The role of astrometry in the detection and confirmation of exoplanets

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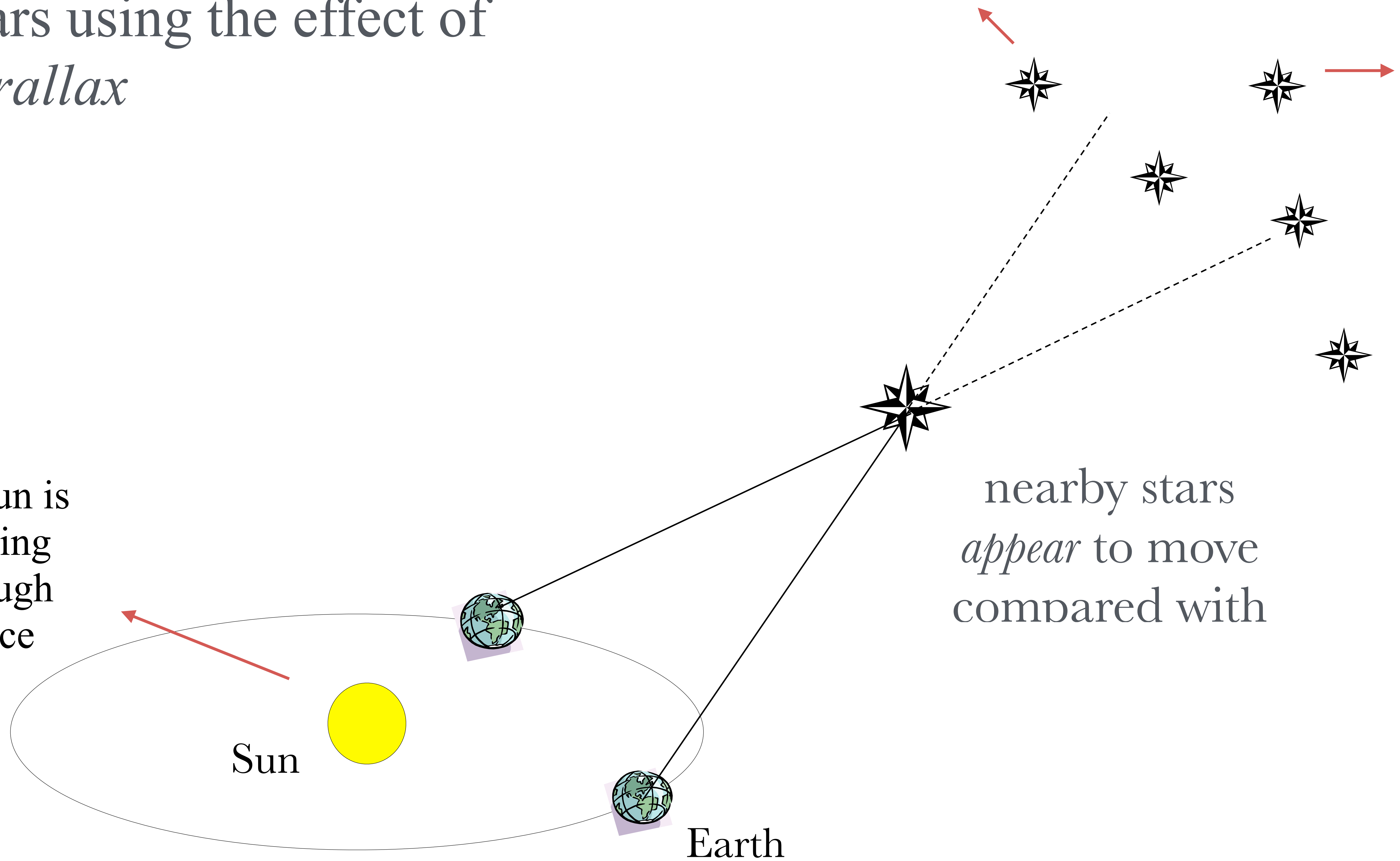
Sagan Summer Workshop, Caltech, 25 July 2022

It is the Earth’s motion around the Sun that makes it possible to measure distances to the stars using the effect of *parallax*



stars are moving
through space

the Sun is
moving
through
space

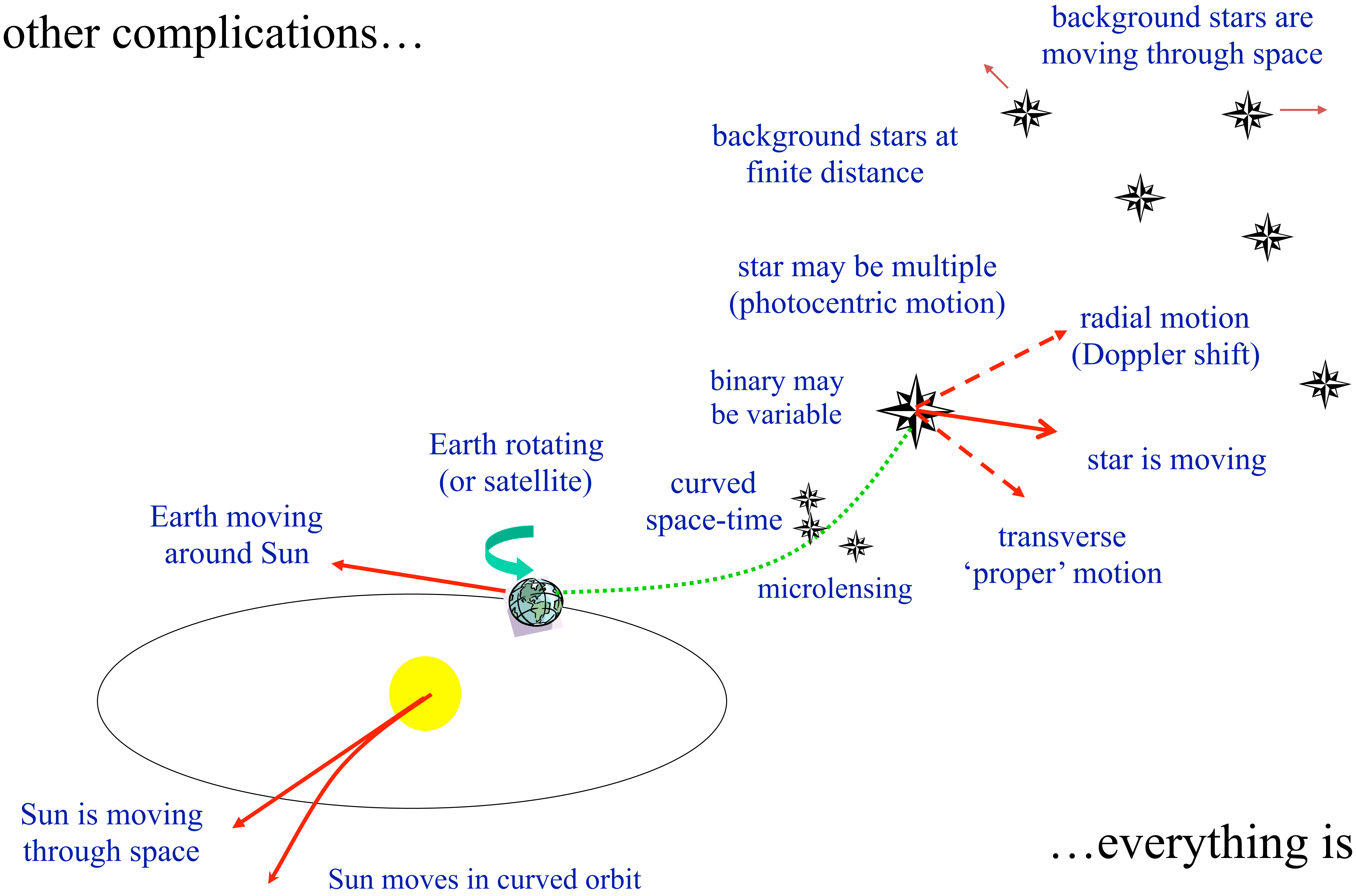
Sun

Earth

nearby stars
appear to move
compared with

nearest star ~ 1 pc (1 arcsec)
Galactic centre ~ 8,000 pc ~ 100 microarcsec

Many other complications…



background stars are moving through space

background stars at finite distance

star may be multiple (photocentric motion)

radial motion (Doppler shift)

binary may be variable

star is moving

Earth rotating (or satellite)

curved space-time

Earth moving around Sun

transverse ‘proper’ motion

microlensing

Sun is moving through space

Sun moves in curved orbit

…everything is moving!

The first star distances...

After a 250 year marathon journey,
Friedrich Bessel, Thomas Henderson, and
Wilhelm Struve measured the first star
distances around 1838–39

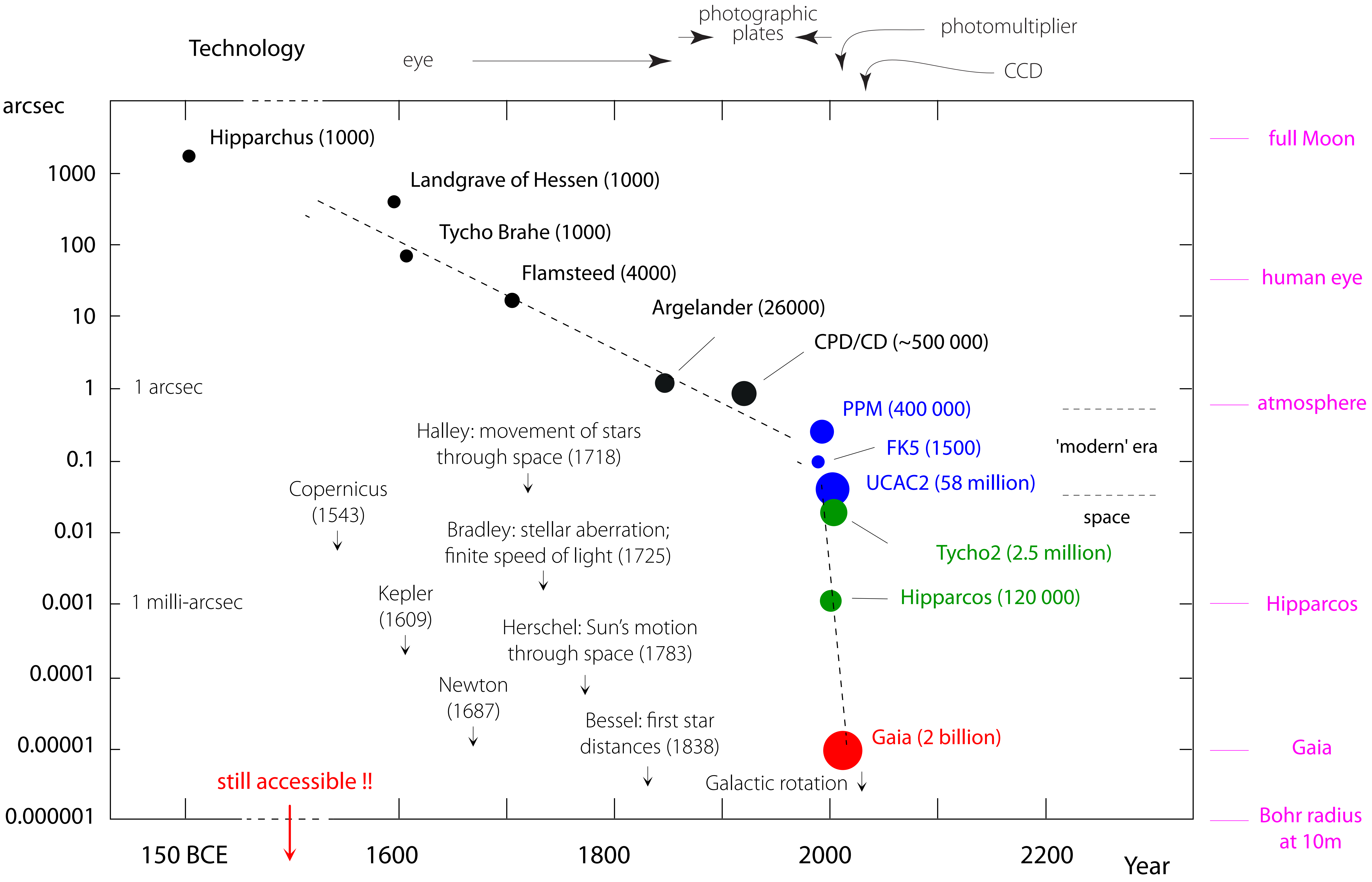
Bessel was awarded the Royal Astronomical
Society Gold Medal, for
“*the greatest and most glorious triumph which
practical astronomy has ever witnessed*”

Struve’s refractor, Tartu (Estonia)

Herschel: “*To drop a pea at the end of every mile of a voyage on a limitless ocean to the nearest fixed star,
would require a fleet of 10,000 ships of 600 tons burthen, each starting with a full cargo of peas.*”

Perryman: “*The world’s population, of 7 billion people, would reach the nearest star if each spaced by… 5000 km.*”

Accuracy of star positions through history



Astrometry provides star distances and ‘space’ motions

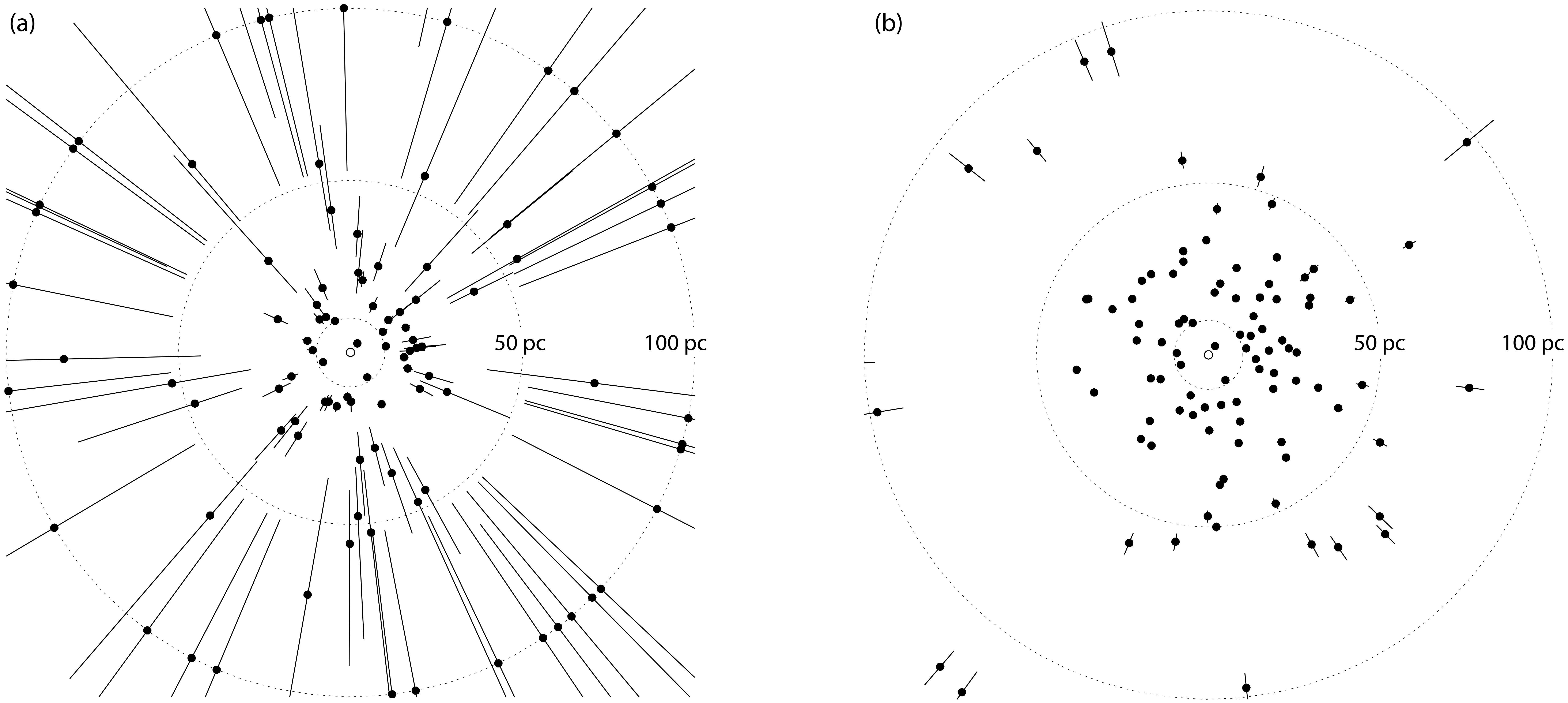
(more on these in talks by Dan Huber and Melissa Ness)

Applications include:

- distances provide stellar parameters:
    - luminosity/radius essential ingredients for stellar evolutionary models
    - for exoplanets, transit-derived areas ∝ stellar diameters
    - verification of asteroseismology models versus mass/radius
- proper motions characterise populations:
    - disk (thin/thick) versus halo
    - systems ejected from open clusters
    - Galactic birthplace based on metallicity–age

Hipparcos distances to exoplanet host stars

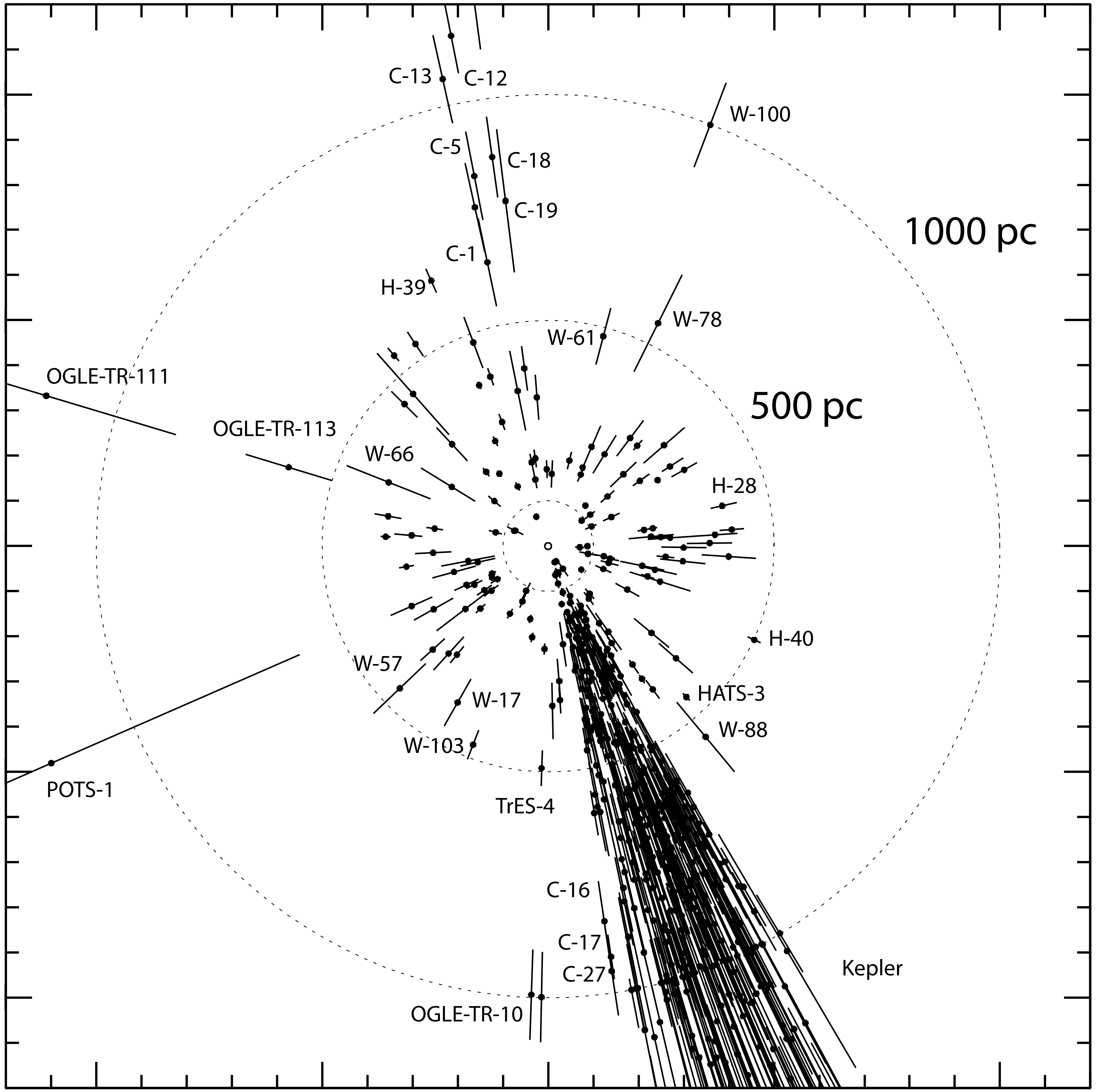
100 brightest radial velocity host stars, status as of end 2010 (versus right ascension)



ground-based: van Altena et al (1995)
(unknown assigned $\pi = 10 \pm 9$ mas)

Hipparcos parallaxes

Distances to exoplanet host stars, pre-Gaia

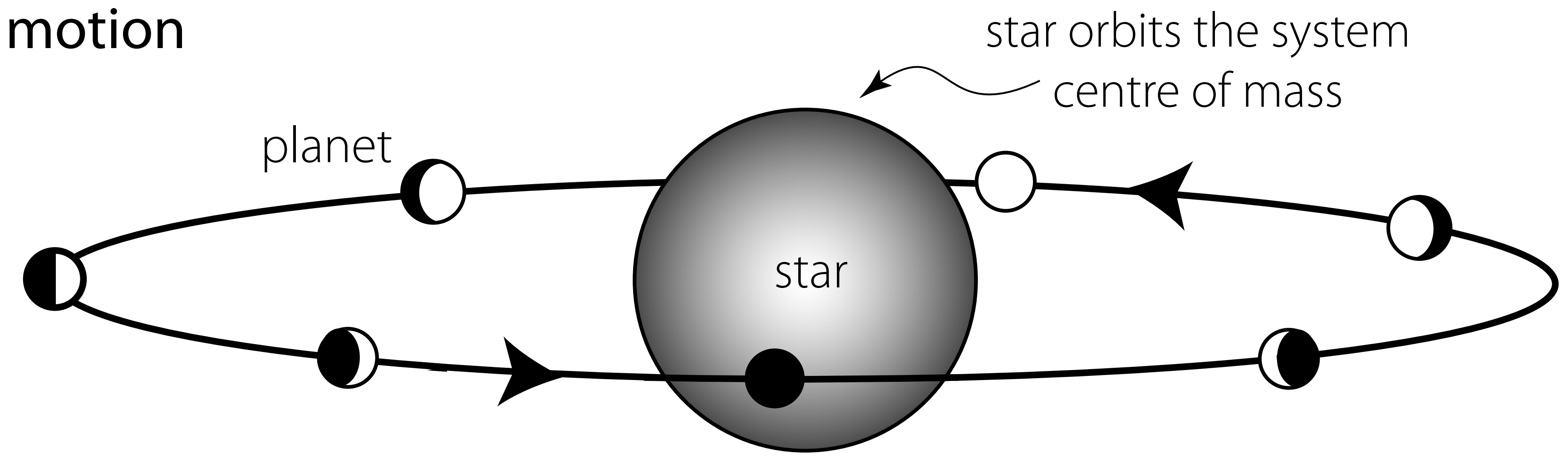


1129 transiting planets
(2014 May 1)

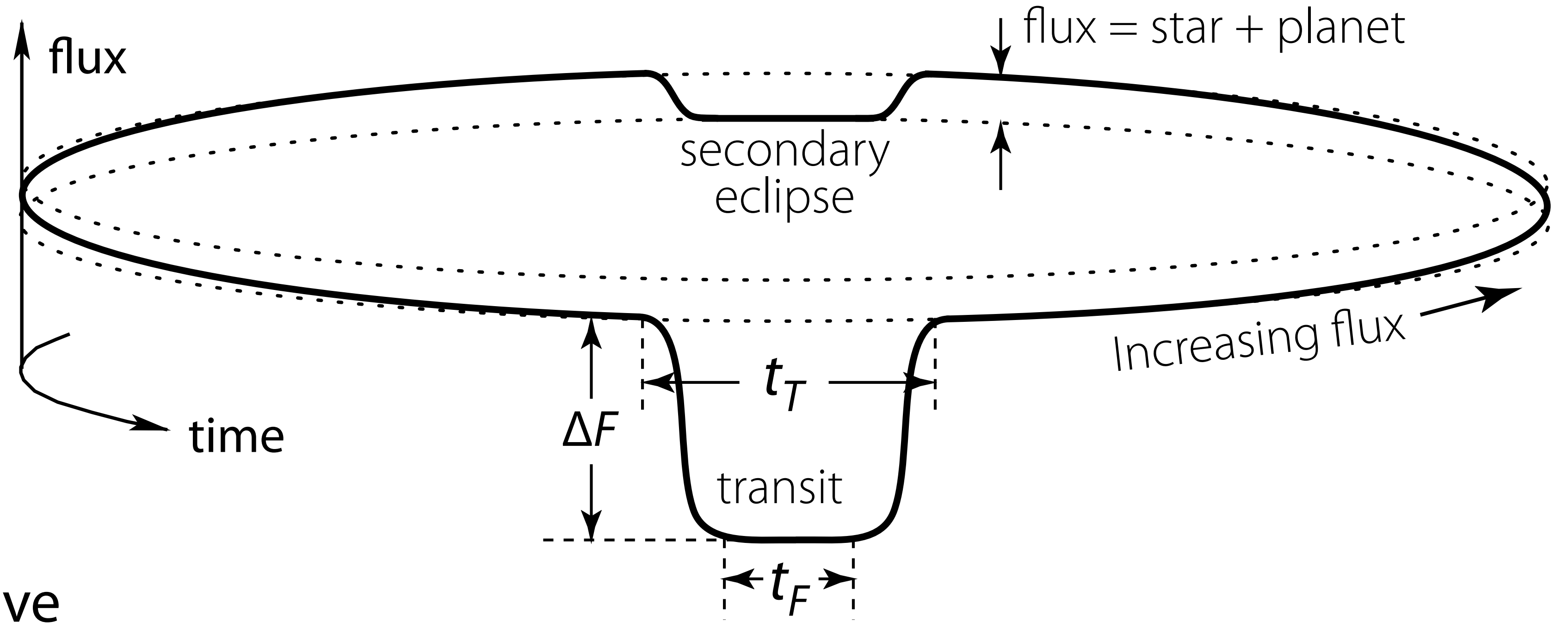
There were:
- 582 distinct host stars
- 188 Hipparcos distances
- 366 Kepler from $K - M_K$
  - median ~670pc
- 28 placed at 1 kpc

Exoplanet discoveries: summary of methods

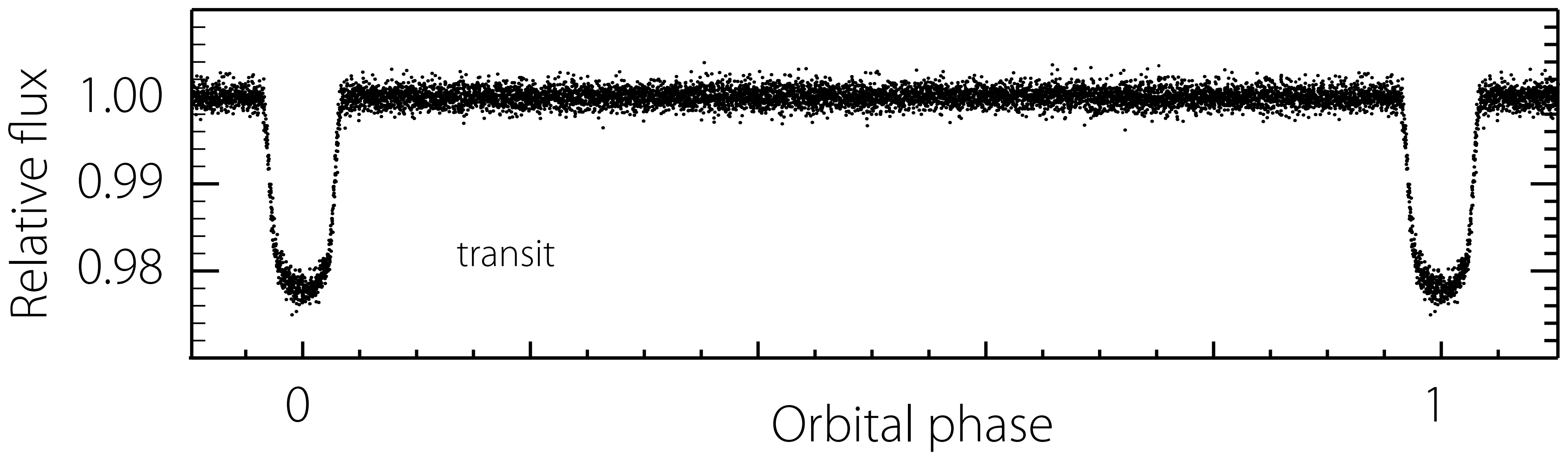
(a) Orbital motion



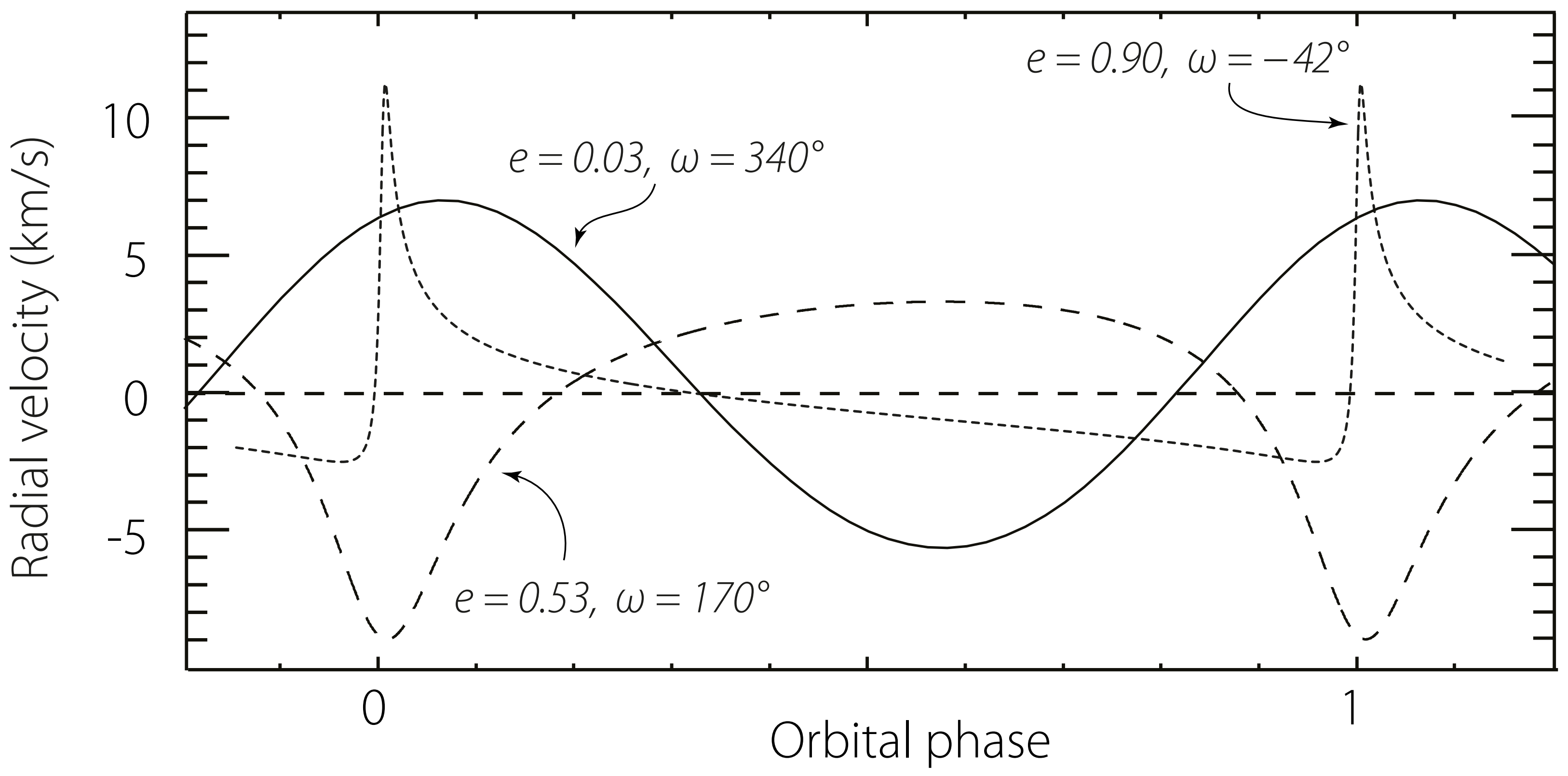
(b) Orbit schematic



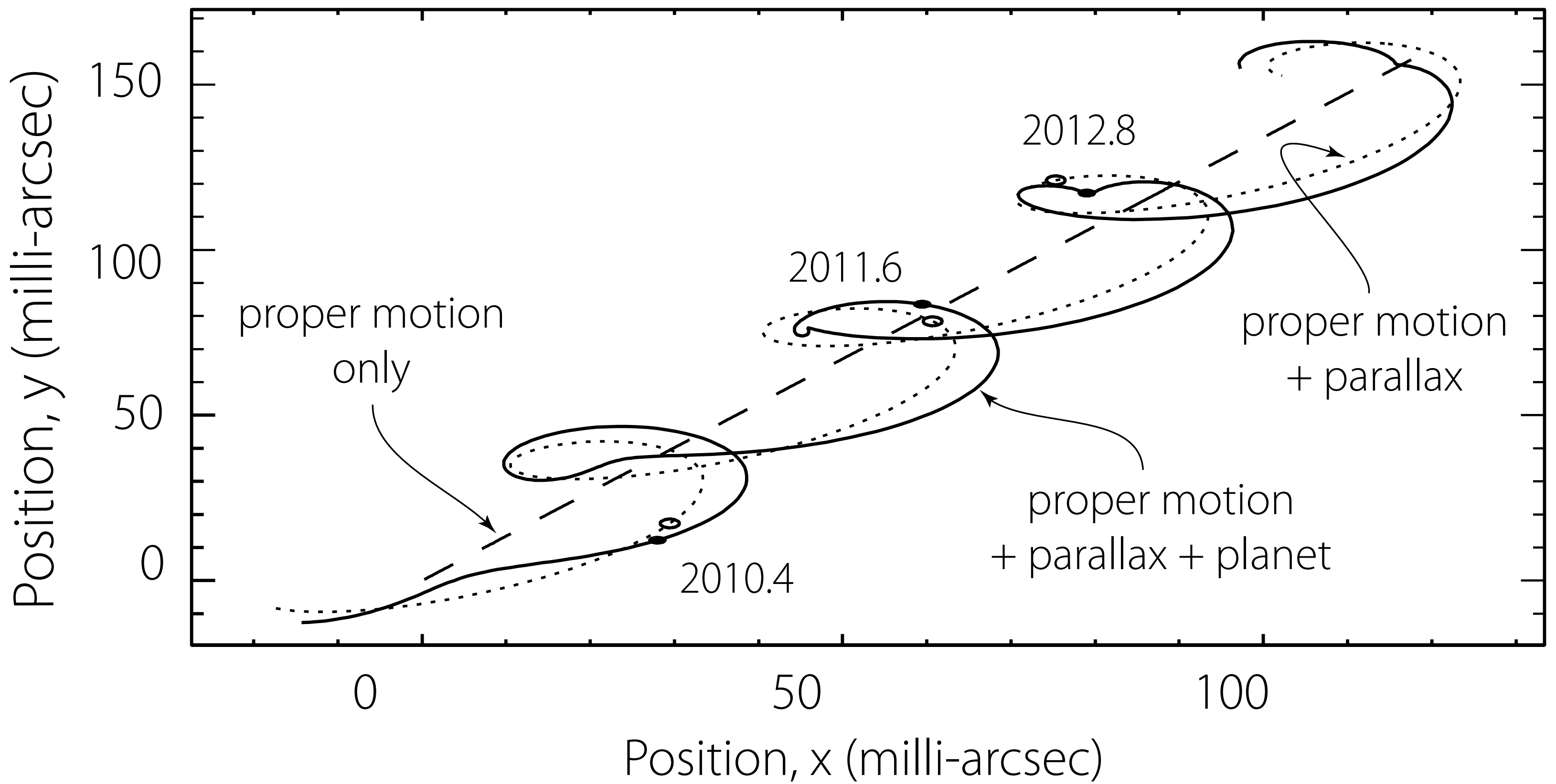
(c) Light curve



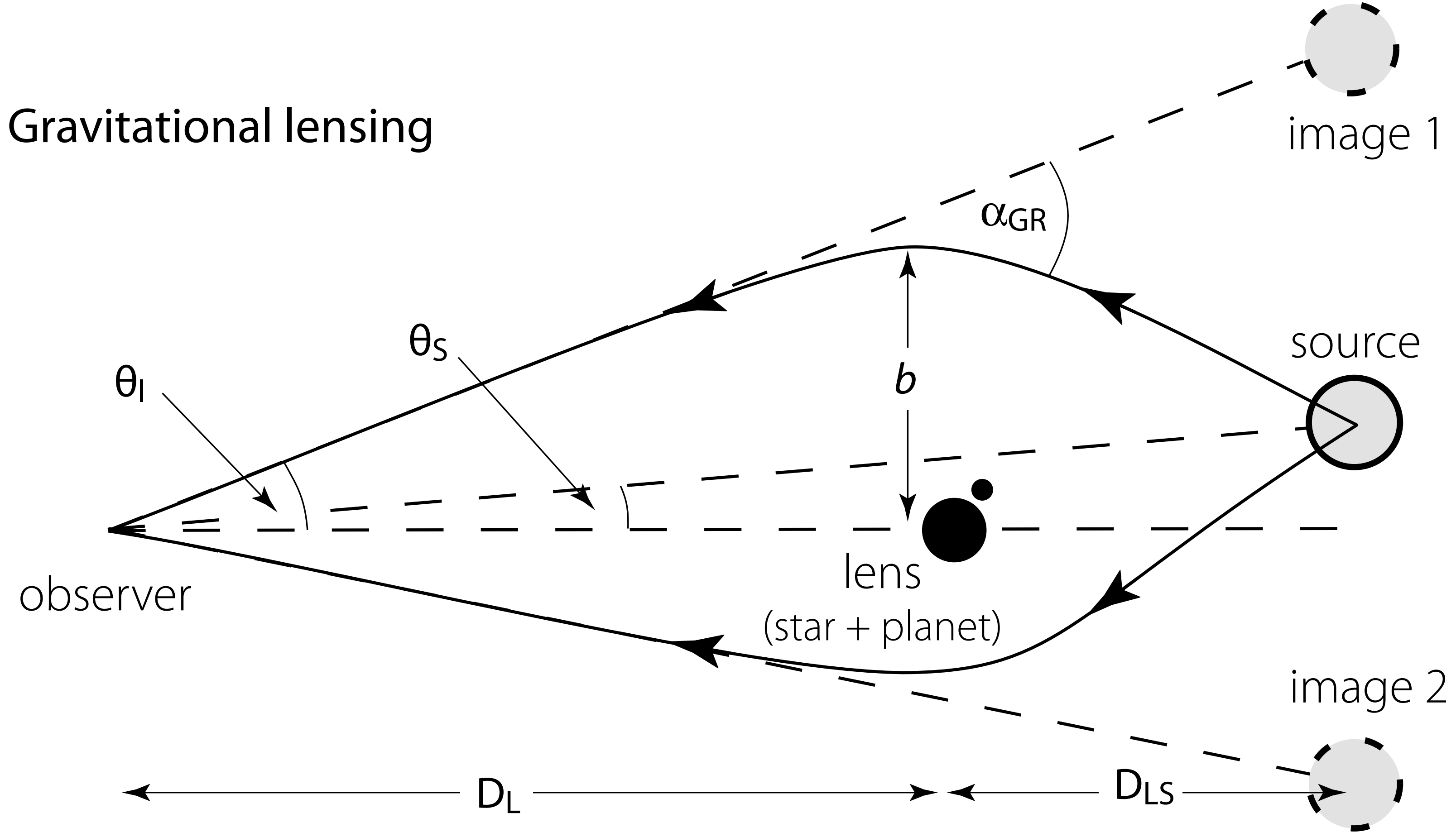
(d) Stellar radial velocity



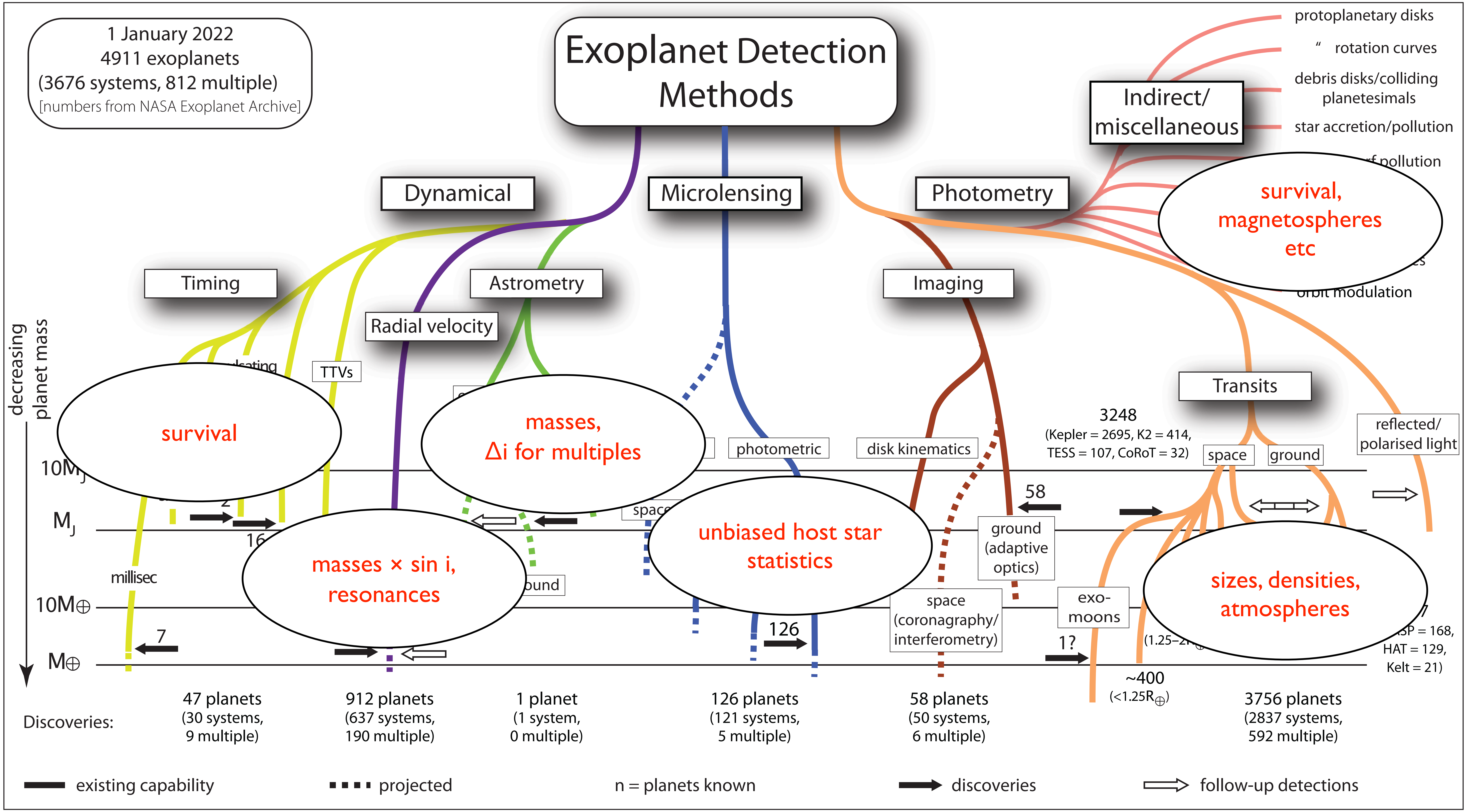
(e) Position on sky



(f) Gravitational lensing



Astrometry in the context of exoplanet discoveries, 2022



1 January 2022
4911 exoplanets
(3676 systems, 812 multiple)
[numbers from NASA Exoplanet Archive]

Exoplanet Detection Methods

Dynamical

Microlensing

Photometry

Indirect/ miscellaneous

protoplanetary disks
" rotation curves
debris disks/colliding planetesimals
star accretion/pollution
f pollution
rbit modulation

Timing

Astrometry

Radial velocity

Imaging

Transits

lsating

TTVs

millisec

photometric

disk kinematics

space

ound

ground (adaptive optics)

space (coronagraphy/ interferometry)

exo- moons

space

ground

reflected/ polarised light

3248
(Kepler = 2695, K2 = 414, TESS = 107, CoRoT = 32)

58

2

16

7

126

1?

~400
(<1.25R⊕)

(1.25–2

SP = 168, HAT = 129, Kelt = 21)

decreasing planet mass

10MJ

MJ

10M⊕

M⊕

survival

masses, Δi for multiples

masses × sin i, resonances

unbiased host star statistics

survival, magnetospheres etc

sizes, densities, atmospheres

Discoveries:

47 planets
(30 systems,
9 multiple)

912 planets
(637 systems,
190 multiple)

1 planet
(1 system,
0 multiple)

126 planets
(121 systems,
5 multiple)

58 planets
(50 systems,
6 multiple)

3756 planets
(2837 systems,
592 multiple)

existing capability

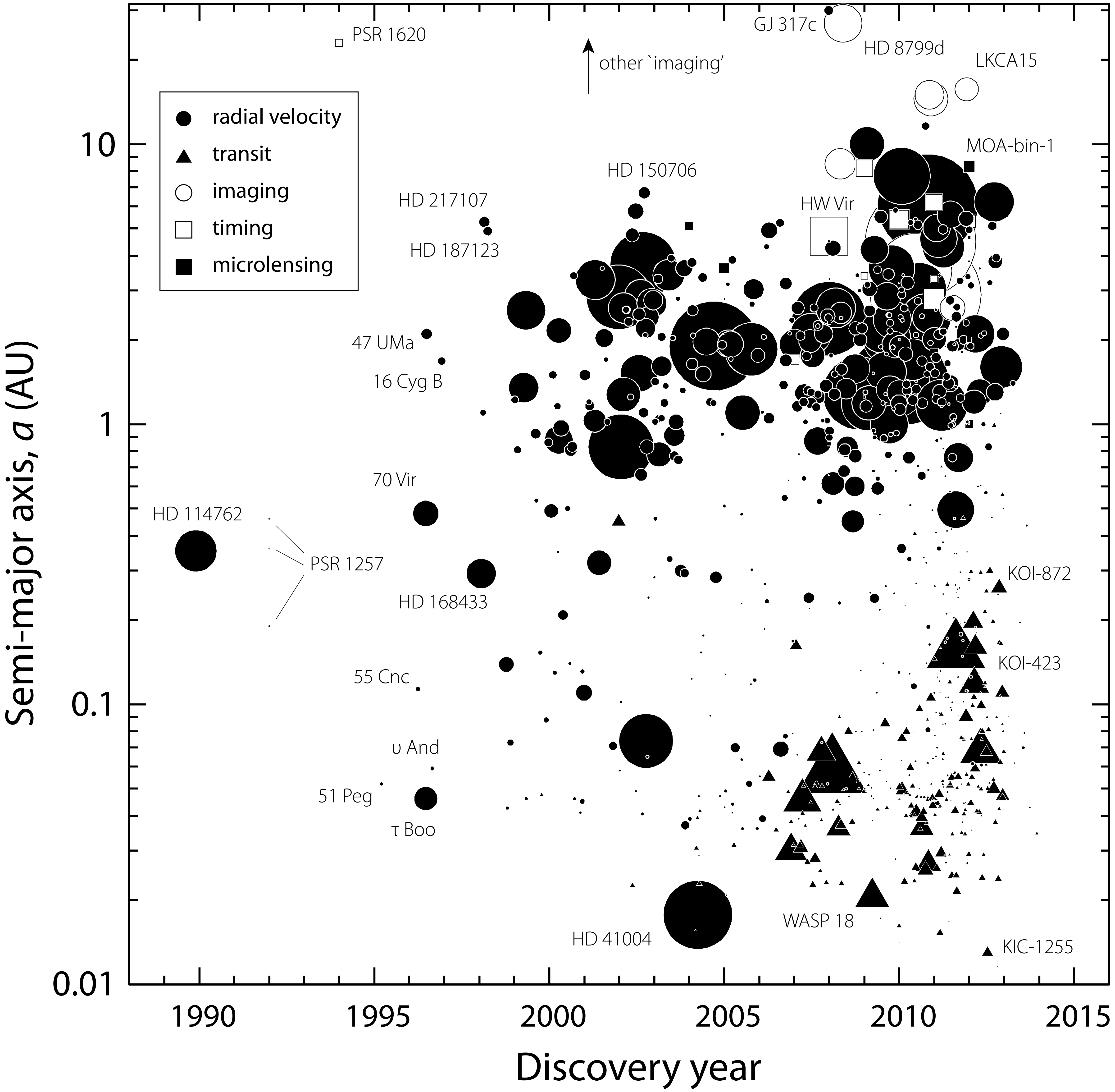
projected

n = planets known

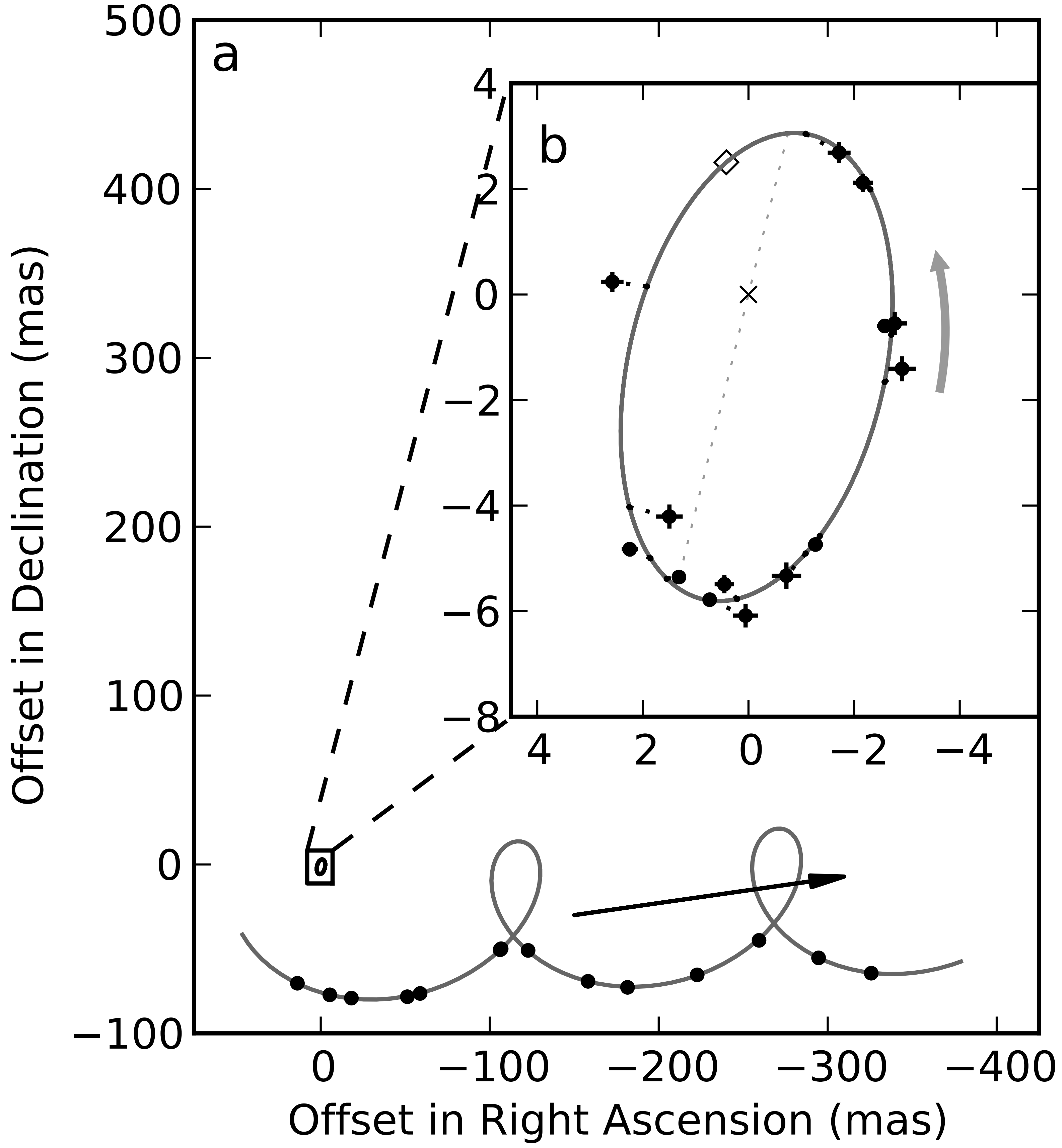
discoveries

follow-up detections

The rapid pace of discovery, 1990–2015



The only astrometric discovery in the NASA exoplanet archive…



DE 0823–49 from VLT-FORS2 imaging
(Sahlmann et al. 2013)

- ultracool L dwarf (0.07 M_{sun}) at 20 pc
- 246-day orbit
- 28 Jupiter mass

The ‘tragic history’ of astrometric discoveries

Has included:

- 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
- van der Kamp (1963, 1982): lengthy disputes about planets around Barnard’s star
- Lippincott (1960): similarly for Lalande 21185
- Pravdo & Shaklan (2009) vB10 with Palomar-STEPS, later disproved (Bean 2010)
- Muterspaugh et al. (2010) HD~176051: *‘may represent either the first such companion detected, or the latest in the tragic history of this challenging approach’*
- early discussions of space astrometry and Hipparcos exoplanet capabilities:
  Couteau & Pecker (1964), Gliese (1982)

Principles underpinning *global* space astrometry

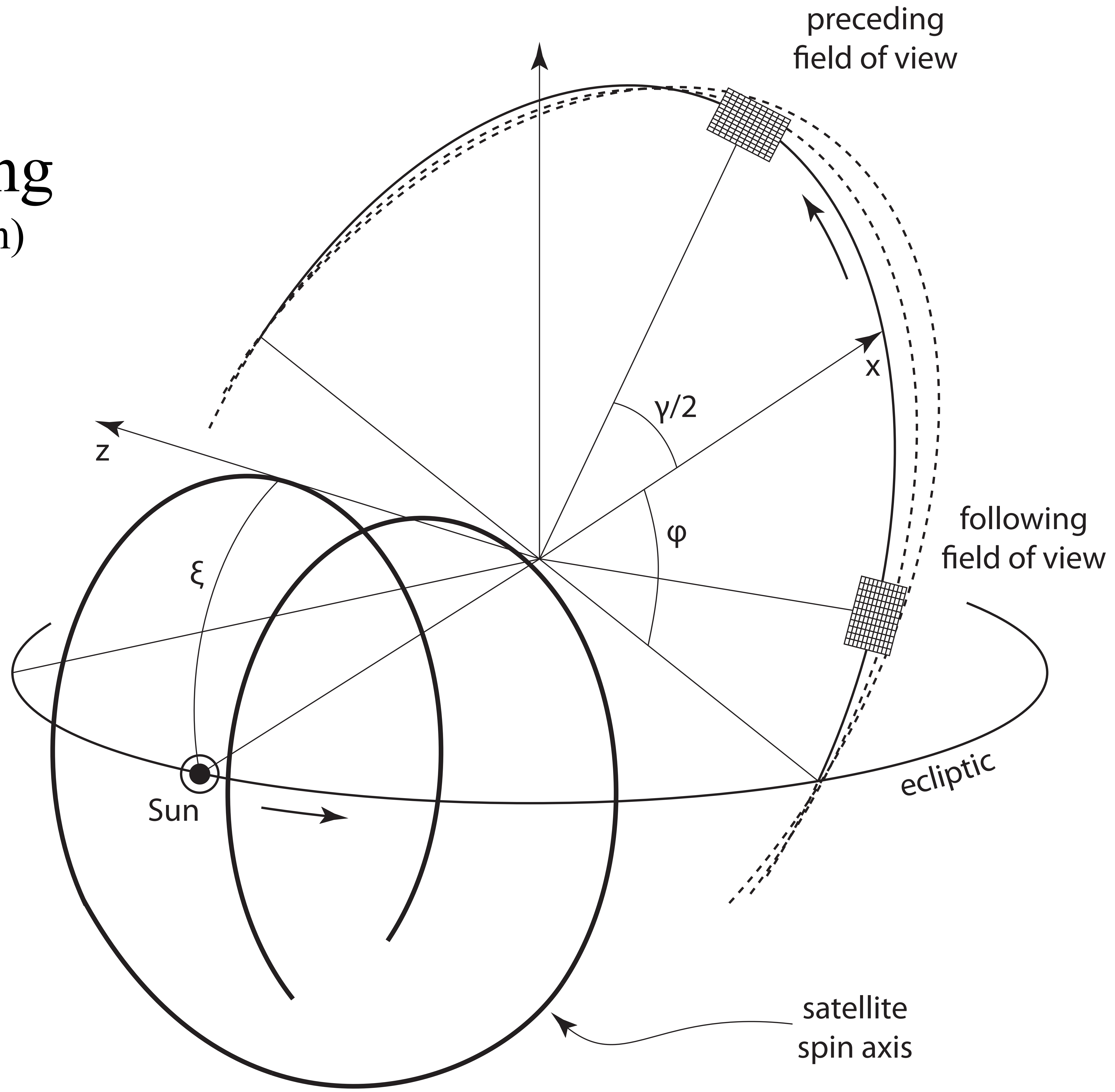
(i.e. Hipparcos and Gaia)

Measurements at these accuracies rest upon:

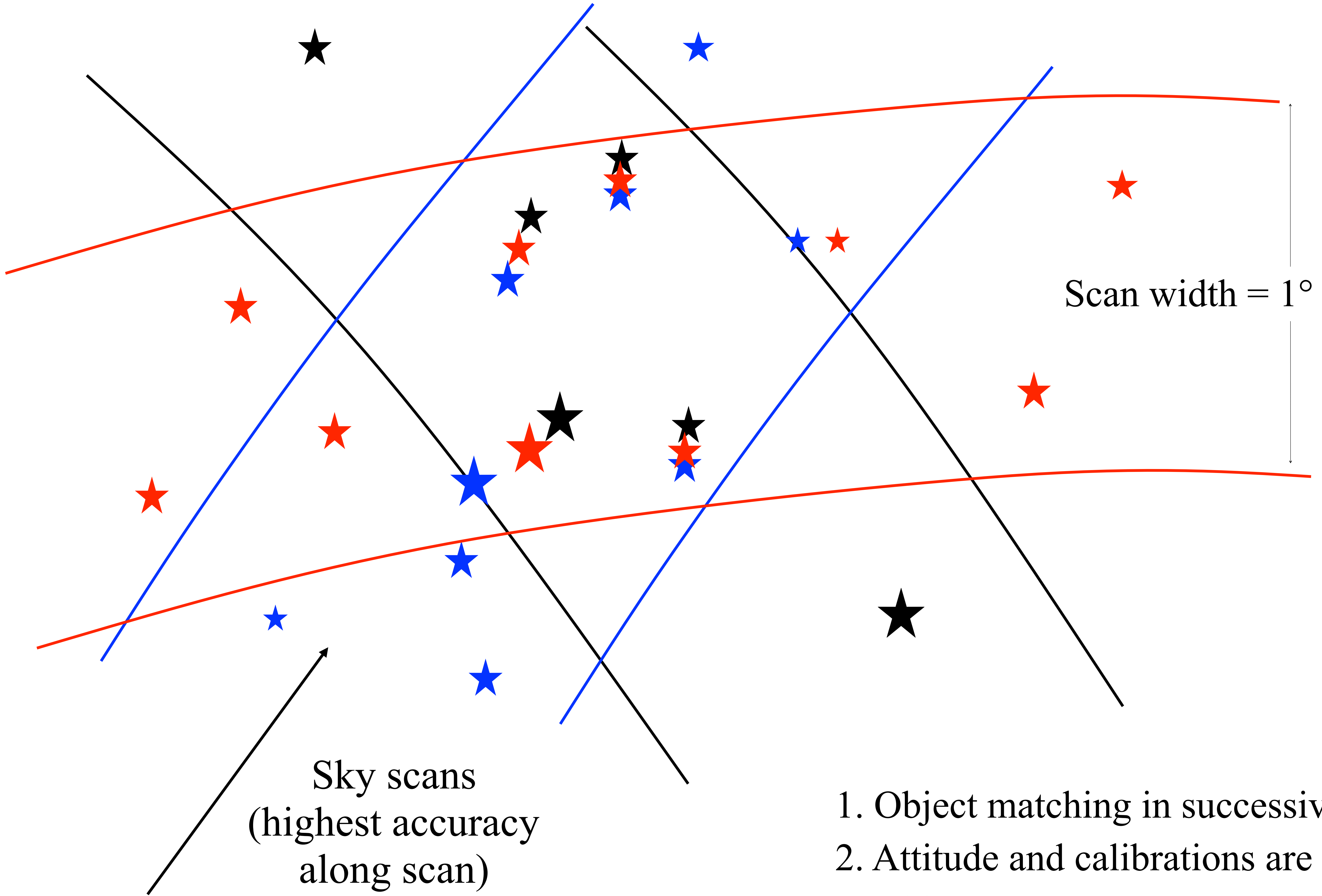
- observations *above the atmosphere* to eliminate turbulence (‘seeing’)
- two *widely separated* fields yield absolute parallaxes (rigidity condition)
- one-dimensional measurements, along scan (hence… rectangular mirrors & CCD pixels)
- image location based on image *centroid* (not the diffraction-limit resolution!)
- simultaneous photometry to allow correction of chromatic aberration
- repeated measures (~100) at a wide range of position angles
- constant Sun aspect angle (thermal load) ensured by ‘revolving scanning’
- extremely high thermo-mechanical instrument stability (10 pm)

Gaia sky scanning

(talk by Anthony Brown)

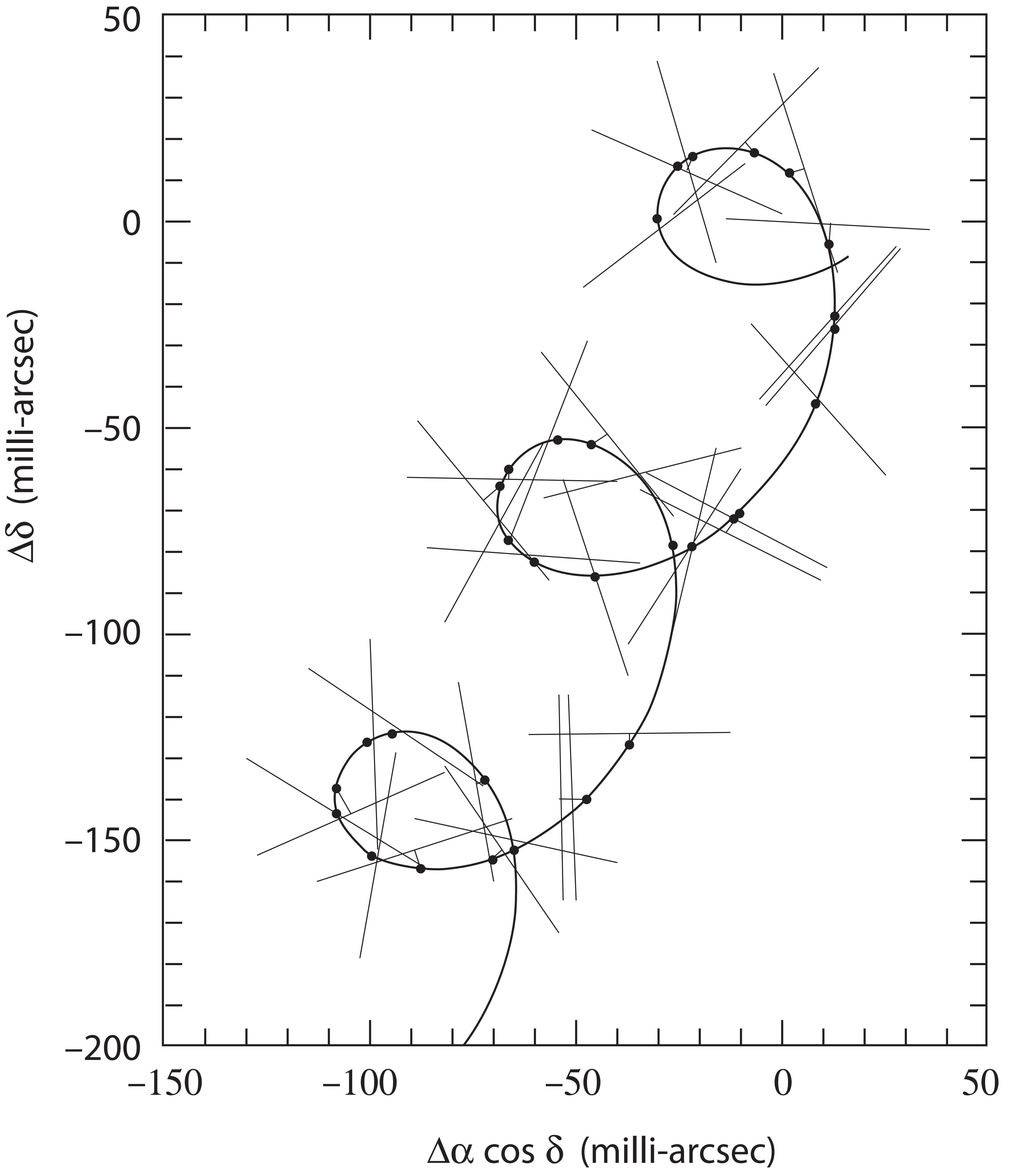


Observing principles: Hipparcos and Gaia



1. Object matching in successive scans
2. Attitude and calibrations are updated
3. Objects positions etc. are solved
4. Higher-order terms are solved
5. More scans are added
6. System is iterated (global iterative solution)

Astrometry: manifestation of parallax and proper motion



Great-circle approach (Hipparcos):

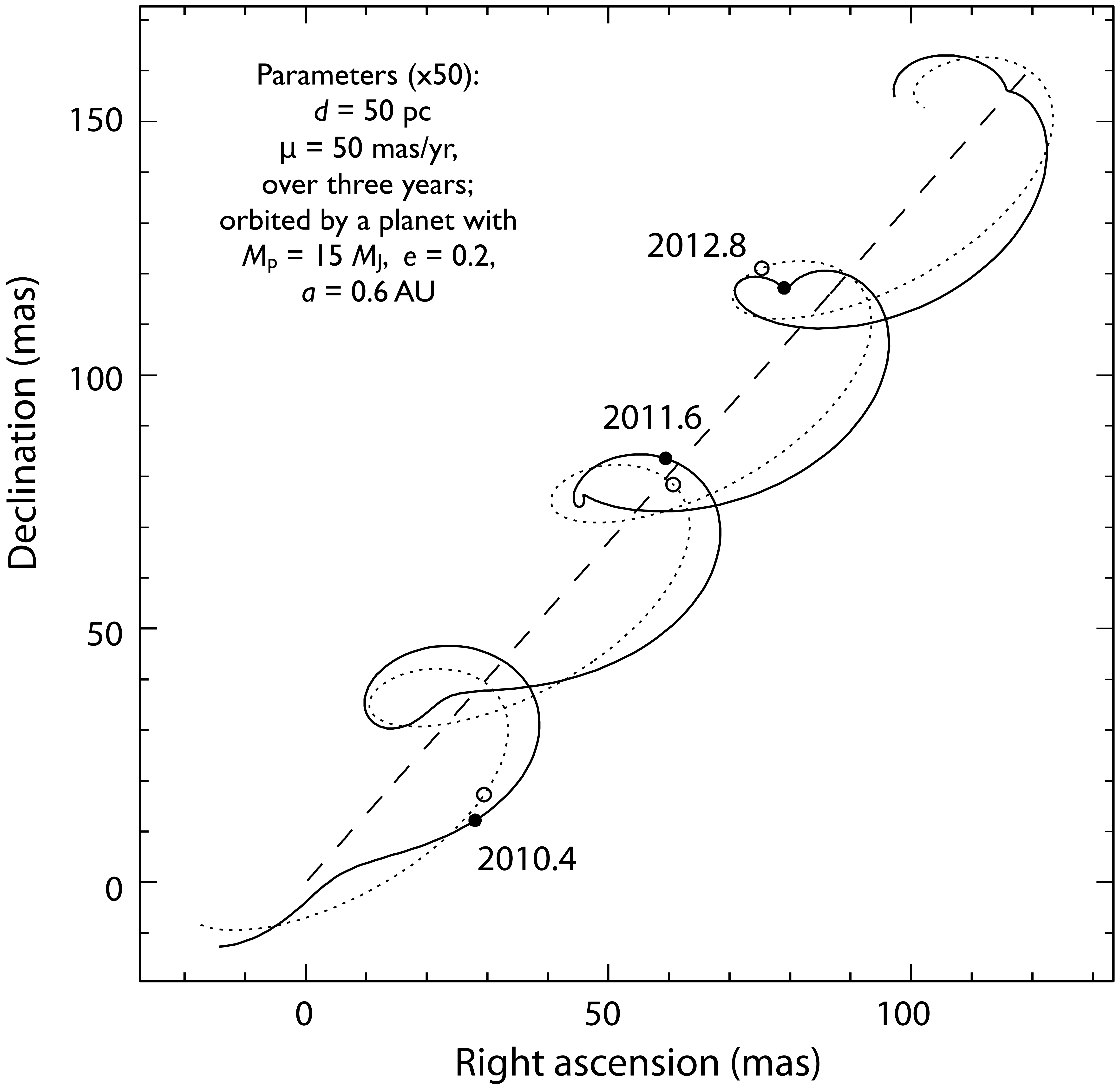
- as the satellite traces out great circles on the sky, stars are (effectively) stationary
- each star has a 2d position (abscissa and ordinate) projected onto that great circle
- in principle one could/should solve for both coordinates
- for Hipparcos, the projection along the great circle dominates the ‘great-circle solution’
- least-squares adjustment gives the along-scan position of each star at that epoch
- all great circles over the mission are then ‘assembled’
- star position at any time *t* is given by just five parameters: position (*xy*), proper motion (μ_x, μ_y), parallax (π)
- binaries, planets etc. demand more parameters

Gaia solves for both coordinates!!

Exoplanet inferred from a star's additional barycentric motion

An unseen planet perturbs the
photocentre, which moves with
respect to the barycentre
(as for Doppler measures)

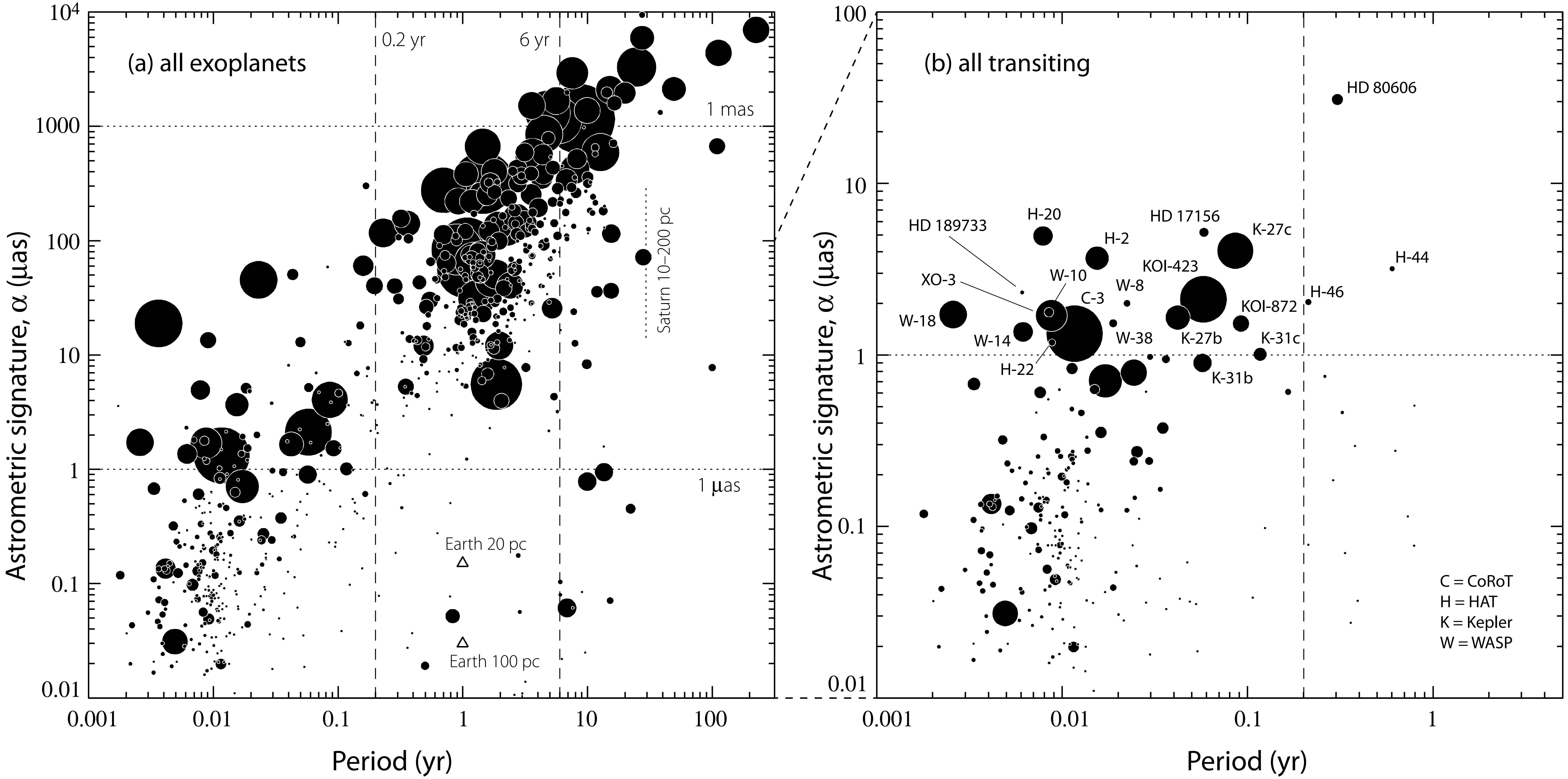
I will focus on stars orbited
by a single planet!



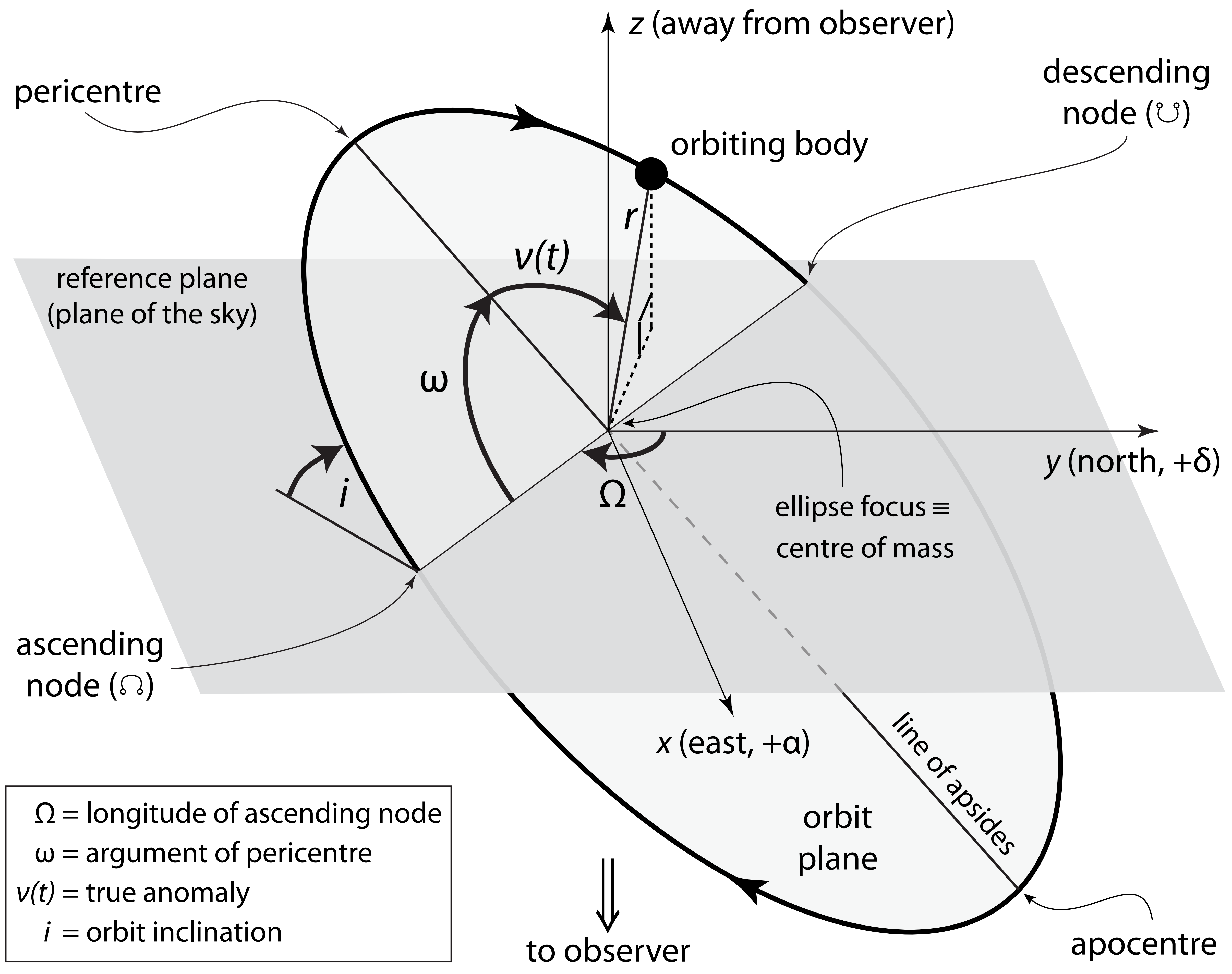
Introducing the astrometric ‘signature’

$$\alpha = \frac{M_p}{M_\star + M_p} a \simeq \frac{M_p}{M_\star} a \equiv \left(\frac{M_p}{M_\star}\right)\left(\frac{a}{1\ \mathrm{AU}}\right)\left(\frac{d}{1\ \mathrm{pc}}\right)^{-1} \mathrm{arcsec}$$

Status: 2018… evidently Hipparcos astrometry was marginal for detection (and mass determination)



Astrometry gives access to planet mass and Δi



Keplerian orbit in 3d is determined by 7 parameters:

- a, e: specify the orbit 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: projections with respect to observer

Note that radial velocity measures:

- cannot determine Ω,
- can only determine the combination $a \sin i$
- *can* only determine $M_\mathrm{p} \sin i$ if M_* can be estimated
- cannot determine Δi for multiple planets

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

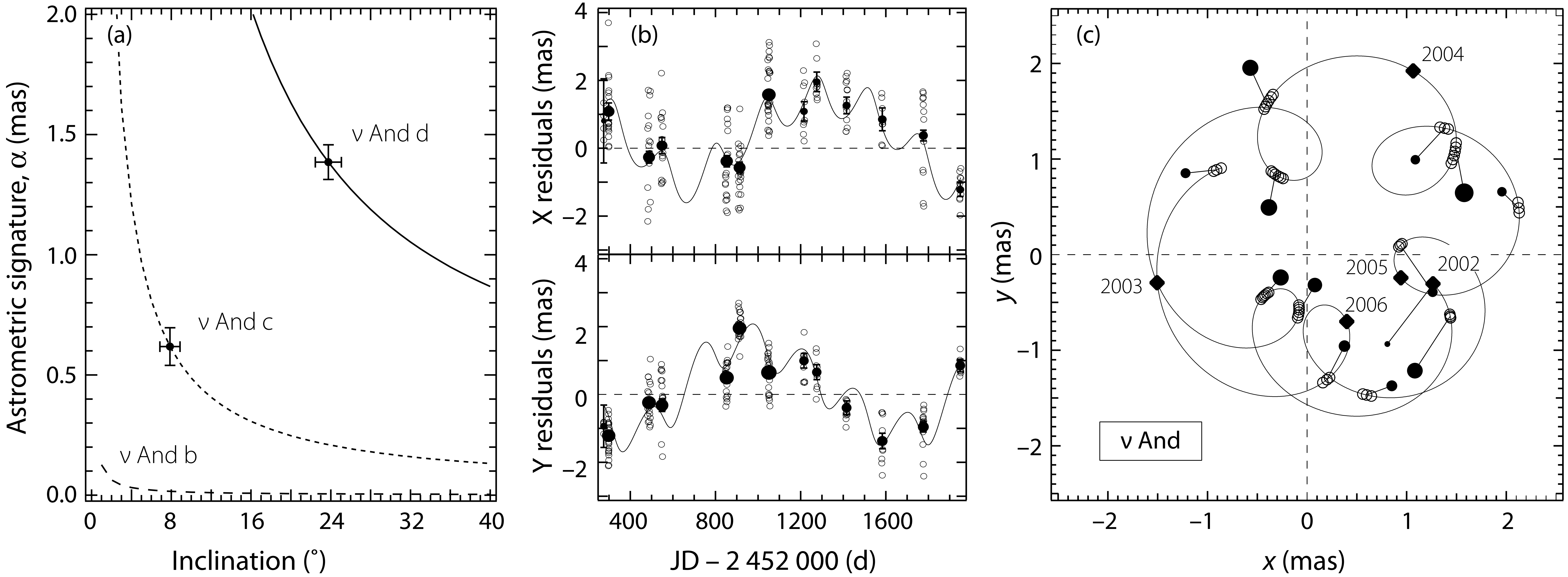
- *xy(t)* yields max/min angular rates, hence line of apsides (major axis)
- then appeal to Kepler's third law fixes the orbit inclination

⇒ astrometry can determine M_p, inclination, and Δi for multiple planets
Example: the HST–FGS astrometry of ν And (McArthur et al, 2010)

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

How many planets will Gaia detect?

(Perryman et al. 2014; see also Casertano et al. 2008; Sozzetti et al. 2014)

Based on:

- pre-launch Gaia accuracies: along-scan error versus magnitude
- a Galaxy population synthesis model (TRILEGAL; by Girardi et al 2012)
- known exoplanet occurrence frequencies (single planet) versus stellar type, mass, etc
- detailed observational model (field-of-view crossings) versus sky position
- planet detectability dependent on number and distribution of field-of-view crossings

Our predictions:

- 20,000 (5-yr mission) to 70,000 (10-yr mission) [assuming a single massive planet]

This should open a new area of exoplanet studies:

- it will pin-point a huge number of new systems which are Jupiter-like
- very different architectures from typical (short-period) transiting systems
- follow-up can aim to identify inner orbit, lower-mass, Earth-like planets
- perhaps these are the most likely to harbour (and protect) habitable planets…

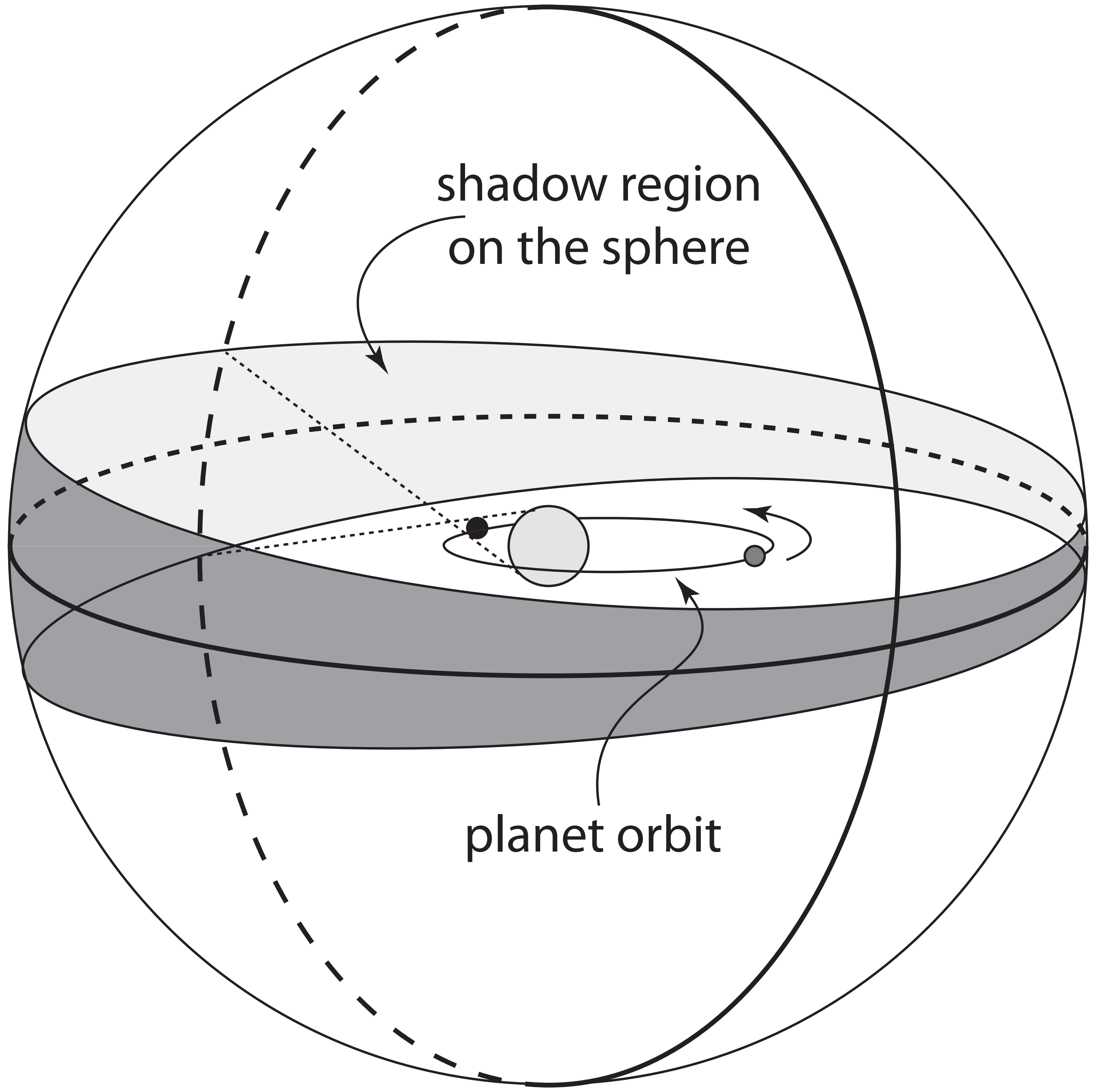
How many of these are transiting?

- probability given by the solid angle
- for circular orbits (e.g. Borucki & Summers 1984):

$$p = \frac{R_\star}{a_\mathrm{p}} \simeq 0.005 \left(\frac{R_\star}{R_\odot}\right) \left(\frac{a_\mathrm{p}}{1\ \mathrm{AU}}\right)^{-1}$$

- for eccentric orbits (e.g. Barnes 2007):

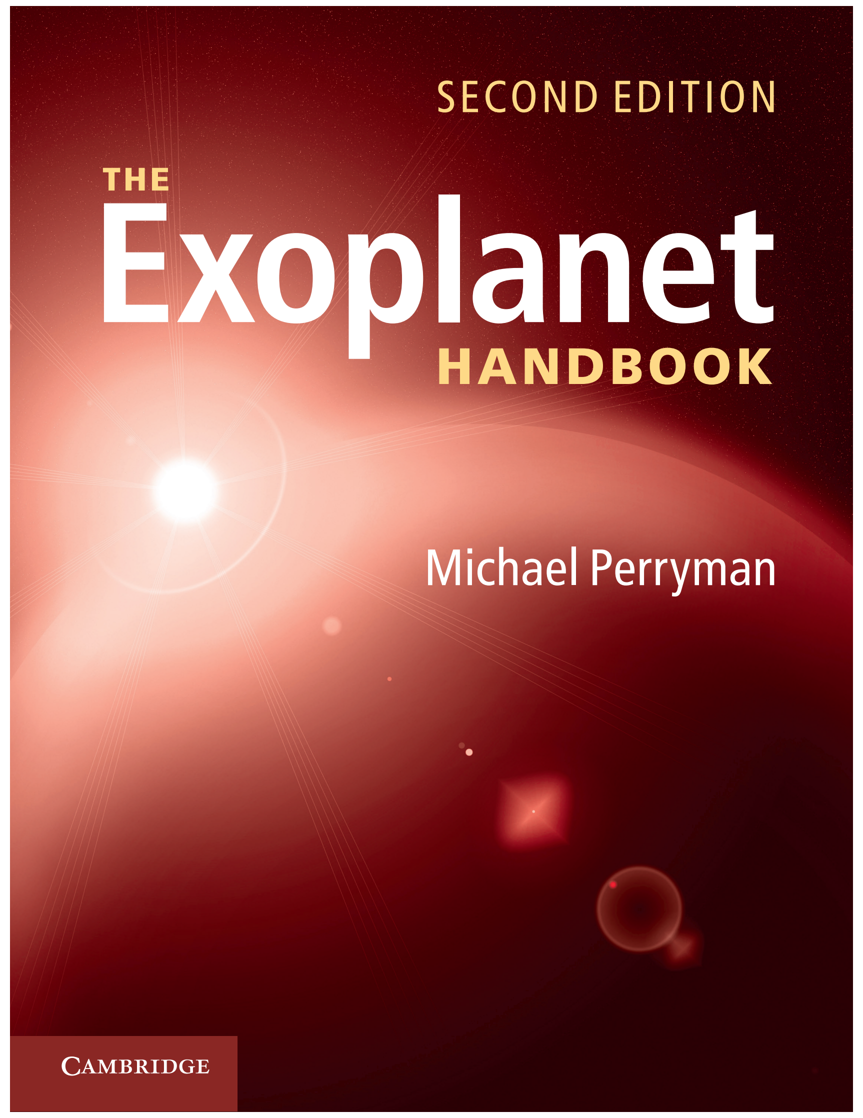
$$p = \left(\frac{R_\star + R_\mathrm{p}}{a_\mathrm{p}}\right) \left(\frac{1}{1 - e^2}\right)$$



Perryman et al. (2014) estimated ~ 40 – 100 transiting planets

A small number, but potentially very interesting:

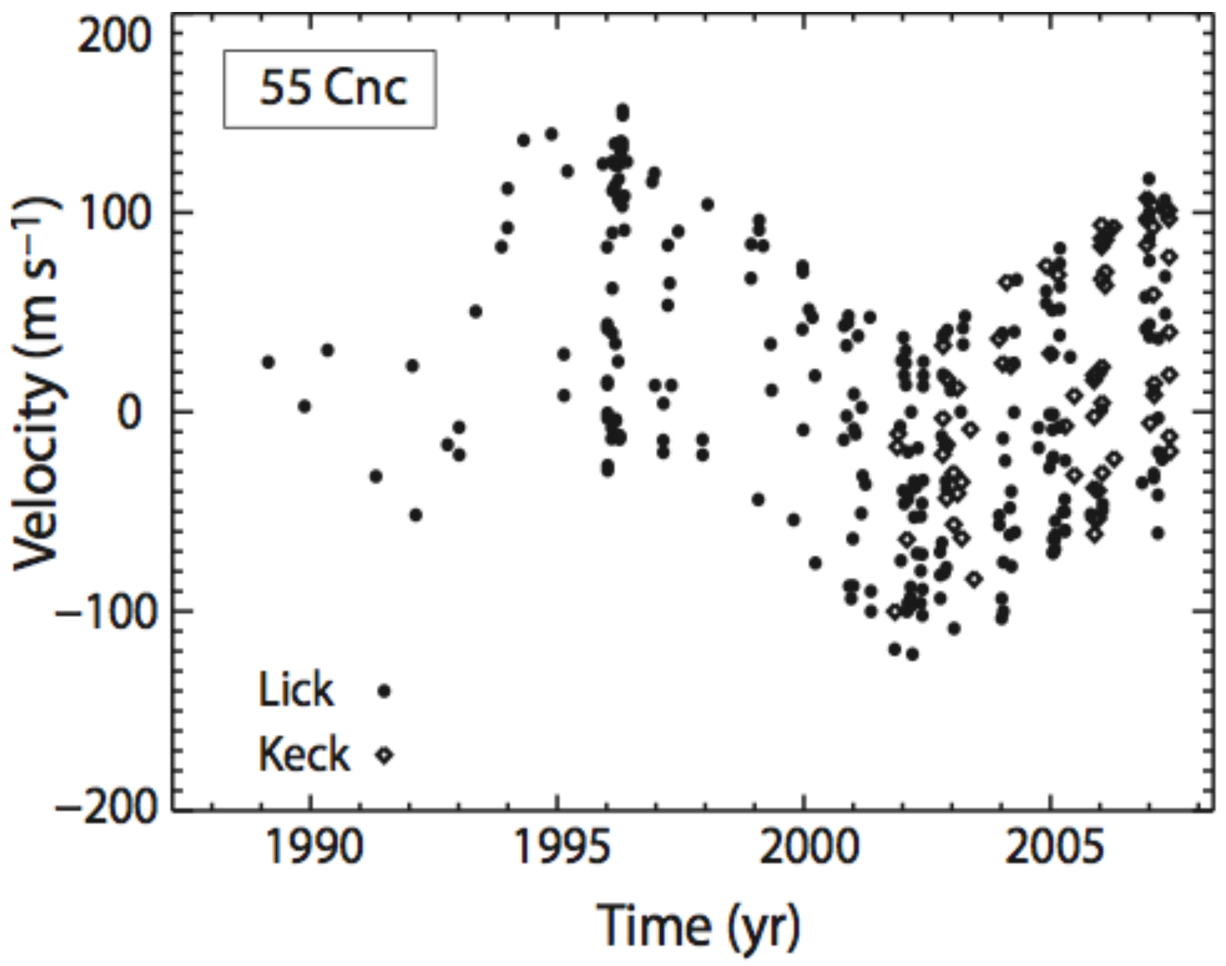
- periods: 1–5 years, i.e. ‘middle region’ planets
- ~1–2 M_{Jupiter}, so (bright star) transits will be very pronounced, although…
- discovering these precisely transiting planets will not be easy…
- some may be in the Gaia photometry
- some may be in existing transit databases
- interesting for amateur/citizen science, to find inner transiting planets
- characterisation of planets poorly characterised by other means
- particularly amenable to studies of atmospheric refraction and stellar mirages (e.g. Exoplanet Handbook, 2018, Section 6.14.11)



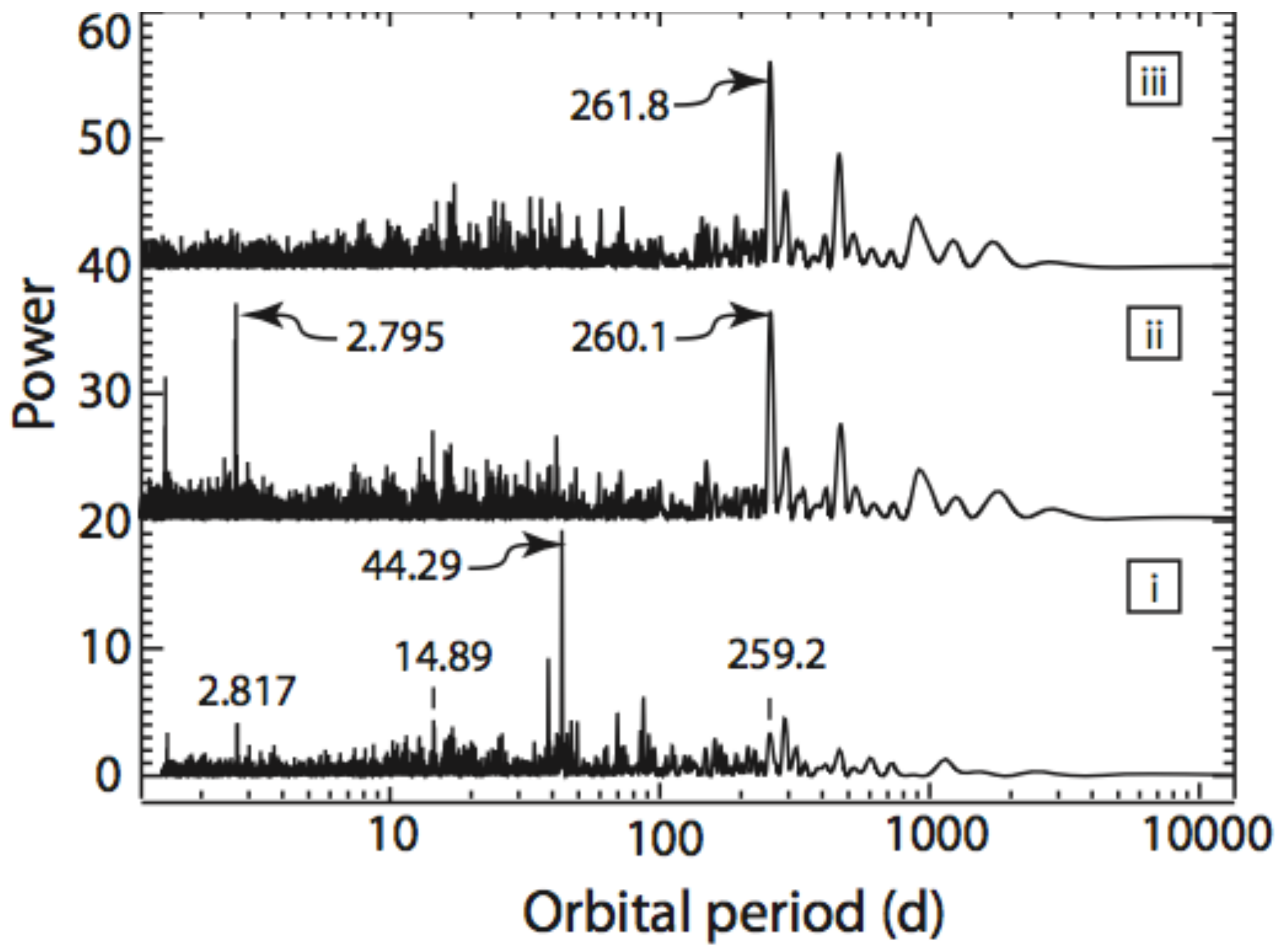
For multiple planet systems...

Drawing on radial velocity work, multiple systems can be fit by recursive decomposition

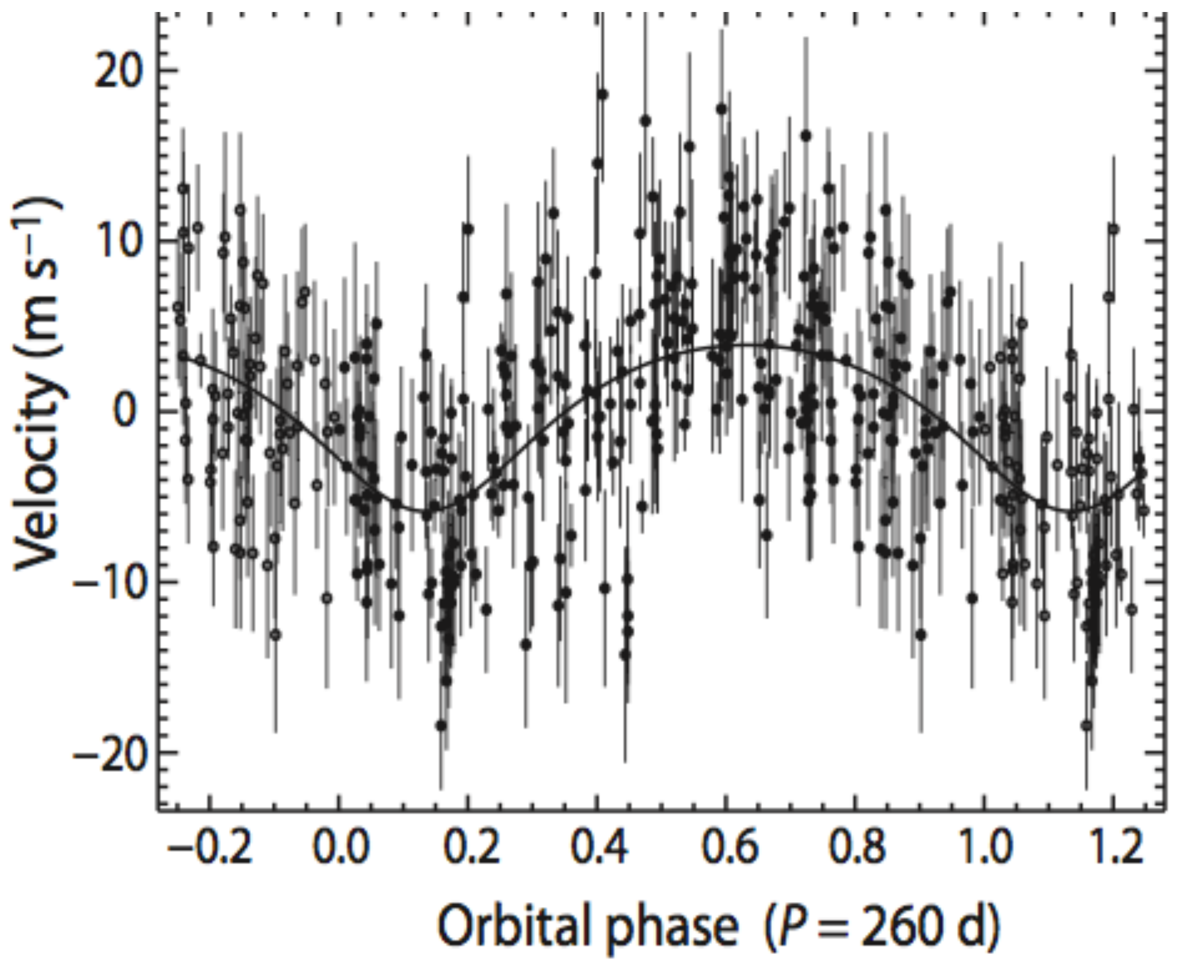
(e.g. Casertano et al. 2008; Wright & Howard 2009; Traub et al. 2010)



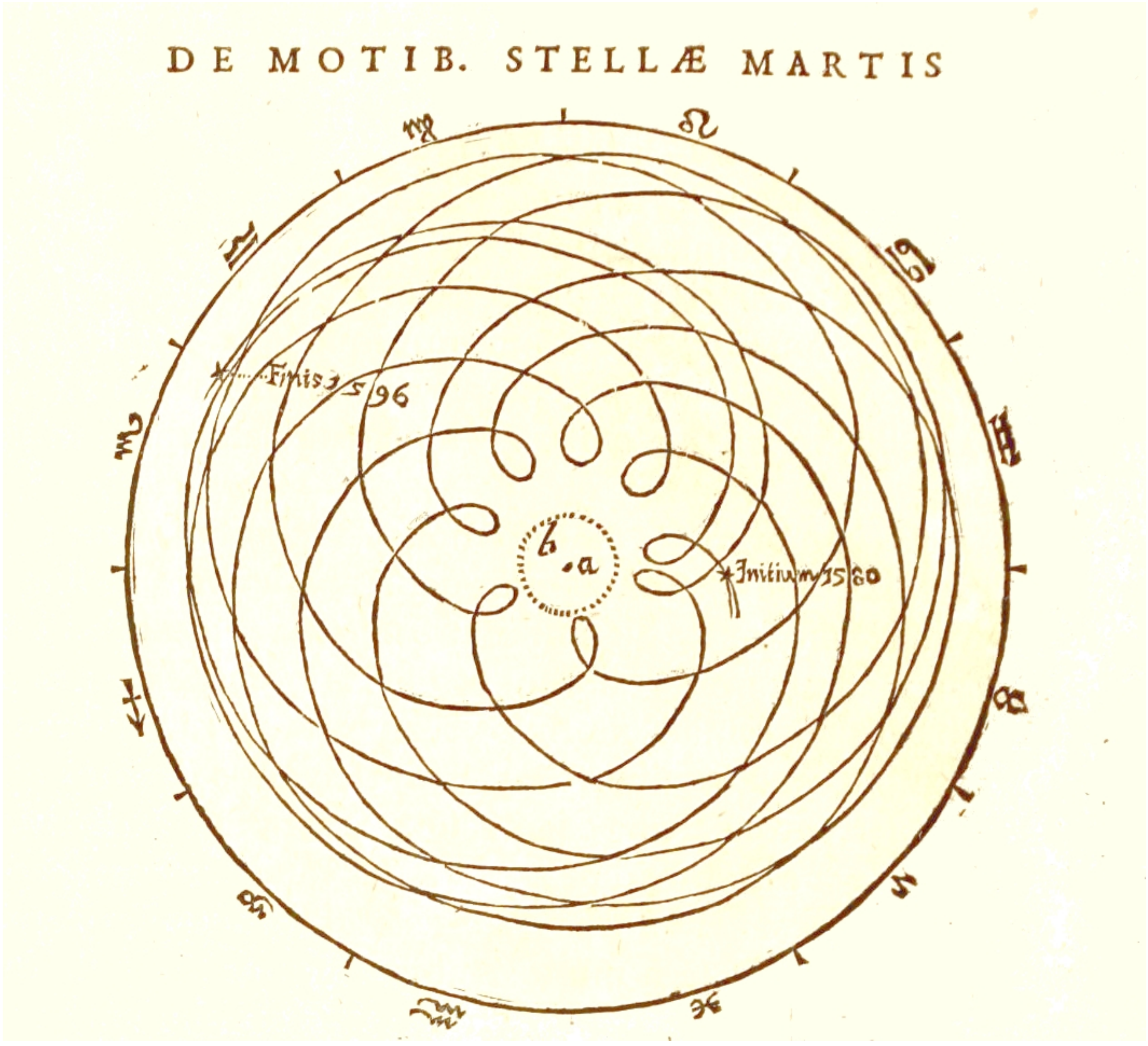
5-planet system 55 Cnc
(Fischer et al 2008)



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

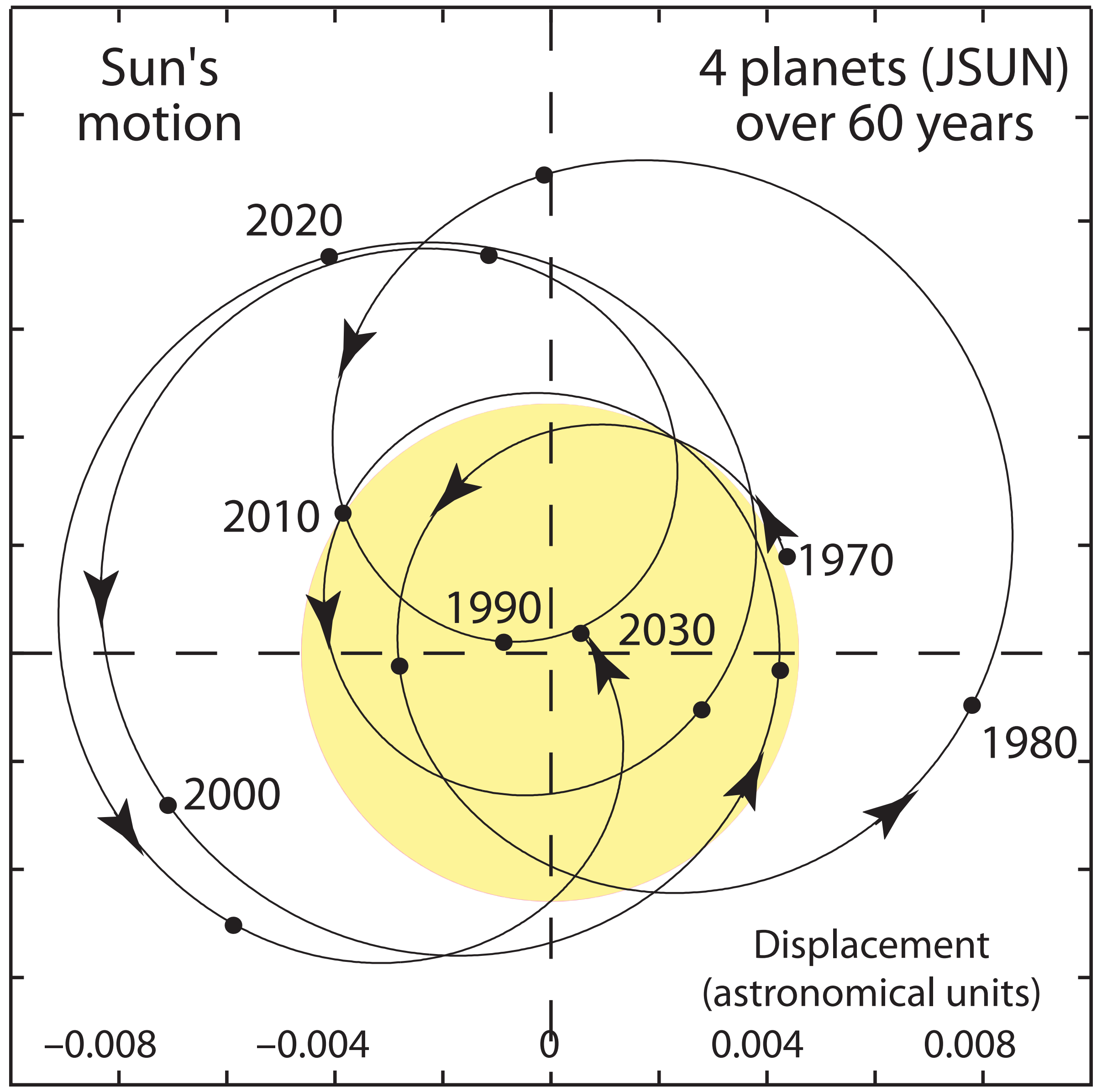


Periodicity of the fifth planet
in the Keck data

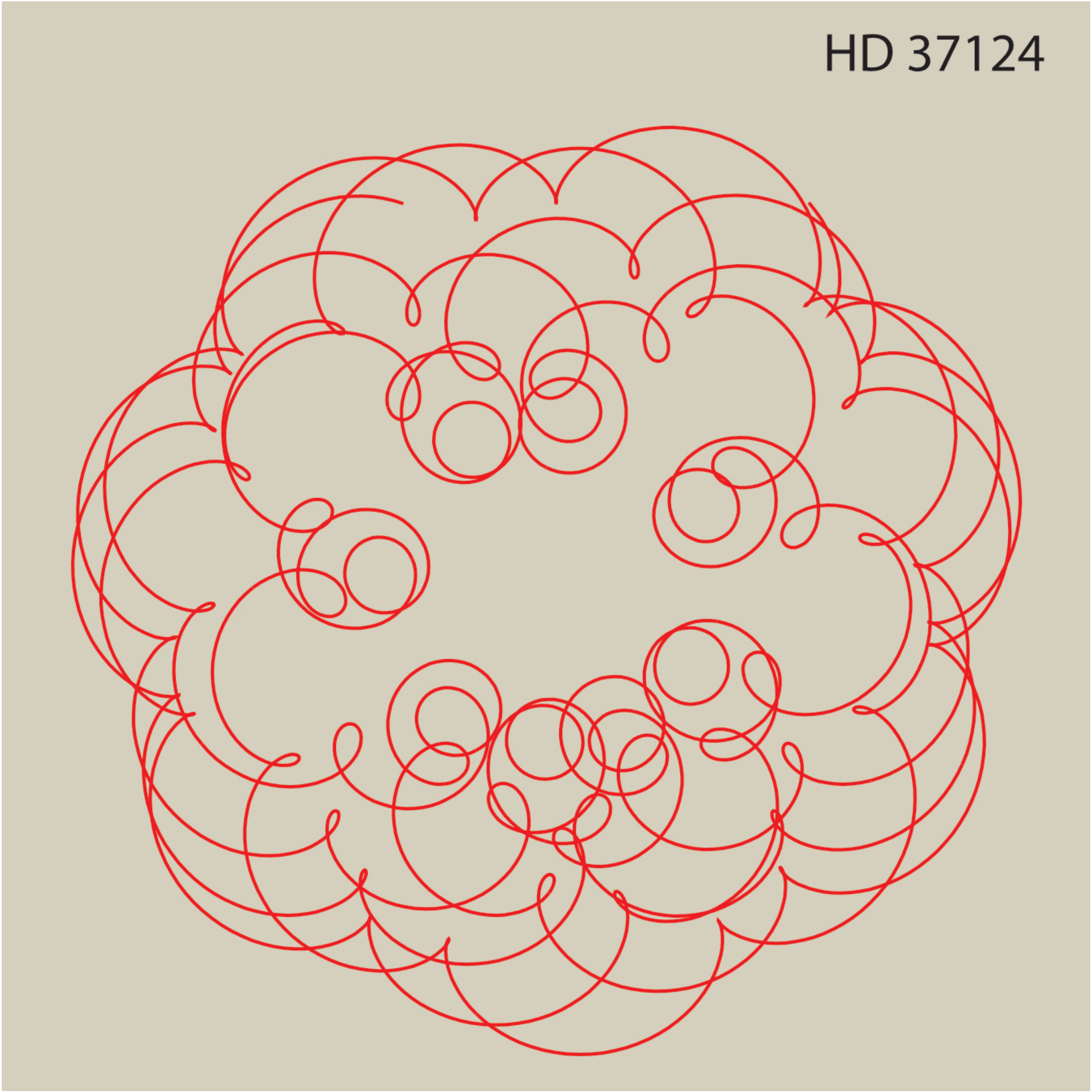


Kepler’s orbit of Mars seen from Earth

Star motion around barycentre for multiple planets



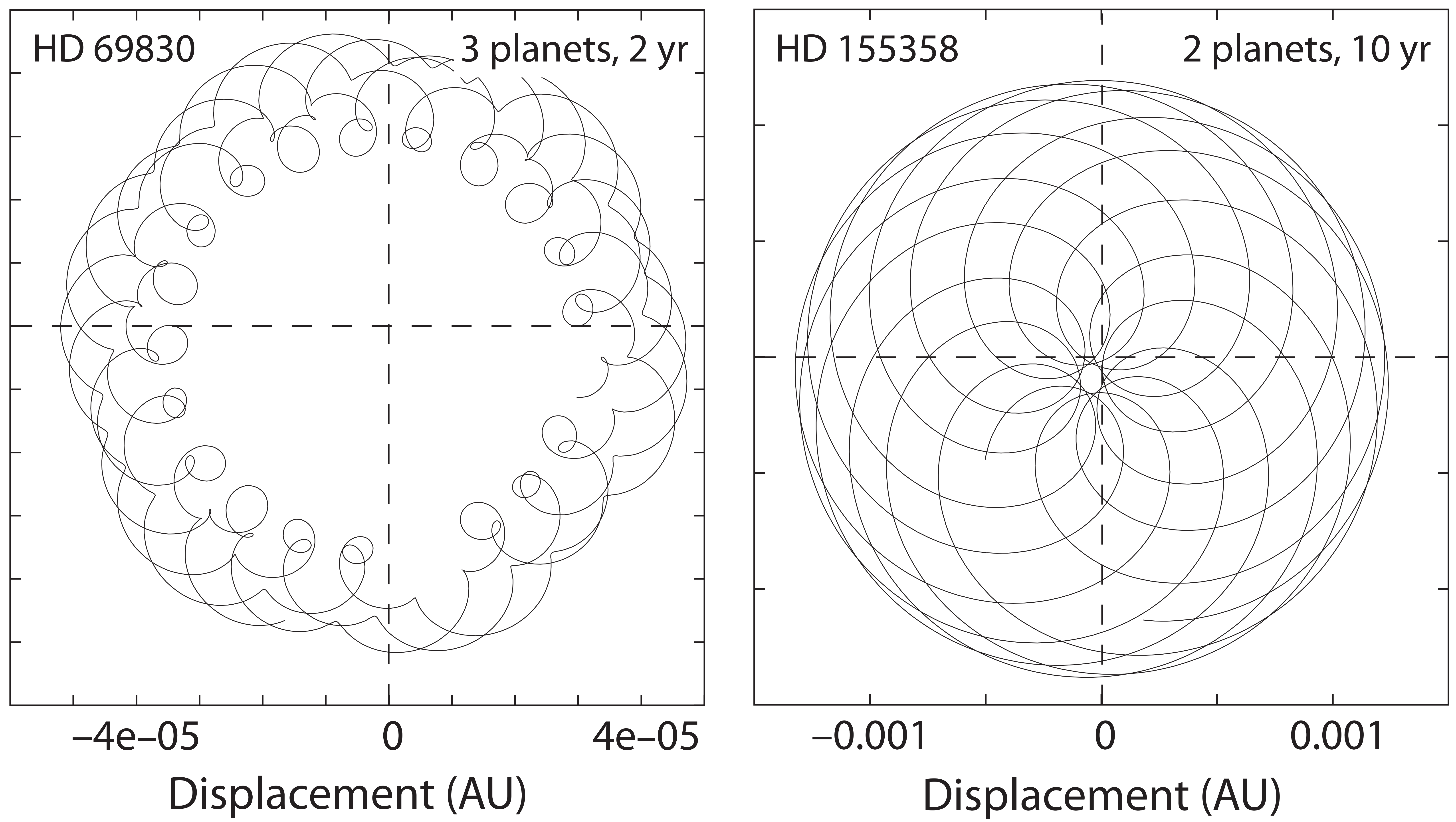
Sun’s orbit wrt solar system barycentre



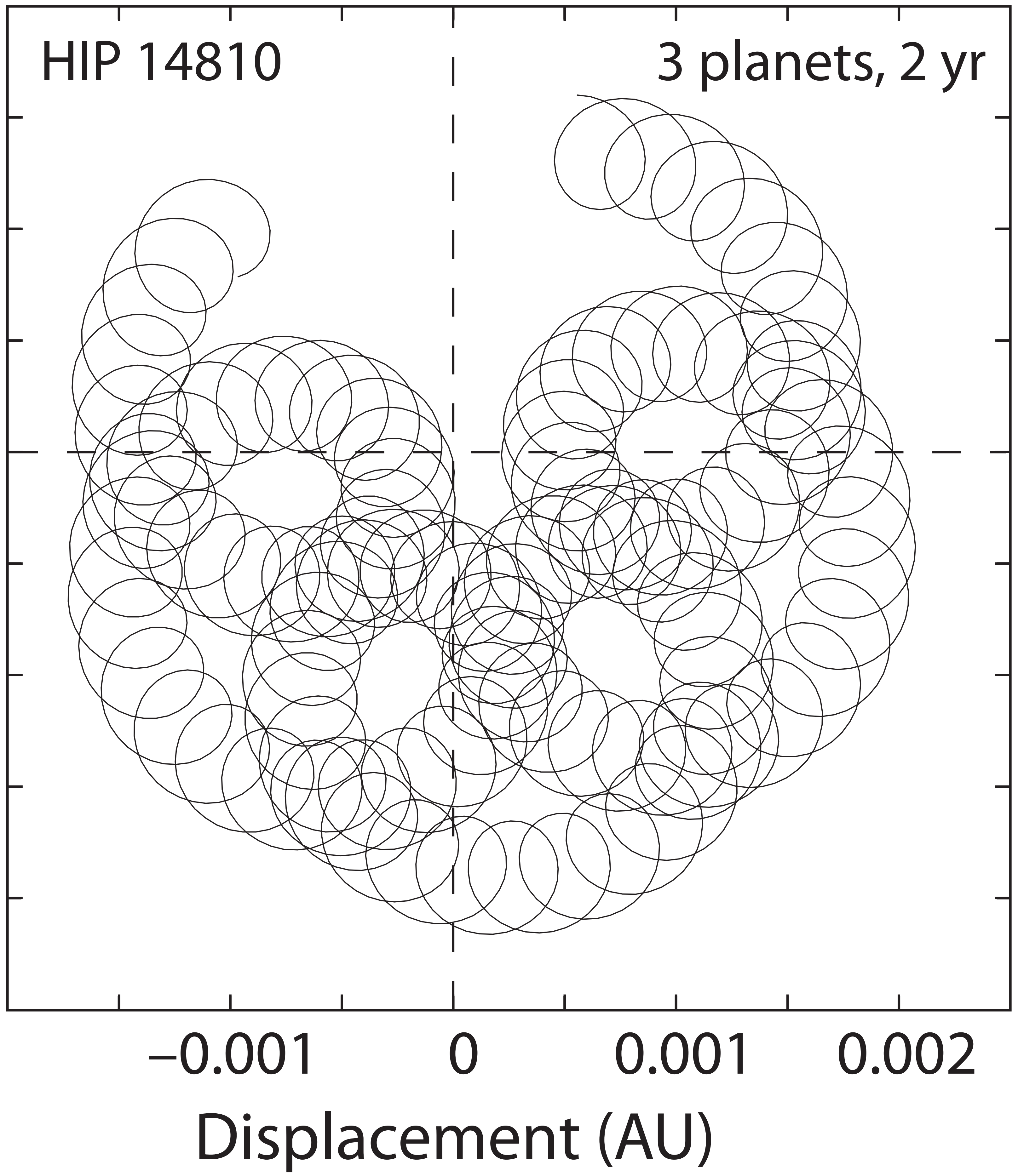
Two or more (massive) planets result in a family of beautiful and complex patterns of the host star motions, termed ‘mandalas’

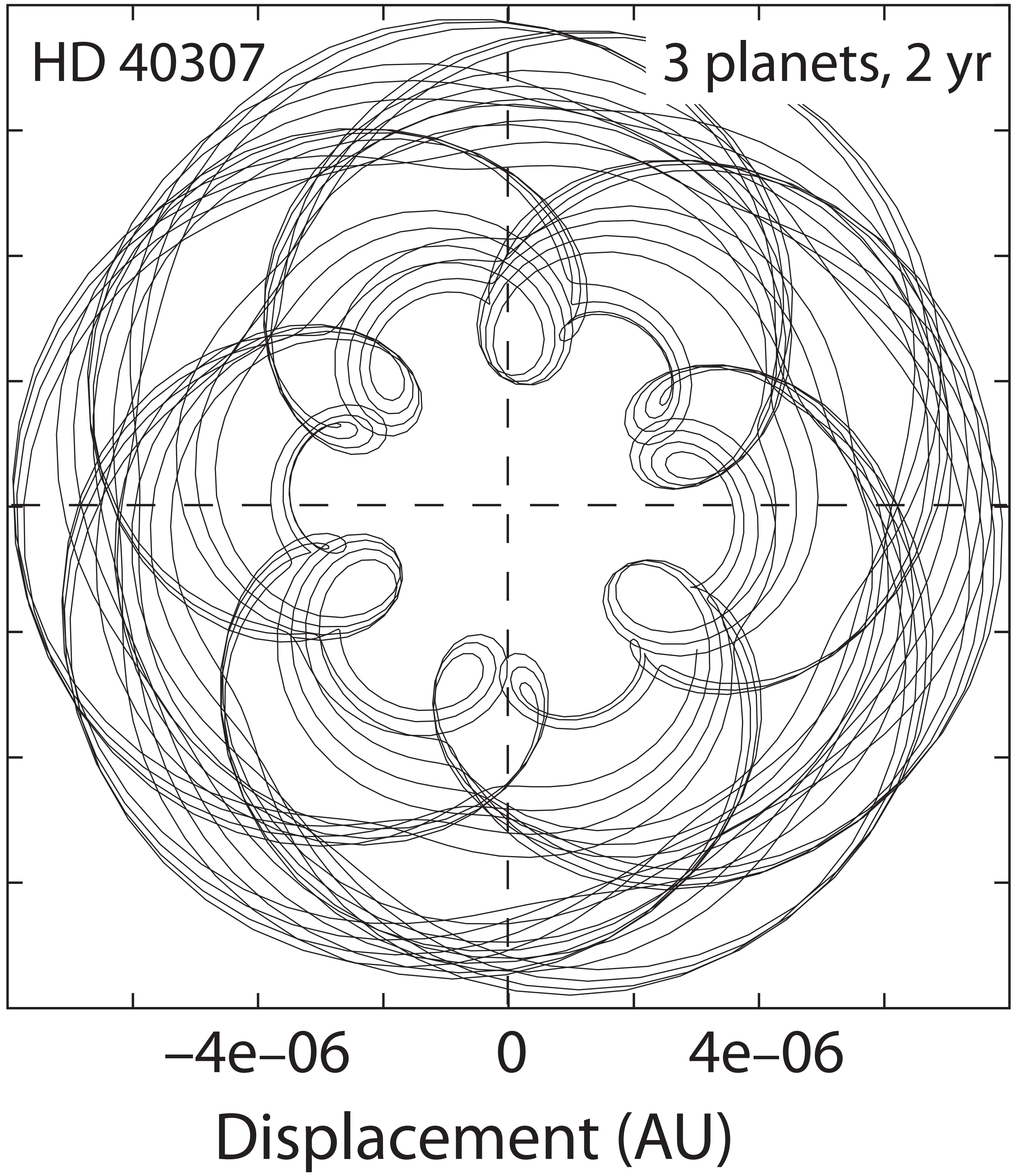
Astrometric ‘predictions’
(assuming coplanarity)

Star motion around barycentre for multiple planets (cont.)



Star motion around barycentre for multiple planets (cont.)





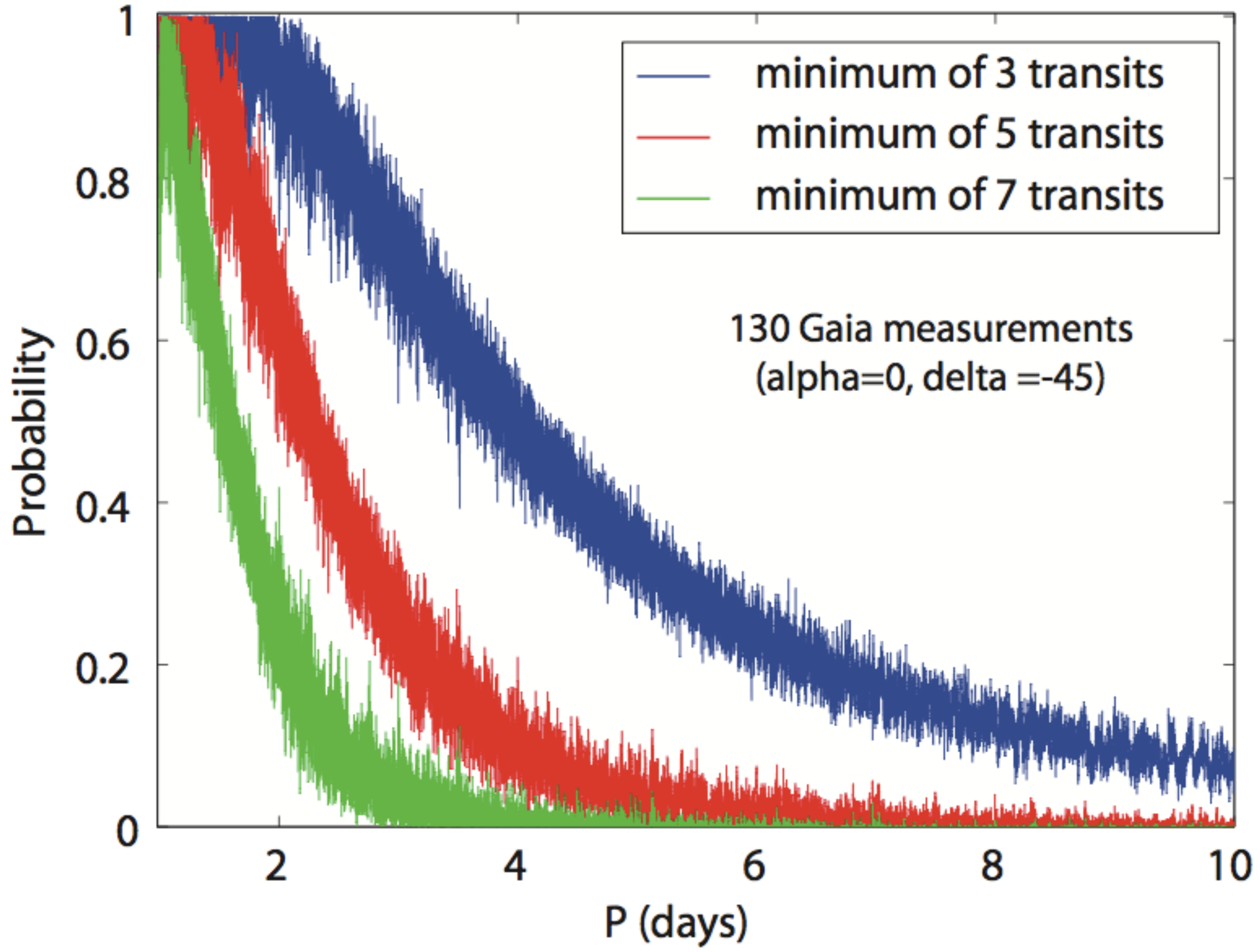
Gaia: transit estimates for (very) hot Jupiters

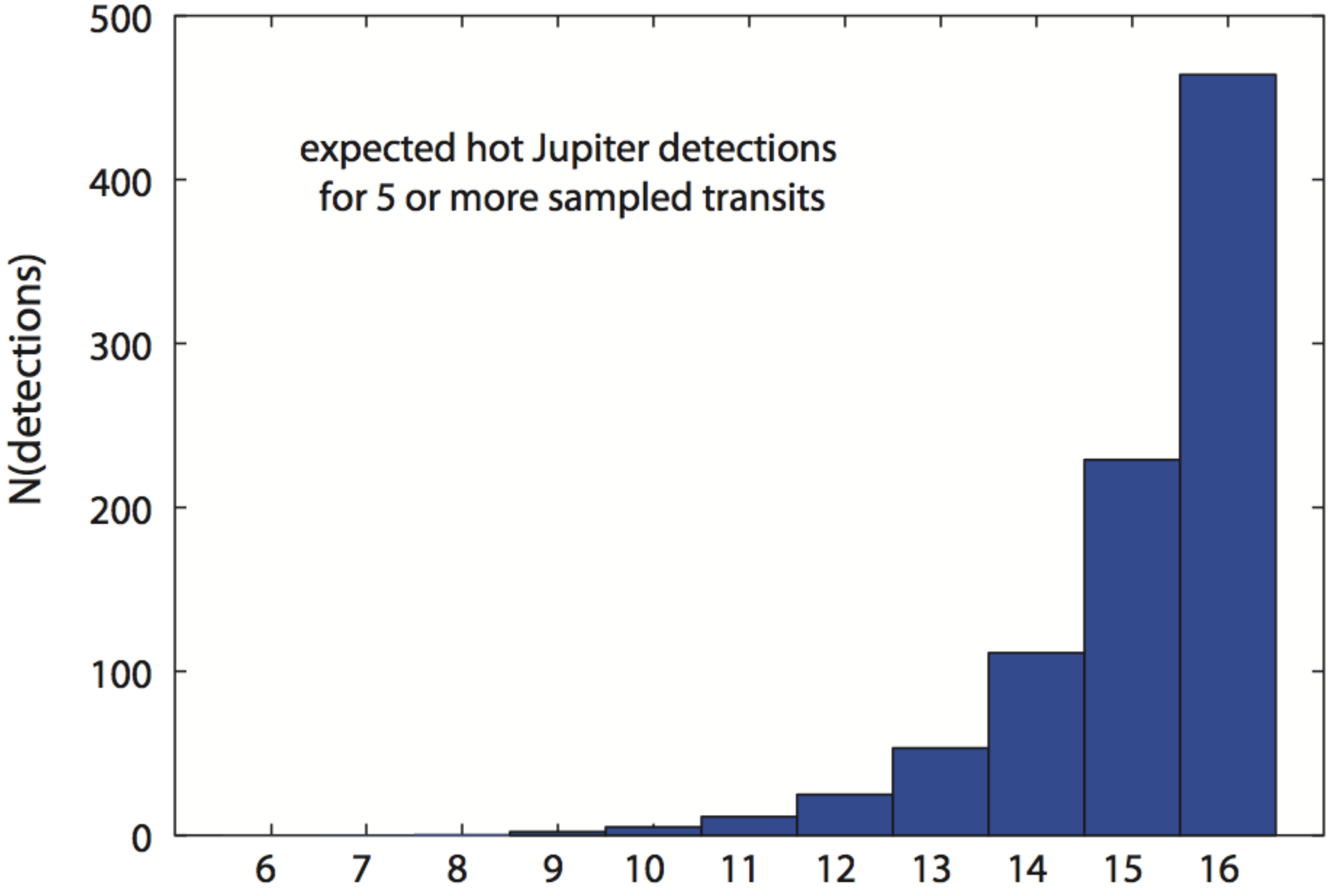
(e.g. Dzigan & Zucker 2012)

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 radial velocity follow-up)

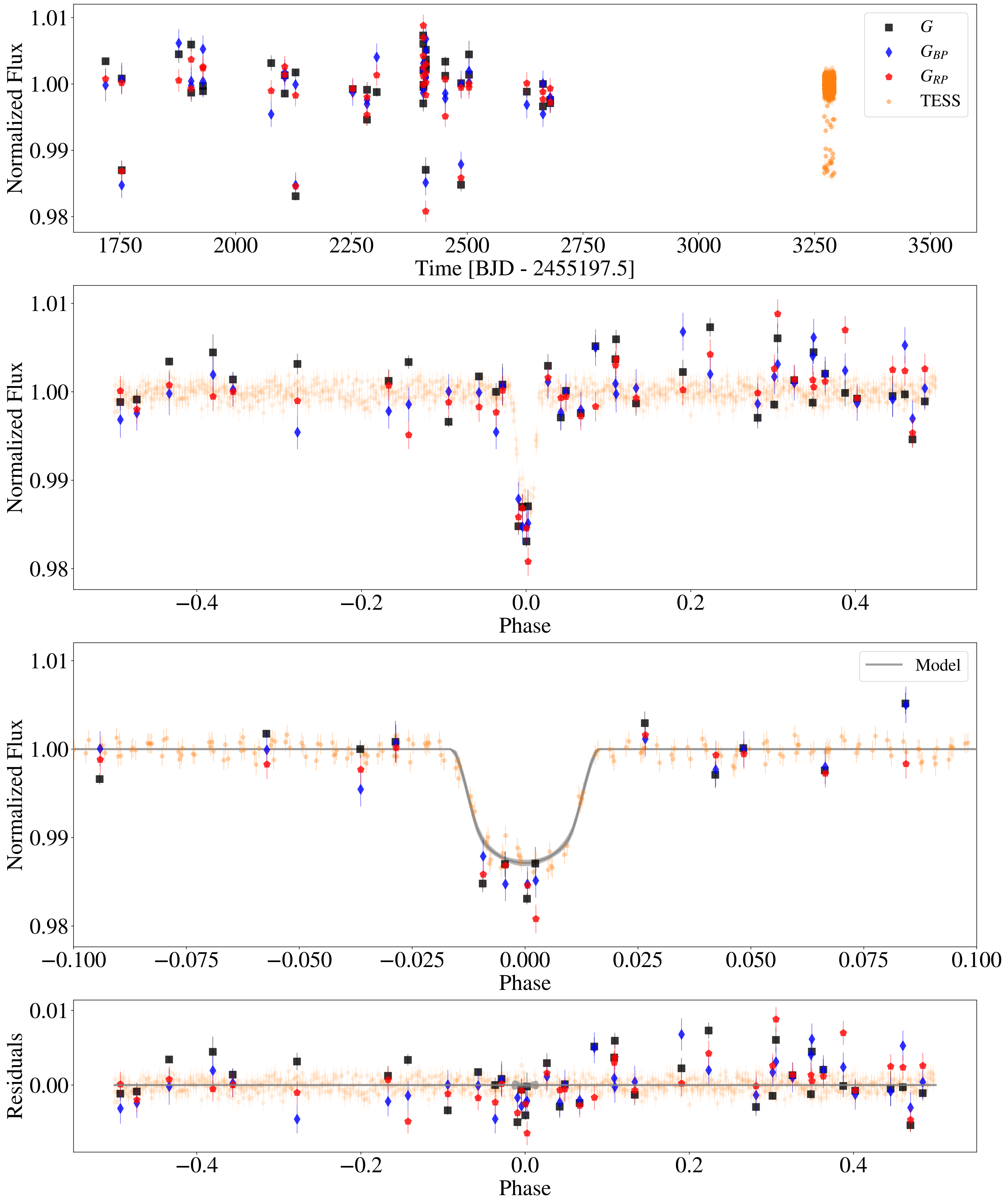
Gaia’s first planets from photometric transits

Panahi et al. (2022), based on Early Data Release 3 (EDR3, 34 months data, 2014–17)

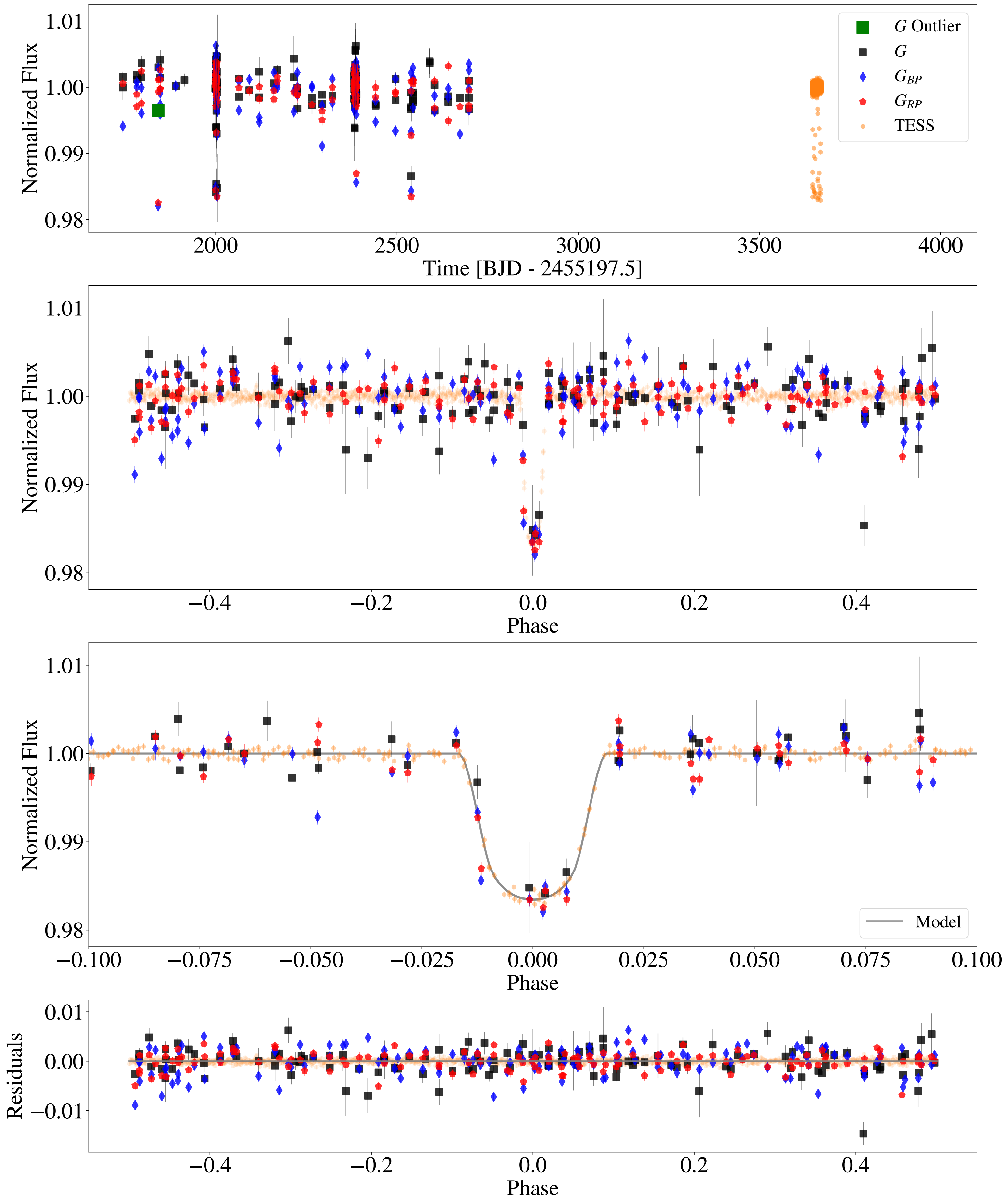
- candidates: 18383 > 89 > 41 not EBs > 21 transit-like signals > 2 confirmed by radial velocities
- both are hot Jupiters, *P* ~ 3 day, ~1 Jupiter mass; and confirmed by TESS photometry

Predictions by Dzigan & Zucker (2012): up to a few thousand planets with P < 10 days [limited number of observations]

Gaia–1

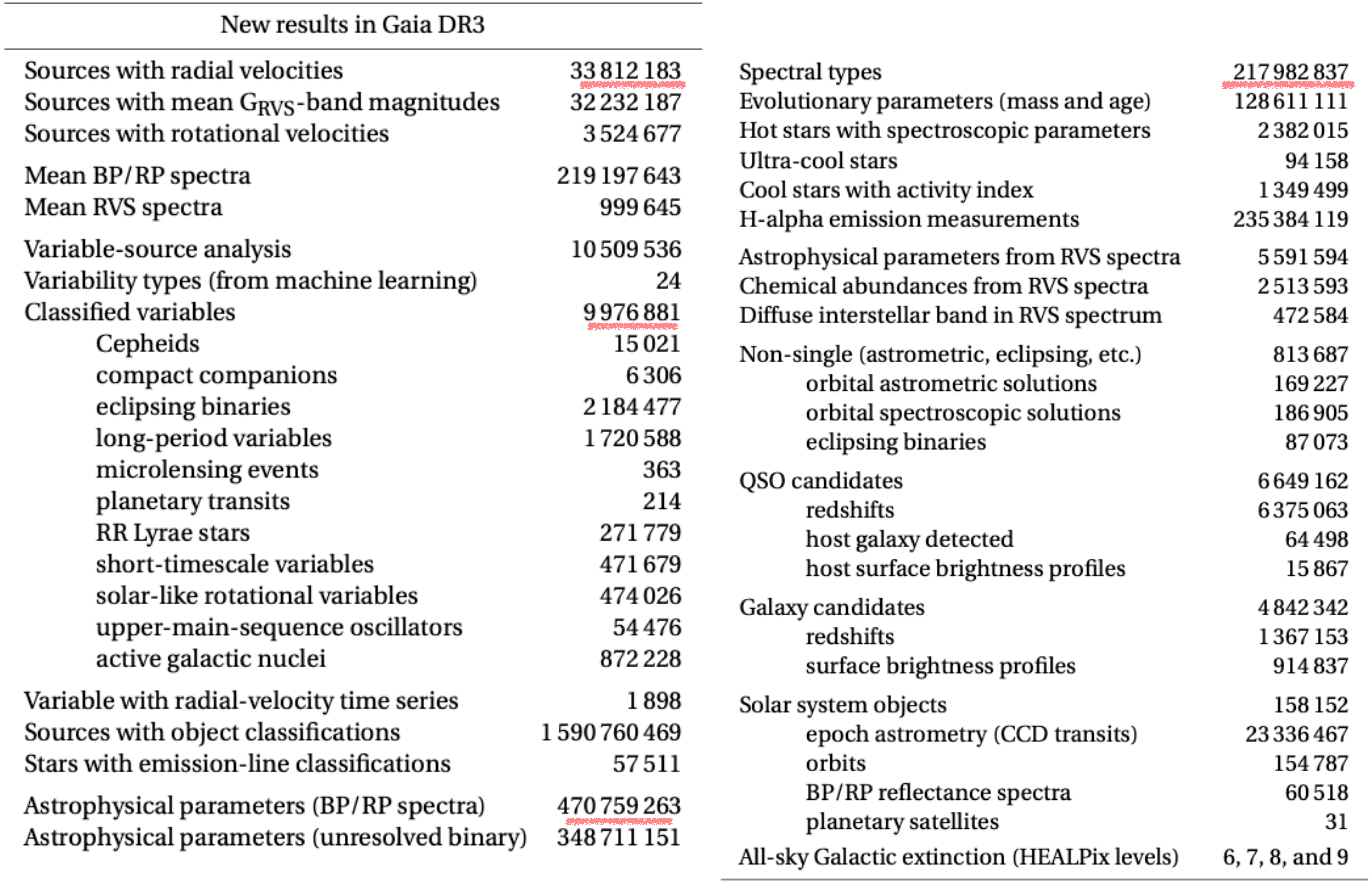


Gaia–2



Gaia Data Release 3: 13 June 2022

	Gaia DR3
Observations:	
– time period	Jul 2014–May 2017
– observations duration	34 months
– reference epoch	J2016.0
– catalogue release date	13 June 2022
Astrometry:	
– total number (3–21 mag)	1,811,709,771
– 5–parameter solutions	585,416,709
– 6–parameter solutions	882,328,109
– 2–parameter solutions	343,964,953
Photometry:	
– mean G magnitude	1,806,254,432
– mean G_{BP} photometry	1,542,033,472
– mean G_{RP} photometry	1,554,997,939
Radial velocities (4–13 mag)	7,209,831



New results in Gaia DR3	
Sources with radial velocities	33 812 183
Sources with mean G_{RVS}-band magnitudes	32 232 187
Sources with rotational velocities	3 524 677
Mean BP/RP spectra	219 197 643
Mean RVS spectra	999 645
Variable-source analysis	10 509 536
Variability types (from machine learning)	24
Classified variables	9 976 881
Cepheids	15 021
compact companions	6 306
eclipsing binaries	2 184 477
long-period variables	1 720 588
microlensing events	363
planetary transits	214
RR Lyrae stars	271 779
short-timescale variables	471 679
solar-like rotational variables	474 026
upper-main-sequence oscillators	54 476
active galactic nuclei	872 228
Variable with radial-velocity time series	1 898
Sources with object classifications	1 590 760 469
Stars with emission-line classifications	57 511
Astrophysical parameters (BP/RP spectra)	470 759 263
Astrophysical parameters (unresolved binary)	348 711 151
Spectral types	217 982 837
Evolutionary parameters (mass and age)	128 611 111
Hot stars with spectroscopic parameters	2 382 015
Ultra-cool stars	94 158
Cool stars with activity index	1 349 499
H-alpha emission measurements	235 384 119
Astrophysical parameters from RVS spectra	5 591 594
Chemical abundances from RVS spectra	2 513 593
Diffuse interstellar band in RVS spectrum	472 584
Non-single (astrometric, eclipsing, etc.)	813 687
orbital astrometric solutions	169 227
orbital spectroscopic solutions	186 905
eclipsing binaries	87 073
QSO candidates	6 649 162
redshifts	6 375 063
host galaxy detected	64 498
host surface brightness profiles	15 867
Galaxy candidates	4 842 342
redshifts	1 367 153
surface brightness profiles	914 837
Solar system objects	158 152
epoch astrometry (CCD transits)	23 336 467
orbits	154 787
BP/RP reflectance spectra	60 518
planetary satellites	31
All-sky Galactic extinction (HEALPix levels)	6, 7, 8, and 9

Gaia Data Release 3 results from Coordination Unit 4

CU4 processes: (a) non-single stars; (b) solar system; (c) galaxies

Binary systems classified as: visual; astrometric; spectroscopic; eclipsing

Solutions organised as: measured orbits; non-linear proper motion; + two others

Gaia DR3 contains (Arenou et al. 2022):

- 800,000 solutions with either orbital or trend parameters
- of which 130,000 are full orbit solutions, and 300,000 show non-linear motions
- 40× more orbit solutions than the *Sixth Catalog of Orbits of Visual Binary Stars* (Hartkopf et al. 2001)

Note that:

- most Hipparcos stars with 7- or 9-parameter solution also show proper motion anomalies
- all will be improved in future data releases (more data, better calibration)
- many of the ‘non-linear’ will progress to ‘orbits’ as temporal baseline improves
- full validation (excluding equal mass binary stars) can be a tricky problem

Status today

(more in talk by Alessandro Sozzetti)

For sub-stellar companion masses, Arenou et al. (2022) reported these *candidates*:

- 1843 brown dwarfs
- 72 exoplanets
- of these, only 10 brown dwarfs and 9 exoplanets were previously known (good agreement in their properties)
  - includes DENIS-P J082303.1–491201 (only astrometric planet in NASA archive)
  - also includes GJ 876, HD 114762, HD 162020, HD 164604 (previous discoveries from radial velocities)

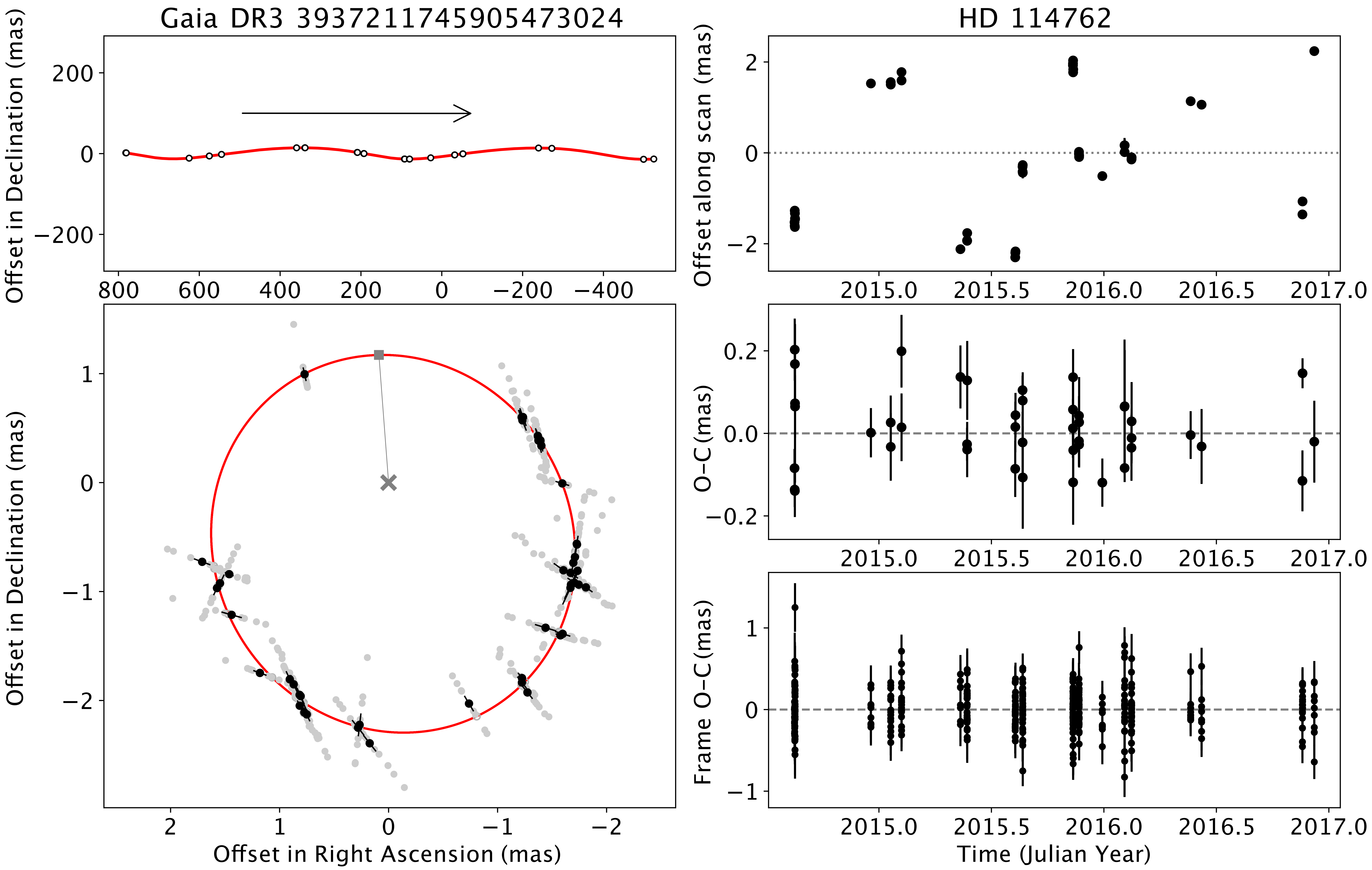
So far, just two new candidates have *validated* orbits:

- HIP 66074: $P = 297 \pm 2.8$ day, $e = 0.46 \pm 0.17$, $a_0 = 0.21 \pm 0.03$ milli-arcsec, $M_\mathrm{p} = 7.3 \pm 1.1\ M_\mathrm{Jupiter}$
- HIP 28193: $P = 827 \pm 50$ day, $e = 0.07 \pm 0.10$, $a_0 = 0.25 \pm 0.02$ milli-arcsec, $M_\mathrm{p} = 5.3 \pm 0.6\ M_\mathrm{Jupiter}$

Other candidates include:

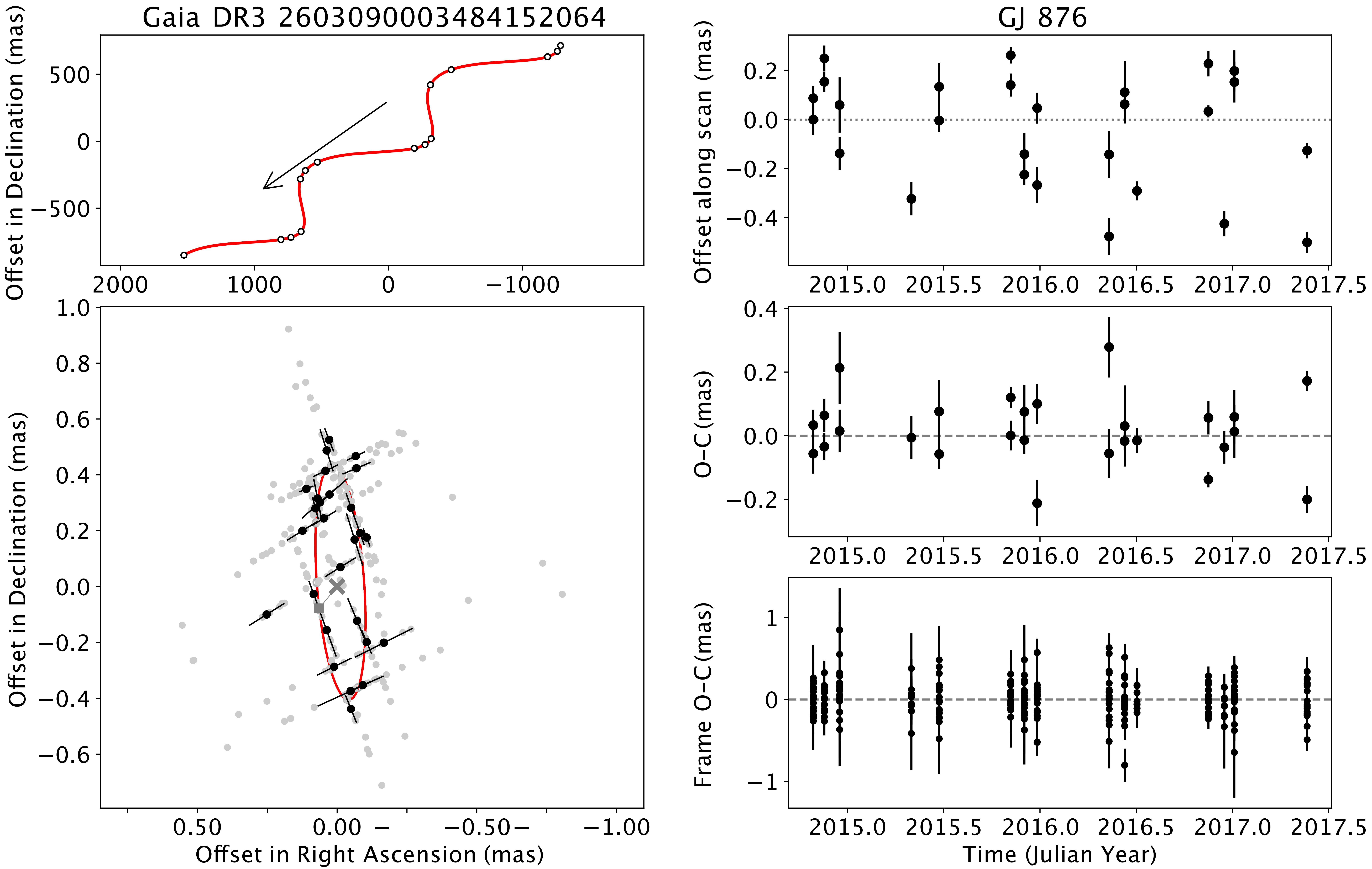
- WD 0141–675 (9.8 pc): a (rare) giant planet orbiting a white dwarf (metal-enriched system ⇒ debris capture?)

Example orbit fitting (Holl et al 2022)



HD 114762 $G = 7.15$, $P = 83.74 \pm 0.12$ day, $e = 0.32 \pm 0.0.4$, parallax = 25.36 ± 0.04 milli-arcsec

Example orbit fitting (Holl et al 2022)



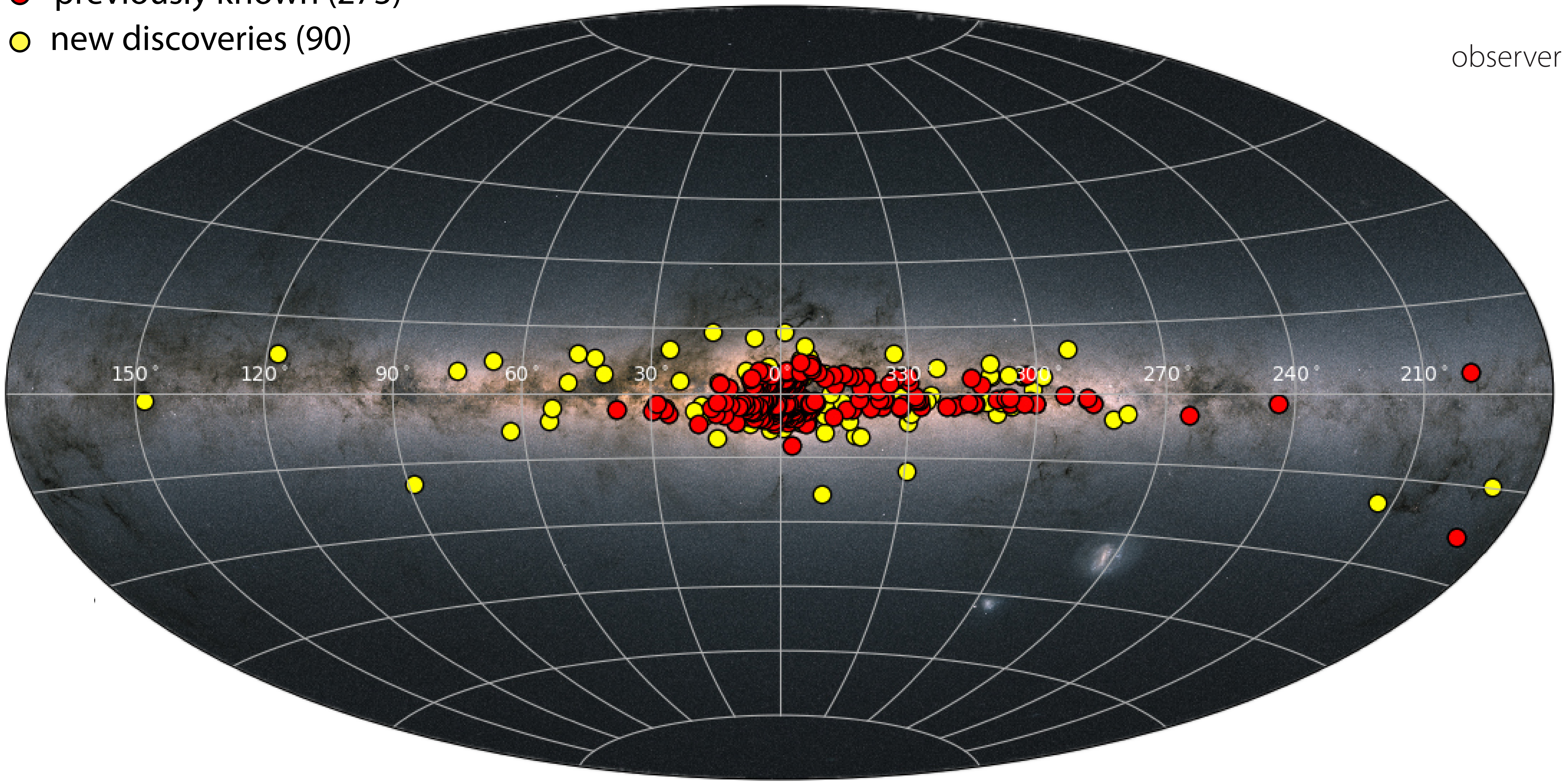
GJ 876

Microlensing

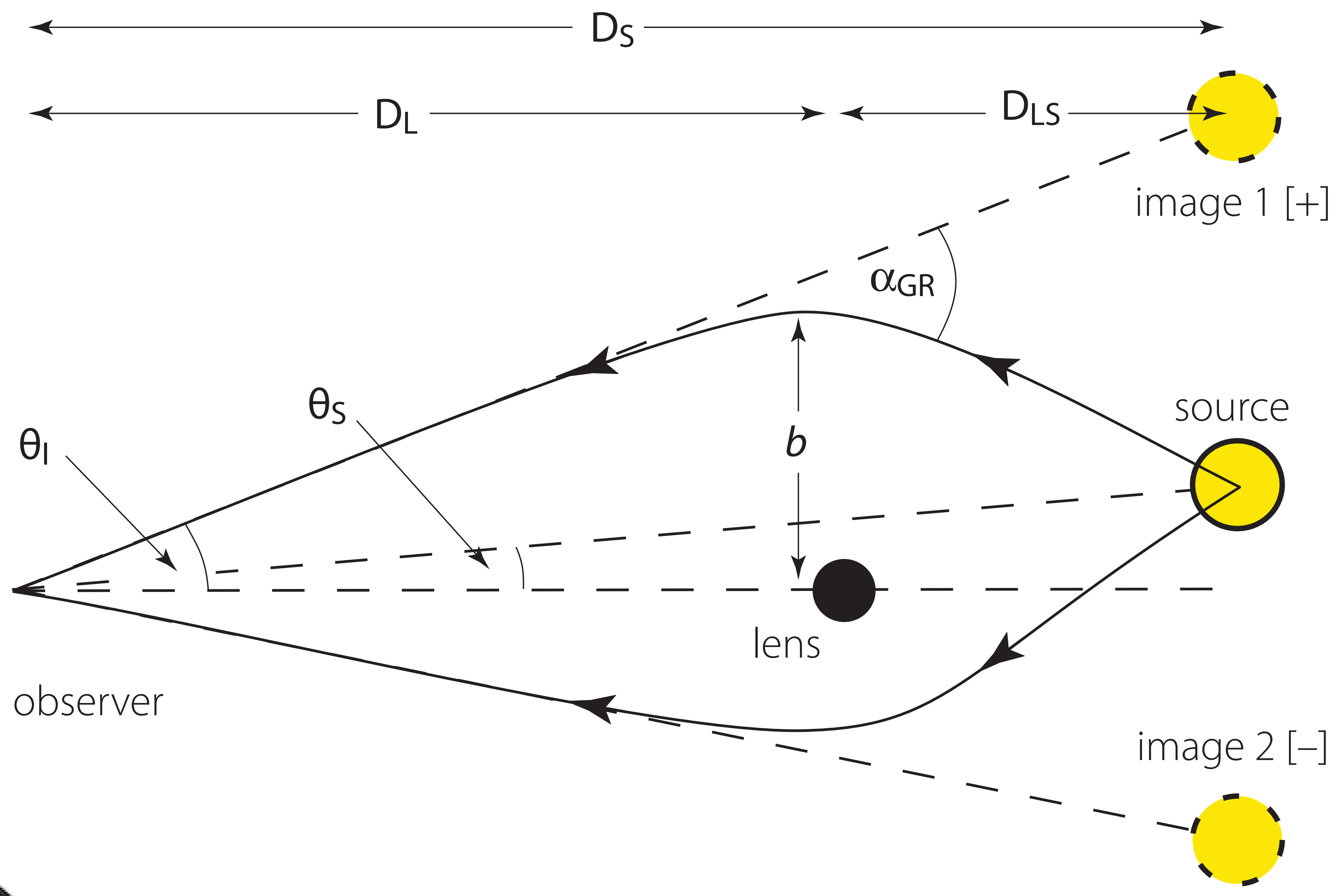
A remarkable manifestation of General Relativity…

If the observer (Gaia), some star at intermediate distance (lens), and some distant background star (source) align precisely, then the light from the background star can be strongly magnified!

- 🔴 previously known (273)
- 🟡 new discoveries (90)

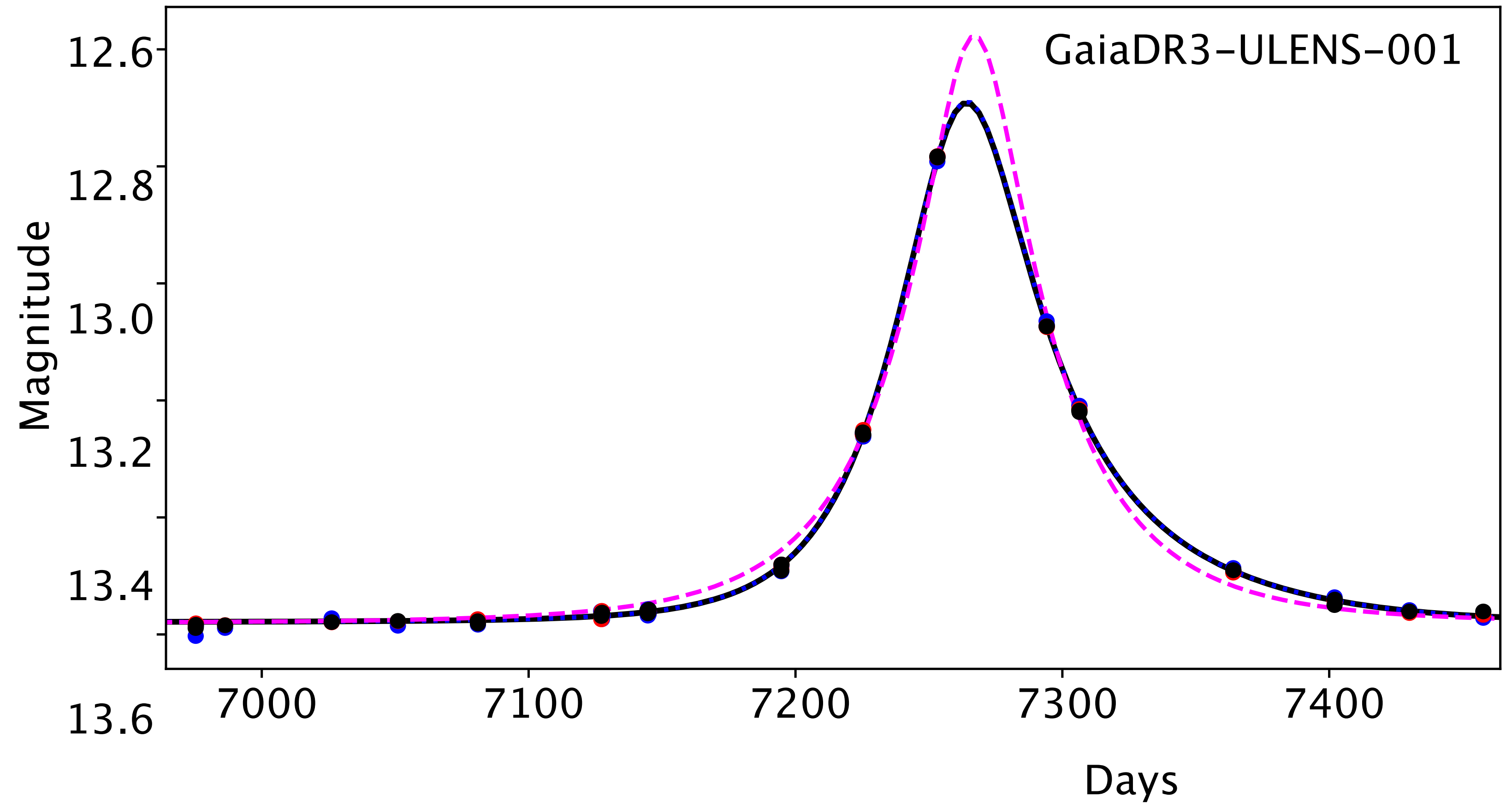


While thousands have been found from ground, Gaia is discovering more, all across the sky



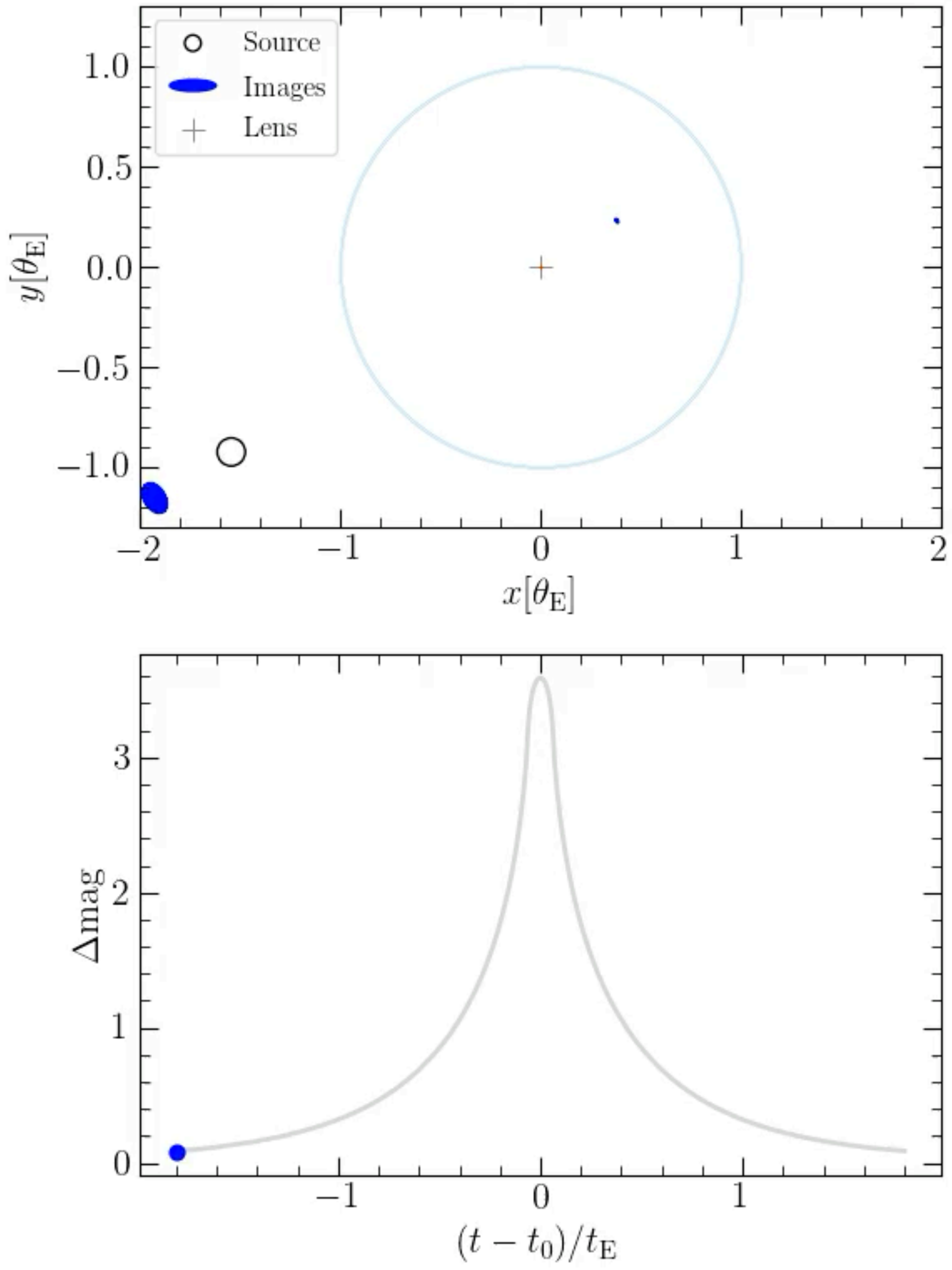
The first of Gaia's discoveries

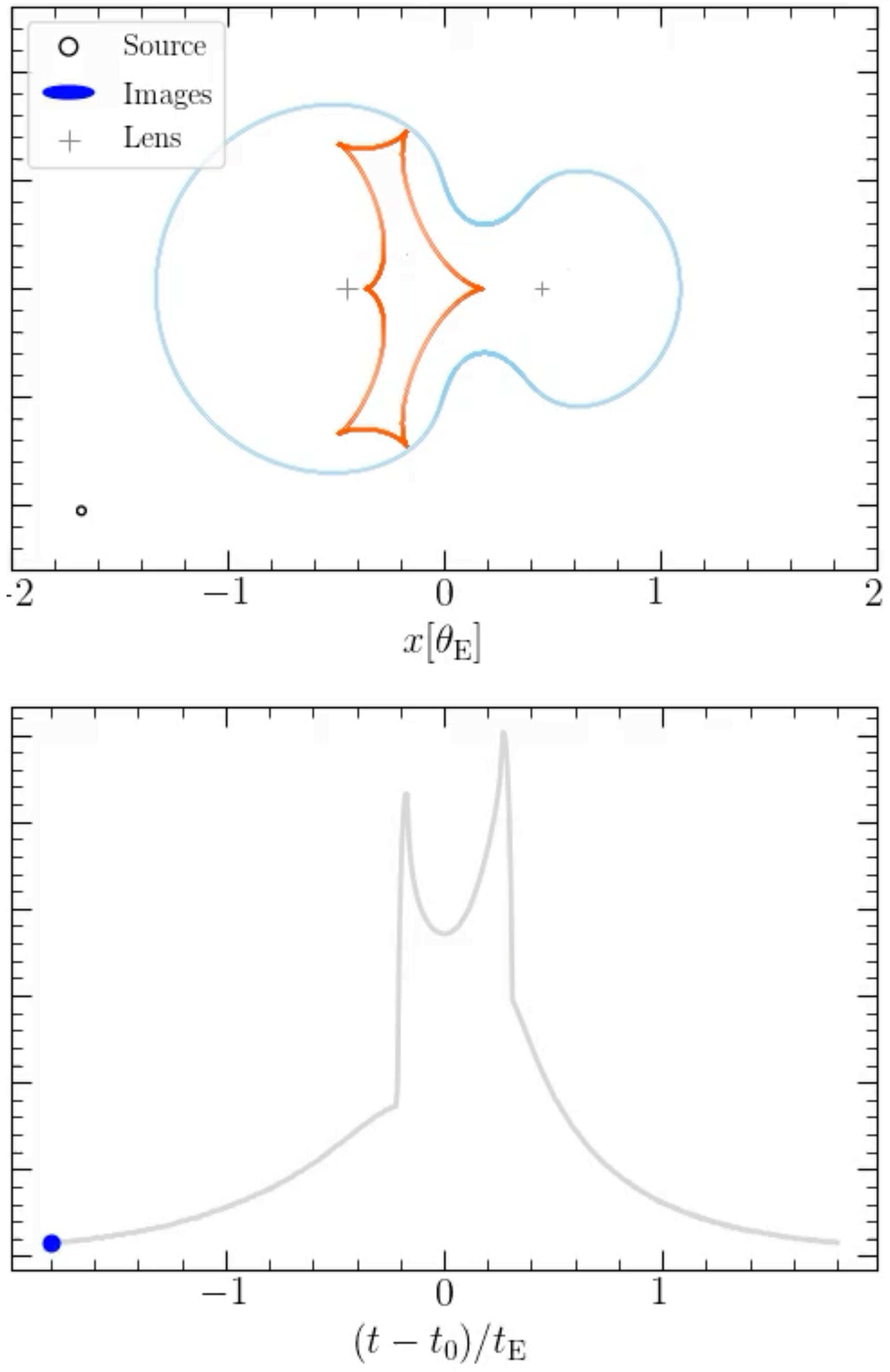
(Wyrzykowski et al., 2022)



These animations, with different lens–source geometries, show what's happening during observations by Gaia

Expected in the future: *astrometric* lensing (the position of the light moves), and hence *mass* of lensing events (e.g. black holes, isolated planets)





Animations by Kris Rybicki,
University of Warsaw

Summary

Gaia could discover:

- 20,000 – 70,000 massive long-period planets to *d* ~ 500 pc
- 1000 − 1500 around M dwarfs out to 100 pc (predictions for other spectral types)
- orbit determination for orbital periods 0.6 − 6 years
- hundreds of multiple systems with tests of coplanarity
- 1000 or more others from photometric transits, P < 10 days

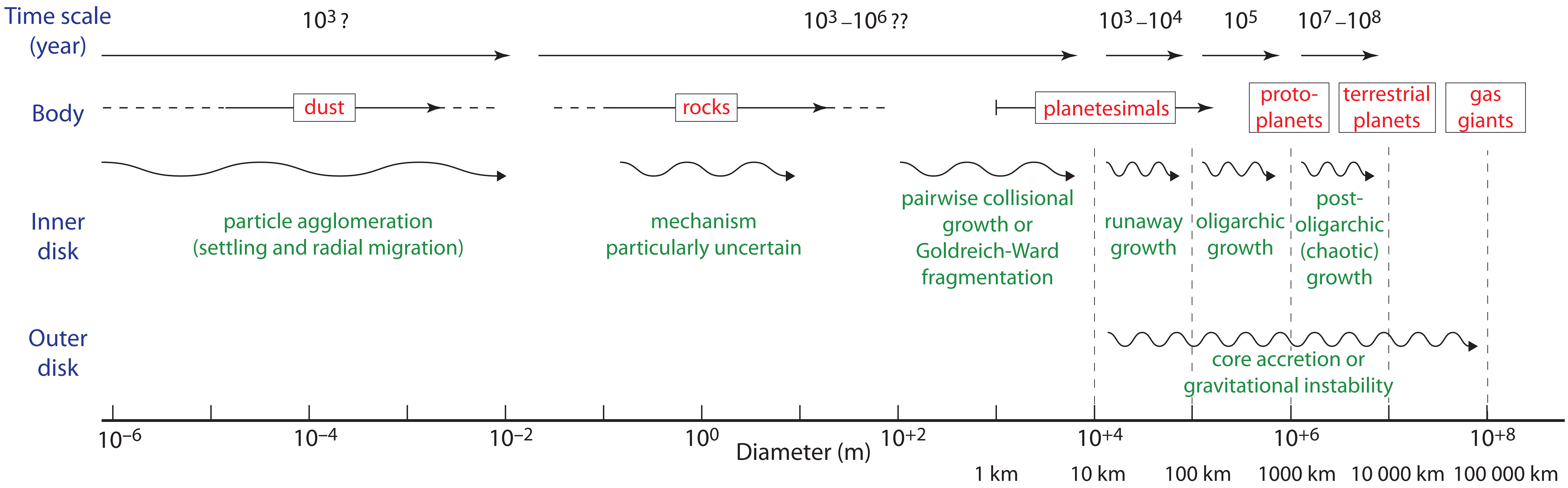
Transiting planets:

- Gaia will not measure astrometric displacements of *known* transiting planets
- there will be 40 – 120 transiting planets amongst the astrometric discoveries
- nearly transiting systems are of interest for nearly coplanar systems

Goal: to understand planet formation and evolution…

… its growth over 14 orders of magnitude

… and many other very interesting phenomena along the way



Time scale (year)

10^3 ?

$10^3 – 10^6$??

$10^3 – 10^4$

10^5

$10^7 – 10^8$

Body

dust

rocks

planetesimals

proto-planets

terrestrial planets

gas giants

Inner disk

particle agglomeration (settling and radial migration)

mechanism particularly uncertain

pairwise collisional growth or Goldreich-Ward fragmentation

runaway growth

oligarchic growth

post-oligarchic (chaotic) growth

Outer disk

core accretion or gravitational instability

10^{-6} 10^{-4} 10^{-2} 10^0 10^{+2} 10^{+4} 10^{+6} 10^{+8}

Diameter (m)

1 km 10 km 100 km 1000 km 10 000 km 100 000 km

Thank you

And do talk to me in the next three days!