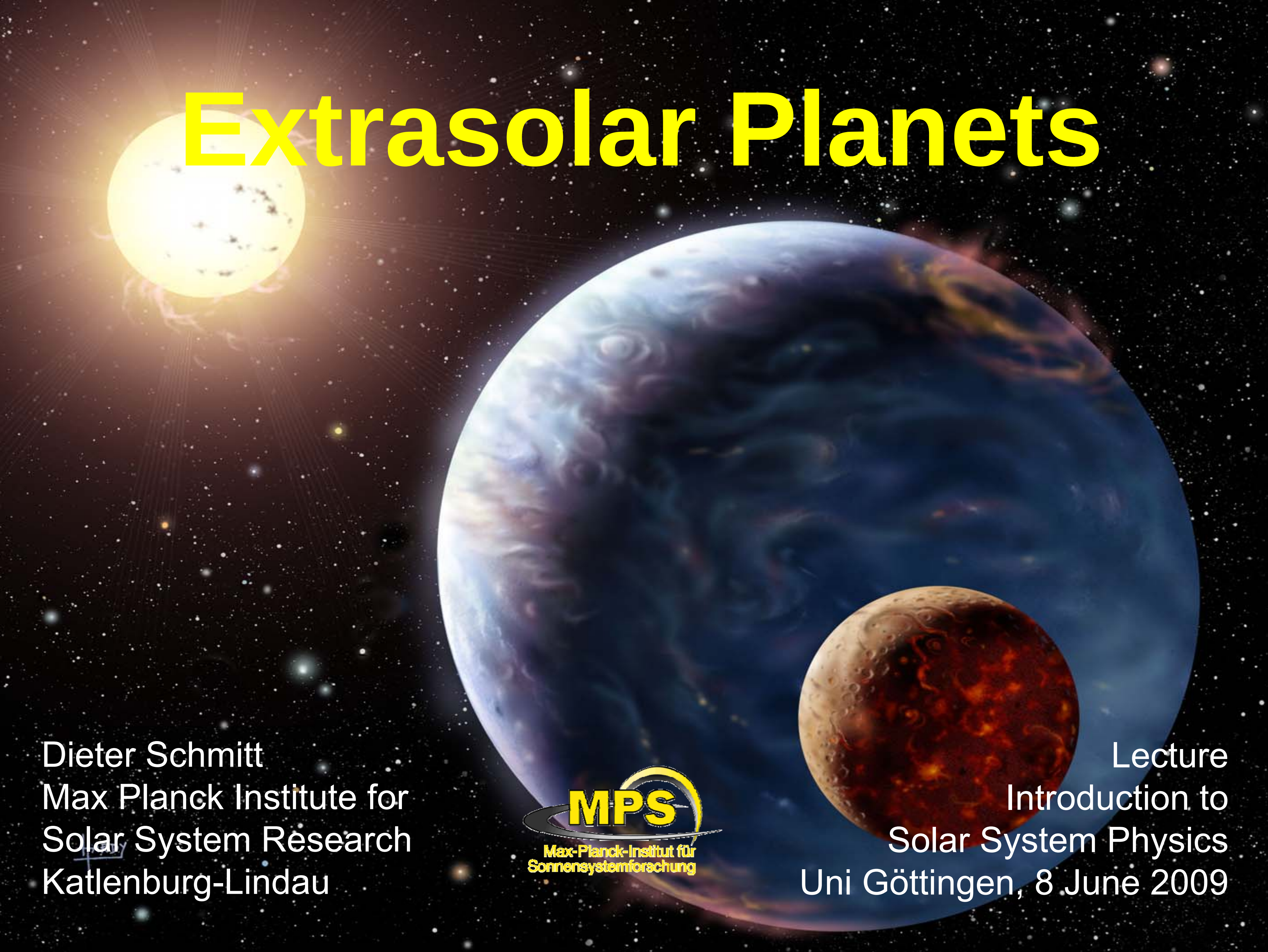
Extrasolar Planets



Dieter Schmitt
Max Planck Institute for
Solar System Research
Katlenburg-Lindau

MPS
Max-Planck-Institut für
Sonnensystemforschung

Lecture
Introduction to
Solar System Physics
Uni Göttingen, 8 June 2009

Outline

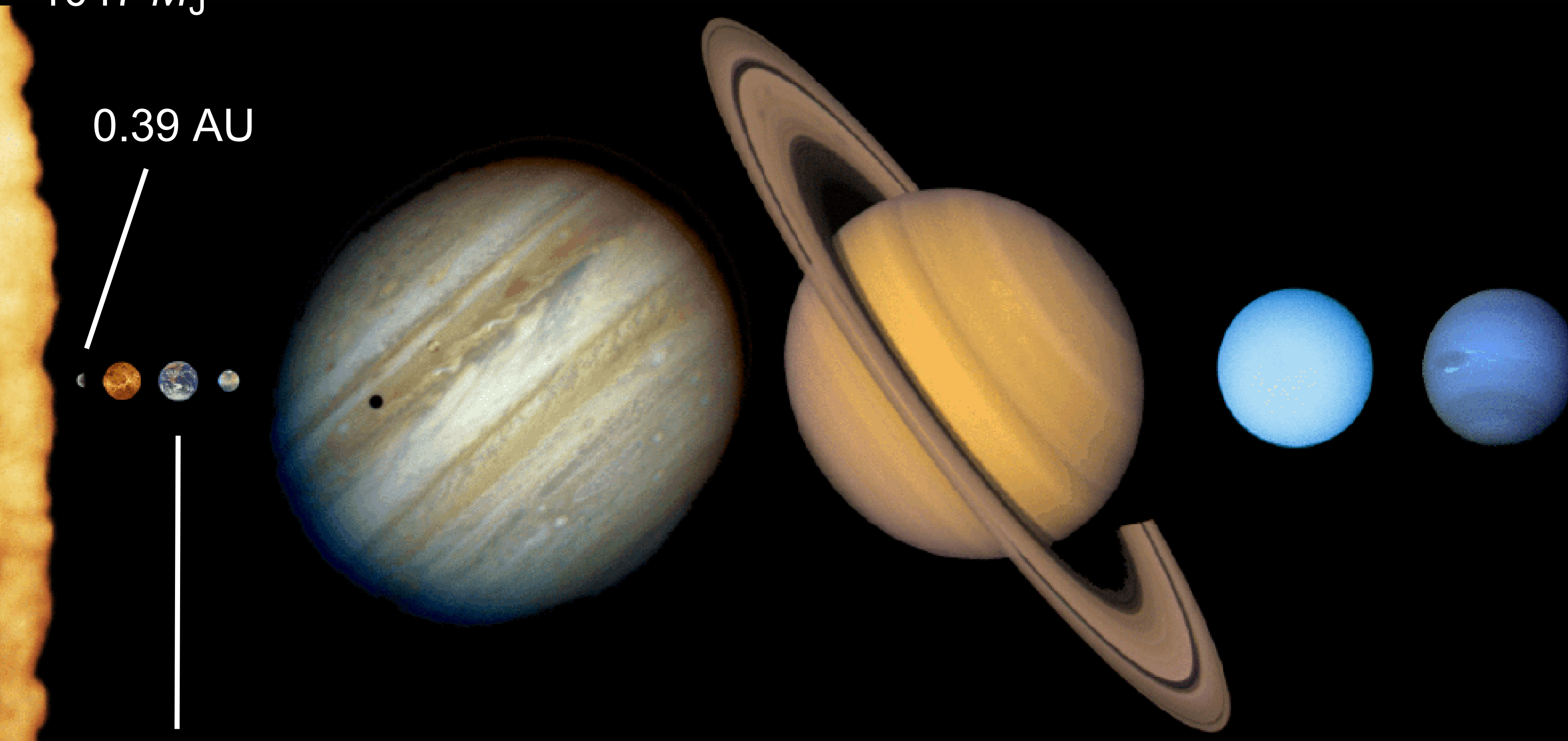
- Historical Overview
- Detection Methods
- Planet Statistics
- Formation of Planets
- Physical Properties
- Habitability

Historical overview

- 1989: planet / brown dwarf orbiting HD 114762 (Latham et al.)
- 1992: two planets orbiting pulsar PSR B1257+12 (Wolszczan & Frail)
- 1995: first planet around a solar-like star 51 Peg b (Mayor & Queloz)
- 1999: first multiple planetary system with three planets Ups And (Edgar et al.)
- 2000: first planet by transit method HD 209458 b (Charbonneau et al.)
- 2001: atmosphere of HD 209458 b (Charbonneau et al.)
- 2002: astrometry applied to Gliese 876 (Benedict et al.)
- 2005: first planet by direct imaging GQ Lupi b (Neuhäuser et al.)
- 2006: Earth-like planet by gravitational microlensing (Beaulieu et al.)
- 2007: Gliese 581d, small exoplanet near habitability zone (Selsis et al.)
- 2009: Gliese 581e, smallest exoplanet with 1.9 Earth masses (Mayor et al.)
- As of 7 June 2009: 349 exoplanets in 296 systems (25 systems with 2 planets, 9 with 3, 2 with 4 and 1 with 5)

www.exoplanet.eu

Our Solar System



Definition Planet

IAU 2006:

- in orbit around the Sun / star
- nearly spherical shape / sufficient mass for hydrostatic equilib.
- cleared neighbourhood around its orbit

Pluto: dwarf planet, as Ceres

Brown dwarf:

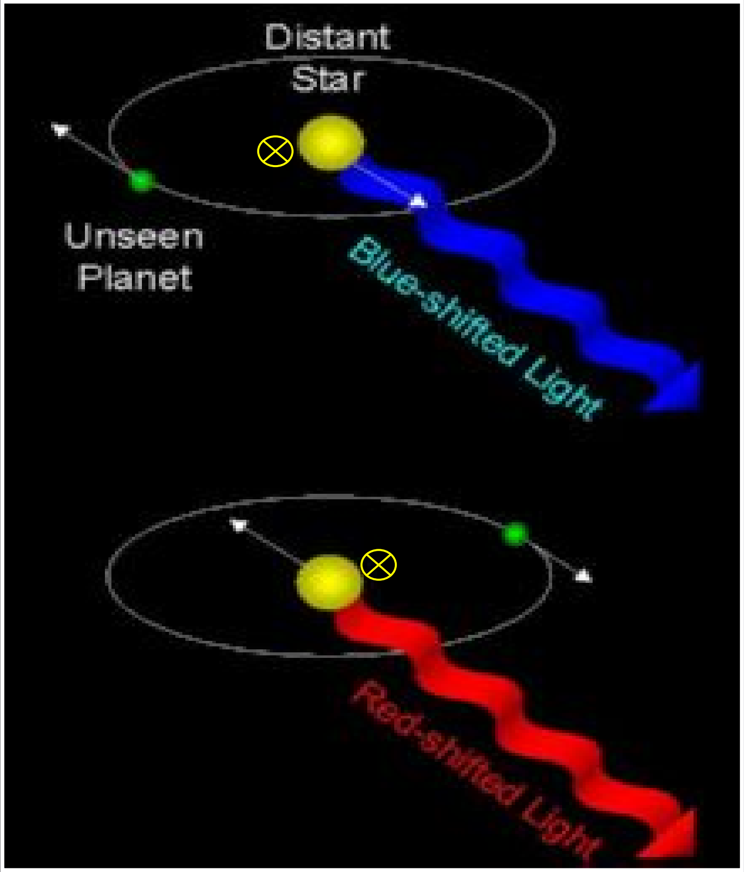
- masses between 14 M_J and 80 M_J (= 0.08 $M_\odot$)
- fully convective, no hydrogen fusion, but deuterium fusion
- M < 14 M_J : planet, M > 80 M_J : star (red dwarf)

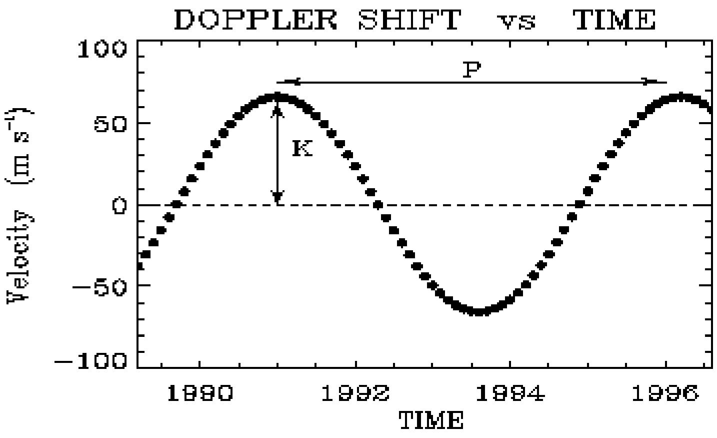
How can we detect extrasolar planets around main sequence stars?

The main detection methods:

- Radial velocity method
- Astrometry
- Transit method
- Gravitational microlensing
- Direct imaging

Radial velocity method





$$\Delta\lambda / \lambda = v_r / c = v_S \sin i / c$$

$$\frac{a_P^3}{P^2} = \frac{GM_S}{4\pi^2}$$

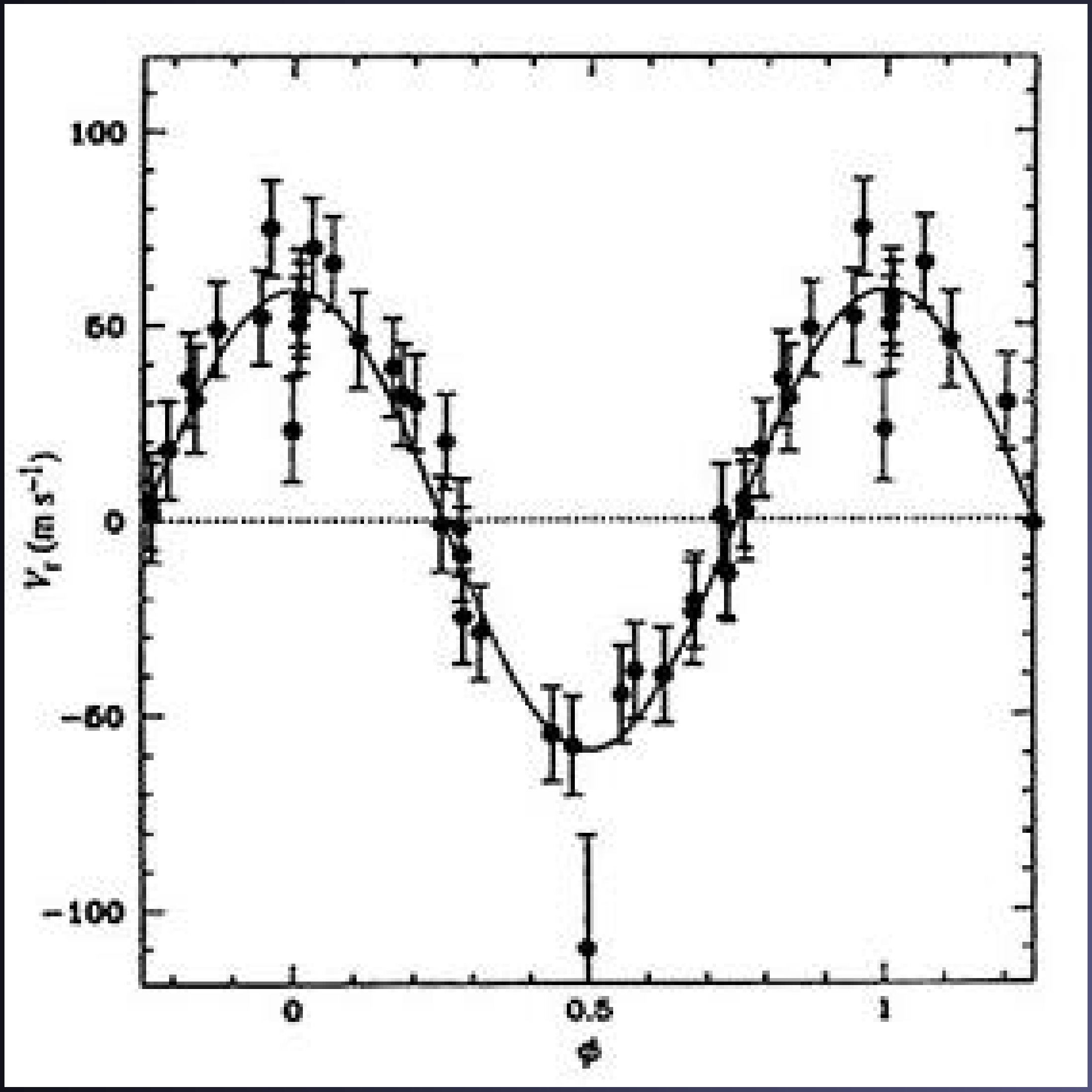
$$M_P << M_S$$
$$a_P >> a_S$$

$$a_S M_S = a_P M_P$$

$$a_S = \frac{P v_S}{2\pi}$$

$$M_P \sin i = v_r \left(\frac{M_S^2 P}{2\pi G} \right)^{1/3}$$

51 Peg b



detected 1995 by Mayor & Queloz and Marcy & Butler

51 Peg:

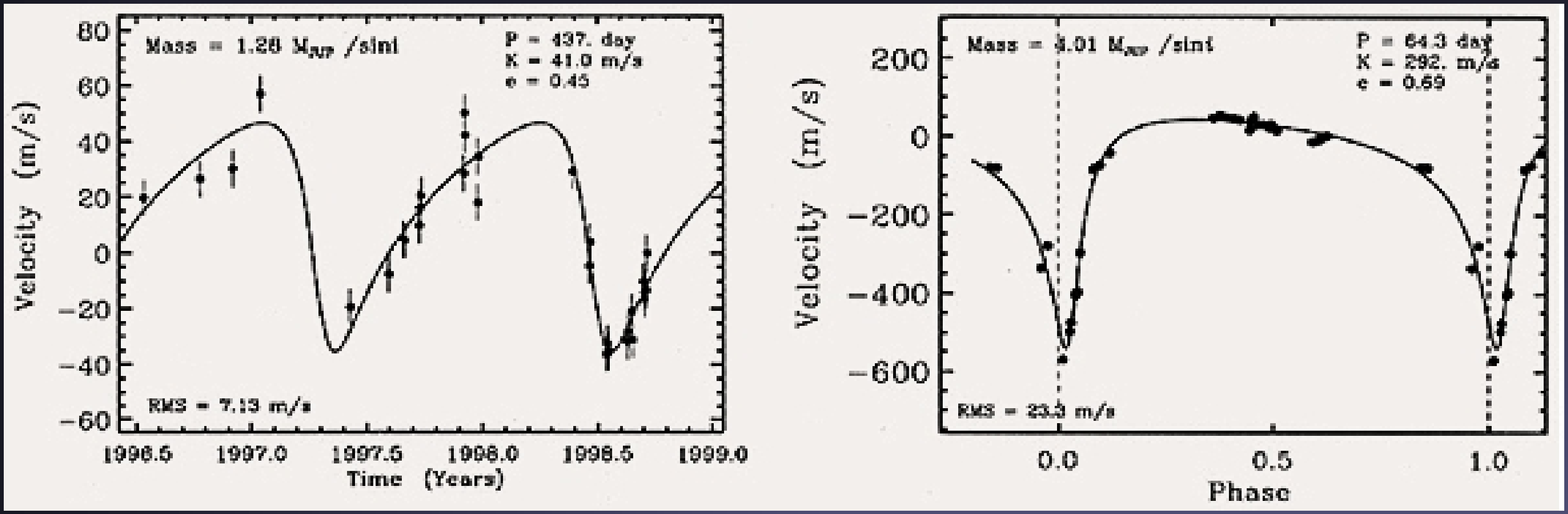
G2IV, V = 5.5, 15 pc

51 Peg b:

P = 4.23 d
a = 0.05 AU
$M \sin i$ = 0.47 M_J

Pegasus

Third parameter: eccentricity



Detection limit:

51 Peg b: $v_r \sim 50$ m/s

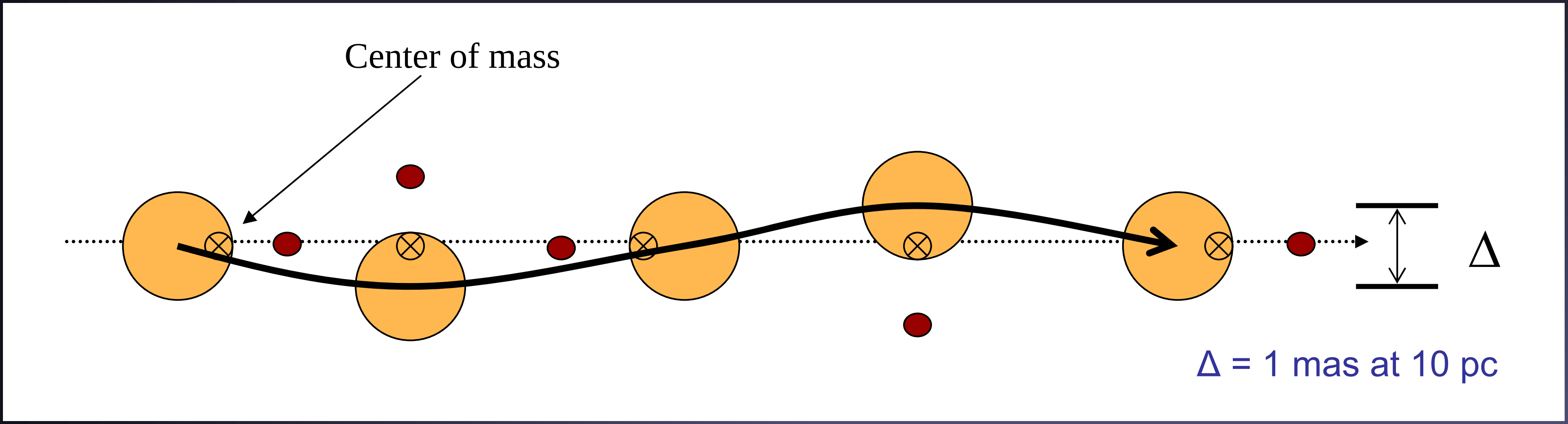
today: $\lambda/\Delta\lambda \sim 10^8 \longrightarrow v_r \sim 3$ m/s

theoretical: $v_r \sim 1$ m/s (effect of star spots)

in comparison: Jupiter around Sun: 12.5 m/s

Earth 0.05 m/s

Astrometry

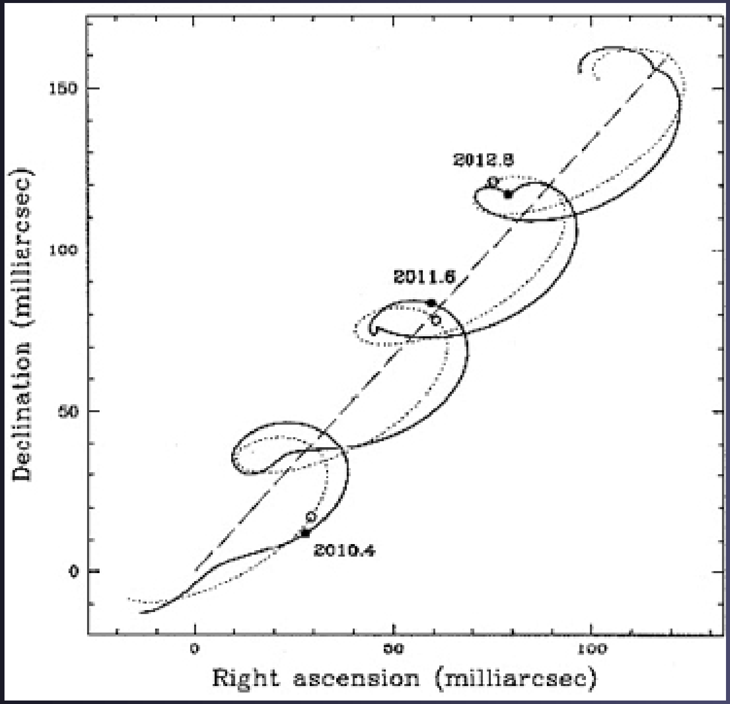


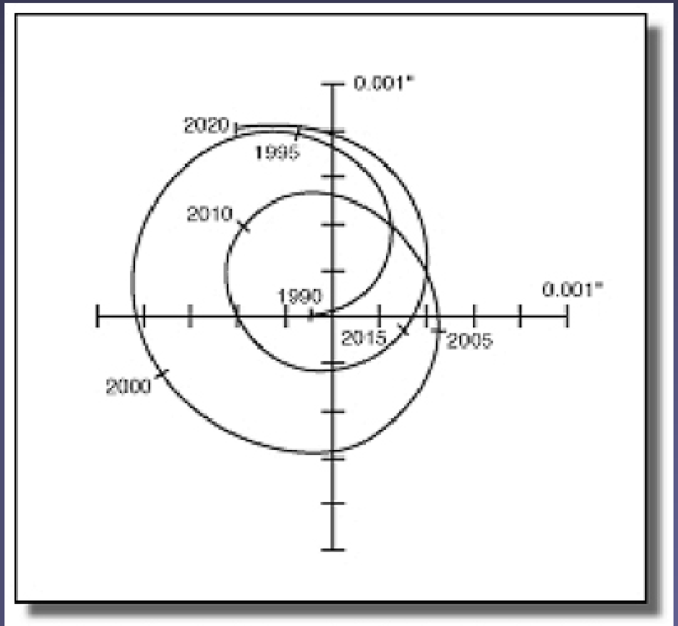
Measurement of the spatial wobble of the star around the center of mass

- $\Delta = (M_P/M_S)(a_P/d)$: near stars, large orbital distances
- current resolution: 1-2 mas (from ground), 0.1 mas (HST)
- example: Gliese 876 b (Benedict et al. 2002)
- in future: Gaia (ESA Mission)

Simulations:

- star in 50 pc, planet with 15 M_J, a = 0.06 AU, e = 0.2, proper motion of 50 mas/yr
- motion of Sun in 10 pc distance



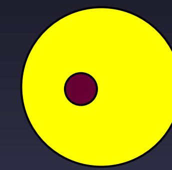


Astrometric displacement of the Sun due to Jupiter as seen from 10 parsecs.

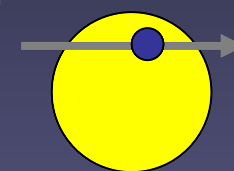
- measurement of two velocity components

  ⟶ determination of true mass independent of sin i

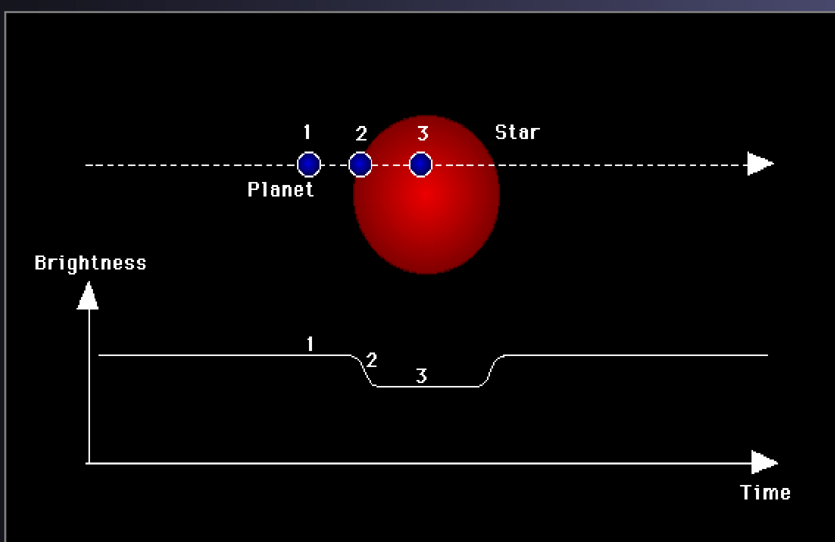
Transit method

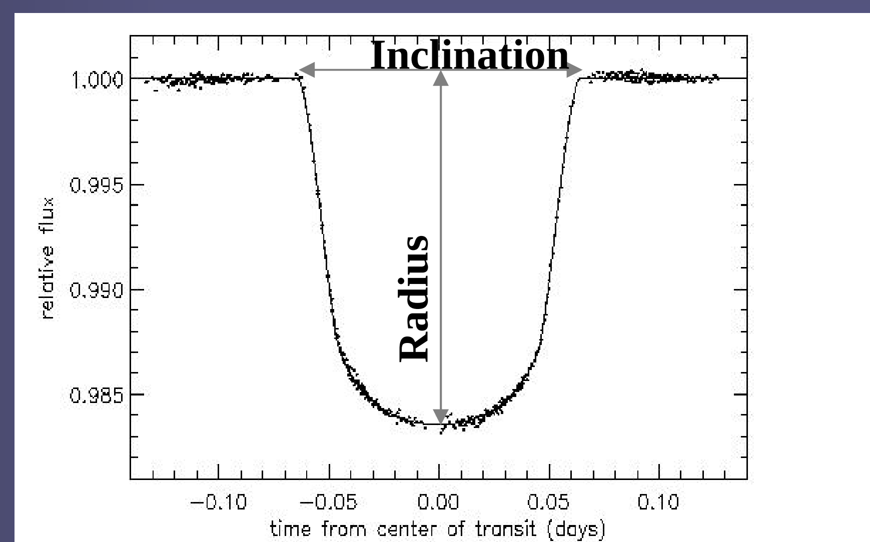


- amplitude: $\Delta I \,/\, I \sim R_P^2 \,/\, R_S^2$
  Jupiter: ~1%, Erde: ~0.01%
- probability: $R_S \,/\, a_P$
- period: orbital period, distance from star

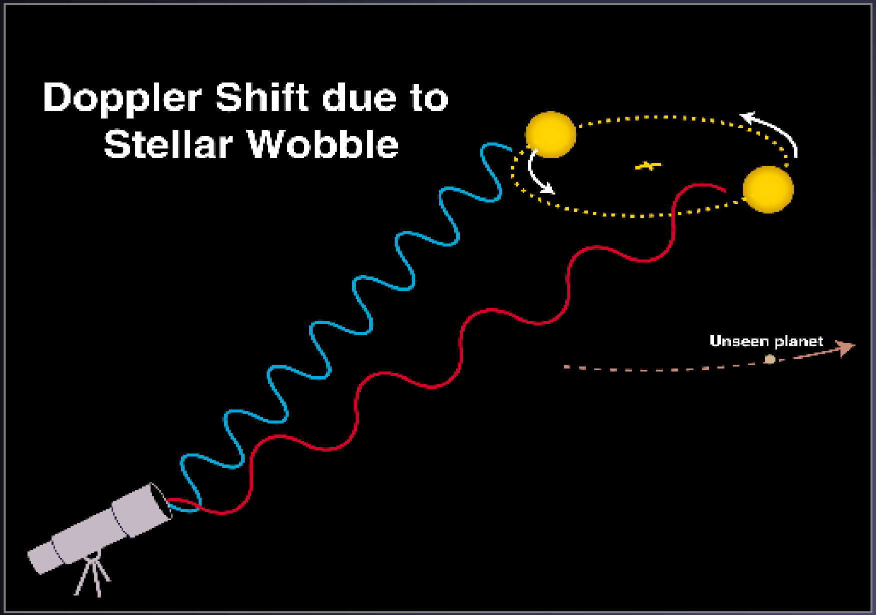


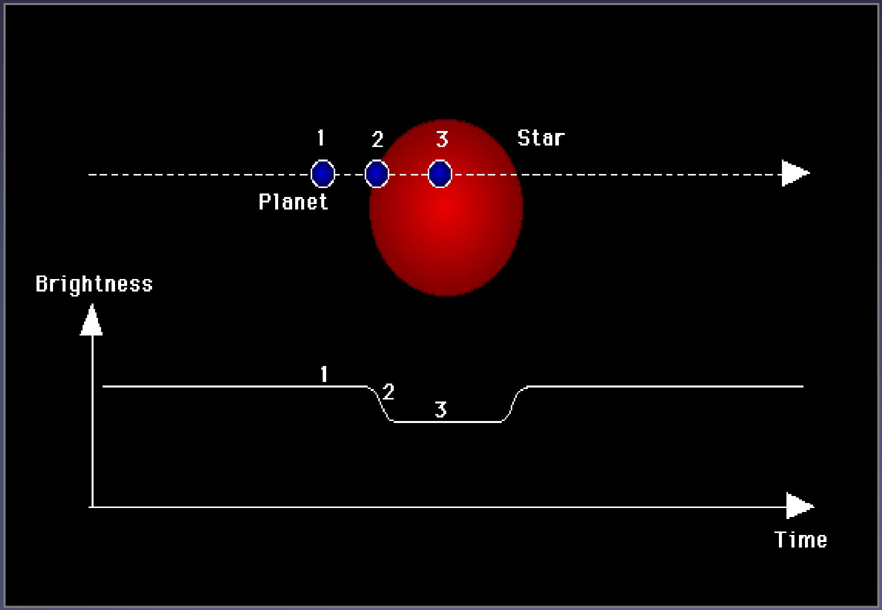
- transit duration: inclination of orbit, $i \sim 90^o$
- HD 209458 b (Charbonneau et al. 2000)





Combination of radial velocity and transit method





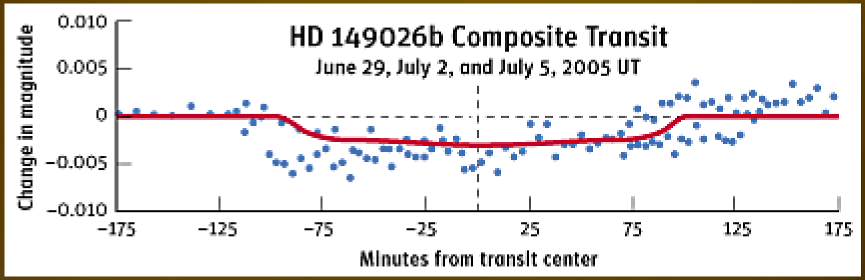
$M \sin i$

i , R

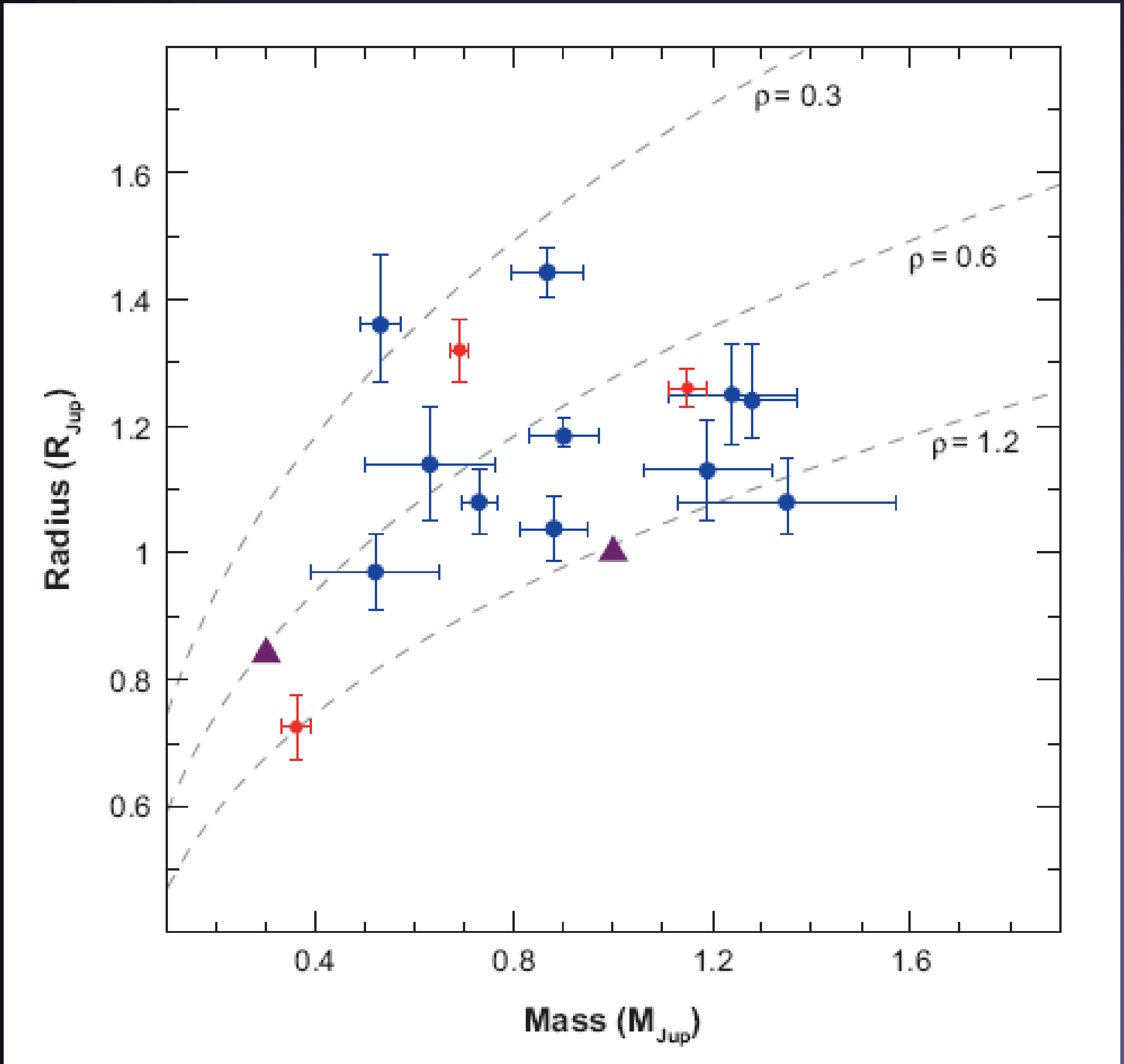
combined: M , mean ρ

HD 149026 b

- discovered with RV by Sato et al. (2005)
- transit by amateur astronomer Bissinger (2005)
- Δm = 0.003 mag !
- P = 2.88 d
- a = 0.042 AU
- M = 0.36 M_J
- R = 0.72 R_J
- T_{eff} = 2300 +/- 200 K



Mass - Radius - Diagram



red: planets detected
by RV method

blue: planets by
transit method

triangles: Jupiter
Saturn

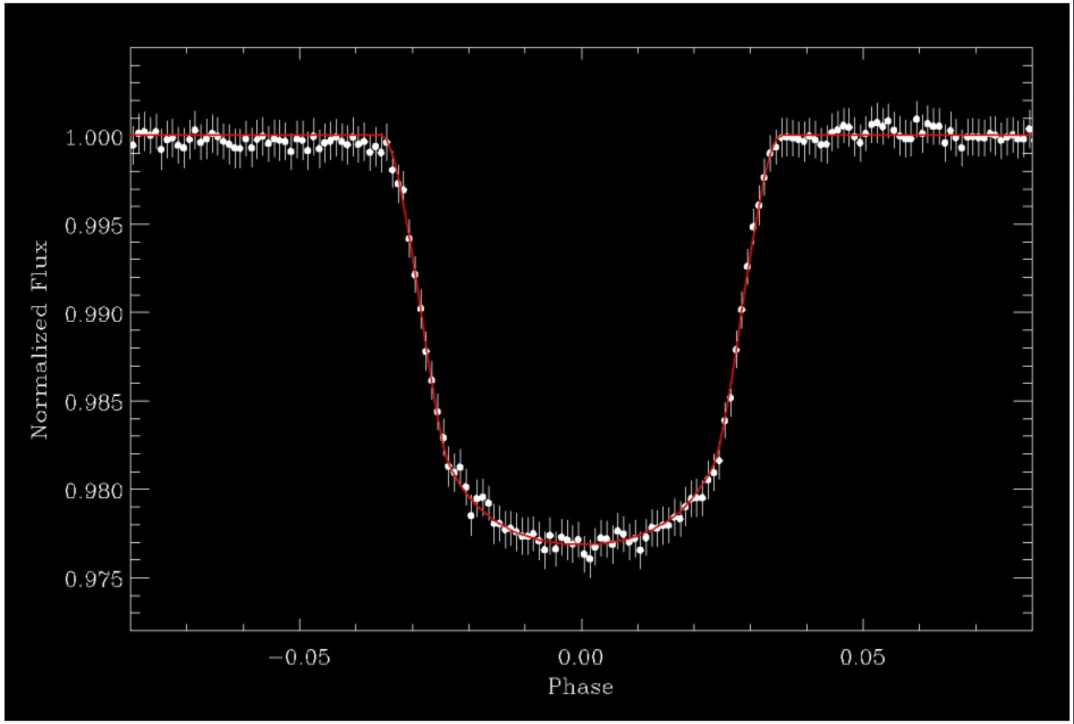
(Udry & Santos 2007)

CoRoT mission

French satellite with 27cm telescope and CCD camera with 2.8°x2.8° field-of-view

Goal: Detection of terrestrial planets on close-in orbits

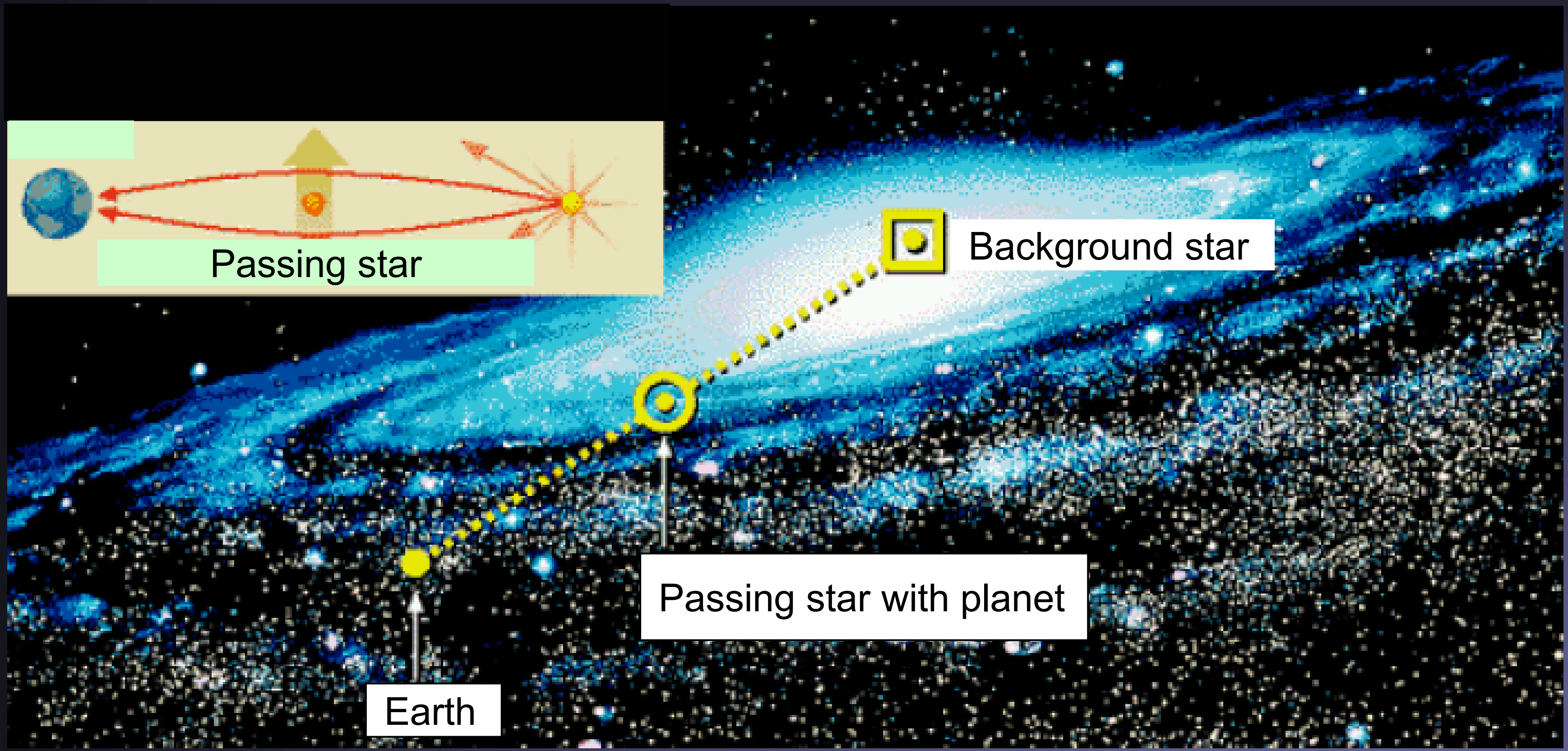
CoRoT-Exo-1b



(Barge et al. 2007)

Launch: 27 December 2006

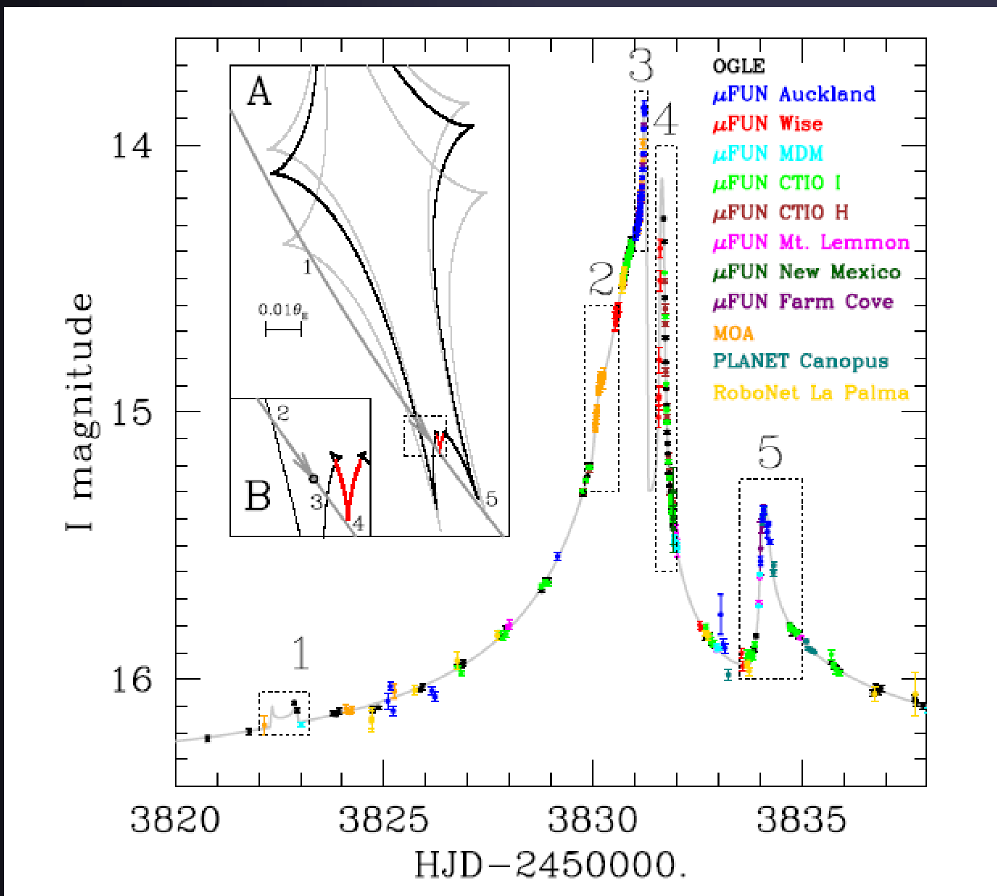
Gravitational microlensing



A foreground star acts as gravitational lens and enhances the apparent brightness of a background star. A planet around the foreground star modifies the lensing signal.

Microlensing can detect small, terrestrial planets. The geometry does not repeat, however. Therefore, good for statistical studies.

Detection of a Jupiter/Saturn analog with microlensing



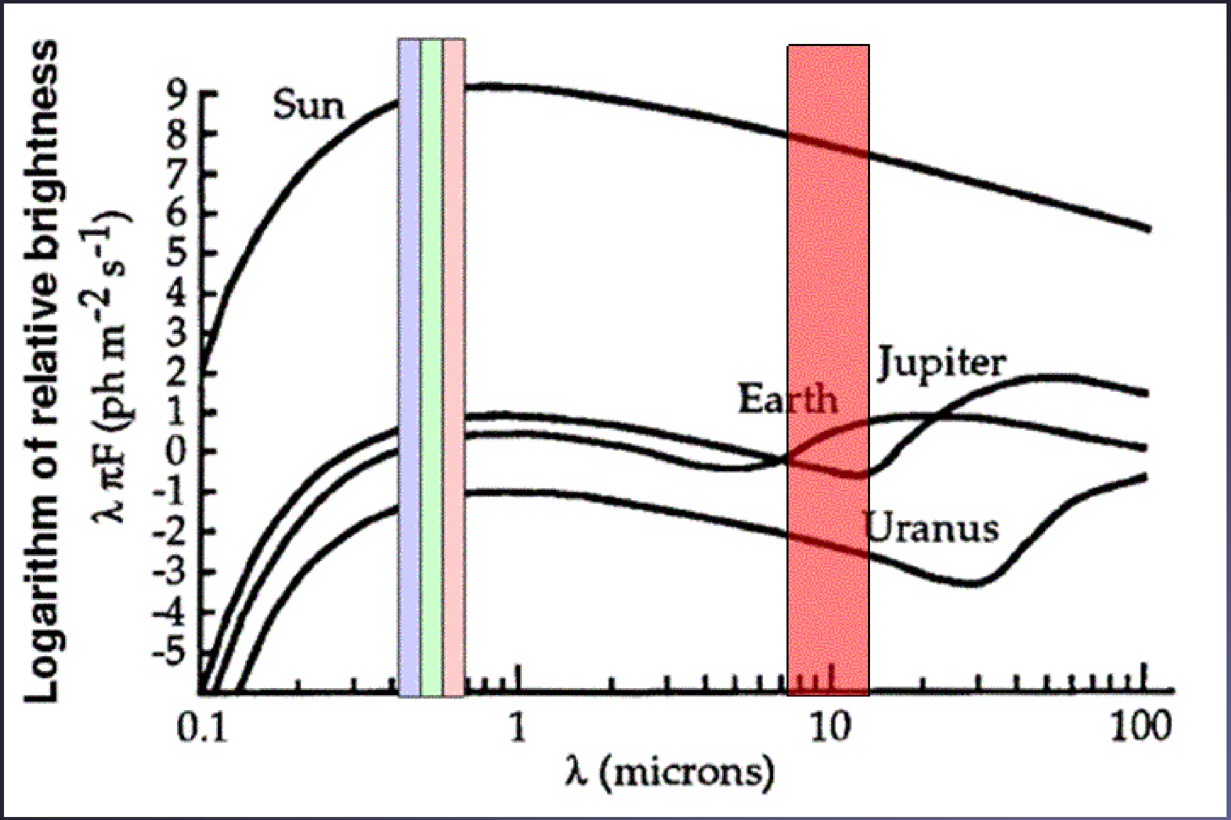
OGLE-06-109L: 0.5 $M_{\odot}$, 1.5 kpc

Name	OGLE-06 -109L b	OGLE-06 -109L c
Mass	0.71 M_J	0.27 M_J
Distance	2.3 AU	4.6 AU
Period	1825 d	5100 d
Eccentricity		0.11
Inclination		59º

OGLE = Optical Gravitational Lens Experiment

(Gaudi et al. 2008)

Direct imaging



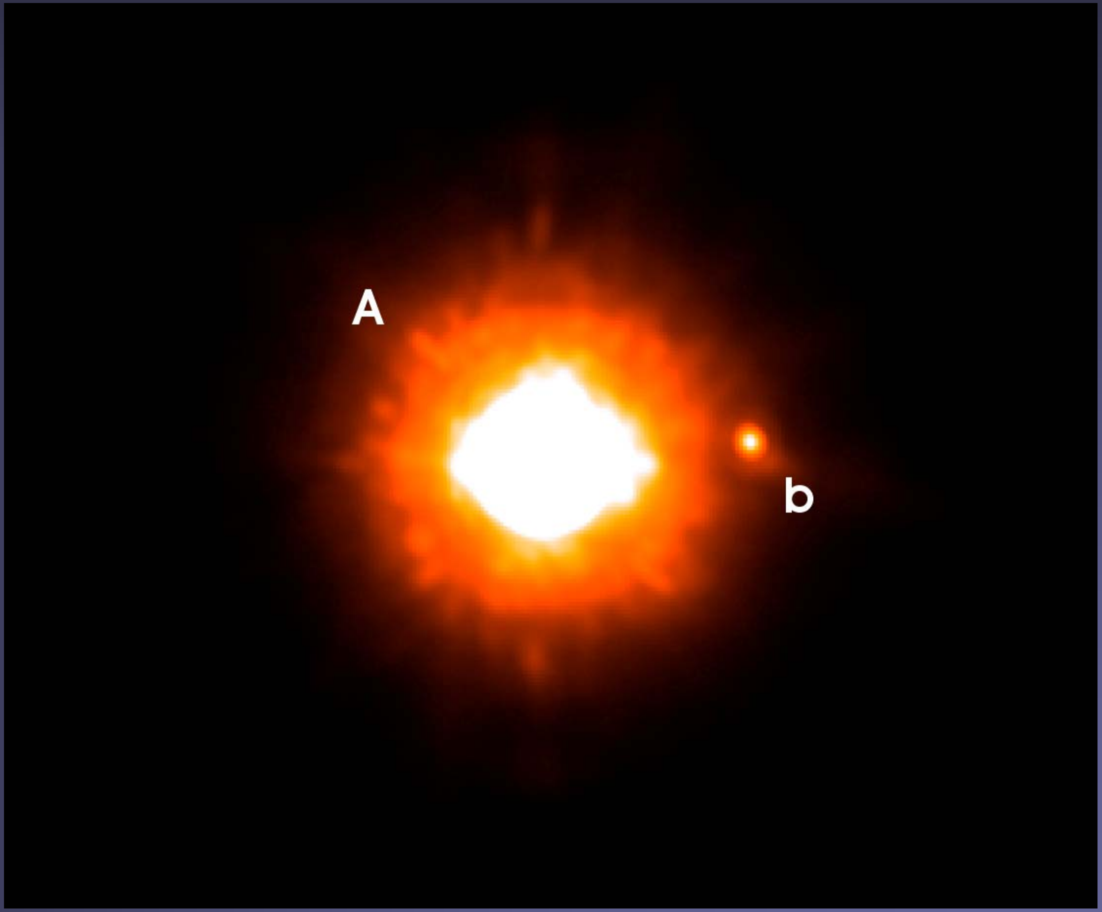
- difficulty: star several orders of magnitude brighter than planet
- situation improves in the infrared spectral range and for joung, hot planets

GQ Lupi b, first directly observed exoplanet

ESO VLT-NaCo K-Band

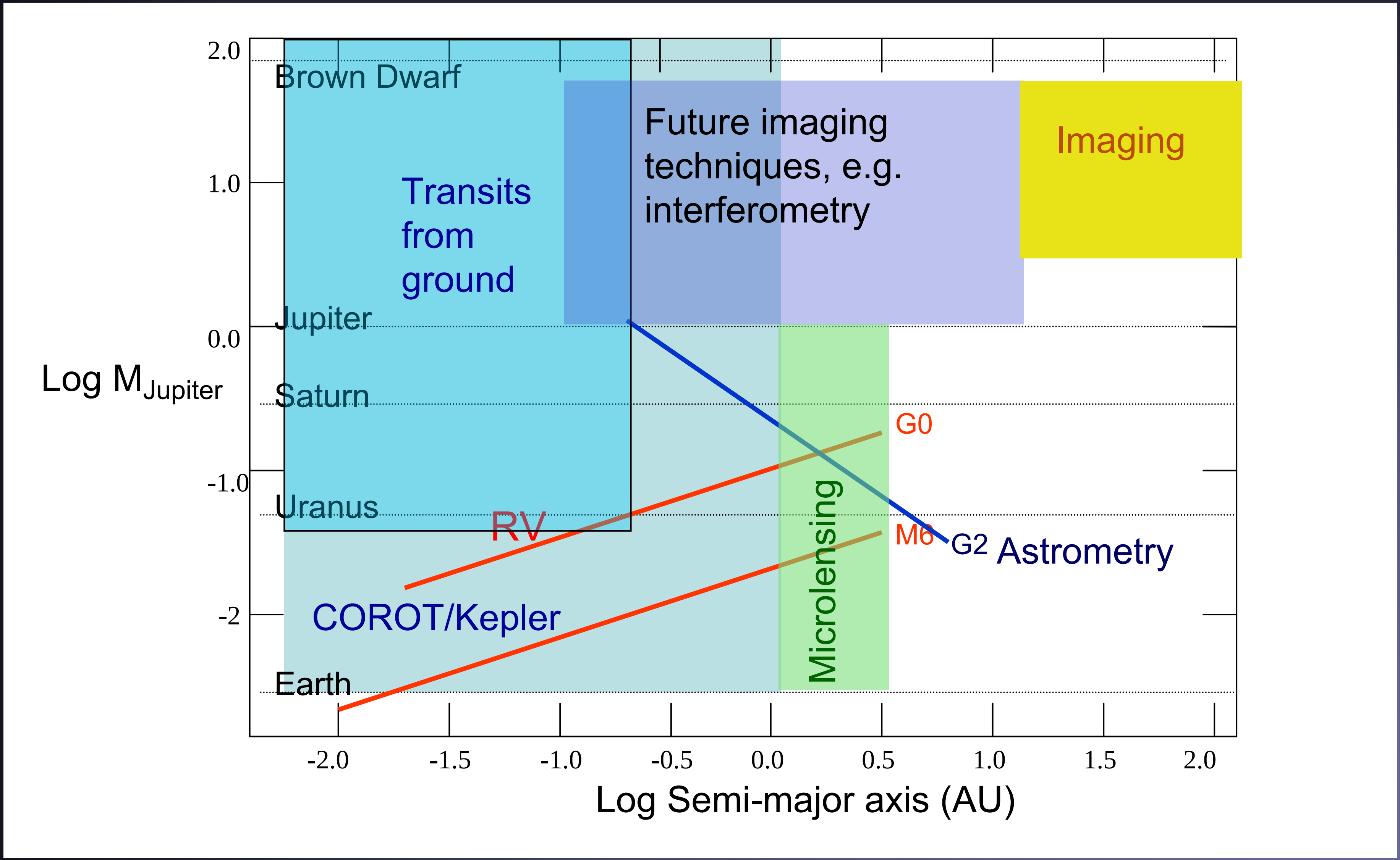
Companion:
6 mag fainter than star
separation ~ 0.7 arc sec
a ~ 100 AU
$M \sim 1\text{-}42\ M_J$

Star:
T Tauri star (K7eV)
$V \sim 11.4$, $L \sim 1.6\ L3$
$M \sim 0.7\ M_\odot$
distance 140+/-50 pc
age ~ 2 Mio years



(Neuhäuser et al. 2005)

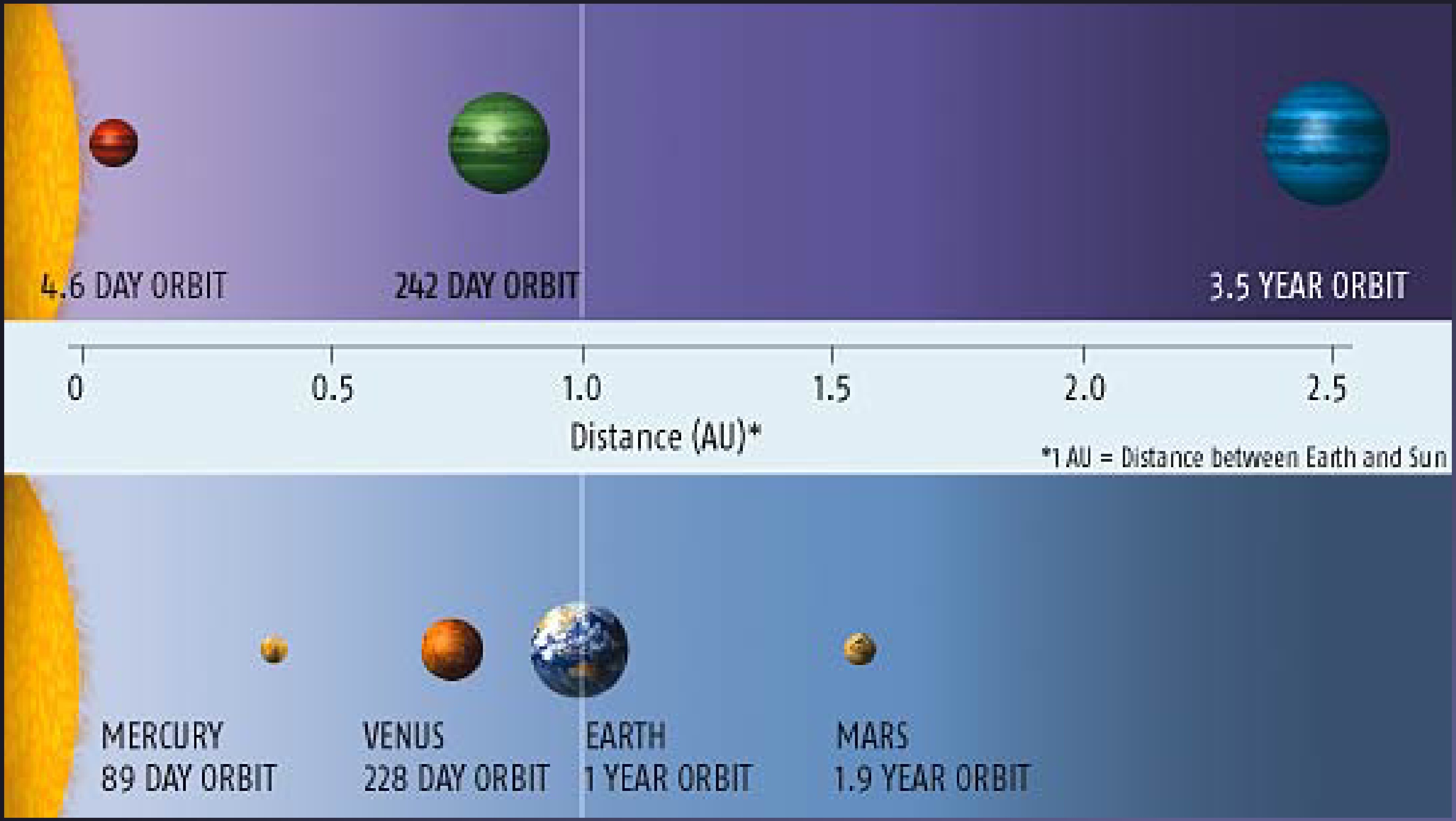
Detection ranges



Summary

Radial velocity method:	+ most effective method so far +/- only lower mass limits
Astrometry:	+ long-period planets - near stars
Transit method:	+ determines radius + in combination with RV: mass and mean density - needs follow-up confirmation
Microlensing:	+ low-mass planets detectable +/- statistical information
Direct imaging:	+ direct observation - only for distant planets

Ypsilon Andromedae



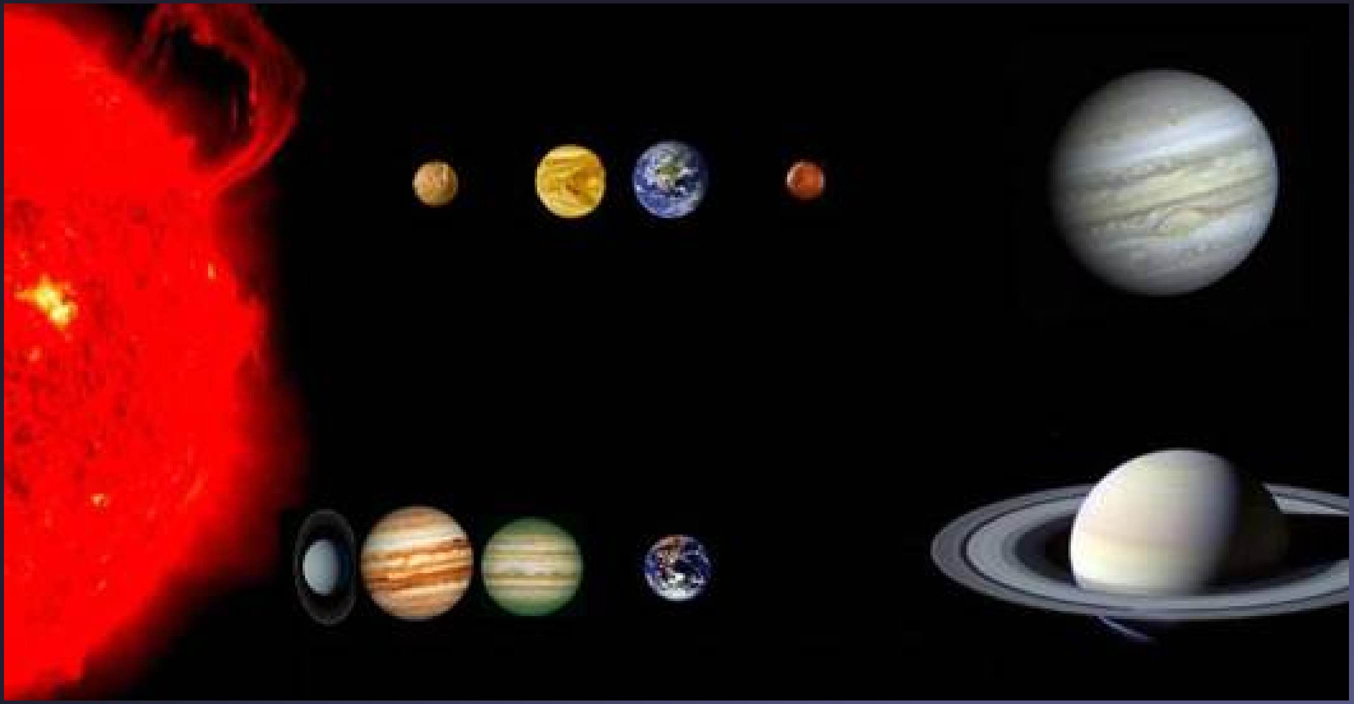
υ And: F8V, 1.27 $M_\odot$, 1.6 $R_\odot$, 6200 K, 3.8 Gyr, 13.5 pc

υ And b: 0.06 AU, 4.62 d, 0.69 M_J

υ And c: 0.83 AU, 242 d, 1.97 M_J

υ And d: 2.54 AU, 1290 d, 3.93 M_J

55 Cancri



55 Cnc: G8V, 0.95 $M_\odot$, 0.96 $R_\odot$, 5250 K, 4.5 Gyr, 12.5 pc

55 Cnc e: 0.038 AU, 2.82 d, 0.03 M_J

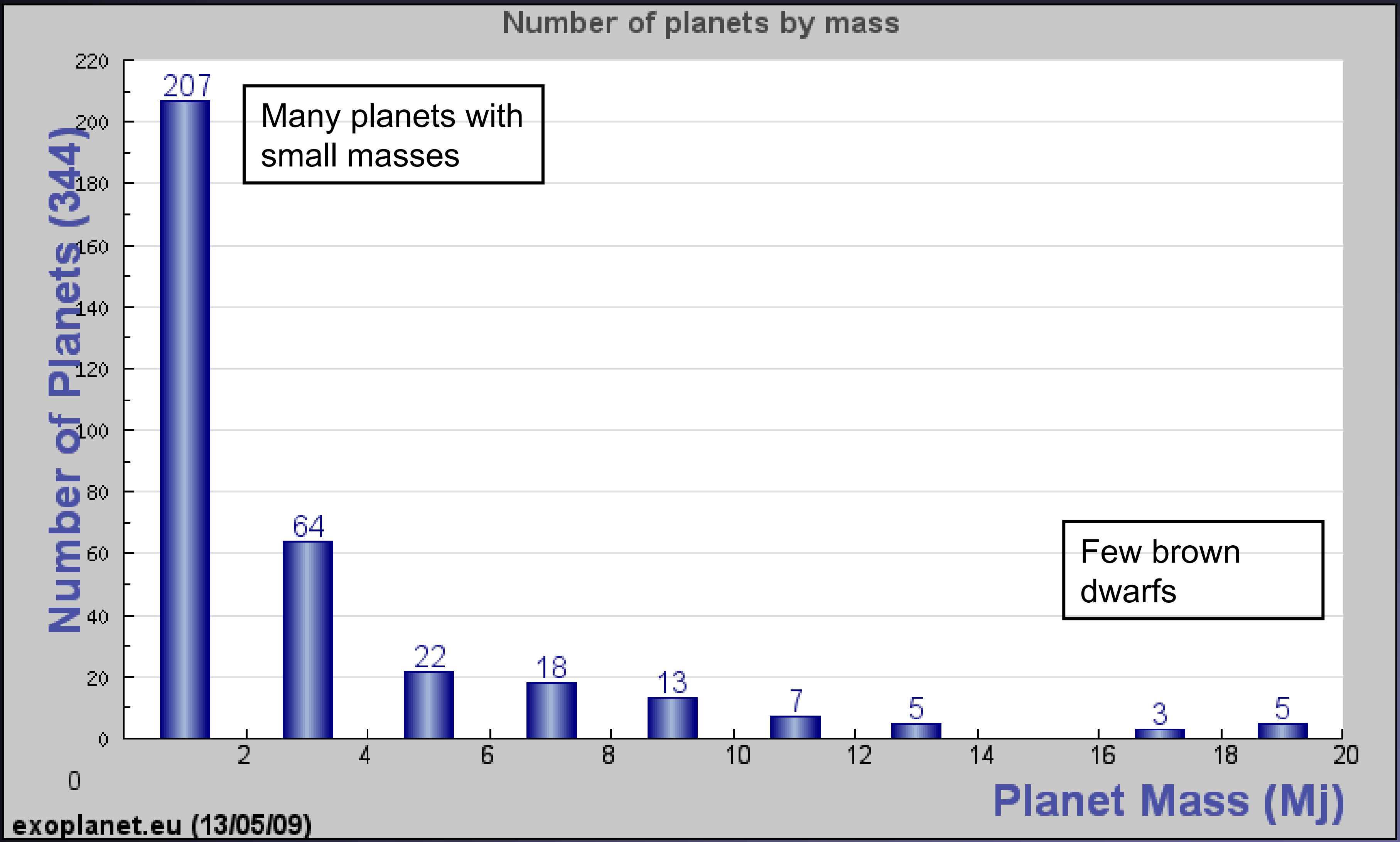
55 Cnc b: 0.115 AU, 14.6 d, 0.82 M_J

55 Cnc c: 0.240 AU, 43.9 d, 0.17 M_J

55 Cnc f: 0.781 AU, 260 d, 0.14 M_J

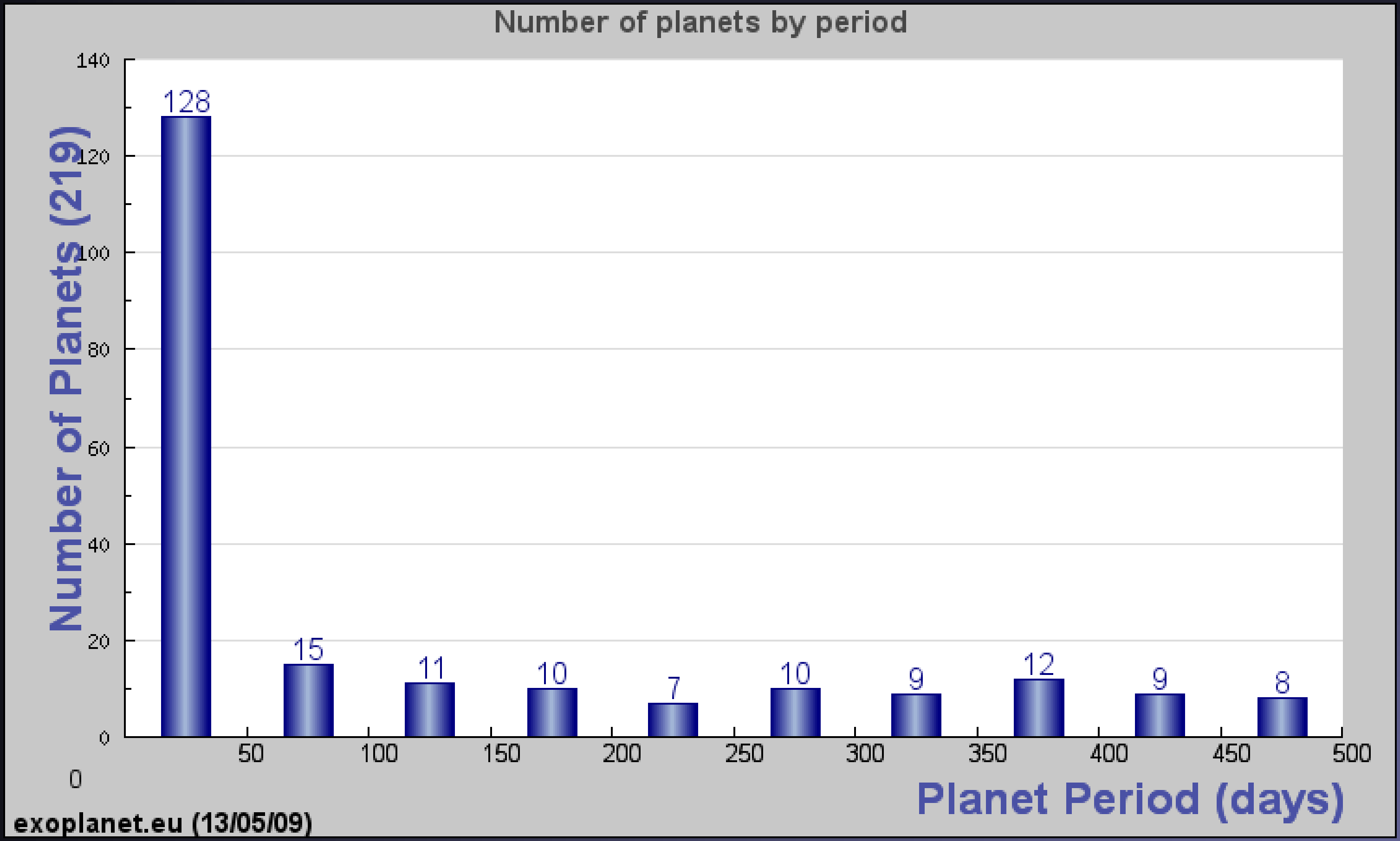
55 Cnc d: 5.77 AU, 5218 d, 3.84 M_J

Planet statistics



Most planets discovered are on short orbital periods

→ selection effect



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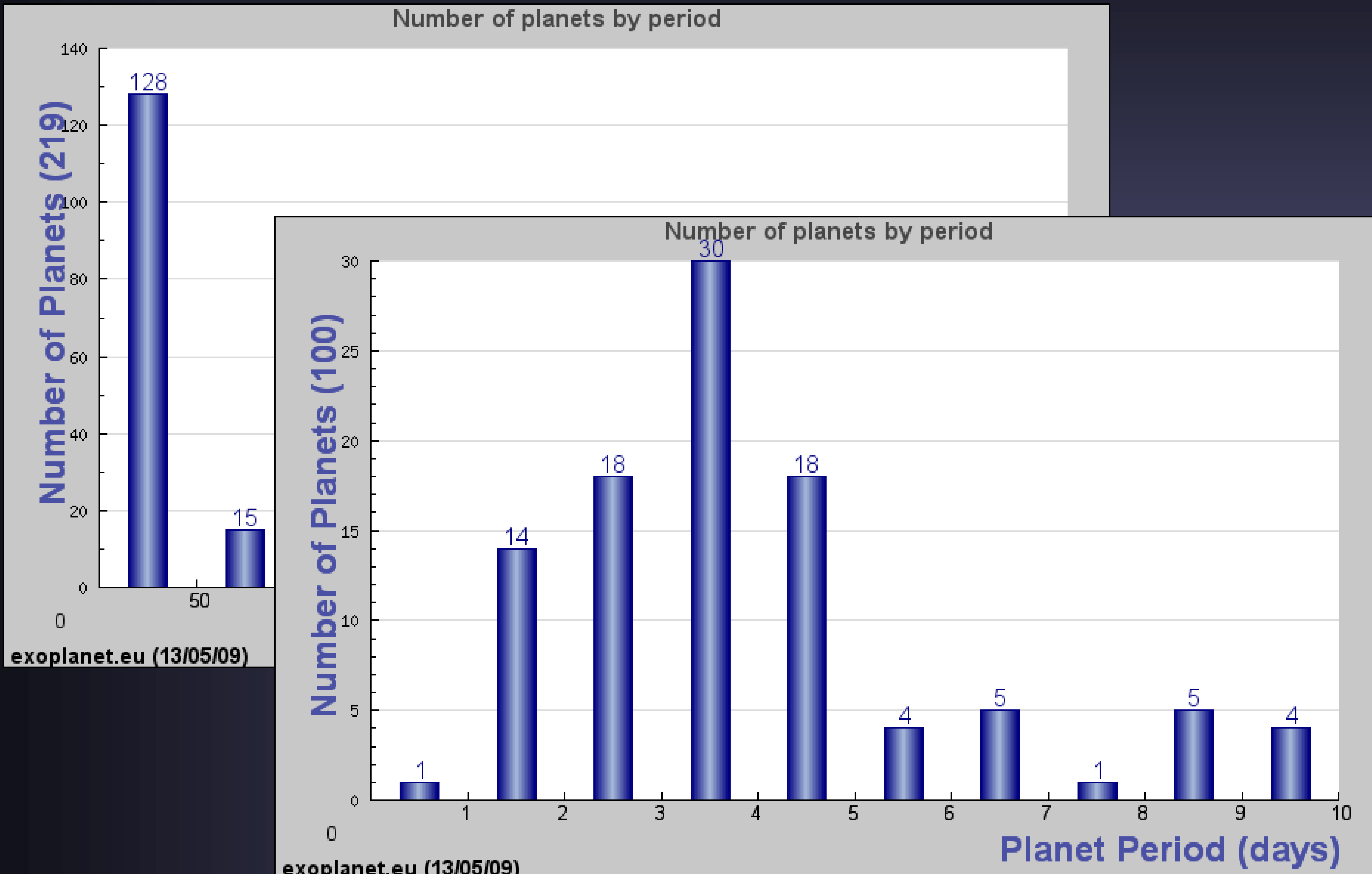
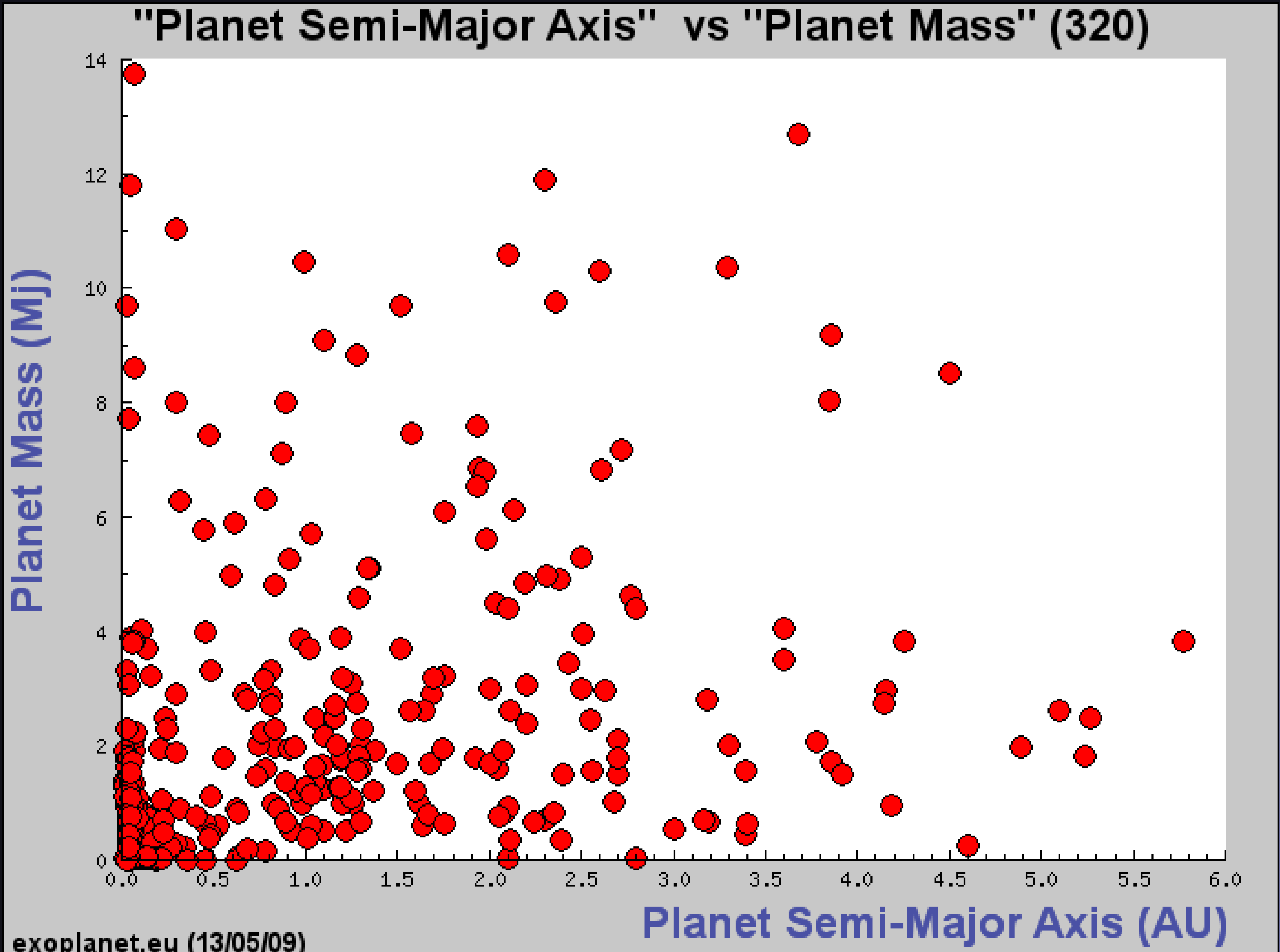
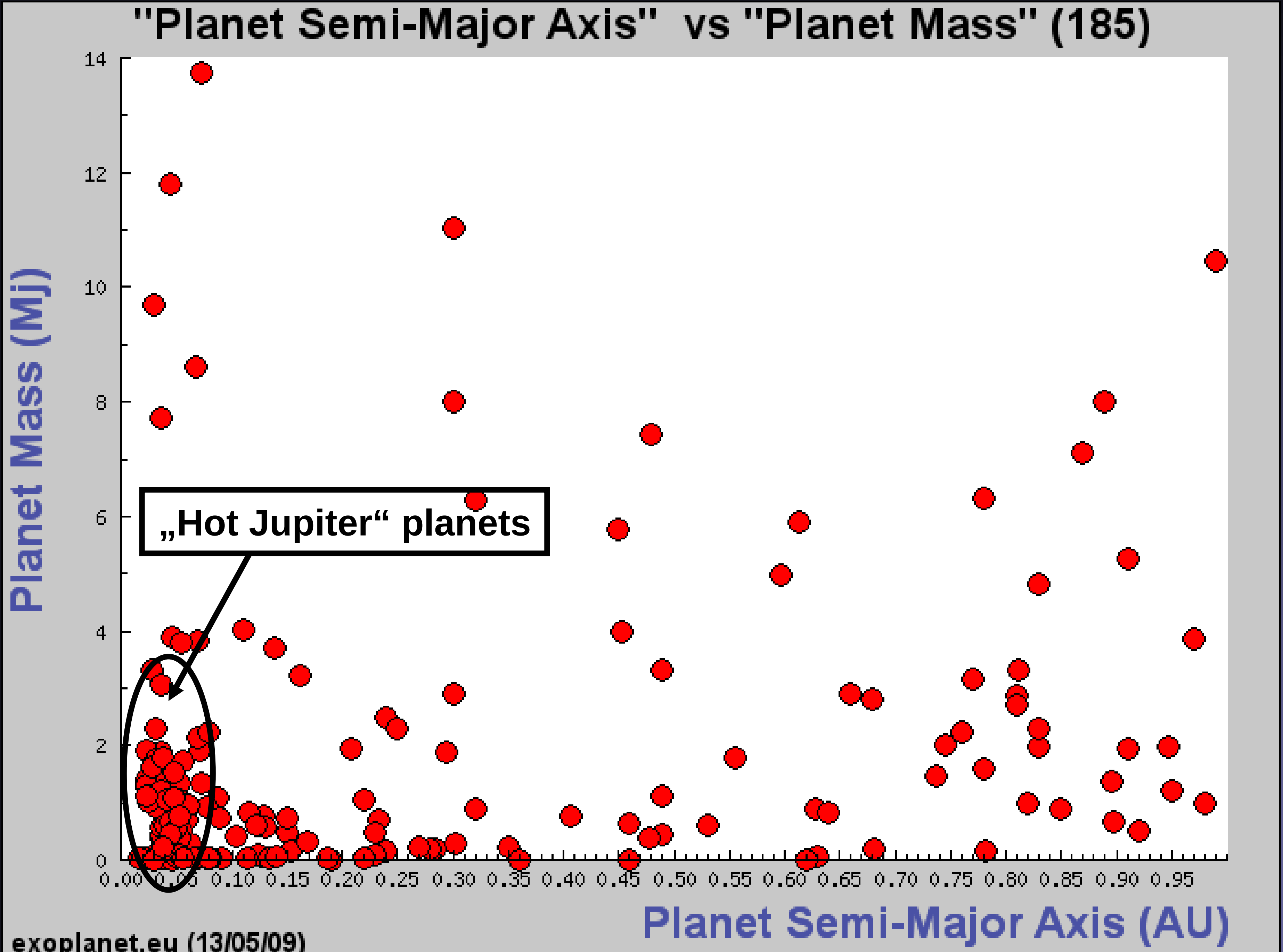
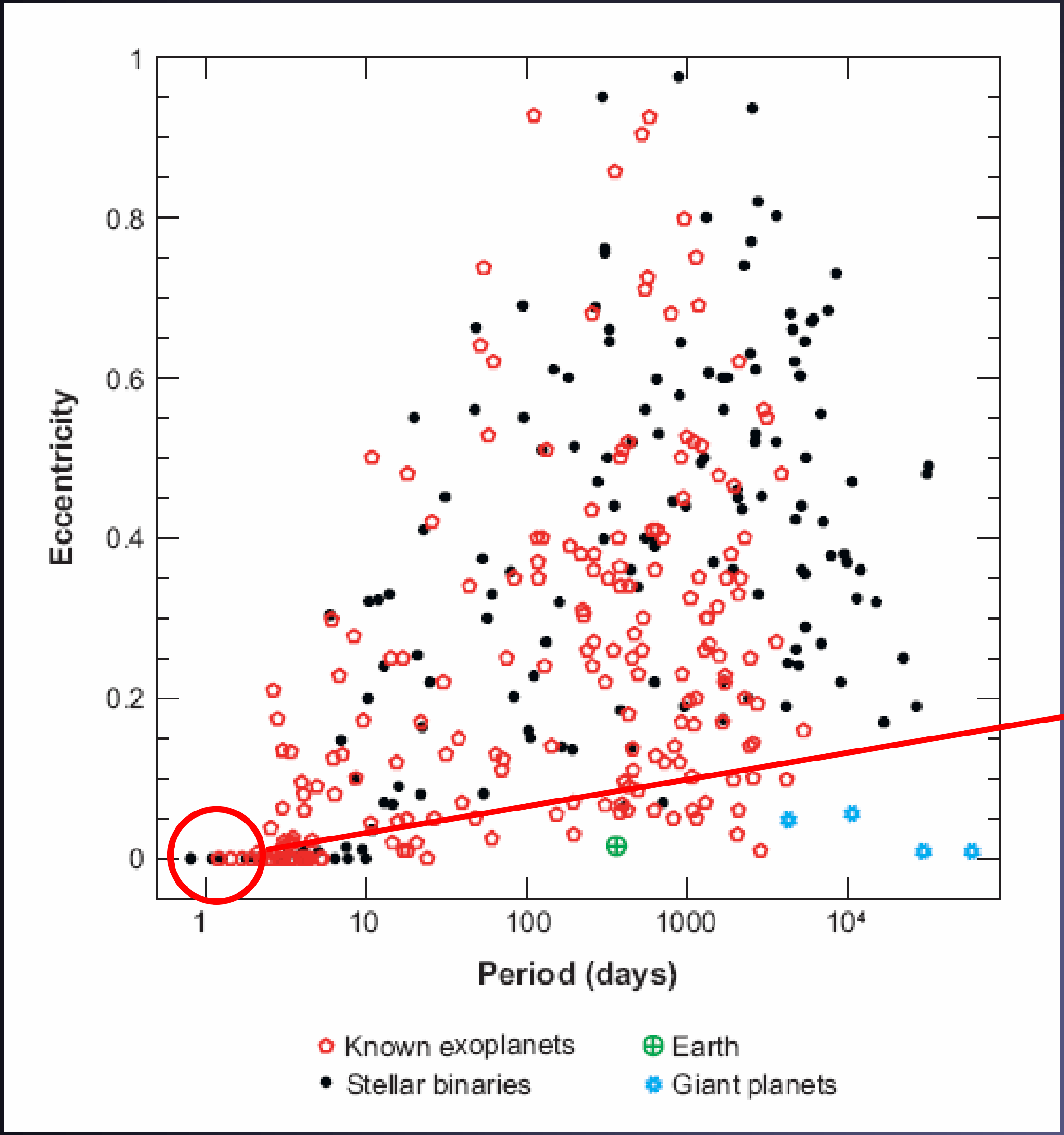



"Planet Semi-Major Axis" vs "Planet Mass" (320)
14
12
10
8
6
4
2
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
Planet Mass (Mj)
Planet Semi-Major Axis (AU)
exoplanet.eu (13/05/09)


"Planet Semi-Major Axis" vs "Planet Mass" (185)
Planet Mass (Mj)
Planet Semi-Major Axis (AU)
„Hot Jupiter“ planets
0 2 4 6 8 10 12 14
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95
exoplanet.eu (13/05/09)

Orbital eccentricity



Eccentricities roughly in the same range as for binary stars.

Close-in planets are on circularised orbits due to tidal interaction with their central star.

(Udry & Santos 2007)

Planet formation

in a nutshell

Molecular clouds in the ISM

cold, dense, H_2, molecules, ~50% of ISM

Gravitational collaps

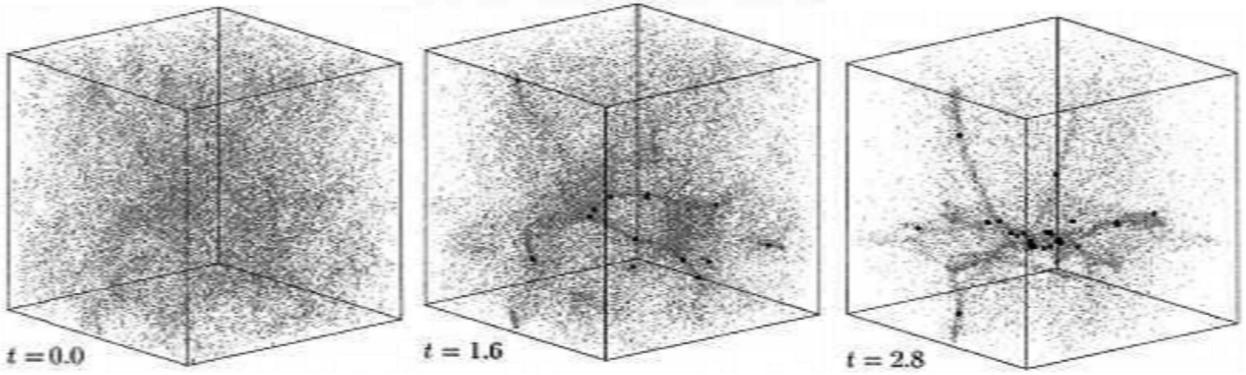


Fig. 2.— The gravitational fragmentation of molecular cloud is shown from a simulation containing initial structure (*Klessen et al.*, 1998). The gravitational collapse enhances this structure producing filaments which fragment to form individual stars. The time t is given in units of the free-fall time.

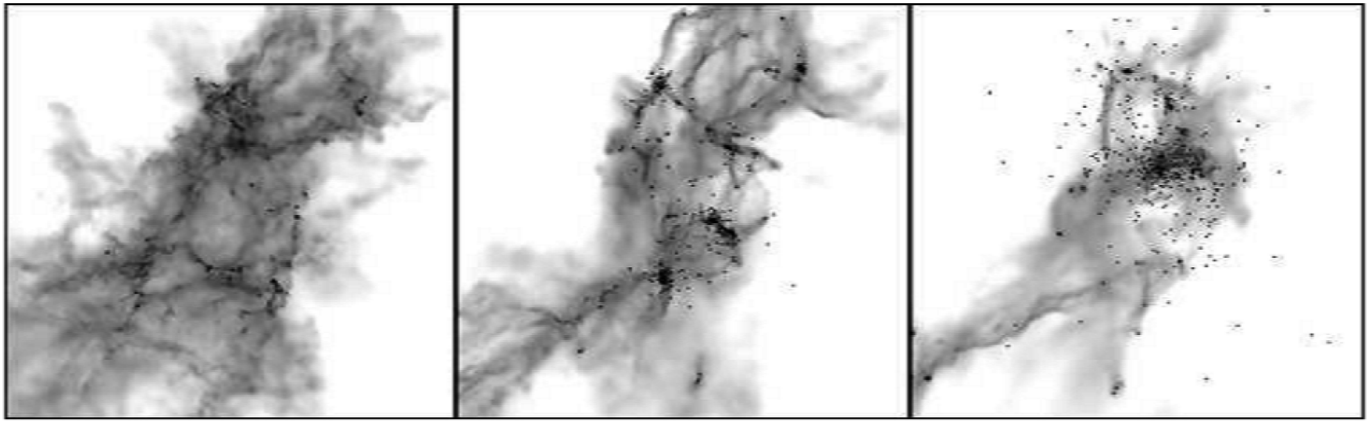
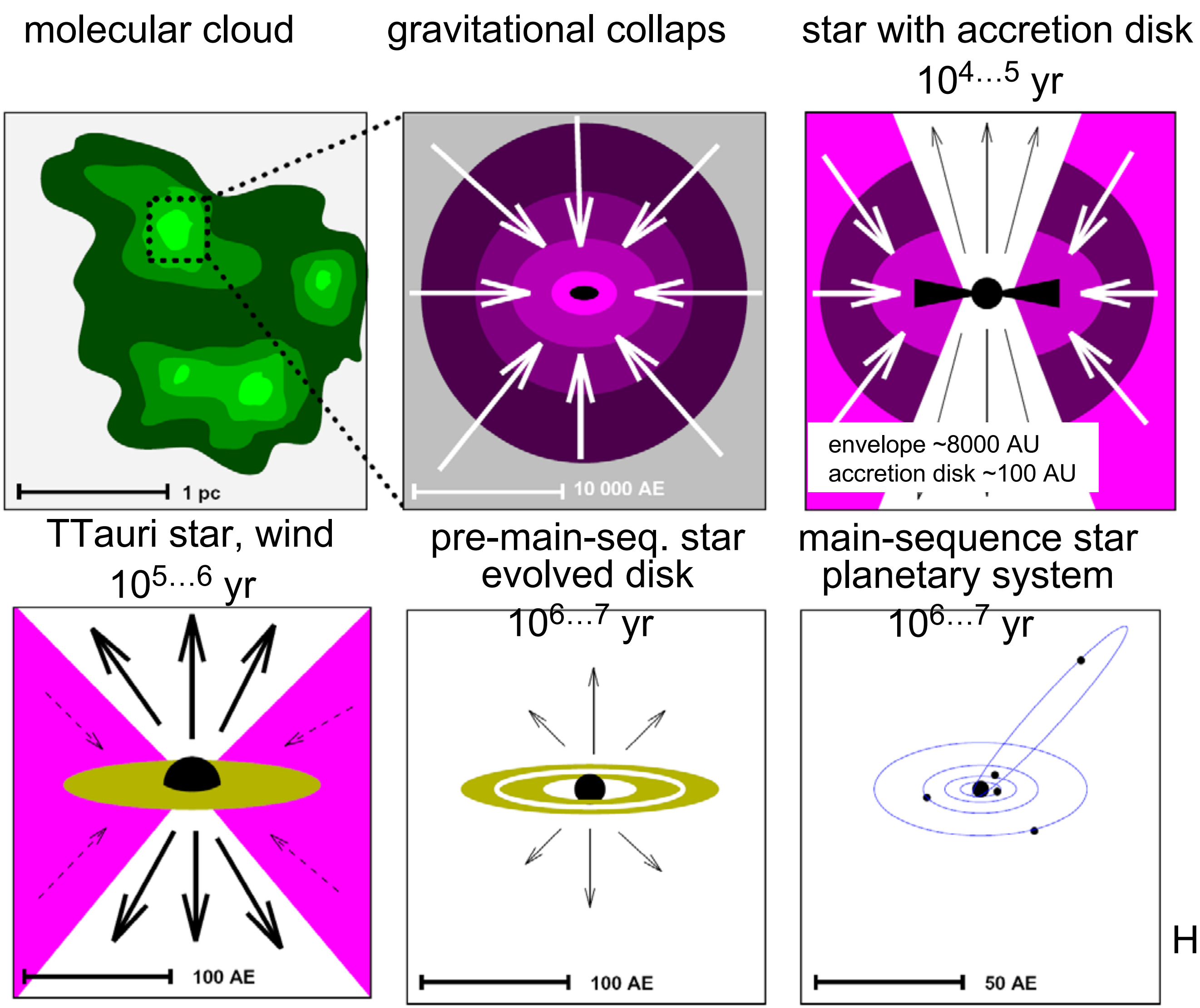


Fig. 8.— The fragmentation of a 1000 $M_\odot$ turbulent molecular cloud and the formation of a stellar cluster (*Bonnell et al.*, 2003). Note the merging of the smaller subclusters to a single big cluster.

Jeans mass, trigger, cloud fragmentation, star formation in cluster

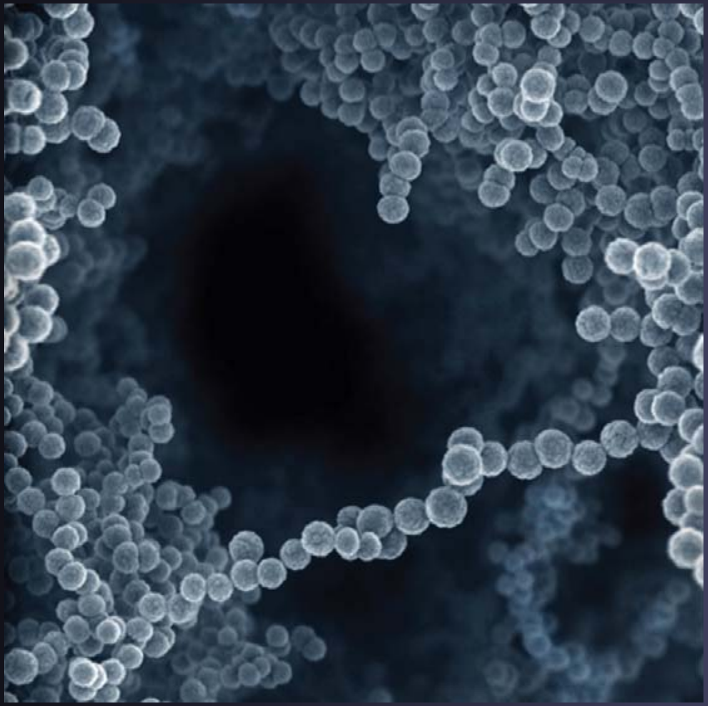
Circumstellar / protoplanetary disk

angular momentum conservation



Hogerheijde 2001
Kley 2008

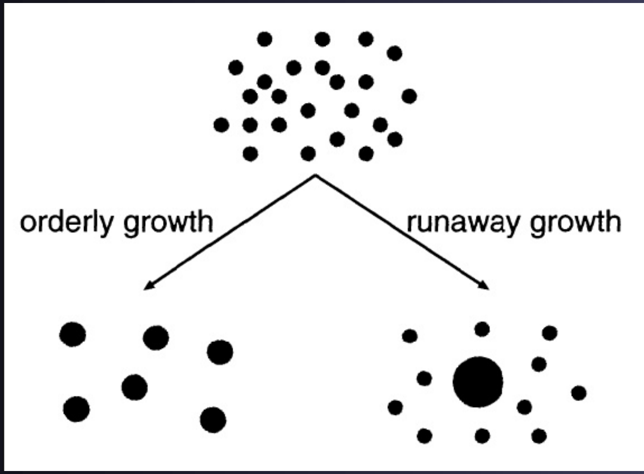
Condensation, dust agglomeration, formation of planitesimals

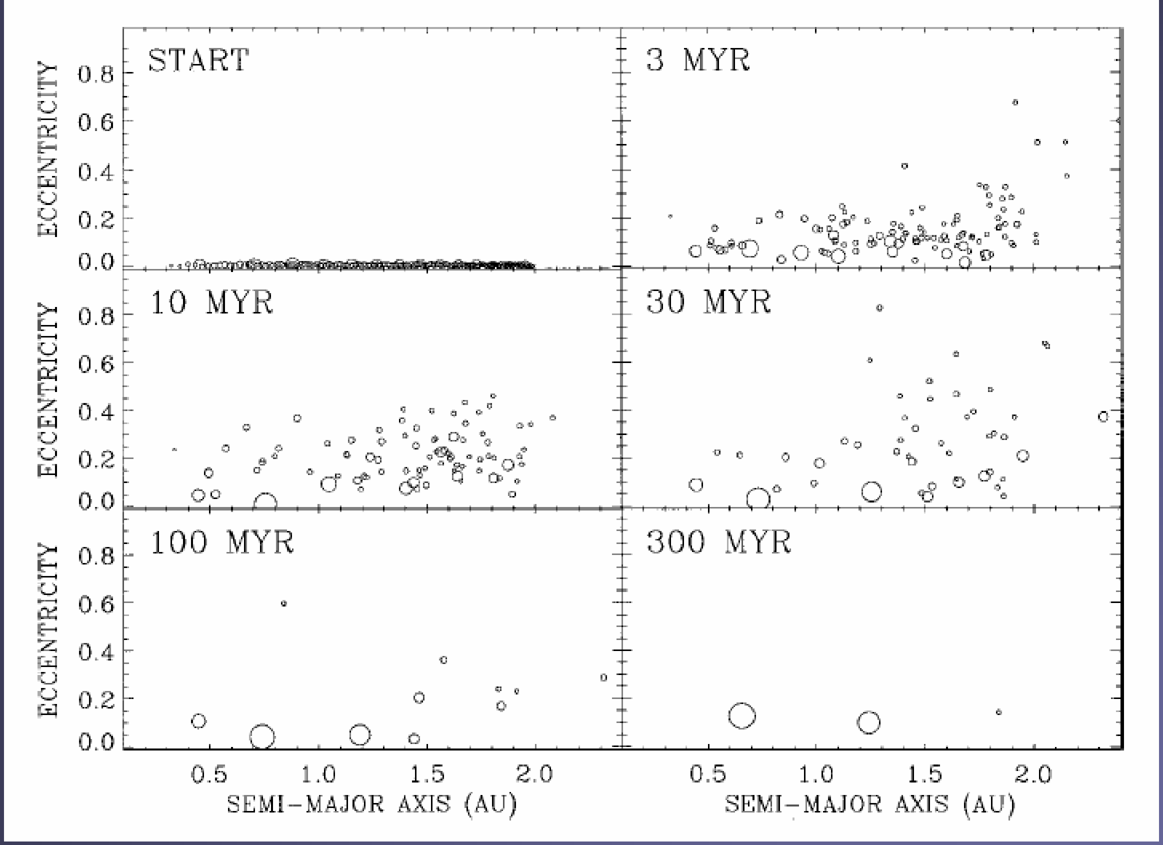


- Condensation of molecules: gas to solid, 1 μm, some 1000 yr
- Agglomeration / coagulation of dust: 10 cm, takes longer further out, frost line at 5 AU: ice
- Planitesimals: 10 km, meter-size barrier

Formation of terrestrial planets

planitesimals of ~10km – gravitational focusing – collisions – fragmentation of smaller body – accretion of fragments – larger and fewer bodies – runaway growth – oligarchic growth – ends when reservoir exhausted





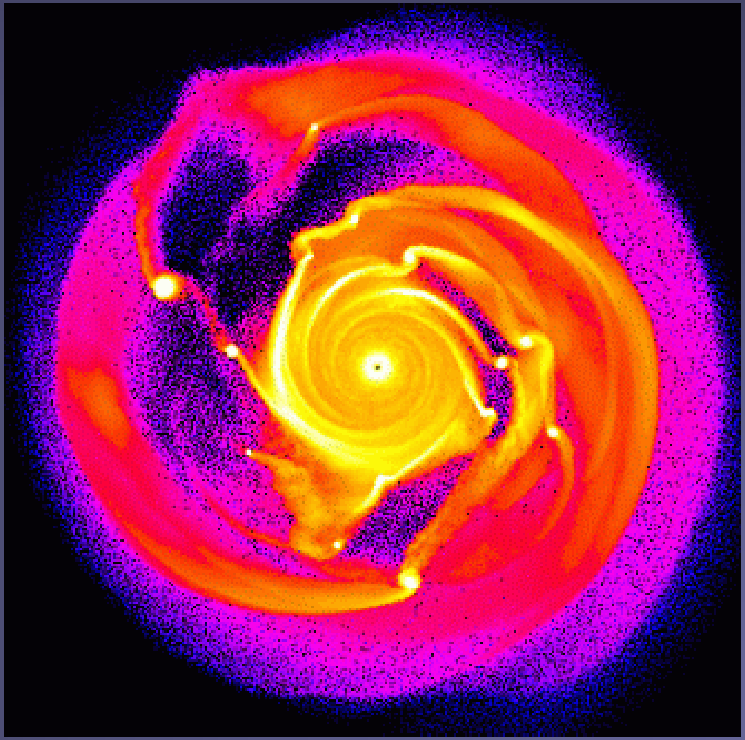
Formation of gasplanets

Core accretion model

- large planetary embryo of ~10M_E
- fast accretion of gas (H_2, He, …)
- time scale:
  Jupiter: 0.5 Myr
  Saturn: 2 Myr
  Uranus: 10 Myr
  Neptune: 30 Myr
- end of growth:
  - stellar wind (TTauri phase)
  - evaporation of disk

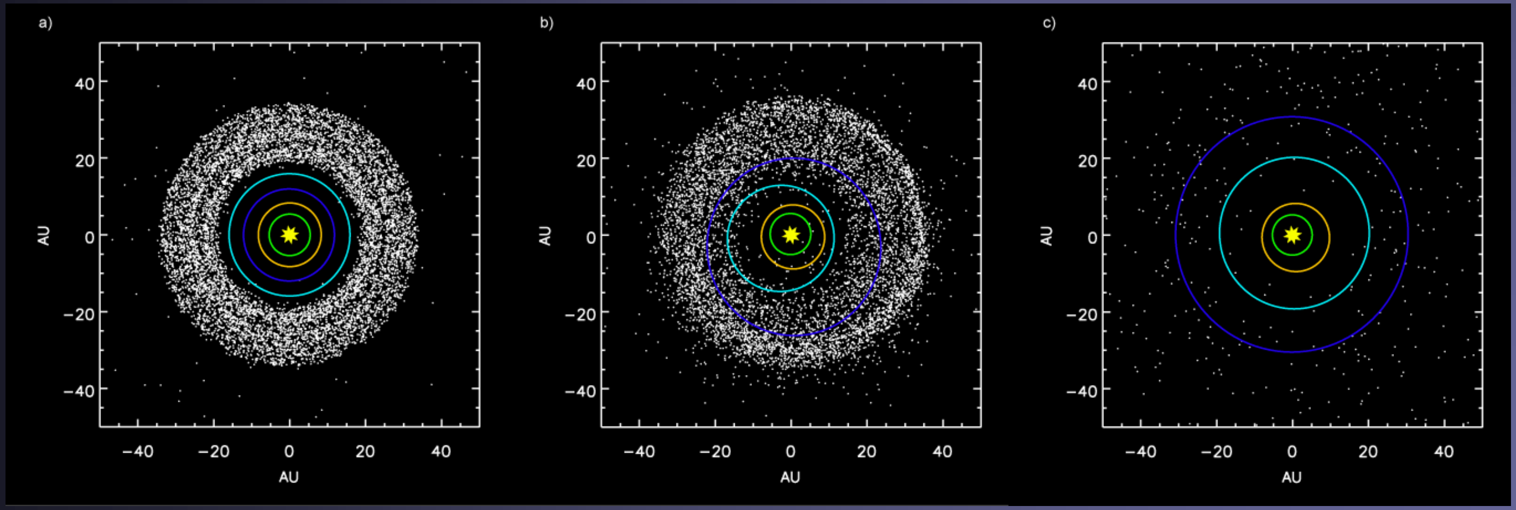
Gravitational instability model

- gravitational instability of knots in mass-rich disks



Planetary migration

- change of orbital radius (i.e. semimajor axis) of a planet in time
- still controversial, supported by Kuiper Belt Objects, Hot Jupiters, atmos. composition of Jupiter
- caused by interaction of planet with gas or planetary disk
- Type I migration: planet – spiral density wave in disk – imbalance inside and outside the orbit – net torque inward – loss of angular momentum – inward migration
- Type II migration: large planets – clear gap in disk – gas from disk enters gap – moves planet and gap inward



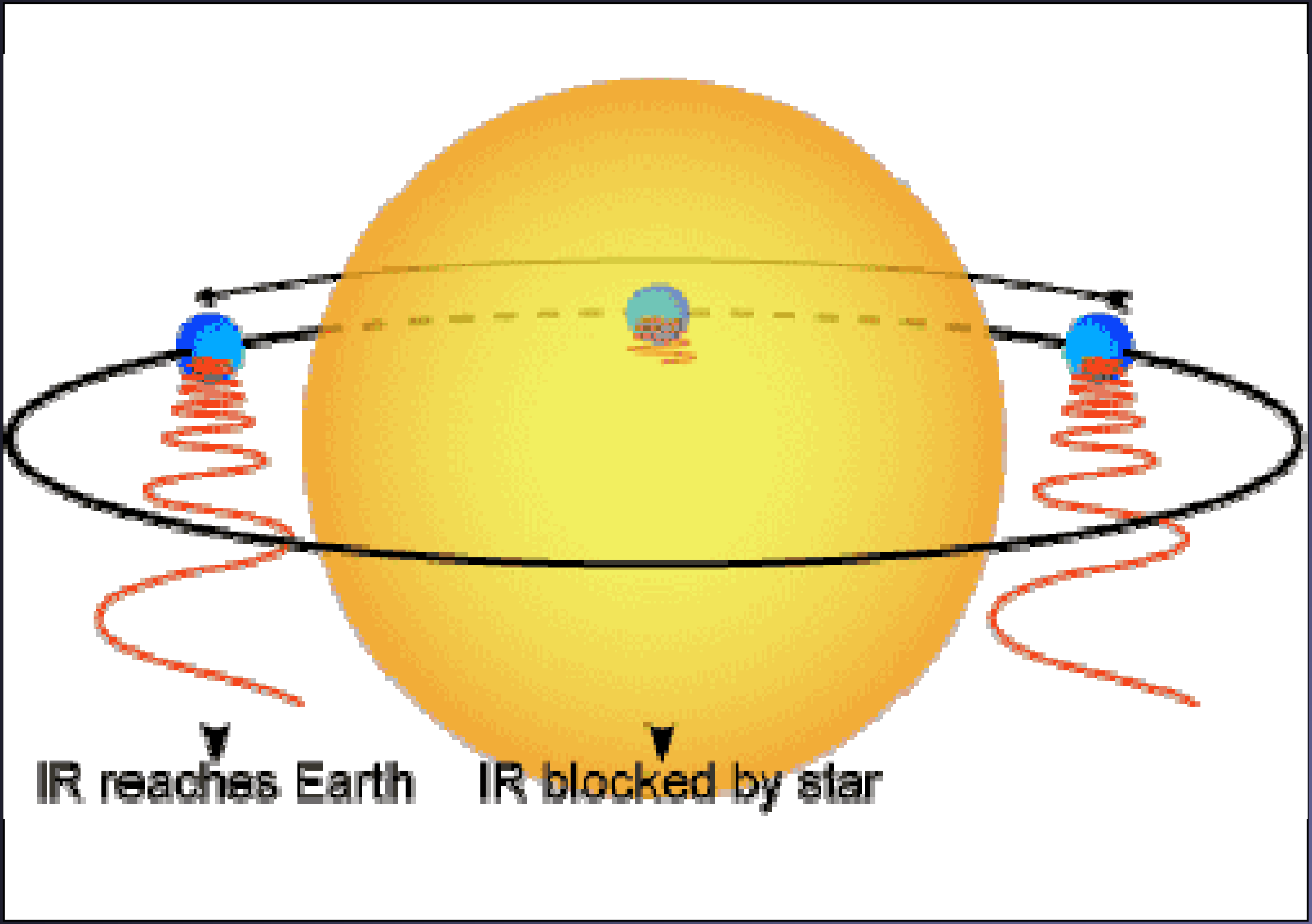
Physical properties

- relatively little known

- observation of „hot Jupiters“ with HST and Spitzer during transits:
    - determination of effective temperature
    - chemical composition of atmosphere

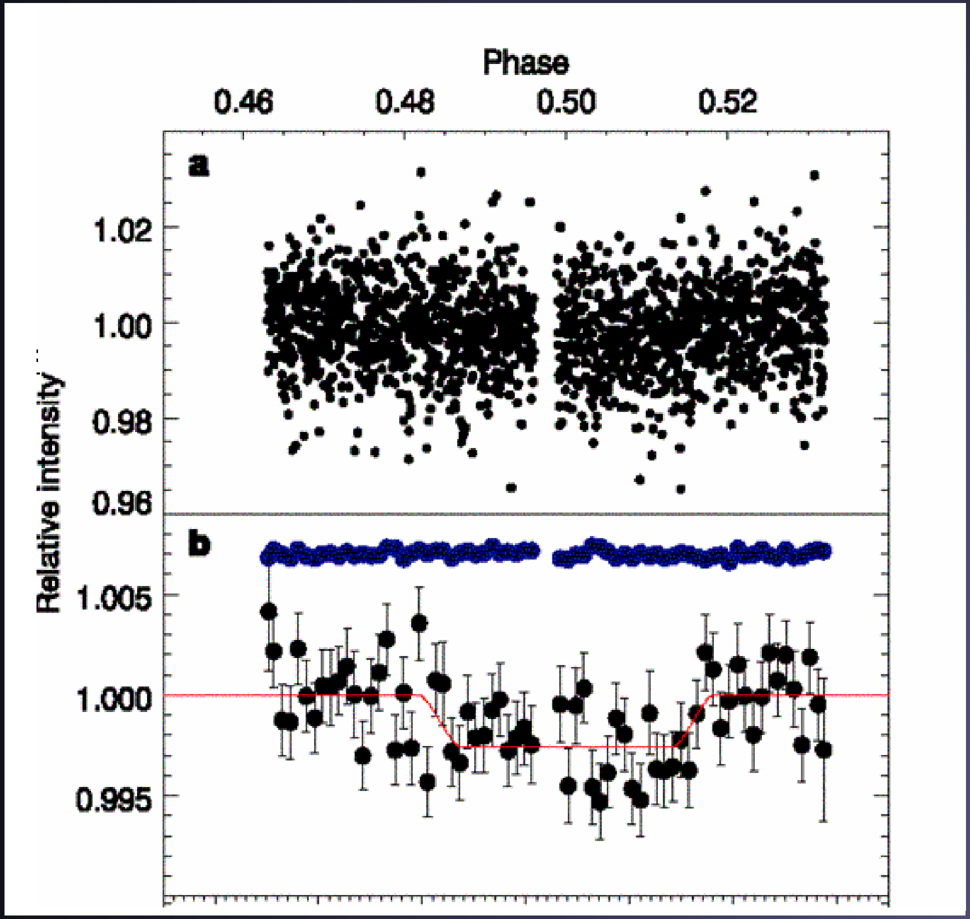
- theoretical studies:
    - planetary formation
    - interior structure
    - atmosphere
    - magnetosphere and plasma interaction with stellar wind and magnetic field
    - ...

Measurement of temperature



during the secondary transit at infrared wavelengths

Secondary transit of HD 209458 b



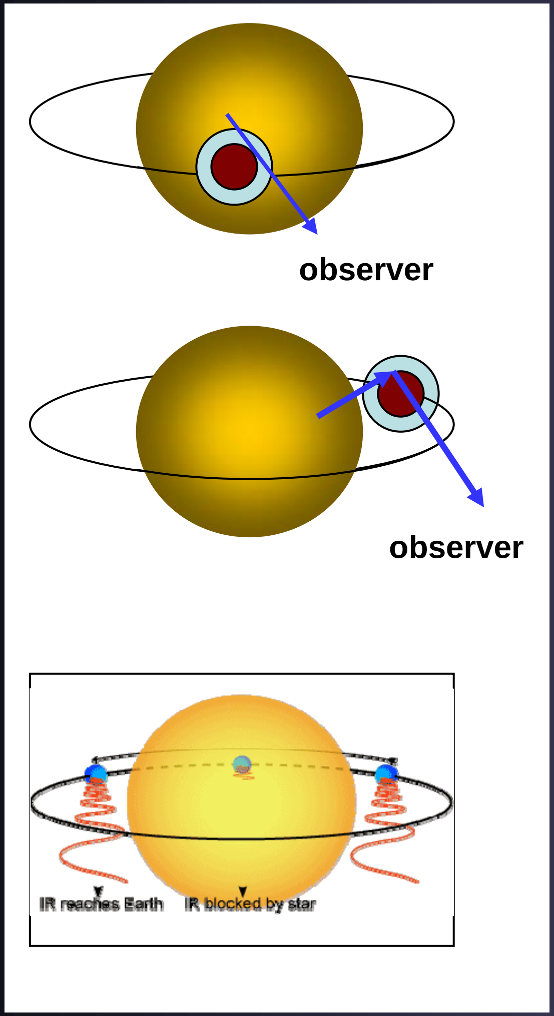
24 micron (Deming et al. 2005)

- orbital period = 3.52 days
- radius = 1.3 R_J
- mass = 0.63 M_J
- density = 0.3 – 0.5 g cm^{-3}
- T_{eff} = 1130 +/- 150 K

- in comparison: Jupiter T_{eff} = 124 K

- heating due to small orbital distance of the planet

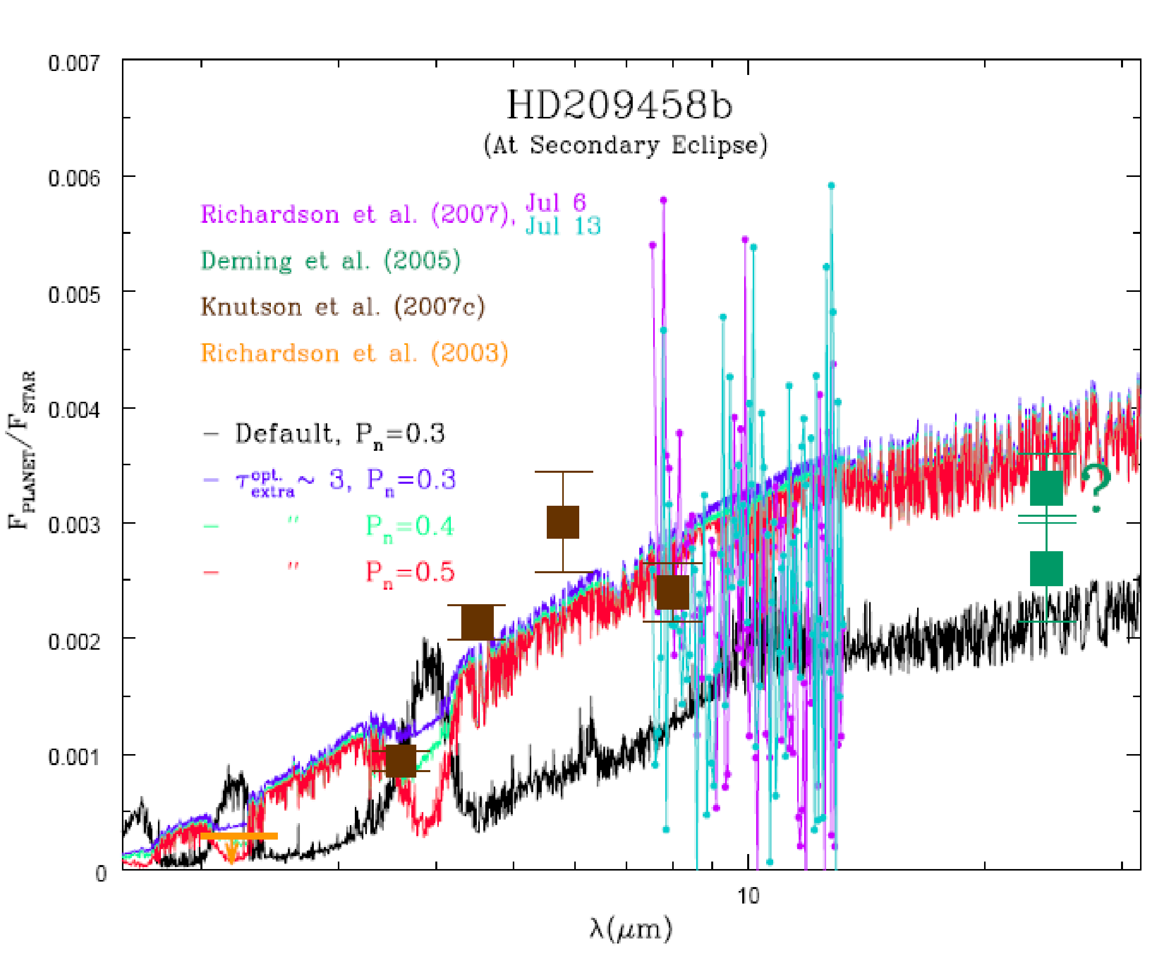
Measurement of atmospheric composition



- Measure stellar light passing through the planetary atmosphere during transit configuration
- Measure stellar light reflected or scattered from the planetary atmosphere
- Measure the infrared radiation emitted by the planetary atmosphere

Water vapour in the atmosphere of HD 209458 b ?

Spectroscopy of the starlight reflected by the planet with the Spitzer IR satellite

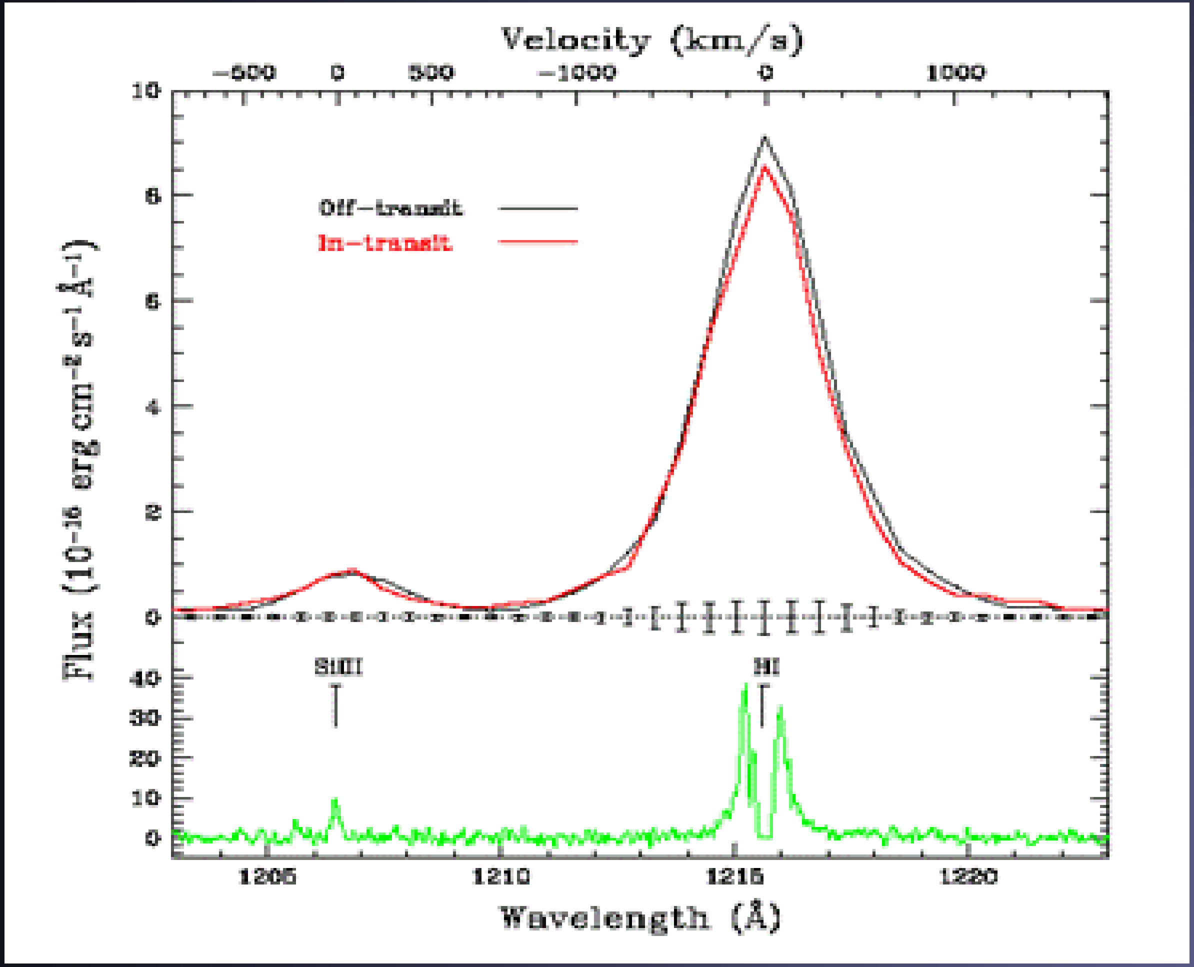


Modelled spectra

(Burrows et al. 2007)

H, O, C and Na in the atmosphere of HD 209458 b

Spectroscopy at optical and ultraviolet wavelengths during a transit (with the HST)



(Charbonneau 2002,
Desert 2003,
Vidal-Madjar et al. 2004)

Habitability

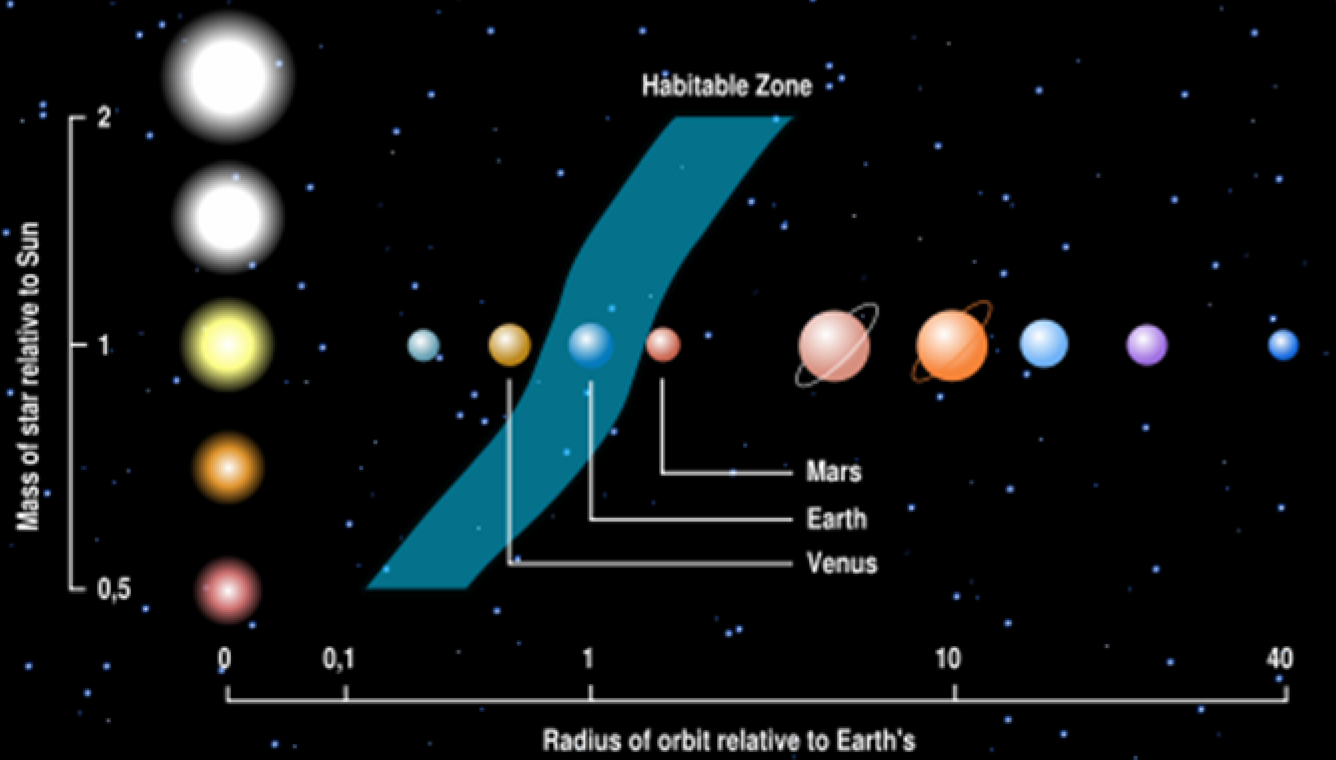
Potential of a planet to develop and sustain life

Absolute requirements:

- energy source
- liquid water on surface
- environment favourable for the assembly of complex organic molecules

Habitable zone

Orbital distance region around a star where an Earth-like planet can maintain liquid water on its surface



Habitable zone depends on luminosity of star

- inner boundary: runaway greenhouse effect, loss of water to space
- outer boundary: dependent on amount of greenhouse gases (CO_2 and H_2O)

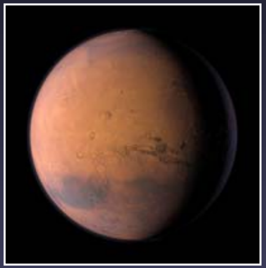
Constraints on star

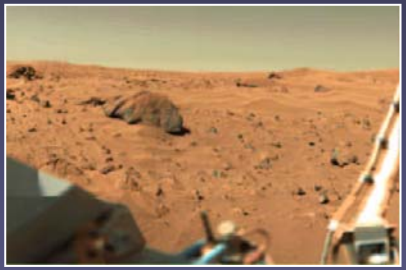
- main sequence star, spectral type F - K
    - sufficient long stellar life
    - UV radiation for atmospheric dynamics and chemistry
    - habitable zone at distances outside tidal locking,
      no good news for M stars
- stability of habitable zone
    - slow stellar evolution
    - no gas giants close to habitable zone
- low stellar variability, red dwarf often very active
- high metallicity favours planet formation

Constraints on planet

- terrestrial
- sufficient mass
    - for thick atmosphere
    - for hot core and geological activity
    - for iron core, dynamo, magnetic protection from stellar wind and cosmic rays
- small orbital eccentricity, moderate rotation, moderate tilt of rotation axis because of seasons
- chemistry: C, H, O, N — amino acids
- satellites of gas giants

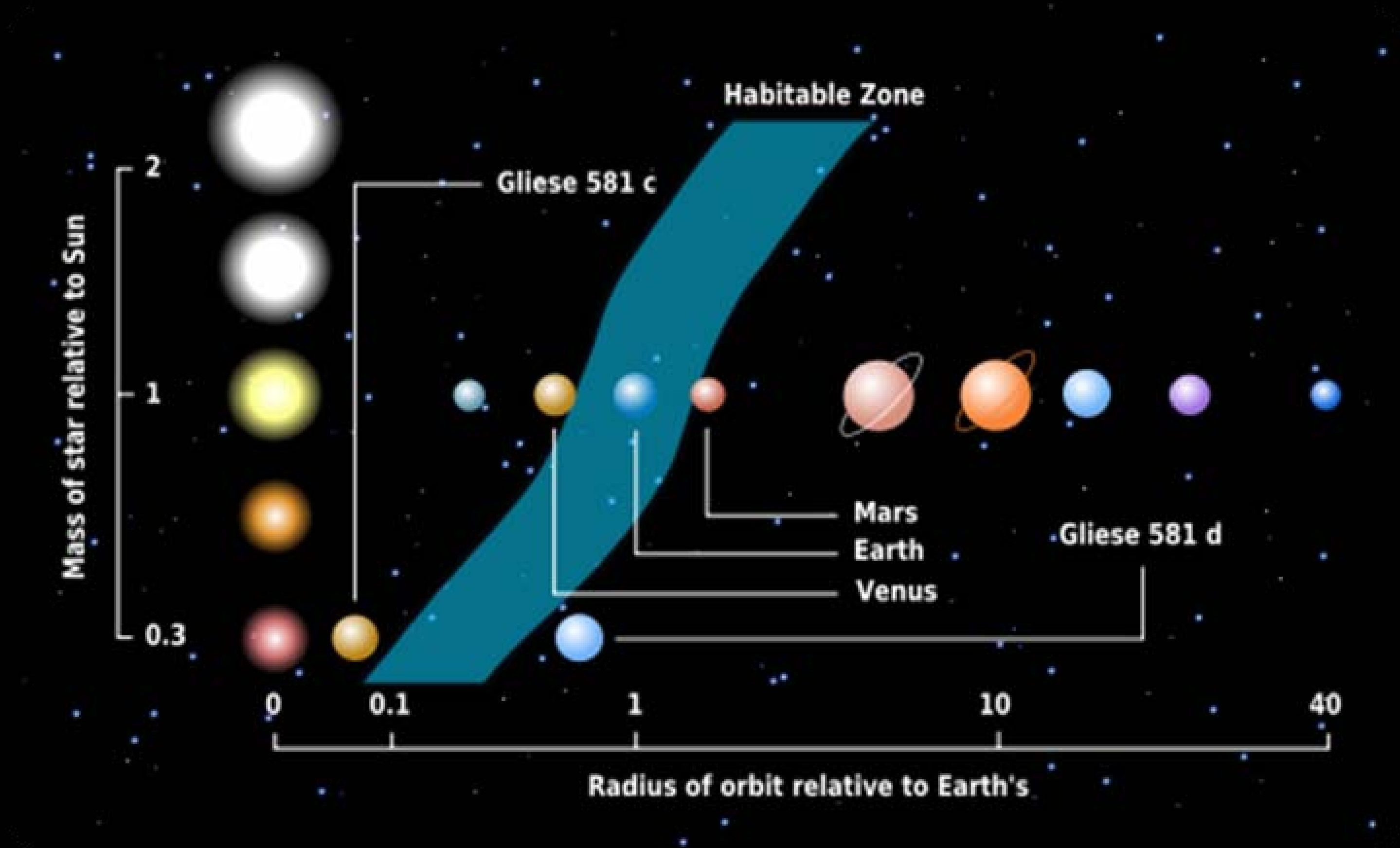
Venus – Earth – Mars





Venus	Earth	Mars
T = 457°C	**T = 15°C**	**T = - 80°C**
p = 90 bar	**p = 1 bar**	**p = 0.007 bar**
Atmosphere:	Atmosphere:	Atmosphere:
96 % CO_2	77 % N_2	95 % CO_2
3,5 % N_2	21 % O_2	2,7 % N_2
	1 % H_2O	
runaway greenhouse		global fridge

Gliese 581 c,d,e



Gliese 581: M3V, 0.31 $M_{\odot}$, 6.3 pc

Gliese 581 c: 0.073 AU, 12.9 d, 5 M_E

Gliese 581 d: 0.22 AU, 67 d, 7.1 M_E

Gliese 581 e: 0.03 AU, 3.15 d, 1.9 M_E

Future missions

2006 — **CoRoT** (CNES)

Transits:
„Hot" Earths

2009 — **Kepler** (NASA)

Transits:
Earth-like planets

2012 — **Gaia** (ESA)

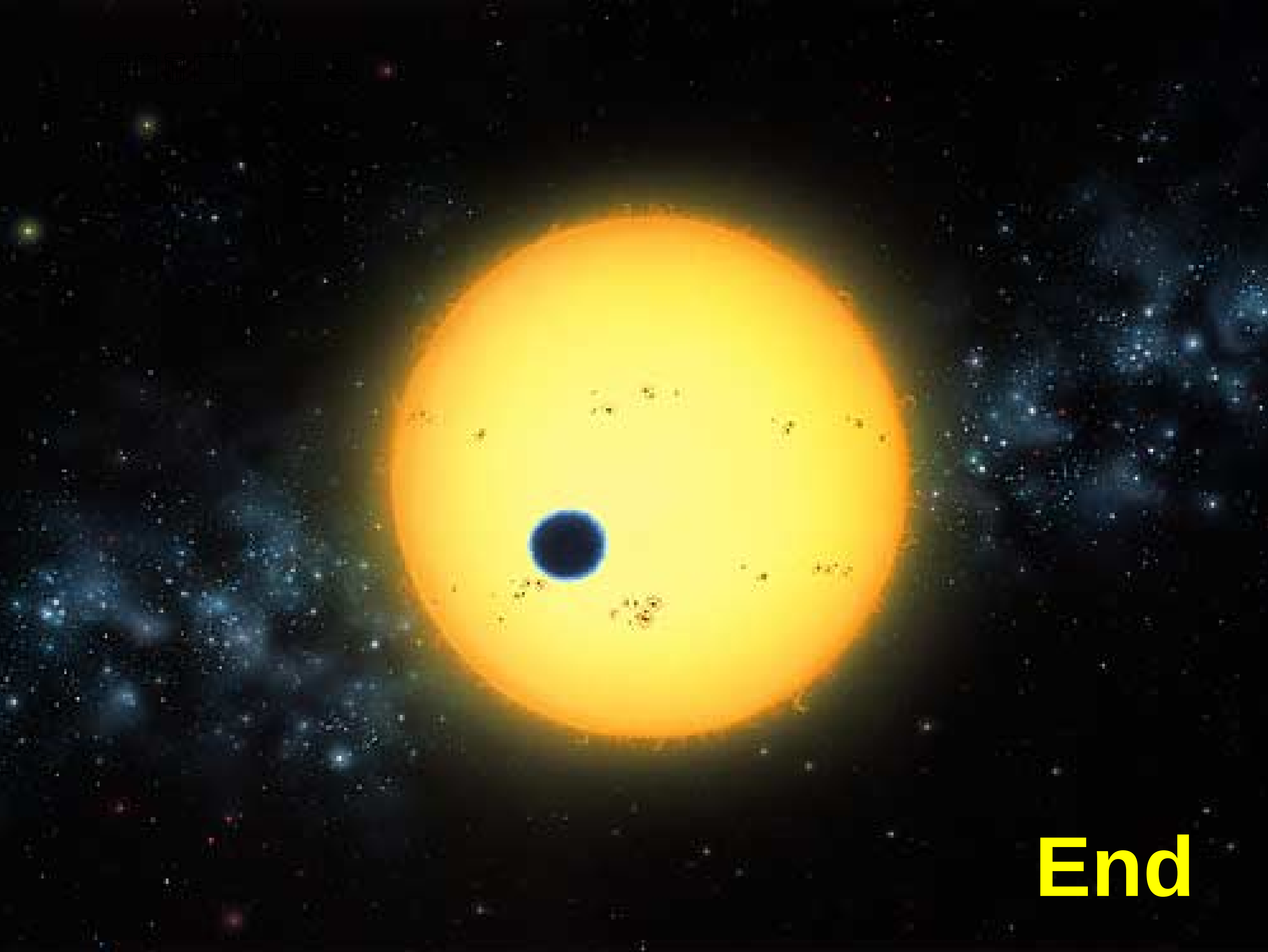
Astrometry:
Statistics of gas giants

2017 — **Plato?** (ESA)

Transits:
Earth-like planets

2020+ — **Darwin?** (ESA)

Direct imaging:
Search for biomarkers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