EXOPLANETS – frontiers of modern planetology

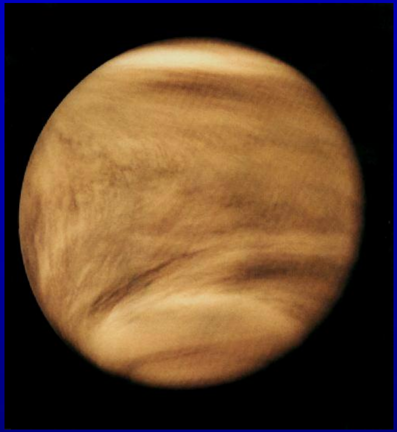
Maxim Khodachenko

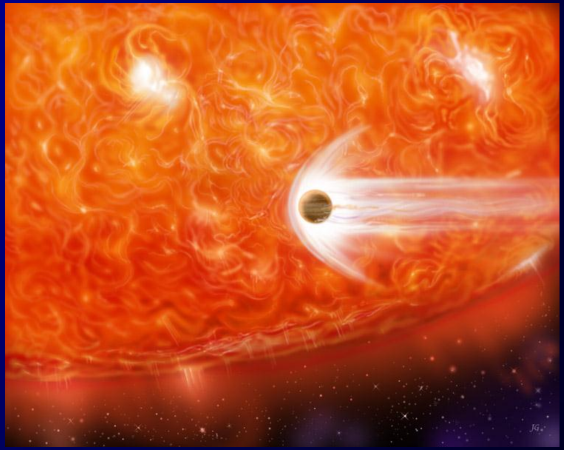
Institut für Weltraumforschung, Österreichische Akademie der Wissenschaften, Schmiedlstr. 6, A-8042 Graz.

E-mail: maxim.khodachenko@oeaw.ac.at

CONTENT of the lecture

- Planet definition. What are the planets?
- Exoplanet definition
- Exoplanet search methods
- Some intriguing features of exoplanets orbital distribution

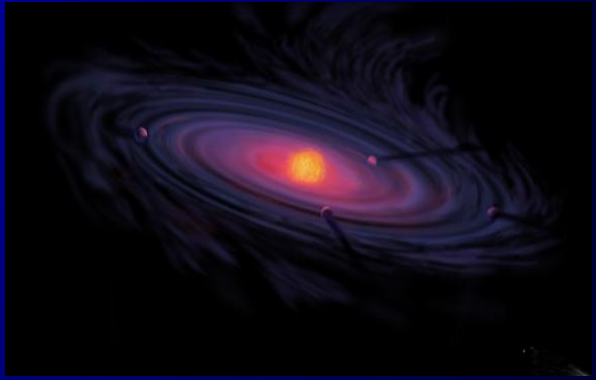





General definition (by IAU = Intrnational Astronomical Union, 2006)

- A **planet** (from Greek πλανήτης, a derivative of the word πλάνης = "moving") is a celestial body, which
  - (a) orbits a star or stellar remnant;
  - (b) is massive enough to be rounded by its own gravity (hydrostatic equil.);
  - (c) is not too massive to cause thermonuclear fusion ($M < 13\ M_{\mathbf{Jupiter}}$);
  - (d) has cleared its neigbouring region of **planetesimals**.

- A **planetesimals** -- solid objects, arising during accumulation of planets in protoplanetary disks
  (a) are kept by self-gravity;
  (b) orbital motion is not much affected by gas drag.



Planetesimals in the solar nebula:

- objects larger than ~ 1 km (can attract gravitationally other bodies)
- most were ejected from the Solar system, or collided with larger planets
- a few may have been captured as moons (e.g., Phobos, Deimos and small moons of giant planets).
- Sometimes Planetesimals = small solar system bodies, e.g. asteroids, comets

General definition (by IAU = Intrnational Astronomical Union, 2006)

- orbiting the Sun,
- sufficient mass for hydrostatic equilibrium (~ round shape)
- ~~has „cleared neighbourhood" around its orbit.~~

⇒ **Dwarf Planet**

- orbiting the Sun,
- ~~sufficient mass for hydrostatic equilibrium (~ round shape)~~
- ~~has „cleared neighbourhood" around its orbit.~~

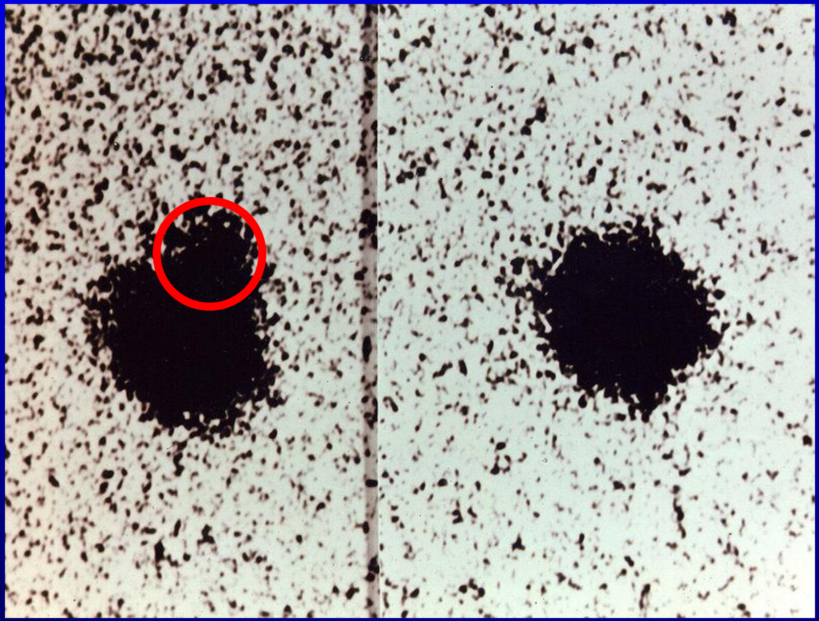
⇒ **Small solar system body (SSSB)**

General definition (by IAU = Intrnational Astronomical Union, 2006)

- Reasons for the new definitions (Planet / Dwarf planet / SSSB):

  (a) discovery of Pluto (1930) and its moon Charon (1978) → new estimate for M_{Pluto} (~ 1/20 $M_{Mercury}$)

  (b) discovery of other objects comparable to Pluto (size, orbit) → **plutinos**



James Christy (June 22, 1978)
magnified images of Pluto on photographic plates

1996 image of Pluto & Charon (right)
ESA/Dornier UV camera FOC, NASA Hubble

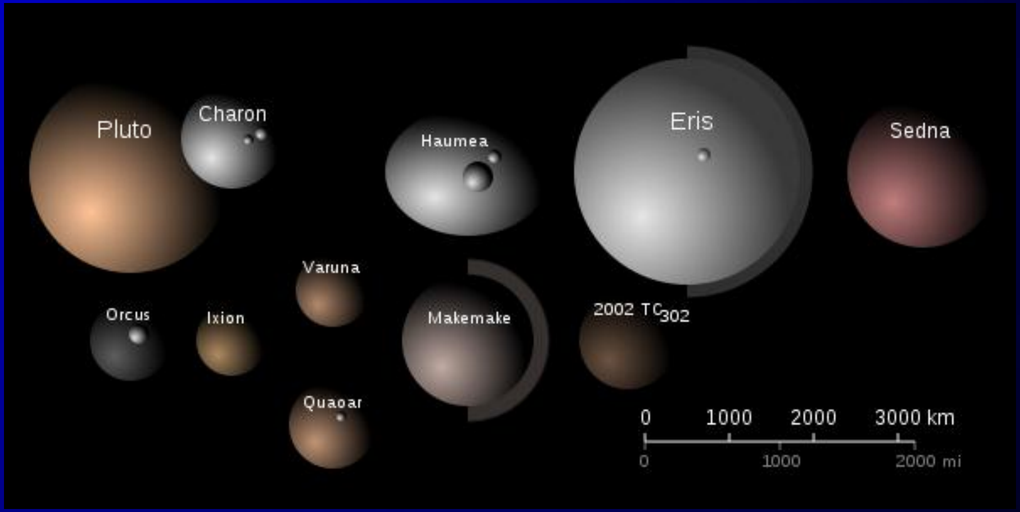
General definition (by IAU = Intrnational Astronomical Union, 2006)

- **Minor planet / planetoid** -- old official definition (before IAU 2006) for an astronomical object in orbit around the Sun that is ***neither a planet nor a comet***.
  - used since the 19th century (Ceres discovery in 1801)
  - > 200,000 minor planets have been discovered (asteroid & Kuiper belts)
  - on IAU 2006 meeting

Minor planets and **Comets**

Small solar system bodies

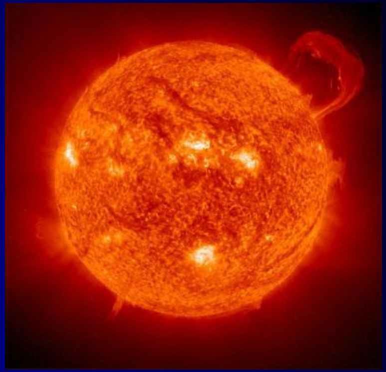
Dwarf planets

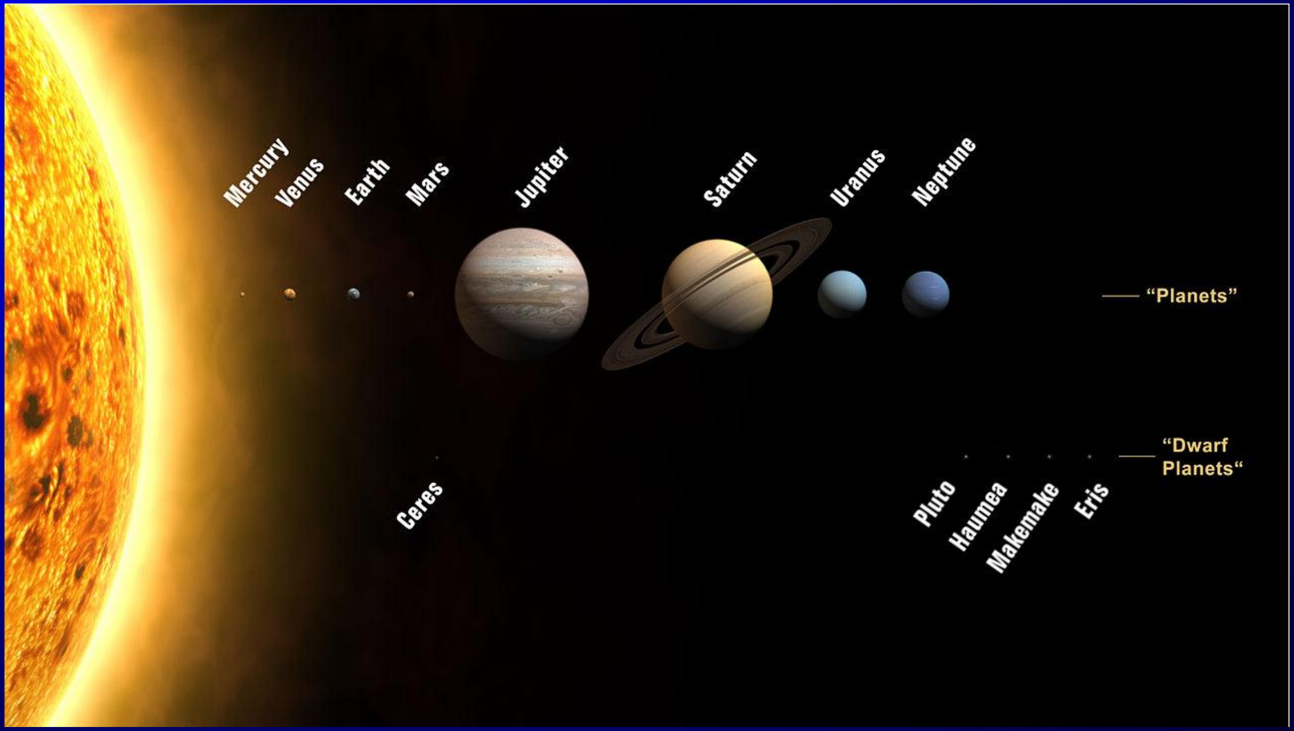


- The IAU states: „the term 'minor planet' may still be used, but generally the term 'small solar system body' will be preferred.“

Solar system planets

- **Central star** (host star)
  - The Sun: G2 V (~4.57 billion years old)
- **Planets** 8 planets and 5 dwarf planets:
  - ***Internal*** planets (Mercury, Venus, Earth, Mars)
  - ***External*** planets (Jupiter, Saturn, Uranus, Neptune)
  - ***Dwarf*** planets (Ceres, Pluto, Haumea, Makemake, Eris)





Extrasolar planets / Exoplanets

- An **extrasolar planet**, or **exoplanet**, is a planet beyond our solar system, orbiting a star other than our Sun.
  - at 1 September 2012: 624 planetary systems; 778 planets
    105 multiple planet systems
- The "working" definition for extrasolar planets (IAU 2001, 2003) → criteria:
  - Objects with masses below the limiting mass for thermonuclear ***fusion of deuterium*** (~ 13 $M_{Jupiter}$, for the same isotopic abaundance as the Sun);
  - Orbit stars or stellar remnants;
  - Minimum mass & size for an extrasolar object to be considered a planet are the same as that used in Solar system.
- Substellar objects with masses > 13 $M_{Jupiter}$ (allow thermonuclear fusion of deuterium, ***but not eneough for hydrogen burning fusion***) → **brown dwarfs**
- ***Free-floating objects*** (not orbiting any star), in young star clusters with masses < 13 $M_{Jupiter}$ → "**sub-brown dwarfs**" not planets !!!

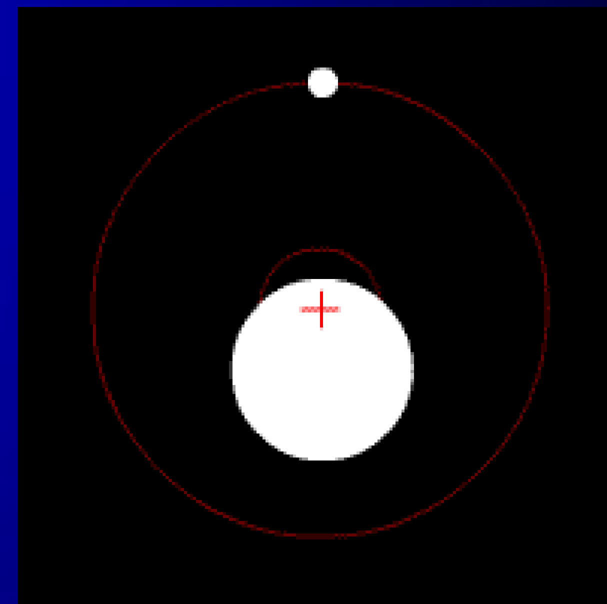
Methods of detecting extrasolar planets (10 major)

- **Astrometry**: tiny variations of a star's position
- **Radial velocity / Doppler method**: speed variations at which star moves towards/away from the Earth (observer)
- **Pulsar timing**: anomalies in the timing of pulsar's pulses.
- **Transit method**: periodic depletions of stellar btightness due to planet transit in front of the star disk
- **Gravitational microlensing**: anomalies, produced by a planet in the microlensing effect of the host star
- **Direct imaging**: image of planets directly.
- **Polarimetry**: periodic variations of polarization of the star light caused by an orbiting planet
- **Circumstellar disks**: specific features in dust distribution around stars
- **Eclipsing binary**: disturbances in the character of eclipses of double star systems
- **Orbital phase**: light variations due to changing amount of reflected light from a planet (orbital phase of a planet)

Methods of detecting extrasolar planets

- **Astrometry**: **precise measuring a star's position in the sky and observing the ways in which that position changes over time.**

  - gravitational influence of a planet causes the star itself to move in a tiny circular or elliptical orbit about the common center of mass (barycenter).



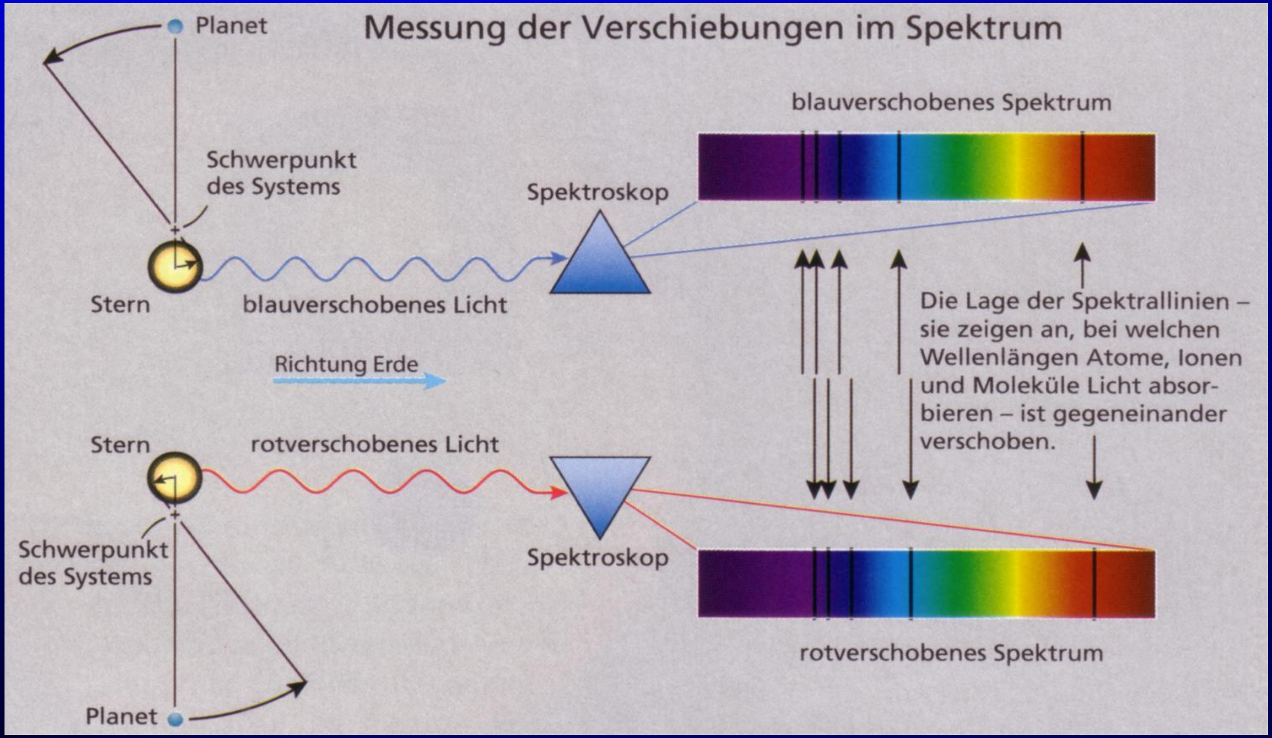
  - Ground-based observations are not enough precise → ***observations from space*** (Hubble)
  - Characterization of exoplanetary systems, (in combination with other methods) gives
    - ***masses***,
    - ***number*** of planets
    - ***orbit inclination***
  - **Gliese 876** system (1998, 2001, 2005)

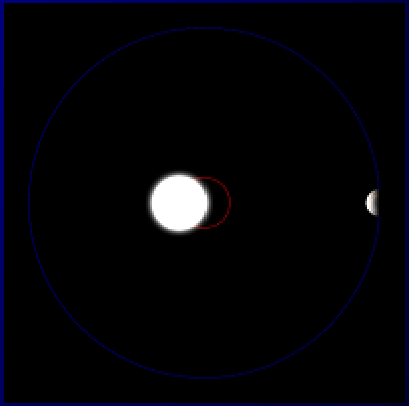
Companion (in order from star)	Mass	Semimajor axis (AU)	Orbital period (days)	Eccentricity
d	$8.41^{+0.78}_{-0.75}$ $M_{\oplus}$	$0.020700^{+0.0000004}_{-0.0000004}$	1.9379	0.0
c	$0.78^{+0.05}_{-0.03}$ M_J	$0.13062^{+0.00005}_{-0.00005}$	30.48	$0.2683^{+0.0058}_{-0.0052}$
b	$2.64^{+0.11}_{-0.09}$ M_J	$0.20700^{+0.00010}_{-0.00009}$	60.81	$0.0363^{+0.0028}_{-0.0026}$

Methods of detecting extrasolar planets

- <u>**Radial velocity / Doppler method**</u>: **measure of the speed variations at which star moves towards/away from the Earth (observer)**

variations in the star's velocity ⇒ displacement in the star's spectral lines (**Dopper effect**)

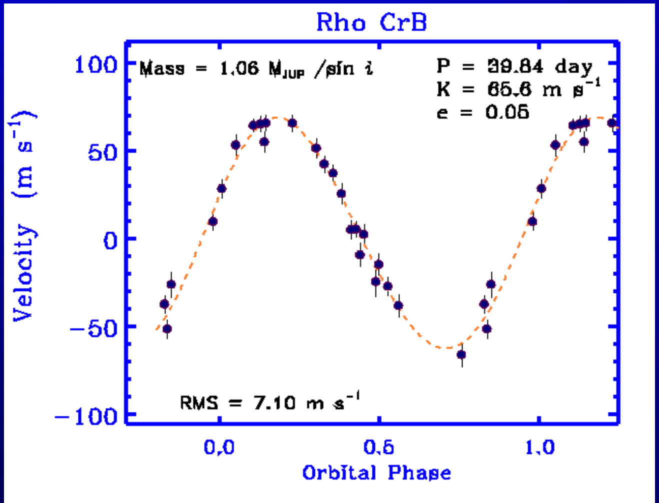


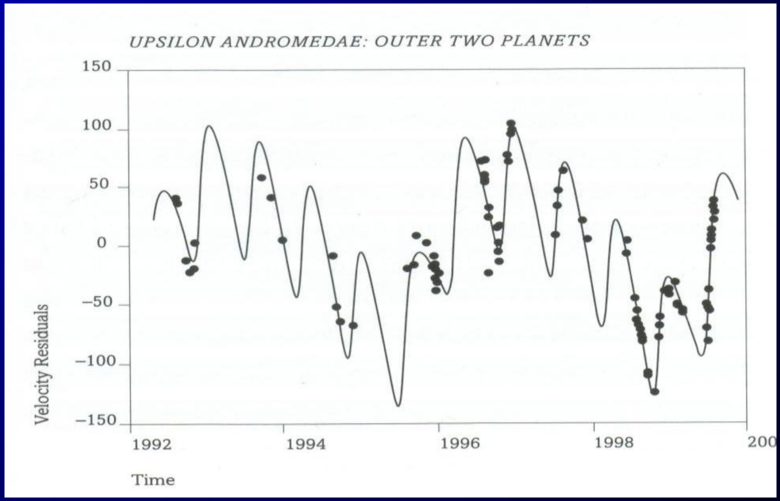


Methods of detecting extrasolar planets

- **Radial velocity / Doppler method**: **measure of the speed variations at which star moves towards/away from the Earth (observer)**

- Most productive technique used so far:
  - velocity variations **≥ 1 m/s** can be detected ($V_{star} << V_{planet}$);
  - used to confirm findings made by other methods (e.g., transit);
  - gives an estimate of planet ***minimum mass, M_{min}***; ***true mass*** is within 20% of M_{min} (depends on orbit inclination relative the line of sight)





Methods of detecting extrasolar planets

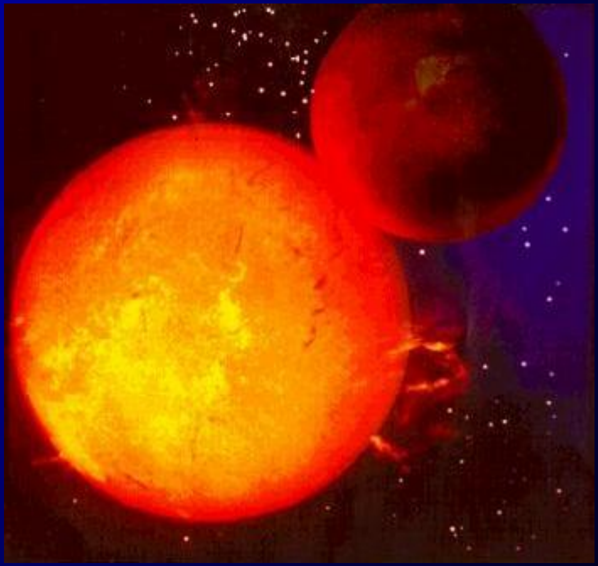
- **Radial velocity / Doppler method**: **measure of the speed variations at which star moves towards/away from the Earth (observer)**

- Typical example: ***51 Pegasi b*** (unofficially ***Bellerophon***), Oct.1995

  - Parent star: ***51 Pegasi*** - the first Sun-like star found to have a planet :

    - Yellow dwarf, in ***Pegasus*** constellation (~50,1 light-years)
    - Spectral type G2.5V (Sun is G2V)
    - 4–6% more massive then Sun
    - Apparent magnitude: 5.49
    - 7.5 billion years old

  - Hot Jupiter planet 51 Pegasi b, **T ~ 1300 K**



The 51 Pegasi system

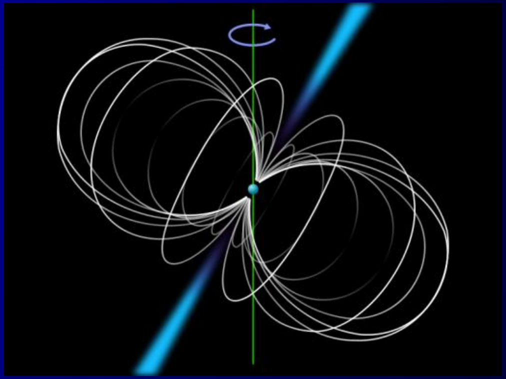
Companion (in order from star)	Mass	Semimajor axis (AU)	Orbital period (days)	Eccentricity
b	>0.468 ± 0.007 M_J	0.052	4.23077 ± 0.00005	0

  - Discovery and confirmations:
    - Obs. De Haute-Provence (France), ELODIE spectrograph.
    - Lick Observatory, San Jose, CA, USA, Hamilton Spectrograph

Methods of detecting extrasolar planets

- **Pulsar timing**: **anomalies in the timing of pulsar's pulses are used to track changes in its motion caused by the planets.**

- **Pulsars** are highly magnetized, rotating neutron stars (ultradense remnants of supernova) that emit beamed electromagnetic radiation.
  - Observed periods of pulses: 1.4 msec - 8.5 sec;
  - Existing pulsars emit in radio, visible light, X-rays, and/or γ-rays;
  - The radiation can only be observed when the beam points towards the Earth.
  - The first discovery - in 1967 radio pulsar CP 1919 (PSR 1919+21)



Vela γ-ray pulsar - brightest in the sky;
P = 89 msec; E ~ 300 MeV - 1 GeV;

Movie is constructed from images taken by Fermi Gamma-ray Large Area Space Telescope - GLAST (on orbit since 2008)

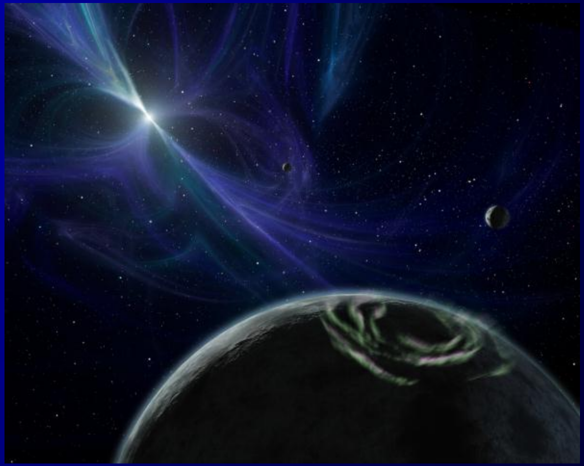
Image - from Chandra X-ray obs. (1999).

Methods of detecting extrasolar planets

- **Pulsar timing**: **anomalies in the timing of pulsar's pulses are used to track changes in its motion caused by the planets.**

Motion of a pulsar with a planet around a common center of mass ⇒ Disturbance of pulse-timing ⇒ parameters of pulsar‘s orbit

- enables detection of planets $\leq 1/10\ M_{Earth}$ (far smaller than any other method can)
- capable of detecting multi-planet system
- reveals information about planets orbital parameters.



- Traditional life forms could not survive on planets orbiting pulsars (high-energy radiation, postexplosion stage of star evolution).

Methods of detecting extrasolar planets

- **Pulsar timing**: **anomalies in the timing of pulsar's pulses are used to track changes in its motion caused by the planets.**

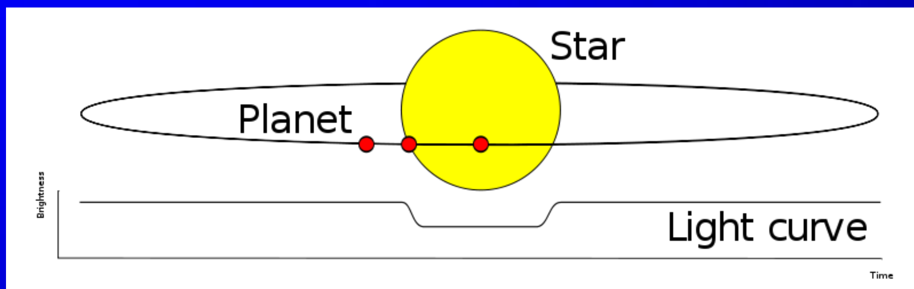
- **PSR B1257+12** in the constellation of Virgo – first pulsar having a planet (PSR 1257+12b), which is the first confirmed planet outside Solar system
  - Discovery of pulsar in 1990 using the Arecibo radio telescope
  - Discovery of planets (b,c) in 1992 by Aleksander Wolszczan & Dale Erail
  - Discovery of small planets (a), in 1994, and (d), in 2002
  - Additionally, this system may have an asteroid belt (like Kuiper belt).

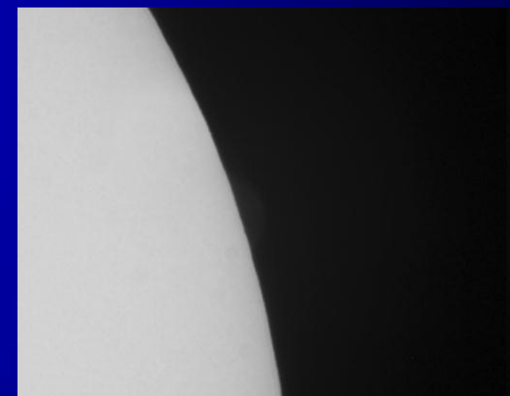
First Dwarf exoplanet

Companion (in order from star)	Mass	Semimajor axis (AU)	Orbital period (days)	Eccentricity
A	0.025 $M_\oplus$	0.19	25.262 (± 0.003)	0.00
B	4.3±0.2 $M_\oplus$	0.36	66.5419 (± 0.0001)	0.0186 (± 0.0002)
C	3.9±0.2 $M_\oplus$	0.46	98.2114 (± 0.0002)	0.0252 (± 0.0002)
D (unconfirmed)	<0.0004 $M_\oplus$	2.6	1250	?

Methods of detecting extrasolar planets

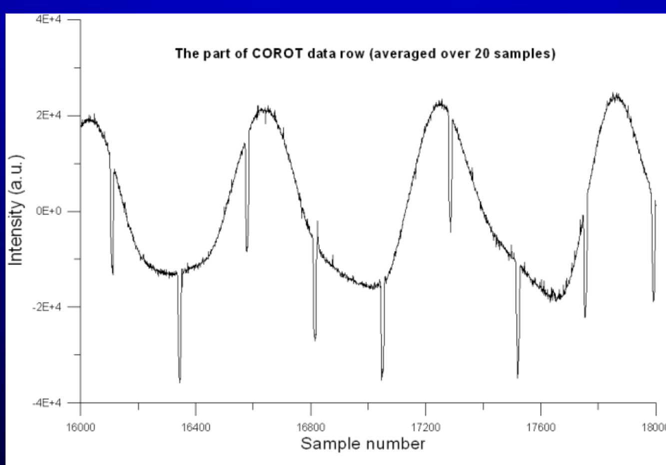
- **<u>Transit method</u>**: measuring of periodic depletions of stellar btightness caused by planet transits in front of the star disk

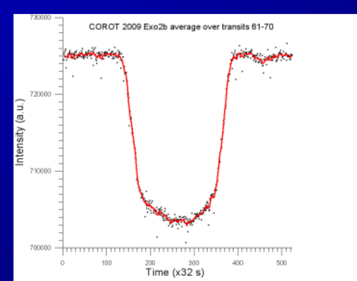




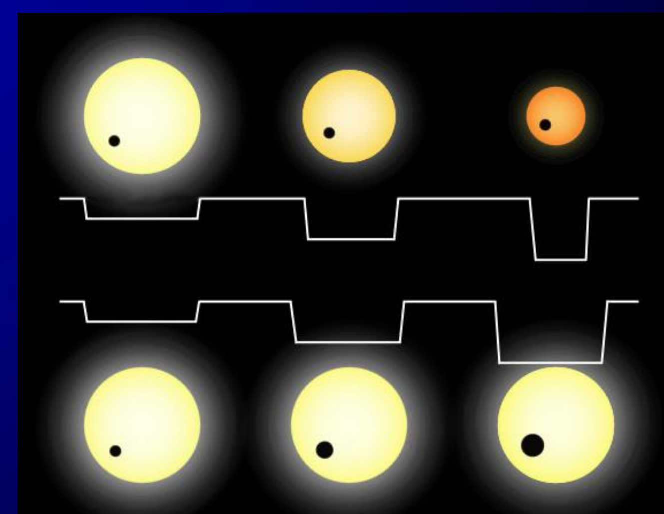
Venus transit
(M. Karrer, St.Radegund / Austria)

- The amount by which the star dims depends on its size and on the size of the planet.





CoRoT2b, (~3.31 M_J)
Serpens,2007



Methods of detecting extrasolar planets

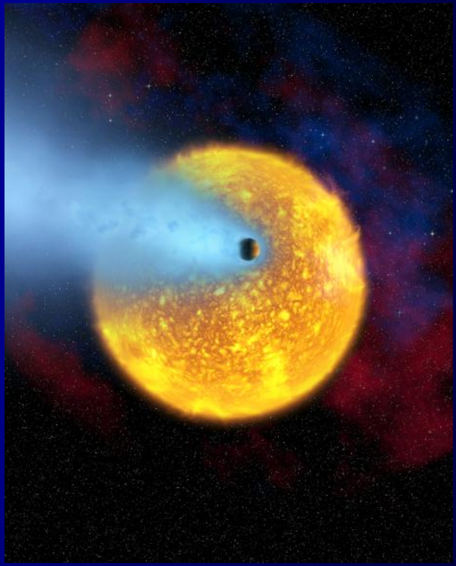
- **<u>Transit method</u>**: **measuring of periodic depletions of stellar btightness caused by planet transits in front of the star disk**

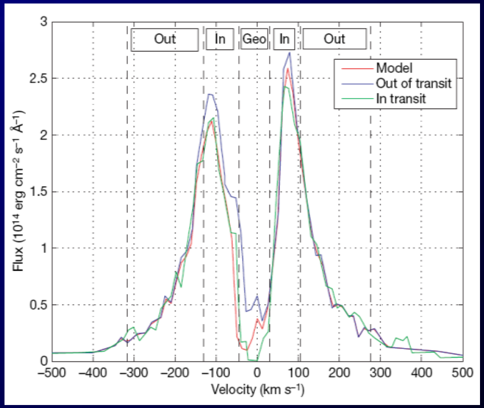
- <u>Advantages:</u>
  - Can determine the <u>size</u> (**R_{planet}**) of a planet;
  - In combination with the radial velocity method (which gives **M_{planet}**) enables determination of the planet density (→ <u>physical properties</u>);
  - <u>Study of atmosphere</u> of a transiting planet:

    → ***chemical composition*** of upper atmosphere (analysis of stellar light, passed through the atmosphere).

    → measurement of the ***planet radiation*** by subtraction from the light curve of the star light measured during secondary eclipse (planet behind the star)

    ⇒ planet's temperature; detection of clouds





Methods of detecting extrasolar planets

- <u>**Transit method**</u>: **measuring of periodic depletions of stellar btightness caused by planet transits in front of the star disk**

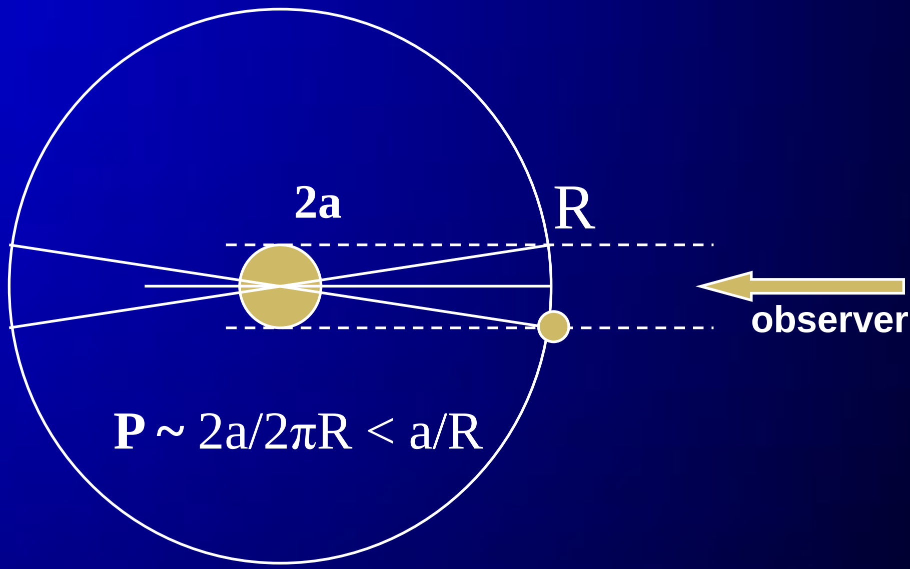
- <u>Ddisadvantages.</u>

  - Transits are only observable for planets with properly aligned orbits (relative to observer)

  - The probability to see transit **P < a/R**:

    a – star rarius
    R – planet orbital distance

    a planet orbiting a sun-sized star at ***1 AU*** ⇒ **P ~ 0.47%**



  - Method suffers from a high rate of false detections ⇒ additional check by other methods (usually radial-velocity method)

Methods of detecting extrasolar planets

- **Transit method**: **measuring of periodic depletions of stellar btightness caused by planet transits in front of the star disk**

- Space observations of transits

  absence of atmospheric scintillation allows improved accuracy

  - ***COROT*** (CNES, France) -- since Dec. 2006

    Objectives:

    - search for exoplanets with short orbital periods (down to Superearth mass),

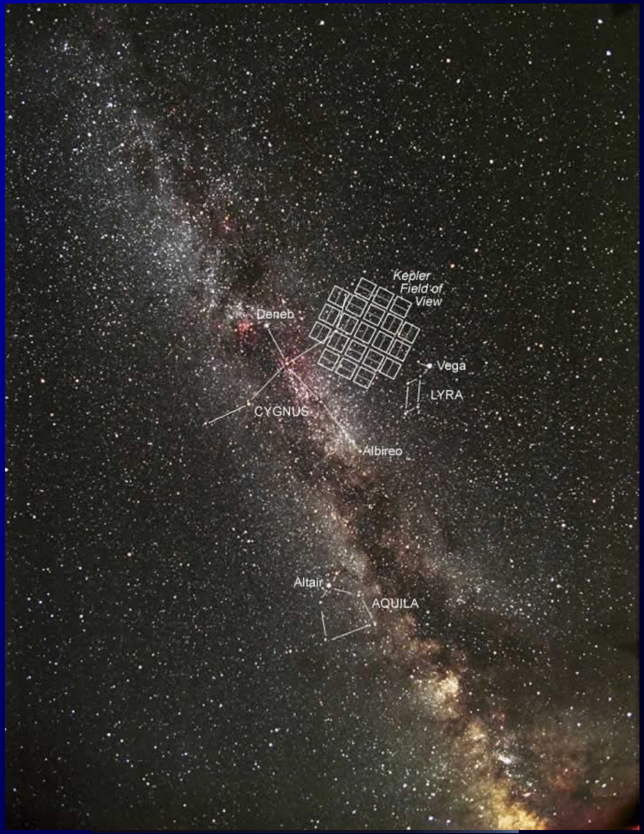
    - perform asteroseismology, i.e. solar-like oscillations in stars.

  - ***Kepler*** (NASA, USA) -- since Mar. 2009

    Objectives:

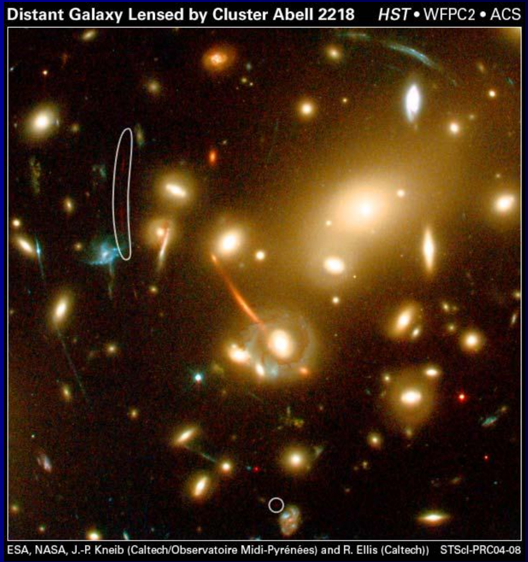
    - monitoring of >100,000 stars in fixed field of view: Cygnus, Lyra and Draco

    - discovery of Earth-like planets



Methods of detecting extrasolar planets

- **Gravitational microlensing**: **detection of anomalies, produced by gravitational field of a planet in the microlensing effect of the host star**

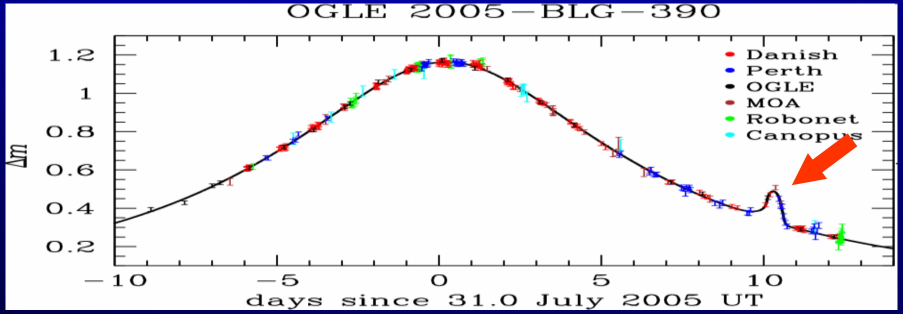


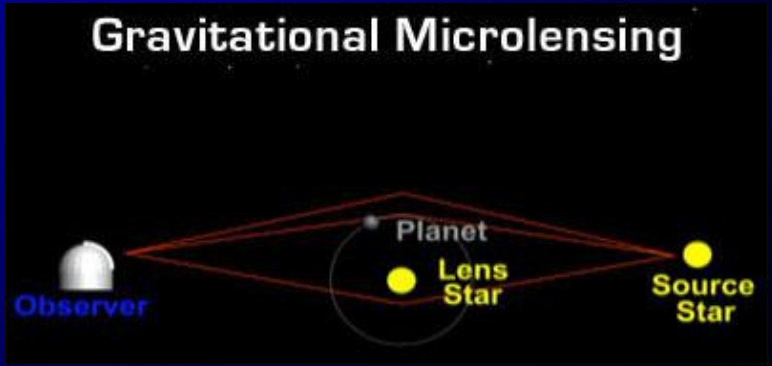
- ***Gravitational lensing*** occurs when the gravitational field of a star acts like a lens, bending the light of a distant background object
  - ⇒ multiple distorted, magnified, and brightened images of the background source.

- ***Gravitational microlensing***

Lensing mass is small → different observation technique

Search for ***transient changes of brightness***





Methods of detecting extrasolar planets

- **Gravitational microlensing**: **detection of anomalies, produced by gravitational field of a planet in the microlensing effect of the host star**

- Advantages:

  - Detection of Earth-like planets at moderately wide orbits (e.g., **OGLE-2005-BLG-390Lb** by M-star in ***Scorpius*** near the center of the ***Milky Way*** in Jan.2006 – 1st low-mass (5,5$M_{\mathbf{Earth}}$) planet on a wide (2.6AU) orbit at 20,000 light years)

  - Most fruitful for planets between Earth and the center of the galaxy (large number of background stars);

  - Enables estimation of $M_{\mathbf{Planet}}$ and orbital distance

  - Can be performed automatically (networks of robotic telescopes)

Methods of detecting extrasolar planets

- **Gravitational microlensing**: **detection of anomalies, produced by gravitational field of a planet in the microlensing effect of the host star**

- Disadvantages:

  - ***Two stars should be almost exactly aligned*** → Lensing events are brief lasting (weeks or days);

  - Very distant planets (several kps, **1 pc = 31 x 10^{12} km ~ 3.26 light-years**) → limited opportunities for confirmation by other methods;

  - Lensing cannot be repeated, because the chance of alignment never occurs again;

- Discoveries:

15 planetary systems **16** planets / **1** multiple planet systems

Methods of detecting extrasolar planets

- **Direct imaging**: **in certain cases modern telescopes may be capable to image planets directly.**

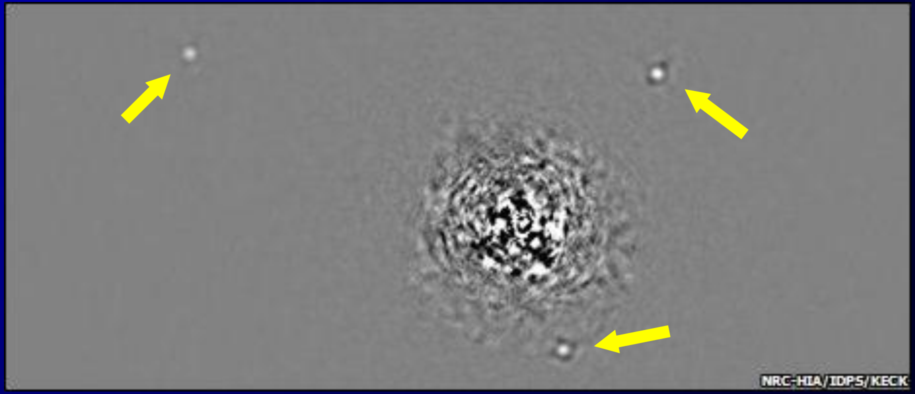
- Imaging may be possible if a planet is
  - large enough (considerably larger than Jupiter),
  - widely separated from its parent star (large orbital distance),
  - young (i.e. hot and emits intense infrared radiation).

- Discoveries:

  27 planetary systems / 31 planets / 2 multiple planet system

The HR 8799 system[6][8]

Companion (in order from star)	Mass	Semimajor axis (AU)	Orbital period (years)	Eccentricity
d	10±3 M_J	~ 24	~ 100	>0.04[16][note 2]
c	10±3 M_J	~ 38	~ 190	?
b	7^{+4}_{-2} M_J	~ 68	~ 460	?
Dust disk	75 AU			



HR 8799 system in *Pegasus* (129 light-years):
HR 8799d (bottom), HR 8799c (upper right), HR 8799b (upper left),
(Keck & Gemini IR telescopes, Hawaii, Nov.2008)

also found in Hubble/NICMOS IR images, dated by 1998

Methods of detecting extrasolar planets

- **Direct imaging:** **in certain cases modern telescopes may be capable to image planets directly.**

- Observational facilities:
  - ***Gemini North***, 8m telescope, Mauna Kea, Hawaii (4.213 m)
  - ***Keck Observatory 10m telescope***, Mauna Kea, Hawaii (4.145 m)
  - ***Subaru*** 8.2m telescope, Mauna Kea, Hawaii (4.139 m)
  - ESO's ***Very Large Telescope (VLT)*** 8.2m, Paranal Obs.,Chile (2,635 m)
  - ***Hubble Space Telescope***

Gemini North, Hawaii

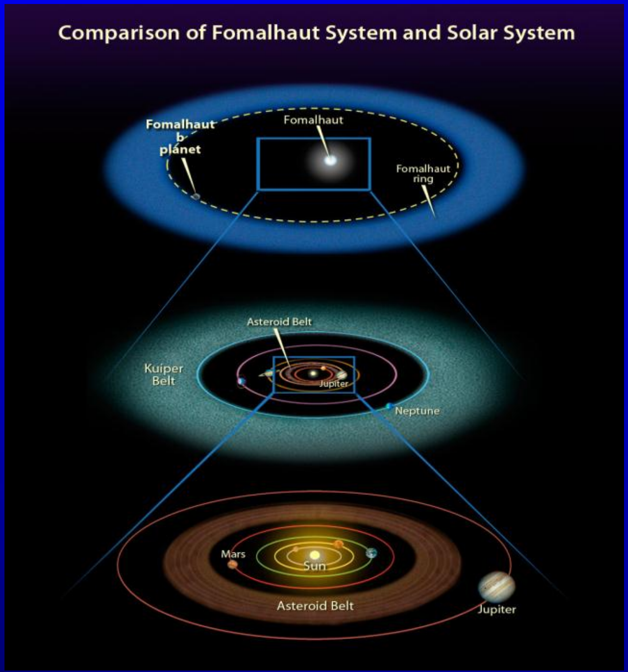
Subaru Telescope, Hawaii

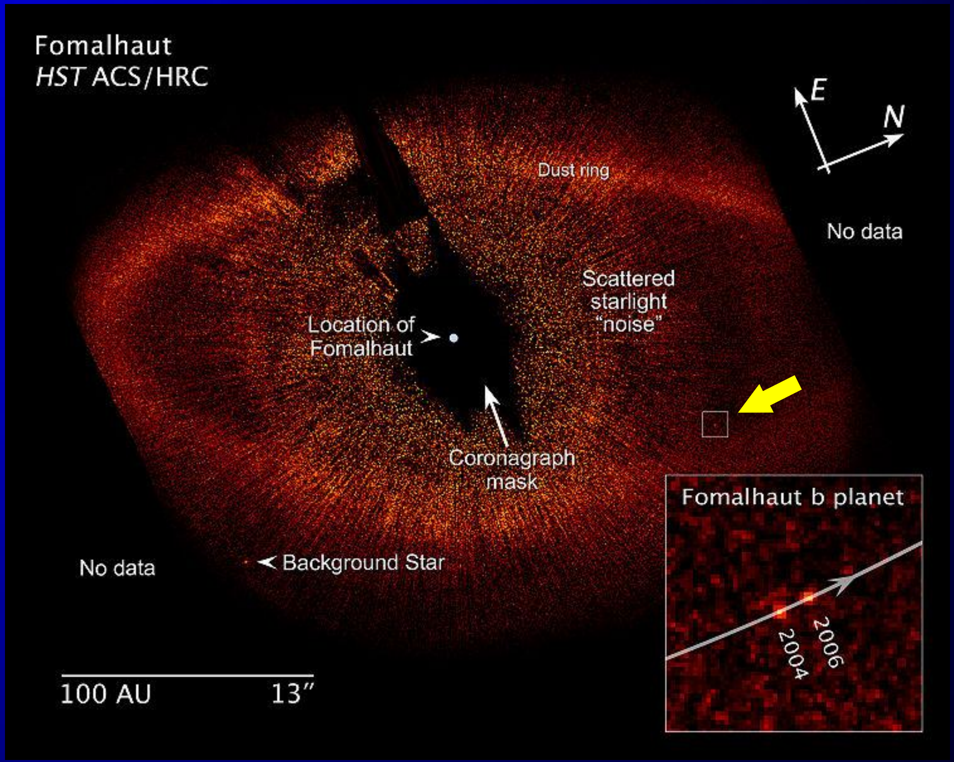
VLT, Paranal Obs., Chile

Methods of detecting extrasolar planets

- **Direct imaging:** in certain cases modern telescopes may be capable to image planets directly.

- Typical example: constell. ***Piscis Austrinus:*** ***Fomalhaut b*** , M < 3 $M_{Jupiter}$





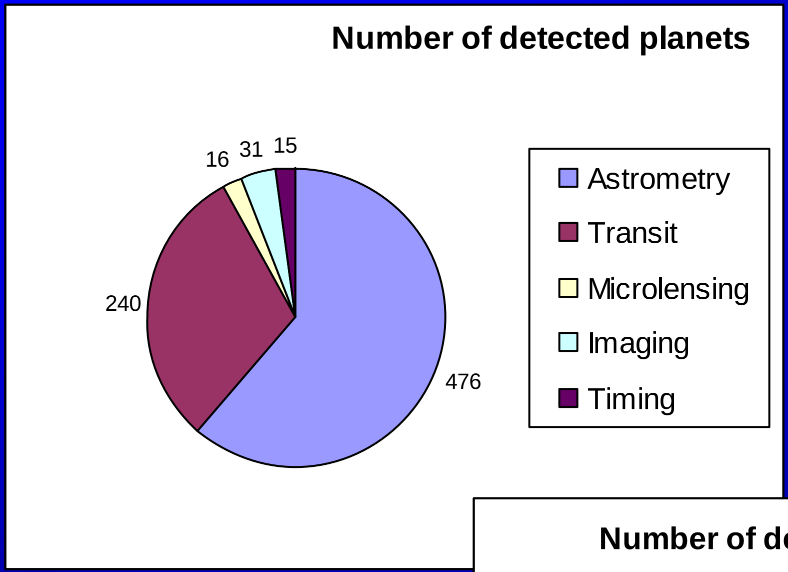
The Fomalhaut system[11]

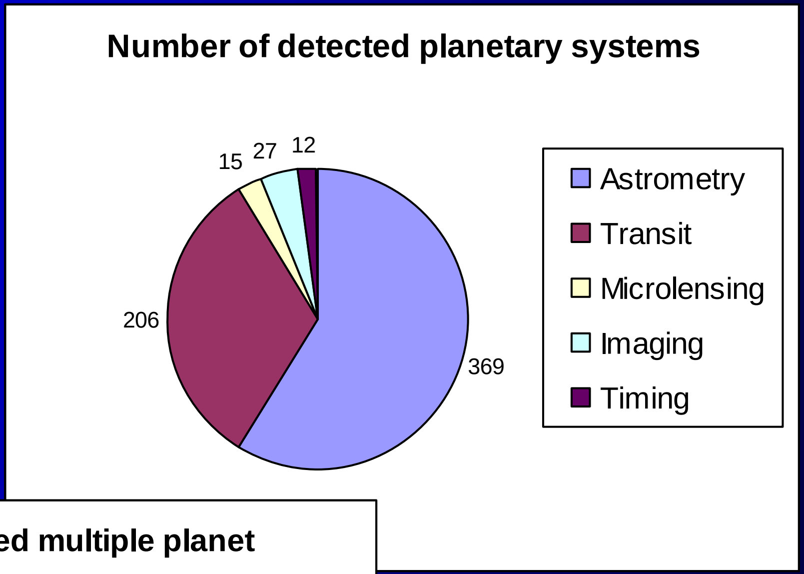
Companion (in order from star)	Mass	Semimajor axis (AU)	Orbital period (years)	Eccentricity
b	0.054 - 3.0 M_J	~115	~872	~0.11
Dust disk	133 — 158 AU			

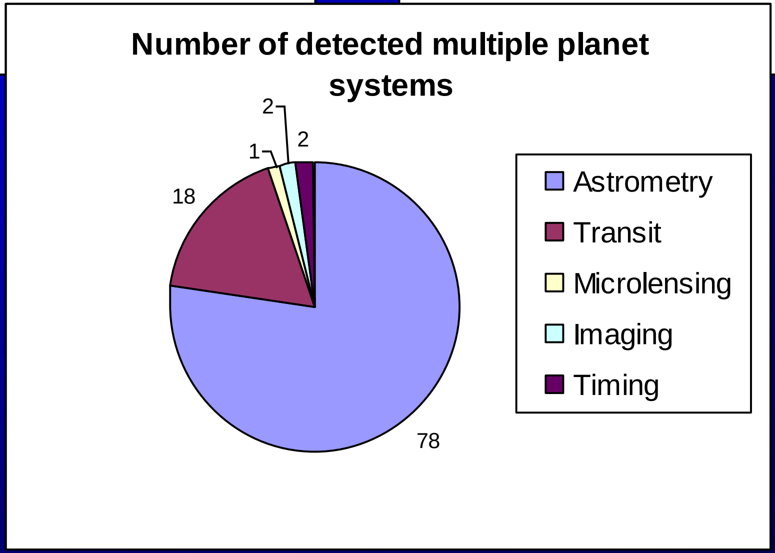
Fomalhaut b (in the Fomalhaut's dust cloud) imaged by The Hubble Space Telescope's coronagraph (ACS/HRC)

Methods of detecting extrasolar planets

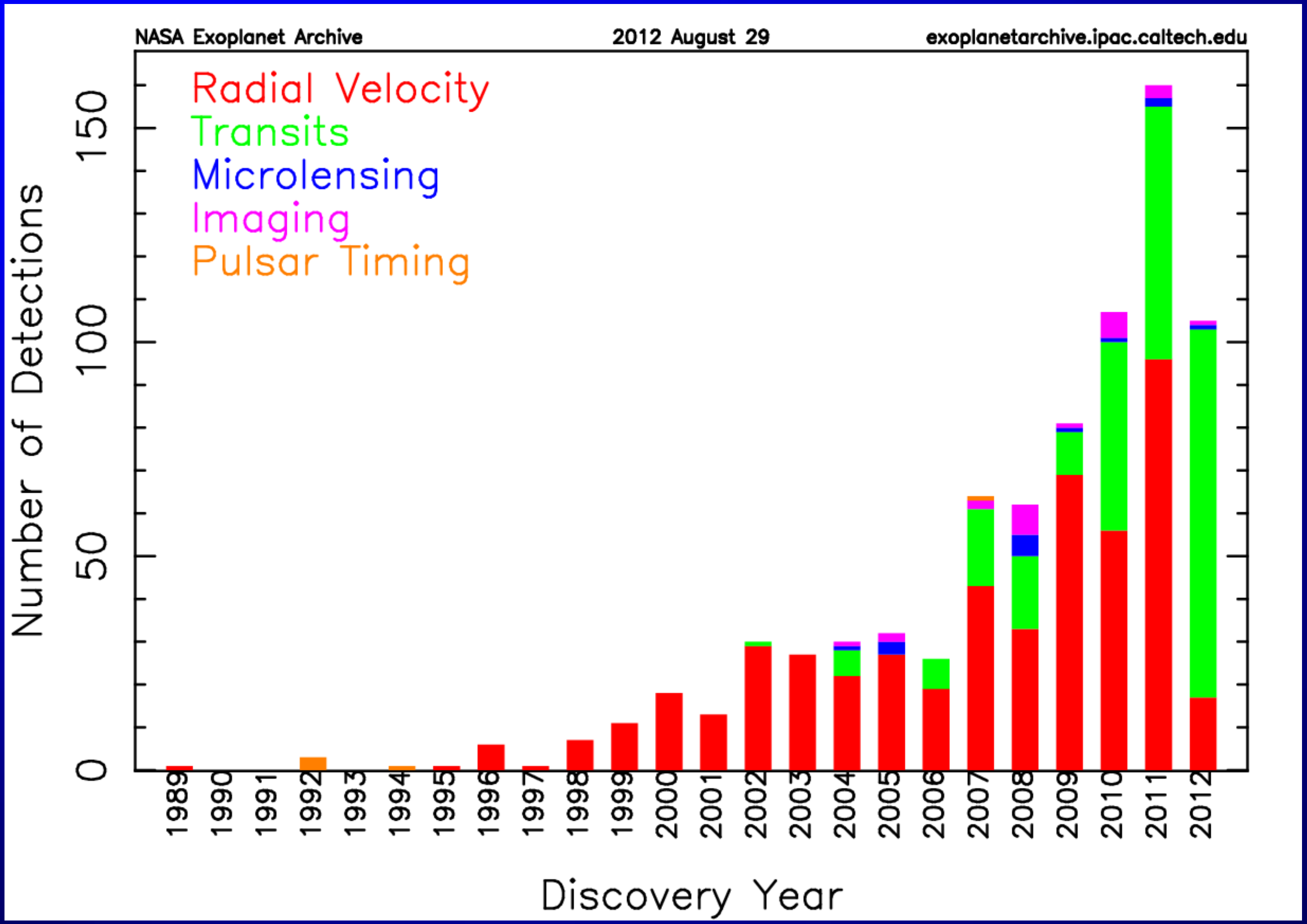
- **Summary of discoveries (September 2012):**







Exoplanets statistic // status Sep. 2012

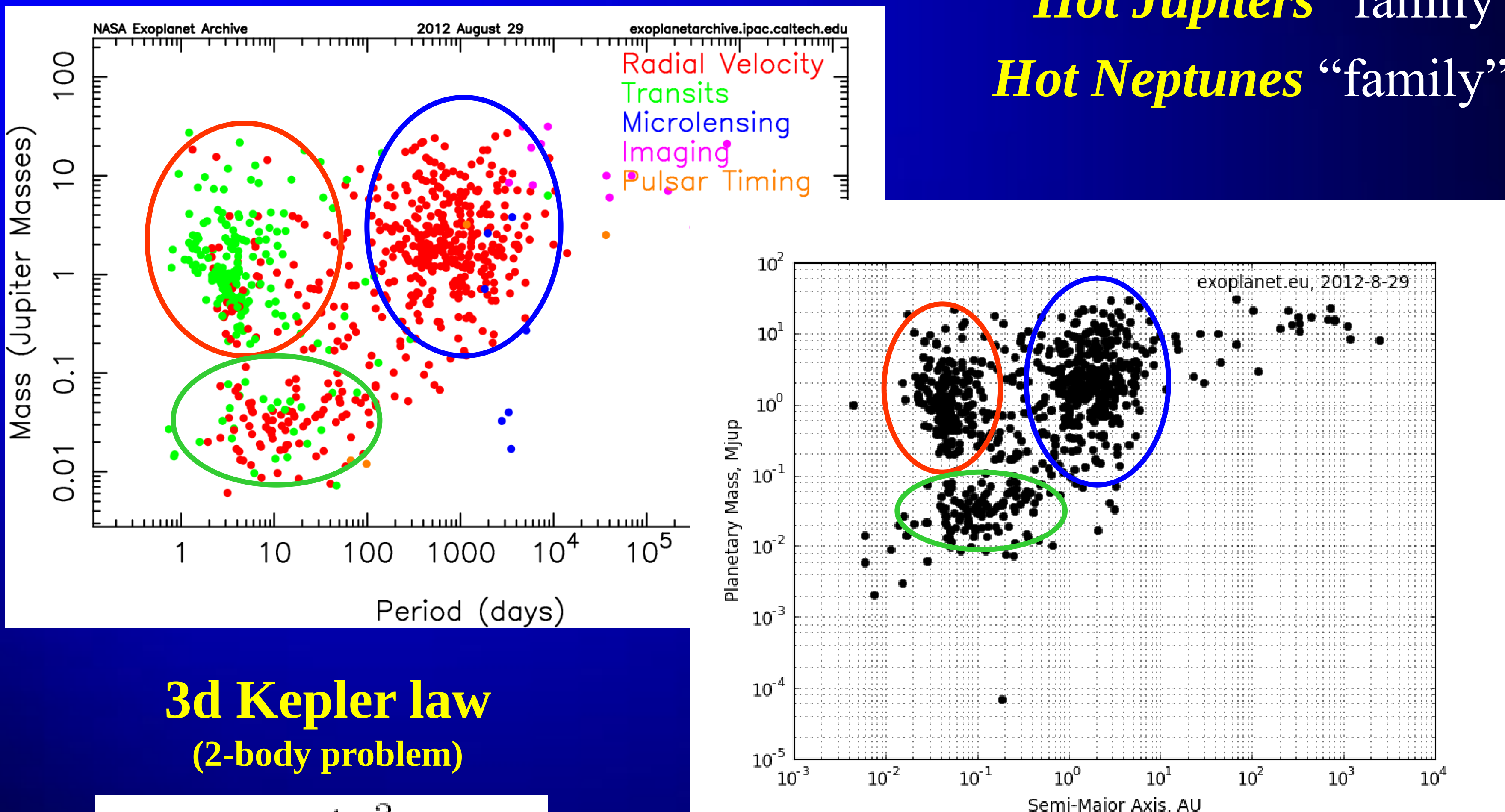


- 627 Exoplanetary systems
- 793 Exoplanets
- 105 Multiple Planetary systems

Source: http://exoplanetarchive.ipac.caltech.edu/

Exoplanets statistic // status Sep. 2012

- **Exoplanet mass vs. semi-major axis:** → ***Jupiters*** "family"
  Hot Jupiters "family"
  Hot Neptunes "family"



3d Kepler law

(2-body problem)

$$T^2 = \frac{4\pi^2}{G(M+m)}a^3$$

Exoplanets statistic // status Sep. 2012

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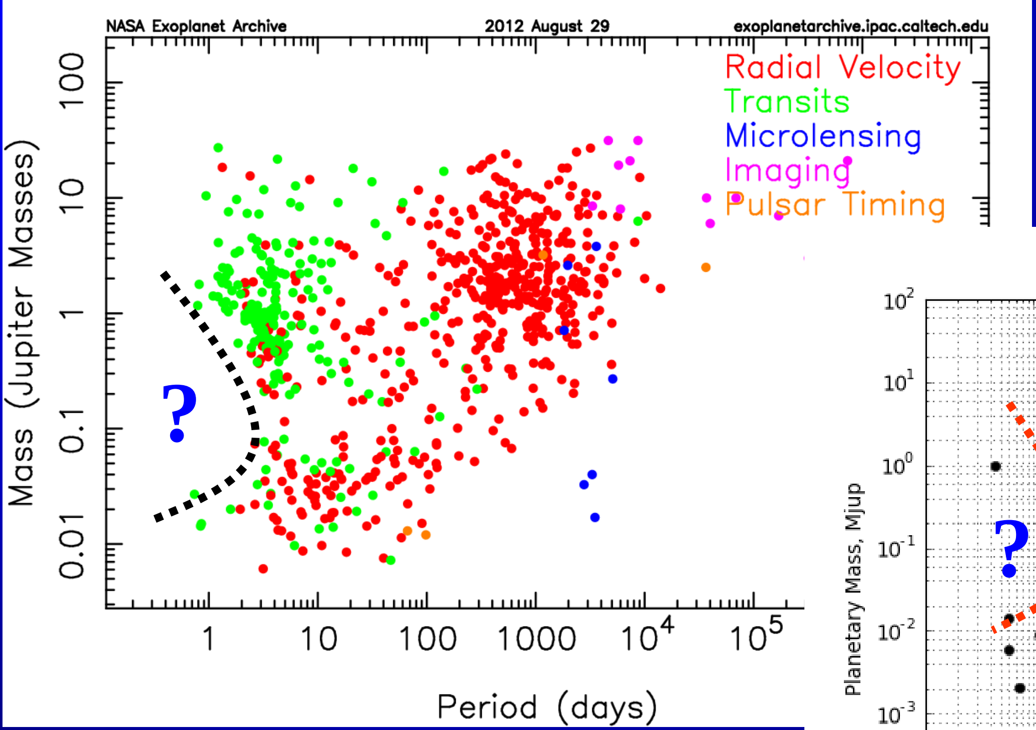

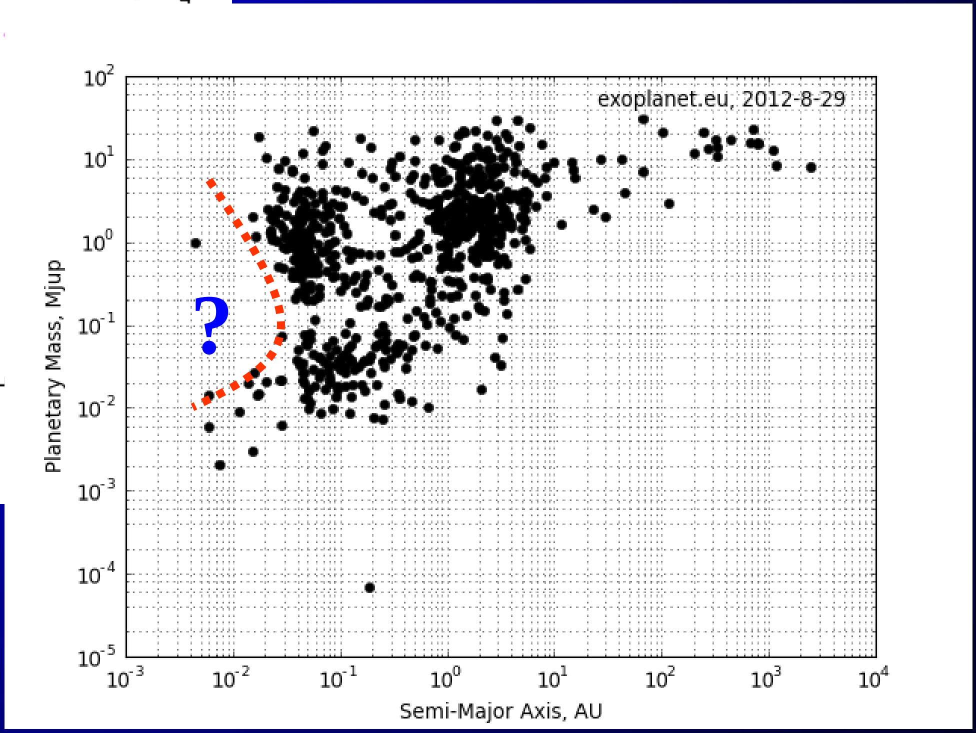

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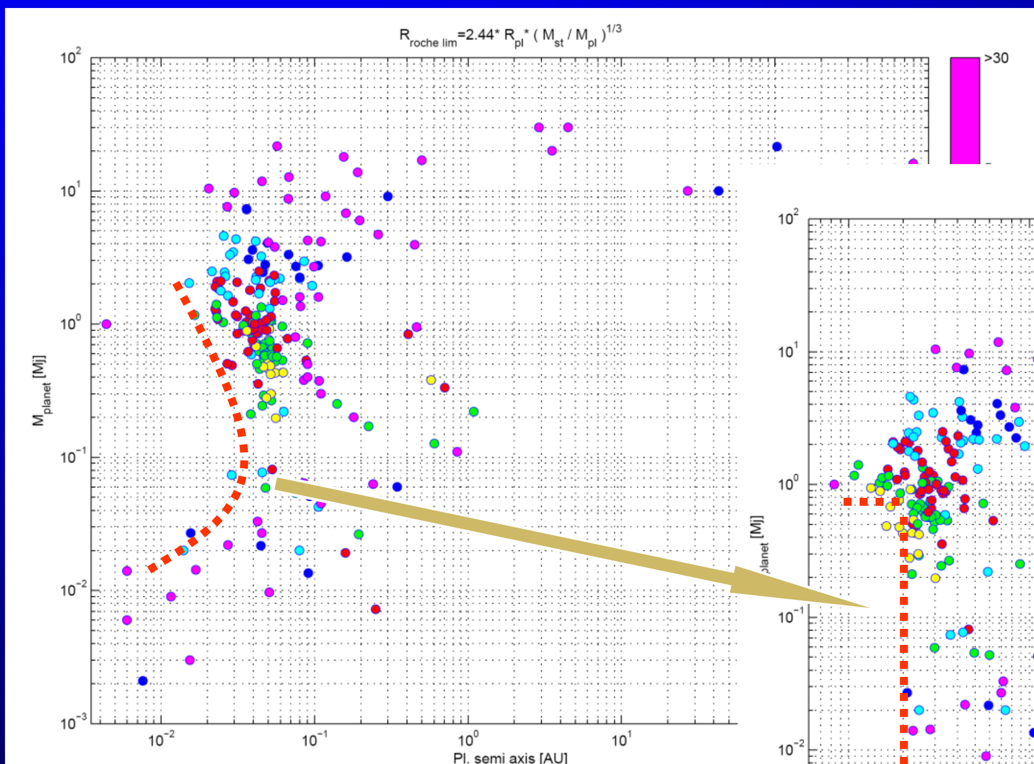
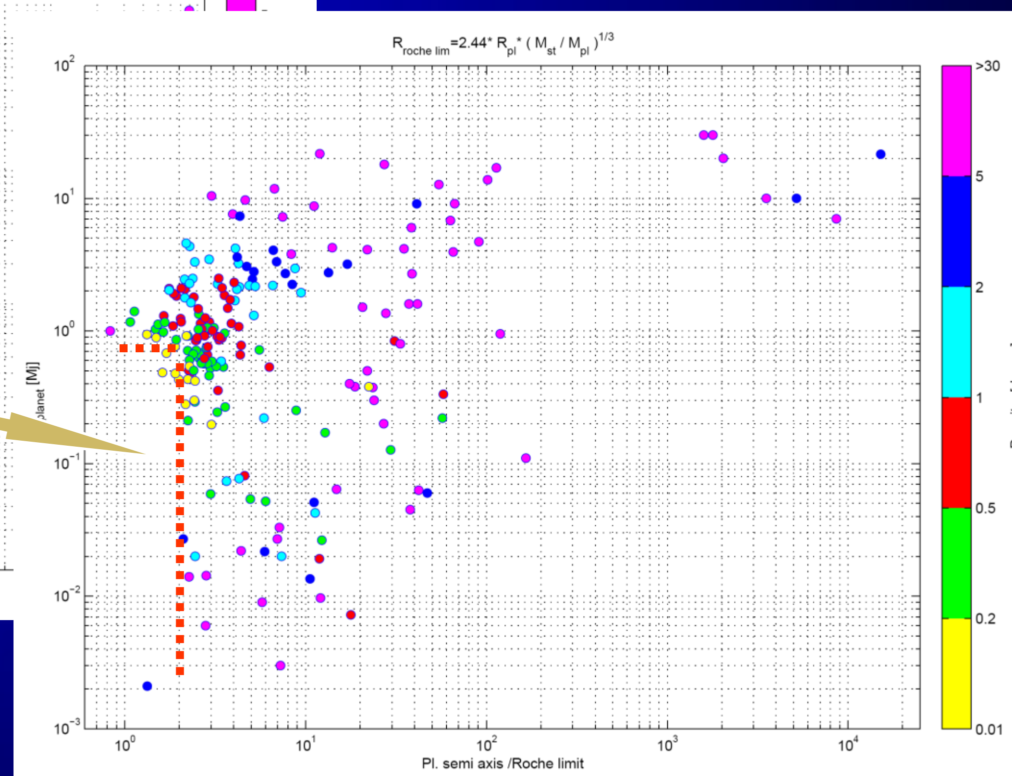
Exoplanets statistic // status Sep. 2012

- **Exoplanet mass vs. semi-major axis:** **Mystery of Gap ?**

Scale orbital distance in units of Roche Limit (unique fore each planet)





New Roche Limit type, dependent on inner structure of a pl.body

Major questions of exoplanetary physics:

- **(?)** ***Way of formation of terrestrial type (rocky) planets***
  - → In-situ formation ?
  - → Migration ?
  - → Evolutional transformation from giant to other type planets ?
- **(?)** ***Evolution of planetary environments***
  - → Magnetic dynamo / Intrinsic magnetic field / magnetosphere
  - → Surface
  - → Atmosphere
- **(?)** ***Could life have evolved somewhere else besides of Earth ?***
  - → Definition of life / life forms
  - → Conditions for life development

⇒ **HABITABILITY** (criteria, key factors, etc.)

Factors, influencing planetary environments evolution:

- ***External, space environmental factors:***
  - → Radiation of the host star and stellar activity
  - → Astrospheric plasma environment (stellar winds, CMEs, shocks)
  - → Cosmic & galactic rays
  - → Stellar – planetary interactions (gravitational, e.-m., etc.)

magnetic field plays an important role

- ***Internal, planet related factors:***
  - → Orbital parameters (distance to host star, eccentricity, etc.)
  - → Planet mass and type (gas giant or rocky planet)
  - → Efficiency of planetary magnetic dynamo (intrinsic m. field)
  - → Atmosphere composition

SUMMARY CONCLUSIONS

- **Exoplanetology is a new fast developing branch** of modern space physics which is based on the continuously growing amount of observational data about extraterrestrial worlds.

- **Specific feature of Exoplanetology consists in its multidisciplinarity** (broad range of research directions from physics & chemistry till biology). Nowadays, strong **engineering aspect** comes, which deals with development of advanced observational techniques and preparation/realization of space missions.

- Research **expertise & knowledge from the solar system study** and other "traditional" space sciences are of high potential interest and importance for Exoplanetology. The traditional stellar physics got new area of application.

- Exoplanetology opens **perspectives for development of "new physics"** (stellar-planetary interactions, extreme conditions, new kind of planetary environments).

Thank you for attention