From Planet Detection to Planet Parameters

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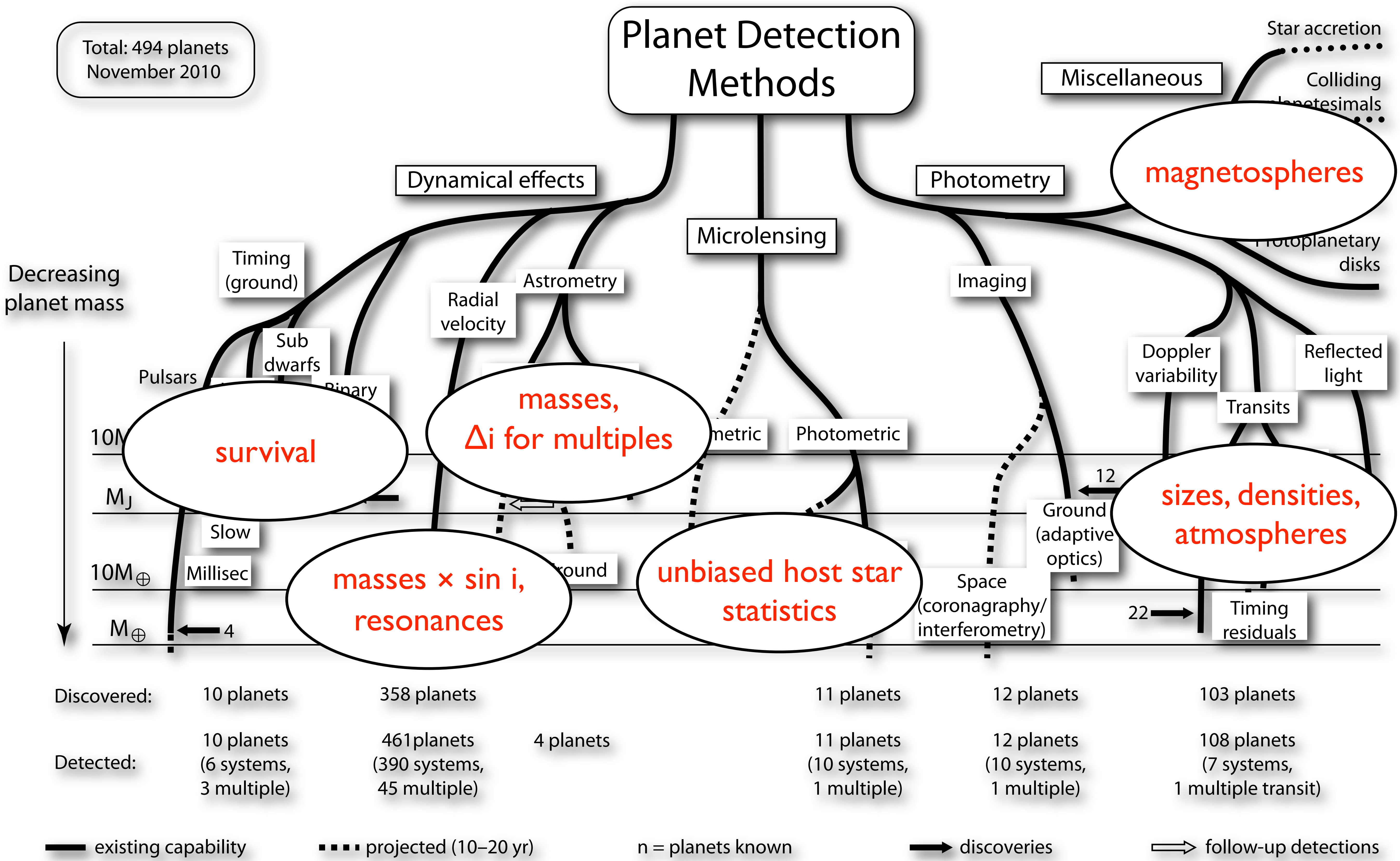
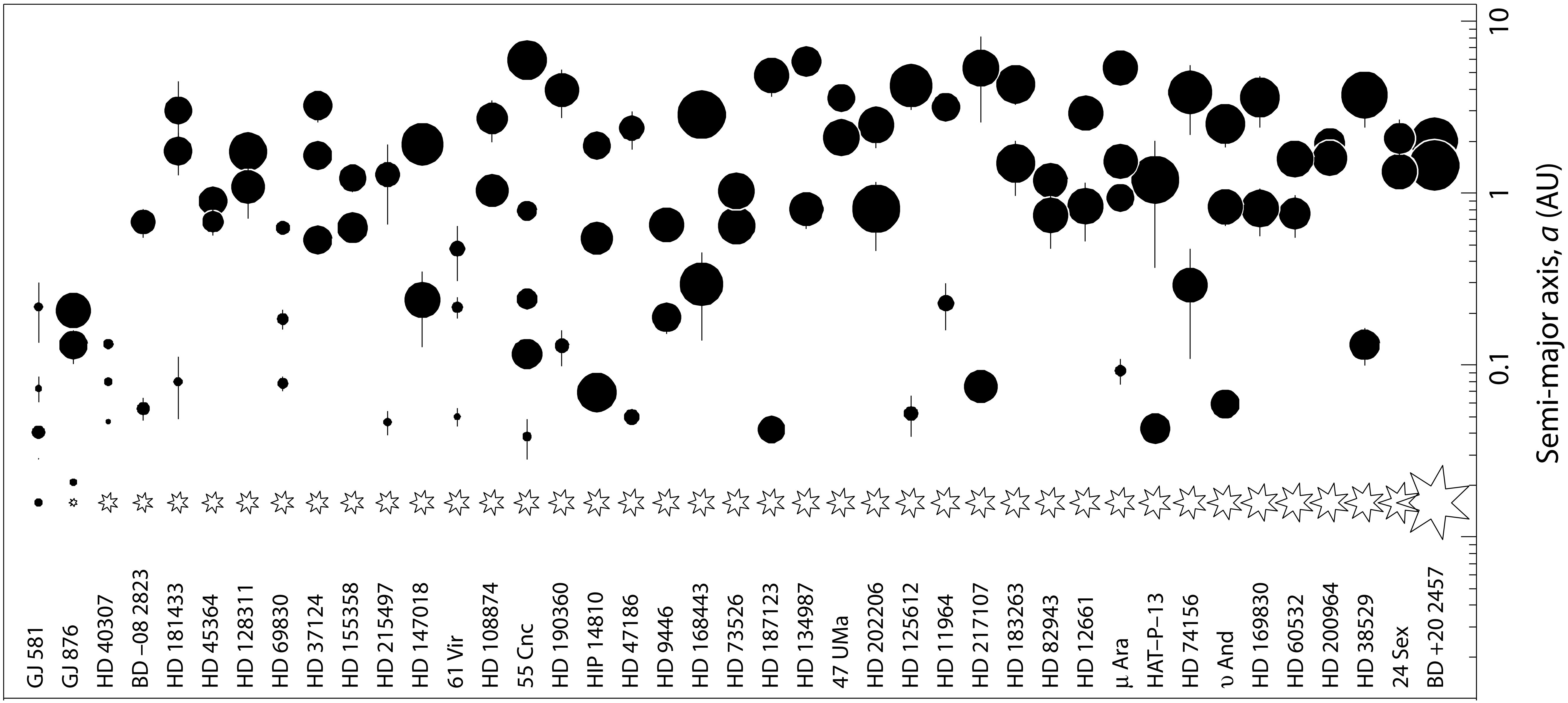
Heraeus Conference, 6 June 2011


Total: 494 planets
November 2010
Planet Detection Methods
Dynamical effects
Microlensing
Photometry
Miscellaneous
Star accretion
Colliding
Decreasing planet mass
Timing (ground)
Radial velocity
Astrometry
Imaging
Sub dwarfs
Pulsars
Doppler variability
Reflected light
Transits
metric
Photometric
12
Ground (adaptive optics)
Slow
Millisec
Space (coronagraphy/ interferometry)
22
Timing residuals
4
M_J
$10M_\oplus$
$M_\oplus$
magnetospheres
survival
masses, Δi for multiples
sizes, densities, atmospheres
masses × sin i, resonances
unbiased host star statistics
disks
Discovered:
10 planets
358 planets
11 planets
12 planets
103 planets
Detected:
10 planets (6 systems, 3 multiple)
461planets (390 systems, 45 multiple)
4 planets
11 planets (10 systems, 1 multiple)
12 planets (10 systems, 1 multiple)
108 planets (7 systems, 1 multiple transit)
existing capability
projected (10–20 yr)
n = planets known
discoveries
follow-up detections

Topics

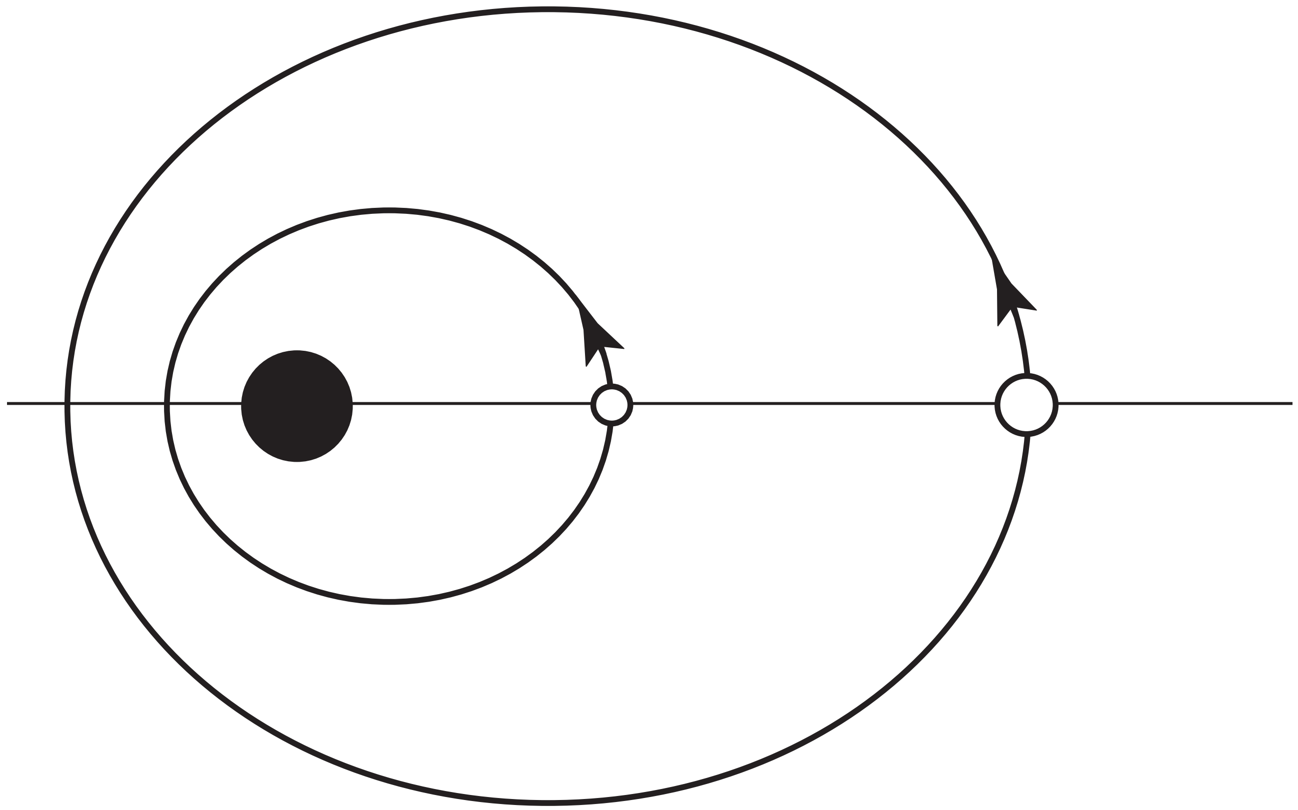
- radial velocities
- astrometry
- transits
- internal structure and composition
- radio emission
- population synthesis

The distribution of multiple systems



increasing host star mass →

Numerous of these multiple systems are in resonance...



For a heuristic physical description, see Peale (1976), ARA&A 14, 215

An object's mean motion, $n \equiv 2\pi/P$

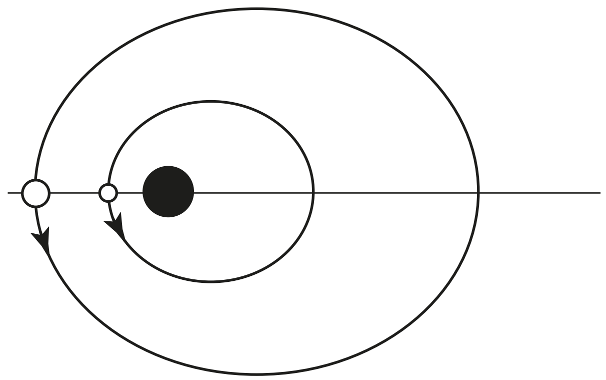
mean motion resonances ($P_1/P_2 \sim i/j$):
2:1, 3:1, 4:1, 5:1, 5:2, etc

Many other types of resonance...

- spin-orbit
  - tidal locking (1:1)
  - Mercury (3:2)
- Kozai resonance (*e* versus *i*)
- Lagrange (1:1) resonance
- retrograde resonances...

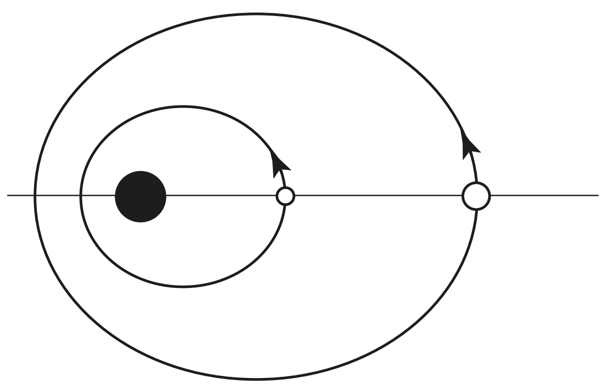
Mean motion resonances come in many different flavours, e.g. for the 2:1

(1) unstable 2:1



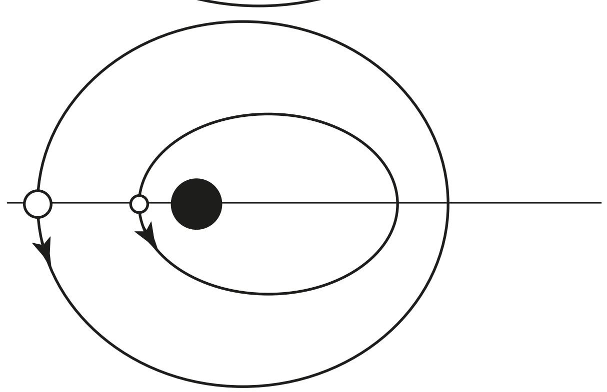
conjunctions
at pericentre

(2) stable 2:1
(aligned)



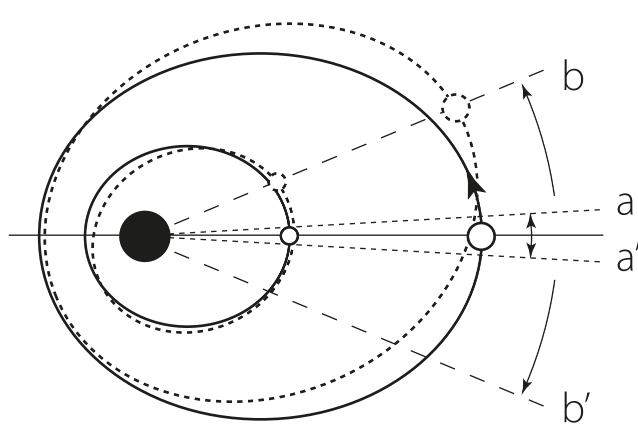
conjunctions
at apocentre
aligned
(symmetric)

or



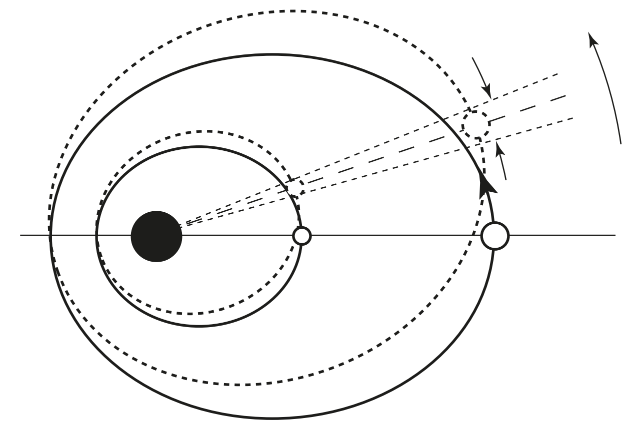
conjunctions
at pericentre
aligned
(symmetric)

(2a) apsidal
libration



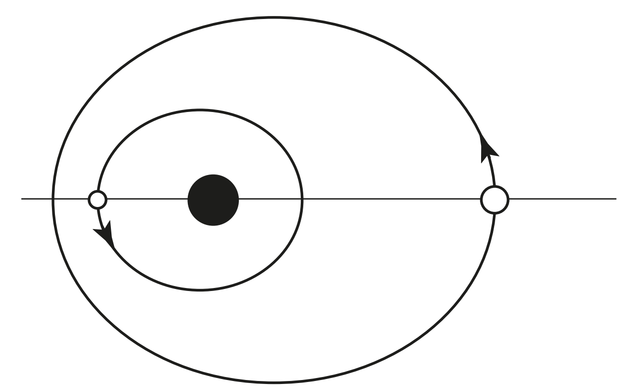
apsidal libration
(small libration
angle ⇔ deep
resonance)

(2b) apsidal
corotation



apsidal
alignment
rotates (usually
with libration)

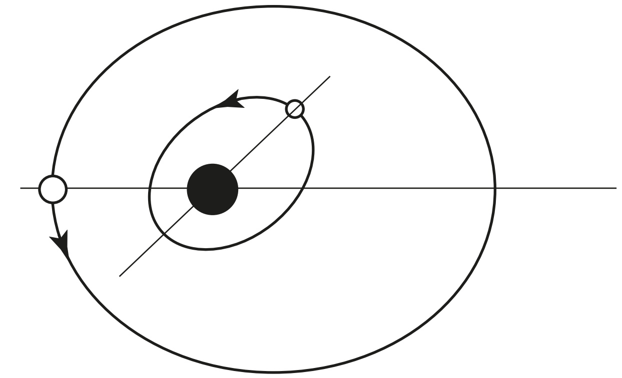
(3) stable 2:1
(anti-aligned)



conjunctions
anti-aligned
(anti-symmetric)

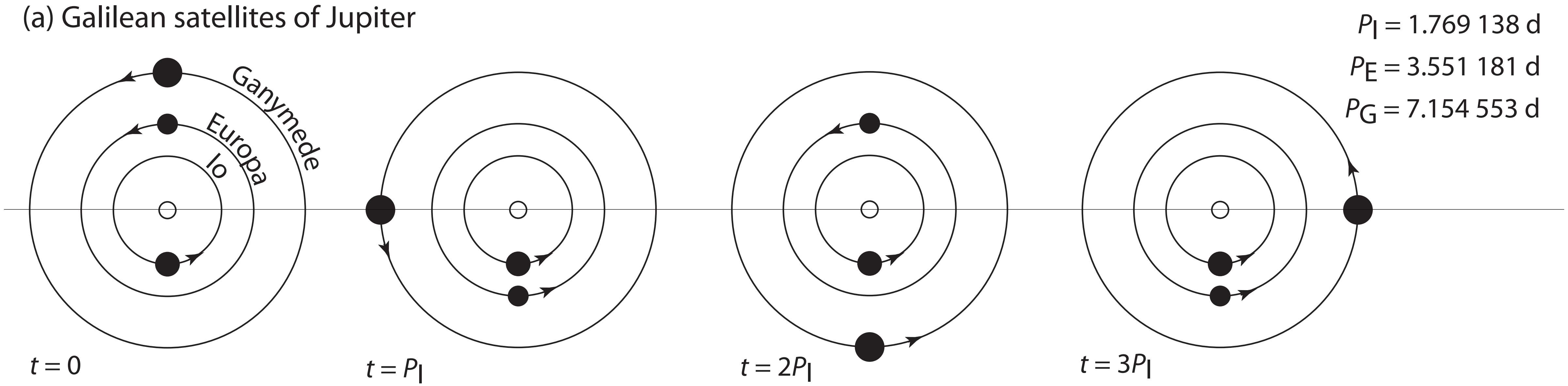
both may corotate
and/or librate

(4) stable 2:1
(asymmetric)

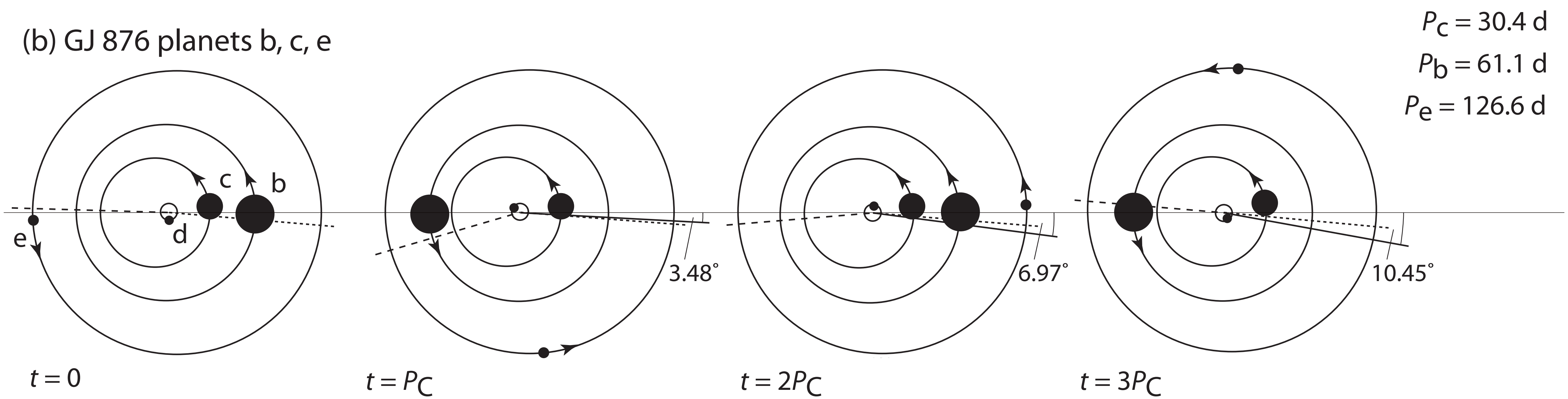


asymmetric
apsidal
configuration

... and the first triple (Laplace) resonance

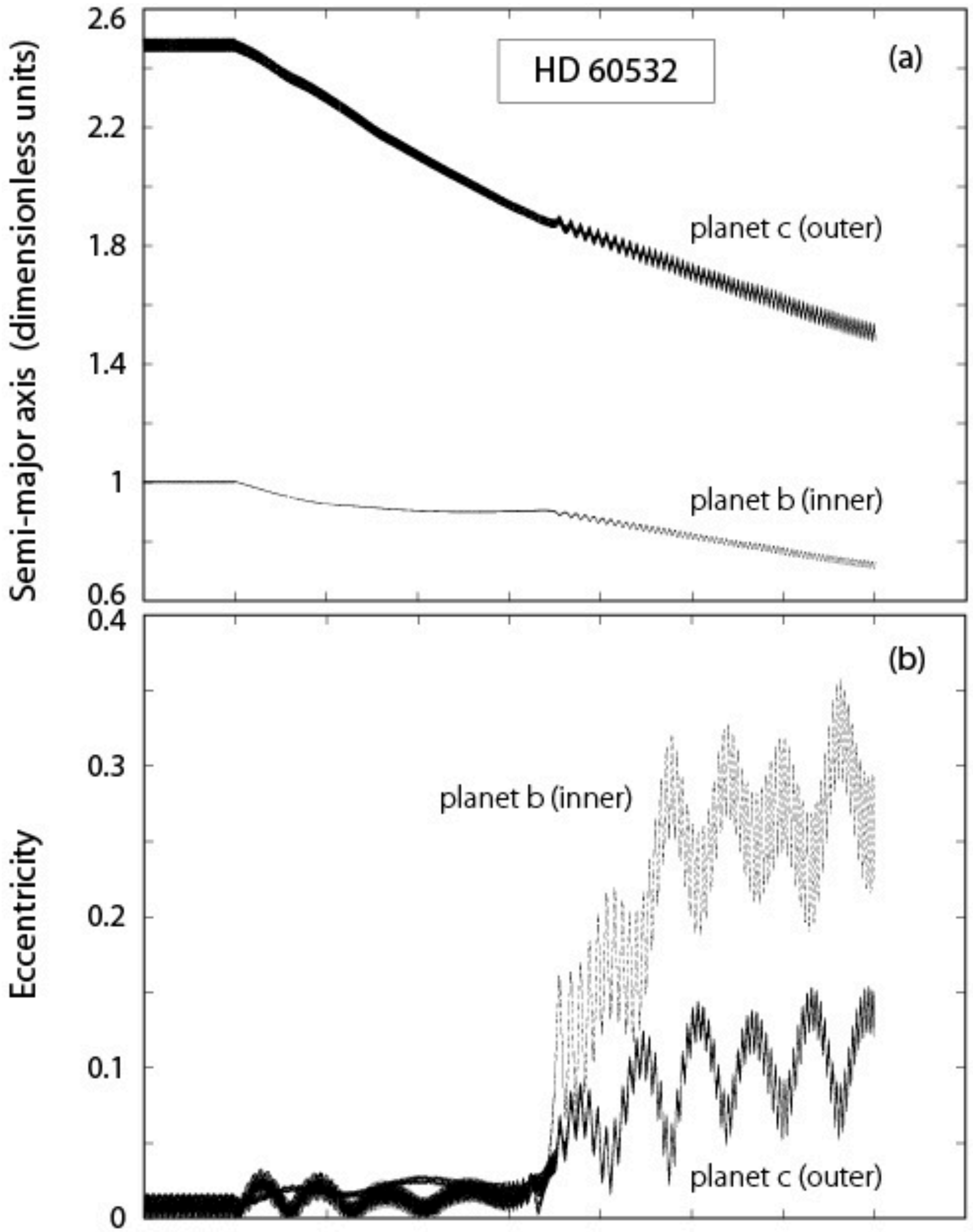


n(Io) - 3n(Europa) + 2n(Ganymede) = 0 ... to 9 significant digits, Peale (1976), ARA&A 14, 215

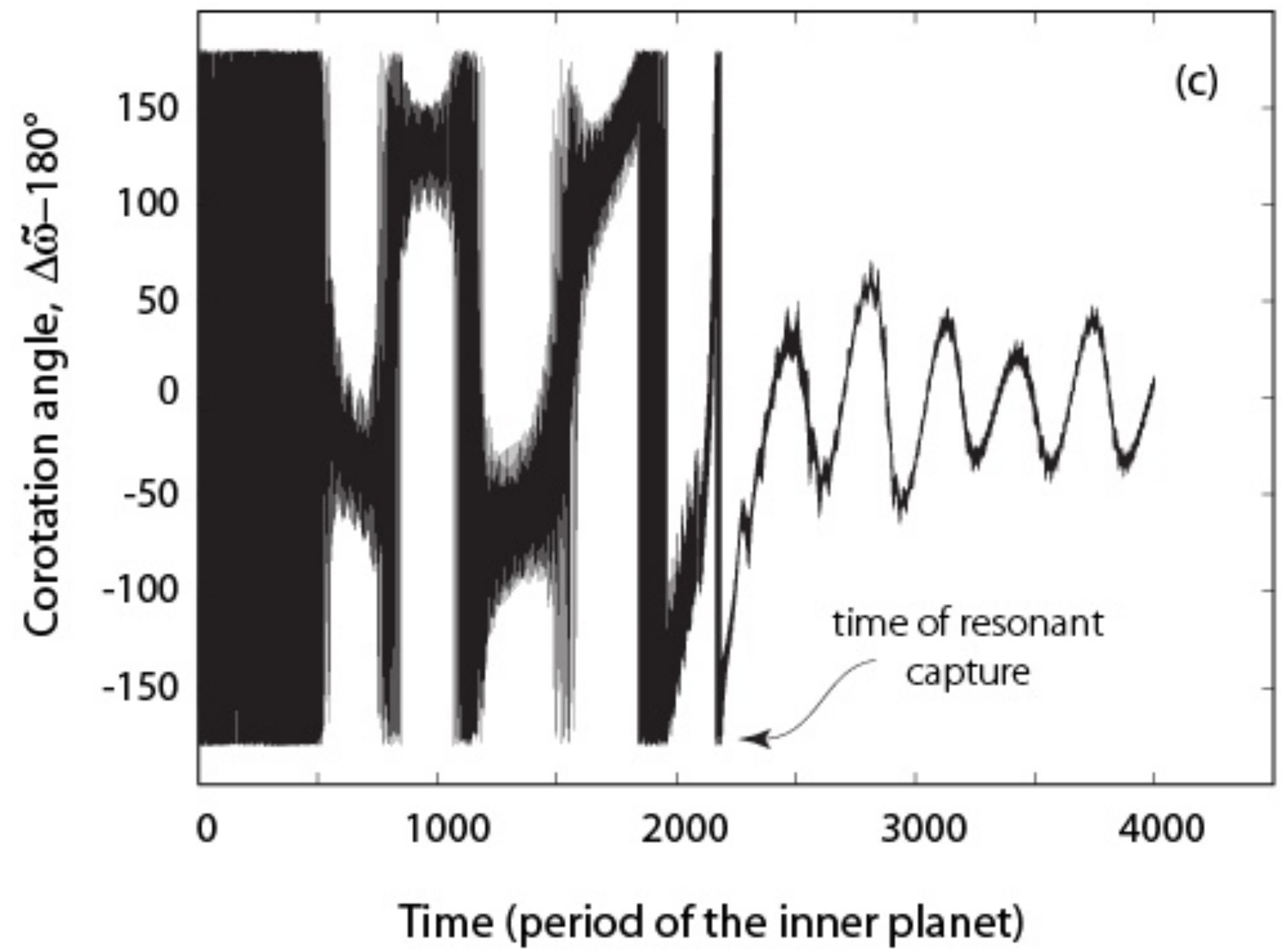


Rivera et al (2010): ApJ 719, 890

Question: how do planets get into resonance?



Answer: differential (convergent) migration in the residual gas disk



Sándor et al (2010), A&A 517, A31

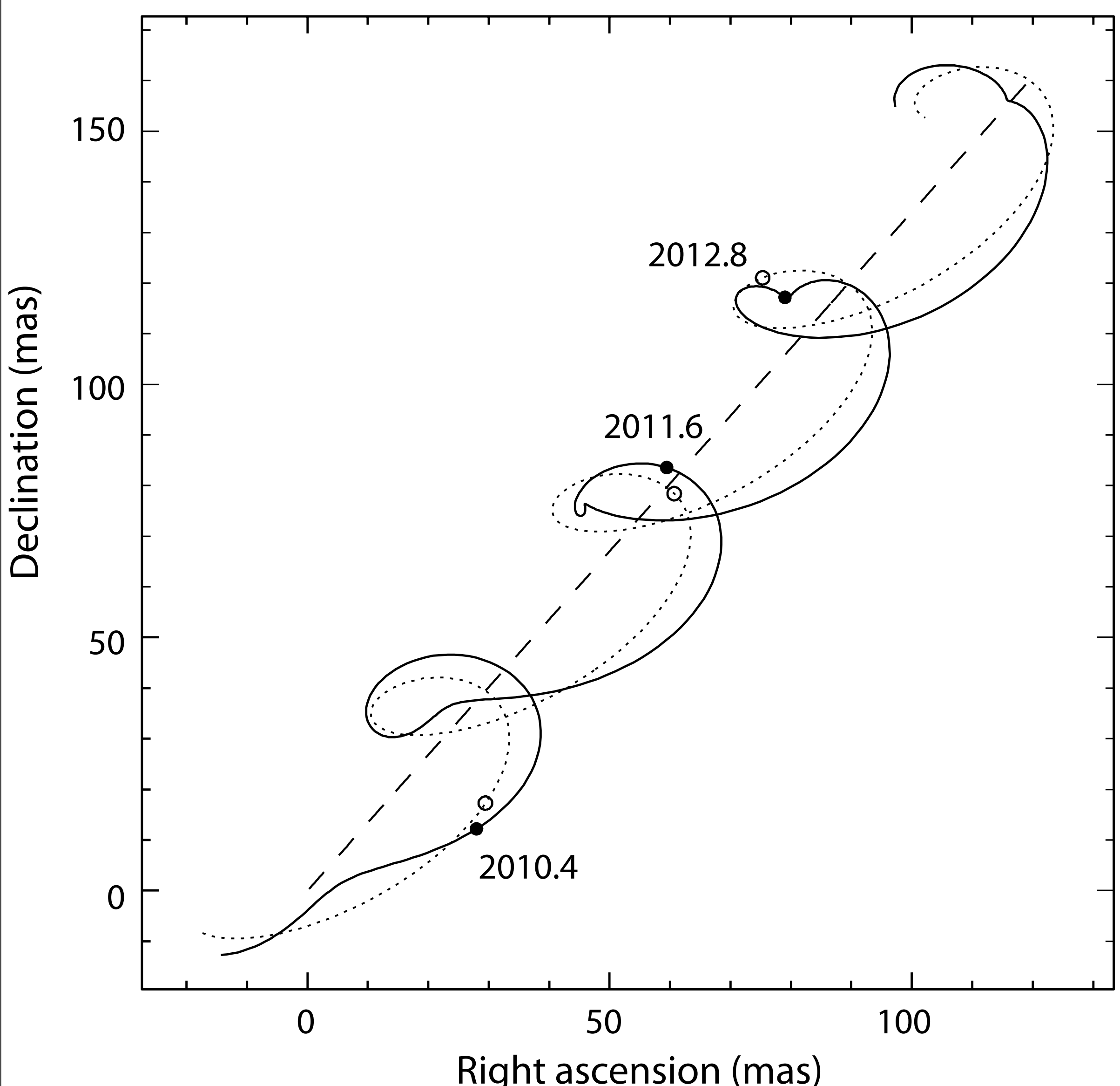
Topics

- radial velocities
- astrometry
- transits
- internal structure and composition
- radio emission
- population synthesis

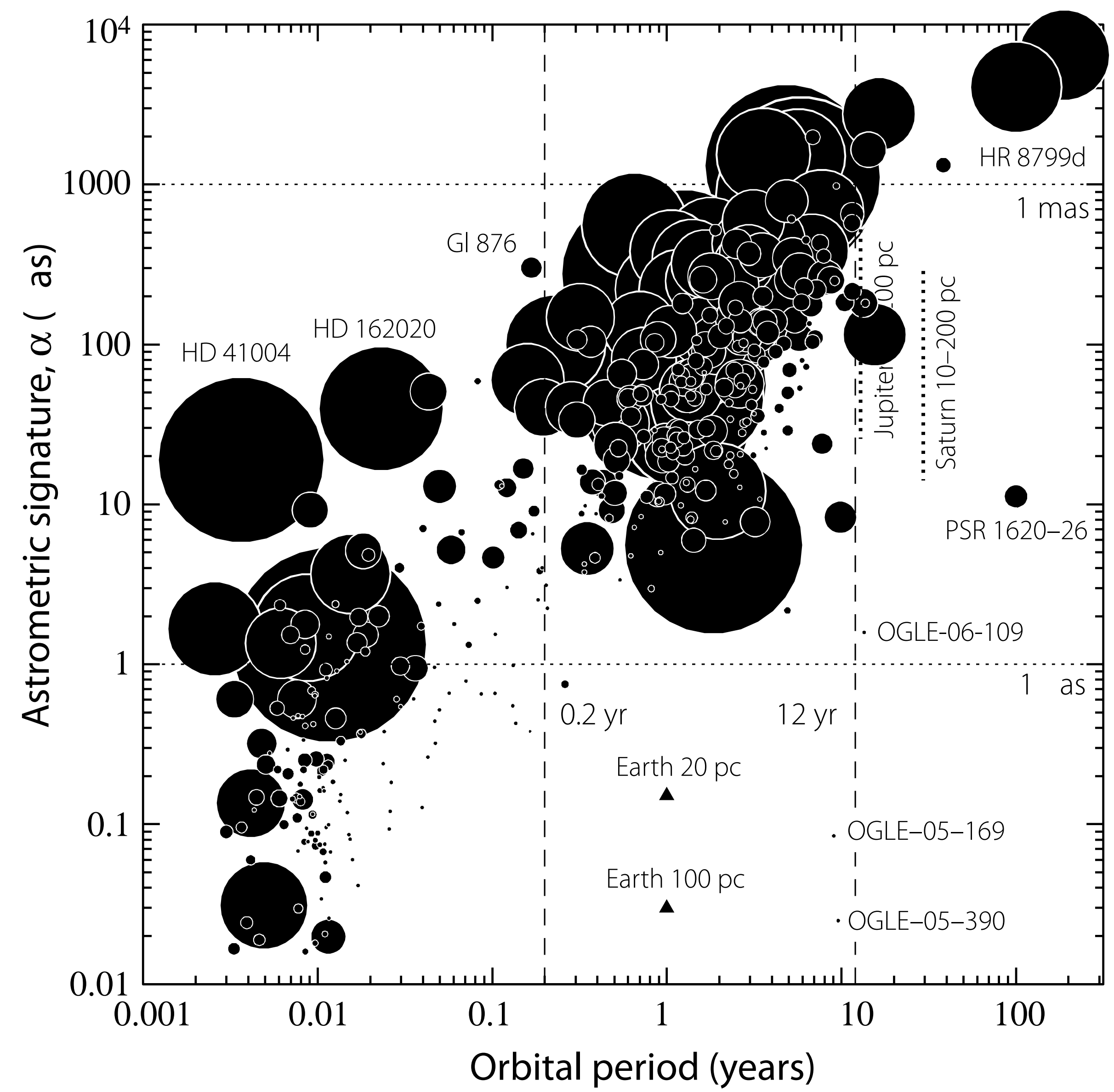
Astrometry...

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

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



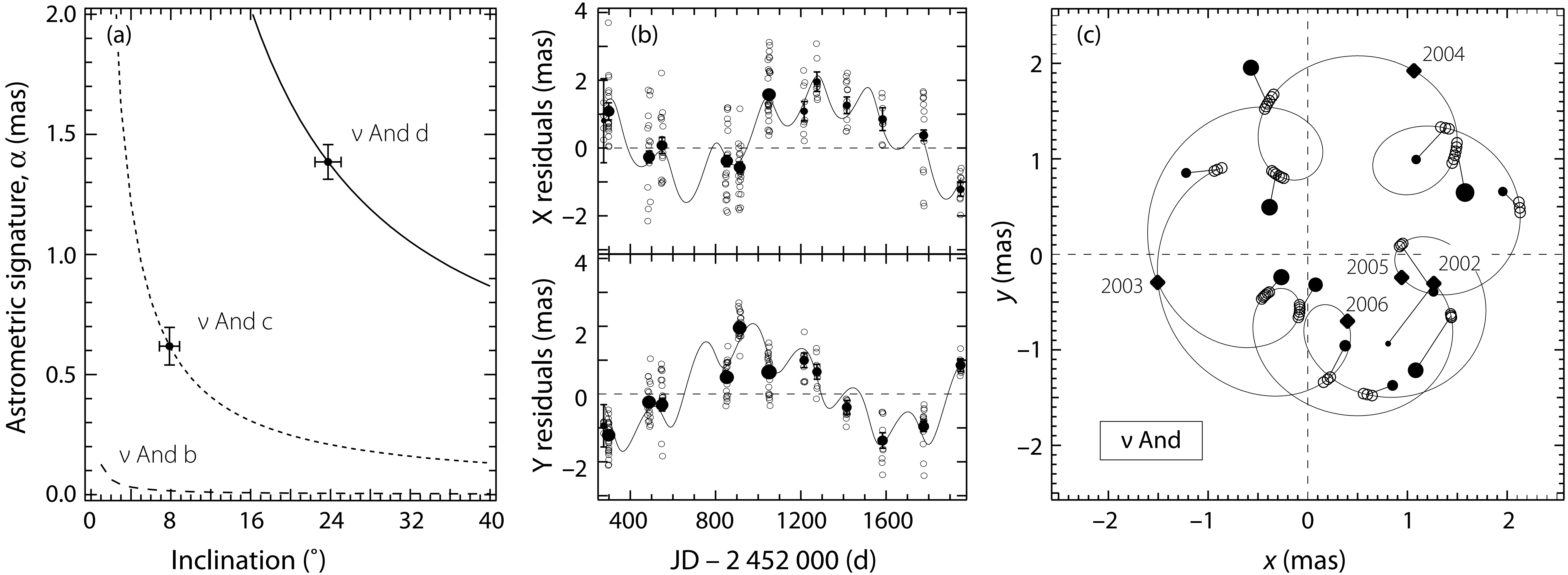
Effect on the star's motion around the barycentre



But the size of the effect is small...

ν And observed with the Hubble Space Telescope Fine Guidance Sensors

radial velocity orbit + astrometric displacement = orbit inclination

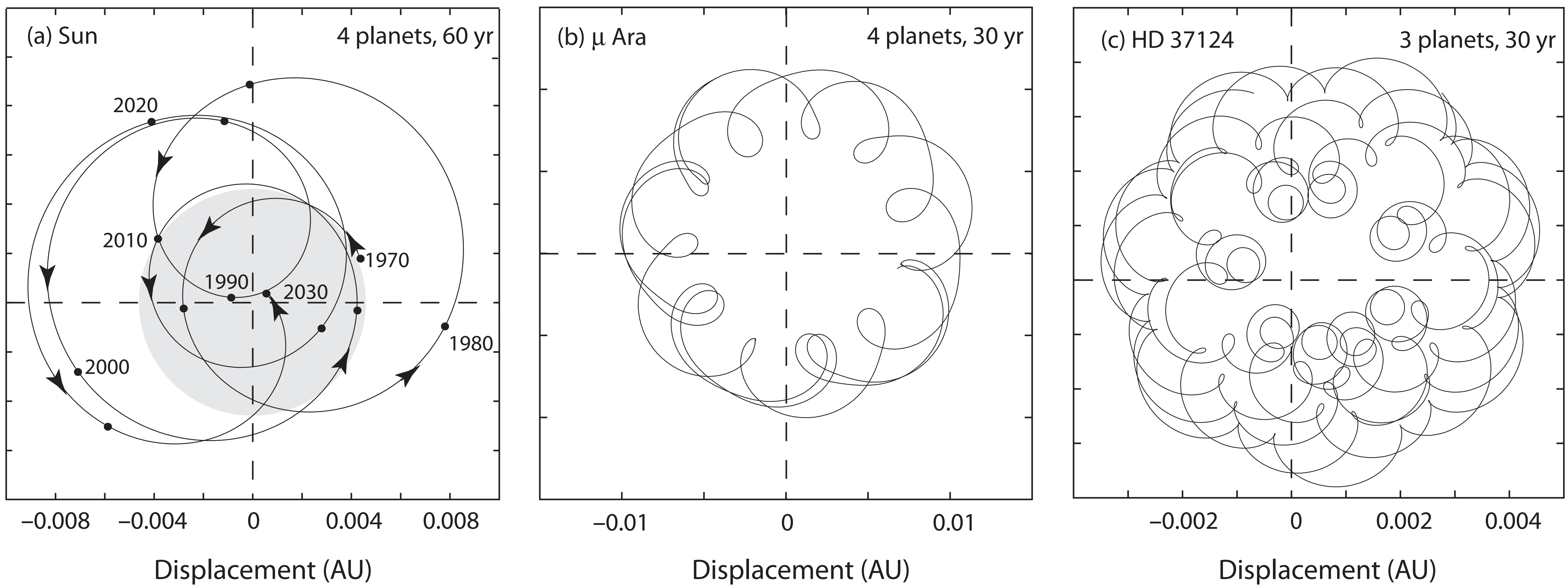


gives a (large) mutual inclination between planet orbits of Δ_{cd} = 29.9 deg

McArthur et al (2010): ApJ 715, 1203

Important for determining statistics of co-planarity, as inputs to theories of formation and dynamical stability (in future: Gaia, PRIMA)

Planet mandalas...
.. and the nature of the solar dynamo



... exoplanets may allow verification whether angular momentum changes are responsible for some of the solar activity modulations
(Perryman & Schulze-Hartung (2011): A&A 525, 65)

Topics

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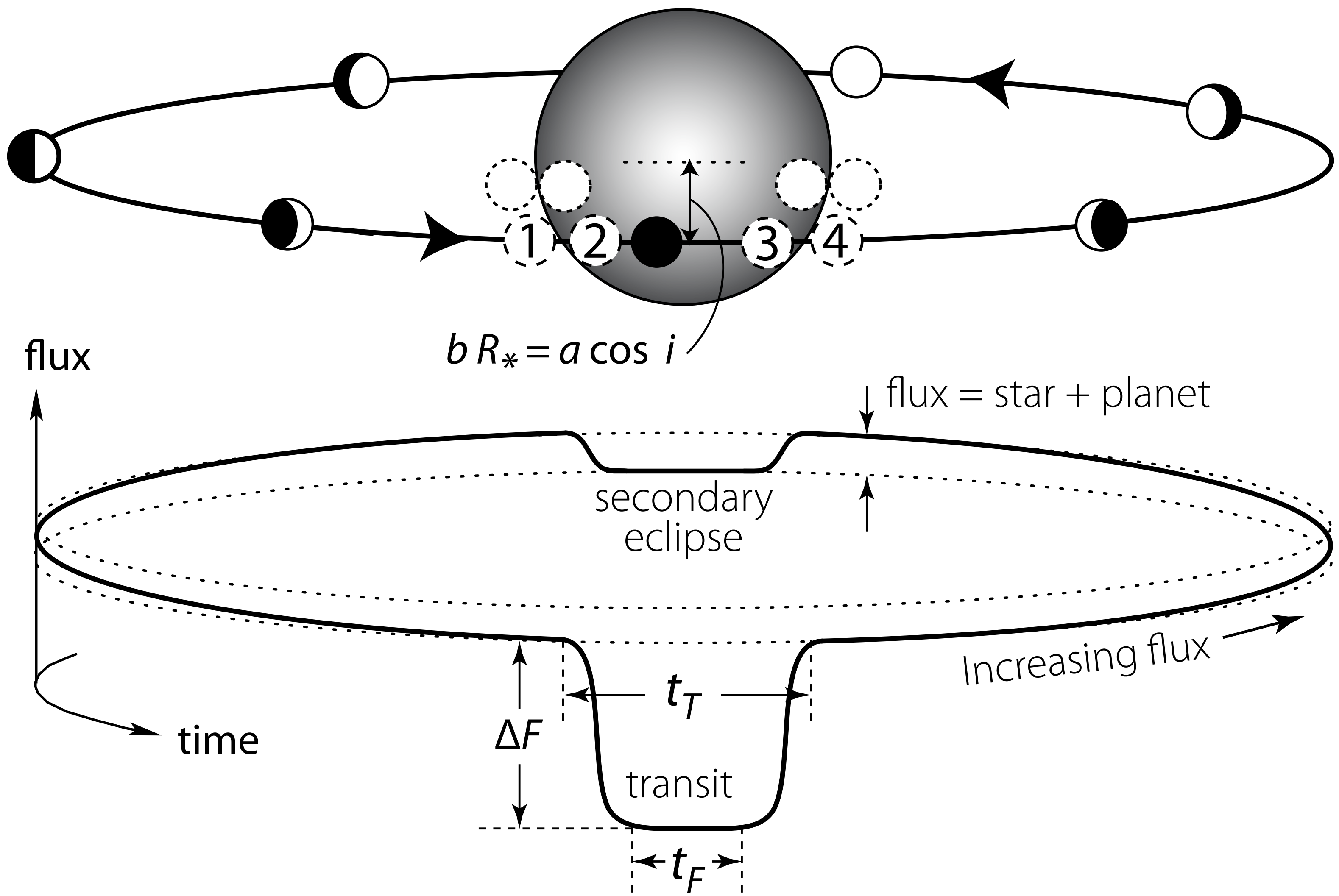
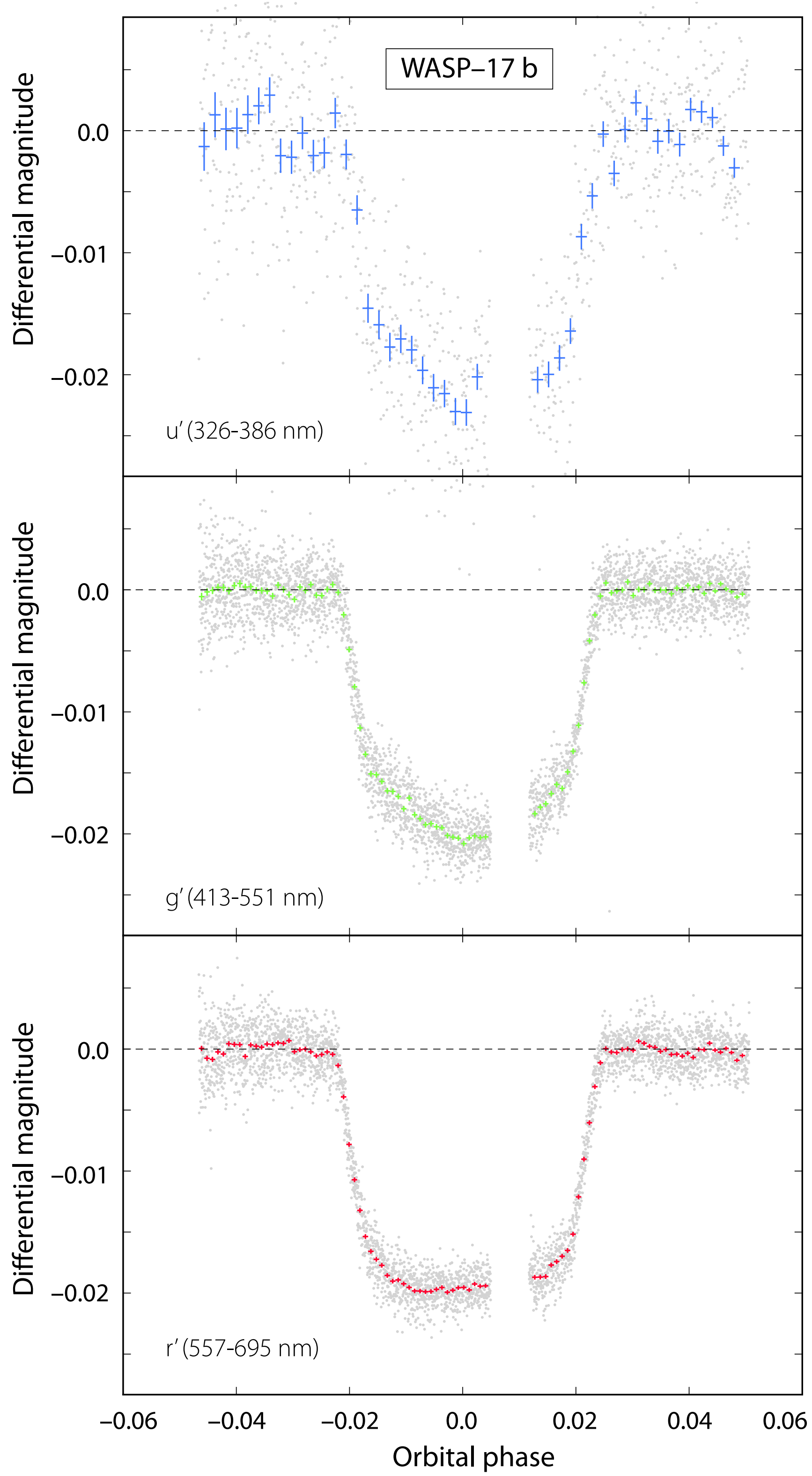
Transits



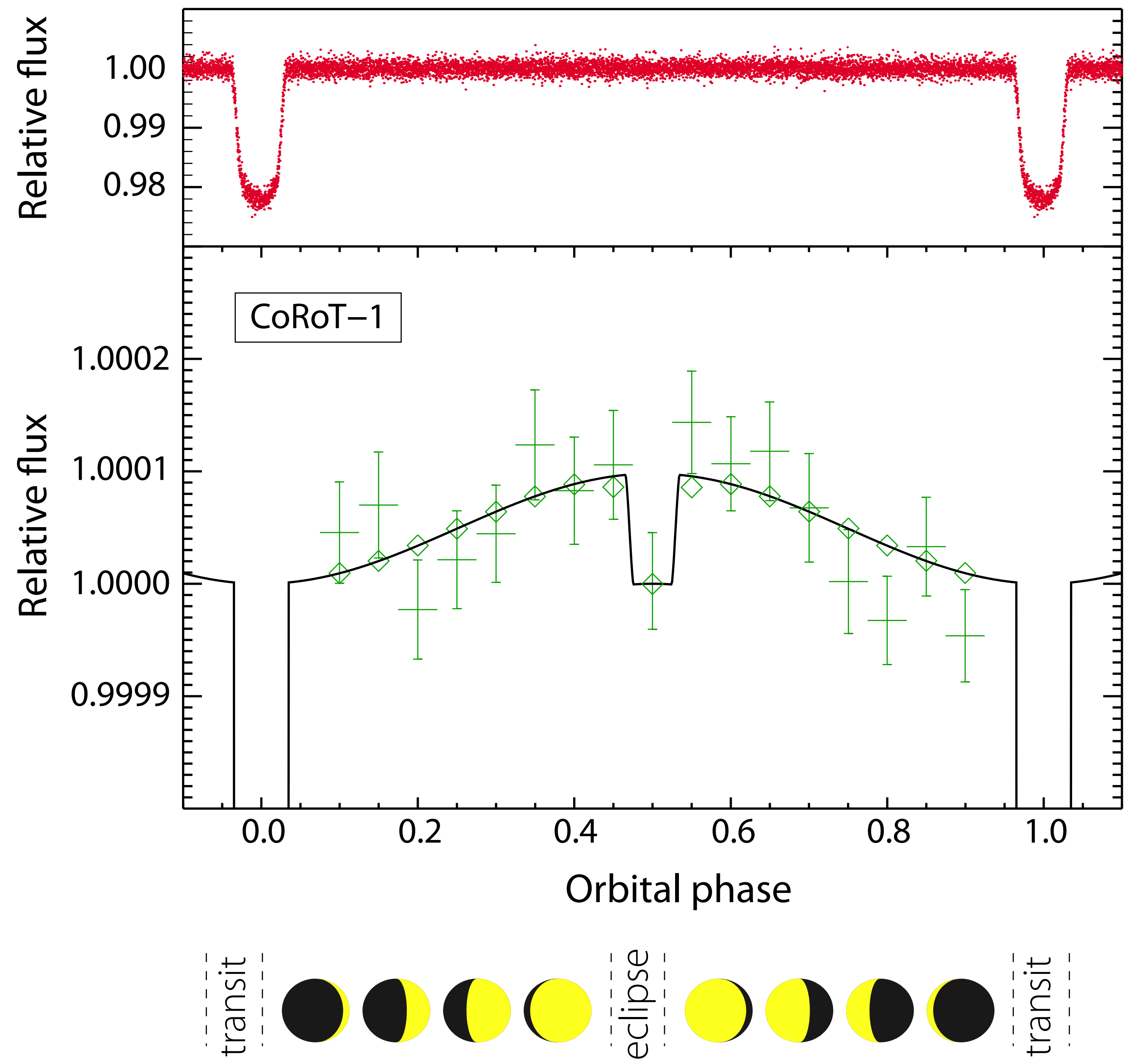
The transiting systems have proven of great importance:

- for densities from absolute masses + accurate radii
- atmospheric probes from transits and secondary eclipses

Transit photometry: example state-of-the-art

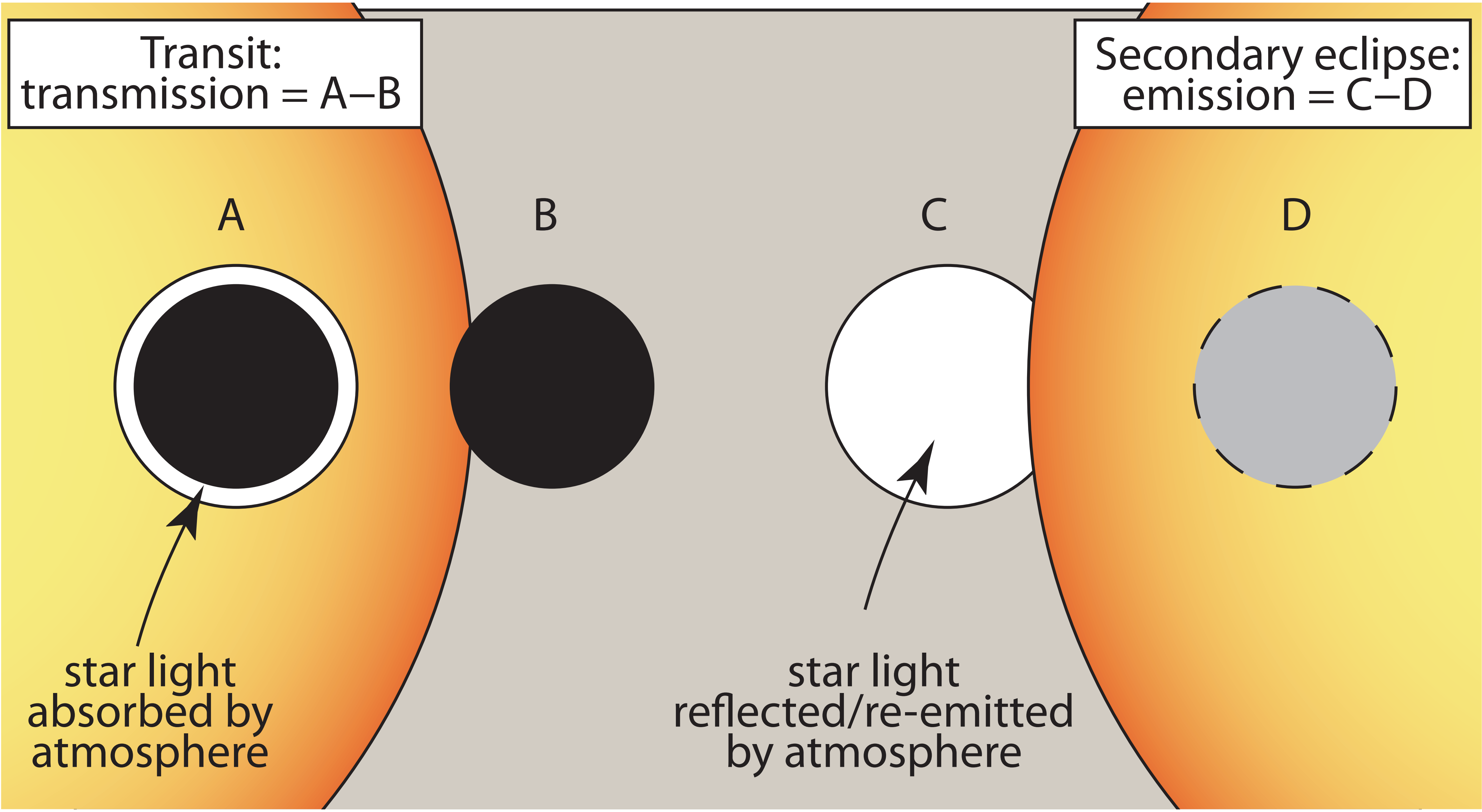


...from the ground, using ULTRACAM
Bento et al 2011, in preparation



...from space, using CoRoT
Snellen et al (2009), Nature 459, 543

Principle of transmission & emission spectroscopy

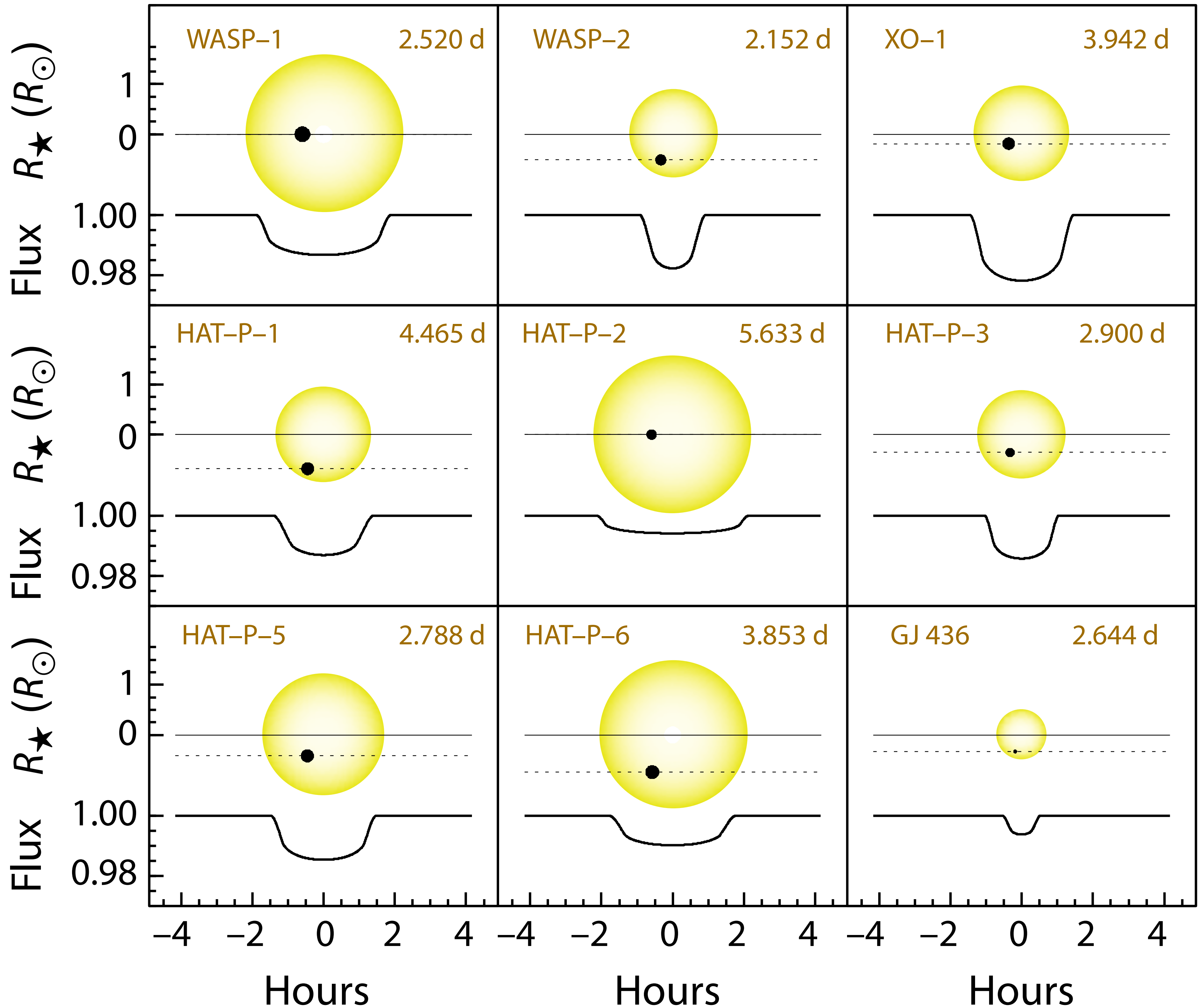


area of planetary atmosphere intercepted:
annulus of width ~5H, where

$$H = \frac{kT}{\mu_m g_p}$$

Many results (e.g. Spitzer) from, notably
HD 209458 and HD 189733:
H, H_2O, CO_2, CH_4, Na, etc

Other transit examples...

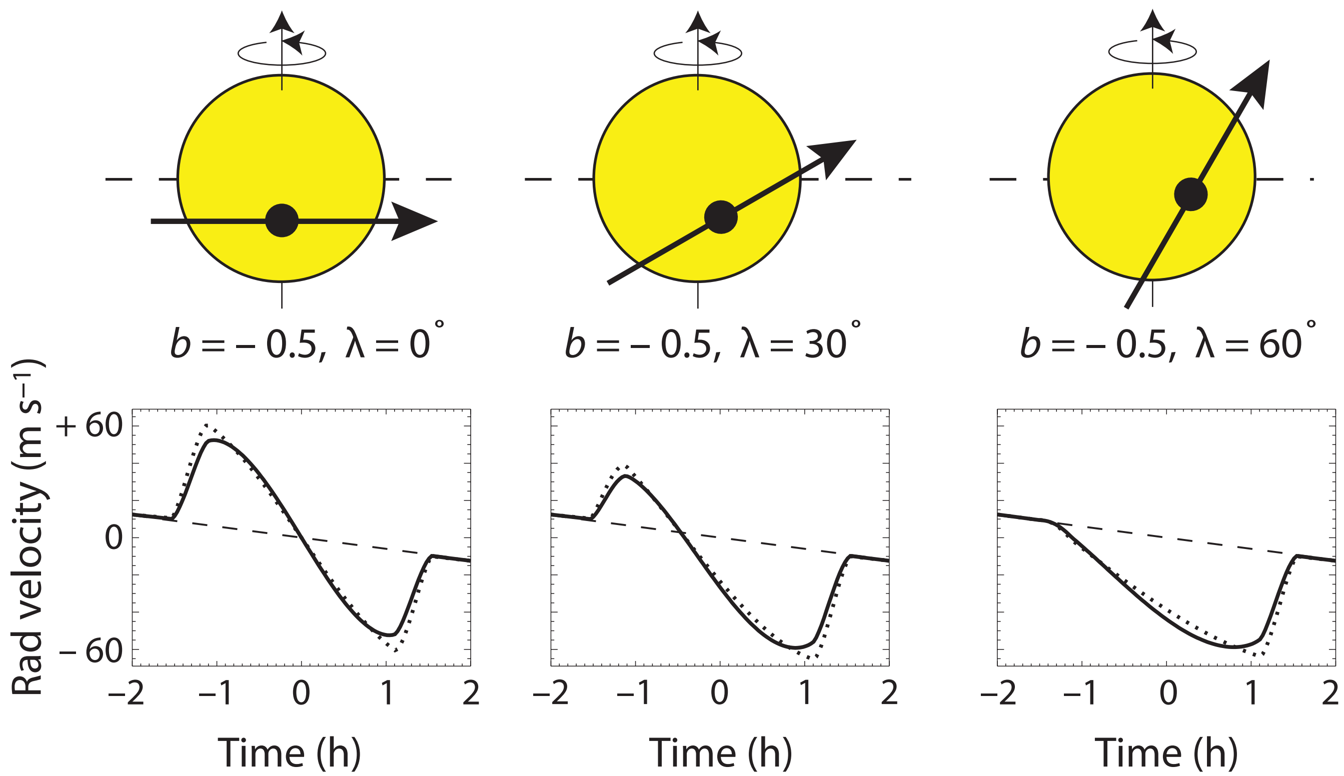


Torres et al (2008)
ApJ 677, 1324

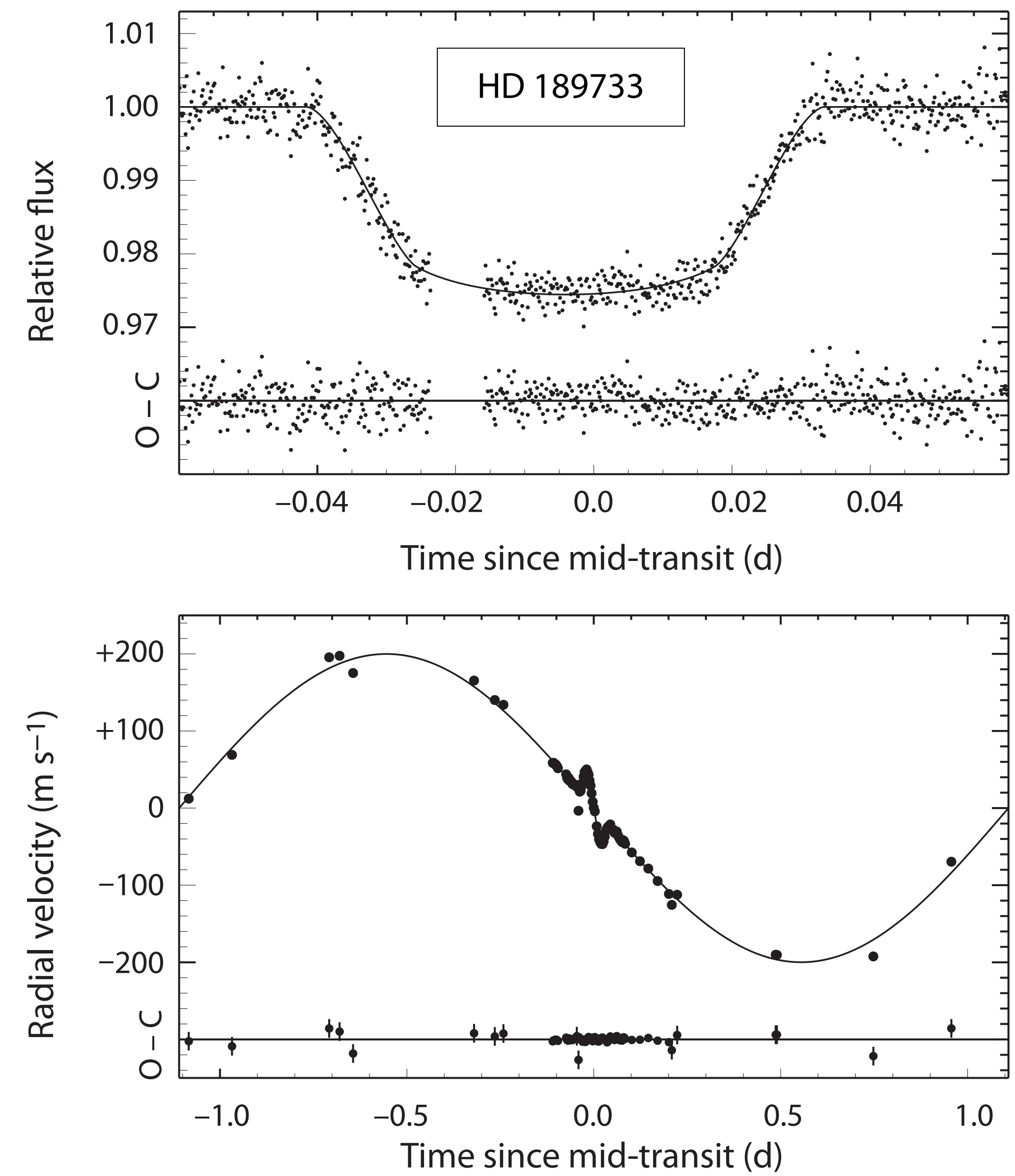
Higher-order effects

- from transit light-curve:
  - stellar density, ρ_*
  - planet surface gravity, $g_p = GM_p/R_p$
  - planet limb darkening
- higher-order photometric effects:
  - planet: satellites, rings/comets, planet oblateness, rotation, weather, bow shocks
  - star: spots, effects of rapid rotation, ellipsoidal variations
- higher-order spectroscopic effects:
  - projected angle between stellar spin axis and planet orbit (Rossiter-McLaughlin)
  - effects of atmospheric opacity, atmospheric winds
- higher-order timing effects:
  - apsidal precession due to tidal bulges, rotational flattening, general relativity
  - nodal precession in the case of polar orbits (WASP-33)
  - effects of planet satellites
  - effects of other planets, including Trojans
  - perspective effects due to star's parallax and proper motion
  - magnetic breaking, non-gravitational forces (Yarkovsky effect)

Rossiter-McLaughlin effect

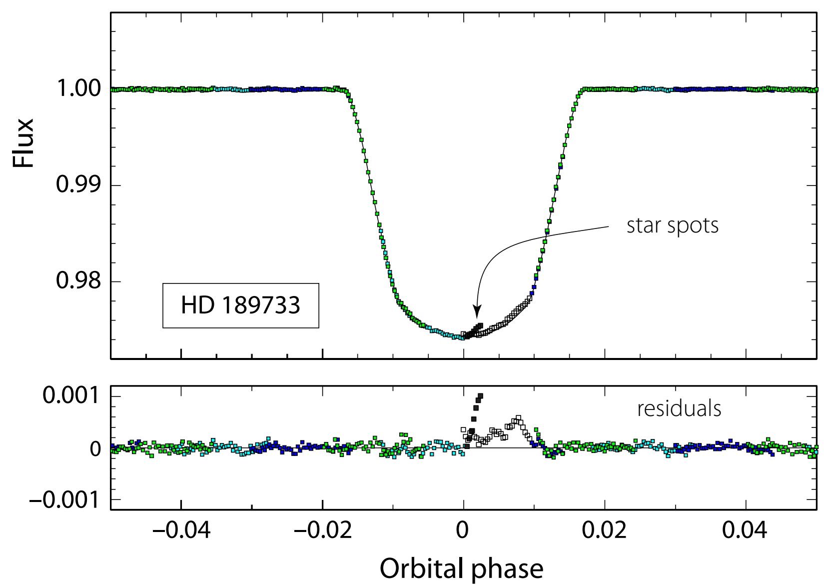


Winn et al (2006), ApJ 653, L69

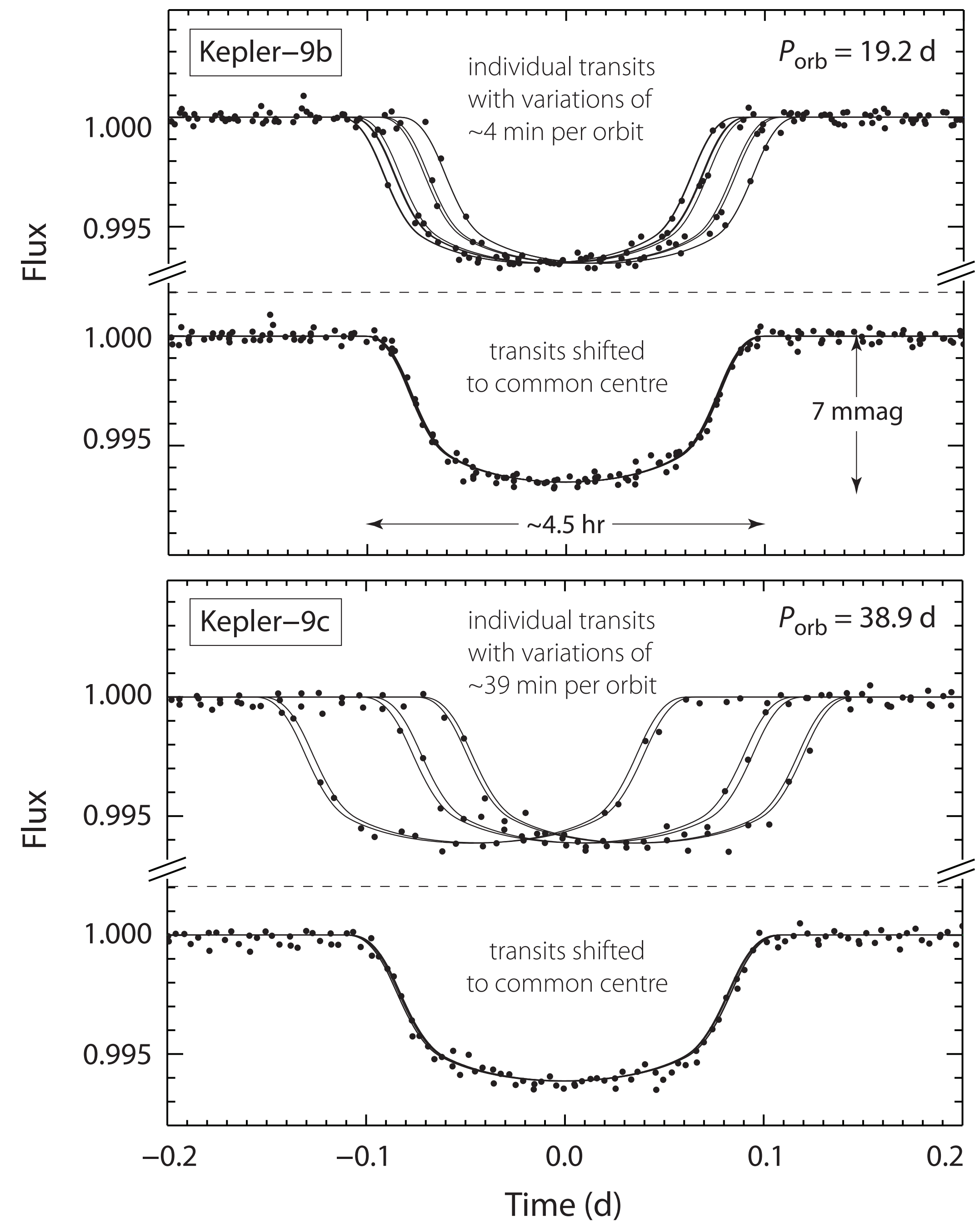


- some orbits are retrograde
- statistics suggest scattering: Triaud et al (2010), A&A 524, 25
- or scattering + migration: Marchi et al (2009), MNRAS 394, L93
- but not migration alone

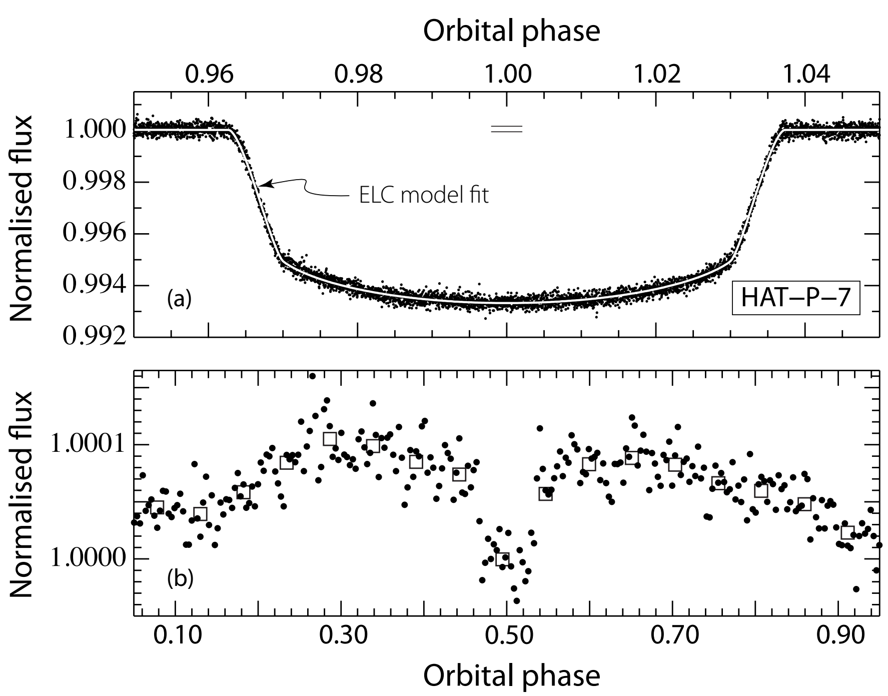
Other transiting phenomena observed...



star spots: Pont et al (2007)



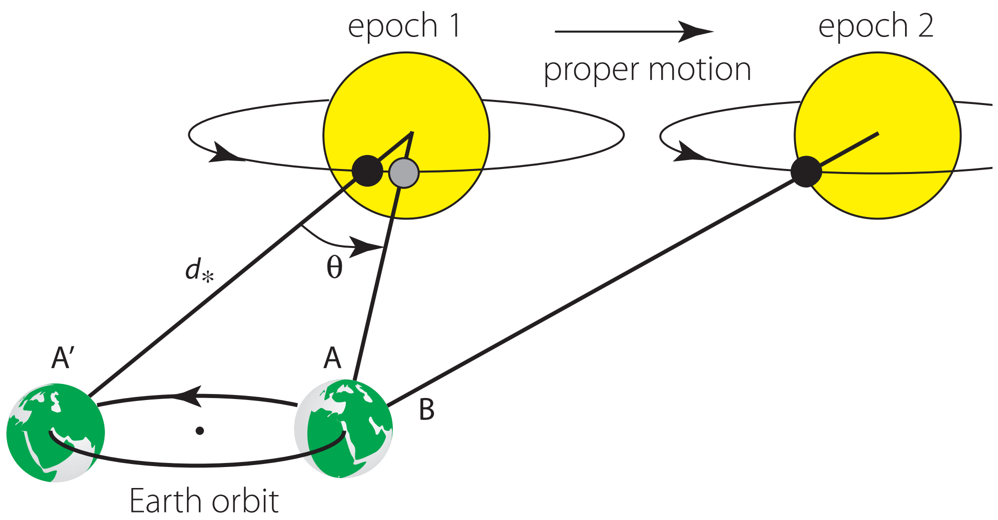
transit time variations due to resonant planets: Holman et al (2010)



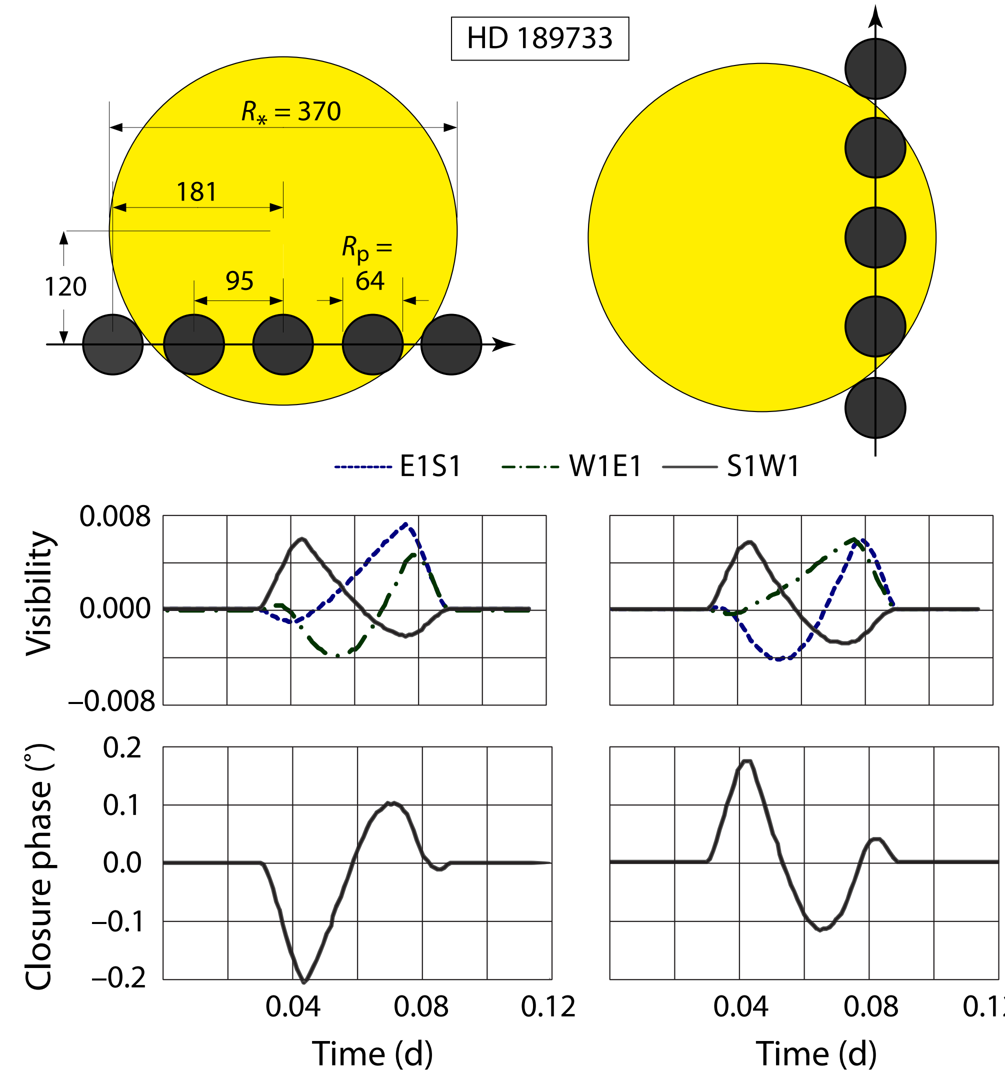
ellipsoidal effects: Welsh et al (2010)

- Kepler-11 has 6 transiting planets, with periods of 10, 13, 22, 32,47, and 118 days

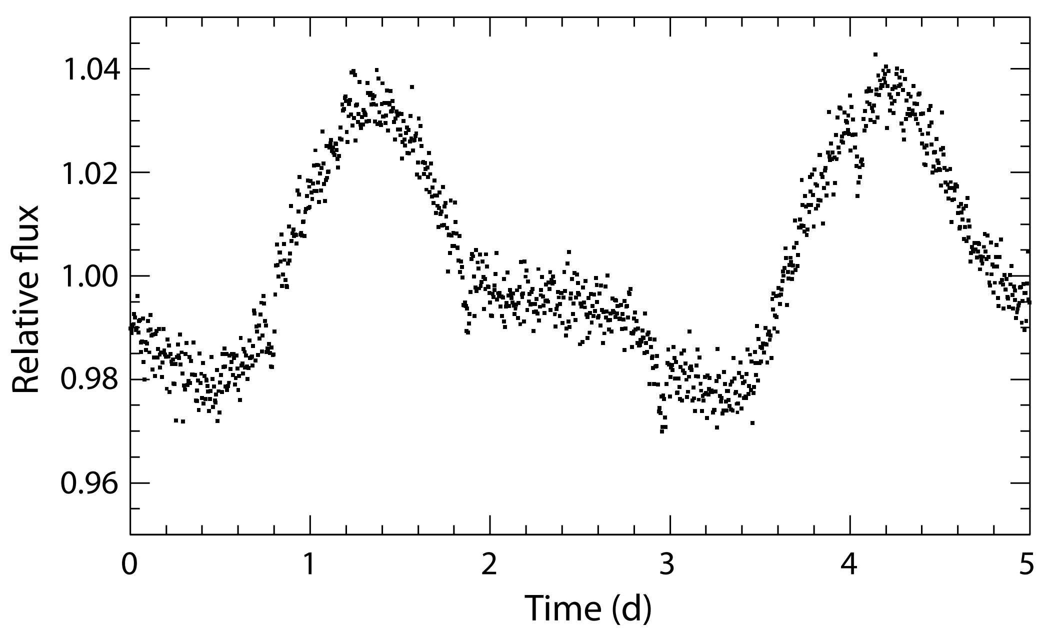
.. and which may be observable...



perspective effects
(Rafikov 2009, Scharf 2007)

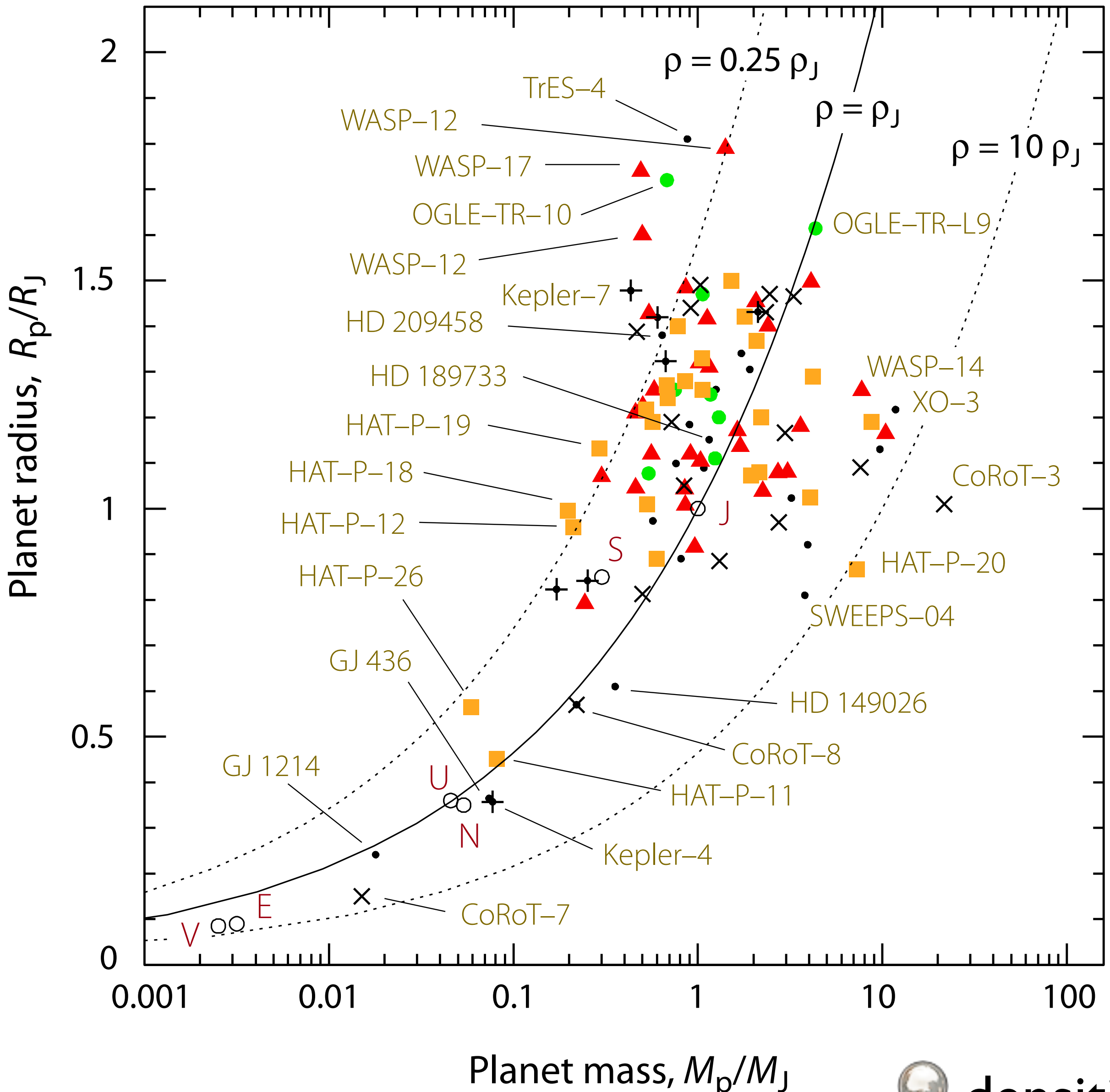


Transit geometry from 2d interferometry
(van Belle 2008: PASP, 120, 617)



close-in, spun-up systems
(Pont 2009: MNRAS 396, 1789)

These transiting systems are extreme laboratories:



- densities are as low as 0.09 Mg m^{-3} (WASP-17)
- shortest orbital periods of 0.79 day (WASP-19)
- the stellar disk subtends up to 35 degrees (WASP-12)
- longest orbital period (with e = 0.93) is 111 day (HD 80606)
- some orbits are highly misaligned or retrograde
- extreme tidal bulges, up to 70 km
- high relativistic apsidal and nodal precession (WASP-33)

Topics

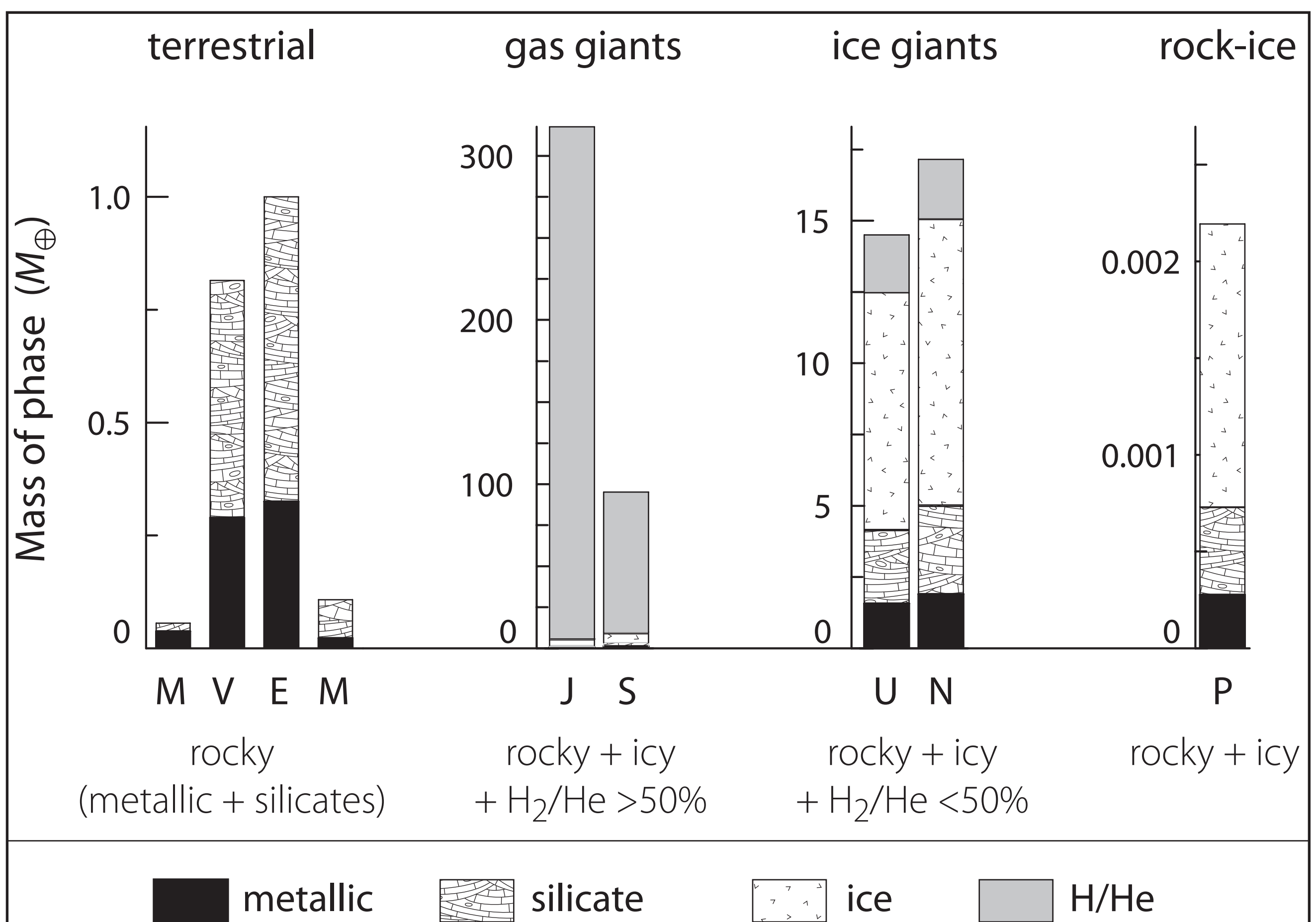
- radial velocities
- astrometry
- transits
- internal structure and composition
- radio emission
- population synthesis

Chemical composition and condensation

Several areas of exoplanet research require estimates of composition versus temperature and pressure (agglomeration during formation, modeling interiors and bulk properties, formation of atmospheres, etc)

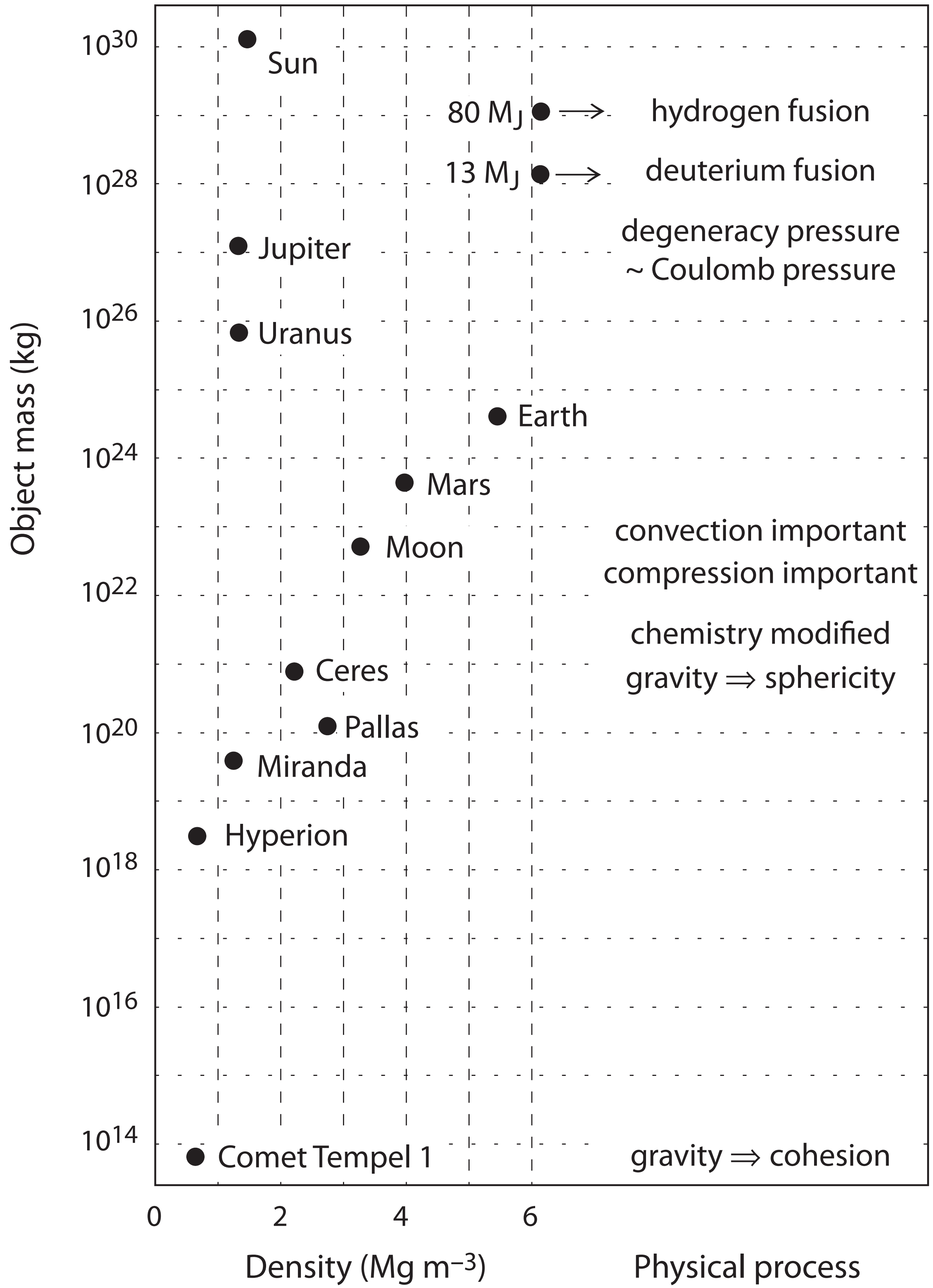
Steps (see, e.g., Lodders 2003, ApJ 591, 1220):

1. start with a certain initial elemental composition (e.g. assumed solar nebula composition)
2. assume time for the relevant chemical reactions to reach equilibrium at given T and P
3. use thermodynamic equilibrium calculations to predict gas/gas-grain/solid phase reactions
4. predict which gases form, which elements or compounds condense, and in which proportions

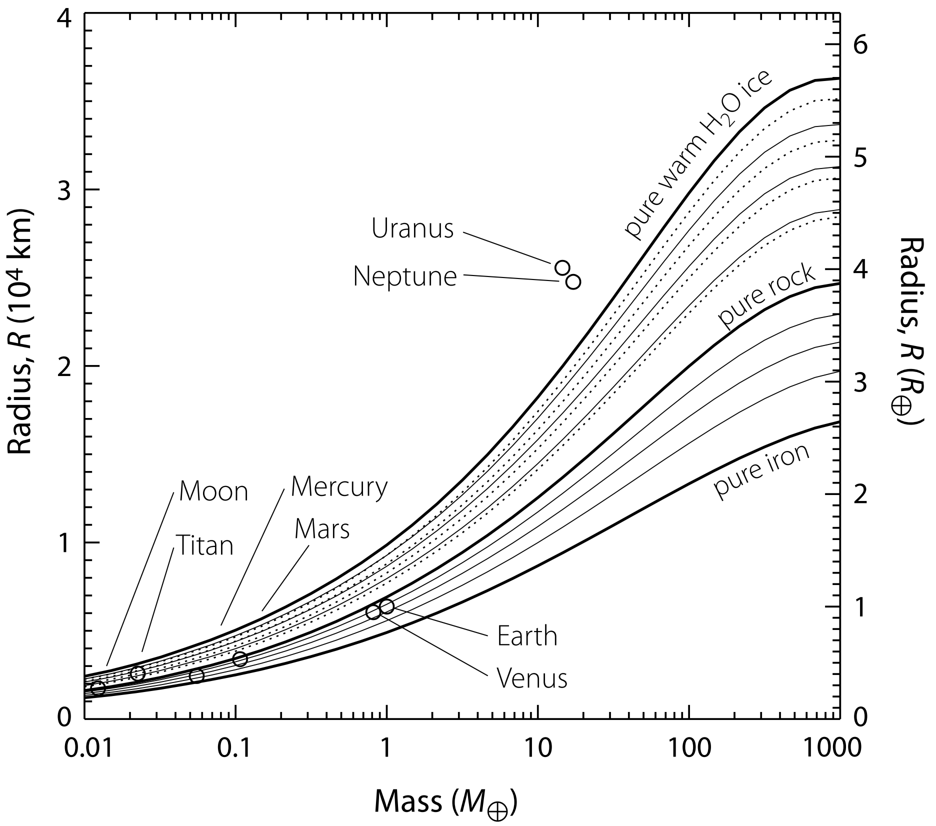


classification of solar system bodies into four compositional types: terrestrial, gas giants, ice giants, and dwarf planets
(Lodders 2010, Exoplanet Chemistry)

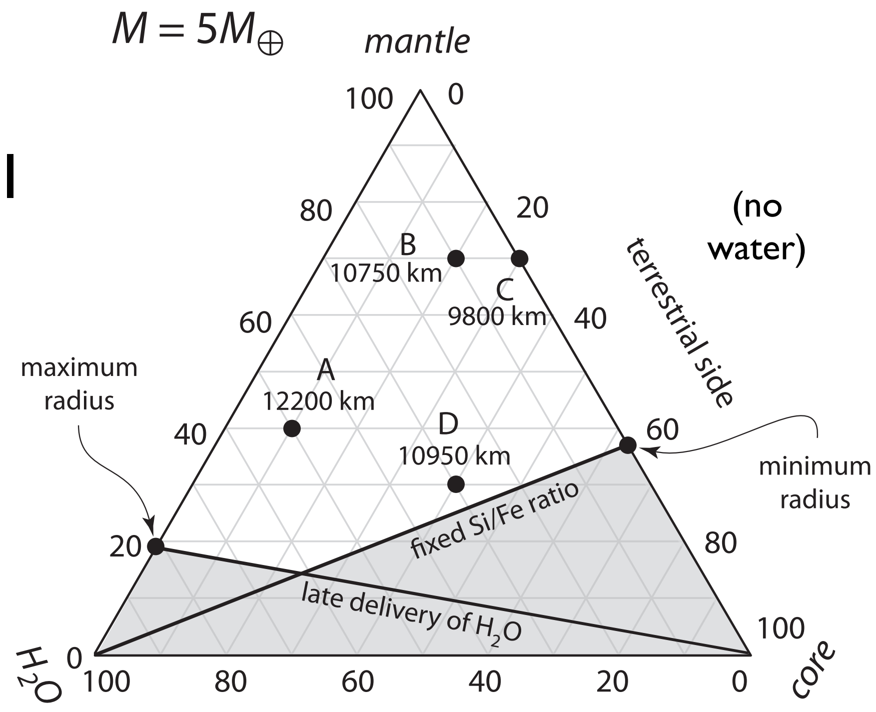
Effect of gravity on shape and structure versus mass



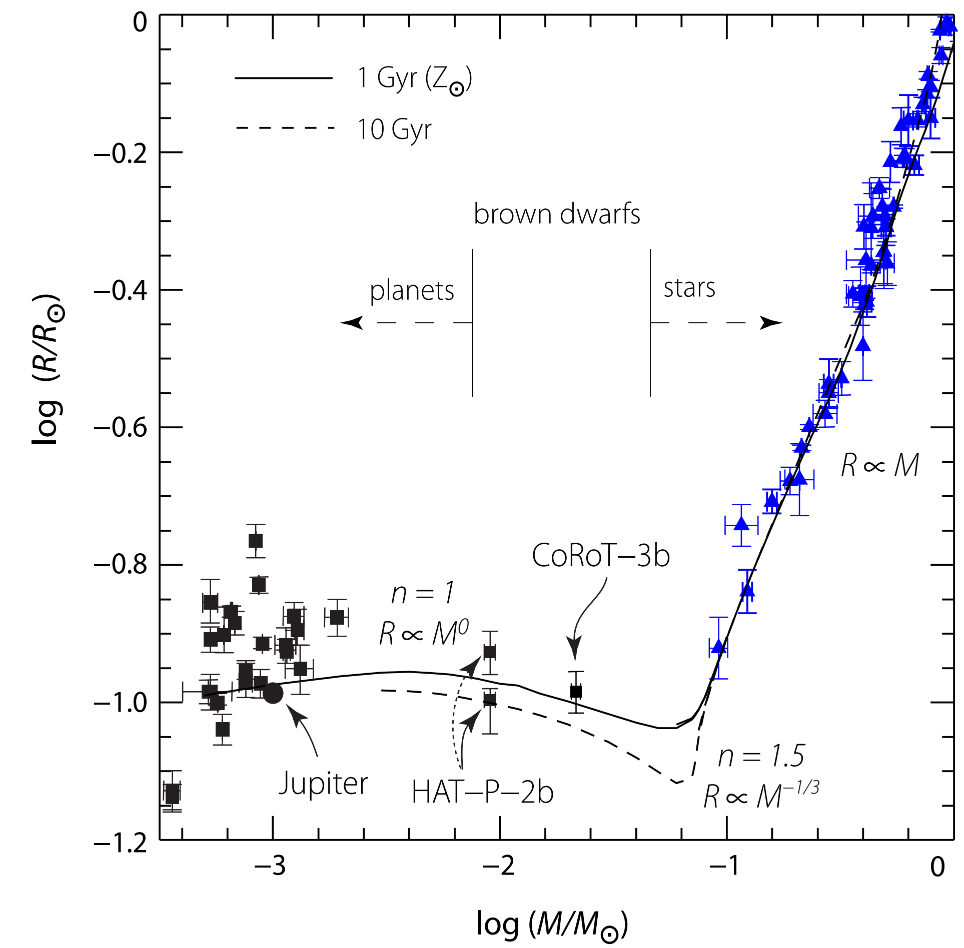
Mass versus radius
(a powerful diagnostic of interiors)



Fortney et al (2007), ApJ 659, 1661

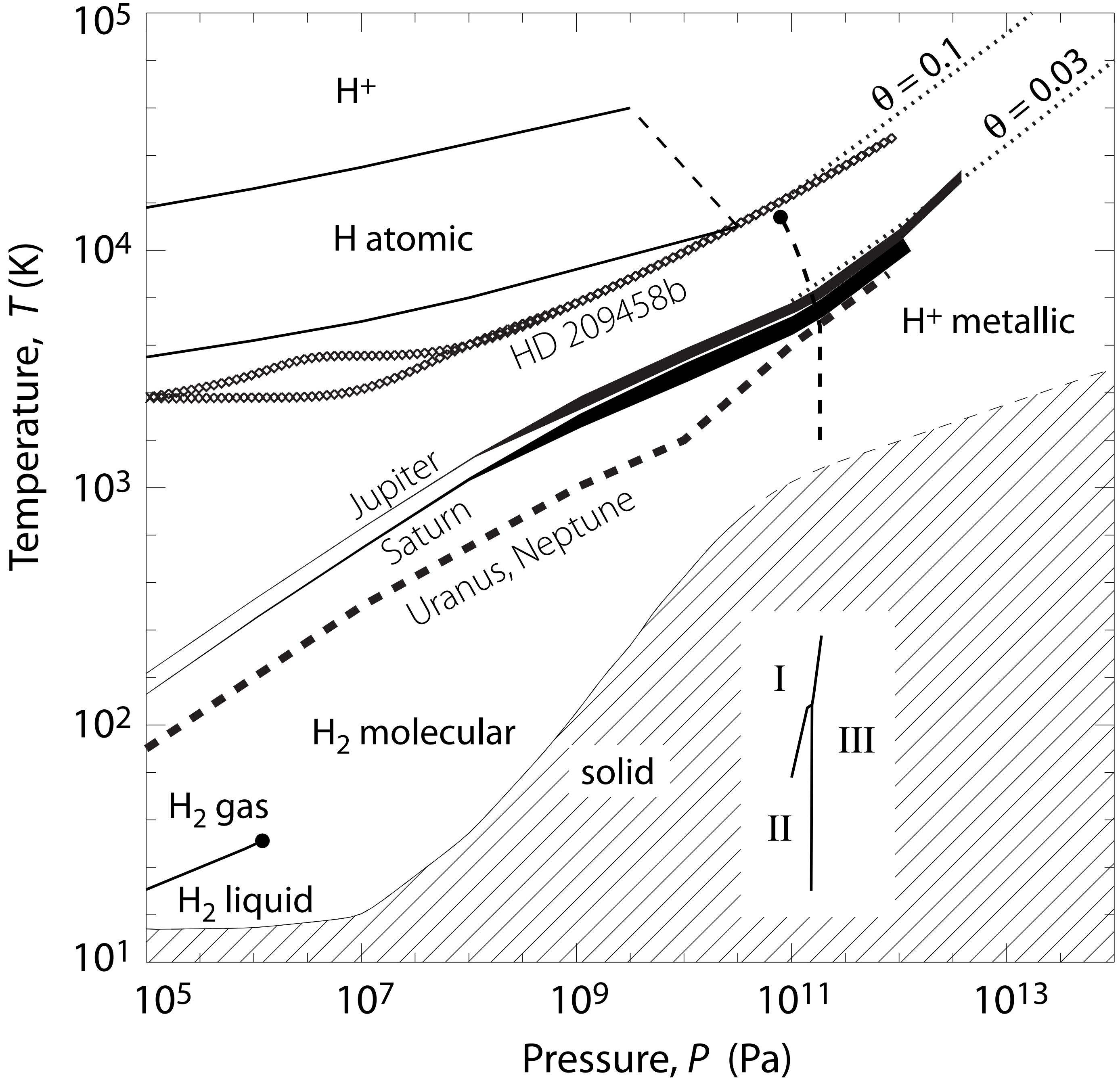


ternary diagrams
(Valencia et al 2007, ApJ 665, 1413)



Chabrier et al (2009),
AIP Conf 1094, 102

Interiors and atmospheres: hydrogen



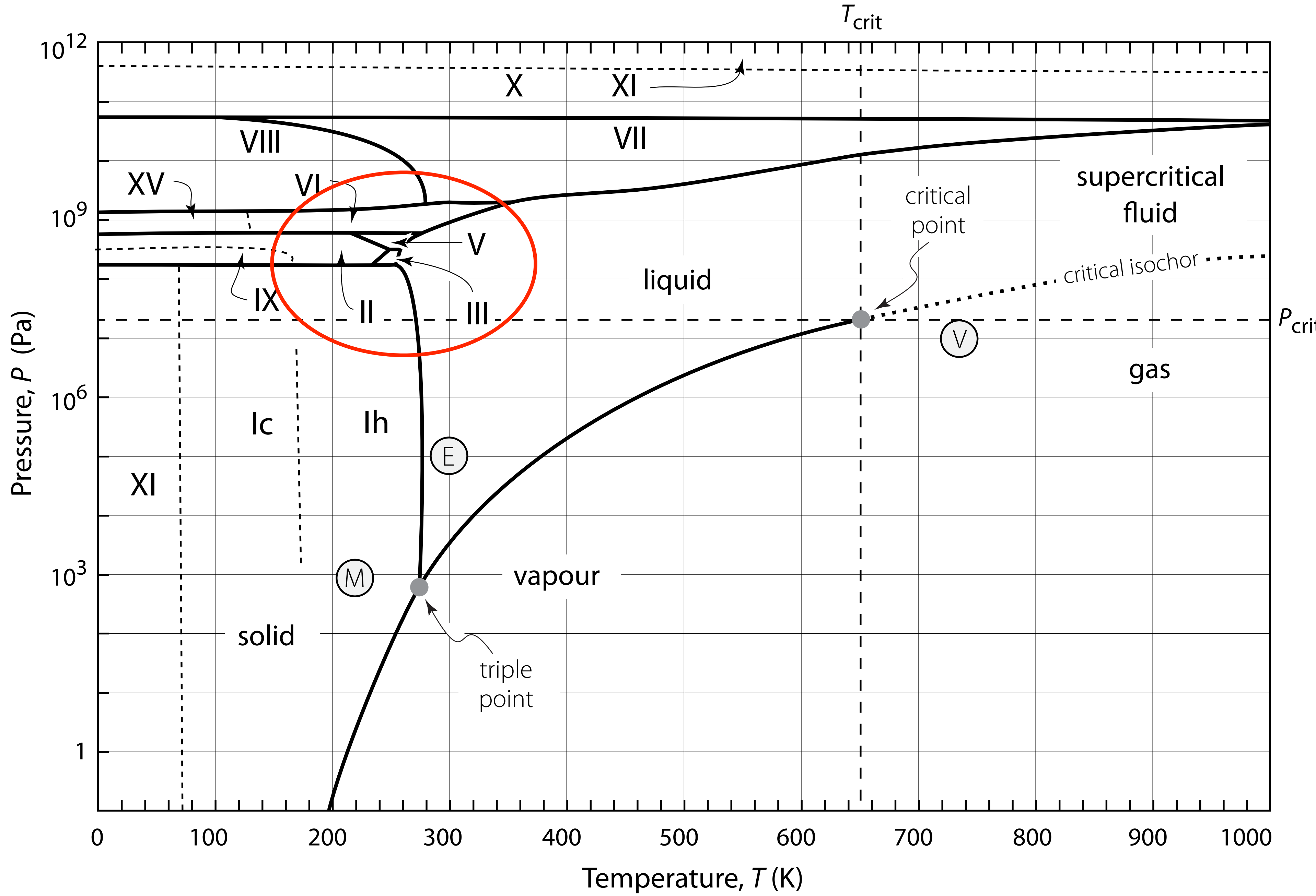
Guillot (2005), AREPS, 33, 493

Notes:

* molecular-metallic transition
* solidification possible at low *T* and high *P*, but relevant for an isolated Jupiter only after ~1000 Gyr of cooling (Hubbard 1968)
* *P*−*T* profiles for solar system giants and HD 209458

Interiors and atmospheres: water (1/2)

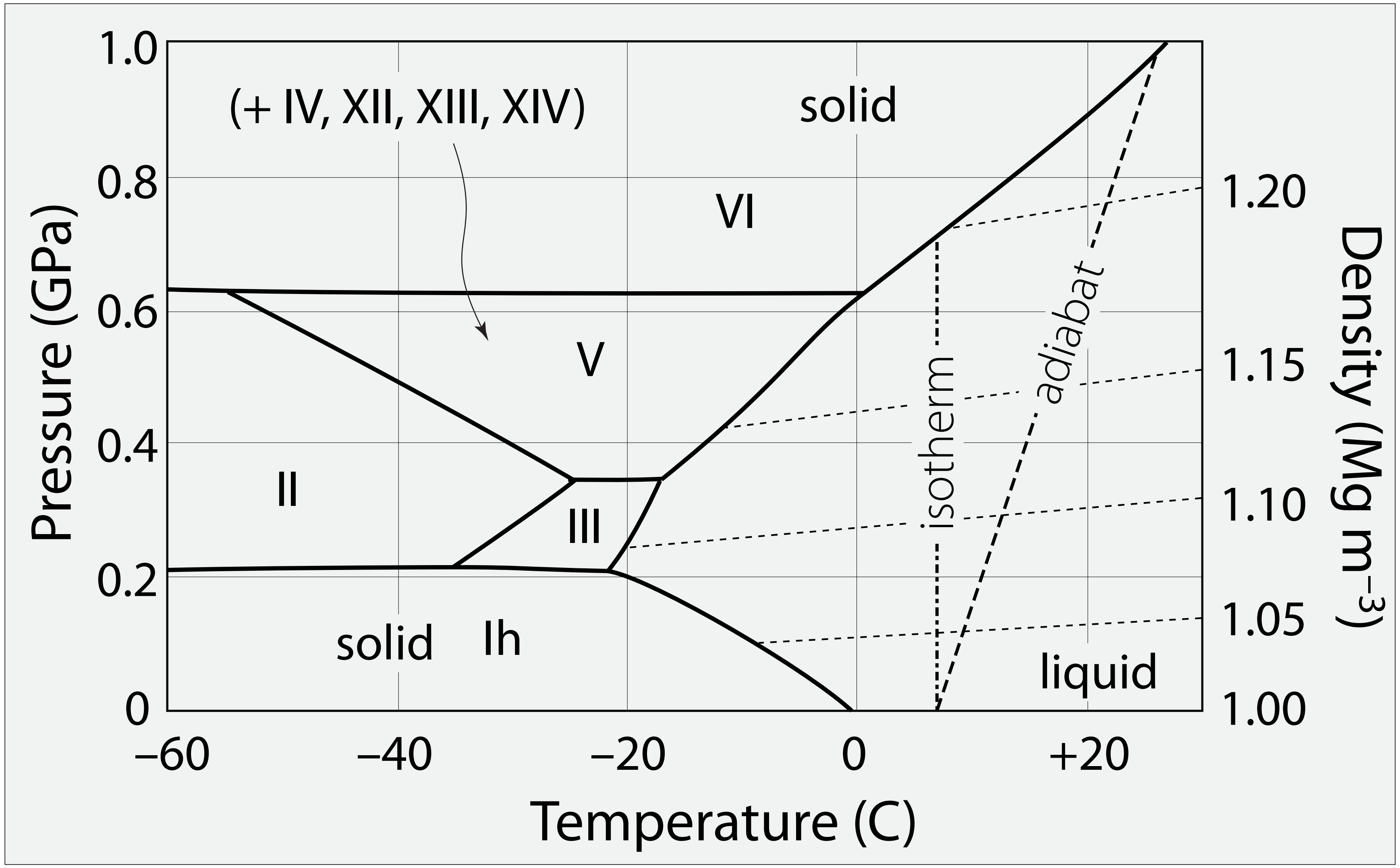
Phase diagram for water (Chaplin 2010)



- 19 solid phases: ice XII discovered in 1996, XIII-XIV in 2006, and XV in 2009
- 16 crystalline polymorphs: hexagonal, cubic, monoclinic, orthorhombic, tetragonal...
- densities are <1 for Ih/Ic only, and reach 2.5 for ice X
- ice VII (and perhaps X/XI) are most relevant for planetary interiors (Valencia et al 2007)

[properties collated by the International Association for the Properties of Water and Steam]

Interiors and atmospheres: water (2/2)



For a $6M_{Earth}$ ‘ocean planet’ in the habitable zone with $T_{surface}$ = 7C, Leger et al (2004, Icarus 169, 499) derived: ocean depth = 45−72 km (isothermal-adiabatic)

Topics

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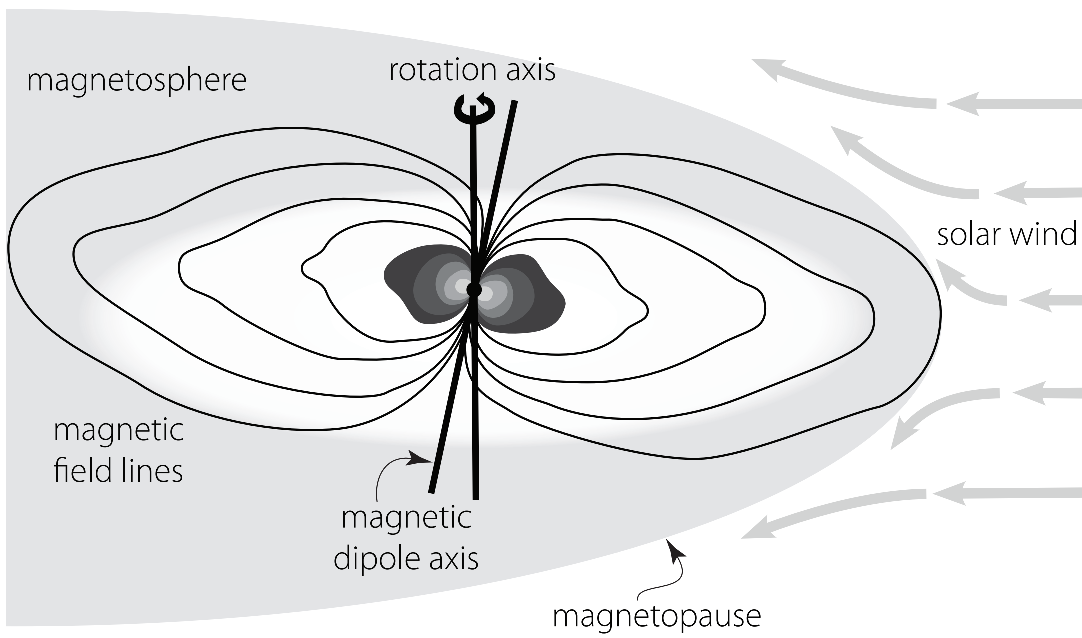
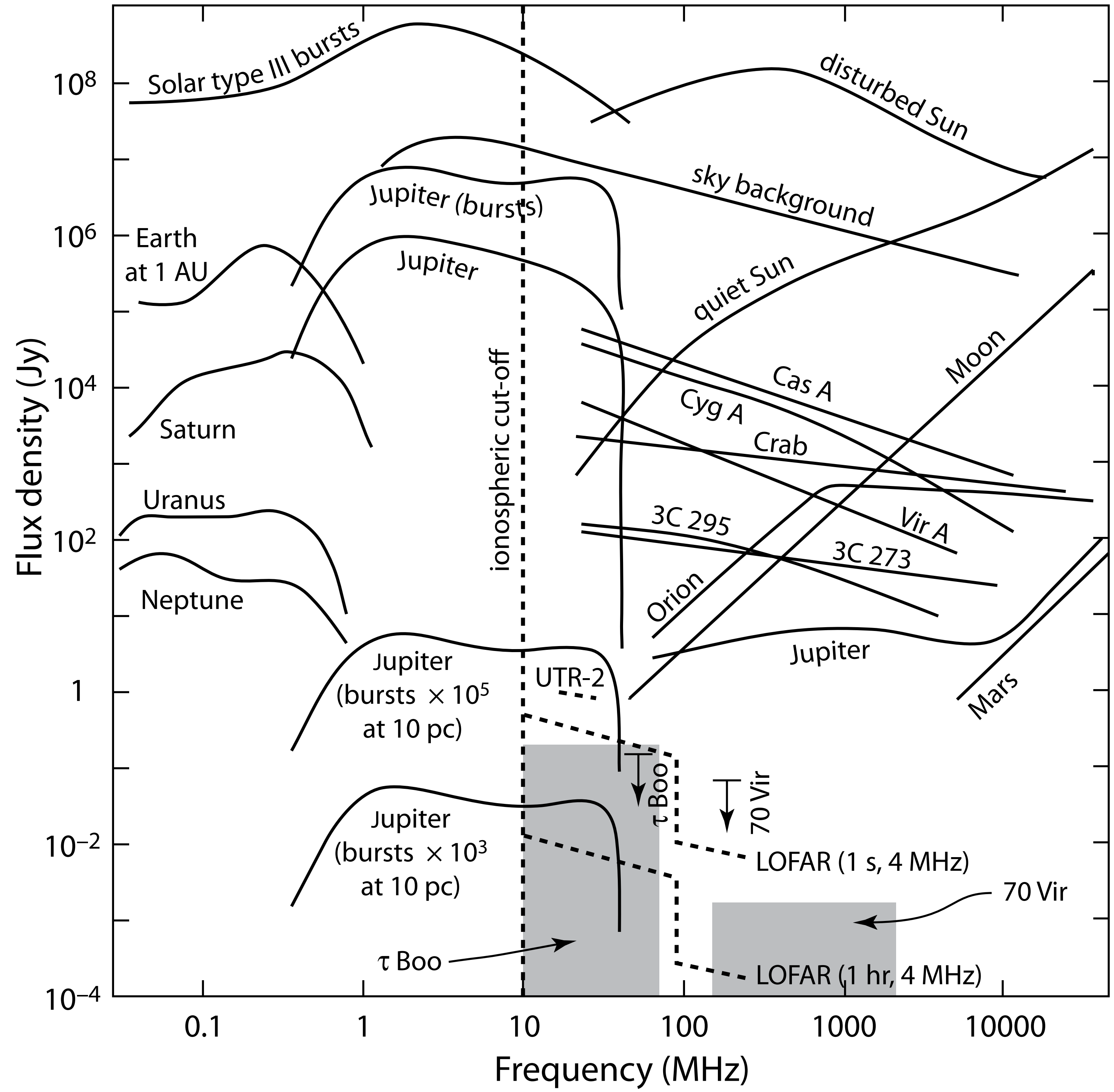
Radio emission





Five of the solar system planets with dynamo-driven magnetic fields produce low frequency (cyclotron) emission.
So far, no exoplanets....

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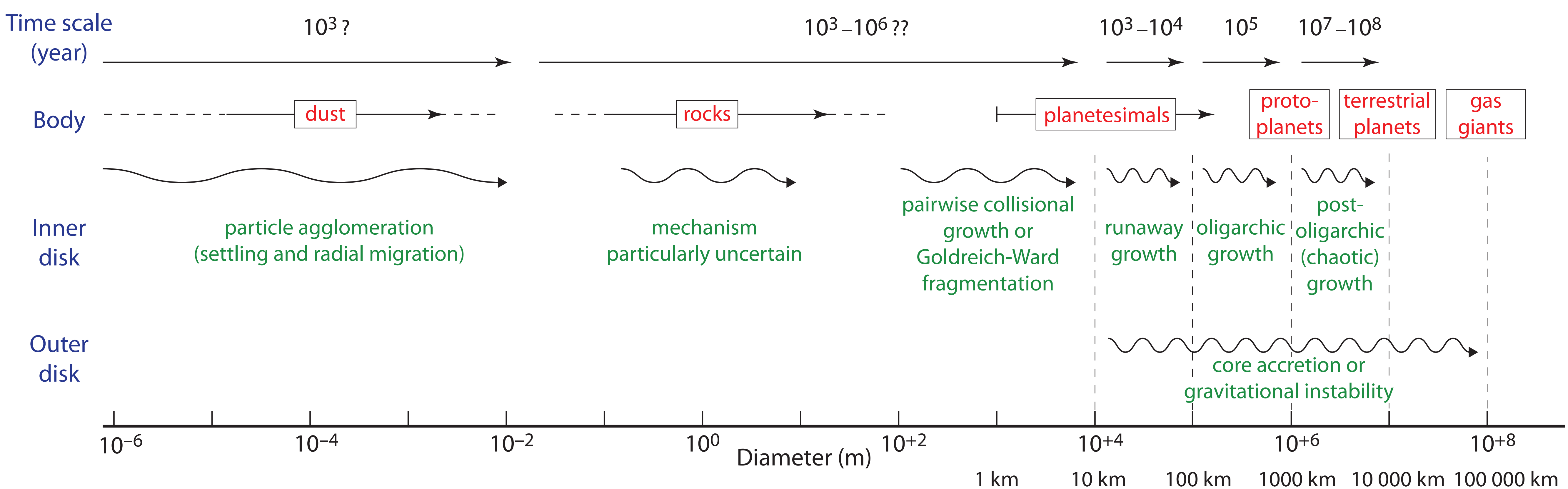
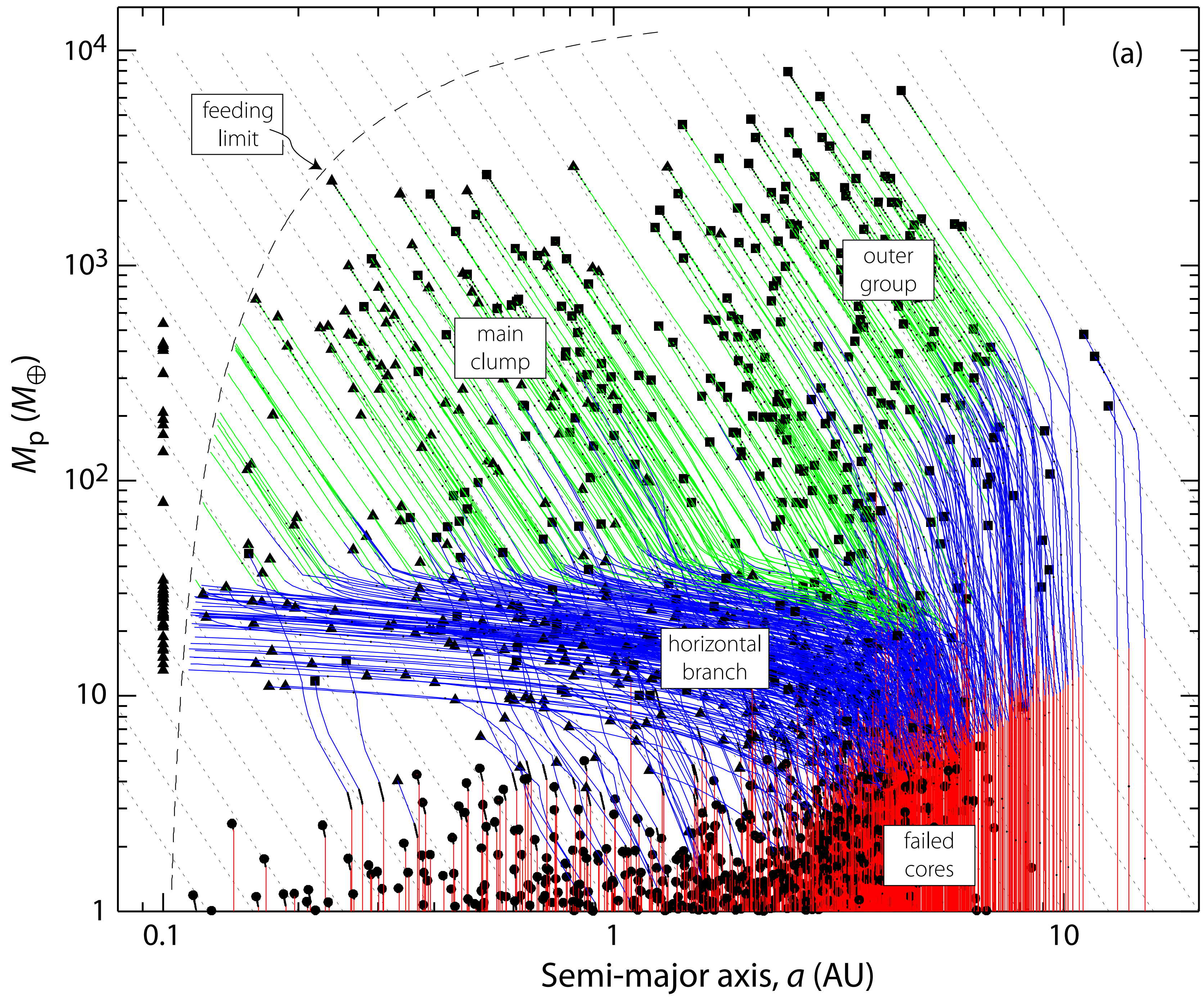
Planet formation:

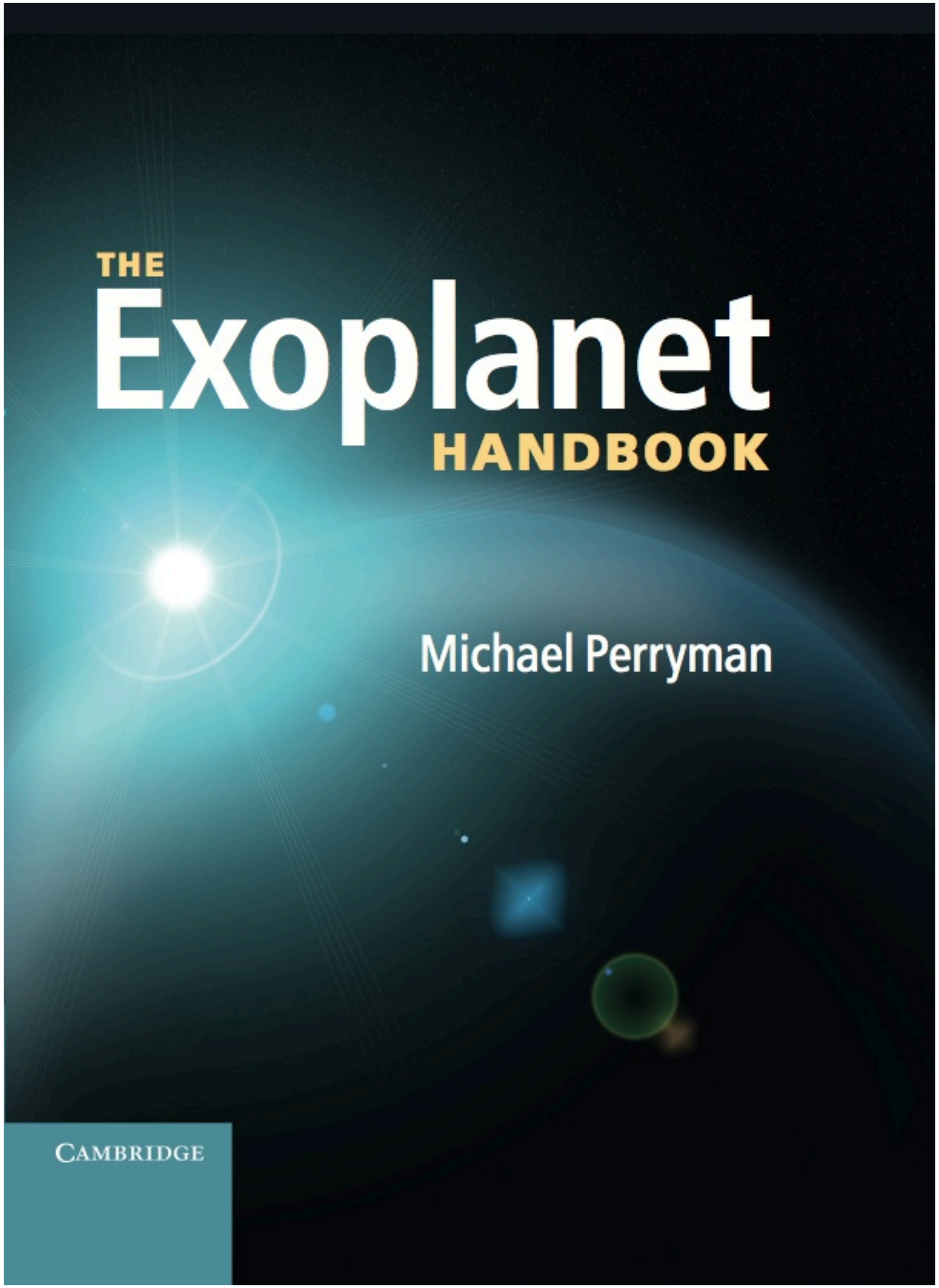
growth by 14 orders of magnitude
(in one viewgraph)



Population synthesis



there are enough planets that a statistical approach to model results is now possible
e.g. Mordasini et al (2009): A&A 501, 1139



Just published - topics covered:

1. Introduction
2. Radial velocities
3. Astrometry
4. Timing
5. Microlensing
6. Transits
7. Imaging
8. Host stars
9. Brown dwarfs
10. Formation and evolution
11. Interiors and atmospheres
12. The solar system

The End