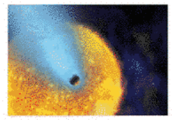
The Extraction of Dynamical Information from Radial Velocity Data Sets

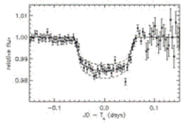
G. Laughlin, A. Wolf, G. Novak, S. Vogt
D. Lin, P. Bodenheimer (UCSC)
D. Fischer (SFSU)
G. Marcy (UC Berkeley)
P. Butler (Carnegie DTM)
F. Adams (Michigan)

Three Case Studies:

1. HD 209458 -- why is the planet so large?
2. GJ876 -- what can be learned from the non-Keplerian interaction?
3. HD80606 -- what's going on?

HD 209458





The problem: HST Time-series photometry permits an accurate measurement of the radius of HD 209458b. Brown et al (2001) obtain:

$$R=1.35 \pm 0.06\ R_{Jup}$$

Current estimates (using Henyey-type Stellar Evolution Codes adapted to model Jovian planets) of the size of HD 209458b by Bodenheimer et al (2003), Burrows et al (2003), Chabrier et al (2003), and Guillot & Showman (2002) all predict considerably smaller radii:

$$R\sim 1.05 \pm 0.1\ R_{Jup}$$

Three hypotheses have been offered to explain HD 209458b's large size:

Hypothesis #1 (Burrows, Sudarsky & Hubbard, 2003)
Irradiation plus a proper interpretation of the transit radius plus no core yields a theoretical radius falling within the low end of the measured error bars.

Hypothesis #2 (Guillot & Showman, 2002)
The radius of HD 209458b can be reproduced if a small fraction (~1%) of the stellar flux is transformed into kinetic energy in the planetary atmosphere, and subsequently converted to thermal energy by dynamical processes at pressures of tens of bars.

(hypotheses for hd209458b's large size, continued)

Hypothesis #3 (Bodenheimer, Lin & Mardling 2001): HD 209458b has non-zero orbital eccentricity, and is receiving internal heating as a result of ongoing tidal circularization. The internal heating is sufficient to maintain the large observed size of the planet.

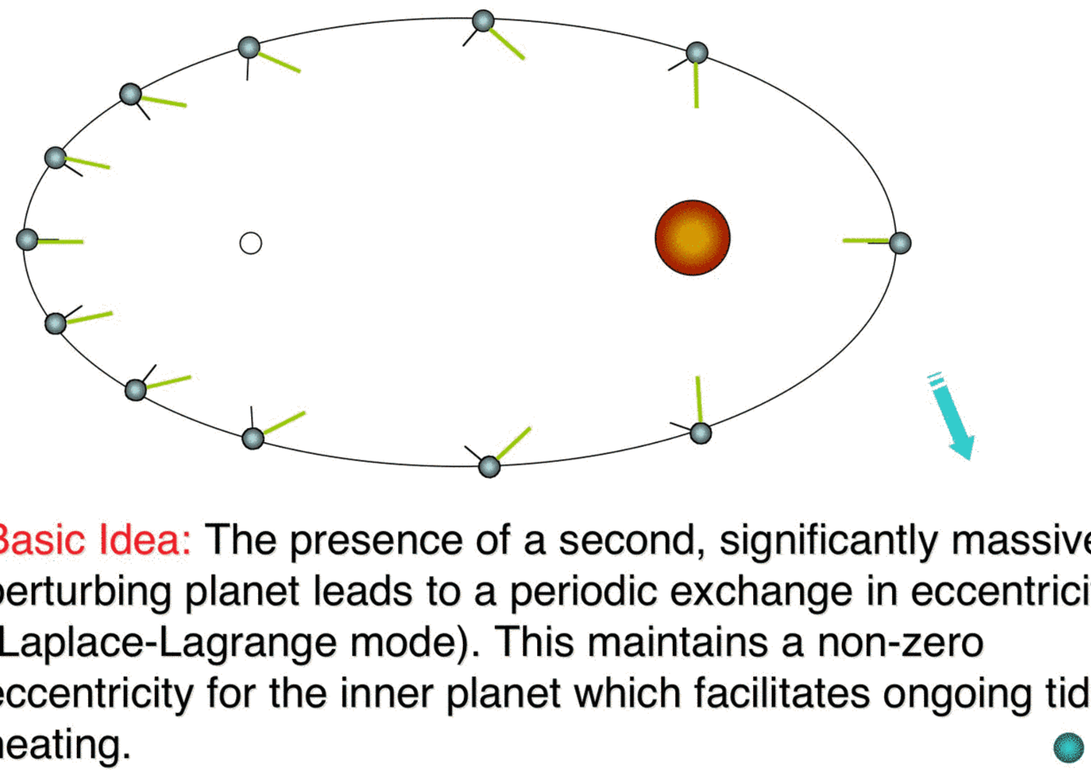
What predictions arise from these hypotheses?

1. If the kinetic heating hypothesis is correct:
   a. other Hot Jupiters should be large.
   b. circularization is enhanced for Hot Jupiters with periods of order one week.

2. If the transit radius interpretation in correct:
   a. measured radii for other hot Jupiters should be somewhat smaller than the current radius estimate for HD 209458b.
   b. Hot Jupiters are unlikely to have solid cores.

3. If the tidal heating hypothesis is correct:
   a. HD209458b should have a companion planet capable of exciting its eccentricity.
   b. other Hot Jupiters should be small.

Tidal Heating Hypothesis for HD 209458b's Large Size



Basic Idea: The presence of a second, significantly massive perturbing planet leads to a periodic exchange in eccentricity (Laplace-Lagrange mode). This maintains a non-zero eccentricity for the inner planet which facilitates ongoing tidal heating.

The rate of tidal energy dissipation in a planet is:

$$\dot{E}_d = \frac{e^2 G M_{star} M_P}{a \tau_{circ}}$$

The tidal circularization timescale is:

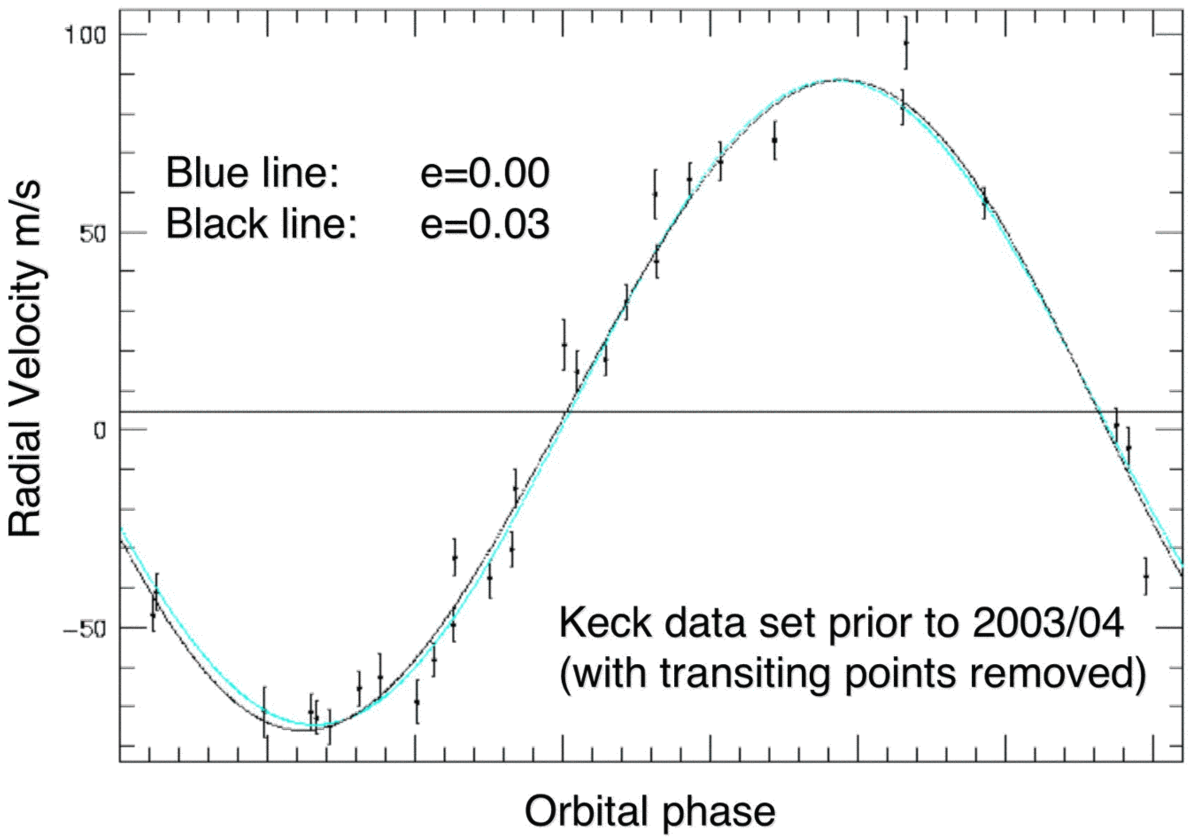
$$\dot{E}_d = (\bar{e}^2)\frac{10^6}{Q} 1.1\times 10^{29}$$

$$\tau_{\rm circ} = \frac{e}{\dot{e}} = 0.63\left(\frac{Q_{\rm Pl}}{10^6}\right)\left(\frac{M_{\rm Pl}}{M_{\rm Jup}}\right)\left(\frac{a}{R_{\rm Pl}}\right)^5 \ {\rm Gyr}$$

For HD 209458b:

$$\tau_{\rm HD209458b} = 0.08\left(\frac{Q}{10^6}\right){\rm Gyr}$$

Does HD 209458b have a nonzero eccentricity?



A one-planet fit to the HD 209458b radial velocities contains four free parameters: (1) radial velocity half-amplitude, (2) orbital eccentricity, (3) argument of periastron, (4) radial velocity zero-point offset.

The period is known very accurately (Wittenmyer 2004):

$P=3.52474541 \pm 0.00000025$ d

For a given choice of (2) and (3) the observed times of the transit midpoint fix the mean anomaly at a given epoch:

$T_{central}$= JD $2452854.825415 \pm 0.00006$ d

Best fit to the pre-2003/04 velocities gives:

$e=0.033$, $\varpi=67$ deg, $M=0.68\ M_{JUP}$

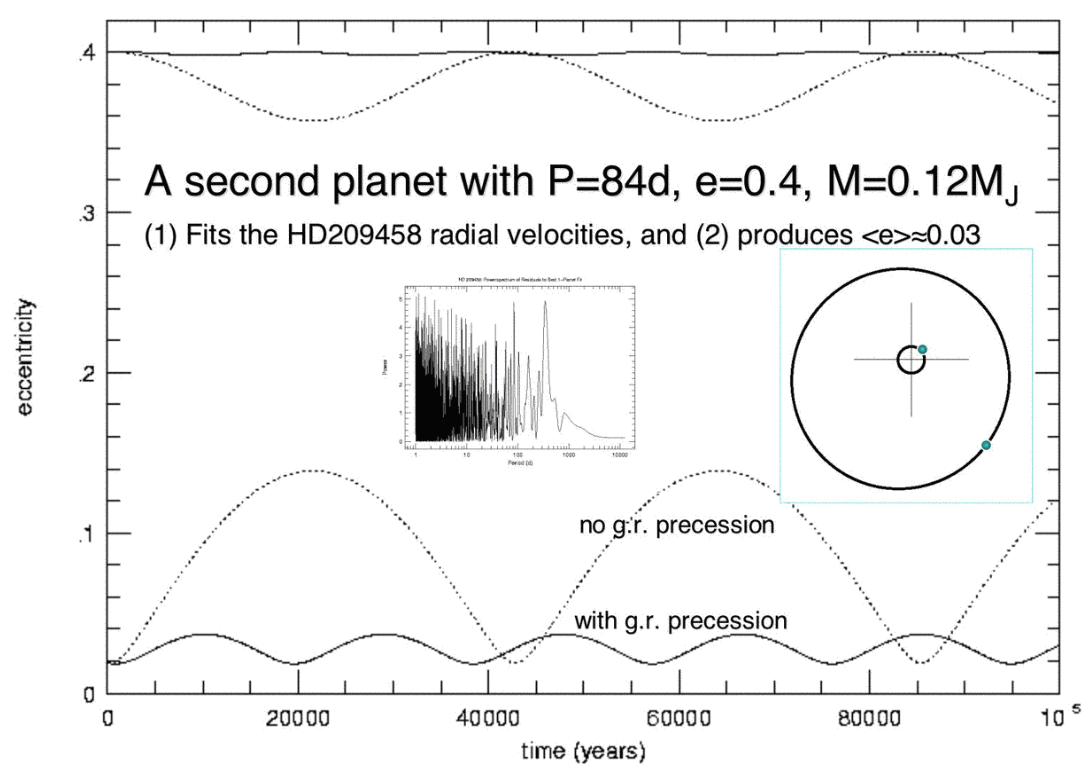
For HD 209458b with e=0.033:

$$\dot{E}_d = 9 \times 10^{25} \frac{10^6}{Q} erg/\mathrm{sec}$$

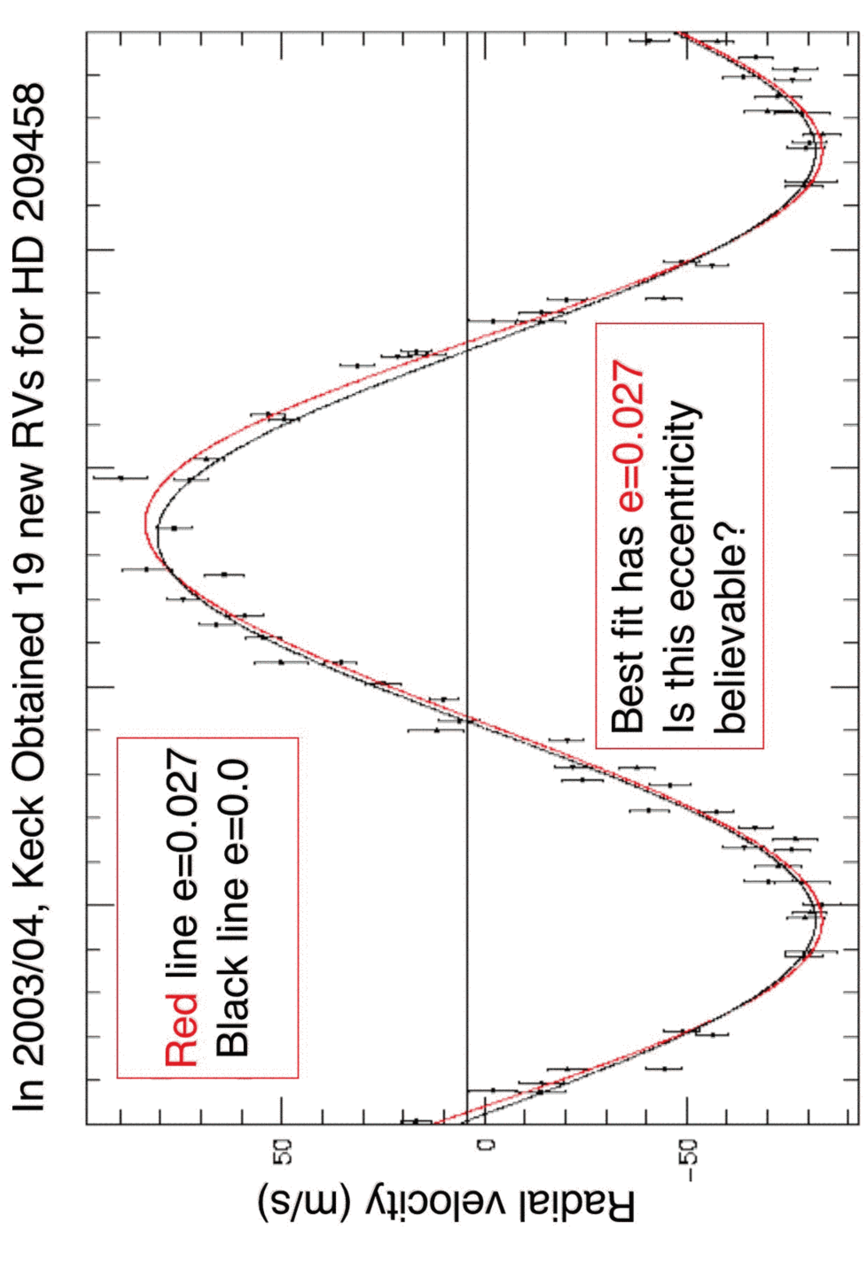
From Peter B.'s models ($Q=10^6$, uniform dissipation):

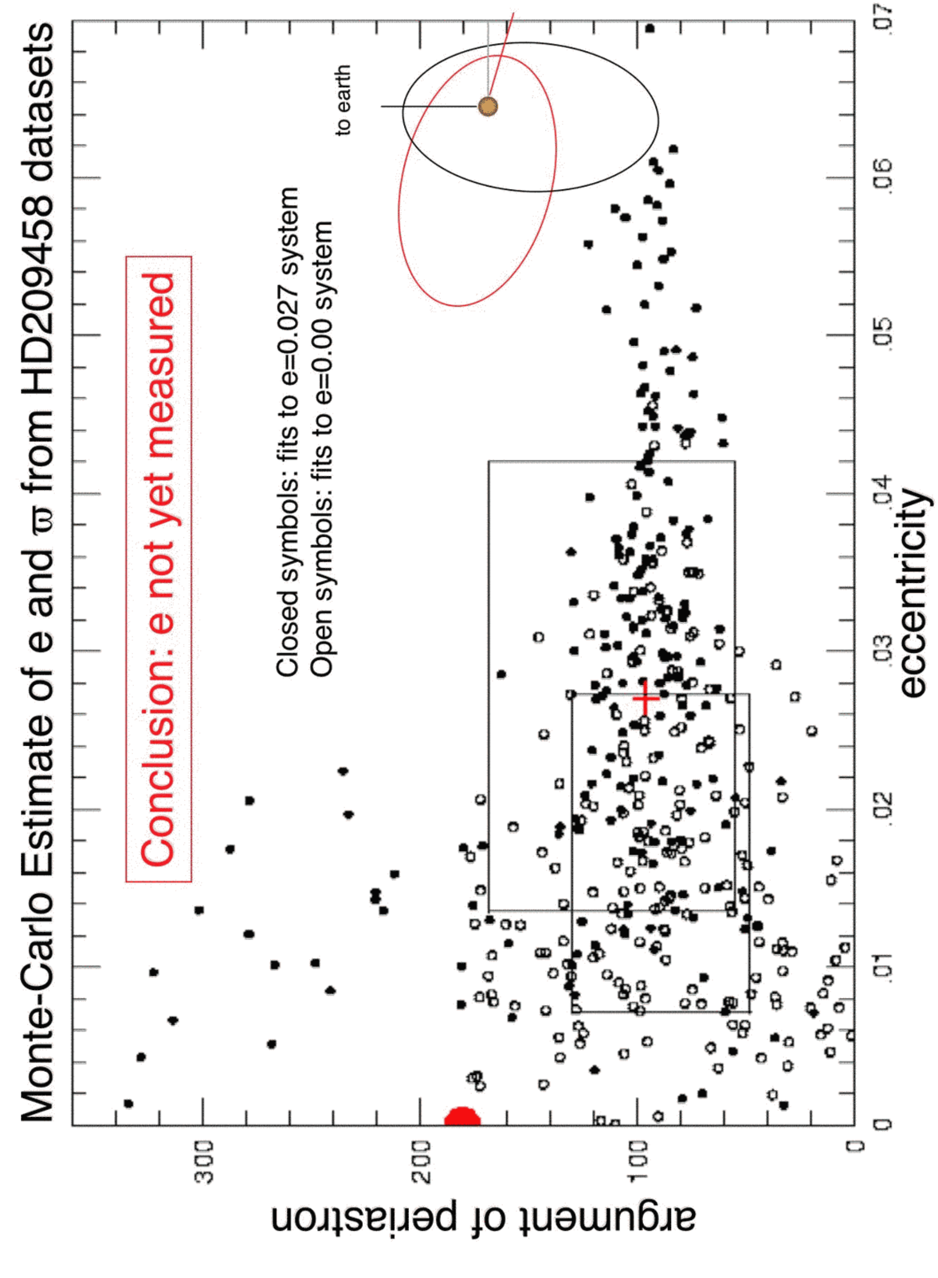
Mass	Core	dE_d/dt	R_{planet}
0.67 M_J	YES	9e+26 erg/sec	1.41 R_J
0.67 M_J	NO	9e+25 erg/sec	1.41 R_J

Tidal energy generation hypothesis is *not unreasonable* for e~0.03. Is the radial velocity dataset, however, consistent with a perturbing companion? Can such a perturbing companion maintain <e>~0.03?

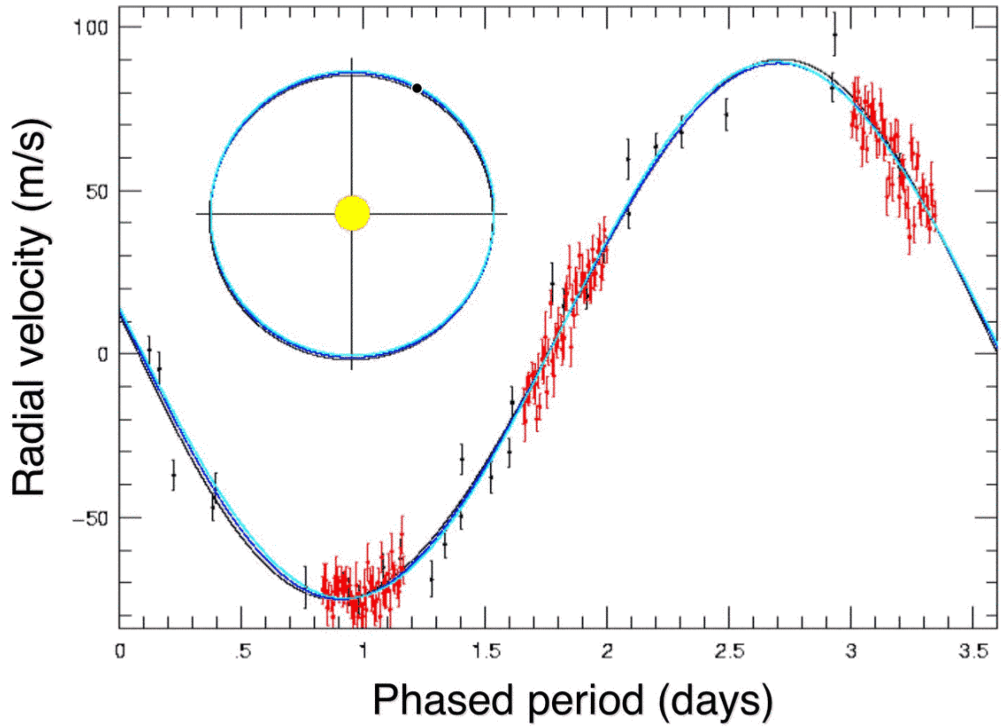


(Note: Just because it fits, it doesn't mean it's there!)

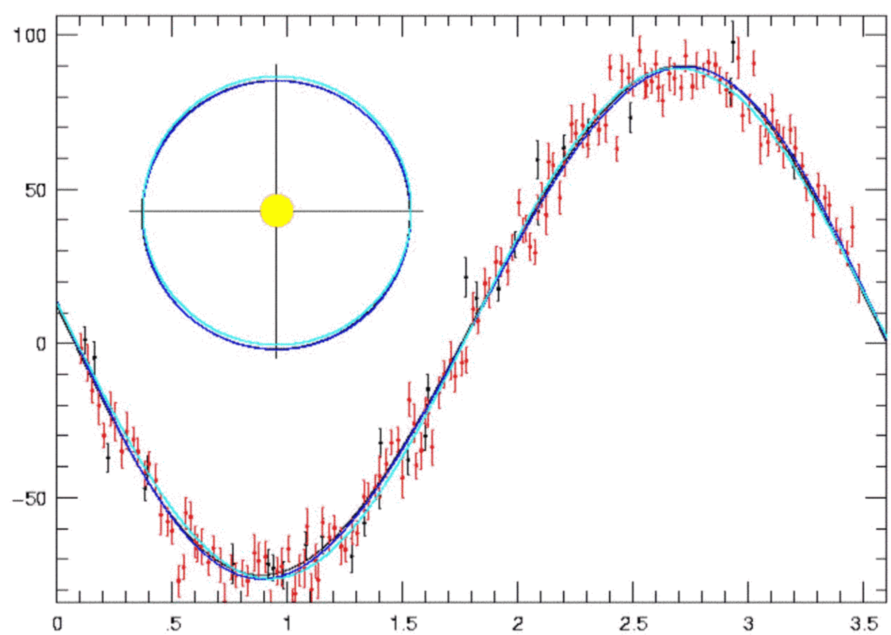

In 2003/04, Keck Obtained 19 new RVs for HD 209458
Red line e=0.027
Black line e=0.0
Best fit has e=0.027
Is this eccentricity
believable?
Phased P (days)
Radial velocity (m/s)

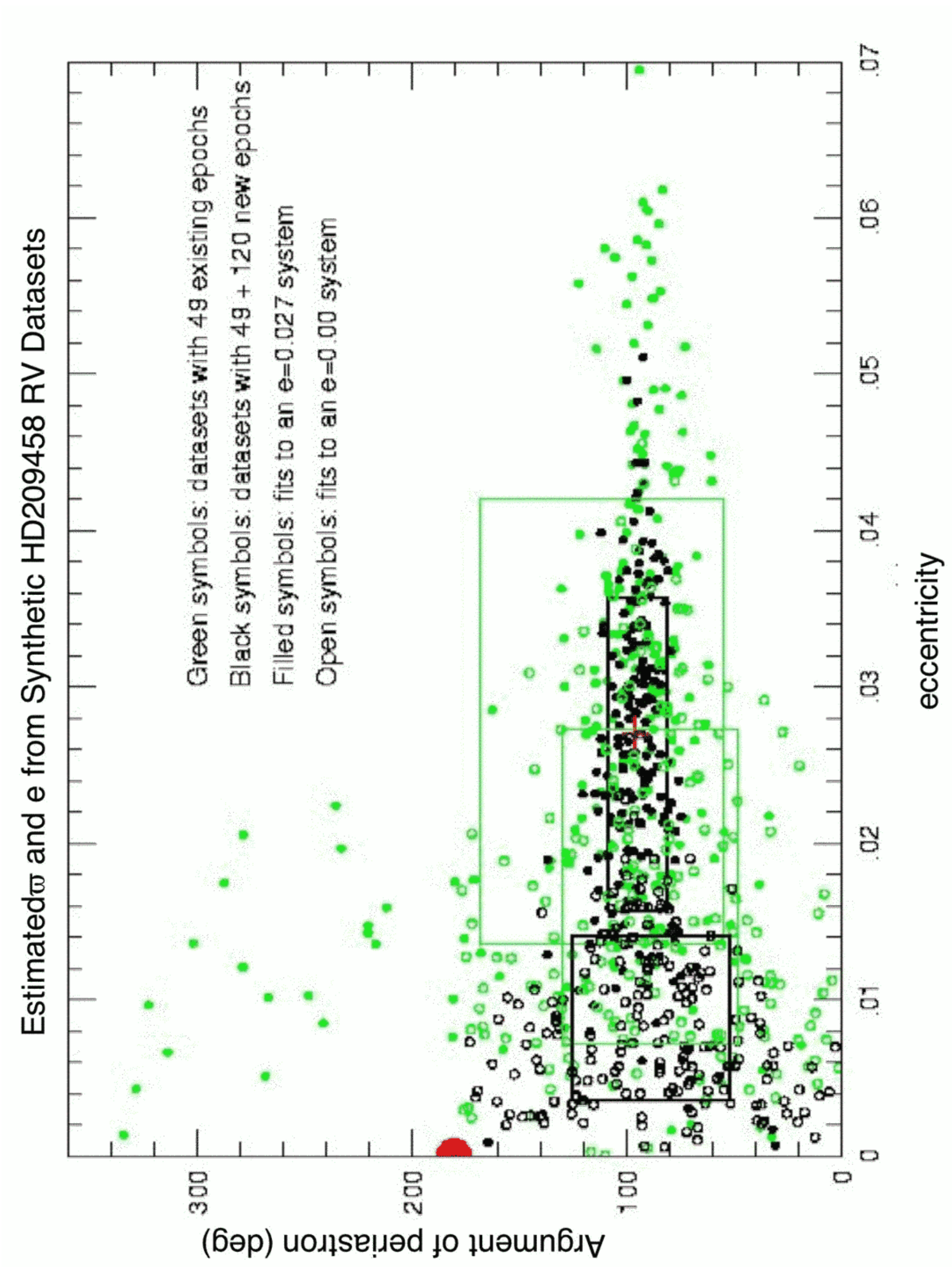

Monte-Carlo Estimate of e and ϖ from HD209458 datasets
Conclusion: e not yet measured
Closed symbols: fits to e=0.027 system
Open symbols: fits to e=0.00 system
to earth
eccentricity
argument of periastron

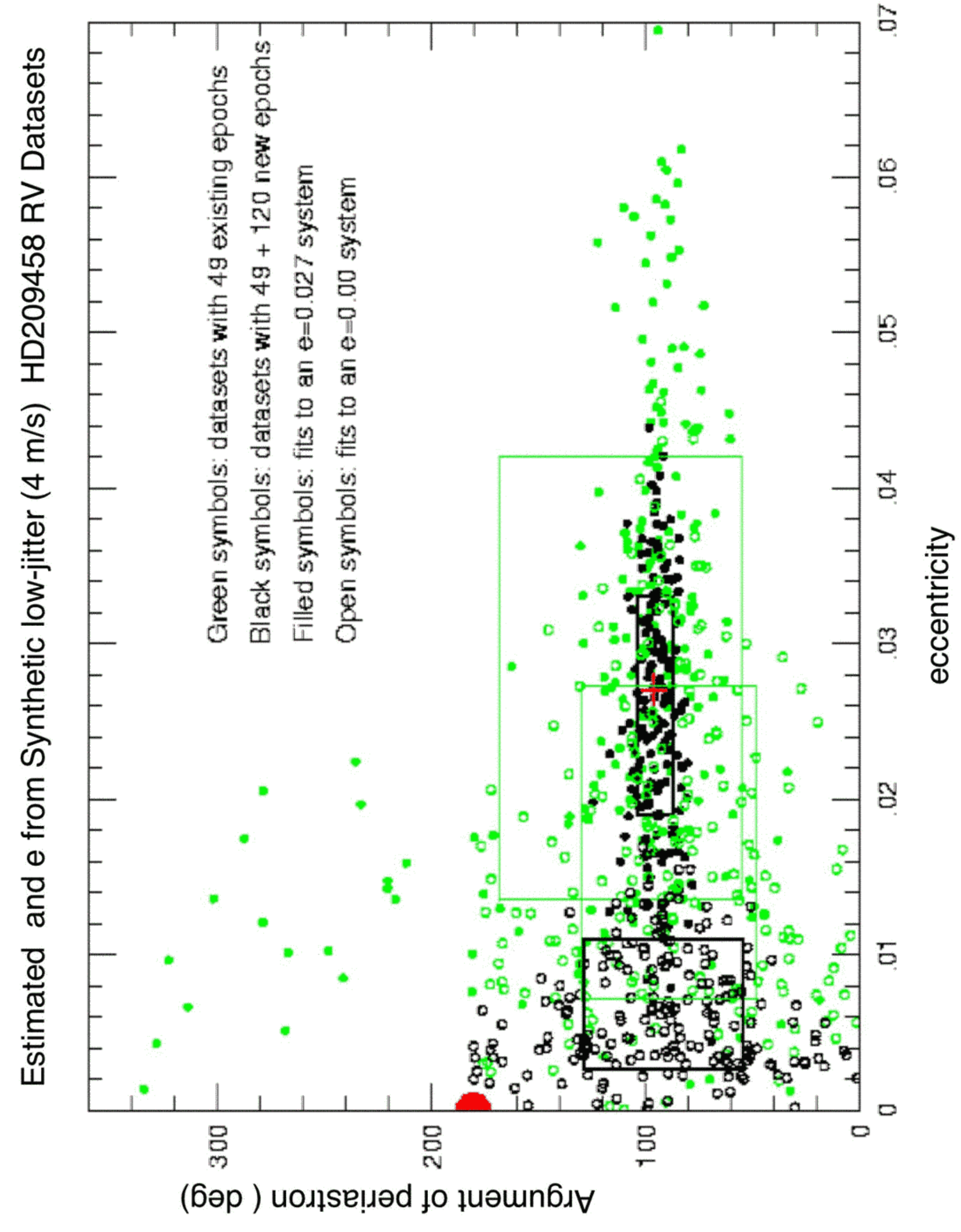
If one observes HD 209458 for three dedicated nights running, one gains almost no new constraint on the orbital eccentricity.

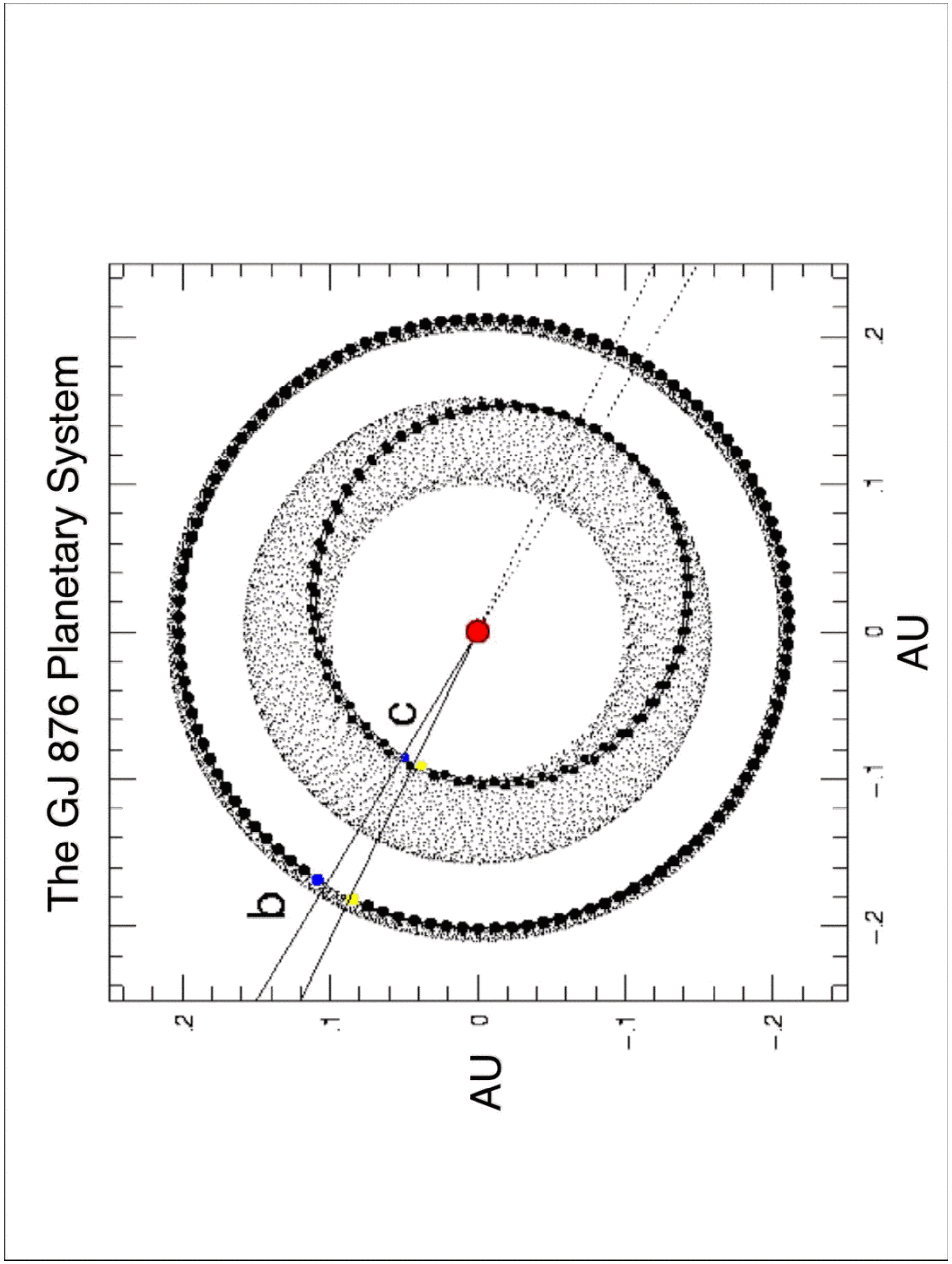


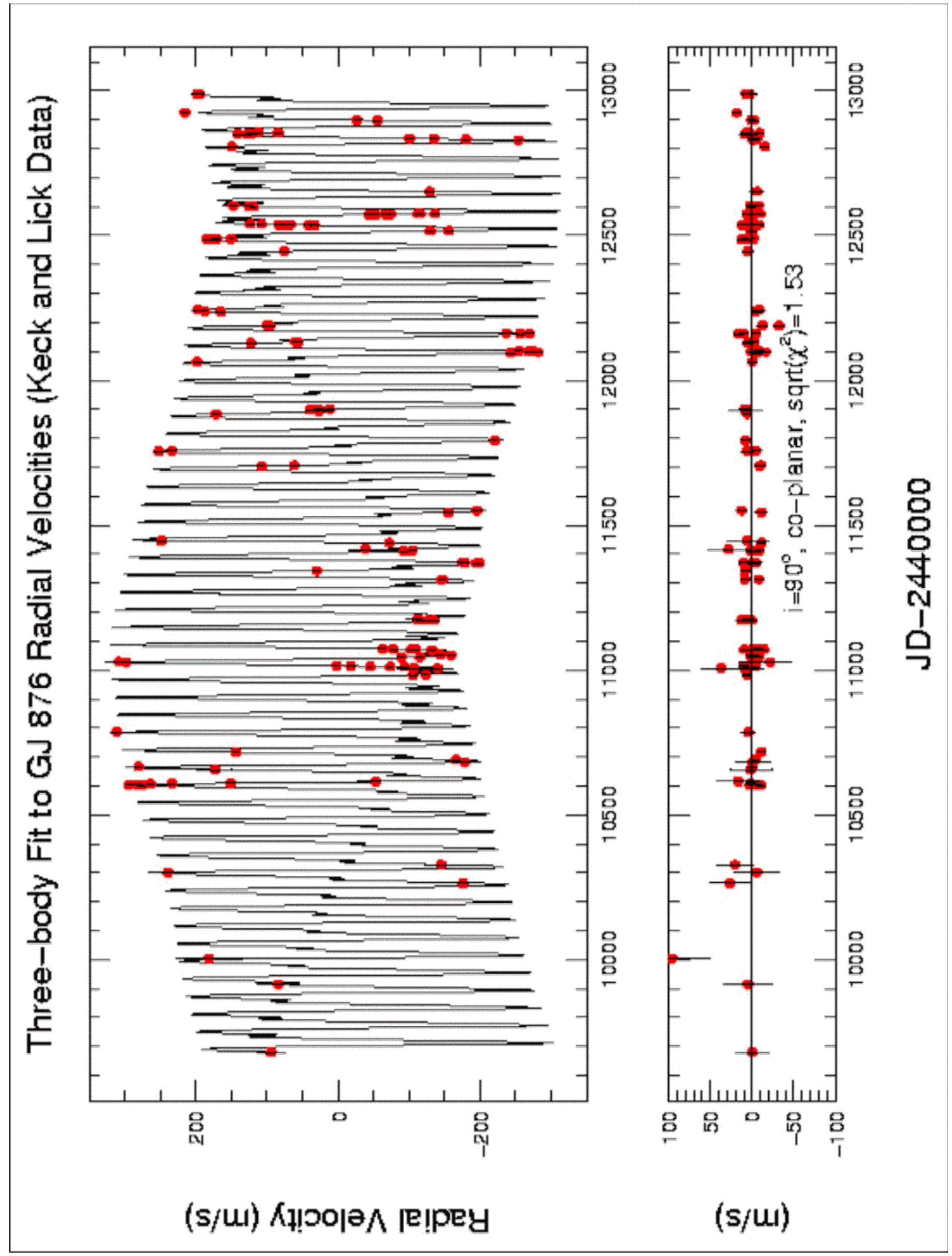
Distribute 120 observations (equivalent of 1 night) across one full season using the "Keck-TAC" subroutine. Use these epochs to construct synthetic data sets for e=0.00 and e=0.027 models:



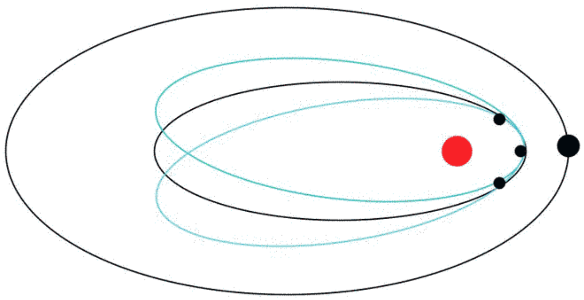

Estimatedϖ and e from Synthetic HD209458 RV Datasets
Green symbols: datasets with 49 existing epochs
Black symbols: datasets with 49 + 120 new epochs
Filled symbols: fits to an e=0.027 system
Open symbols: fits to an e=0.00 system
eccentricity
Argument of periastron (deg)
0
.01
.02
.03
.04
.05
.06
.07
0
100
200
300

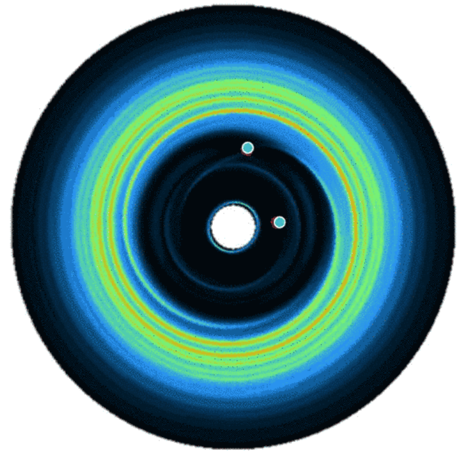

Estimated and e from Synthetic low-jitter (4 m/s) HD209458 RV Datasets
Green symbols: datasets with 49 existing epochs
Black symbols: datasets with 49 + 120 new epochs
Filled symbols: fits to an e=0.027 system
Open symbols: fits to an e=0.00 system
eccentricity
Argument of periastron (deg)
0
.01
.02
.03
.04
.05
.06
.07
0
100
200
300


The GJ 876 Planetary System
b
c
AU
AU


Three-body Fit to GJ 876 Radial Velocities (Keck and Lick Data)
Radial Velocity (m/s)
(m/s)
i=90°, co-planar, sqrt(χ²)=1.53
JD-2440000

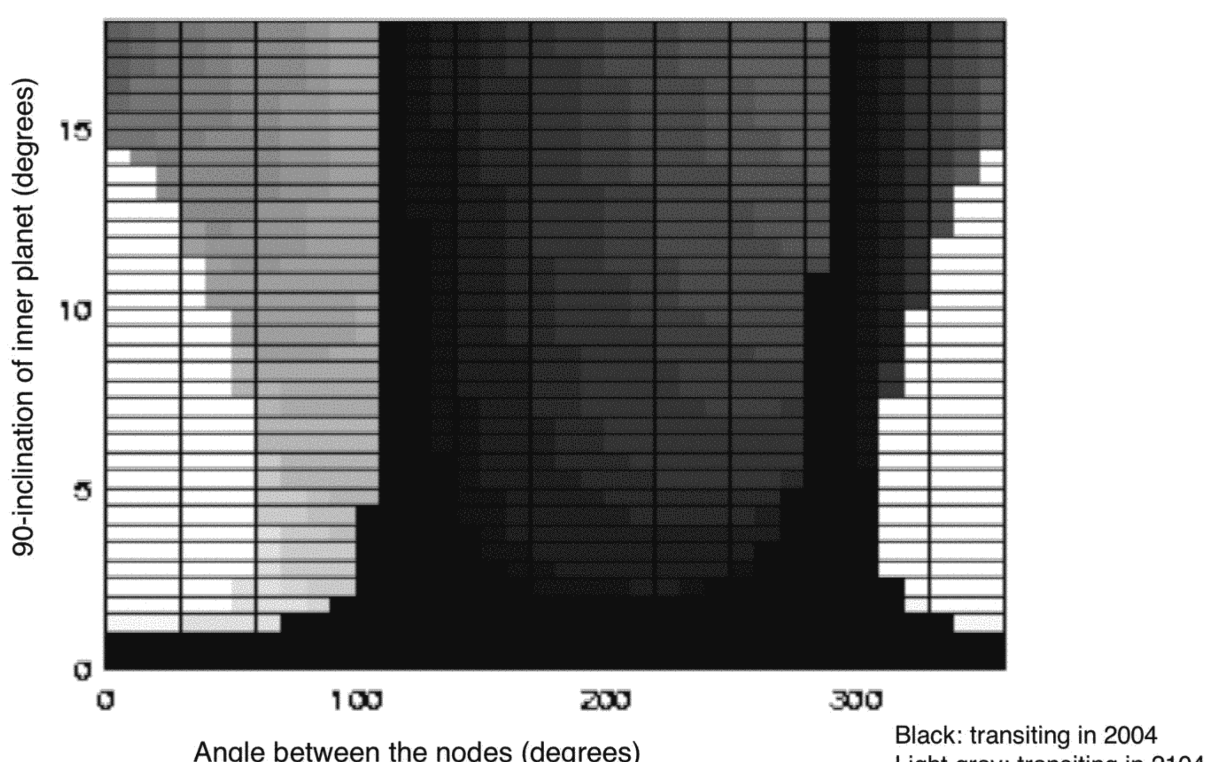
The GJ 876 system is important for understanding the process of differential migration (e.g., talks by Kley, Lee, Nelson)

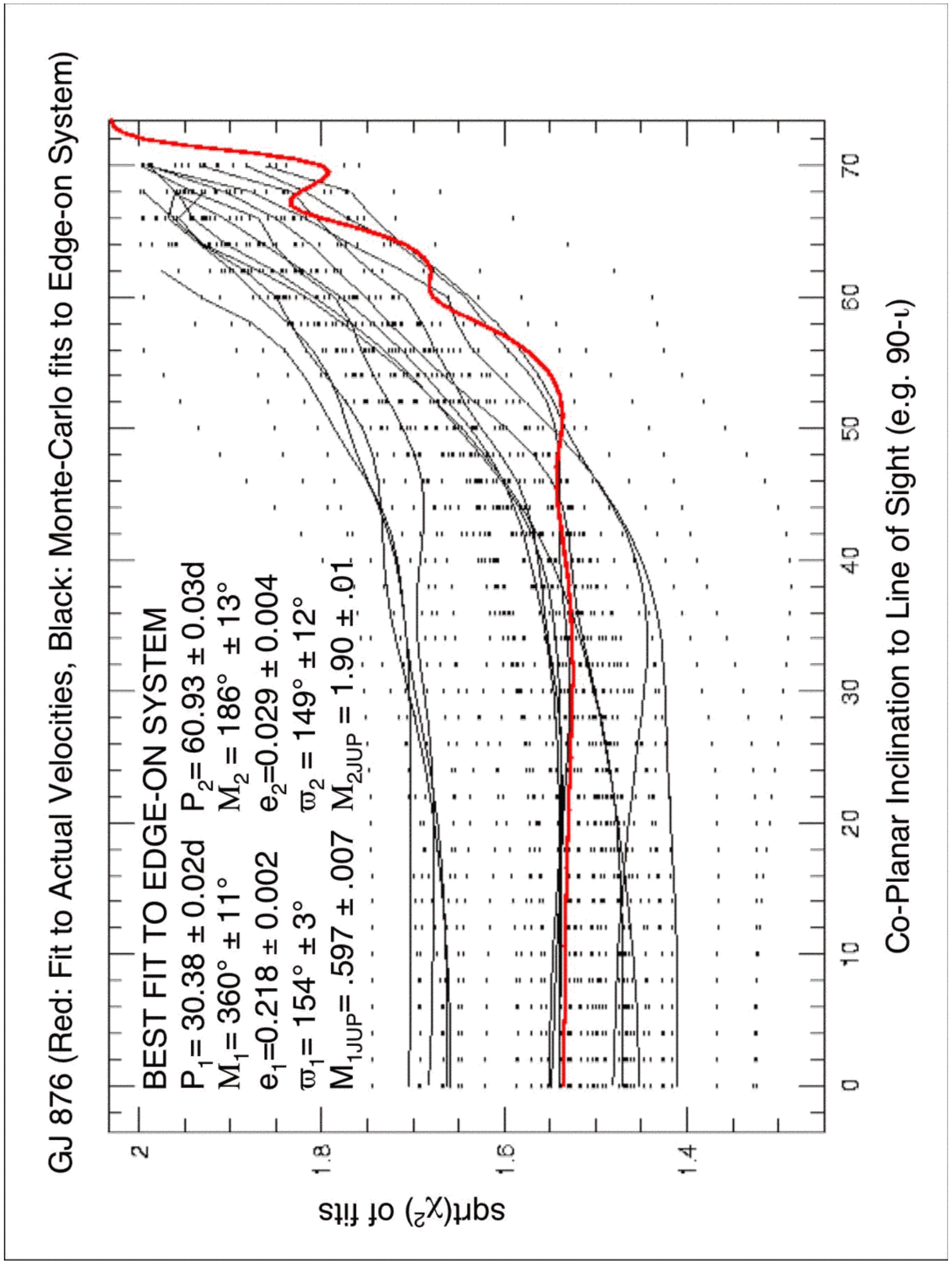


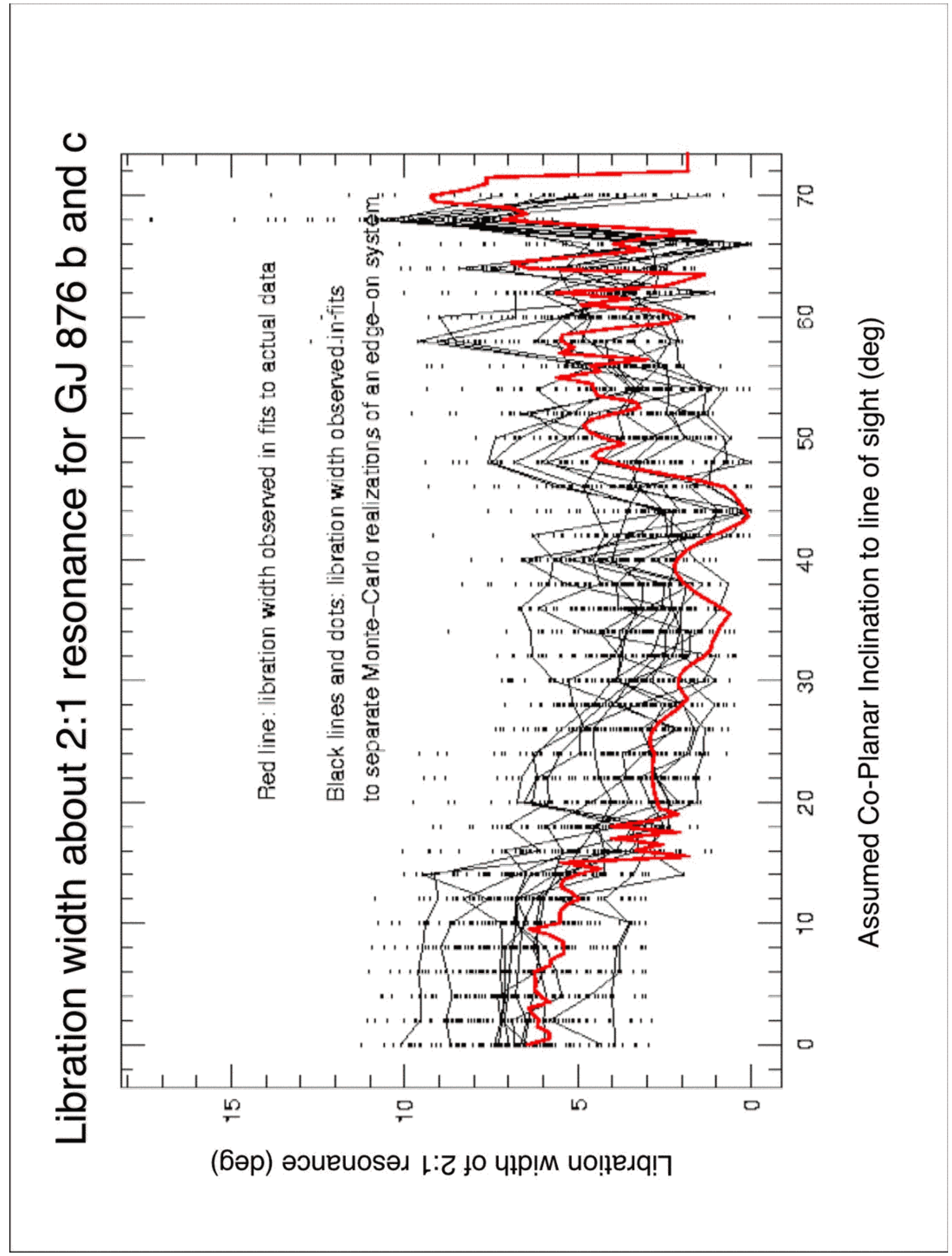


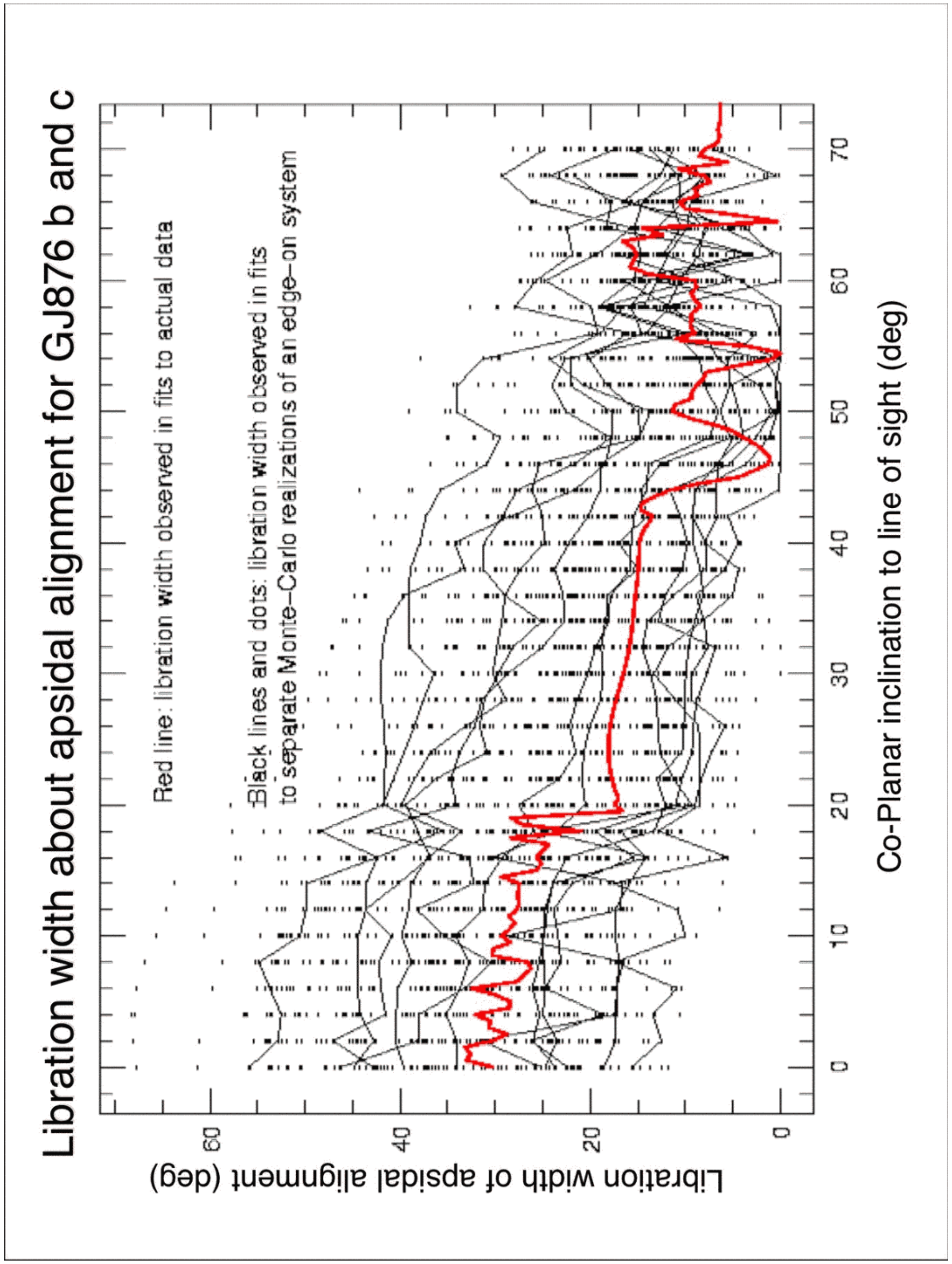
The GJ 876 planets are deep within the 2:1 mean-motion resonances, and also exhibit libration about periapse alignment.

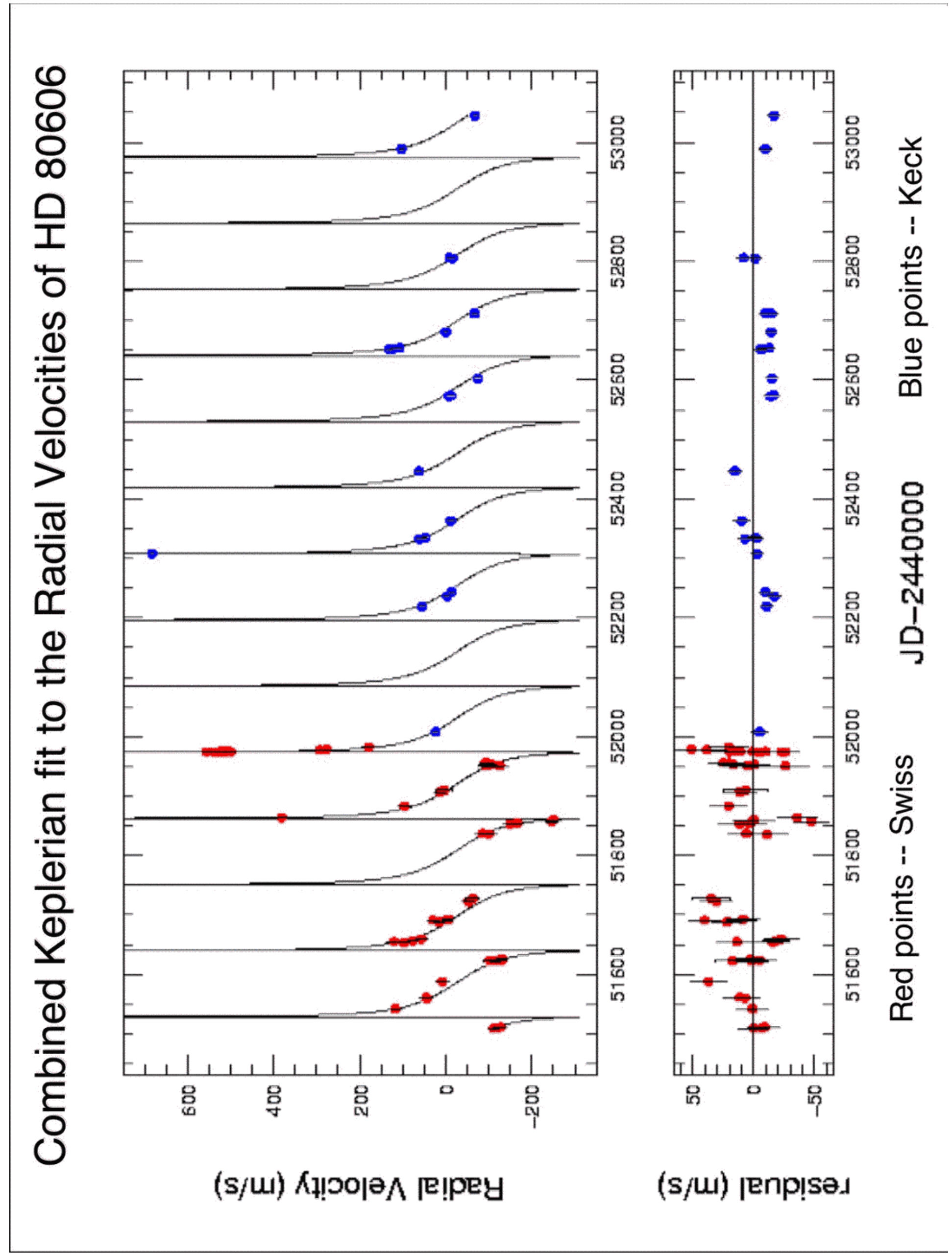
Can information regarding the inclinations be extracted from the radial velocity data set?

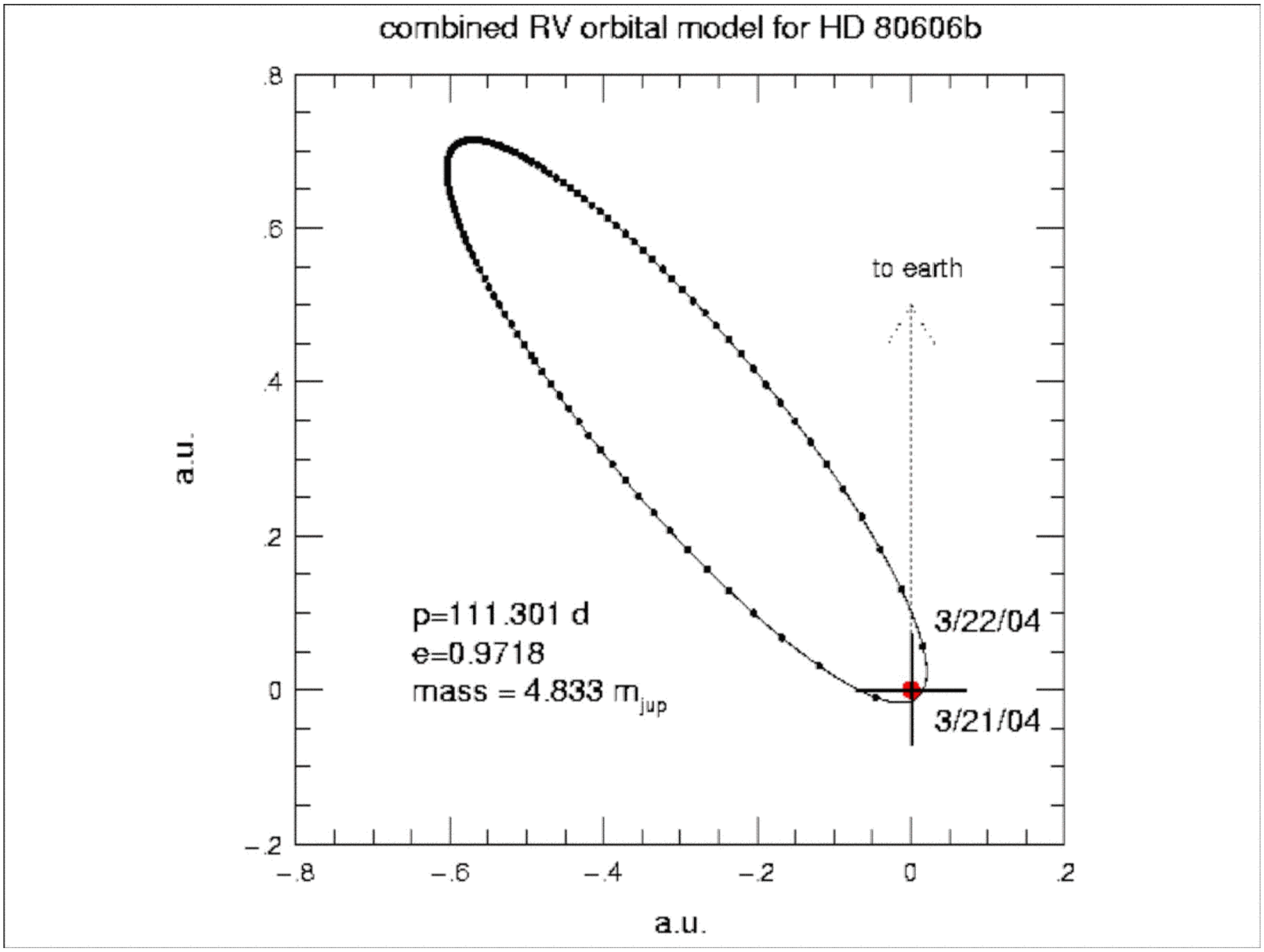


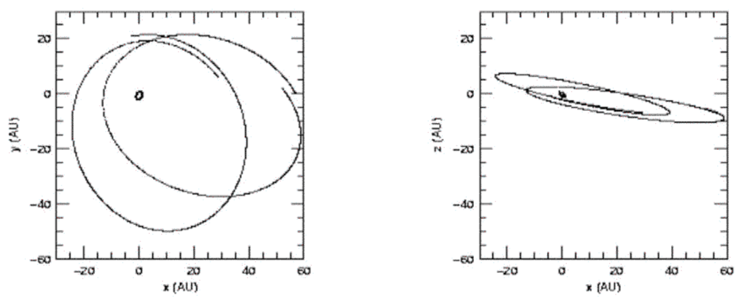

GJ 876 (Red: Fit to Actual Velocities, Black: Monte-Carlo fits to Edge-on System)
BEST FIT TO EDGE-ON SYSTEM
P1= 30.38 ± 0.02d P2= 60.93 ± 0.03d
M1= 360° ± 11° M2 = 186° ± 13°
e1=0.218 ± 0.002 e2=0.029 ± 0.004
ϖ1 = 154° ± 3° ϖ2 = 149° ± 12°
M1JUP= .597 ± .007 M2JUP = 1.90 ± .01
sqrt(χ2) of fits
Co-Planar Inclination to Line of Sight (e.g. 90-ι)


Libration width about 2:1 resonance for GJ 876 b and c
Red line: libration width observed in fits to actual data
Black lines and dots: libration width observed in fits to separate Monte-Carlo realizations of an edge-on system
Libration width of 2:1 resonance (deg)
Assumed Co-Planar Inclination to line of sight (deg)

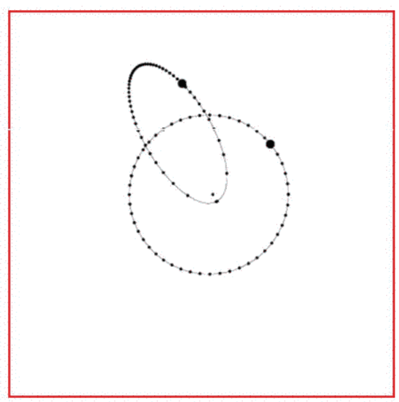

Libration width about apsidal alignment for GJ876 b and c
Red line: libration width observed in fits to actual data
Black lines and dots: libration width observed in fits
to separate Monte–Carlo realizations of an edge–on system
Co-Planar inclination to line of sight (deg)
Libration width of apsidal alignment (deg)
0
10
20
30
40
50
60
70


Combined Keplerian fit to the Radial Velocities of HD 80606
Radial Velocity (m/s)
residual (m/s)
600
400
200
0
−200
50
0
−50
51600
51800
52000
52200
52400
52600
52800
53000
JD−2440000
Red points -- Swiss
Blue points -- Keck

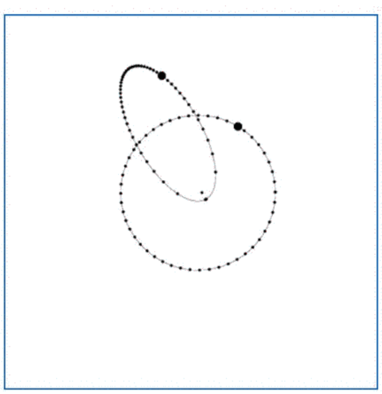




1:1 resonant configurations arise in ~1% of scattering events in crowded planetary systems.



The movie above shows the orbits of two Jovian-Mass planets over 15 years.



This movie on the left shows the secular evolution of two Jovian-Mass planets over several hundred years. Animations by Novak (2002).