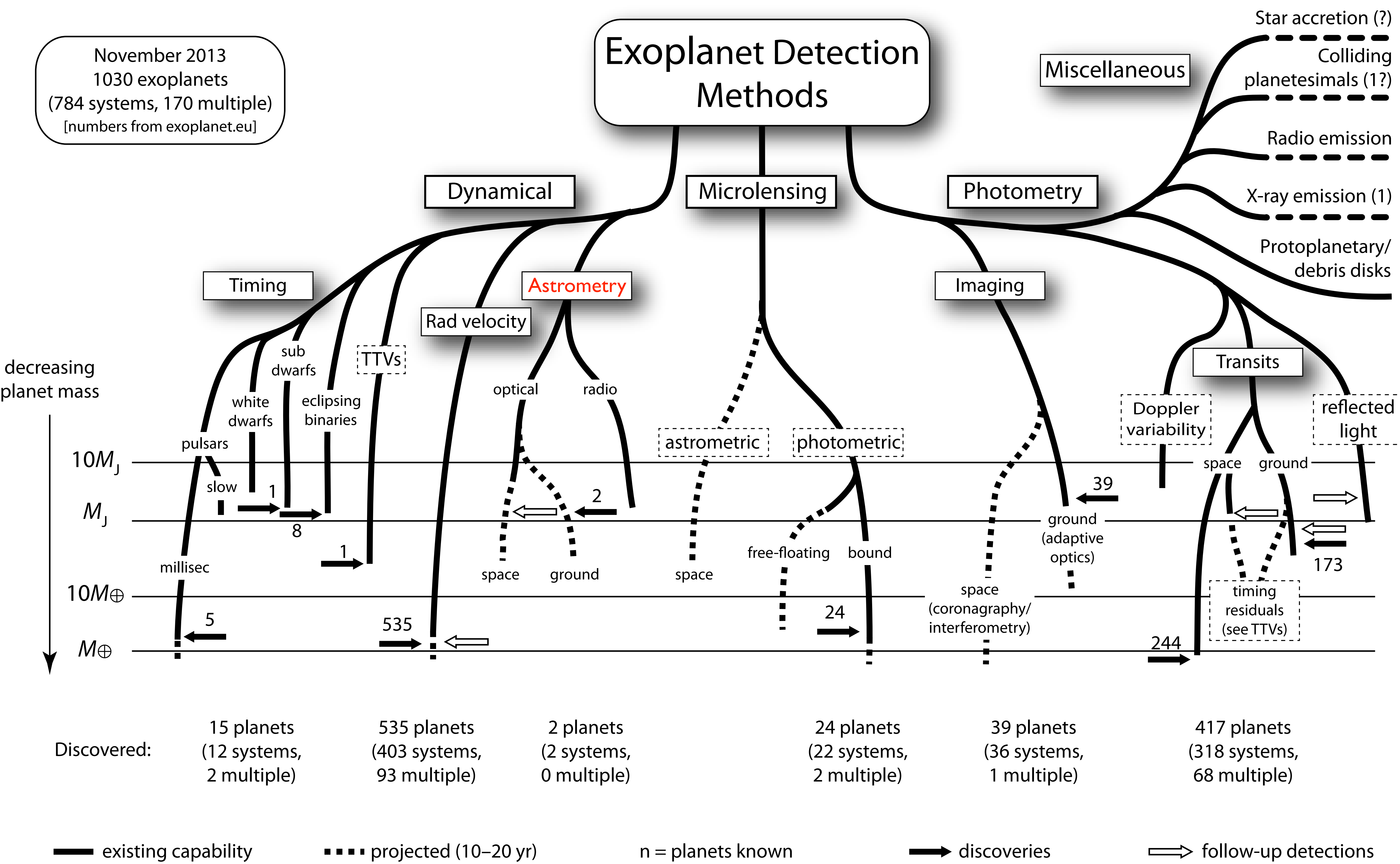
Lecture program

1. Space Astrometry 1/3: History, rationale, and Hipparcos
2. Space Astrometry 2/3: Hipparcos scientific results
3. Space Astrometry 3/3: Gaia
4. **Exoplanets: prospects for Gaia**
5. Some aspects of optical photon detection

Michael Perryman

Astrometry in the context of exoplanet detection/characterisation



Photometry

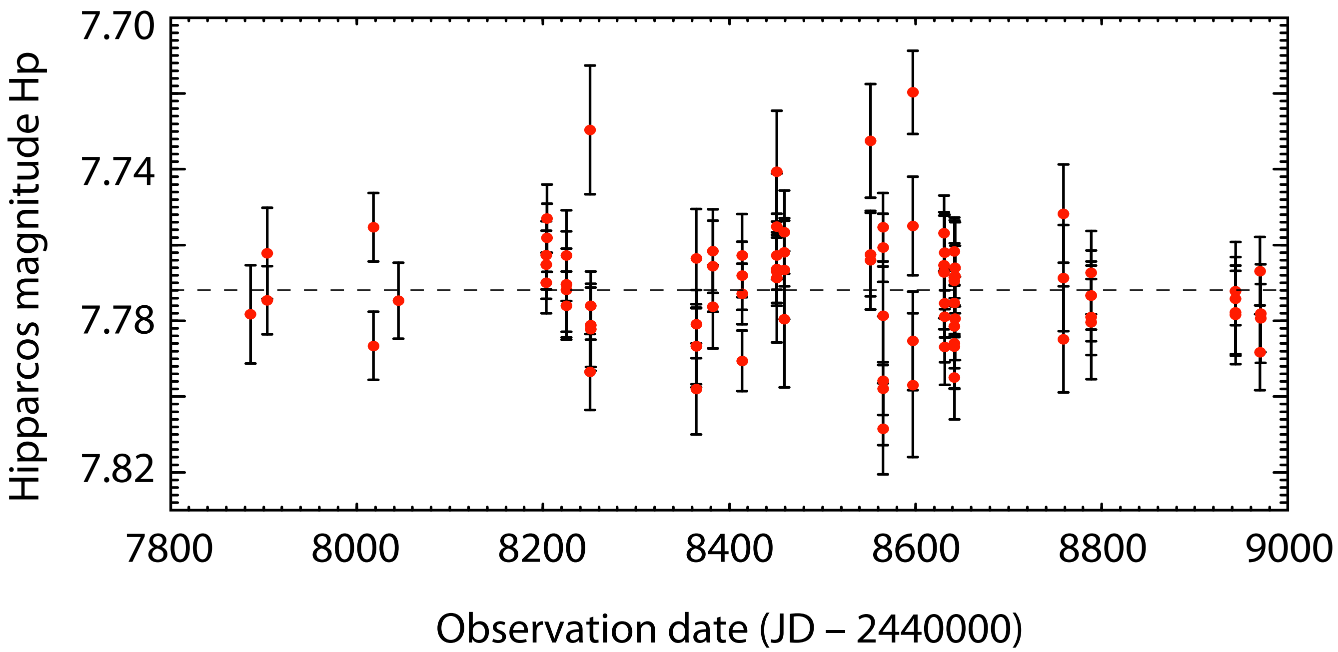
Hipparcos: a posteriori transit detection

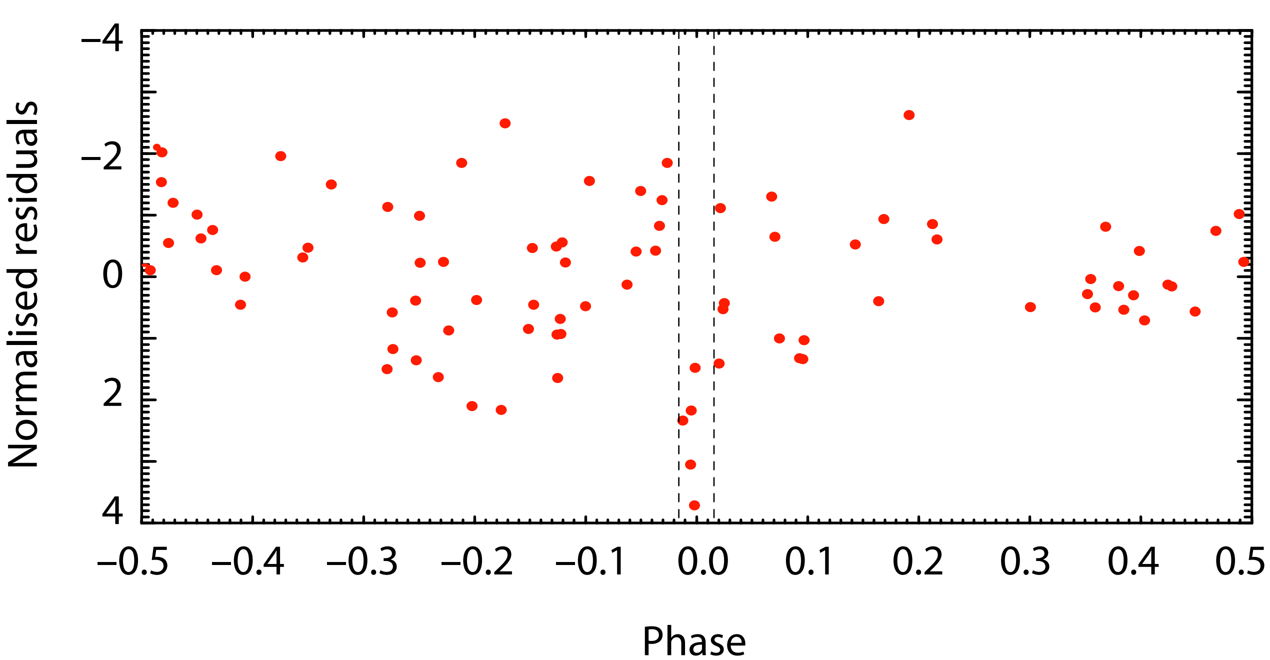
HD 209458 ⇒ P=3.524739(14) days

(Robichon & Arenou 2000; Söderhjelm et al 2000)

89 discrete observations around 1990, with 5 at transit epochs

(P=3.5d and Δt = 0.1 d ⇒ 3% transit probability)





also:

HD 189733 ⇒ P = 2.218574(8) days

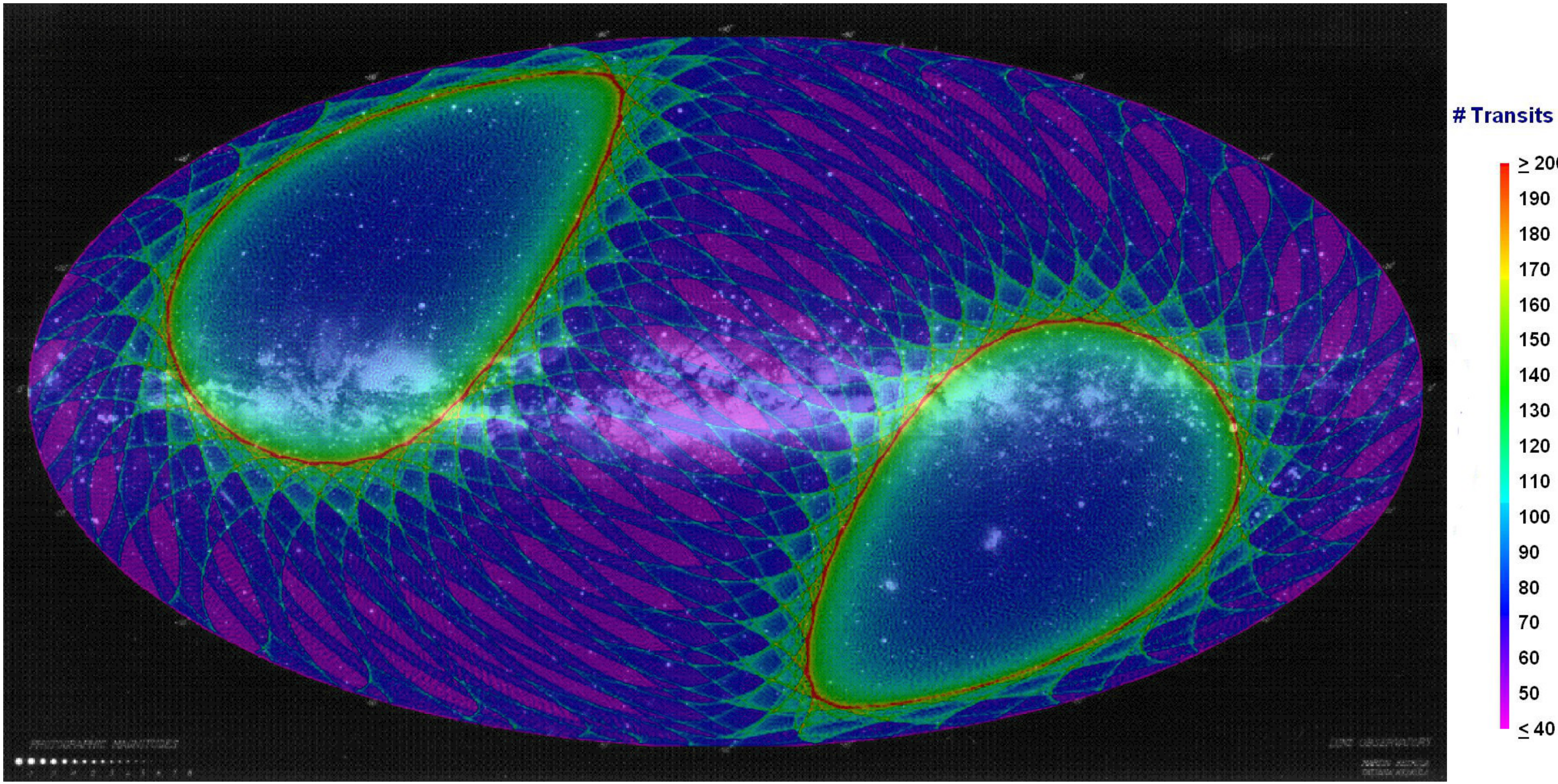
(Bouchy et al 2005;

Hébrard & Lecavelier des Etangs 2006)

Other studies set the scene for Gaia:

- Castellano et al 2000, 2001
- Laughlin 2000
- Koen & Lombard 2002
- Hoeg 2002
- Jenkins et al 2002
- Robichon 2002
- Hebrard et al 2006
- Gould & Morgan 2003
- Hatzes et al 2003, 2006
- Beatty & Gaudi 2008

Number of field of view transits

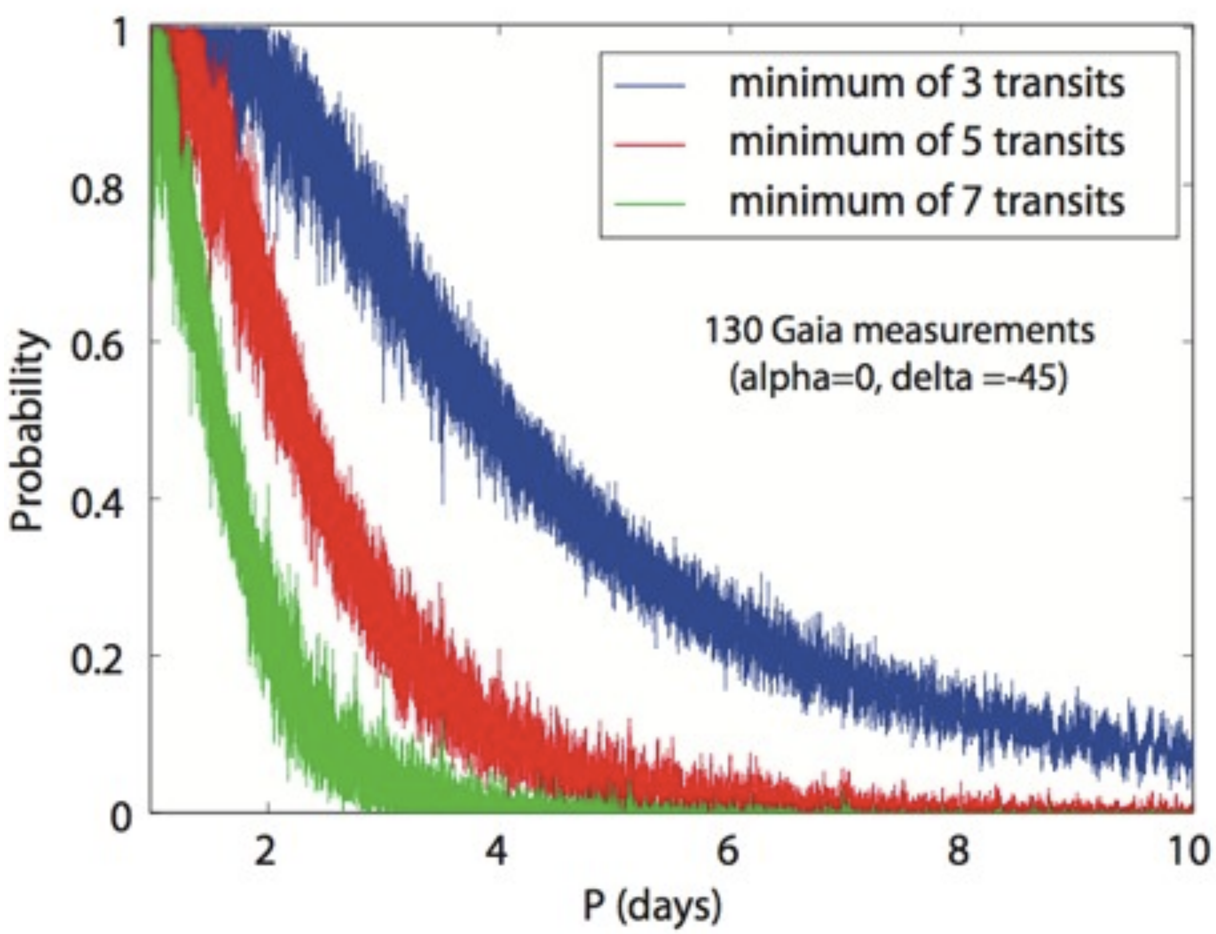


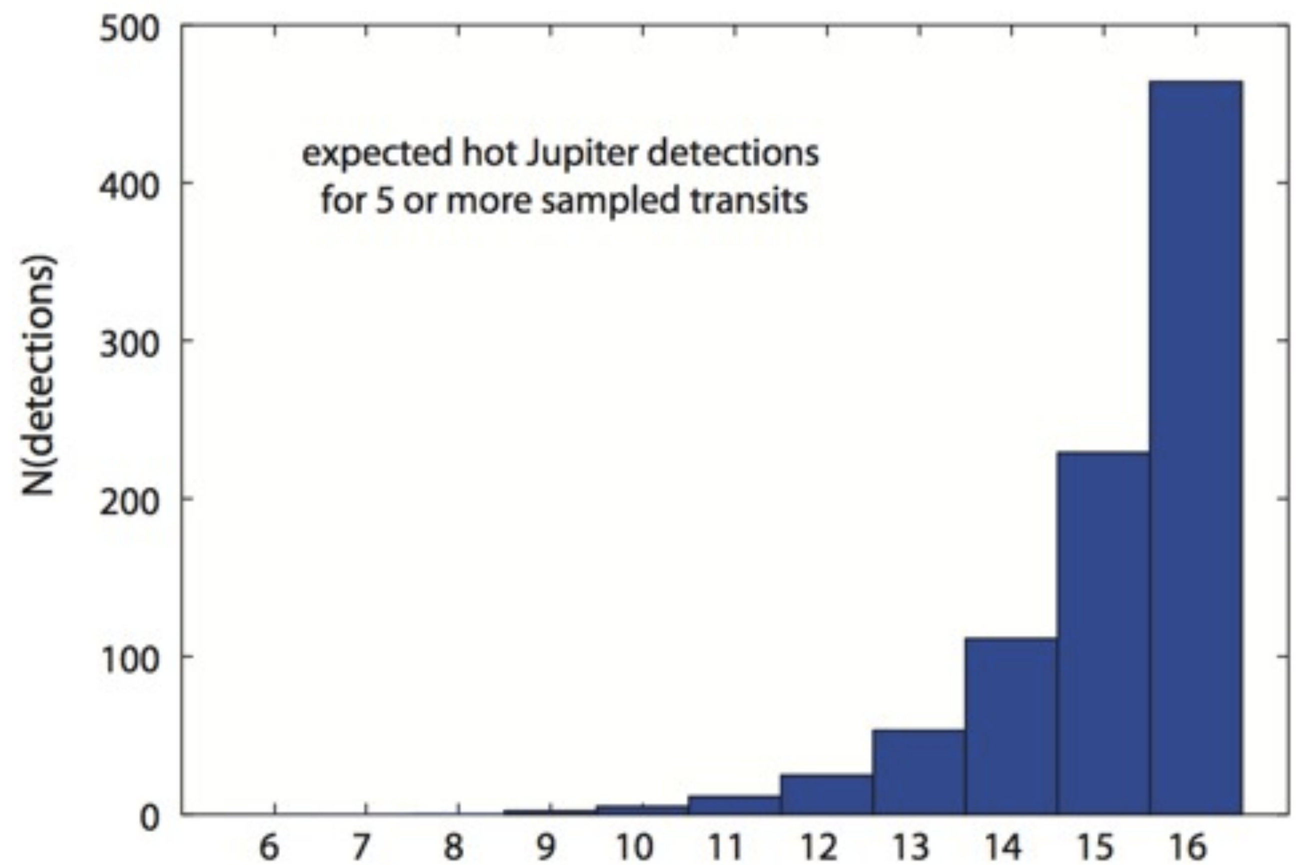
Gaia: estimates for (very) hot Jupiters
(Dzigan & Zucker 2012)

advantages: 1 mmag photometric accuracy
disadvantages: n(measures), low cadence

Simulations account for planet frequency, detection probability, stellar density, false detections, etc

assumes 2-hr transit duration



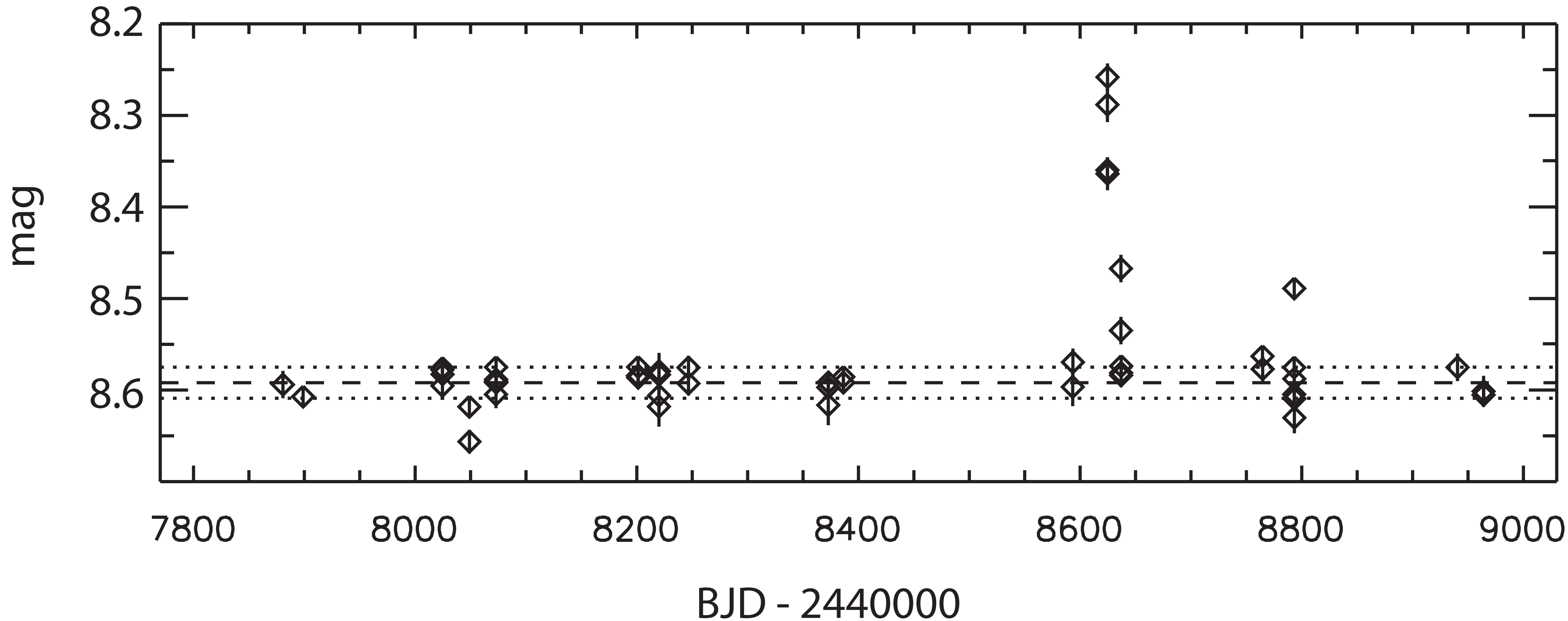


Conclusion: few hundred to a few thousand discoveries
(with the need for high-precision RV follow-up)

Photometry: planetary accretion events?

FH Leo (Dall et al. 2005):

- suggestion: a planetary accretion event
- rapid magnitude rise suggests asteroid mass such as Pallas or Vesta
- decay over ~ 17 days
- abundances of α-elements and Li
- but may be a nova (Vogt 2006)



Distances and space motions

Distances and motions

Examples:

- distances provide stellar parameters
  - e.g. transit planet diameters $\propto$ stellar diameters
- verification of seismology models for *M*, *R*
- proper motions characterise population(s)

  e.g. HIP 13044 low-metallicity Galactic halo stream (Helmi+1999, Setiawan+2010)
- Galactic birthplace based on metallicity-age

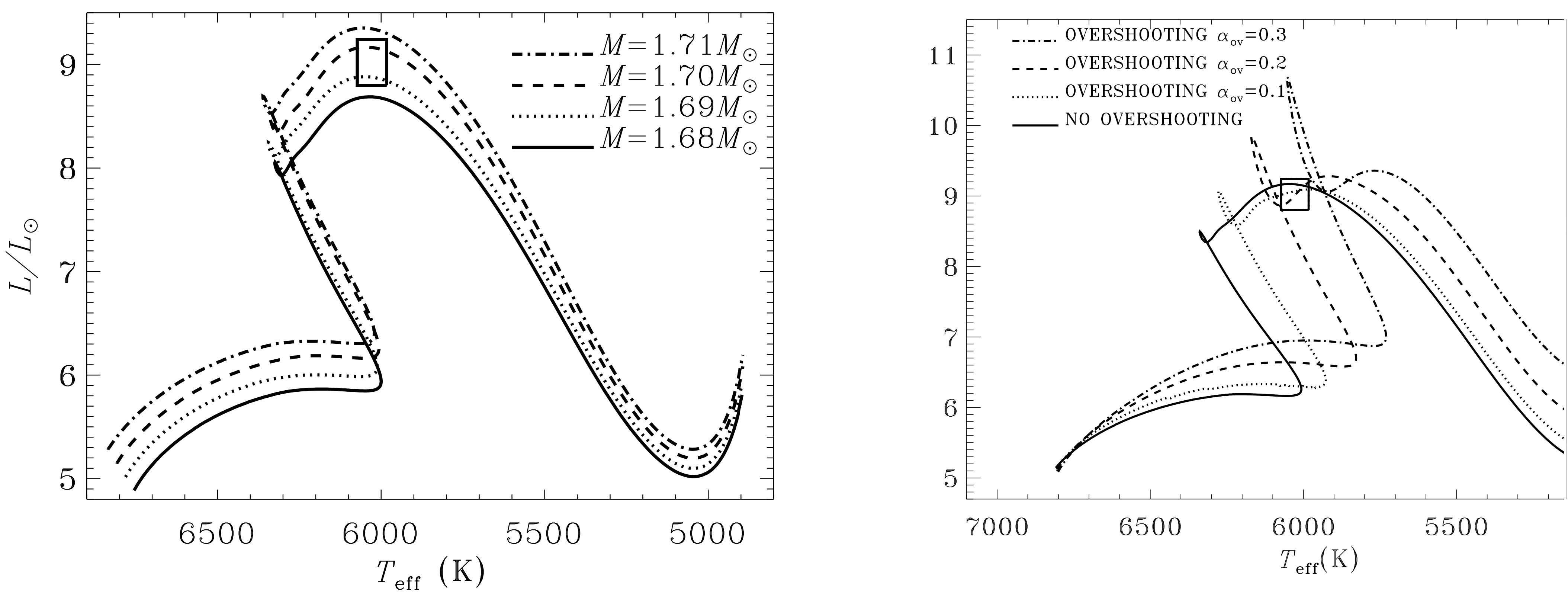
  e.g. Wielen (1996) inferred that the Sun's birthplace was at R=6.6 kpc

Asteroseismology

Can hope to discriminate:

- primordial or self-enriched metallicity (bulk/surface): μ Ara (Pepe 2007), ι Hor (Laymand 2007)
- planet radii calibrated wrt stellar radii: HAT-P-7 (Christensen-Dalsgaard+ 2010)
- mass estimates cf isochrone models: β Gem, HD13189 (Hatzes+ 2008)
- etc

For this, verification of the models by comparing parallax-based L with asteroseismology



Asteroseismology of η Boo, Z=0.04.
Left: M=1.70±0.005 $M_\odot$ Right: with overshooting
(Di Mauro et al 2003)

Galactic birthplace (cont.)

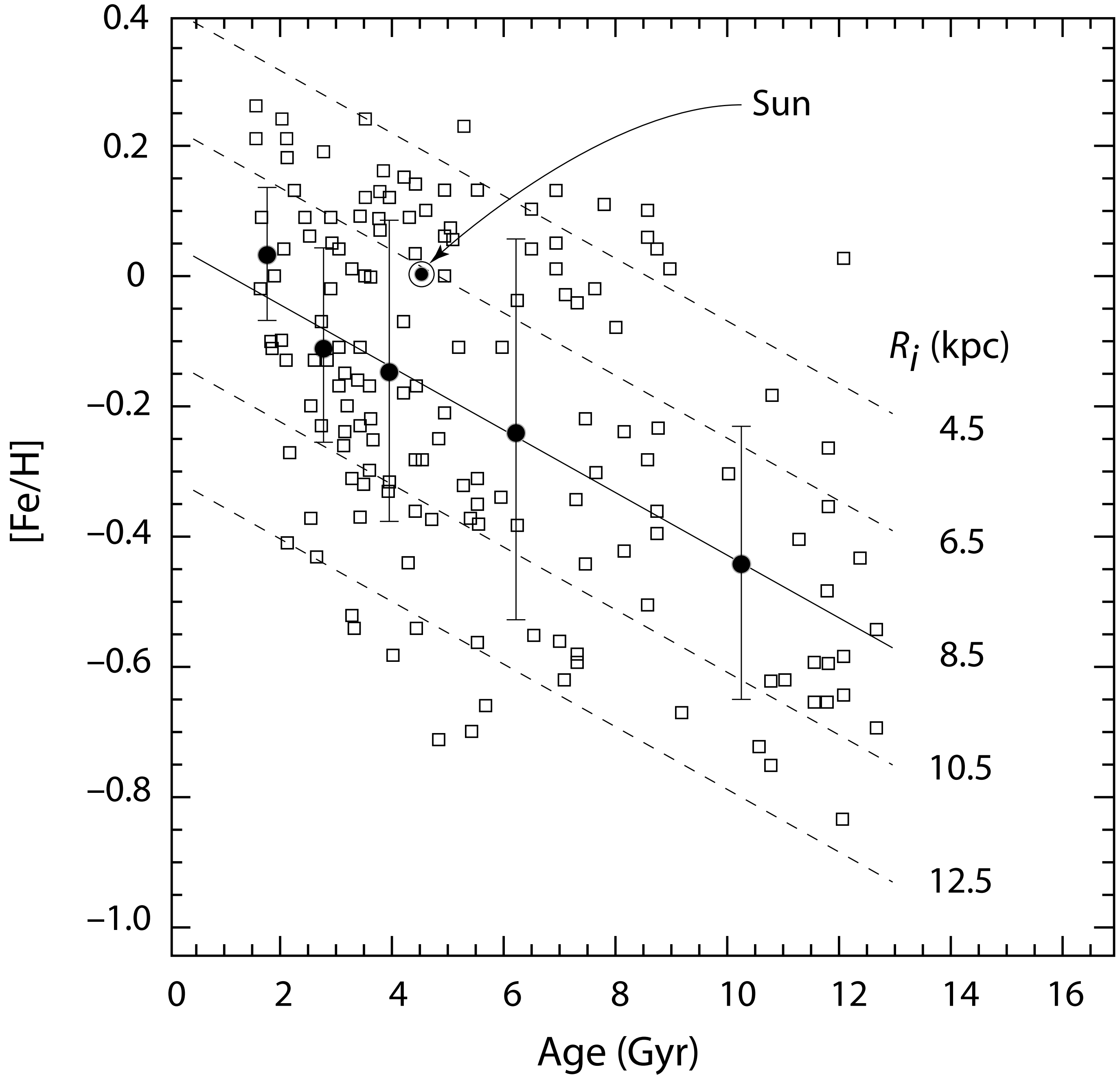
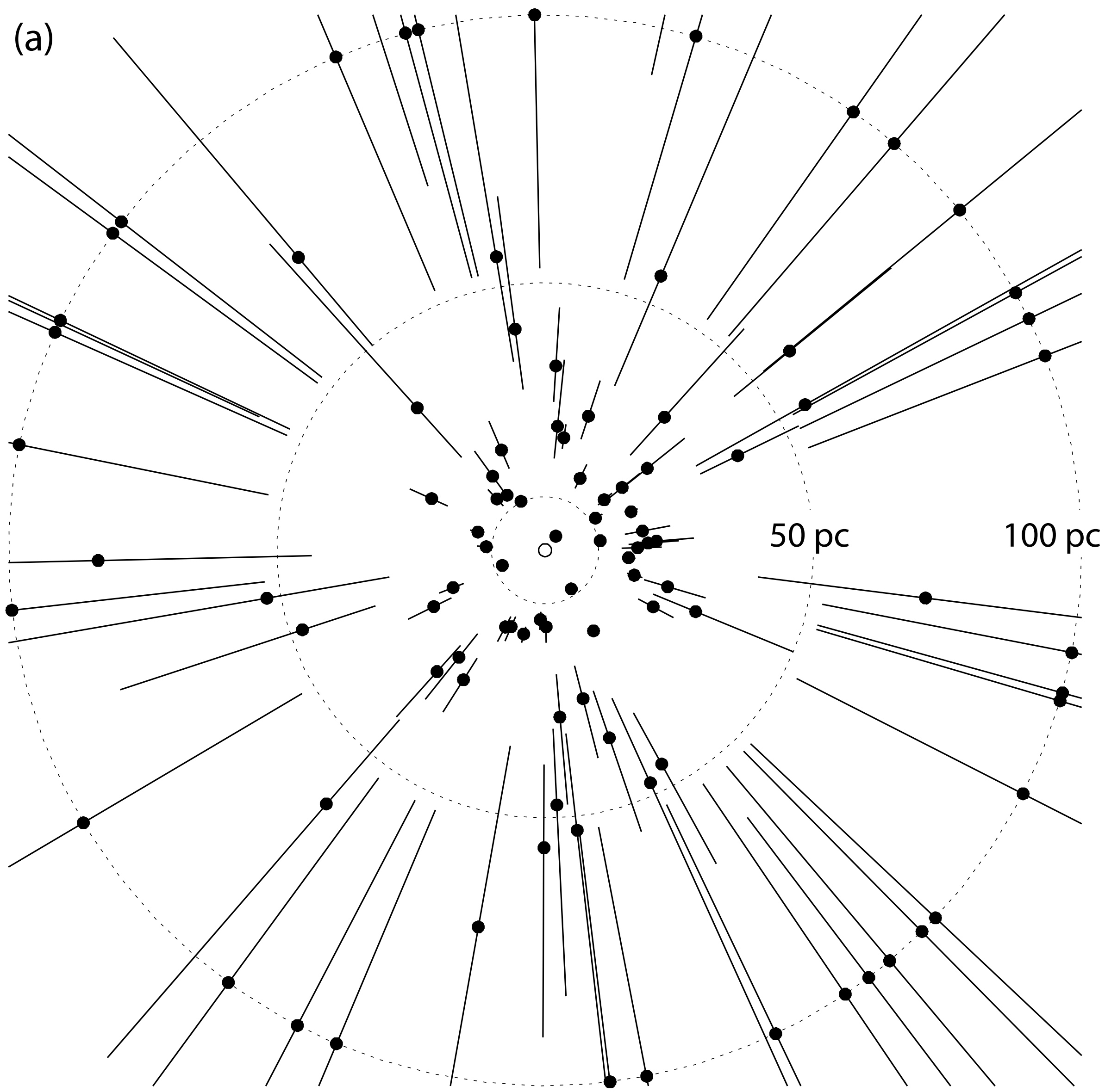


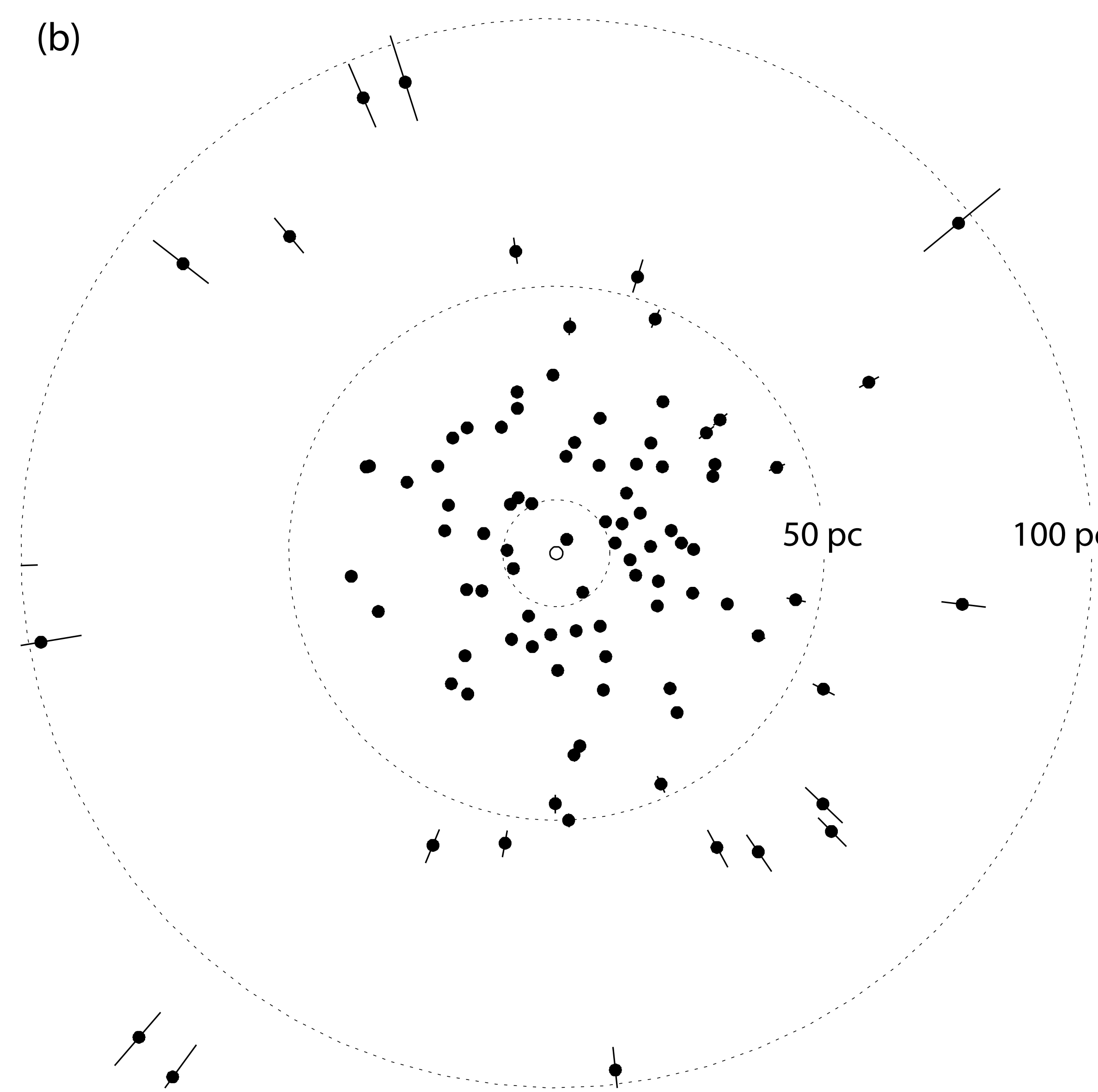
Figure 8.13: Places of formation of stars which are now nearby. Metallicity [Fe/H] is plotted against age for stars from the sample of Edvardsson et al. (1993). The position of the Sun is indicated. Inclined lines are of constant Galactocentric distance for their derived age–metallicity relation, such that the place of formation, R_i, can be determined for each star, including the Sun. Mean metallicities as a function of age are shown as filled circles. From Wielen et al. (1996, Figure 3), reproduced with permission © ESO.

Hipparcos distances to exoplanet host stars

100 brightest radial velocity host stars (end 2010)
(versus RA, independent of dec)



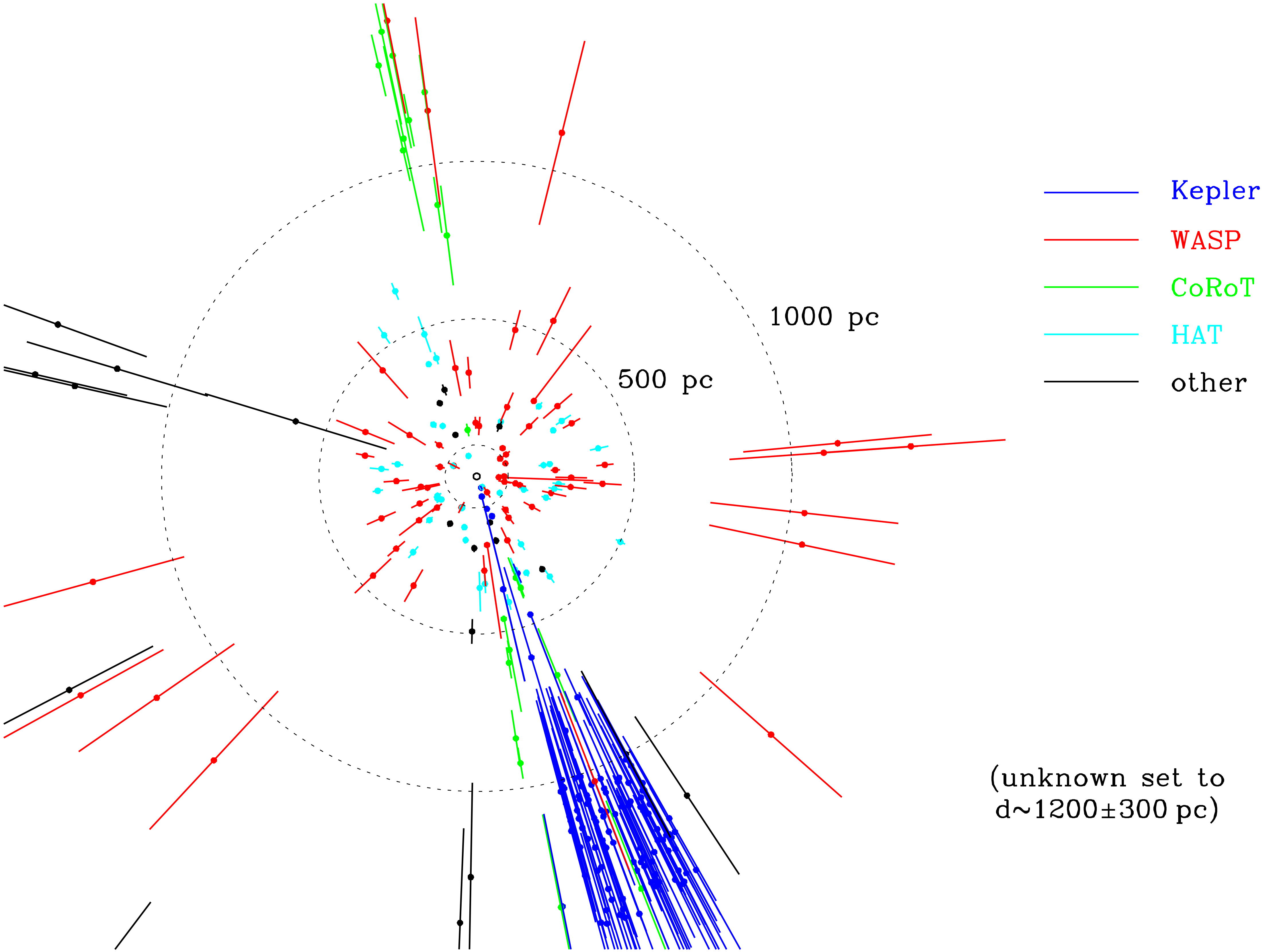
ground-based: van Altena et al (1995)
(unknown assigned π = 10±9 mas)



Hipparcos parallaxes
(Perryman et al 1997)

Gaia distances to exoplanet host stars

Transit host stars (~280, October 2013)

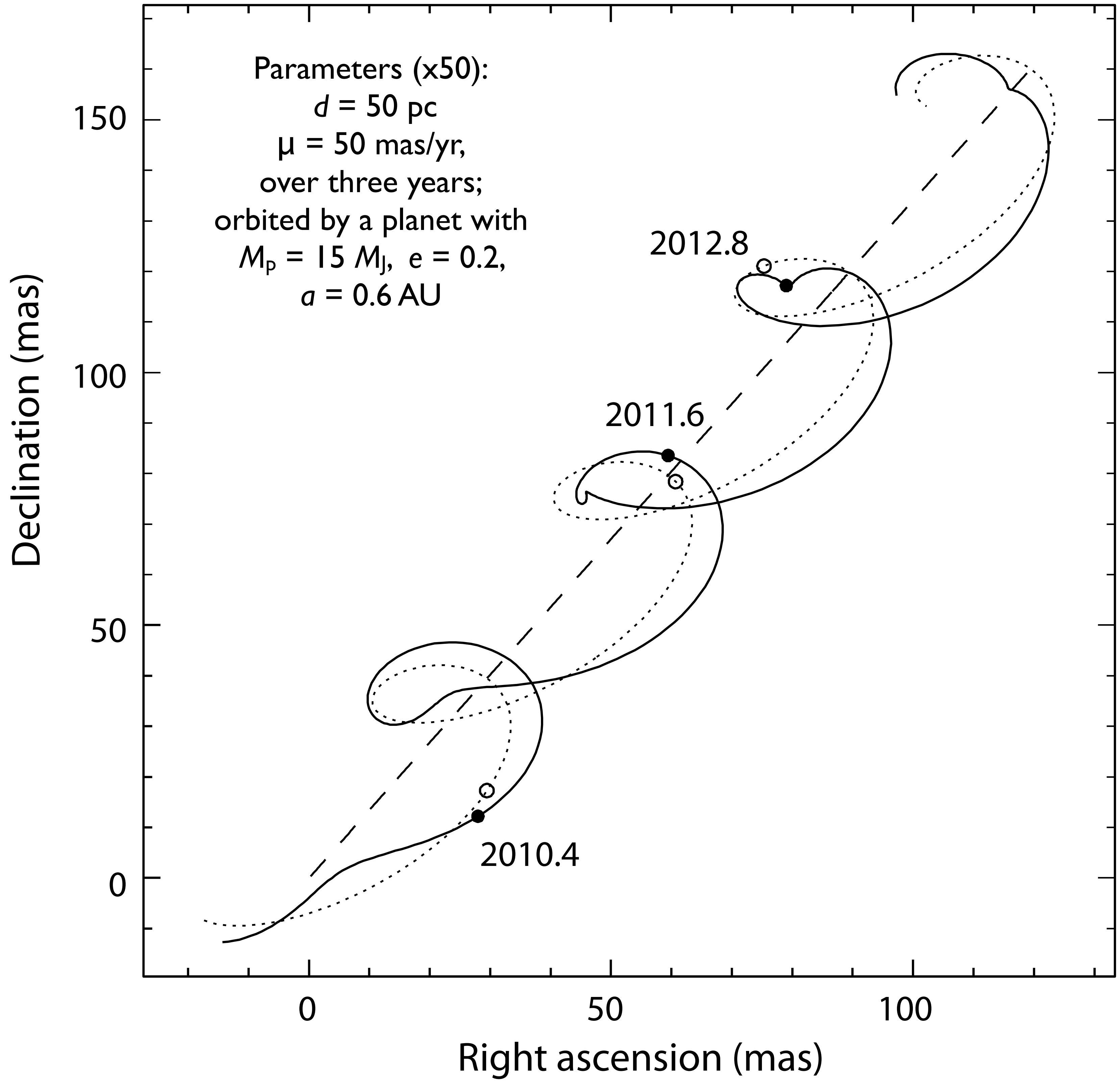


New astrometric detections

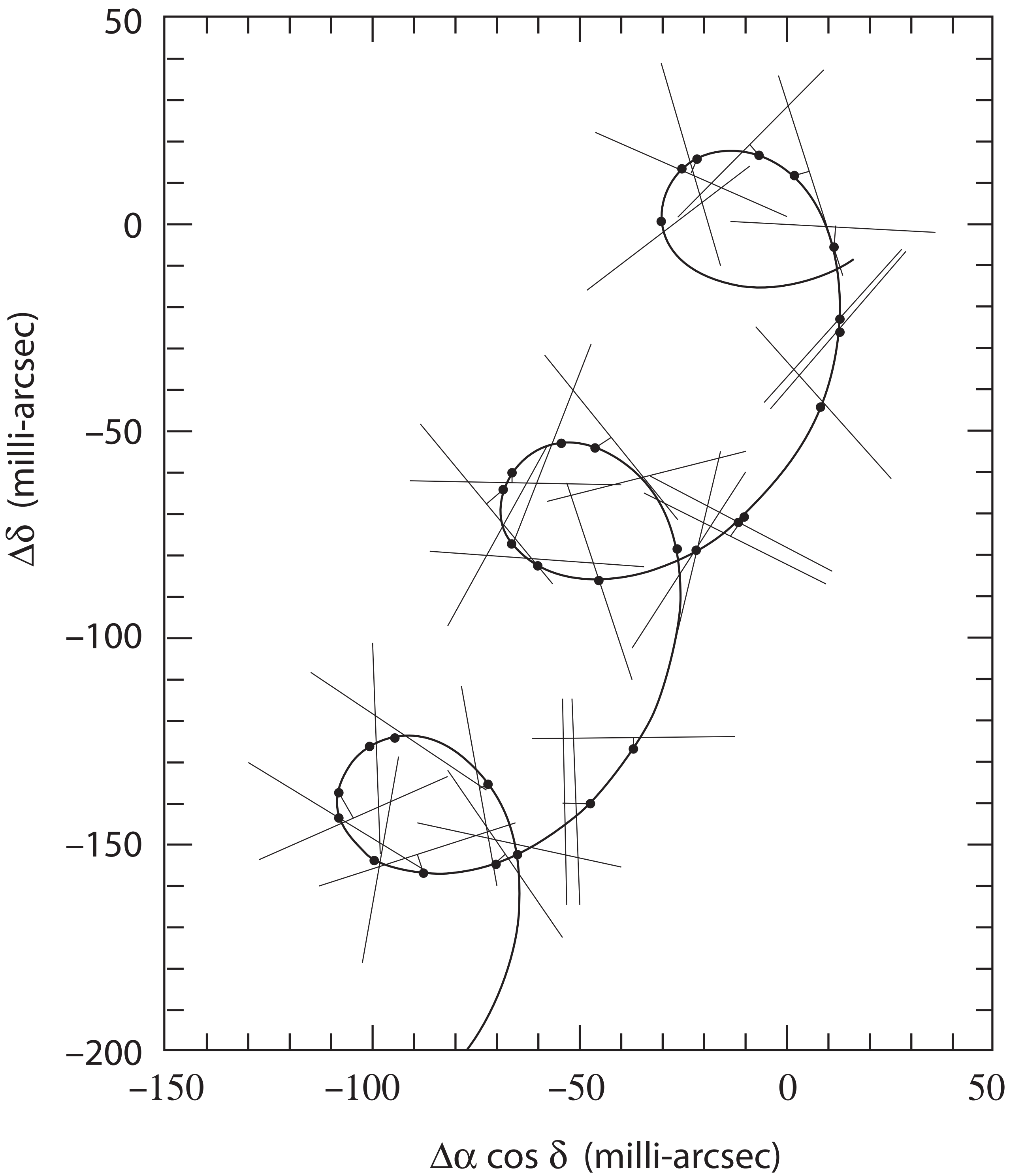
Discovery from 'astrometric signature'

Unseen planets perturb the photocentre, which moves with respect to the barycentre (as for Doppler measures)

and provides *M* directly (not simply *M* sin *i*)

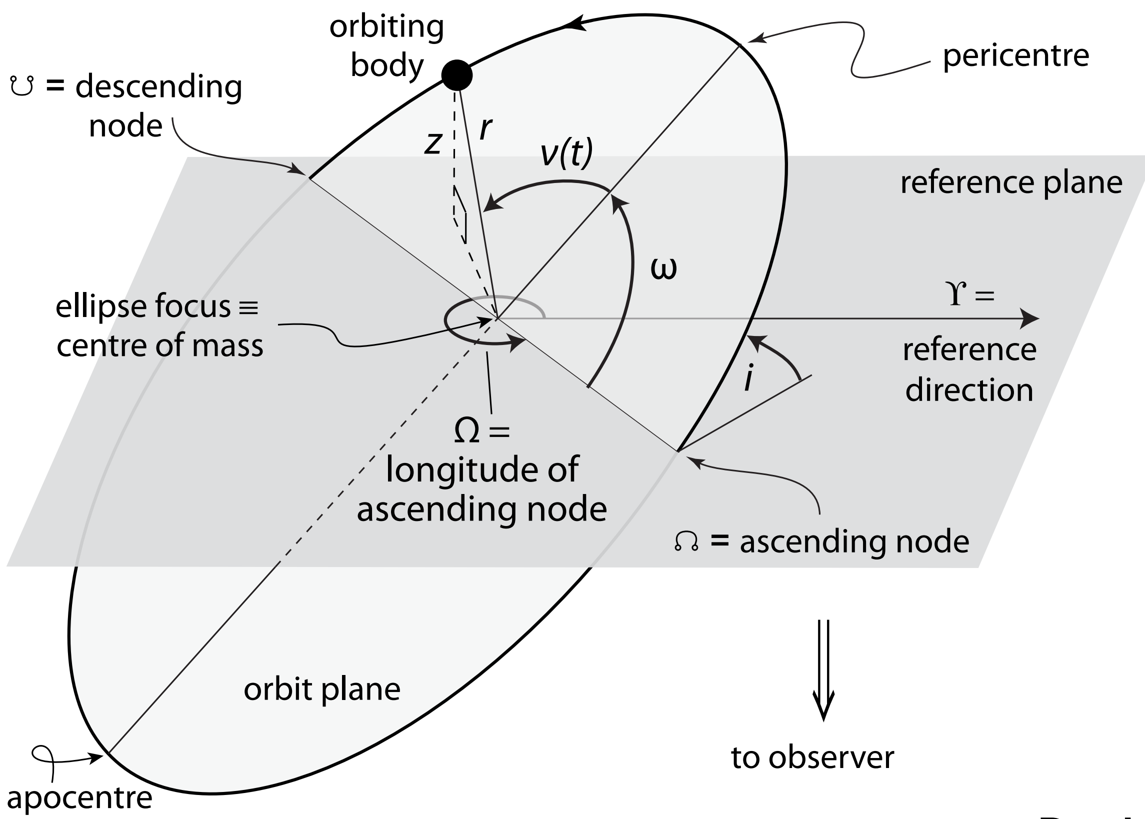


Astrometric analysis: principles



- as the satellite traces out a series of great circles on the sky, each star is (effectively) instantaneously stationary
- each star has a 2d position (abscissa and ordinate) projected onto that great circle
- in principle one should solve for both coordinates
- in practice, only the projection along the great circle (abscissa) dominates the 'great-circle solution'
- least-squares adjustment gives the along-scan position of each star at that epoch
- all great circles over the entire mission are then 'assembled'
- a star's position at any time *t* is represented by just <u>five</u> parameters: position (*xy*), proper motion components (μ_x, μ_y), parallax (π)

Direct access to planet mass



Keplerian orbit in 3d determined by 7 parameters:
a, e: specify size and shape
P: related to *a* and masses (Kepler's 3rd law)
t_p: the position along orbit at some reference time
i, Ω,ω*:* represent projections wrt observer

Radial velocity measures:

- cannot determine Ω,
- only determine the combination *a* sin *i*
- only determine M_P sin *i* if M_* can be estimated
- cannot determine Δ*i* for multiple planets

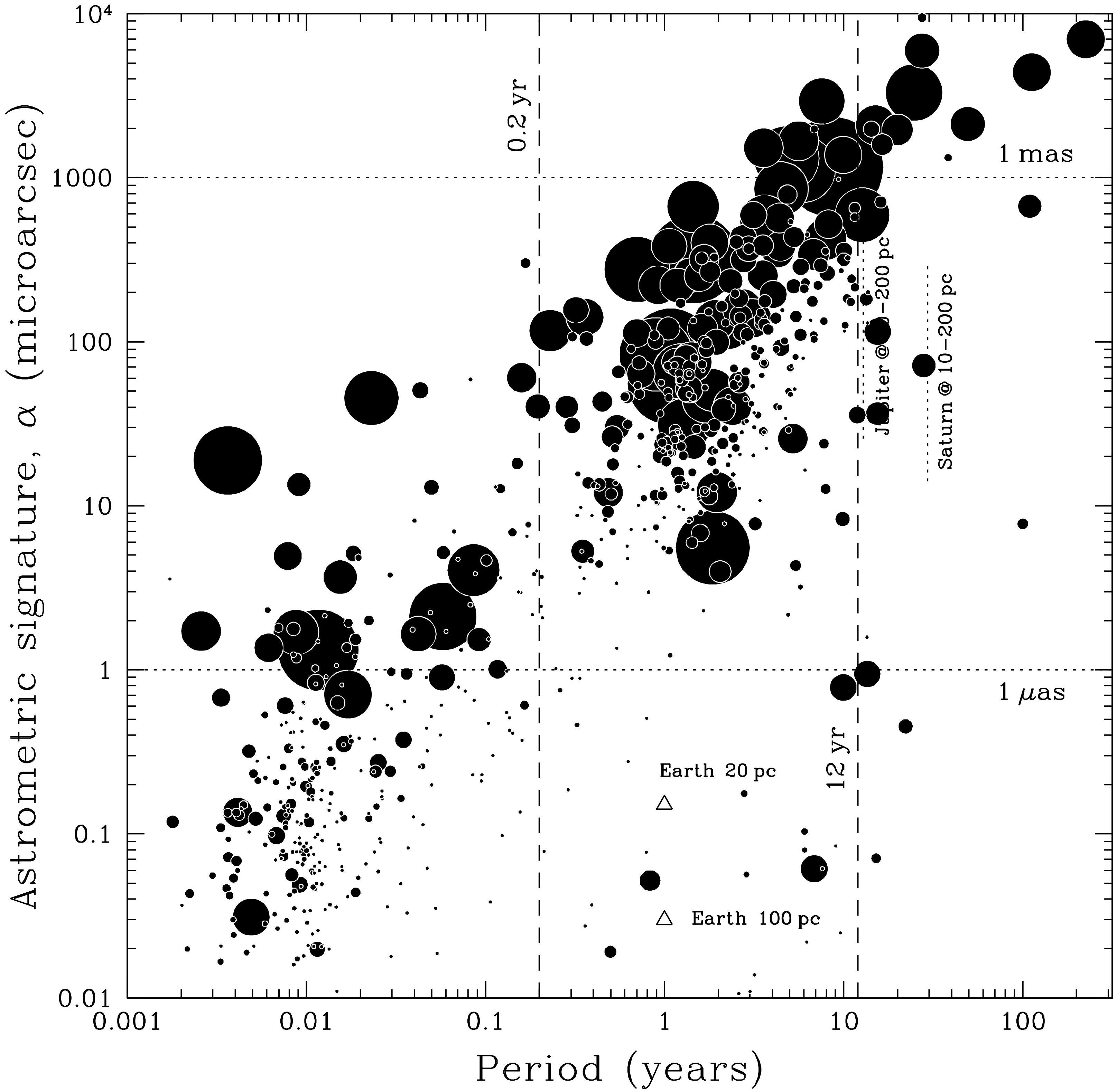
All 7 parameters <u>are</u> determinable by astrometry (±180° on Ω). Conceptually:

- *xy(t)* yields max and min angular rates, and hence the line of apsides (major axis)
- then appeal to Kepler's third law fixes the orbit inclination

The 'tragic history' of astrometric planet detection

- Jacob (1855) 70 Oph: orbital anomalies made it *'highly probable'* that there was a *'planetary body'*; supported by See (1895); orbit shown as unstable (Moulton 1899)
- Holmberg (1938): from parallax residuals... `*Proxima Centauri probably has a companion'* of a few Jupiter masses
- Reuyl & Holmberg (1943) 70 Oph: planetary companion of ~10 M_J
- Strand (1943) 61 Cyg: companion of ~16 M_J
- lengthy disputes about planets around Barnard's star: van der Kamp (1963, 1982)
- similarly for Lalande 21185 (e.g. Lippincott 1960)
- Pravdo & Shaklan (2009) vB10 with Palomar-STEPS, later disproved (Bean 2010)
- Muterspaugh+ (2010) HD~176051, only current detection: *'may represent either the first such companion detected, or the latest in the tragic history of this challenging approach.'*
- early discussions of space astrometry/Hipparcos exoplanet capabilities:
  - Couteau & Pecker (1964), Gliese (1982)

Astrometric signature



$$\alpha = \frac{M_p}{M_\star + M_p} a \simeq \frac{M_p}{M_\star} a$$

$$\equiv \left(\frac{M_p}{M_\star}\right)\left(\frac{a}{1\,\mathrm{AU}}\right)\left(\frac{d}{1\,\mathrm{pc}}\right)^{-1} \text{arcsec}$$

Hipparcos astrometry
is marginal for detection
(and mass determination)

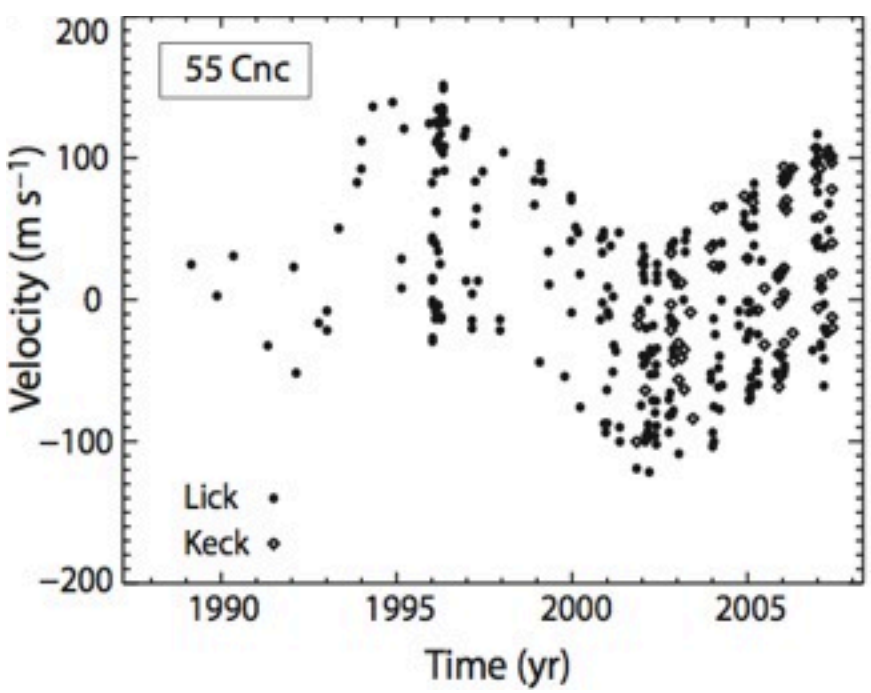
Gaia: number of astrometric detections

- Gaia was studied since 1997; accepted in 2000; launch: 20 December 2013
- early estimates of 10−30,000 detectable exoplanets were based on target accuracies at time of acceptance (Lattanzi et al 2000, Perryman et al 2001, Quist 2001, Sozzetti et al 2001), and are no longer applicable
- more recent estimates (Castertano+ 2008):
    - single measurement error for bright stars σ_ψ ~ 8 μas
    - reliable detections for P<5 years and $\alpha > 3\sigma_\psi$
    - at 2x this limit, errors on orbits and masses are ~ 15−20%
    - > 70% of 2-planet systems with $0.2 < P < 9$ yr and $e < 0.6$ are identified
    - typical uncertainties on Δi for favourable systems are <10°
- bottom line:
    - discover/measure several thousand giant planets with a =3−4 AU and d < 200pc
    - characterise hundreds of multiple systems with meaningful tests of coplanarity

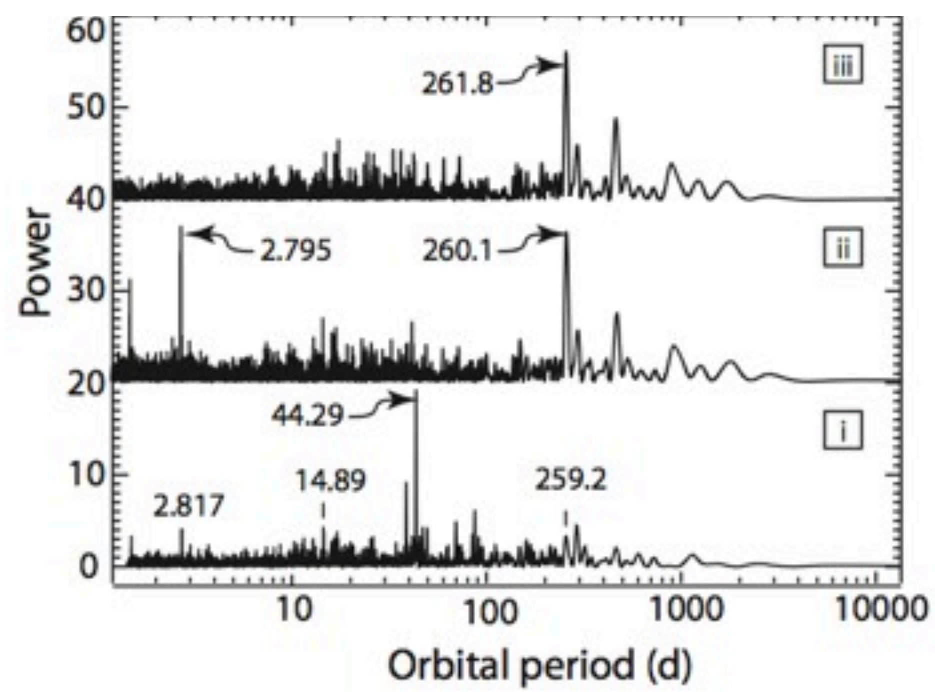
For multiple planet systems...

Drawing on extensive radial velocity work, multiple systems can be fit by (e.g.) recursive decomposition

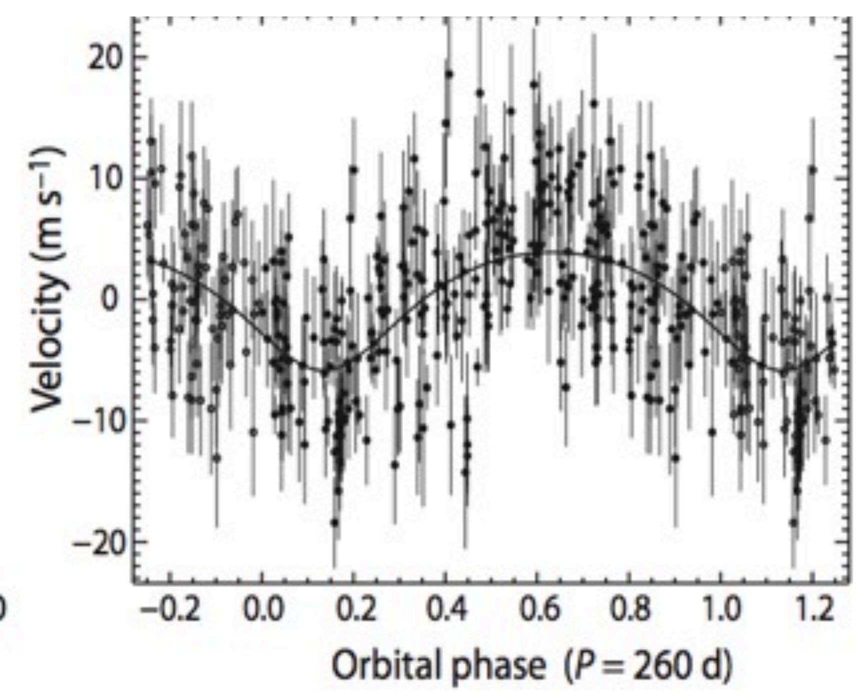
Non-linearity of the fitting for Gaia/SIM: considered by Casertano et al (2008), Wright & Howard (2009), Traub et al (2010)



5-planet system 55 Cnc (Fischer et al 2008)



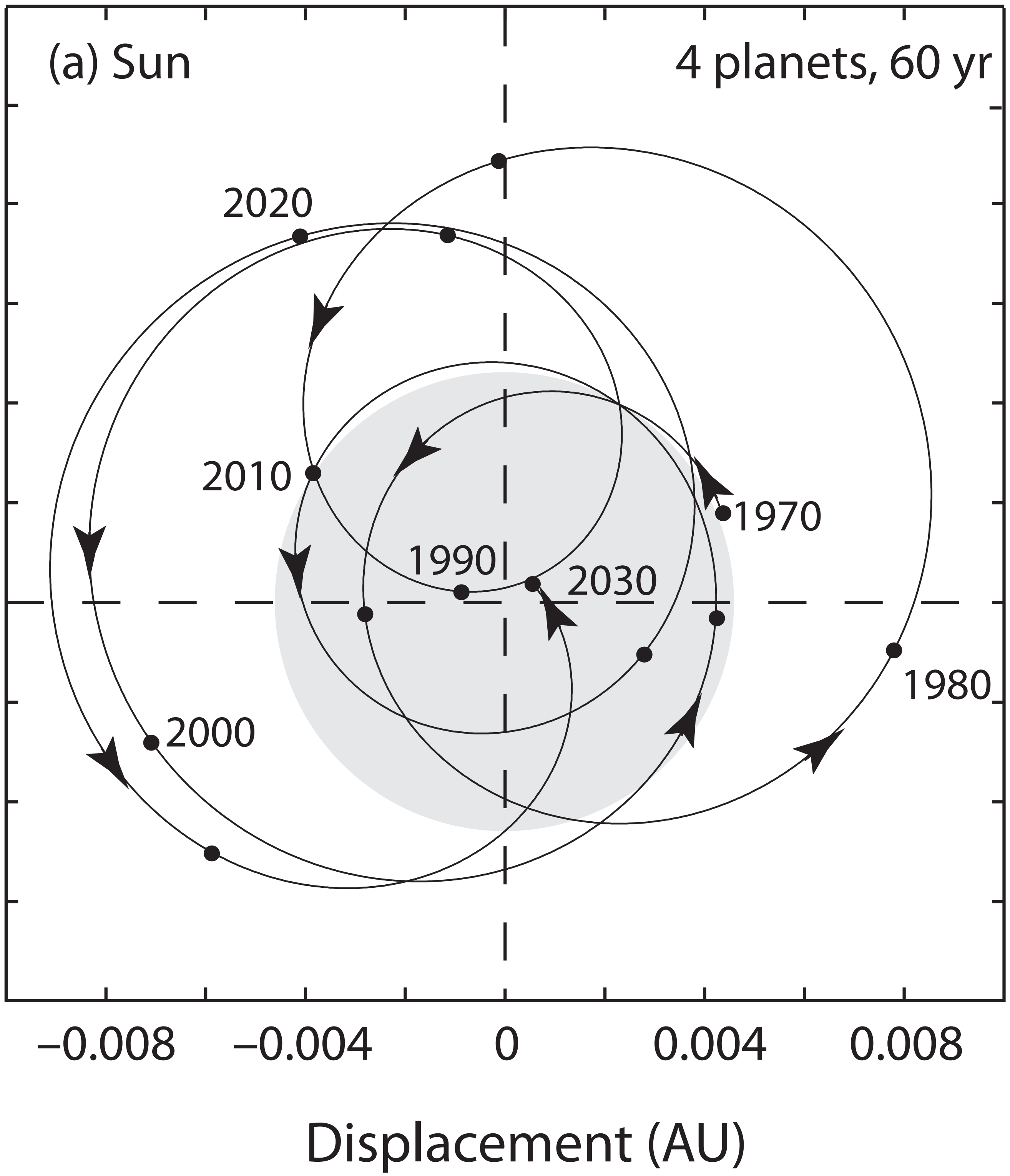
Periodograms wrt:
(i) 2-planet model
(ii) 3-planet model
(iii) 4-planet model



Periodicity of the fifth planet in the Keck data

Astrometric motion for multiple planets...

(assuming orbits are co-planar)

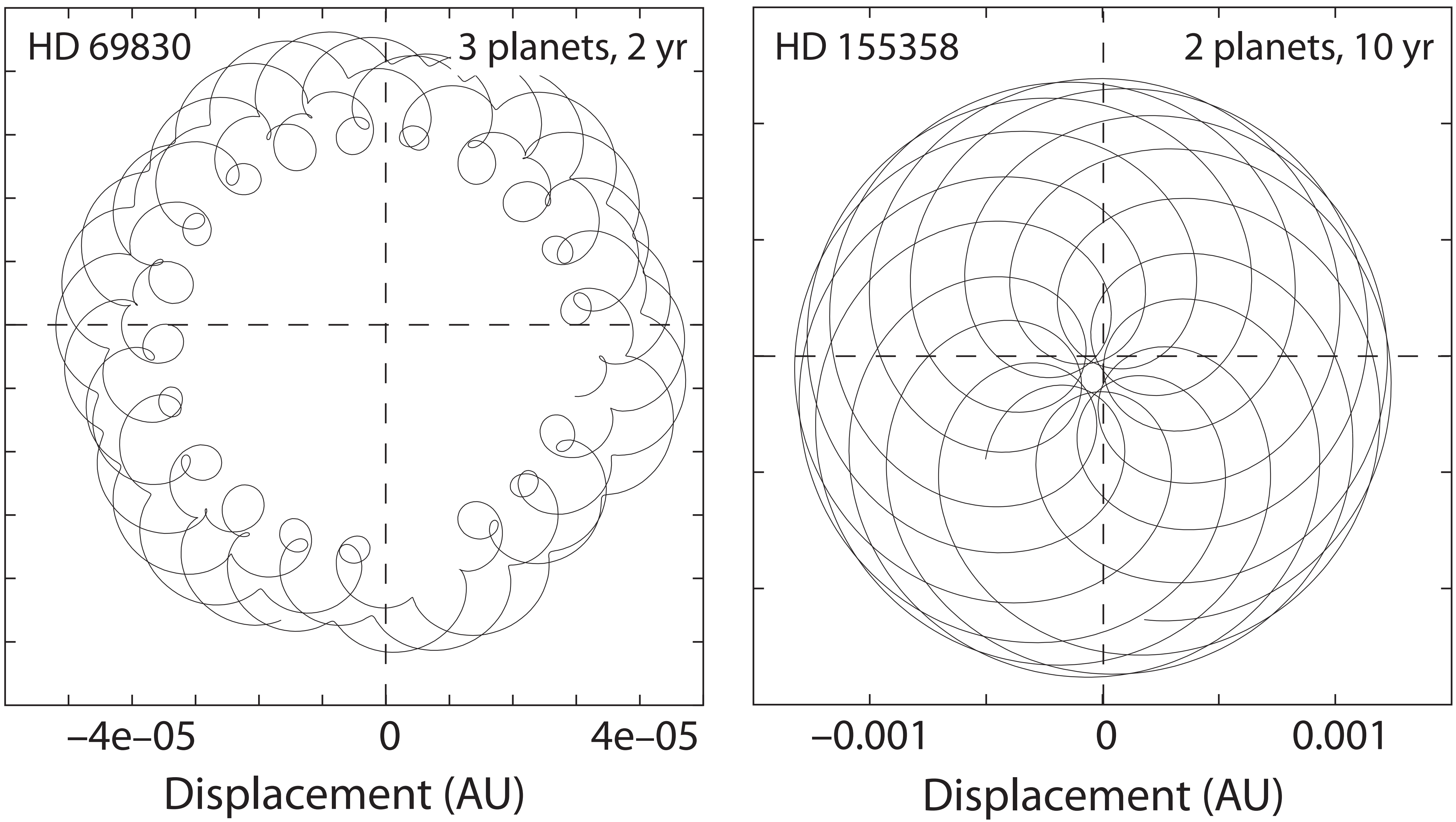


The sun's motion guides us:

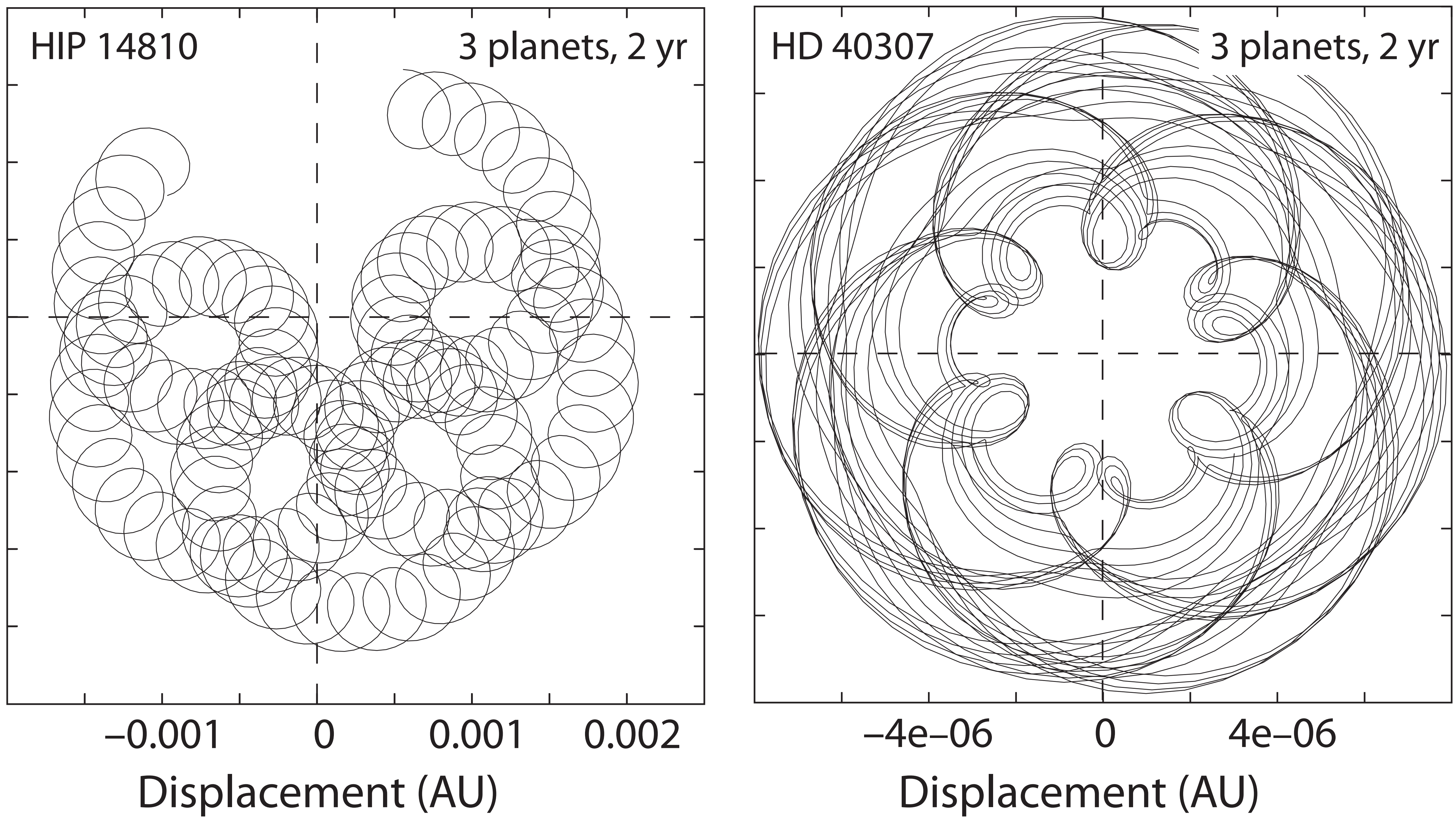
- Newton: *'since that centre of gravity is continually at rest, the Sun, according to the various positions of the planets, must continuously move every way, but will never recede far from that centre' (Cajori 1934)*
- barycentre frequently extends beyond the solar disk
- periods when the Sun's motion is 'retrograde' with respect to the barycentre (~1990, 1811,1632)

Motion of host star around barycentre for multiple exoplanets

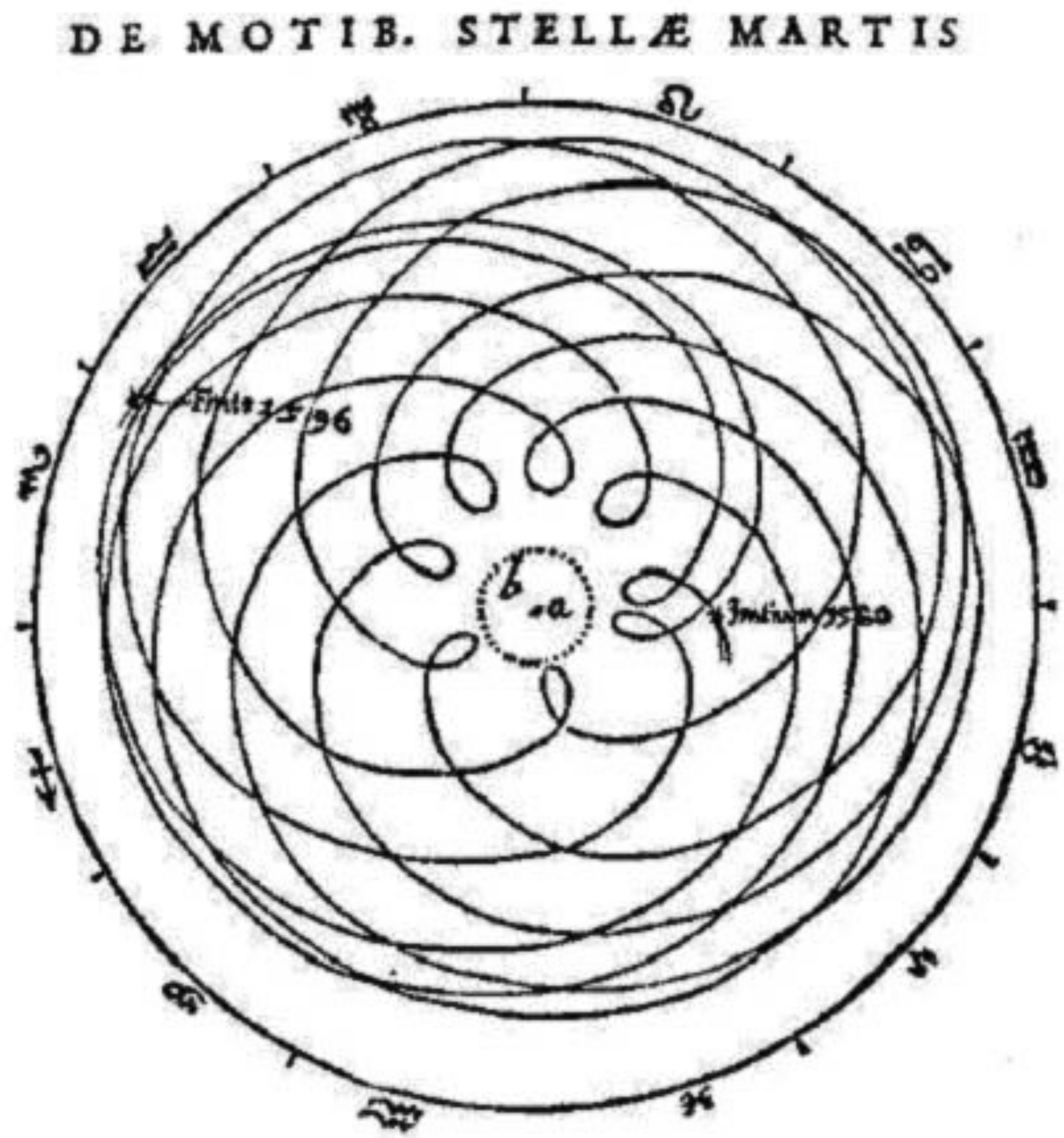
(assuming coplanarity)



Motion for multiple planets (cont.)



Astronomia Nova (1609) includes Kepler's hand drawing of the orbit of Mars viewed from Earth



...designated as 'mandala'
(Sanskrit for circle)
by Wolfram (2010)

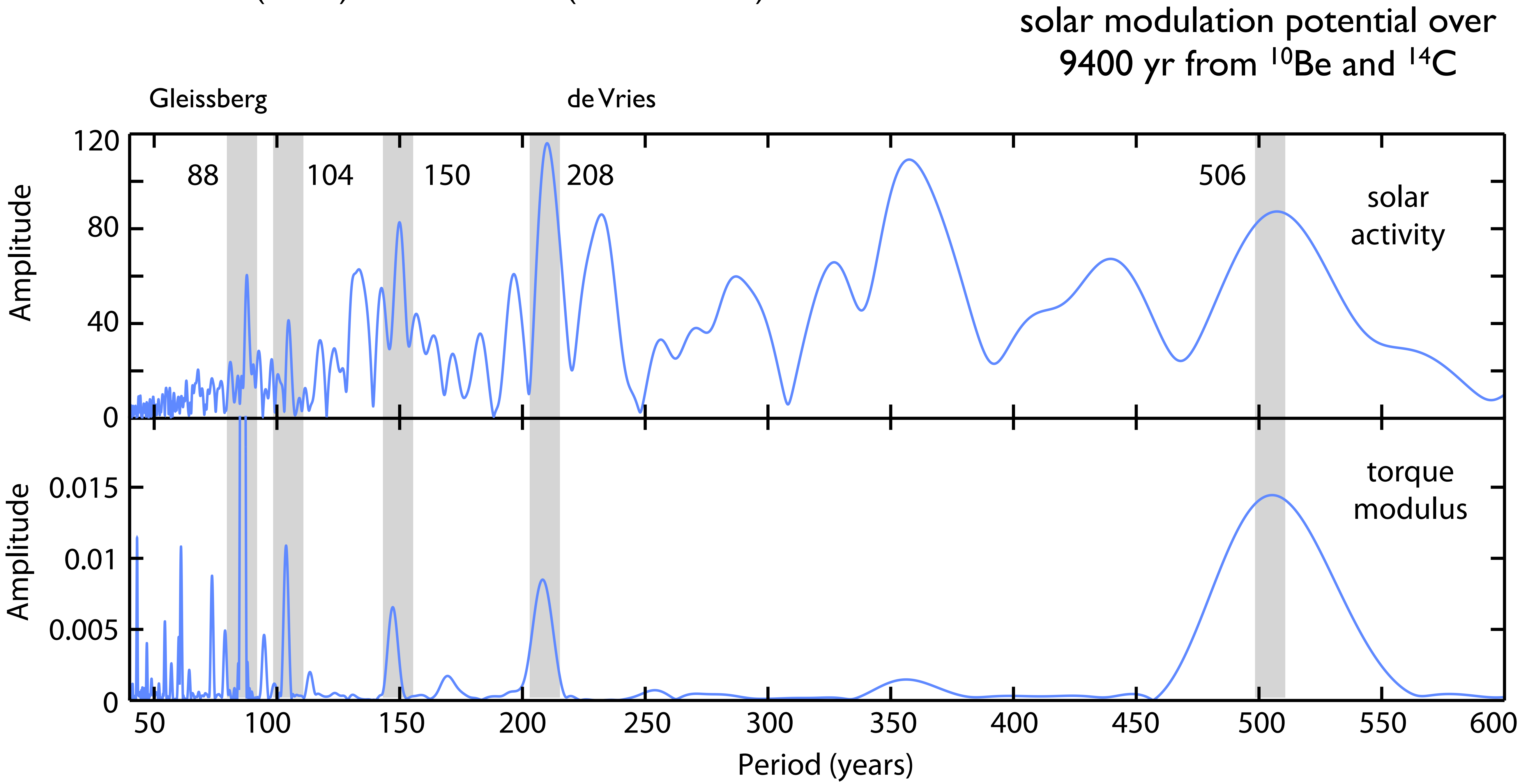
Exoplanets and the solar dynamo

Now for something contentious...

- solar axial rotation is invoked in models of the solar cycle (e.g. turbulent dynamo operating in or below the convection envelope)
- precise nature of the dynamo, and details of associated solar activity (sun spot cycles, and the prolonged Maunder-type solar minima) are unexplained
- empirical investigations have long pointed to a link between the Sun's barycentric motion and various solar variability indices (e.g. Wolf, 1859; Brown, 1900; Schuster, 1911; Jose, 1965; Ferris, 1969), specifically:
  - the Wolf sun spot number counts (Wood & Wood, 1965)
  - climatic changes (Mörth & Schlamminger, 1979; Scafetta, 2010)
  - the 80-90-yr secular Gleissberg cycles (Landscheidt, 1981, 1999)
  - prolonged Maunder-type minima (Fairbridge & Shirley, 1987; Charvátová, 1990, 2000)
  - short-term variations in solar luminosity (Sperber et al., 1990)
  - sun spot extrema (Landscheidt, 1999)
  - the 2400-yr cycle seen in 14C tree-ring proxies (Charvátová, 2000)
  - hemispheric sun spot asymmetry (Juckett, 2000)
  - torsional oscillations in long-term sun spot clustering (Juckett, 2003)
  - violations of the Gnevishev–Ohl sun spot rule (Javaraiah, 2005)

Just one example...

Abreu et al (2012), A&A 548, 88 (ETH Zürich)



Proposed coupling mechanisms between the solar axial rotation and orbital revolution:

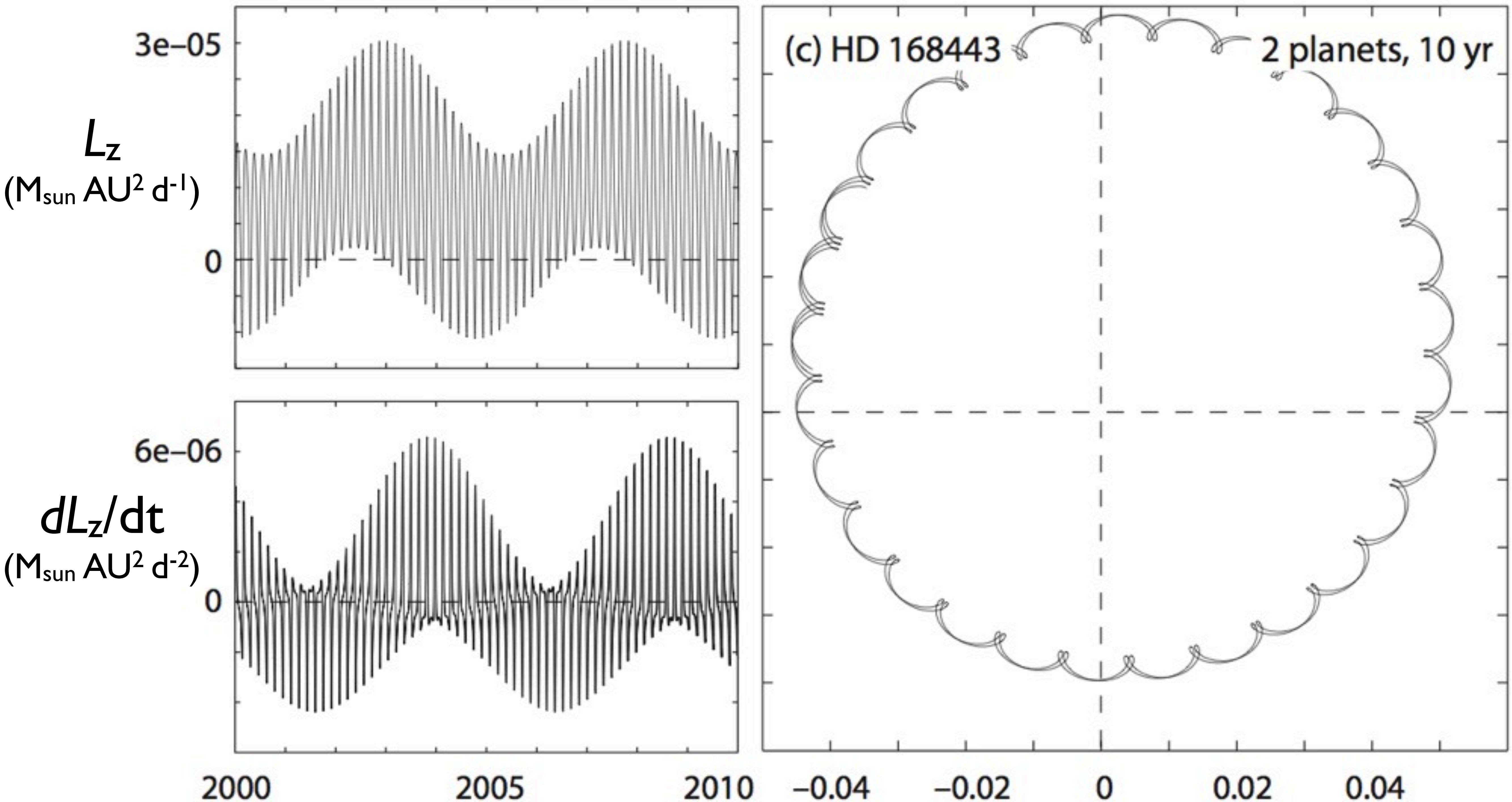
- Zaqarashvili (1997), Juckett (2000), contested by Shirley (2006)
- Abreu (2012): time-dependent torque exerted by the planets on a non-spherical tachocline
- Callebaut & de Jager (2012): effect considered as negligible

Exoplanets can arbitrate

(Perryman & Schulze-Hartung 2011)

- behaviour cited as correlated with the Sun's activity includes
  - changes in orbital angular momentum, dL/dt
  - intervals of negative orbital angular momentum
- these are common (but more extreme) in exoplanet systems
- HD 168443 and HD 74156 have dL/dt exceeding that of the Sun by more than 10^5
- activity monitoring should therefore offer an independent test of the hypothetical link between:
  - the Sun's barycentric motion
  - and the many manifestations of solar activity

HD 168433

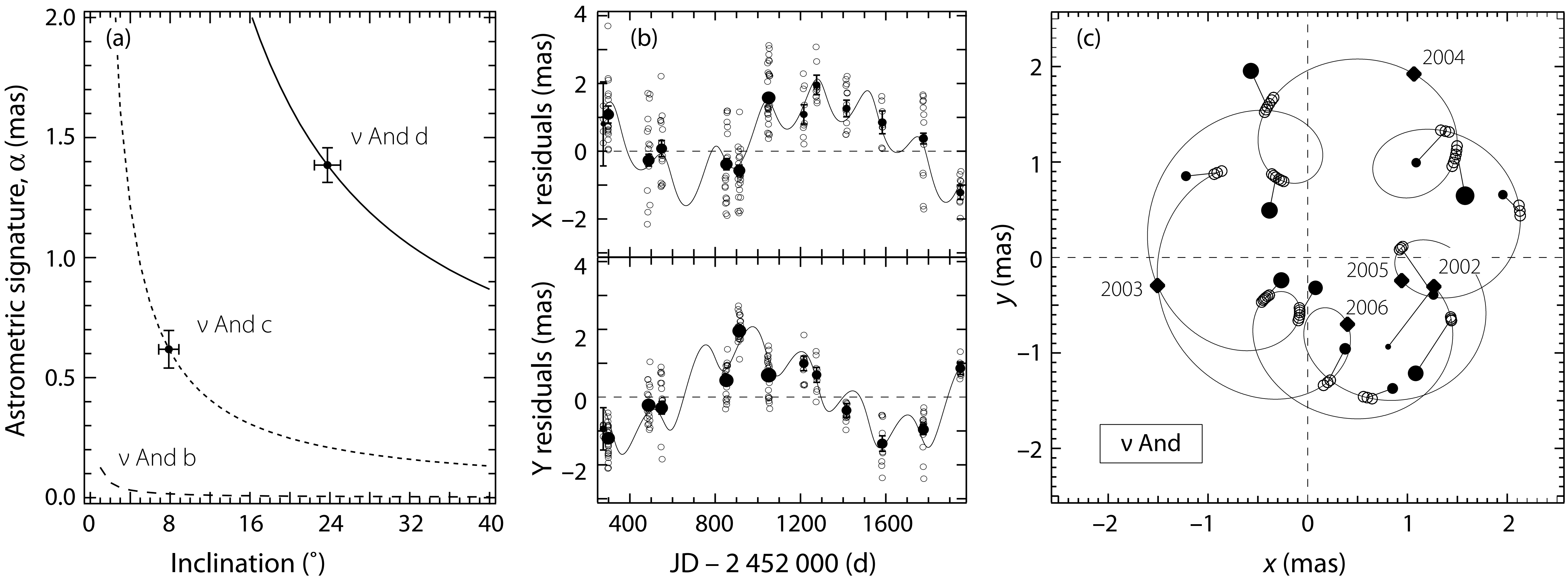


- two massive planets (8−18M_J) at 0.3−3 AU, e_1~0.5
- most extreme negative L_z and largest dL/dt
- periodicity of ~58 days

Coplanarity of orbits
and
transit geometry

Exoplanet detection with HST−FGS

quite a long history, starting with Benedict et al (1993)
[HST−FGS yields relative parallaxes based on assumed luminosities of reference stars]



- radial velocity observations determine only $M_P \sin i$
- astrometric measurements determine M_P directly
- and hence relative inclinations (van der Kamp 1981):

$$\cos \Delta i = \cos i_1 \cos i_2 + \sin i_1 \sin i_2 \cos(\Omega_1 - \Omega_2)$$

For ν And, McArthur et al (2010) found:

- M_P (ν And c) = 14.0 M_J
- M_P (ν And d) = 10.2 M_J
- $\Delta i = 29.9^\circ \pm 1^\circ$

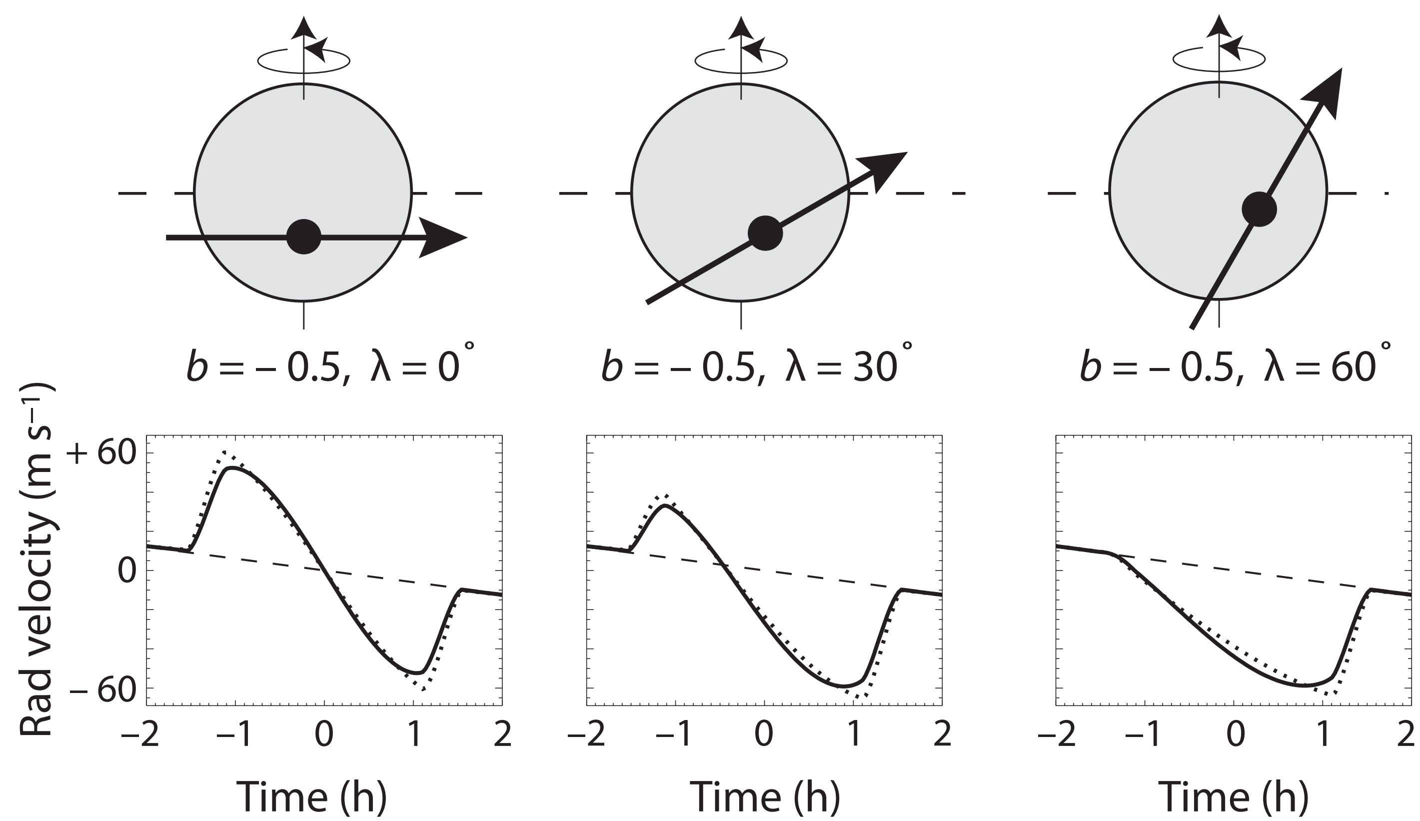
the first direct determination of relative orbit inclinations

Importance of Δi

- $\Delta i \sim 0$ in the solar system
- various evidence that this is not necessarily the rule in exoplanets:

(1) long-term dynamical stability (via numerical integrations) ⇒ some cannot be coplanar

(2) Rossiter-McLaughlin effect used to measure the (sky projection) of the orbital and stellar rotation axes indicates that many orbits are misaligned wrt stellar equator (some retrograde)

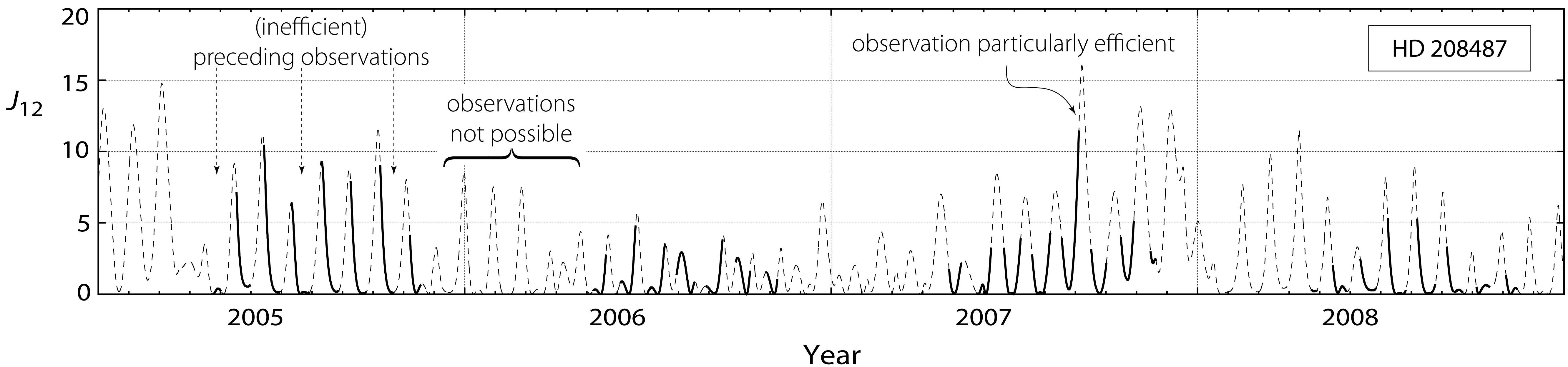


(3) models of formation and evolution admit the possibilities of: (a) asymmetric protoplanetary infall; (b) gravitational scattering during the giant impact stage of protoplanetary collisions; (c) Kozai resonance/migration in which L_z is conserved, and hence i and e can be 'traded' (explains high e in triple systems, and hot Jupiters when combined with tidal friction)

$$L_z = \sqrt{(1-e^2)}\cos i$$

Baluev 2008

optimal strategies of radial velocity observations in search surveys

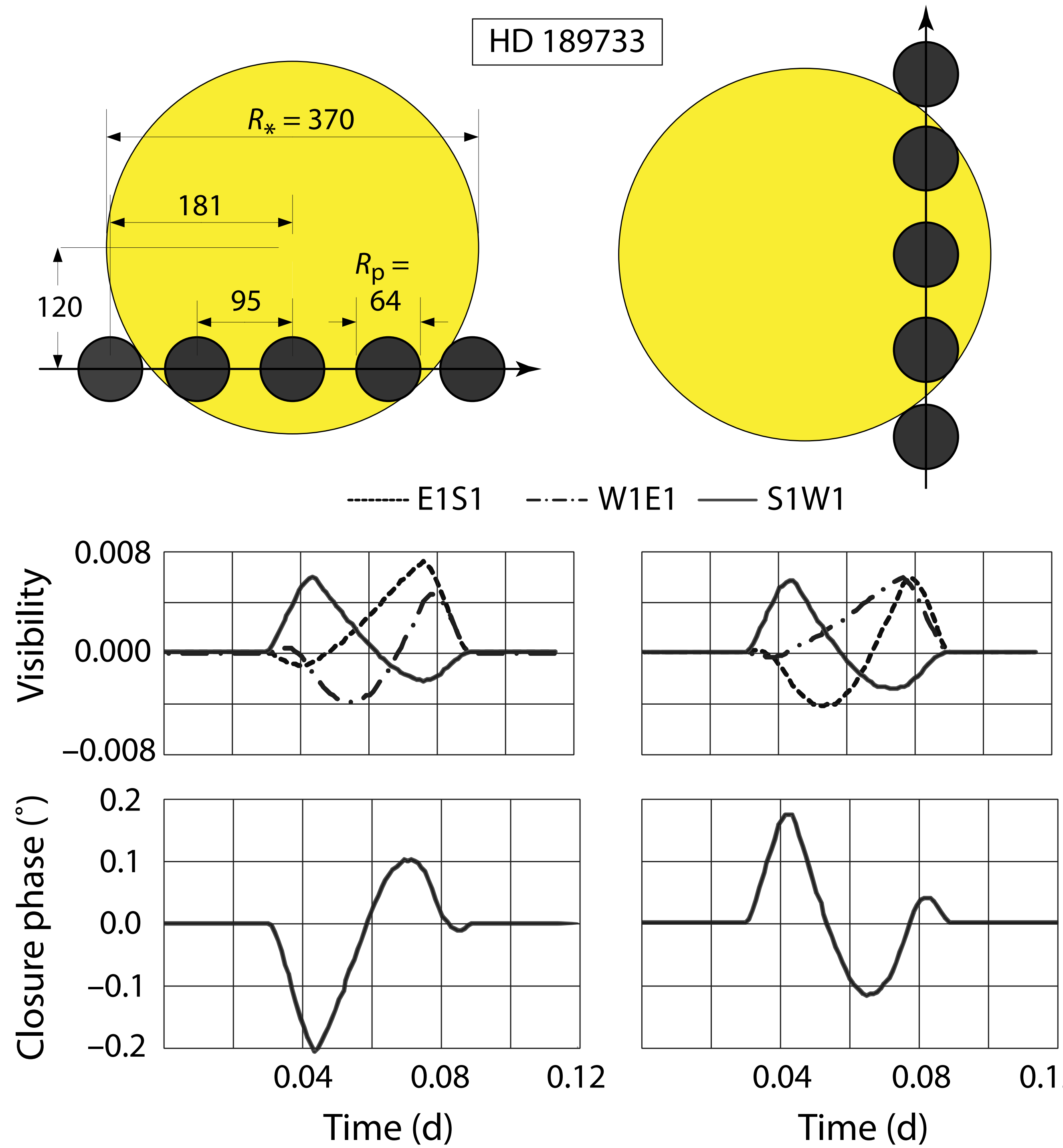


example:

- how to decide between two orbit solutions from 35 measurements (Butler 2006)
- Wright (2007) identified a second planet at P=28.6d or 900d
- J_{12} estimates the maximum information from the two predictions
- maxima give the most promising times for new observations
- here:
  - predictions differed by 20m/s
  - actual observations during 2005 were all at epochs of low information content
  - one observation in 2005 would have resolved the degeneracy, those in 2006 could not

Transit geometry

- normally, there is no information on the position angle of a transiting planet's orbit plane
- provided (in principle) by 2d interferometry: due to asymmetry in the source brightness introduced by the planet
- valuable for higher-order light curve effects?
- provided by Gaia if the astrometric signature of the transiting planet is high



(CHARA)
V = 7.7, K1, d = 19pc

Summary

- accurate distances:
  - calibration of host star parameters, including R for transiting
  - calibration of asteroseismology models
- accurate proper motions: Galactic dynamics and population
- multi-epoch high-accuracy photometry:
  - new transiting systems (several hundred?)
  - calibration of photometric jitter vs spectral type
- multi-epoch astrometry:
  - discovery of new (massive, long-period) planets (3000?)
  - co-planarity of systems: evolutionary models
  - position angle of planet transits (some multiple?)

End