △ triple, □ quadruple

Fig. 5. Diagram eccentricity versus period for the comple
the strong circularization effect due to tidal stresses for sho
are according to the multiplicity of the system: ● double

Hierarchical Systems

- η Vir was a known triple system recently done by NPOI (Hummel et al 2003)
- Non-coplanarity of outer and inner orbits established (diff 5.1 +/- 1.0 deg)





The Triple System η Vir
Hummel et al 2003

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Distance to Pleiades with Atlas

- Controversy between “conventional” and Hipparcos estimates c
  (F. Benedi
- Atlas visua
  estimate yi
- Result stro
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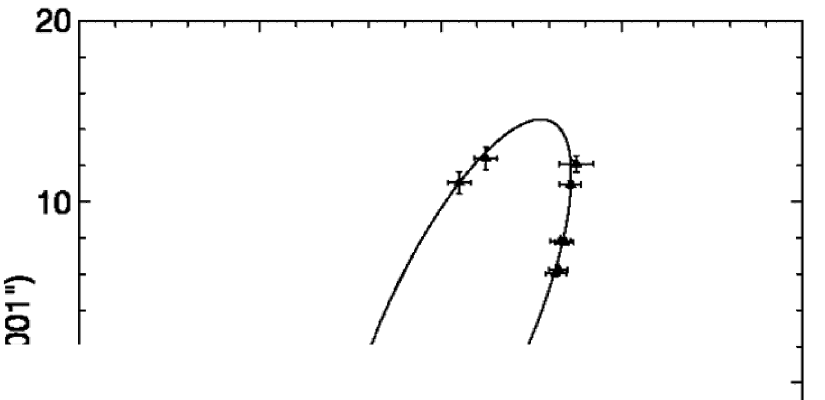
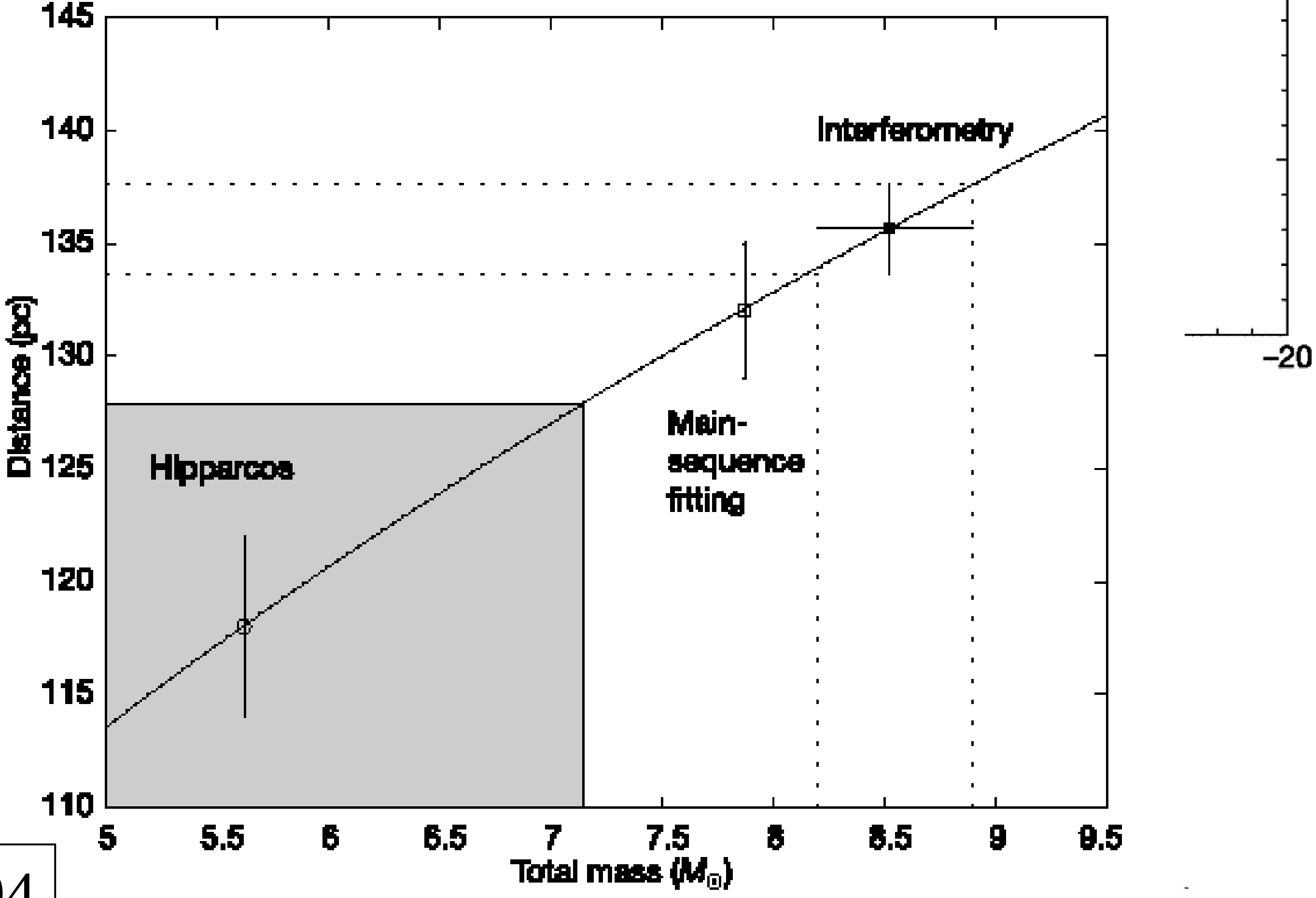
- Additional
  (HD23642
  result – Mu
- Separate A
  (Zwahlen e
  parallax (S
  confirm Pl
  136 pc





Pan et al 2004

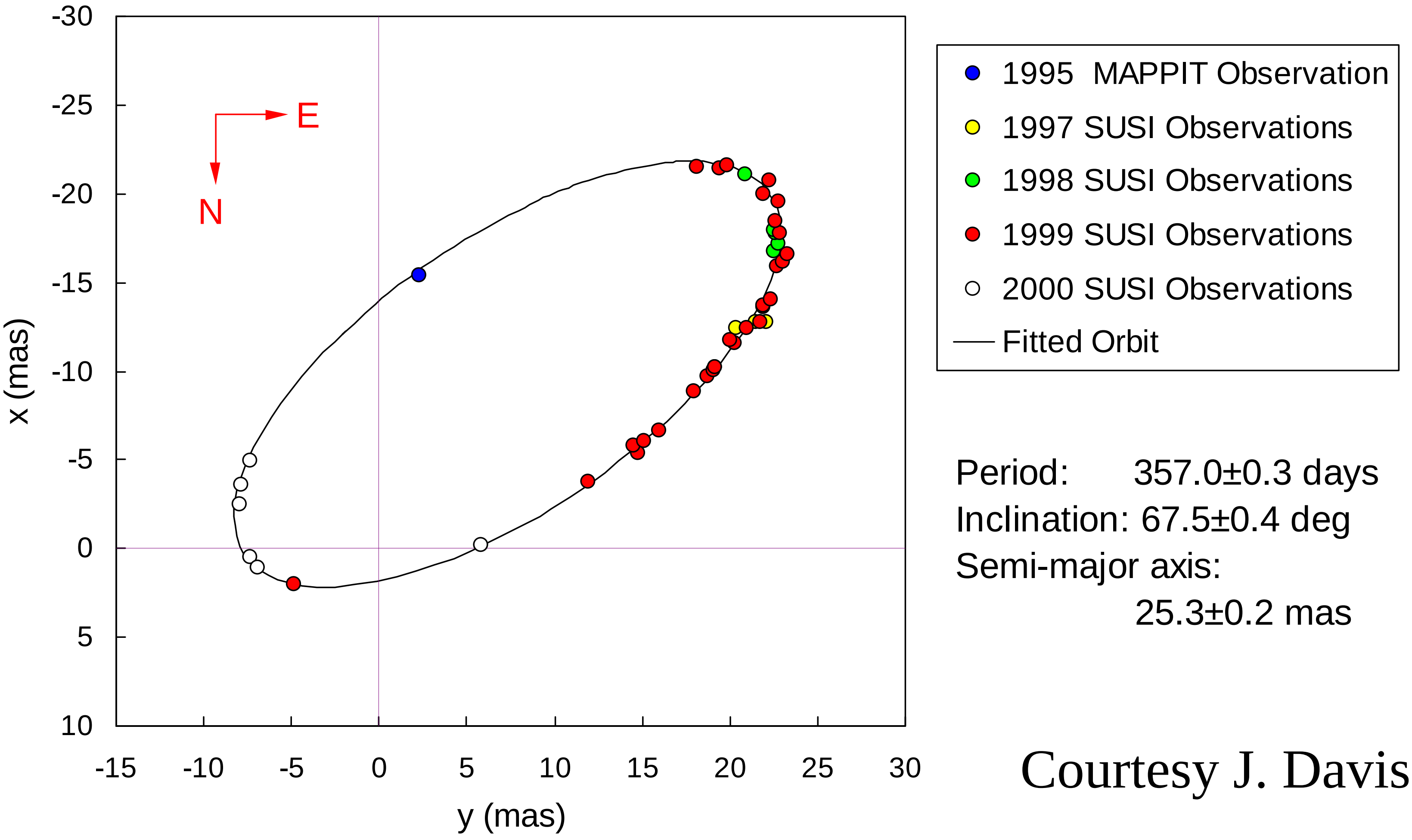
Summary (what to take away…)

- Binaries are important systems to study

  "The hydrogen atoms of stellar astrophysics" argument
- LB Interferometers have an important role to play in binary star studies:
  - Highest-resolution technique available
  - Making "visual" binaries out of "spectroscopic" ones
  - Resolving more distant systems
  - "Competitive" accuracy with eclipsing systems
  - Providing angular scale (distance!) for eclipsing systems
  - Providing additional component diversity beyond eclipsing systems
- LB Interferometers can also provide new windows into physics beyond component parameters
  - Tidal interactions
  - "Yardsticks and chronometers"
- (At least I feel) there's a lot left to do…
  - Establishing component radii (precision mass/luminosity/effective temperature)
- All interferometers should study binary stars

  (…to the exclusion of *all* other science…)
- Enjoy BC…

The orbit of β Centauri determined from SUSI observations



Period: 357.0±0.3 days
Inclination: 67.5±0.4 deg
Semi-major axis:
25.3±0.2 mas

Courtesy J. Davis

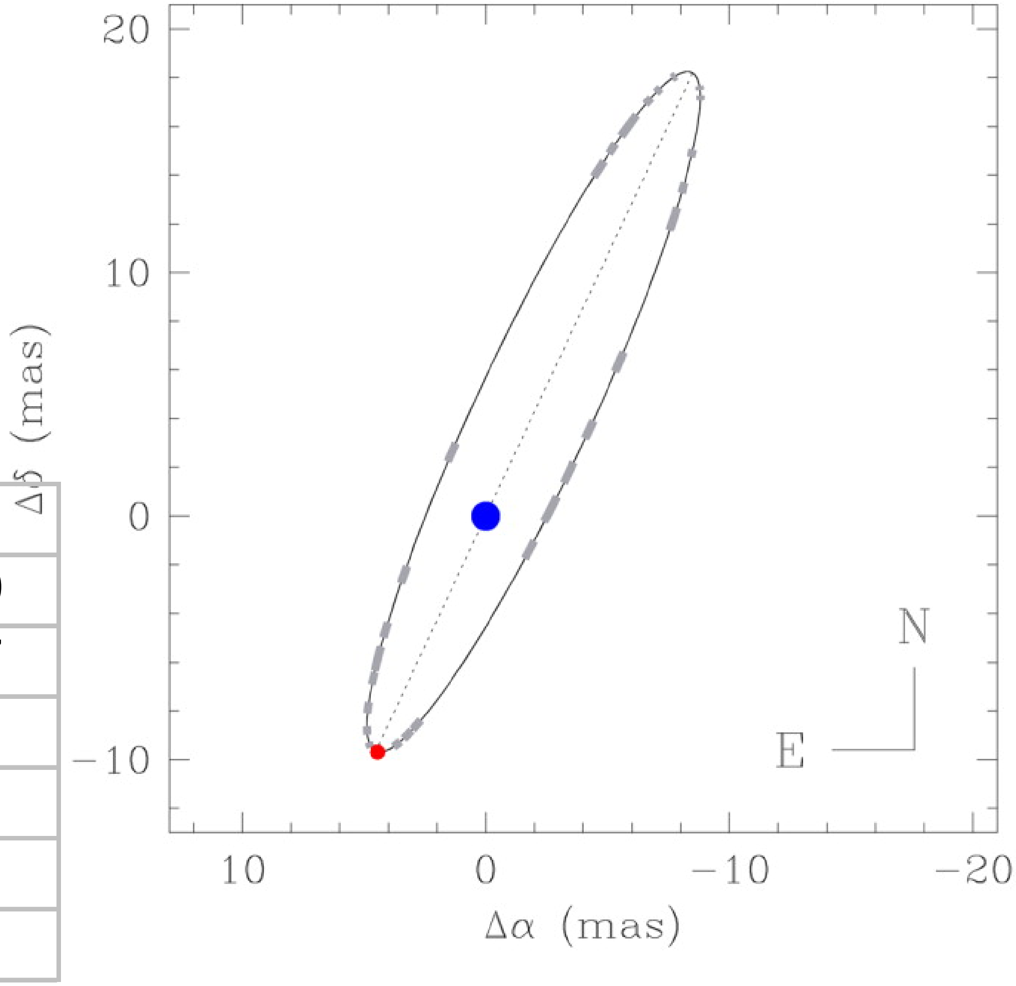
Admonitions From P. Tuthill

- Imaging may well be the “Holy Grail”, but the distinction between imaging and modeling is sometimes unclear
- In all cases, you want to make optimal use of your data
- Usually this means working “as close to your data” as possible

HD 195987 Visual Orbit

- a” ~ 15 mas; easily resolvable with PTI
- K-band operation facilitates measurement of secondary (r ~ 0.38)

P (d)	57.3298 ± 0.0035
T0	51354.000 ± 0.069
e	0.30740 ± 0.00067
a	15.368 ± 0.028
i	99.379 ± 0.088
Ω	335.061 ± 0.082
ω	358.89 ± 0.53



Components rendered 3x actual size