EXOPLANETS – frontiers of modern planetology, where Sci-Fi meets science

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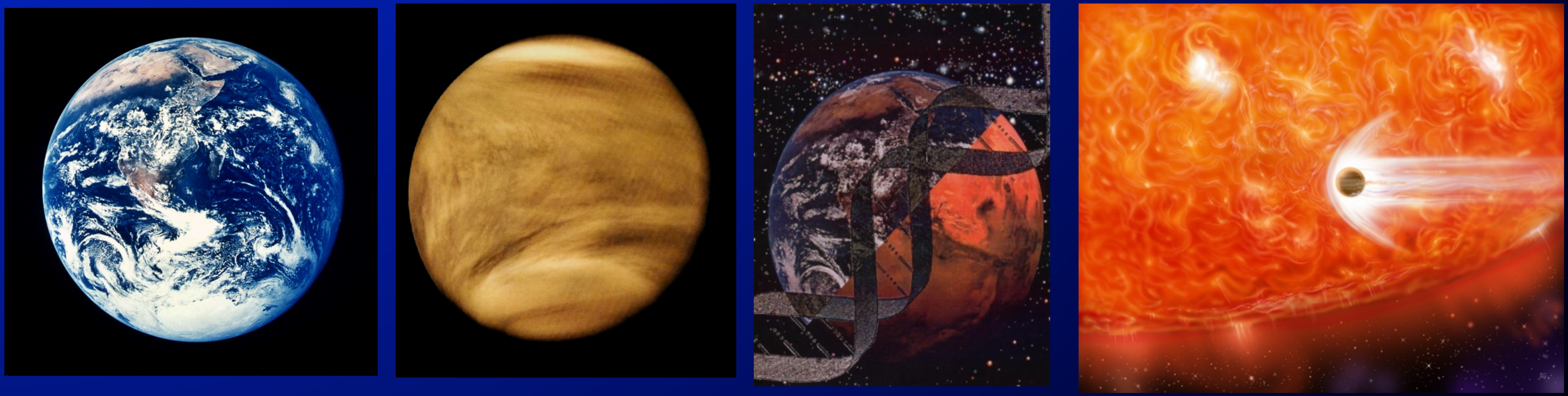
CONTENT of the lecture

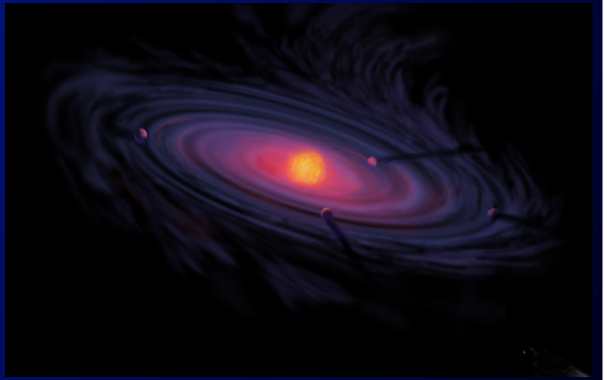
- Planet definition. What are the planets?
- Exoplanet search methods
- Habitable zone and habitability
- Planetary mass loss; the problem of planetary survival at close orbits; How important are magnetospheres



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 ($M < 13\ M_{Jupiter}$);
  - (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.~~

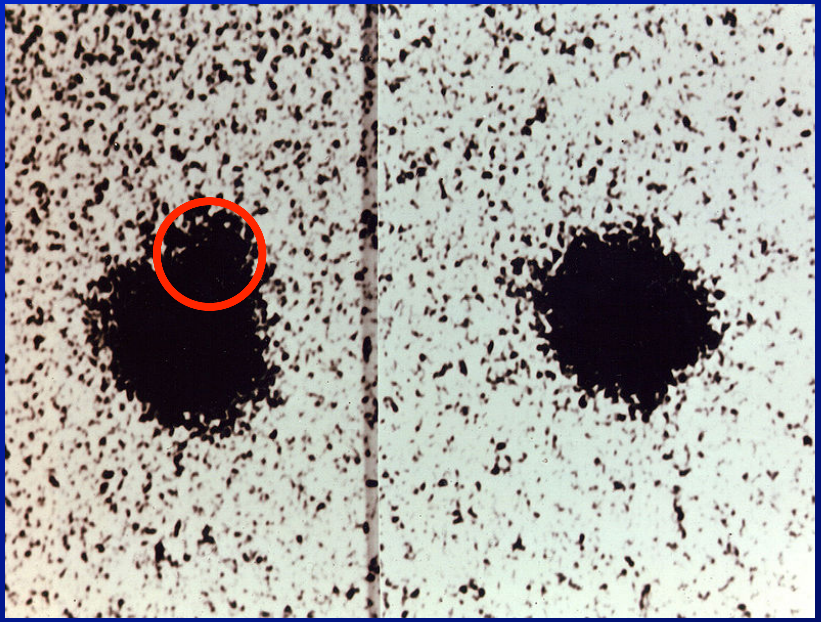
⇒ **Small solar system body (SSSB)**

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

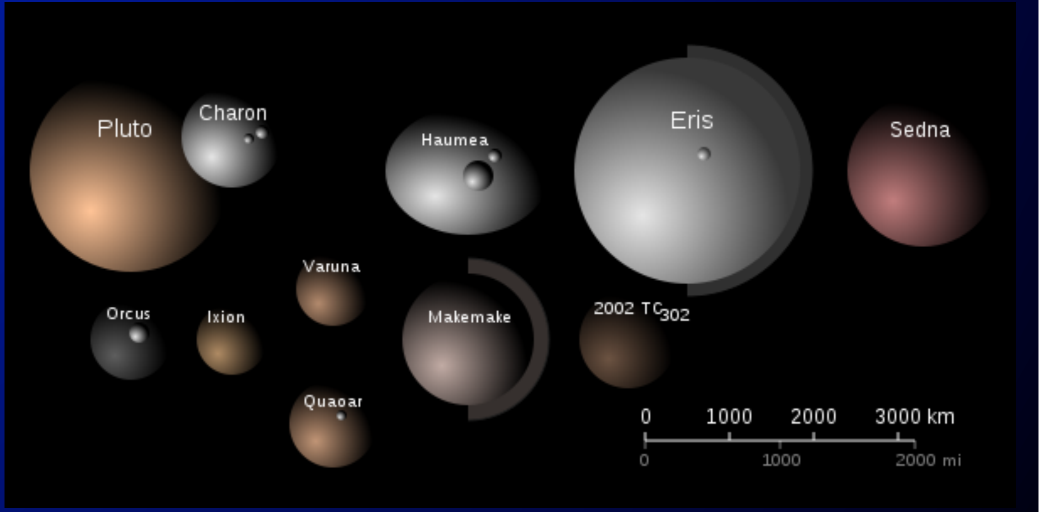
General definition (by IAU = Intrnational Astronomical Union, 2006)

- **Minor planet / planetoid** -- old official definition (before IAU 2006) for an astronomical object in direct 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**

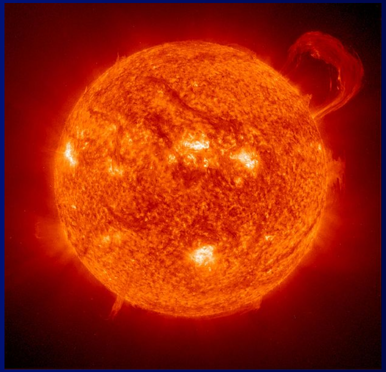
Small solar system bodies

Dwarf planets

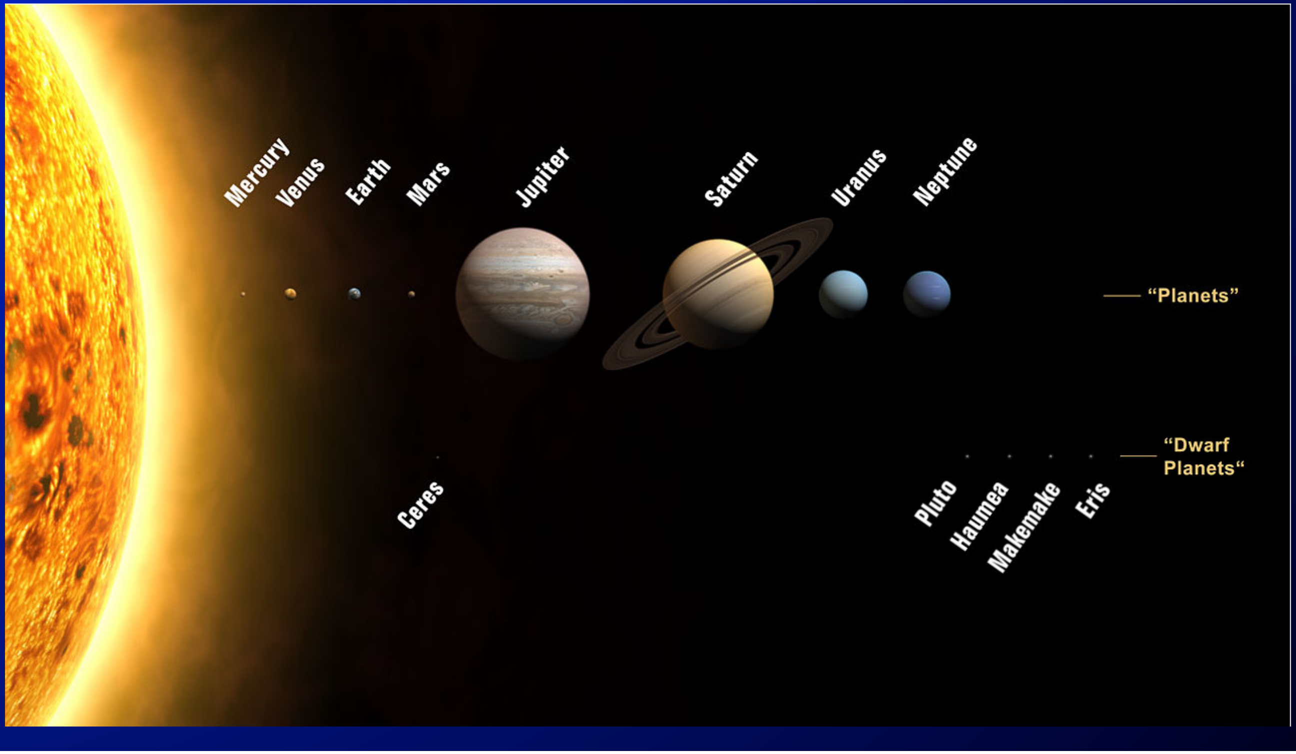


- The IAU states: „the term 'minor planet' may still be used, but generally the term 'small solar system body' will be preferred.“

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)

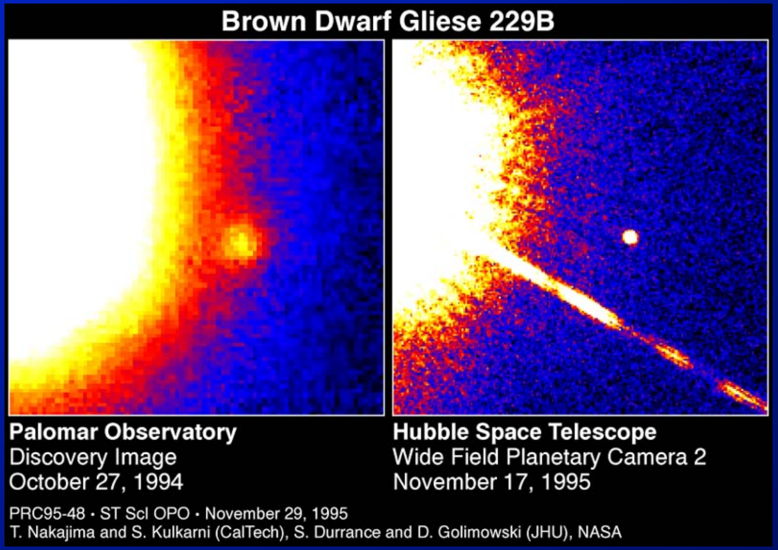


Extrasolar planets / Exoplanets

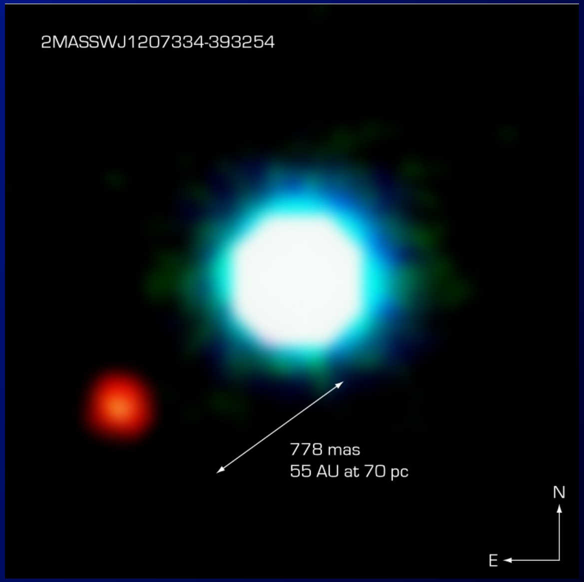
- An **extrasolar planet**, or **exoplanet**, is a planet beyond our solar system, orbiting a star other than our Sun.
  - at 1 September 2010: 413 planetary systems; 490 planets
    49 multiple planet systems
- The "working" definition for extrasolar planets (IAU 2001, 2003) → criteria:
  - Objects with masses below the limiting mass for thermonuclear ***fusion of deuterium*** (~ 13 $M_{\mathbf{Jupiter}}$, 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 $M_{\mathbf{Jupiter}}$ (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 $M_{\mathbf{Jupiter}}$ → "**sub-brown dwarfs**" not planets !!!

Extrasolar planets / Exoplanets

- Free-floating PLANEtary Mass Objects - **Planemos** (IAU, 2003)- called also „*rogue planets*“ or „*interstellar planets*“ -- may have formed as a planet around a star, but were subsequently ejected from that planetary system.
  - Planemo often is used to denote in general ***an object [rounded by self-gravity] that does not achieve core fusion during its lifetime*** (regardless of its orbit)



Gliese 229B, is ~ 20 - 50 $M_{Jupiter}$
near red dwarf in constell. Lepus



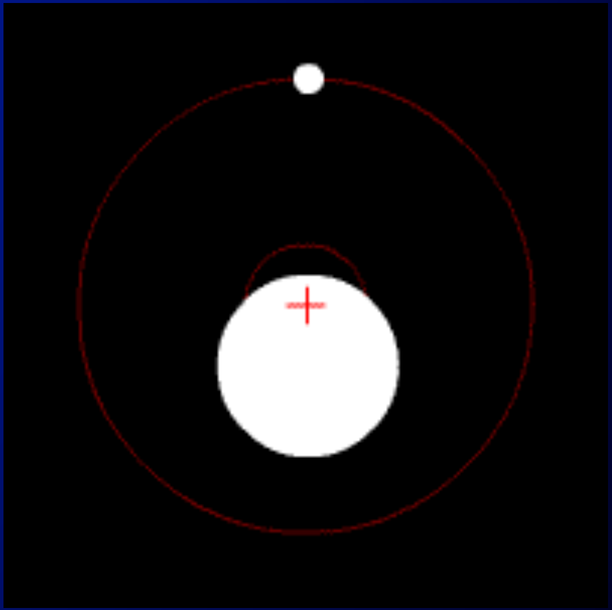
Planemo 2M1207b, ~ 3-10 $M_{Jupiter}$,
orbiting Brown dwarf in Centaurus
(VLT, infrared imaging, Sep.2004)

Methods of detecting extrasolar planets (10 major)

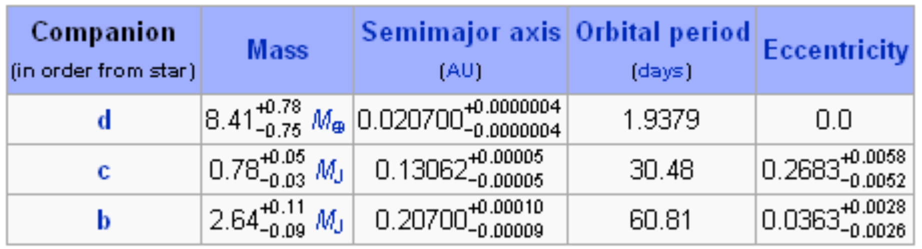
- **Astrometry**: tiny variations of a star's position
- **Radial velocity / Doppler method**: speed variations at which star moves towards/away from the Earth (observer)
- **Pulsar timing**: anomalies in the timing of pulsar's pulses.
- **Transit method**: periodic depletions of stellar btightness due 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)

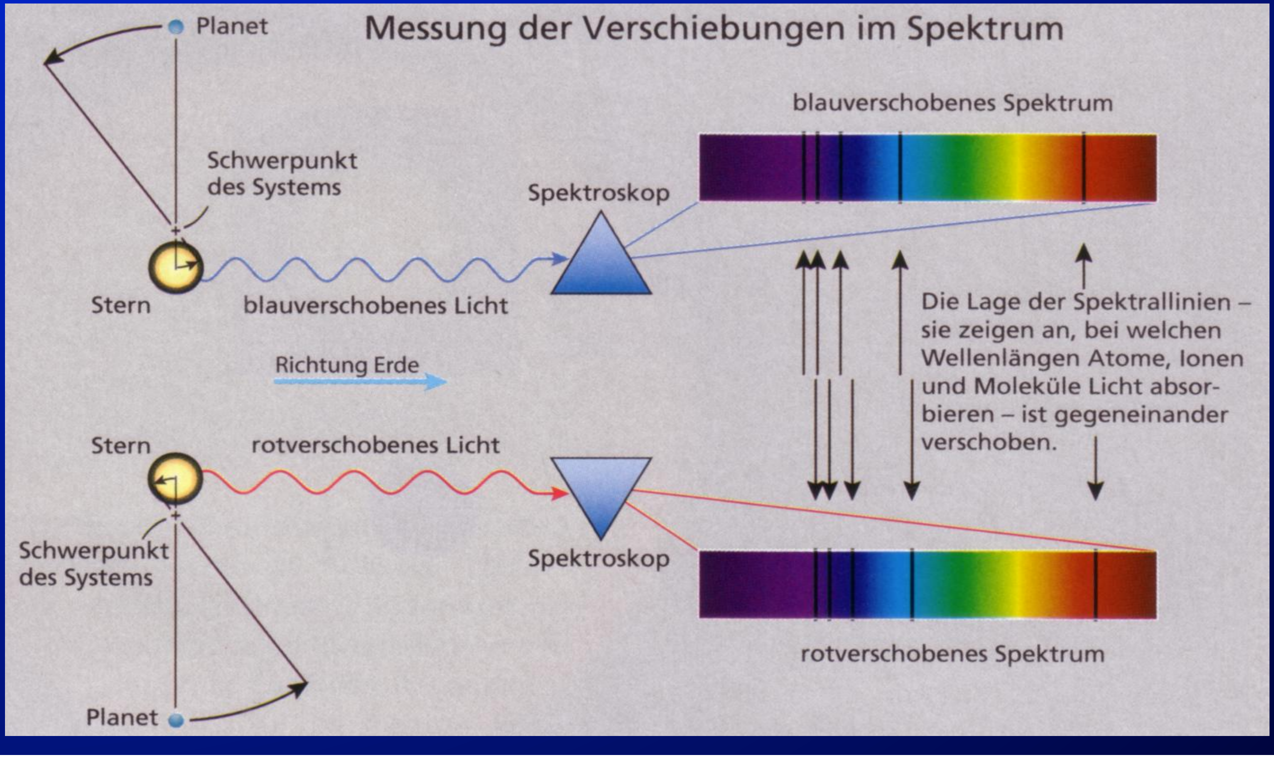


Companion (in order from star)	Mass	Semimajor axis (AU)	Orbital period (days)	Eccentricity
d	$8.41^{+0.78}_{-0.75}$ $M_{\oplus}$	$0.020700^{+0.0000004}_{-0.0000004}$	1.9379	0.0
c	$0.78^{+0.05}_{-0.03}$ M_J	$0.13062^{+0.00005}_{-0.00005}$	30.48	$0.2683^{+0.0058}_{-0.0052}$
b	$2.64^{+0.11}_{-0.09}$ M_J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

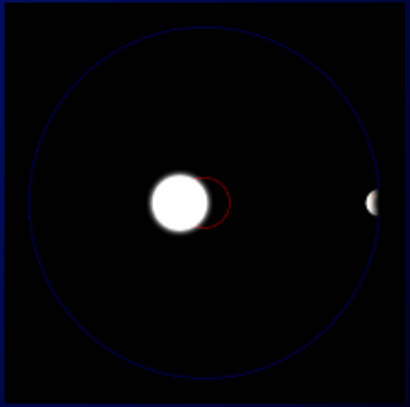
Methods of detecting extrasolar planets

- **Radial velocity / Doppler method**: **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**)



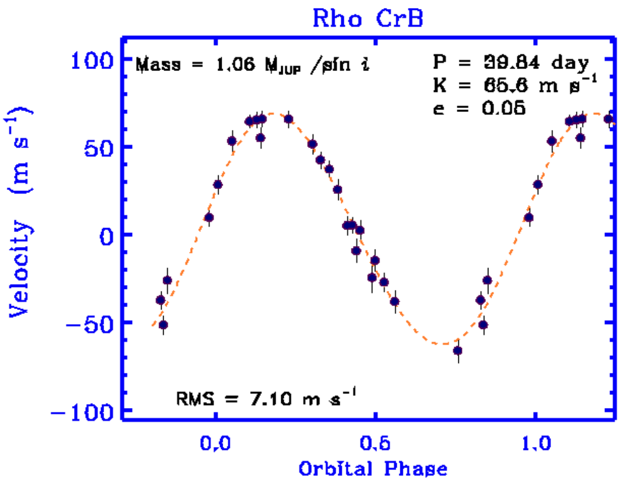
Die Lage der Spektrallinien – sie zeigen an, bei welchen Wellenlängen Atome, Ionen und Moleküle Licht absorbieren – ist gegeneinander verschoben.

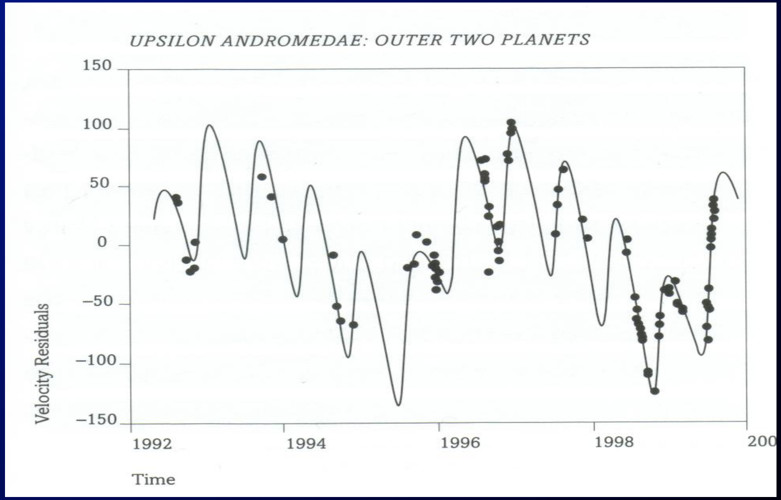


Methods of detecting extrasolar planets

- **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)





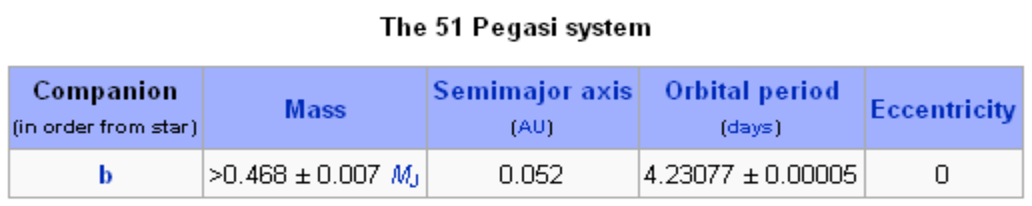
Methods of detecting extrasolar planets

- **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 :

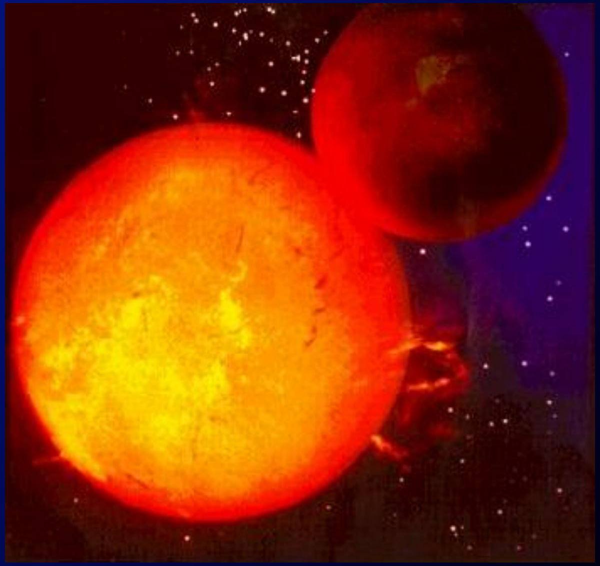
    - Yellow dwarf, in ***Pegasus*** constellation (~50,1 light-years)
    - Spectral type G2.5V (Sun is G2V)
    - 4–6% more massive then Sun
    - Apparent magnitude: 5.49
    - 7.5 billion years old

  - 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



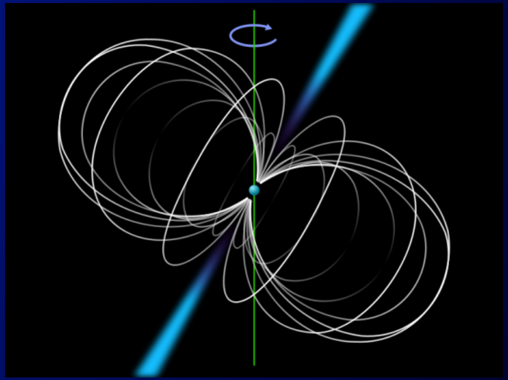
  - Discovery and confirmations:

    - 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)

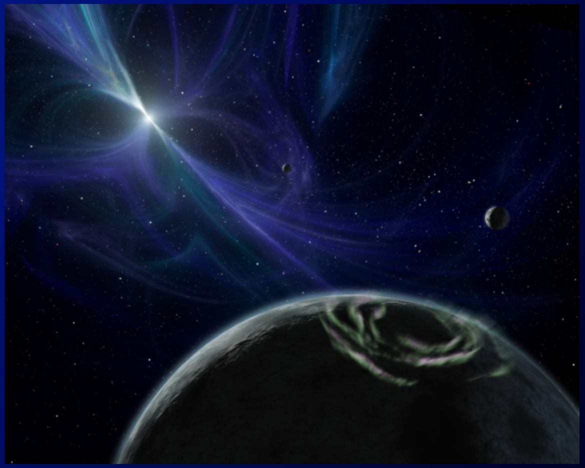
Image - from Chandra X-ray obs. (1999).

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



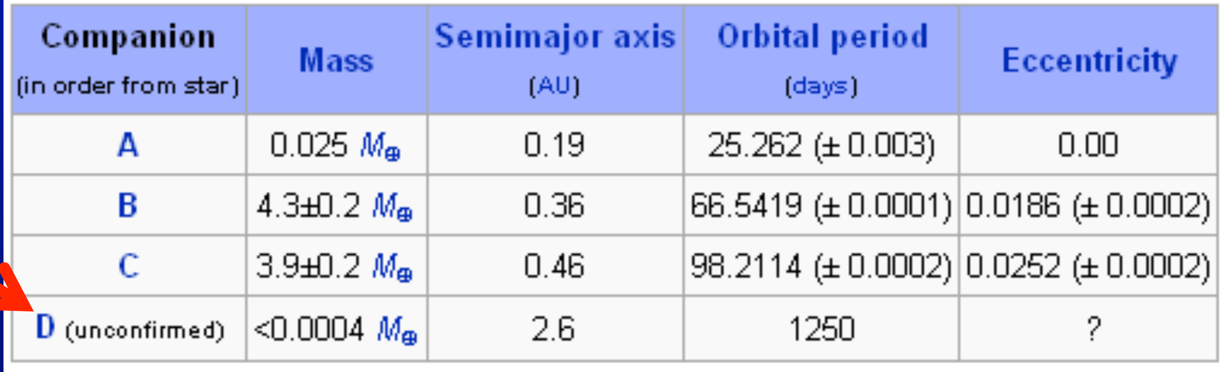
- Traditional life forms could not survive on planets orbiting pulsars (high-energy radiation, postexplosion stage of star evolution).

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).

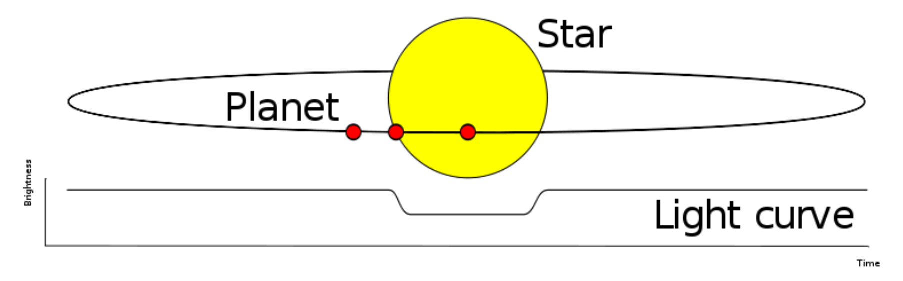
First Dwarf exoplanet

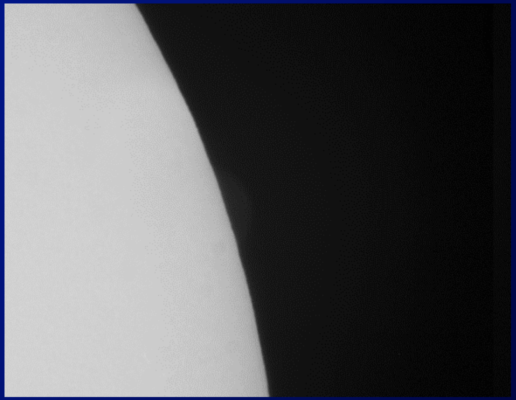


Companion (in order from star)	Mass	Semimajor axis (AU)	Orbital period (days)	Eccentricity
A	0.025 $M_\oplus$	0.19	25.262 (± 0.003)	0.00
B	4.3±0.2 $M_\oplus$	0.36	66.5419 (± 0.0001)	0.0186 (± 0.0002)
C	3.9±0.2 $M_\oplus$	0.46	98.2114 (± 0.0002)	0.0252 (± 0.0002)
D (unconfirmed)	<0.0004 $M_\oplus$	2.6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

Methods of detecting extrasolar planets

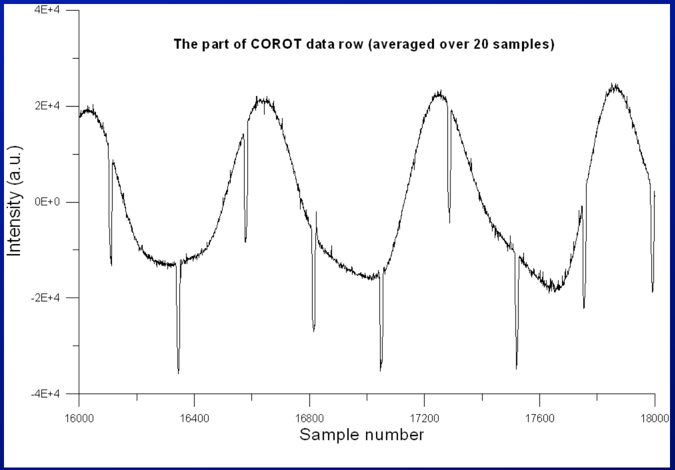
- **Transit method**: measuring of periodic depletions of stellar btightness caused by planet transits in front of the star disk

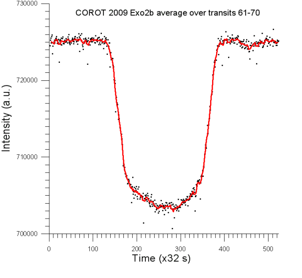




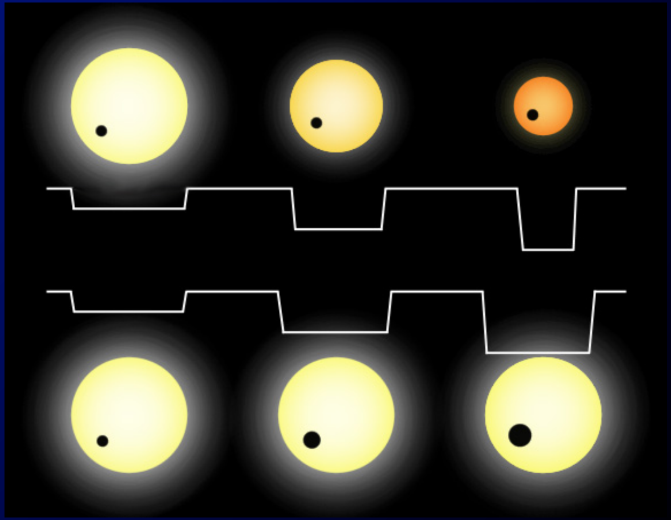
Venus transit
(M. Karrer, St.Radegund / Austria)

- 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

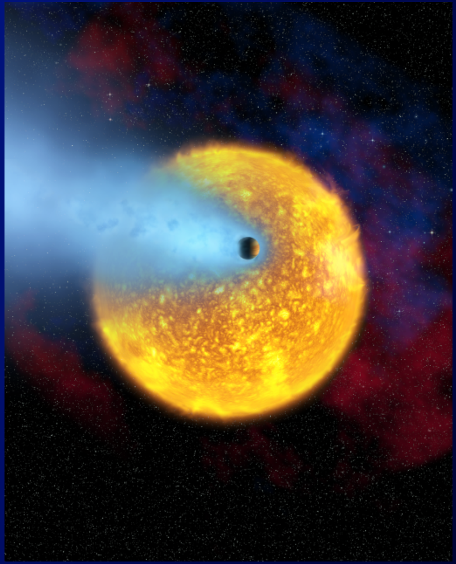
- **Transit method**: **measuring of periodic depletions of stellar btightness caused by planet transits in front of the star disk**

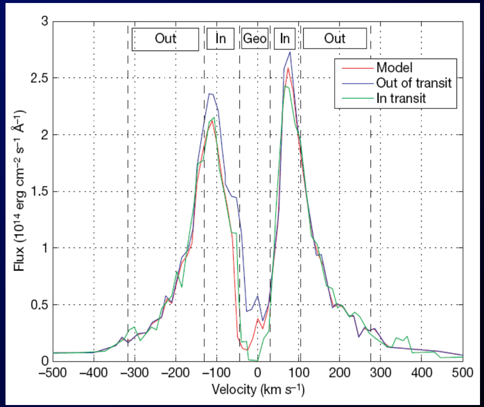
- Advantages:
  - Can determine the size ($\mathbf{R}_{planet}$) of a planet;
  - In combination with the radial velocity method (which gives $\mathbf{M}_{planet}$) enables determination of the planet density (→ physical properties);
  - Study of atmosphere of a transiting planet:

→ ***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



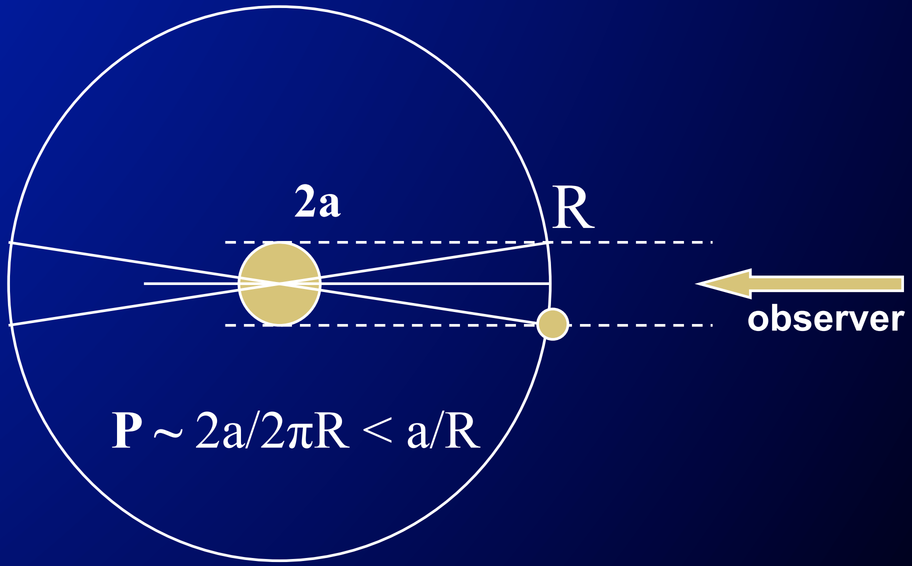


Methods of detecting extrasolar planets

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

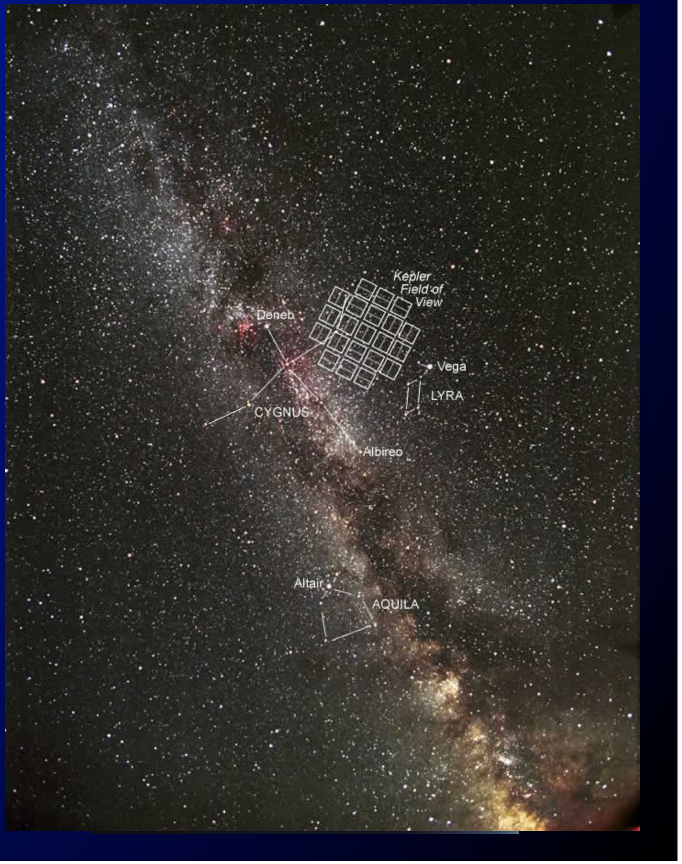
    Objectives:

    - 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

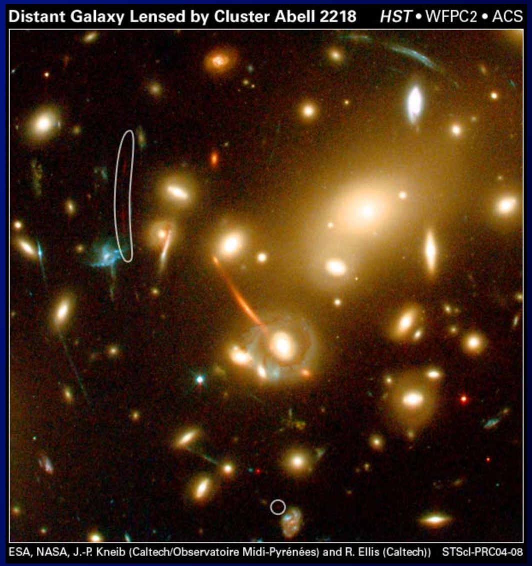
    Objectives:

    - 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**



Distant Galaxy Lensed by Cluster Abell 2218 *HST* • WFPC2 • ACS

ESA, NASA, J.-P. Kneib (Caltech/Observatoire Midi-Pyrénées) and R. Ellis (Caltech)) STScI-PRC04-08

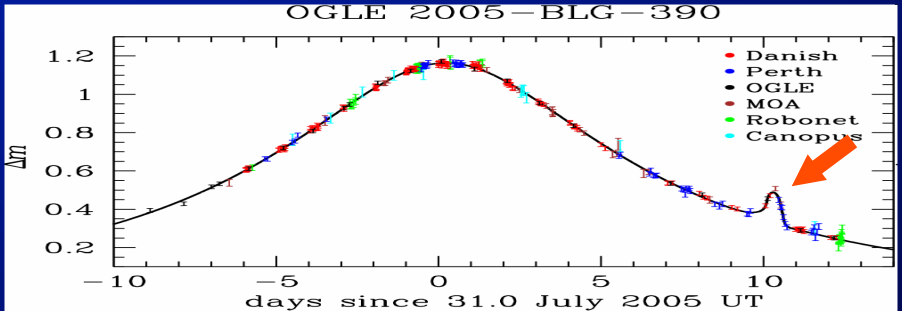
- ***Gravitational lensing*** occurs when the gravitational field of a star acts like a lens, bending the light of a distant background object

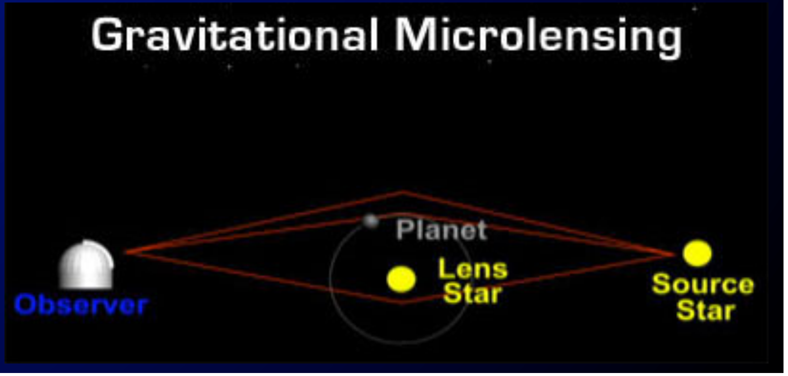
  ⇒ multiple distorted, magnified, and brightened images of the background source.

- ***Gravitational microlensing***

  Lensing mass is small → different observation technique

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

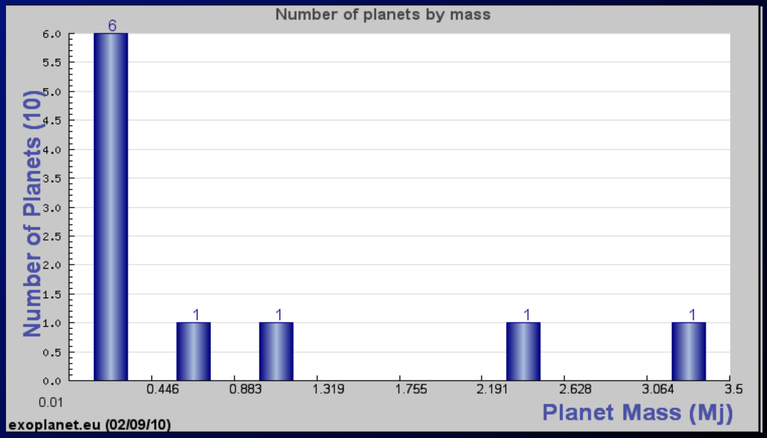




Methods of detecting extrasolar planets

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

- Advantages:
  - can detect Earth-like planets at moderately wide orbits around ordinary main-sequence stars (e.g., **OGLE-2005-BLG-390Lb** by M-star in ***Scorpius*** near the center of the ***Milky Way*** in Jan.2006 – 1st low-mass (5,5M_{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_{Planet} and orbital distance
  - Can be performed automatically (networks of robotic telescopes)



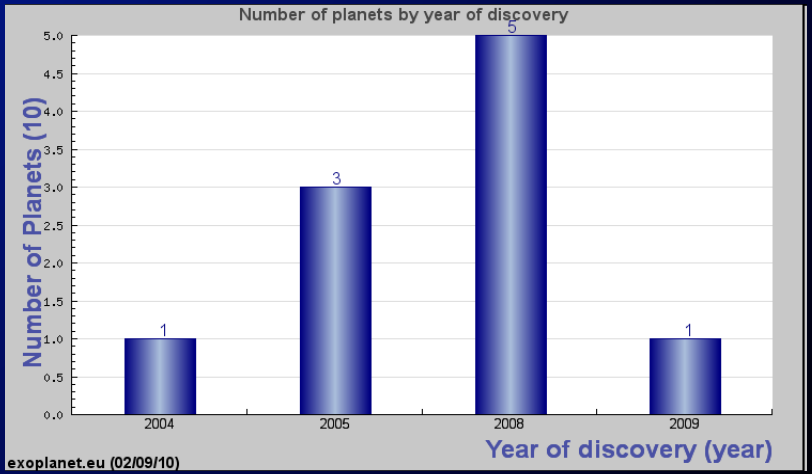
exoplanet.eu (02/09/10)

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

- Discoveries:
  9 planetary systems
  10 planets / **1** multiple planet systems



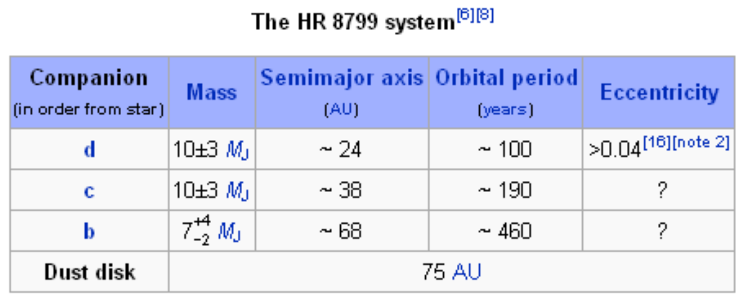
Methods of detecting extrasolar planets

- **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).

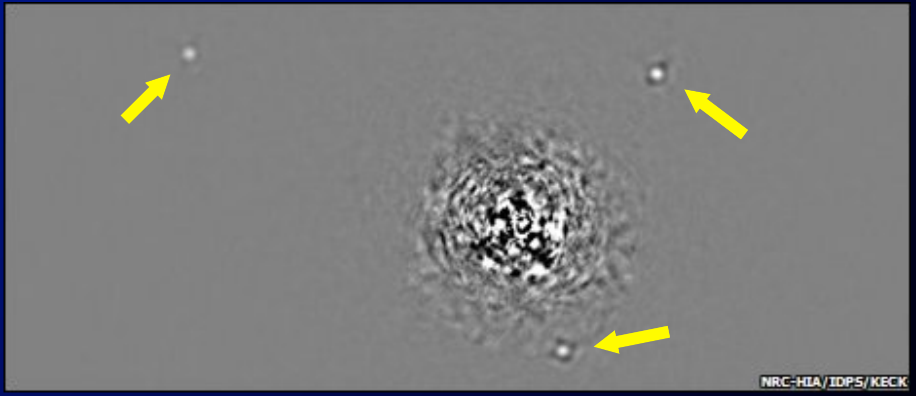
- Discoveries:

  11 planetary systems / 13 planets / 1 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

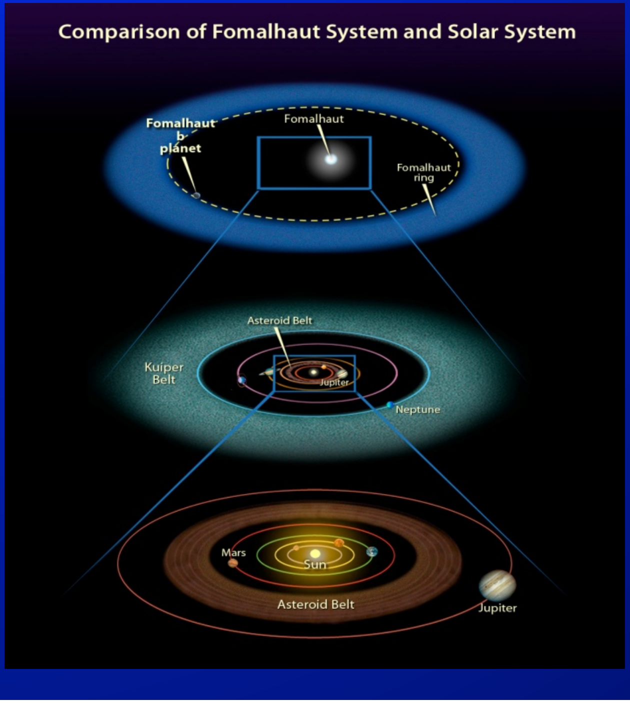
Subaru Telescope, Hawaii

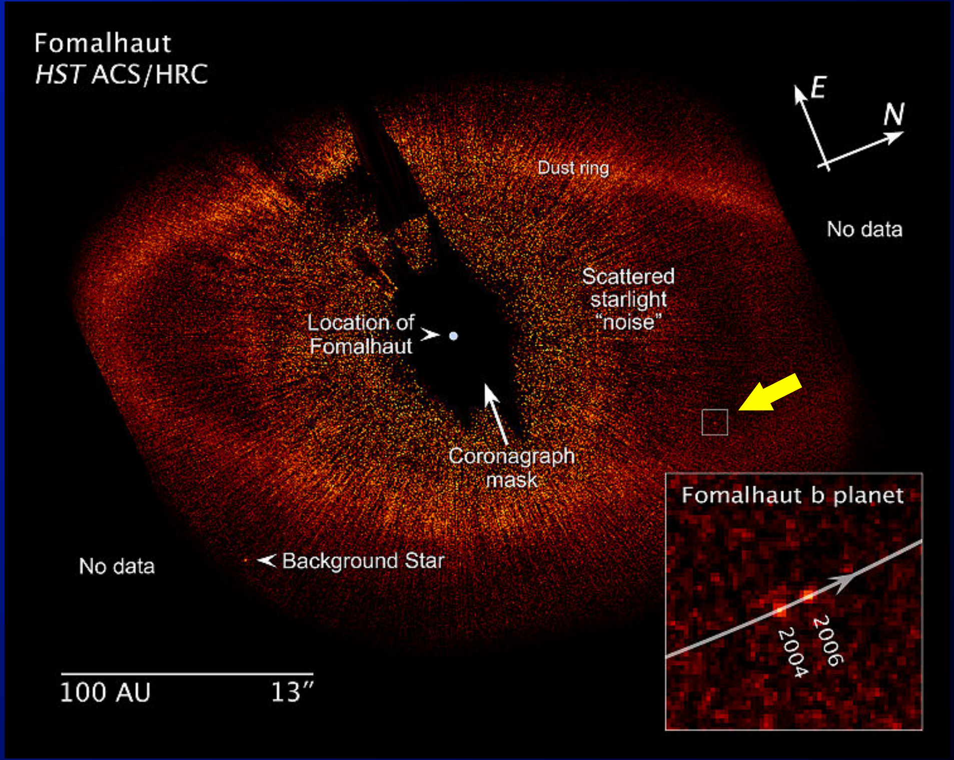
VLT, Paranal Obs., Chile

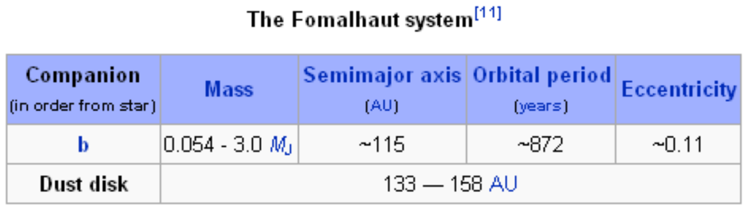
Methods of detecting extrasolar planets

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

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







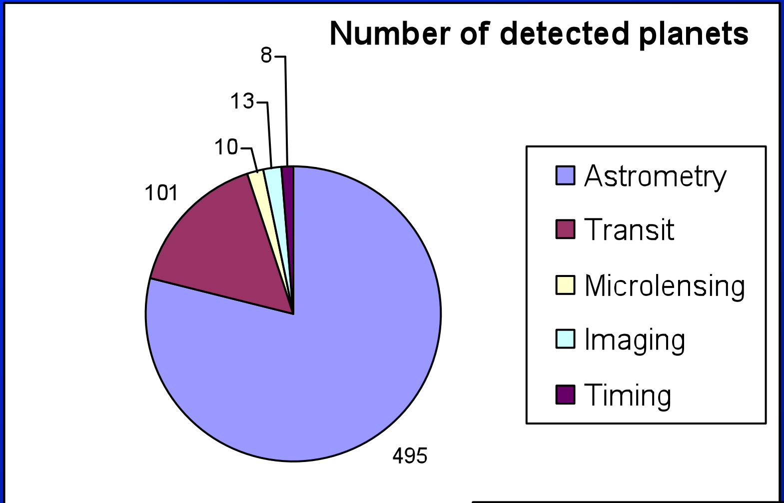
The Fomalhaut system[11]

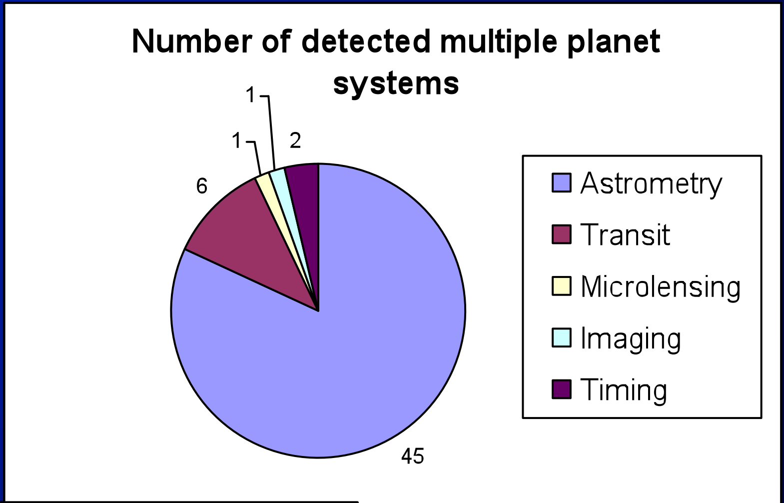
Companion (in order from star)	Mass	Semimajor axis (AU)	Orbital period (years)	Eccentricity
b	0.054 - 3.0 M_J	~115	~872	~0.11
Dust disk	133 — 158 AU			

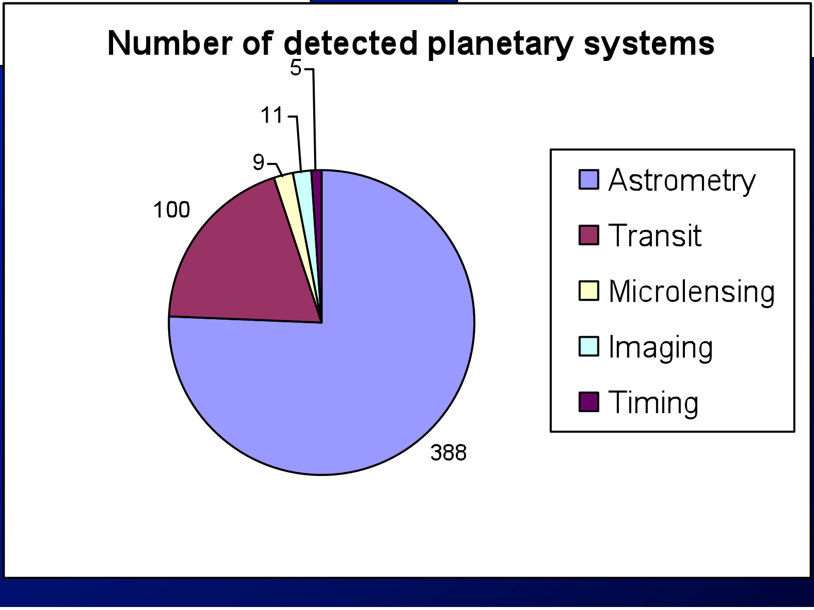
Fomalhaut b (in the Fomalhaut's dust cloud) imaged by The Hubble Space Telescope's coronagraph (ACS/HRC)

Methods of detecting extrasolar planets

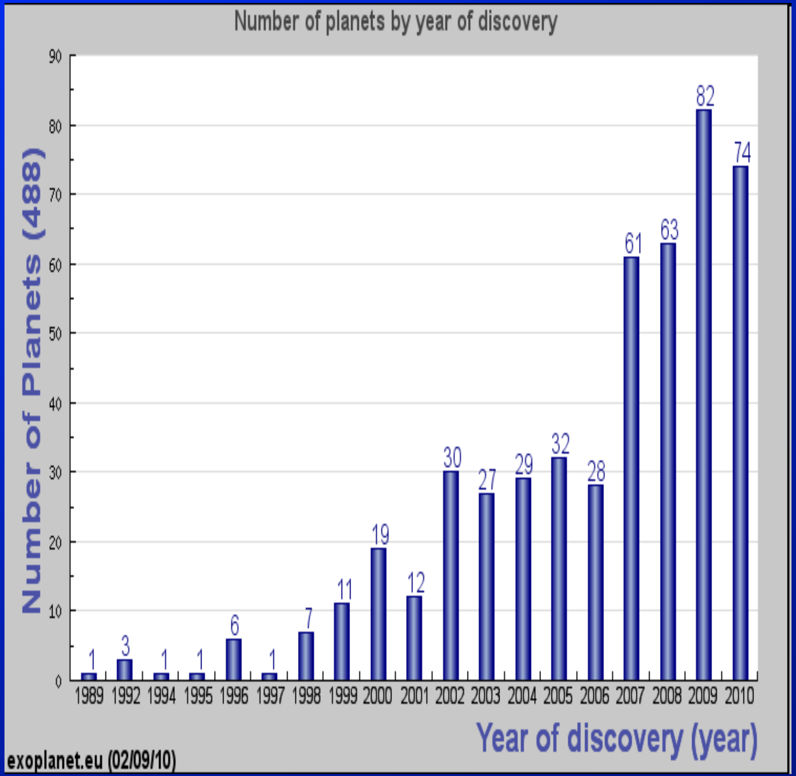
- **Summary of discoveries:**



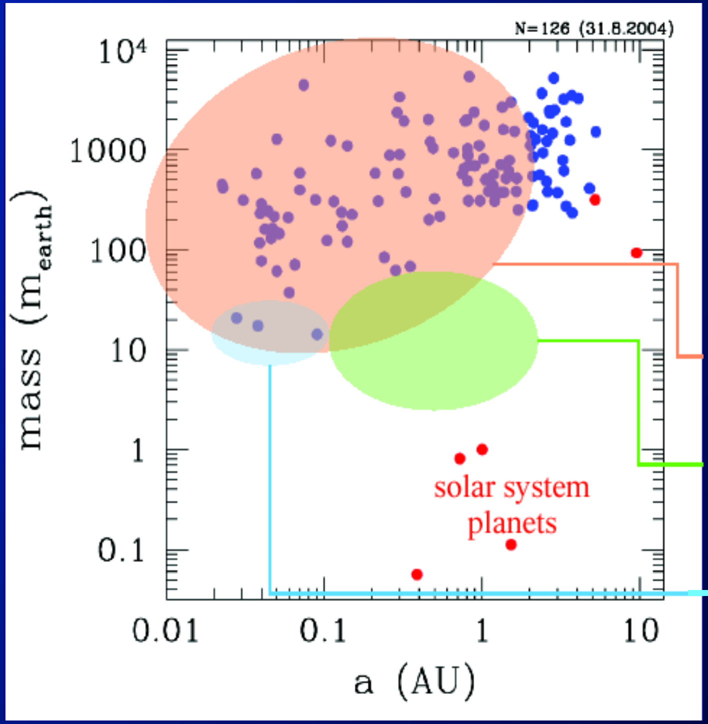




Exoplanets statistic // status Sep. 2010



- 413 Exoplanetary systems
- 490 Exoplanets
- 49 Multiple Planetary systems



In-situ formation vs. Migration ?

Bias ?

? Evolution of planets

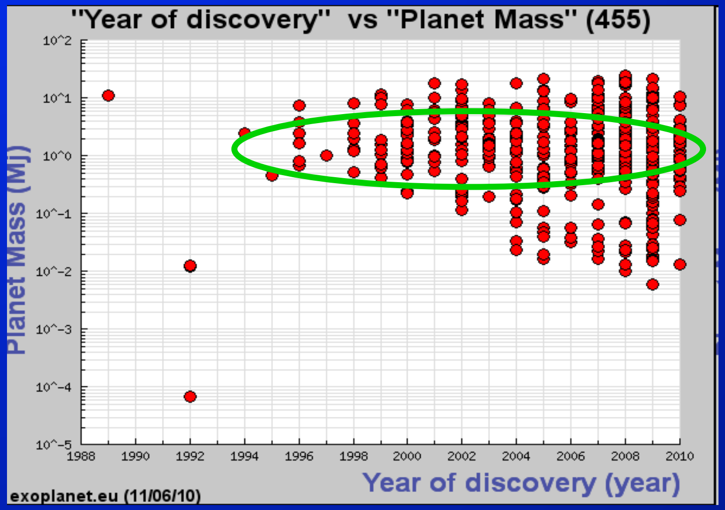
? Formation of terrestrial type worlds

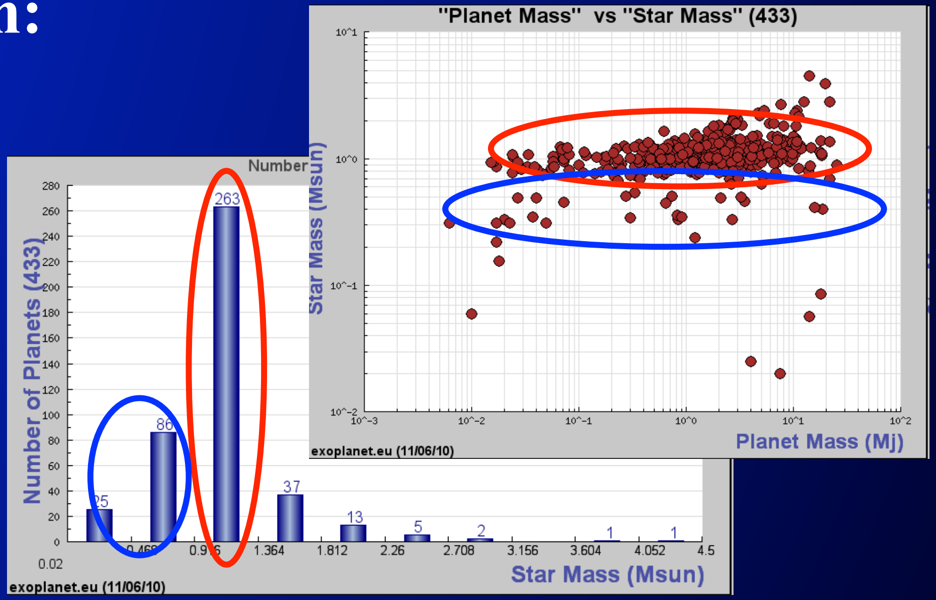
Super-Earths ?

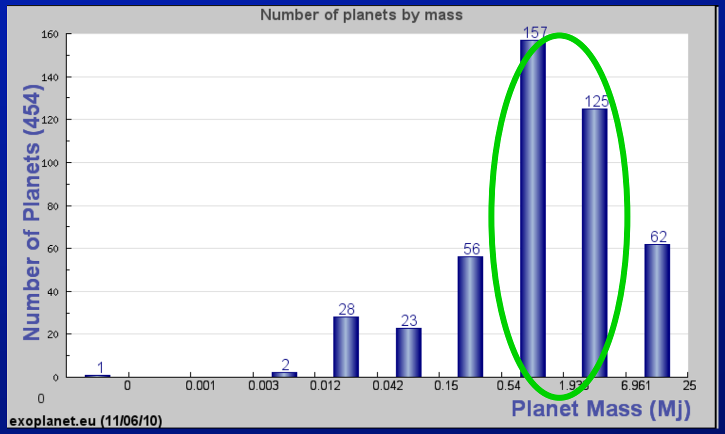
- 25 planets, <10 m_{Earth}

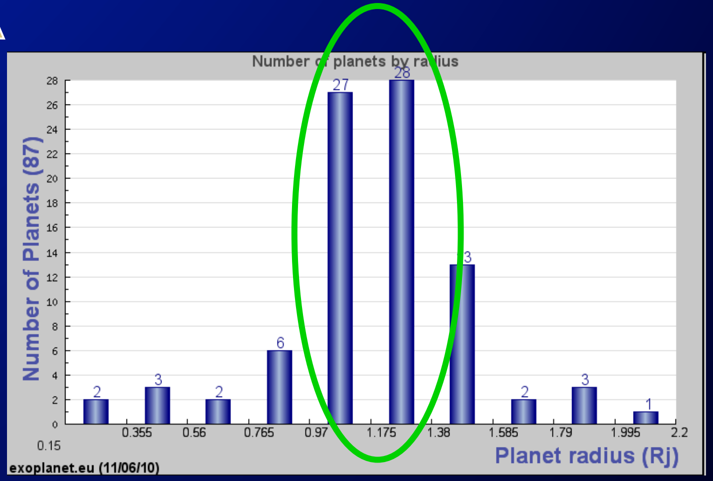
Exoplanets statistic // status Sep. 2010

- Exoplanet characterization:









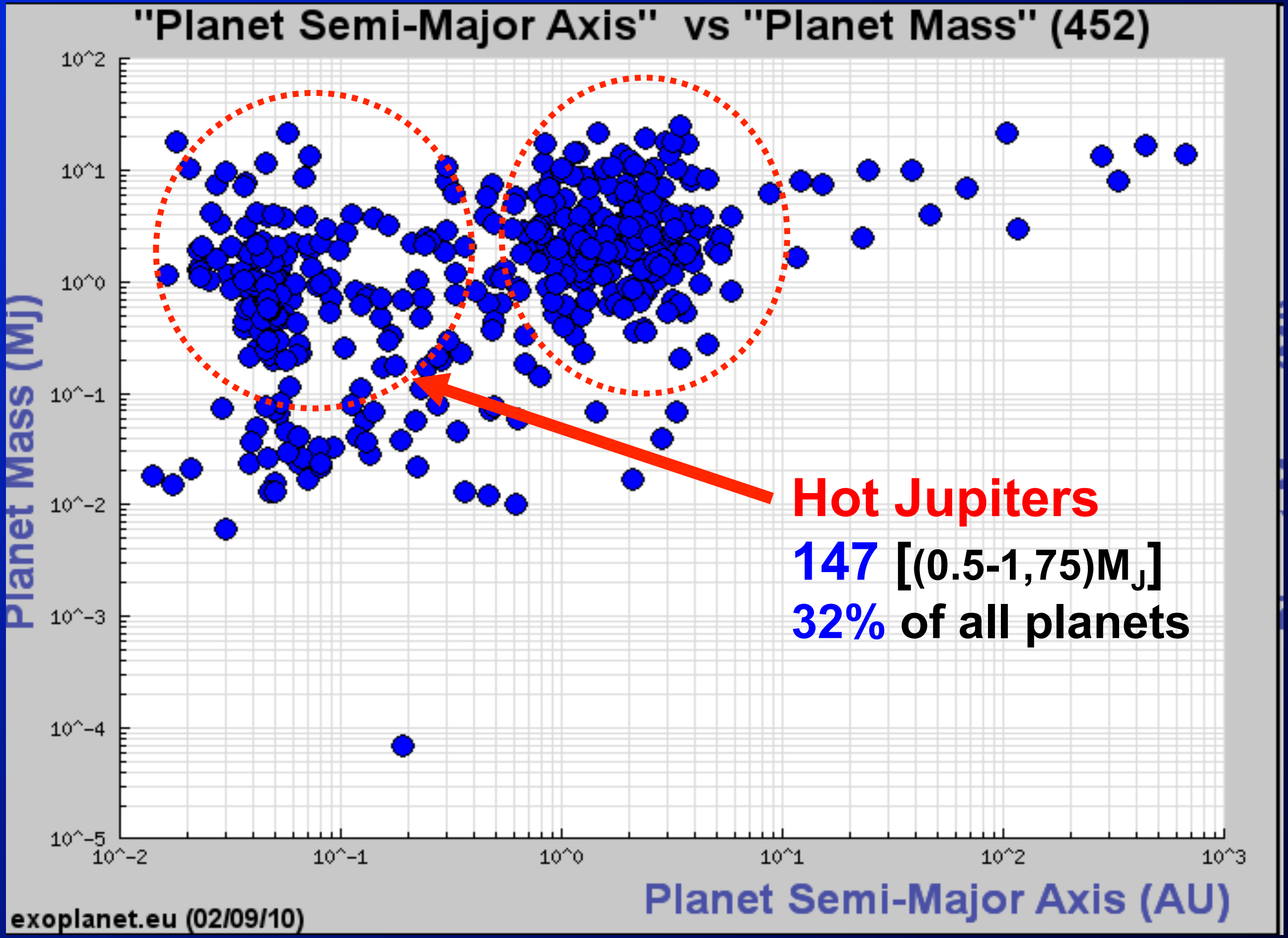
Jupiter-like planets (74%)

Sun-like stars

2-nd large population near dwarf stars

Exoplanets statistic // status Oct. 2009

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



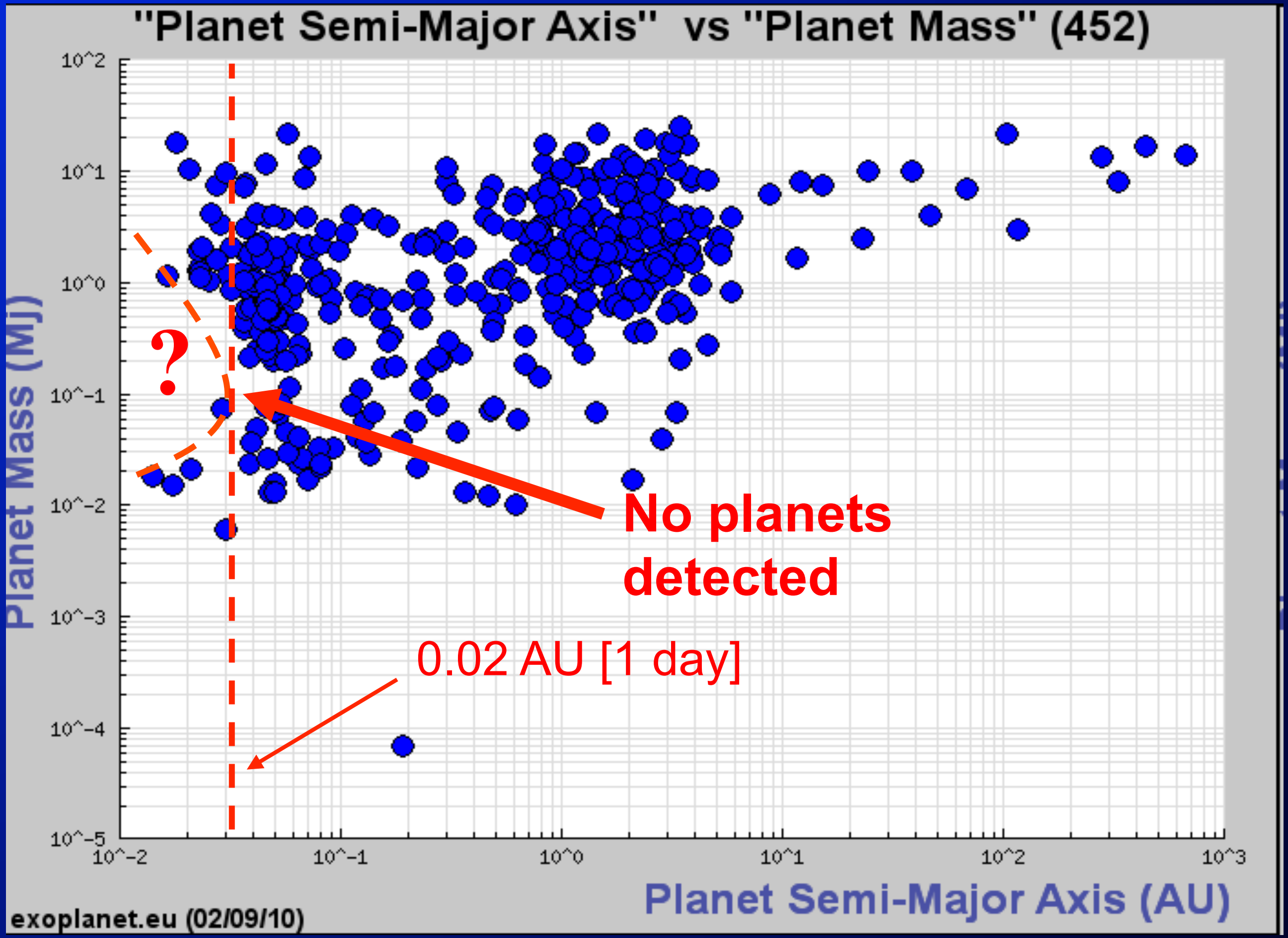
Hot Jupiters

147 [(0.5-1,75)M_J]

32% of all planets

Exoplanets statistic // status Oct. 2009

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



exoplanet.eu (02/09/10)

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 ?

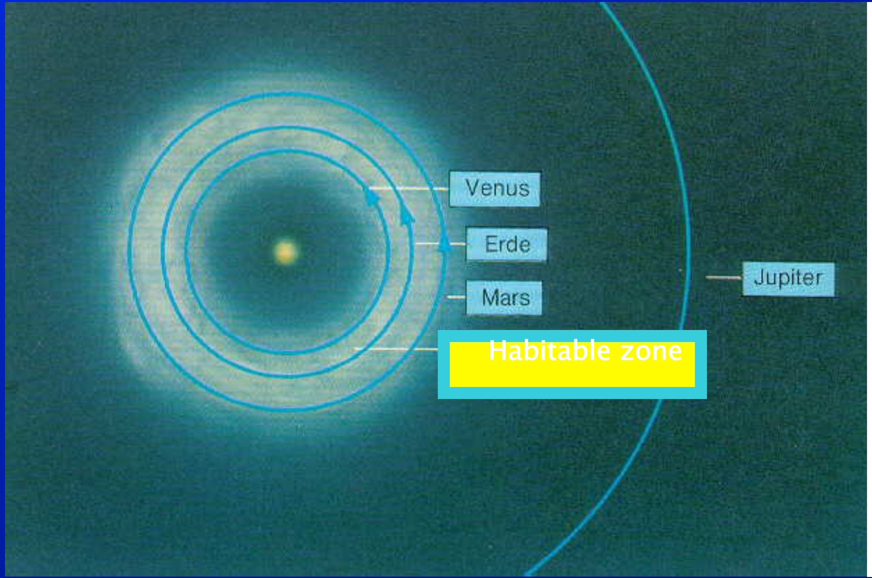
- (?) ***Evolution of planetary environments***
  - → Magnetic dynamo / Intrinsic magnetic field / magnetosphere
  - → Surface
  - → Atmosphere

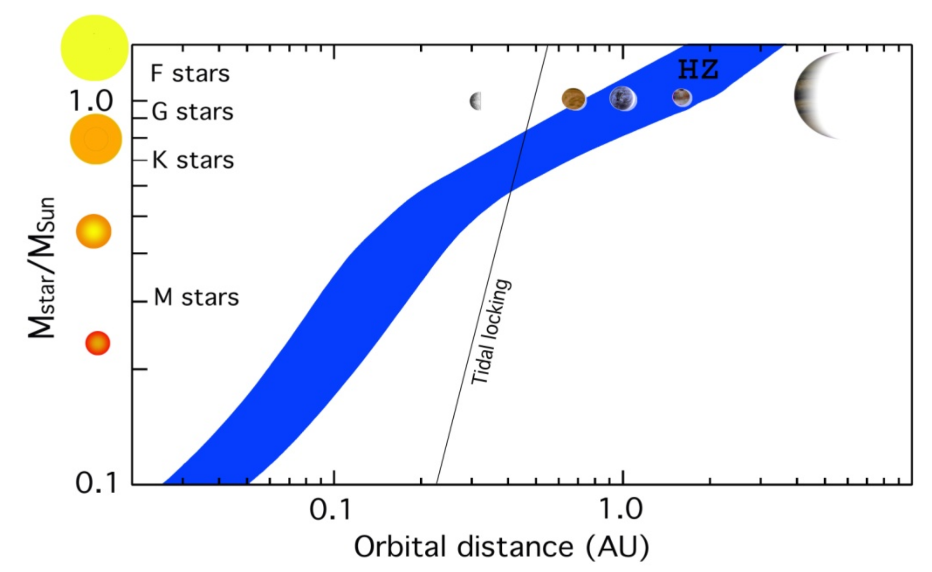
- (?) ***Could life have evolved somewhere else besides of Earth ?***
  - → Definition of life / life forms
  - → Conditions for life development

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

Habitability – definition & major influencing factors:

- **Traditional definition:** Stellar Habitable Zone (HZ) is an area around a star, where climate & geophysical conditions on a planet with an atmosphere allow existence of ***liquid H2O on the surface*** over geological time periods





The width and distance of HZ depends on the stellar luminosity that evolves during the star`s lifetime

Habitability – definition & major influencing factors:

- **Traditional definition:**

- ***Simplifications:***
  - → Consideration of ***Terrestrial-type*** planets
  - → Assumption about ***Stellar luminosity as a major influencing factor***

- ***Limitations:***
  - → ***The classical HZ is defined for surface conditions only***

The question of a planetary habitability is *much more complex than just having a planet located at the right distance* from its host star, in order to keep liquid water on its surface. → Generalized definition of HZ

”

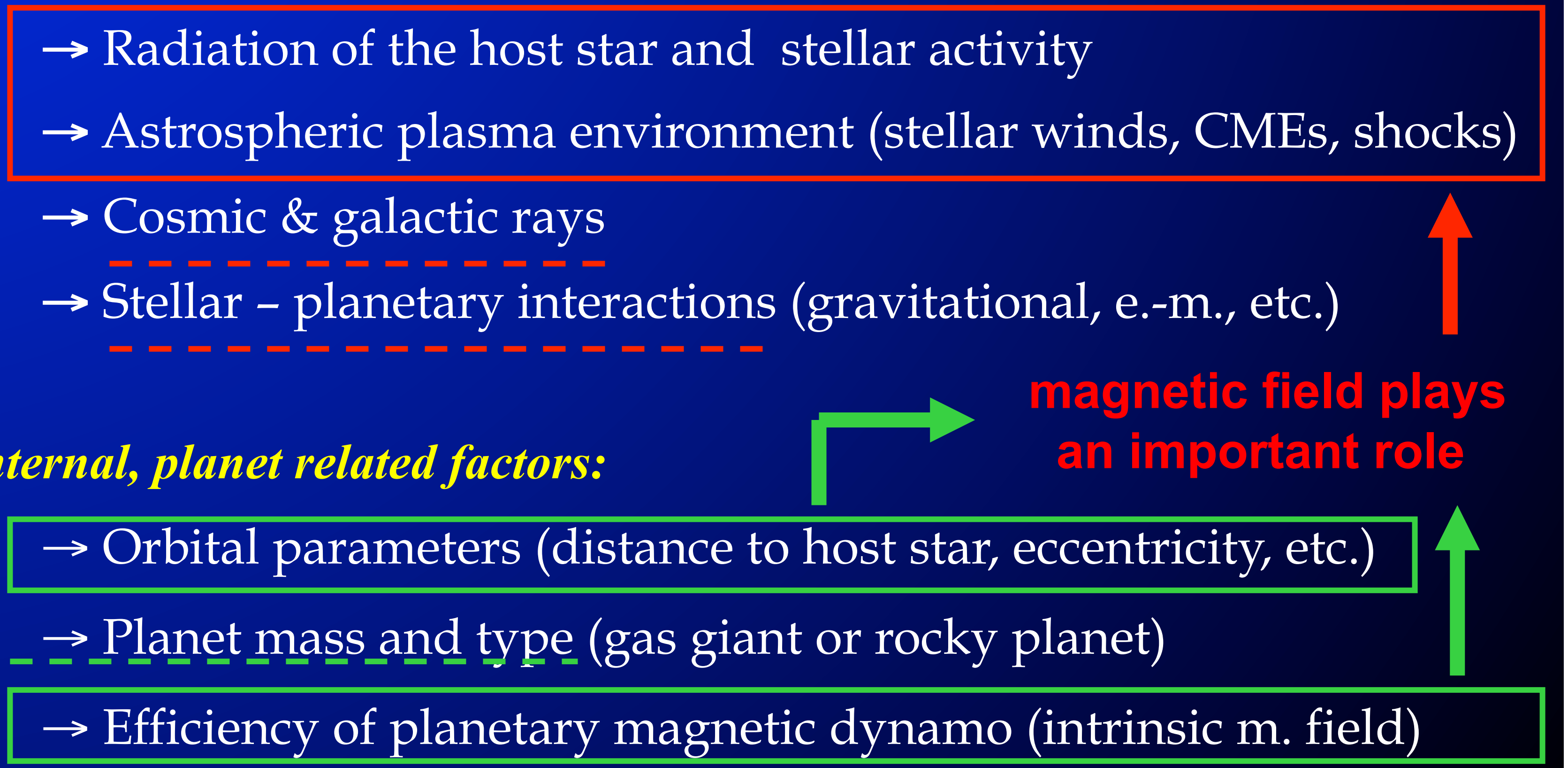
se

crucial parameter -- average stellar flux received by the planet)

Habitability – definition & major influencing factors:

- **Two groups of 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)

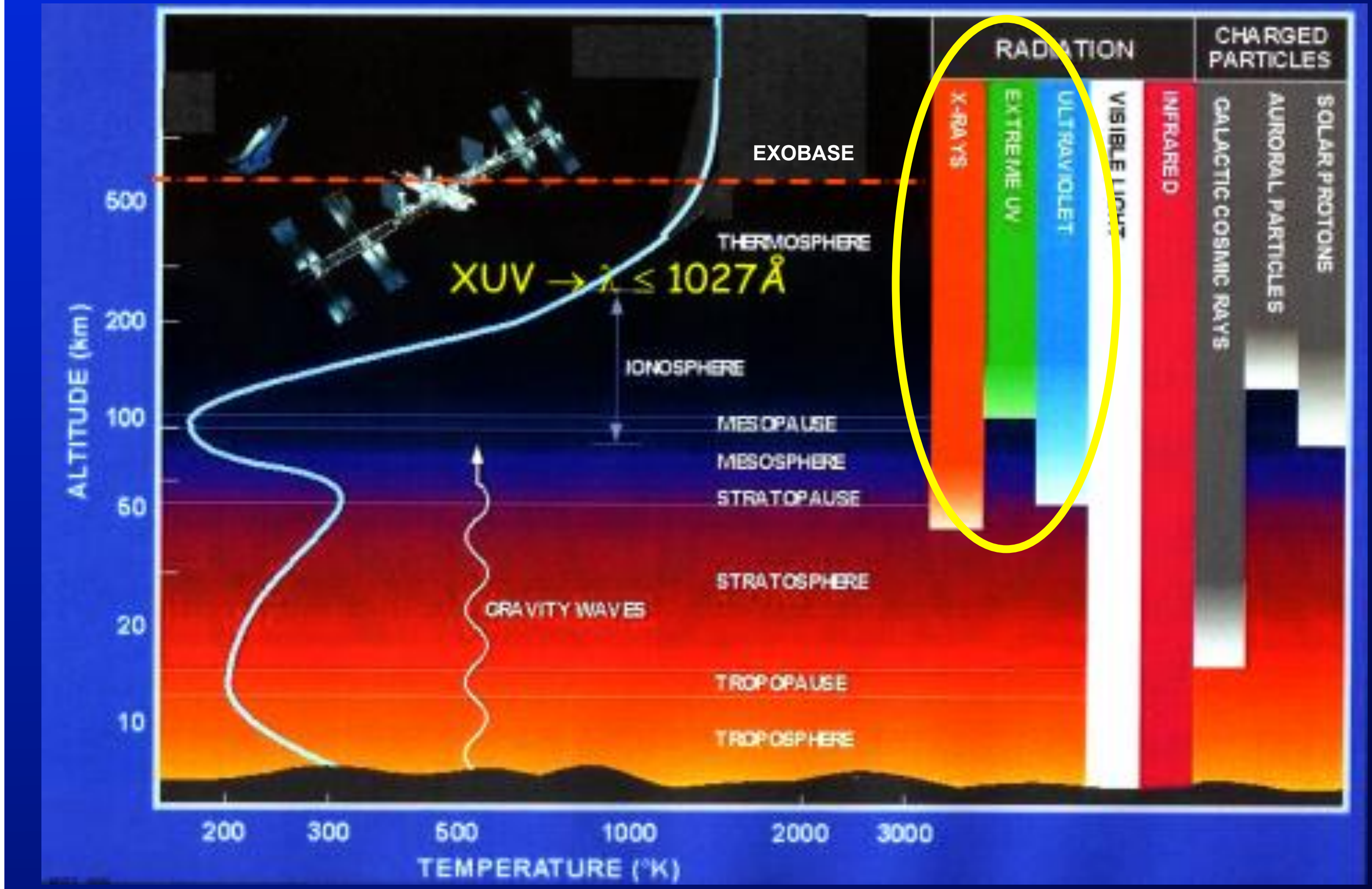
→ Efficiency of planetary magnetic dynamo (intrinsic m. field)

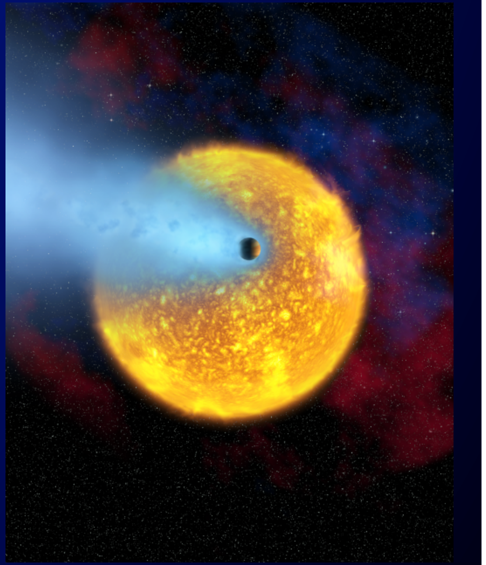
→ Atmosphere composition

Stellar radiation & plasma – key factors for planet evolution

- Stellar X-ray & EUV luminosity → **energy deposition to upper atmospheres**

Stellar XUV induce ***expansion and loss of planetary upper atmospheres***





Stellar radiation & plasma – key factors for planet evolution

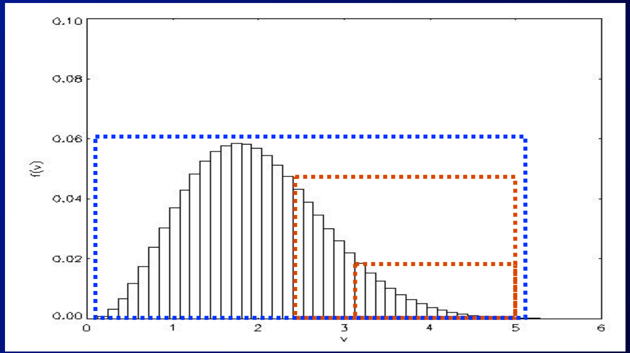
- **Soft X-ray and EUV induced expansion of the upper atmospheres**

  ⇒ high ***thermal*** & ***non-thermal*** loss rates

  - ***Thermal escape***: particle energy > W_{ESC}

    → Jeans escape – particles from “tails”

    → hydrodynamic escape – all particles



  - ***Non-thermal escape***:

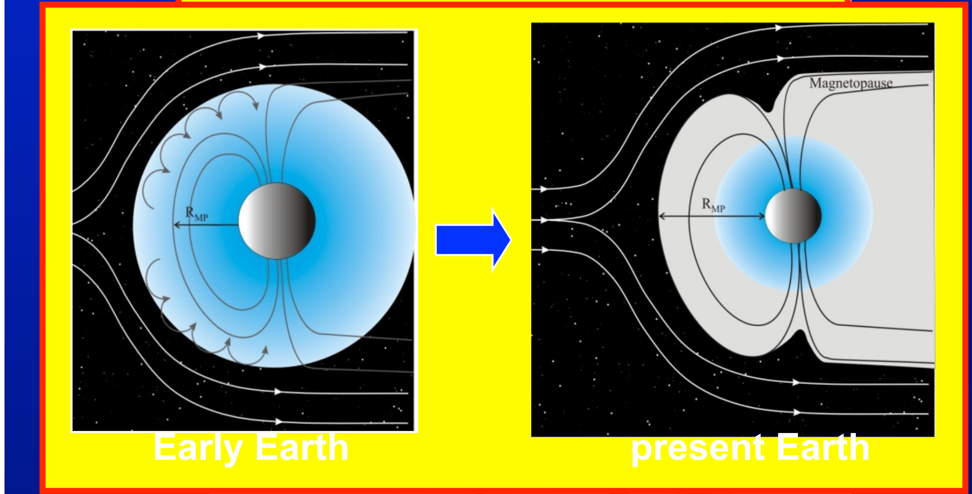
    → Ion pick-up

    → Sputtering (S.W. protons & ions)

    → Photo-chemical energizing & escape

    → Electromagnetic ion acceleration

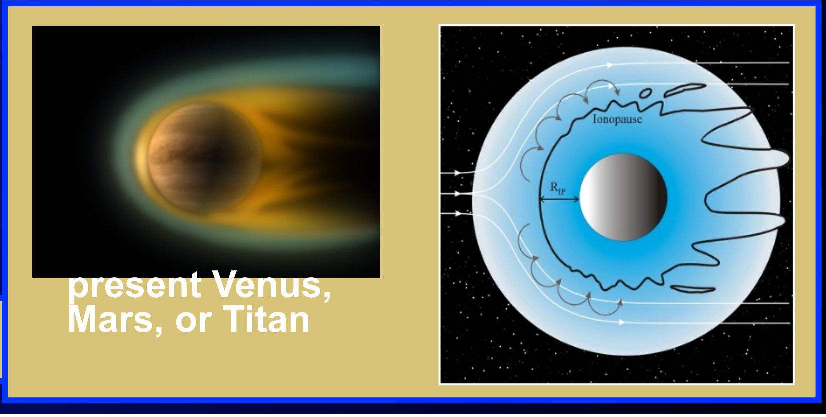
Magnetically protected planet



Early Earth

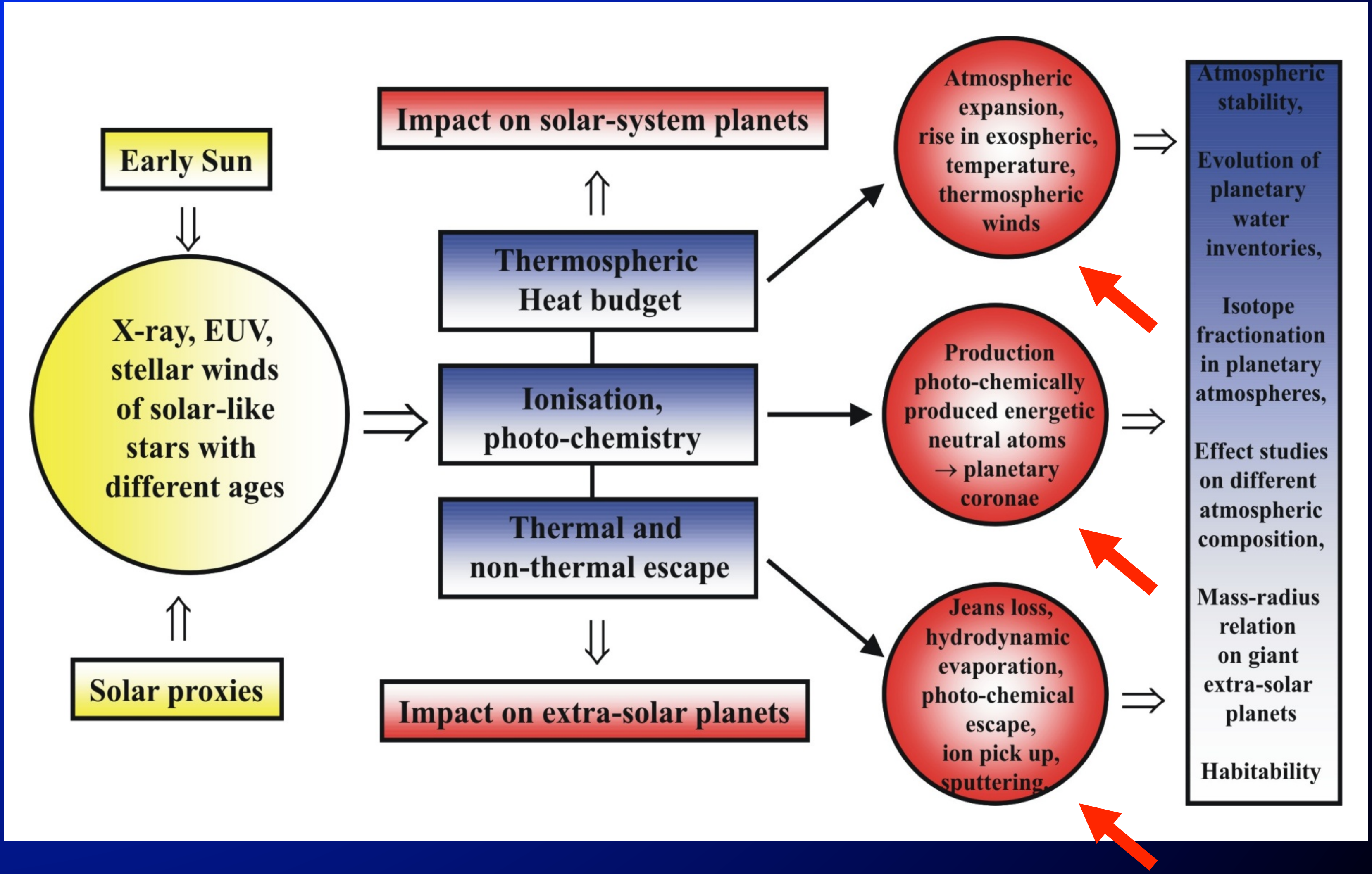
present Earth

Magnetically non-protected planet



present Venus, Mars, or Titan

Stellar radiation & plasma – key factors for planet evolution



Early Sun

X-ray, EUV, stellar winds of solar-like stars with different ages

Solar proxies

Impact on solar-system planets

Thermospheric Heat budget

Ionisation, photo-chemistry

Thermal and non-thermal escape

Impact on extra-solar planets

Atmospheric expansion, rise in exospheric, temperature, thermospheric winds

Production photo-chemically produced energetic neutral atoms → planetary coronae

Jeans loss, hydrodynamic evaporation, photo-chemical escape, ion pick up, sputtering,

Atmospheric stability,

Evolution of planetary water inventories,

Isotope fractionation in planetary atmospheres,

Effect studies on different atmospheric composition,

Mass-radius relation on giant extra-solar planets

Habitability

Planetary magn.field and size of magnetosphere – key factors

Exoplanet magnetic field – planet protecting role

- Magnetic moment estimation from scaling laws → range for possible *M*

$M \propto \rho_c^{1/2}\, \omega r_c^4$	**Busse, F. H., *Phys. Earth Planet. Int.*, 12, 350, 1976**
$M \propto \rho_c^{1/2}\, \omega^{1/2}\, r_c^3\, \sigma^{-1/2}$	**Stevenson, D.J., *Rep. Prog. Phys.*, 46, 555, 1983**
$M \propto \rho_c^{1/2}\, \omega^{3/4}\, r_c^{7/2}\, \sigma^{-1/4}$	**Mizutani, H., et al., *Adv. Space Res.*, 12, 265, 1992**
$M \propto \rho_c^{1/2}\, \omega^{1/2}\, r_c^3\, \sigma^{-1/2}$	**Mizutani, H., et al., *Adv. Space Res.*, 12, 265, 1992**
$M \propto \rho_c^{1/2}\, \omega r_c^{7/2}$	**Sano, Y., *J. Geomag. Geoelectr*, 45, 65, 1993**

$\Longrightarrow$ Interval of possible values for planetary magnetic dipole:

$M_{max} \dots M_{min}$

r_c - radius of the dynamo region (“core radius”): $r_c \sim M_P^{0.75}\, R_P^{-0.96}$

ρ_c - density in the dynamo region

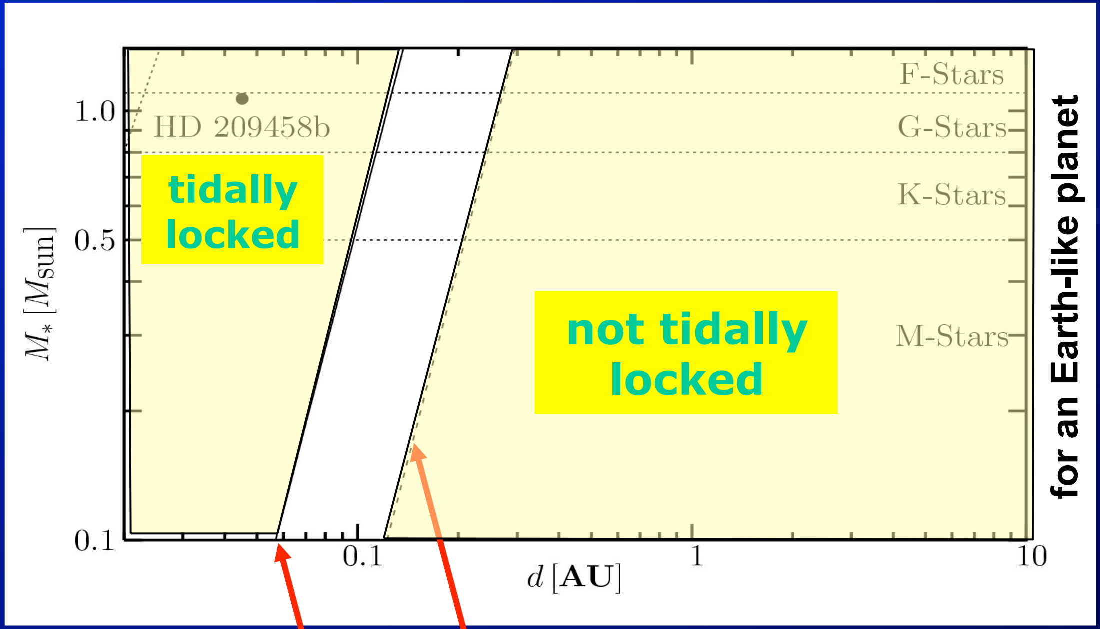
σ - conductivity in the dynamo region

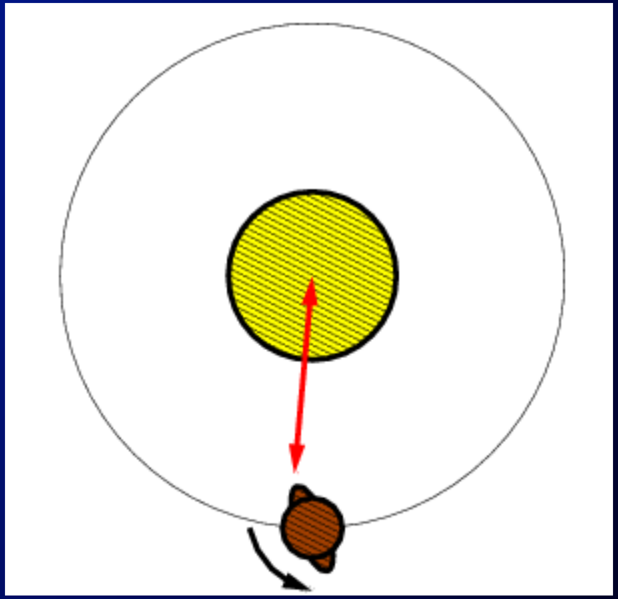
ω - planet angular rotation velocity

Exoplanet magnetic field – planet protecting role

- **Magnetic moment estimation from scaling laws** → **range for possible *M***
  - ***Limitation of M by tidal locking***

$$\tau_{\mathrm{sync}} \approx Q\left(\frac{R_P{}^3}{GM_P}\right)(\omega_i - \omega_f)\left(\frac{M_P}{M_*}\right)^2\left(\frac{d}{R_p}\right)^6$$





0.1 Gyr

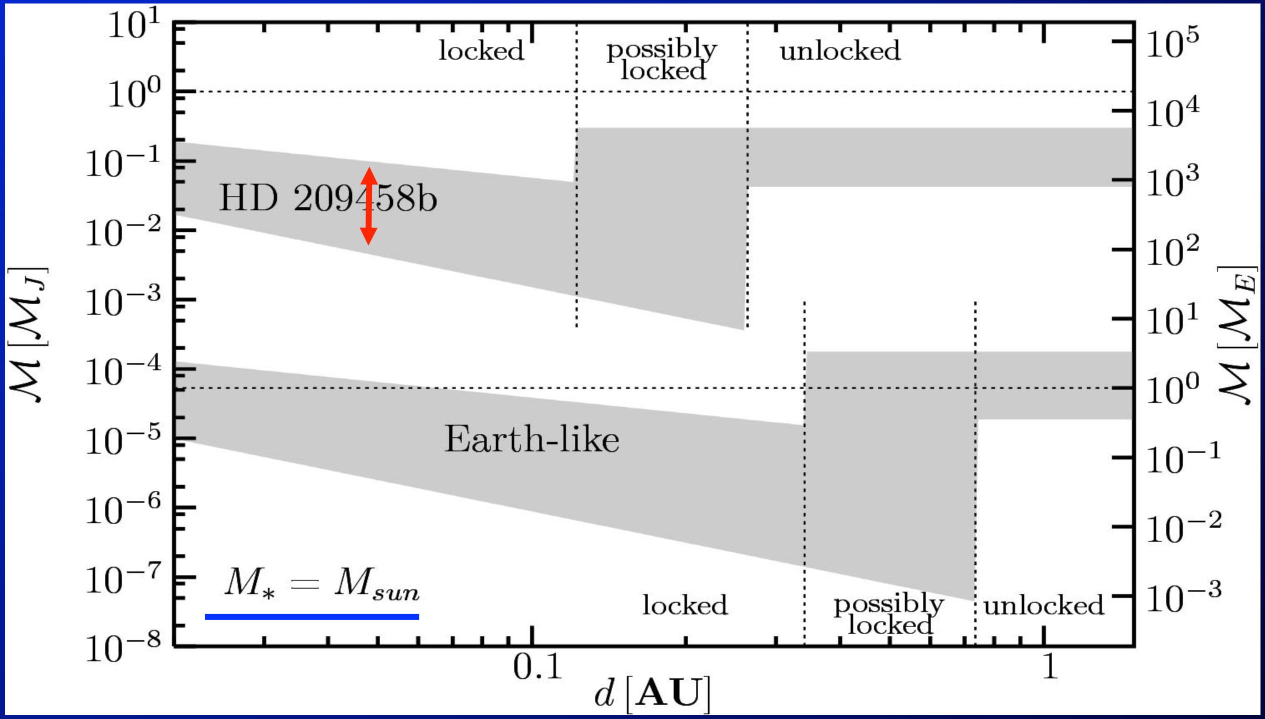
10 Gyr

- final elocity is determined by ***Kepler's law:***

$$\omega_f = \sqrt{\frac{M_* G}{d^3}}$$

Exoplanet magnetic field – planet protecting role

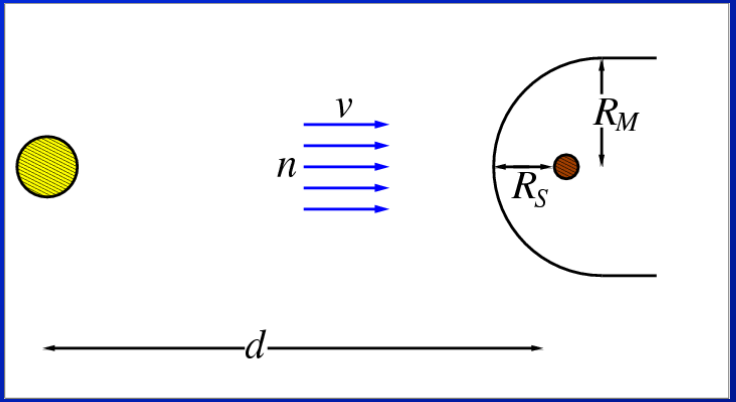
- Magnetic moment estimation from scaling laws → range for possible *M*
  - *Limitation of M by tidal locking*



Tidal locking ⇒ strongly reduced magnetic moments

Exoplanet magnetic field – planet protecting role

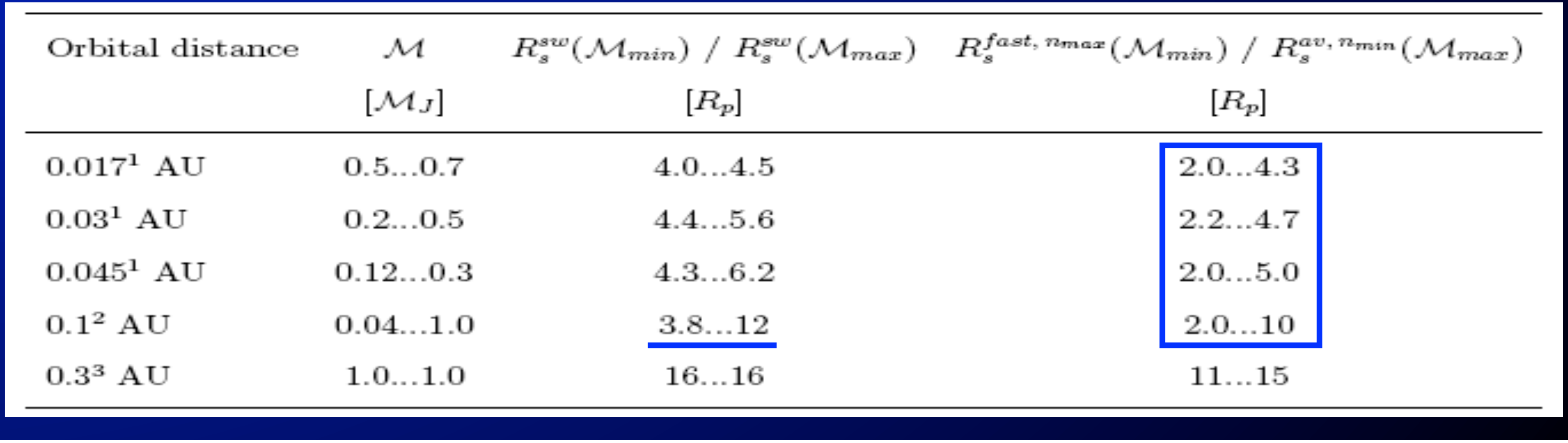
- **Size of magnetosphere (Magnetospheric obstacle)**
- **Magnetopause stand-off distance**



- pressure equilibrium at sub-stellar point:

$$mnv^2 \propto \frac{B_p{}^2}{2\mu_0} \Rightarrow \boxed{R_S \propto M^{1/3}(nv^2)^{-1/6}}$$

- Strong magnetospheric compression by stellar CMEs

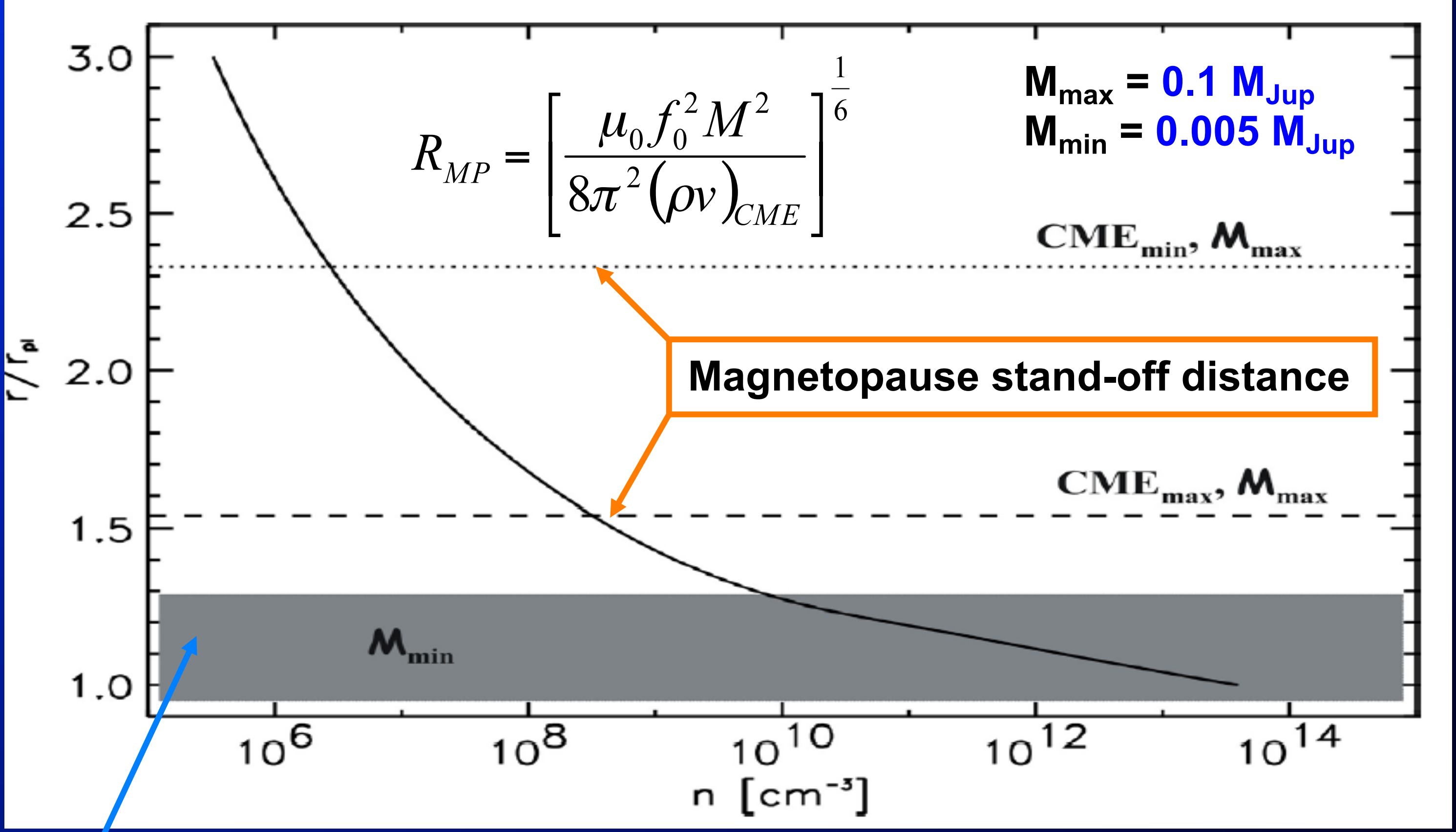


Orbital distance	$\mathcal{M}$ $[\mathcal{M}_J]$	$R_s^{sw}(\mathcal{M}_{min})$ / $R_s^{sw}(\mathcal{M}_{max})$ $[R_p]$	$R_s^{fast,\, n_{max}}(\mathcal{M}_{min})$ / $R_s^{av,\, n_{min}}(\mathcal{M}_{max})$ $[R_p]$
0.017[1] AU	0.5...0.7	4.0...4.5	2.0...4.3
0.03[1] AU	0.2...0.5	4.4...5.6	2.2...4.7
0.045[1] AU	0.12...0.3	4.3...6.2	2.0...5.0
0.1[2] AU	0.04...1.0	3.8...12	2.0...10
0.3[3] AU	1.0...1.0	16...16	11...15

Exoplanet magnetic field – planet protecting role

- **CME induced H+ ion pick-up** → atmospheric erosion & **mass loss** of planet
- Case of 'Hot Jupiters', i.e. d= 0.03-0.1 AU → **HD209458 b** (d=0.045AU)

Neutral H density as a function of planeto-centric distance **r / r_{pl}** (hydrodynamics)



$$R_{MP} = \left[\frac{\mu_0 f_0^2 M^2}{8\pi^2 (\rho v)_{CME}} \right]^{\frac{1}{6}}$$

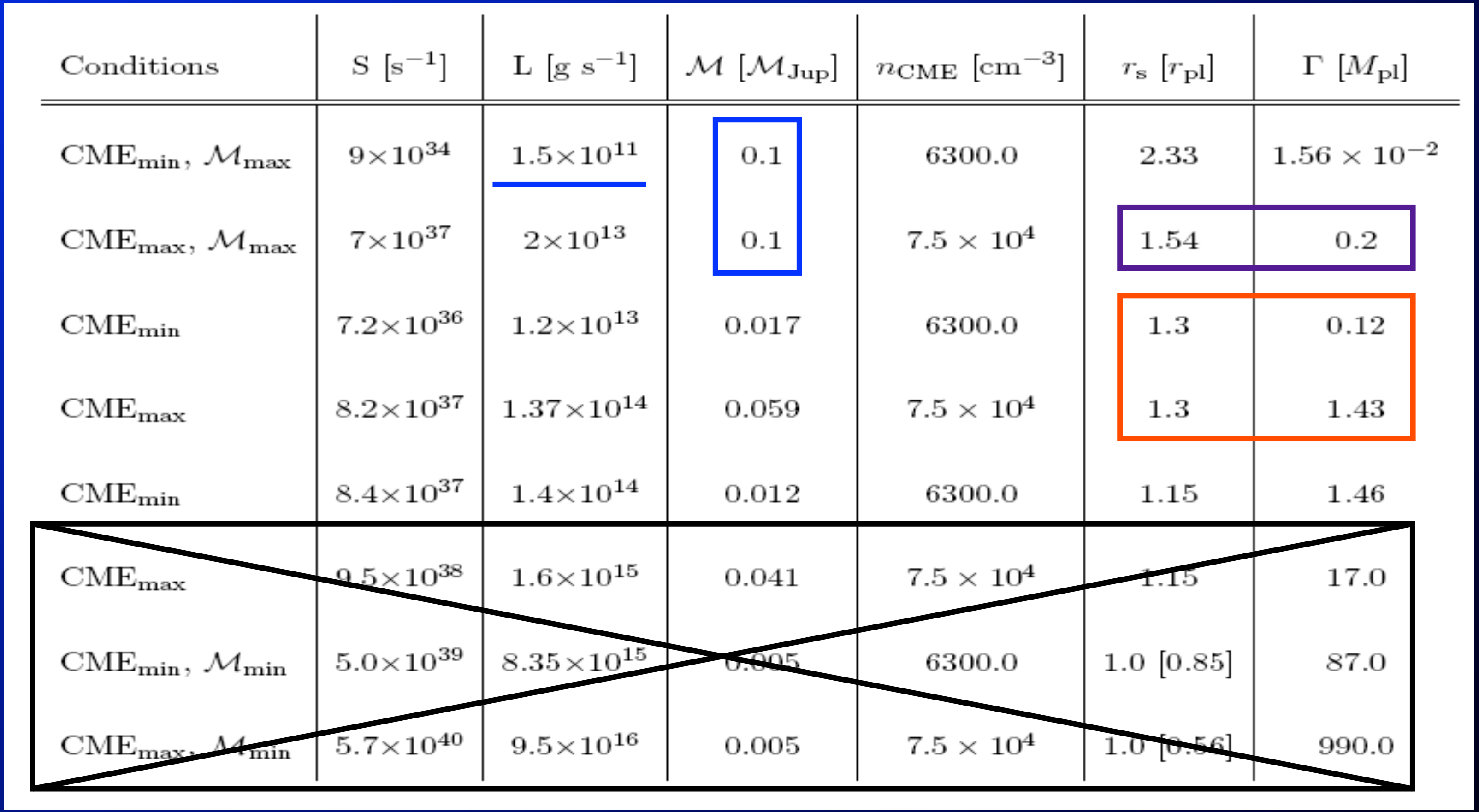
M_{max} = 0.1 M_{Jup}
M_{min} = 0.005 M_{Jup}

Magnetopause stand-off distance

Critical height R_{MP} ~ 1.3 r_{pl} is assumed for M_{min}, since $R_{MP}(M_{min}) < r_{pl}$

Exoplanet magnetic field – planet protecting role

- **CME induced H+ ion pick-up** → atmospheric erosion & **mass loss** of planet
- Case of 'Hot Jupiters', i.e. d= 0.03-0.1 AU → **HD209458 b** (d=0.045AU)

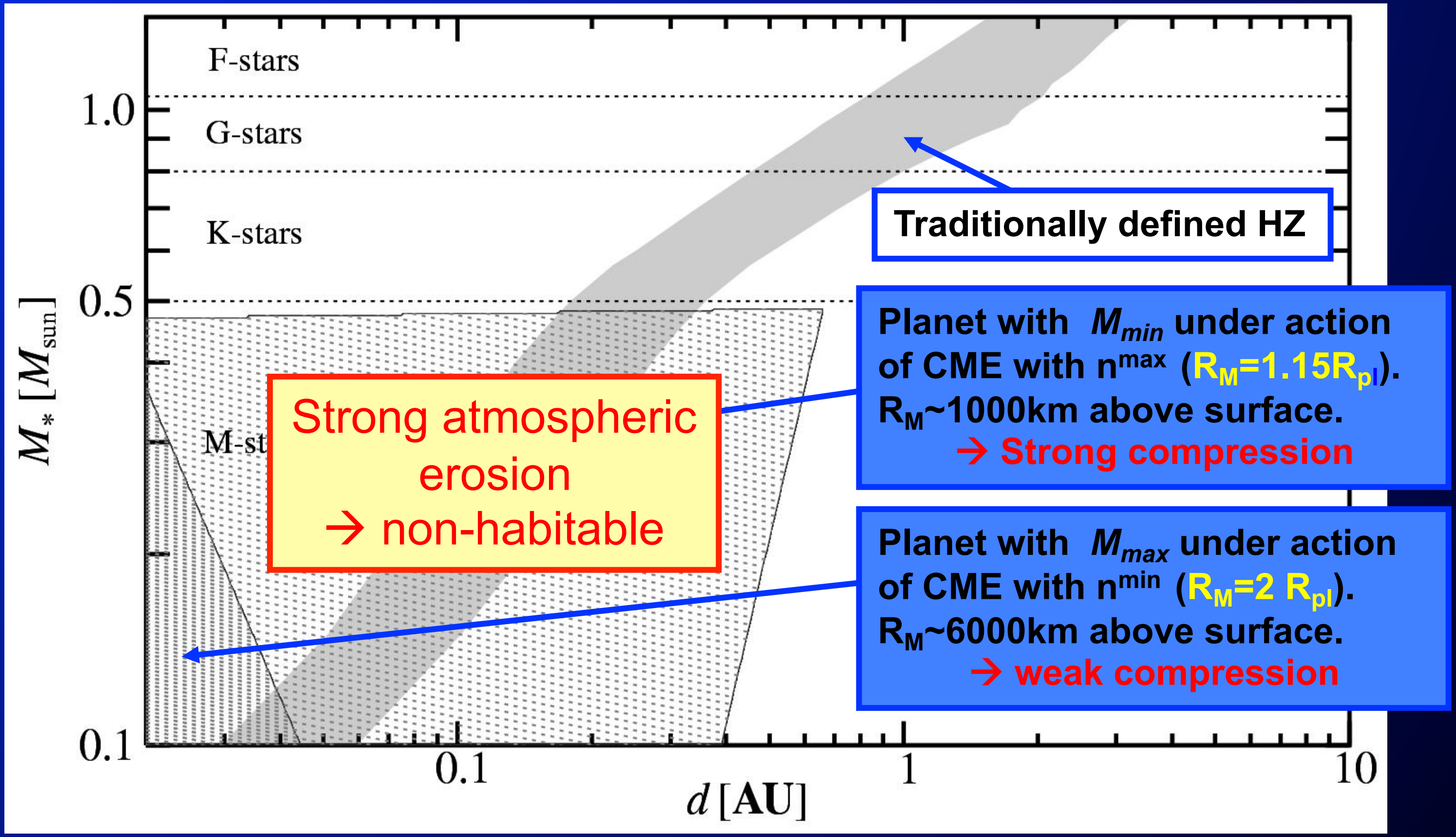


Conditions	S $[s^{-1}]$	L $[g\ s^{-1}]$	$\mathcal{M}\ [\mathcal{M}_{Jup}]$	$n_{CME}\ [cm^{-3}]$	$r_s\ [r_{pl}]$	$\Gamma\ [M_{pl}]$
$CME_{min}, \mathcal{M}_{max}$	9×10^{34}	1.5×10^{11}	0.1	6300.0	2.33	1.56×10^{-2}
$CME_{max}, \mathcal{M}_{max}$	7×10^{37}	2×10^{13}	0.1	7.5×10^{4}	1.54	0.2
CME_{min}	7.2×10^{36}	1.2×10^{13}	0.017	6300.0	1.3	0.12
CME_{max}	8.2×10^{37}	1.37×10^{14}	0.059	7.5×10^{4}	1.3	1.43
CME_{min}	8.4×10^{37}	1.4×10^{14}	0.012	6300.0	1.15	1.46
~~CME_{max}~~	~~9.5×10^{38}~~	~~1.6×10^{15}~~	~~0.041~~	~~7.5×10^{4}~~	~~1.15~~	~~17.0~~
~~$CME_{min}, \mathcal{M}_{min}$~~	~~5.0×10^{39}~~	~~8.35×10^{15}~~	~~0.005~~	~~6300.0~~	~~1.0 [0.85]~~	~~87.0~~
~~$CME_{max}, \mathcal{M}_{min}$~~	~~5.7×10^{40}~~	~~9.5×10^{16}~~	~~0.005~~	~~7.5×10^{4}~~	~~1.0 [0.56]~~	~~990.0~~

Mass loss ~10^{11} g/s even for weak CMEs & **M_{max}** ⇒ ***strong magn. protection***

Exoplanet magnetic field – planet protecting role

- ***Terrestrial planet magnetosphere*** compressed by stellar CMEs



Traditionally defined HZ

Strong atmospheric erosion
→ non-habitable

Planet with M_{min} under action of CME with n^{max} ($R_M=1.15R_{pl}$). R_M~1000km above surface.
→ Strong compression

Planet with M_{max} under action of CME with n^{min} ($R_M=2\ R_{pl}$). R_M~6000km above surface.
→ weak compression

SUMMARY CONCLUSIONS

- Magnetospheric protection of planetary internal environments plays crucial role for the planet evolution and habitability. Weakly magnetized Hot Jupiters may be eroded down to their core-mass/size, whereas atmospheres of terrestrial type planets in close-in HZ of low-mass active stars will be strongly eroded → non-habitable worlds

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- **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).