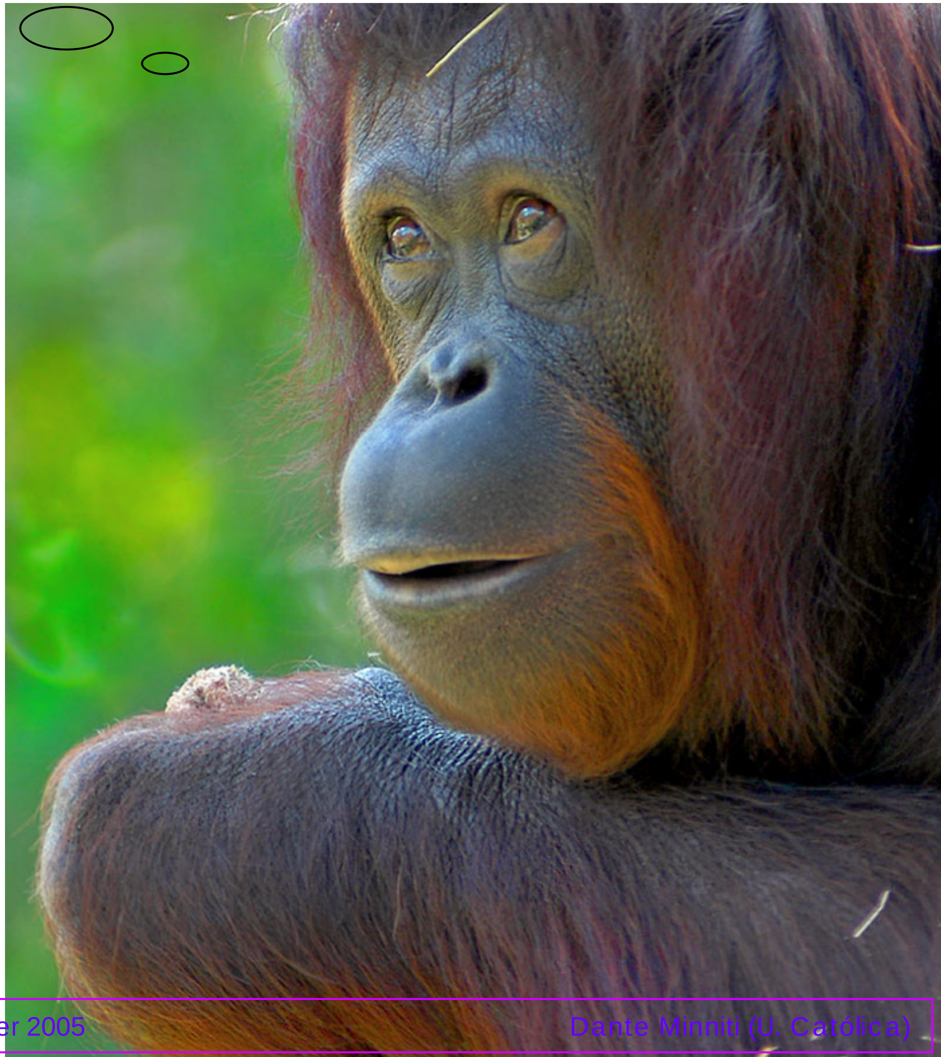
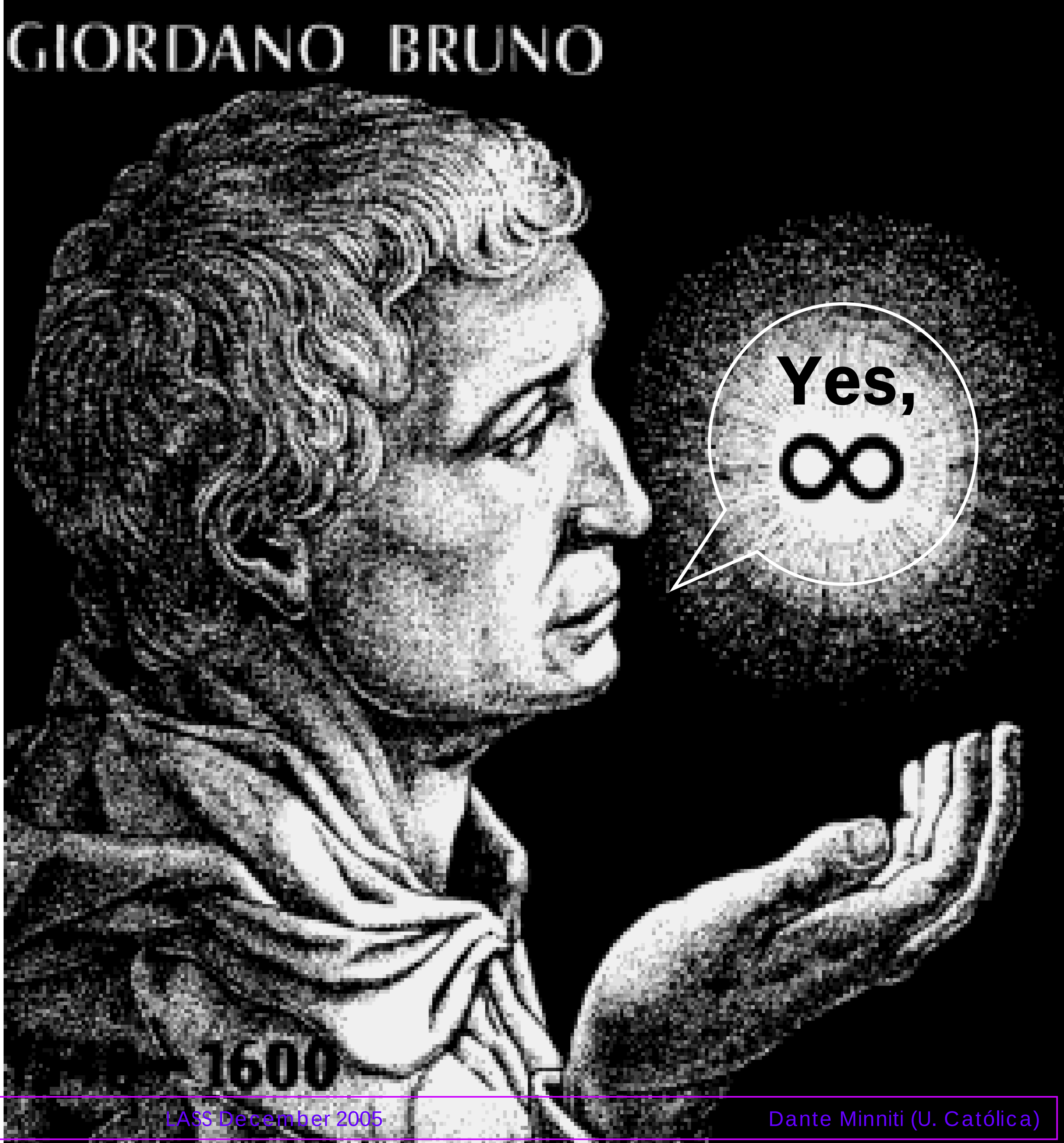
Are there other rocky planets with $273 < T(K) < 373$?




GIORDANO BRUNO
Yes,
∞
1600

Extrasolar Planets

- Why search for extrasolar planets?
- What is the best way to do it?
- What fraction of stars have planetary systems?
- What kinds of extrasolar planets are out there?

What is a planet?

The discovery of planets (particularly transits) forced to discuss the issue, because low mass objects have similar sizes.

Planets are opaque bodies that reflect light from their parent stars (except Jupiter decametric emission).

The planet definition depends on the formation mechanism.

A ``planet" is an object that has a mass between that of Pluto and the Deuterium-burning threshold and that forms in orbit around an object that can generate energy by nuclear reactions.

Here I adopt simple definitions using mass:

$M/M_{\odot} > 0.080$ is a star

$0.015 < M/M_{\odot} < 0.080$ is a brown dwarf

$M/M_{\odot} < 0.015$ is a planet

Searching for exoplanets

– How do planetary systems form and evolve?

- We don’t know. Our knowledge is very incomplete, although a lot of progress is being made: 10 years ago we started detecting planets in nearby stars.

opportunity

- The worst problem for the extrasolar planet searches is the distance. Even the closest stars are very far away.
- Because of this problem, we need advanced techniques and exquisite measurements to detect extrasolar planets.
- Due to the large distances, the exploration of these exoplanets is impossible in a short timescale.

Search techniques

- Radial velocities
- Transits
- Astrometry
- Microlensing
- Timing
- Direct detections

Extrasolar planets

- Radial velocities
  - Technique
  - Results
    1. First planets
    2. a vs e
    3. Masses
    4. Metallicities
    5. Multiple systems
    6. Latest statistics
    7. The future

- We measure the period P from the RV curve.
- Kepler's 3rd law gives semimajor axis:

$$G(M_p + M_*)P^2 = 4\pi^2 a^3$$

- The planet velocity is

$$V_p^2 = GM_*/a$$

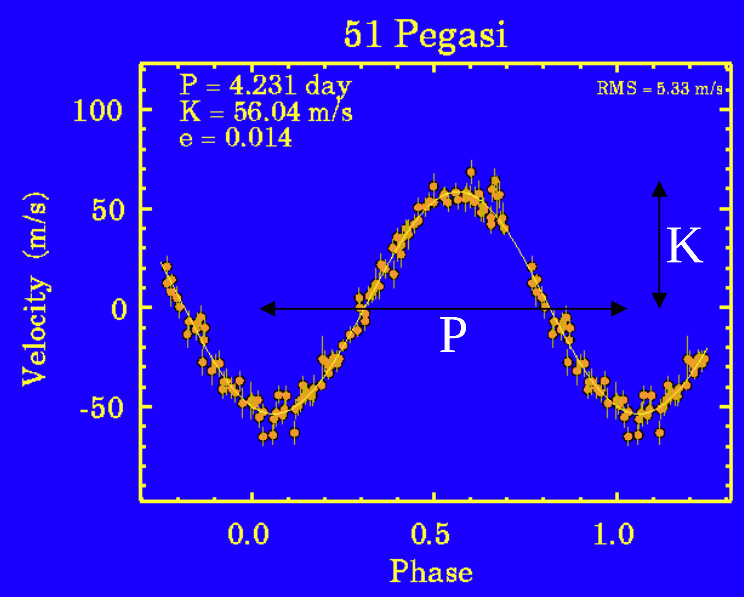
- Momentum conservation gives:

$$M_p = M_* V_* / V_p$$

- From the RV curve we measure the amplitude $K = V_* \sin i$

→ $M_p \sin i$

- The more massive the planet, the better.
- The more inclined the orbit, the better



Butler & Marcy 1995

Units:

1AU = 150×10^{6} km

1R$_\odot$ = 7×10^{5} km

1**M**$_\odot$ = 2×10^{30} kg

Radial velocities

$M_{\odot} = 1.989 \times 10^{30}$ kg

$M_{Jup} = M_{\odot}/1048$

$M_{Sat} = M_{\odot}/3497$

$M_{Tierra} = M_{\odot}/332946$

- Planets orbit around the center of mass of the Solar system. This is located close to the center of the Sun because it is by far the most massive body. But the Sun also orbits around this barycenter.
  - Note that Jupiter contains more than double the mass of all the other planets together.
- Jupiter moves the Sun with an amplitude of *A = 12.5 m/s* and a period of *P = 12 yr*. For Saturn *A = 2.7 m/s*, and *P = 30 yr*.
- Nowadays the search is sensitive to planets with orbits of a < 5 a.u. and planet masses of $M_P > 0.2\ M_J$.
- Current record: hot Neptunes with ~10 ME. We cannot detect Earth mass planets using this technique yet.

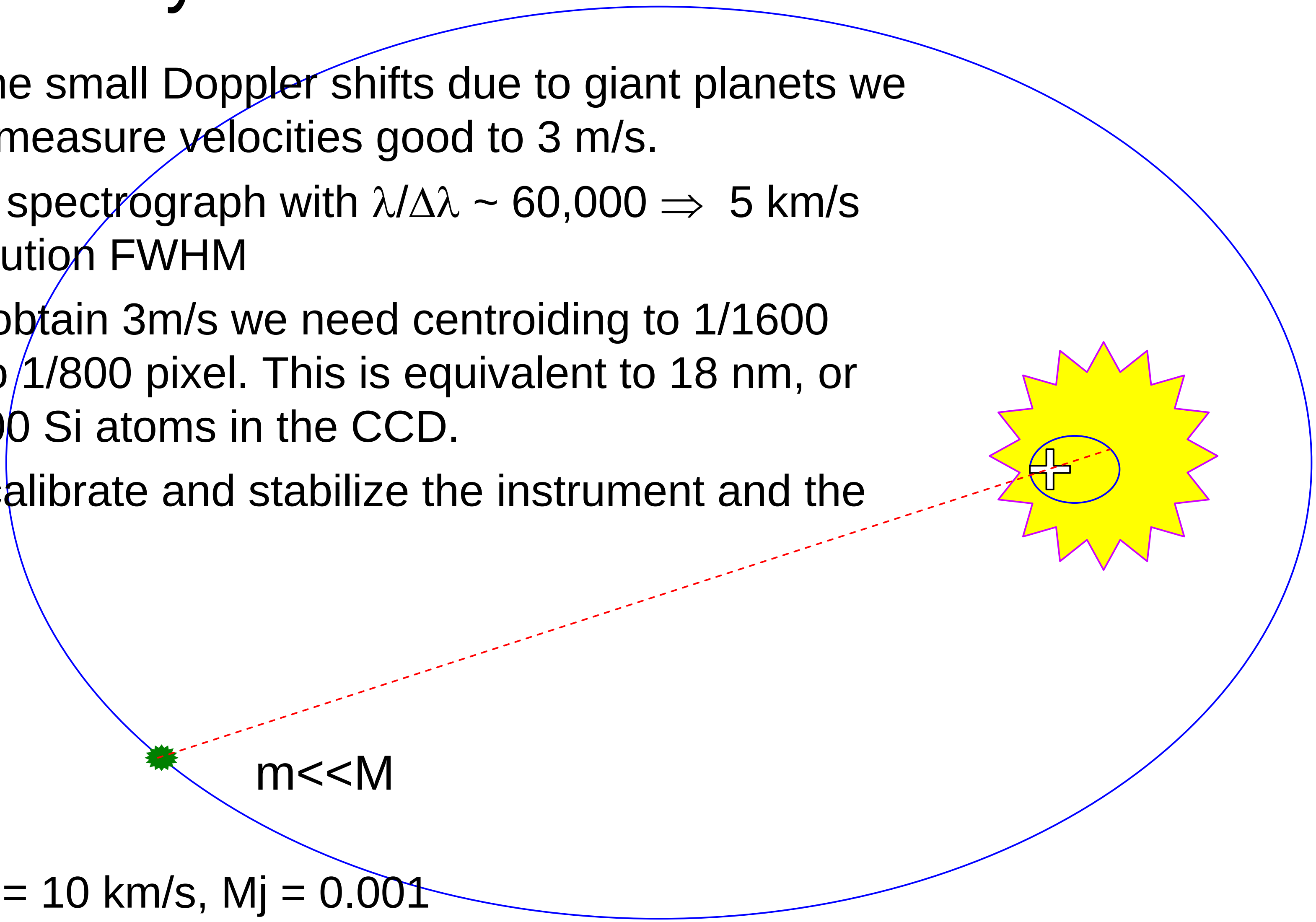
Planetary orbits

To detect the small Doppler shifts due to giant planets we need to measure velocities good to 3 m/s.

echelle spectrograph with $\lambda/\Delta\lambda \sim 60{,}000 \Rightarrow$ 5 km/s resolution FWHM

In order to obtain 3m/s we need centroiding to 1/1600 FWHM o 1/800 pixel. This is equivalent to 18 nm, or about 100 Si atoms in the CCD.

Difficult to calibrate and stabilize the instrument and the PSF.

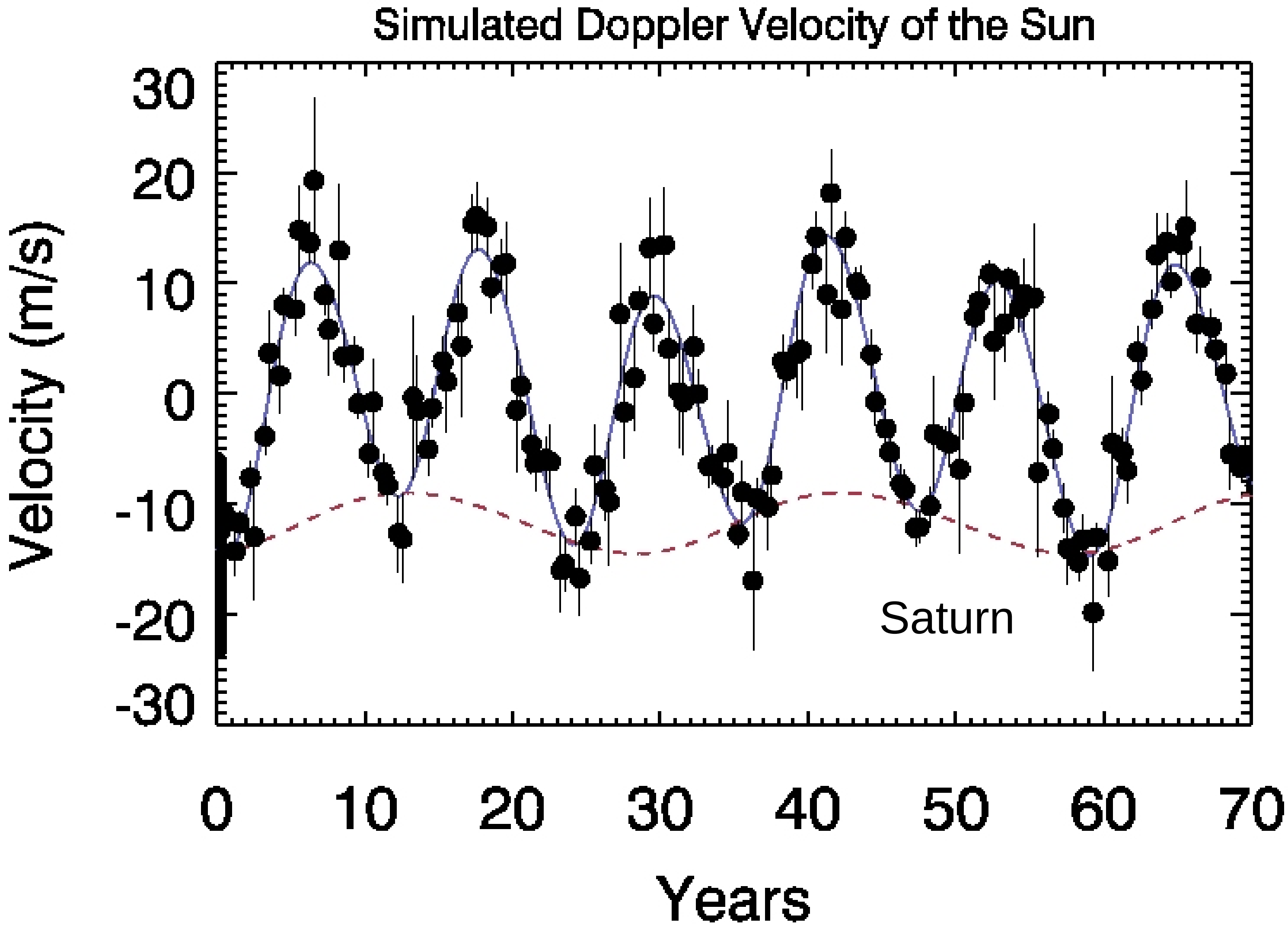


e.g.: Vj = 10 km/s, Mj = 0.001 Mo

➔ Vo = 10 m/s

The Solar system

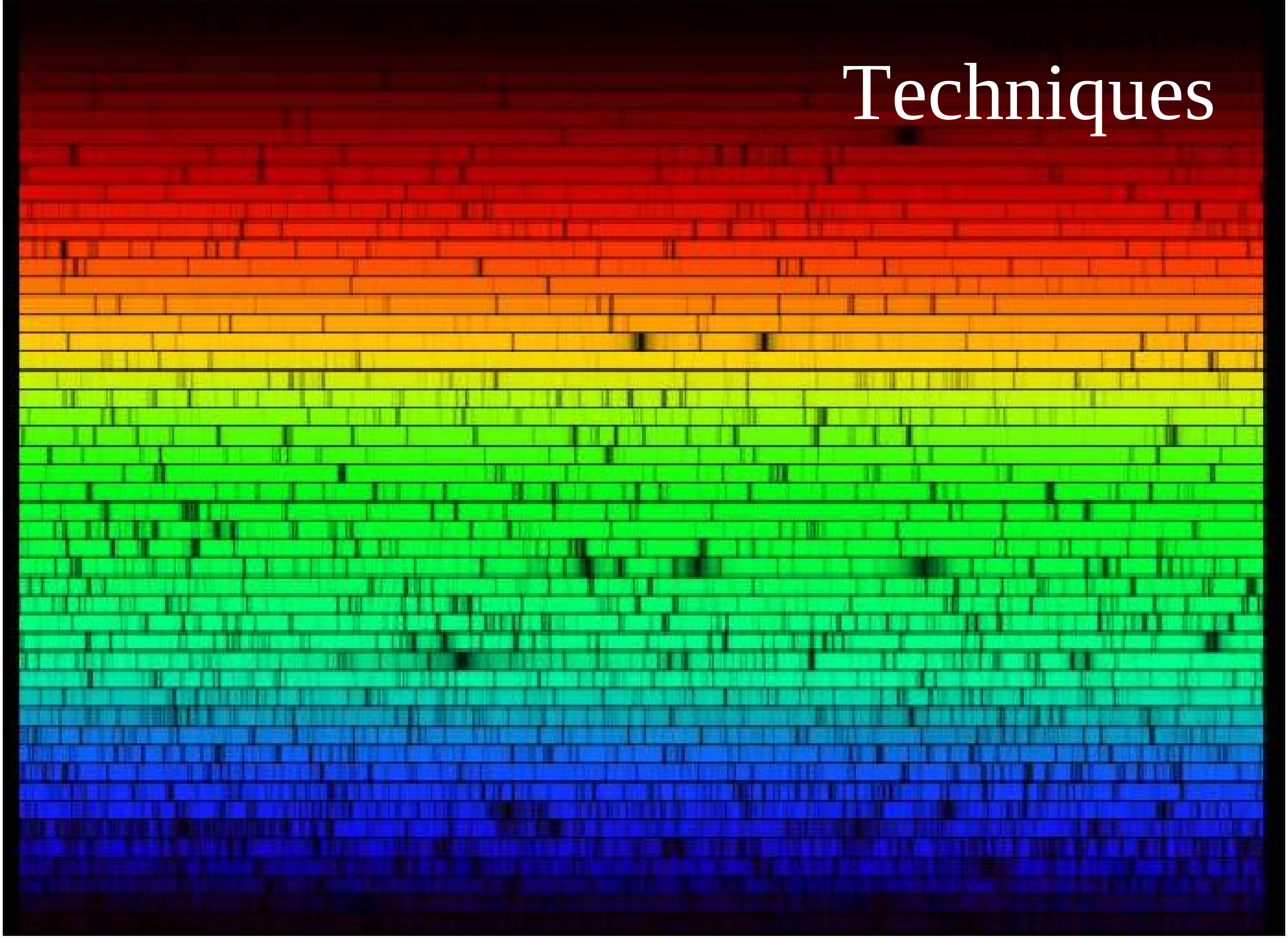
Precision = 10 m/s → Jupiter, Precision = 3 m/s → Saturn



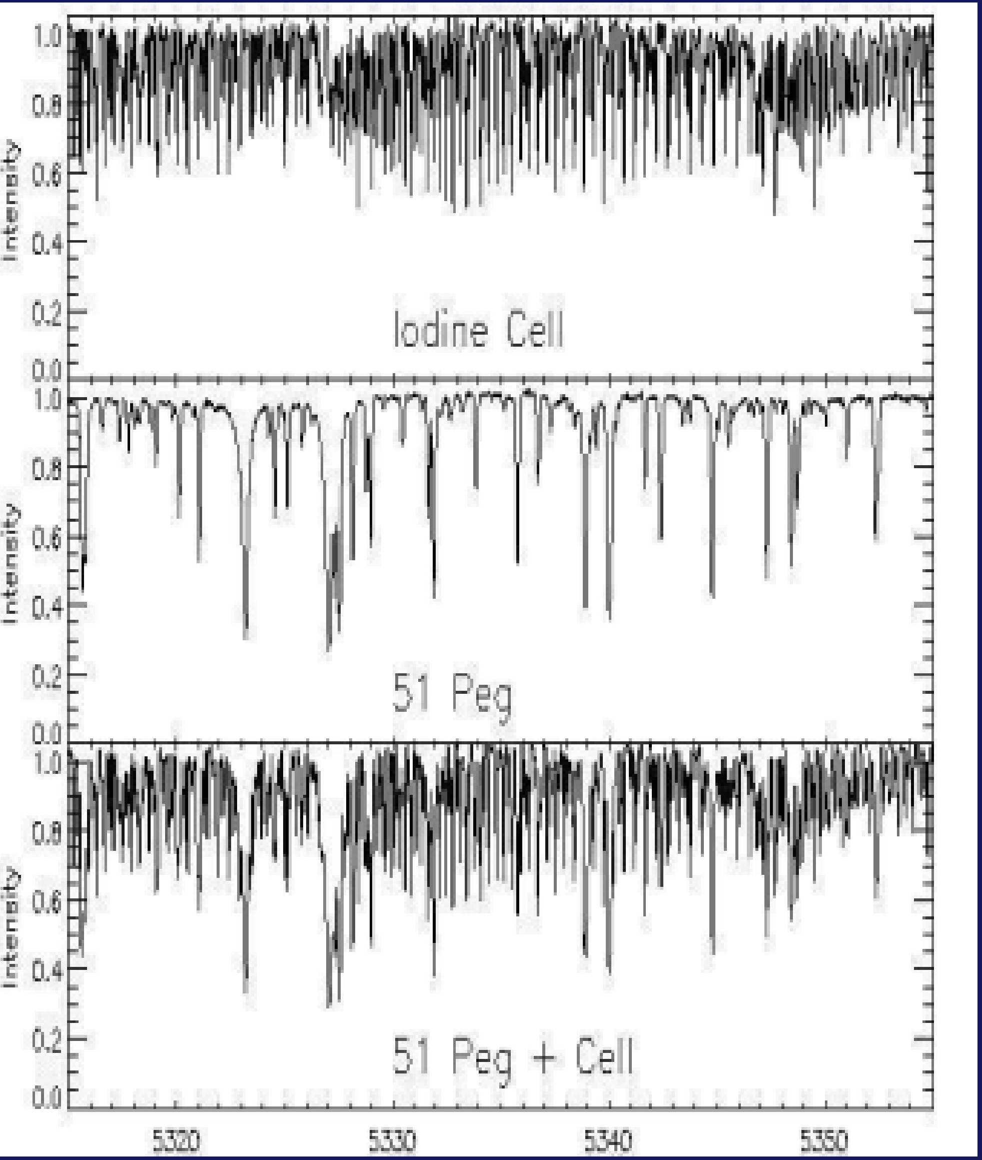
Techniques

- Small telescopes can be used for nearby stars (V<8)
- Large telescopes are preferred to observe many stars per night
- Echelle spectrograph with high dispersion in the optical needed (4000-8000A).
- Need a calibration lamp for the precise determination of lambda
- The search is limited to the Solar vicinity: need too many photons because the light is dispersed into several echelle orders
- Use cross correlations (Tonry & Davies 1979) to measure velocities, e.g. task FXCOR in IRAF

Techniques



The spectrum of the Sun.



Techniques

Two approaches: iodine cell, and TrAr lamp.

Superpose the reference lines to remove the instrumental effects (flexures, focus, etc.).

I_2 y ThAr give thousands of narrow lines in the optical region at high resolution

Require a model of the composite spectrum to obtain high accuracy ($\Delta V < 10$m/s)

Sample stars

- There are ~3500 known stars within D < 50 pc.
- Select those with V < 8.
- ~30% are useless because they are young or belong to close binaries.
- Two main groups follow this sample:
  - Geneva group (Mayor, Queloz, Udry, Naef, Pepe, Melo, etc), usando Haute-Provence, La Silla, Pa…
  - Lick group (Marcy, Butler, Fischer, T… Kec… Lick, AAO.
- About 1000 stars in common, tr…
- They are approaching the 1m/s … imit.

WOW !!

Spectral Classification

Type	Teff	Example	Spectral features
O	>30000	sdO	HeII strong, H weak
B	20000	Rigel	HeI strong, H, weak metals
A	10000	Sirius	HeI weak, H max, few metals
F	7000	Canopus	No He, H strong, some metals (Fe Ca Na)
G	6000	Sun	H, strong metals, G band, no molecules
K	4000	Arcturus	Strong neutral and ionized metals, H weak, molecules
M	3000	Betelgeuse	Molecules dominate (H_2O, TiO, VO, CO), metals
L,T	<2000	Gl229B	Molecules dominate (H_2O, CH_3), no continuum

- Young stars have few broad lines (early spectral types).
- Check rotation and stellar activity: Ca HK doublet.
- Late spectral types (M stars) are very faint.

Milestones

The first planet was discovered in 1995 using radial velocities in the star 51 Peg by Swiss astronomers Michel Mayor and Didier Queloz.

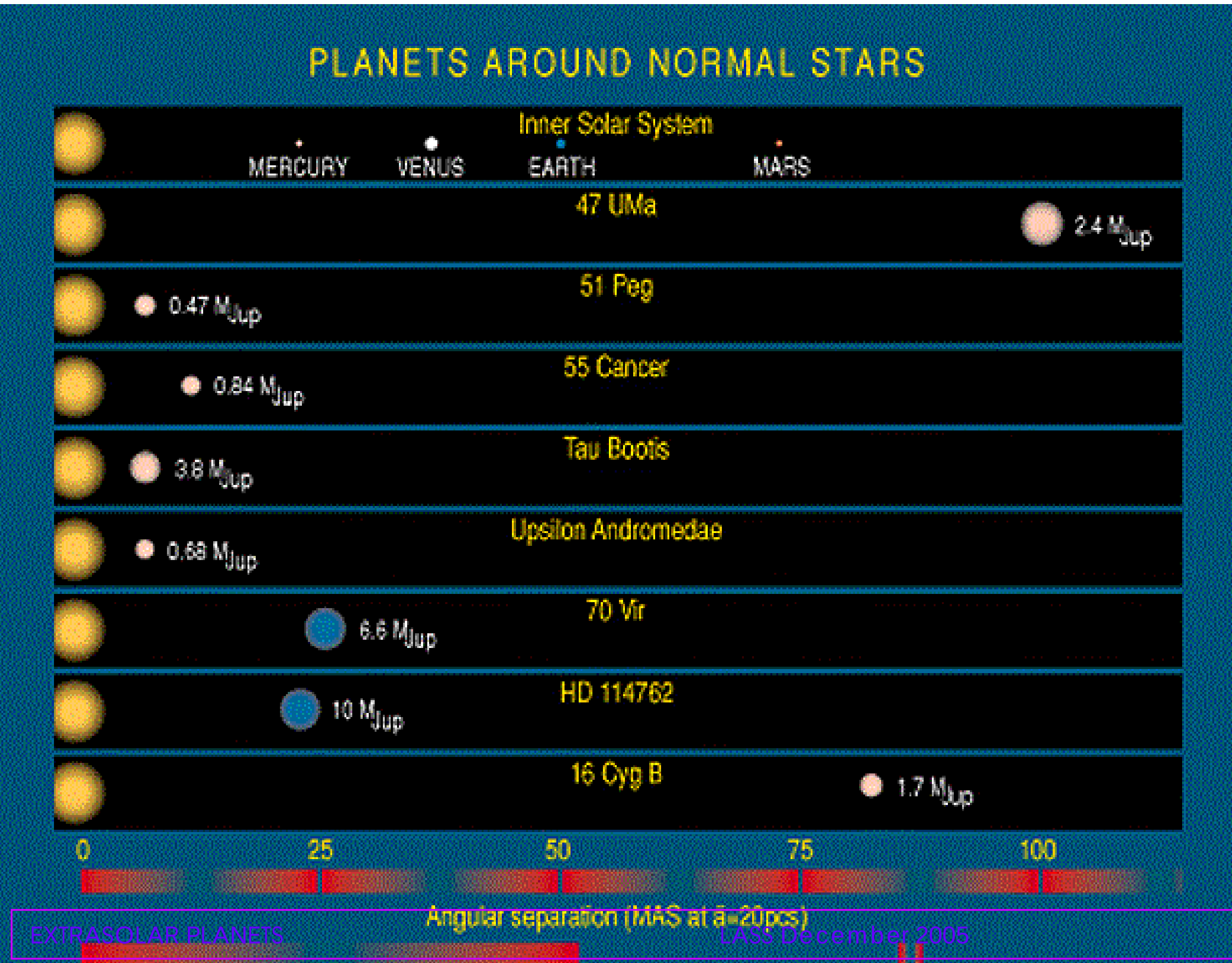
The first multiple planet system was discovered using radial velocities in 1999 in the star Upsilon And by American astronomers Geoff Marcy and Paul Buttler.

These discoveries change our vision:

- We now know that there are other planetary systems.
- There is quite a variety of extrasolar planets.
- These planetary systems could be quite common in our Galaxy.

Radial velocity results

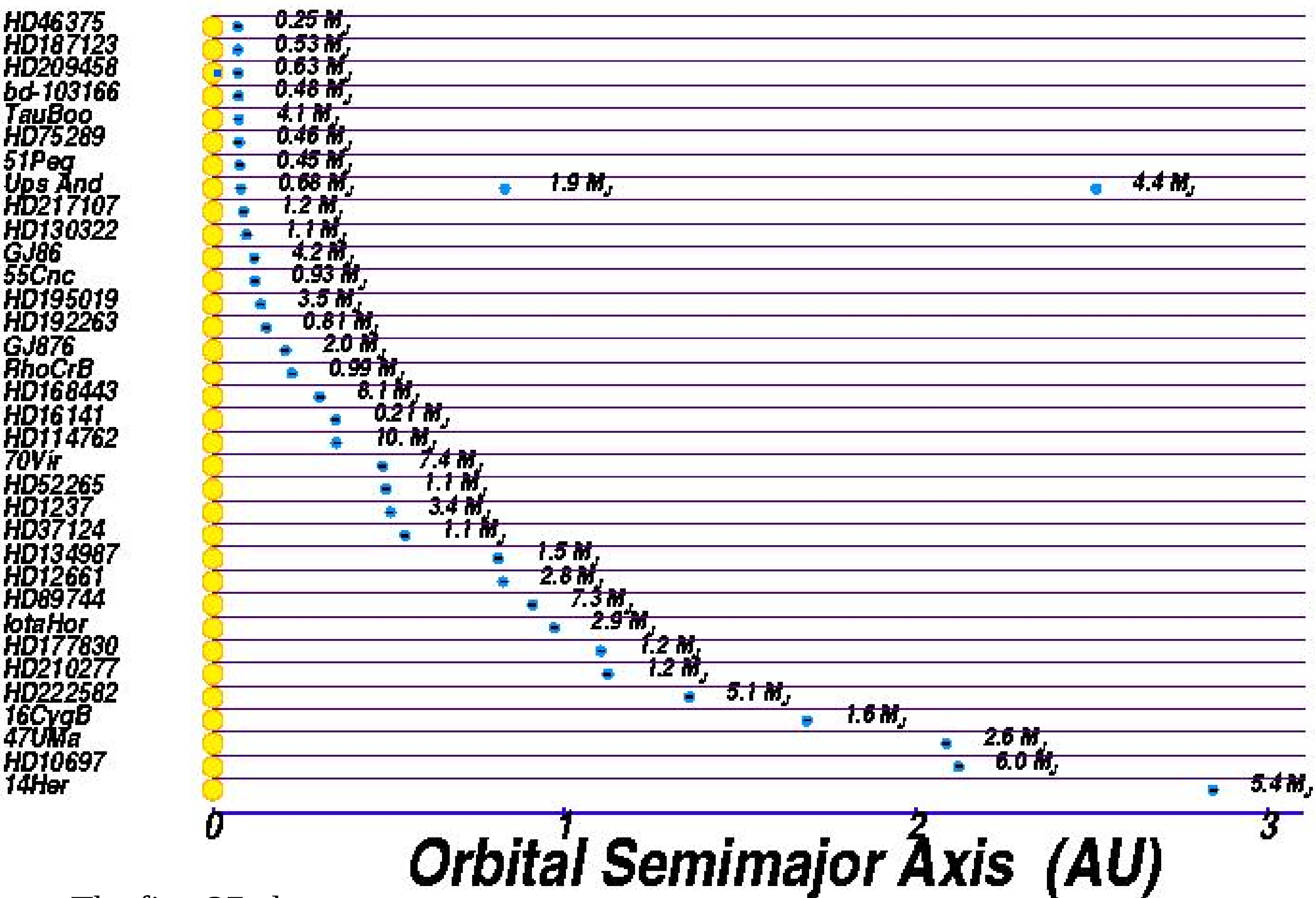
The first 8 planets



The first planets were massive giants in short period orbits around nearby stars.

The radial velocities are more sensitive to this type of planets.

Radial velocity results

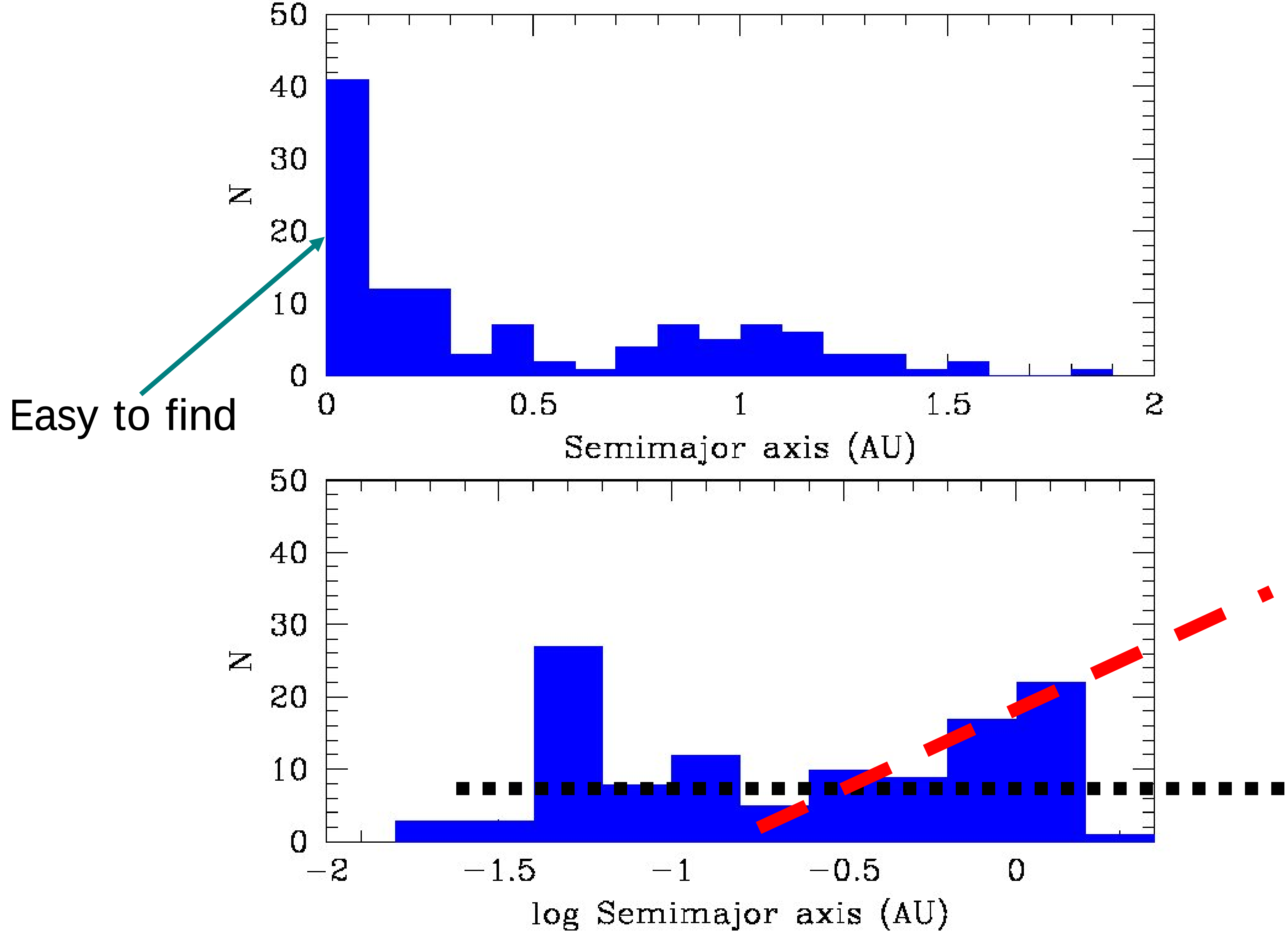


The first 37 planets

Radial velocity results

- This RV technique is very successful: it allowed the discovery of more than 150 planets around nearby stars.
- These planets surprised us because they are very different to the Solar system:
    - Giant planets like 51-Peg, with $a < 0.2$ au
        - (Note: Mercury $a = 0.39$ a.u.)
    - The majority have eccentric orbits with $e > 0.1$
        - (Note: Earth $e = 0.03$, Jovian planets $e < 0.05$)

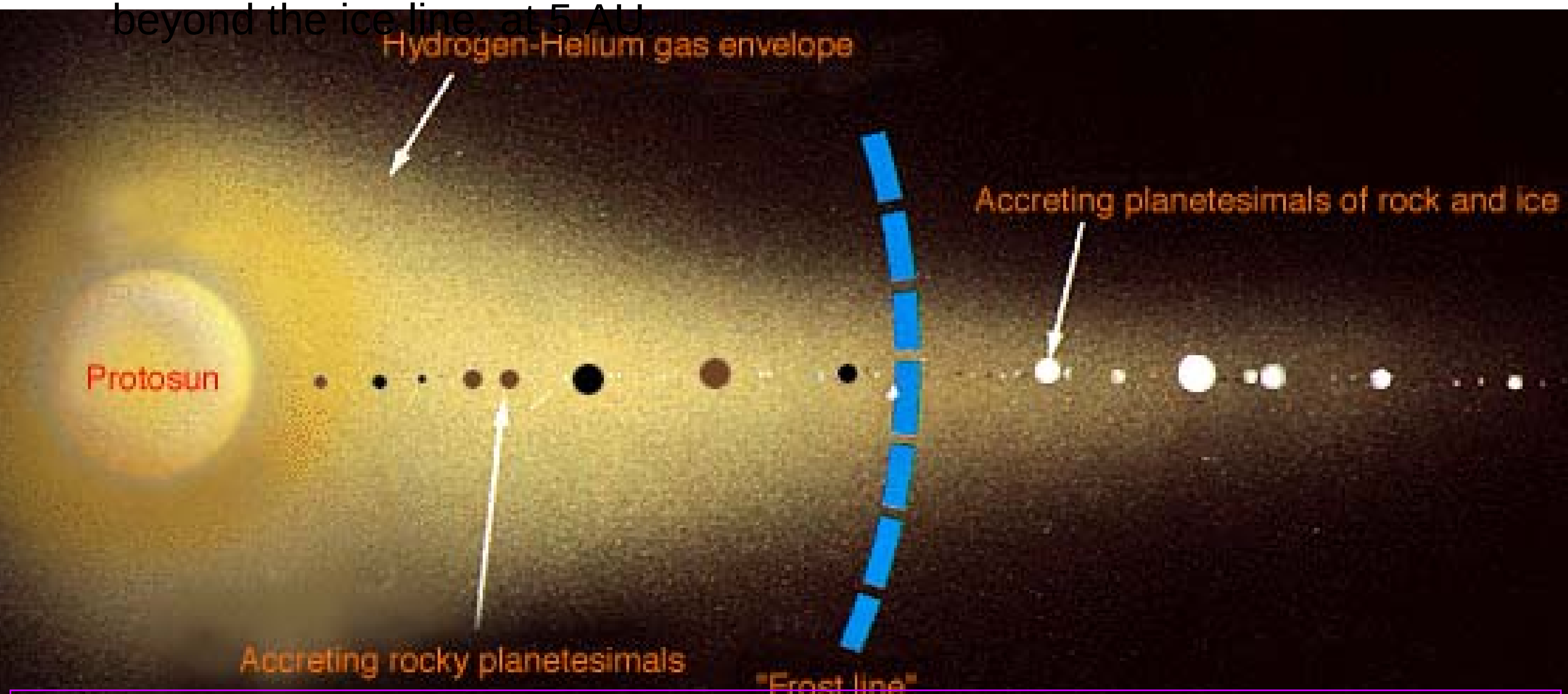
> Is the Solar system unique? Or we just haven't found another Jupiter dominated system because we have not been searching long enough?



Solar system planets go out to 30UA. For a>3UA, the P are long → incomplete samples. But assuming dN / dlog a ~ const, one can estimate how many are missing.

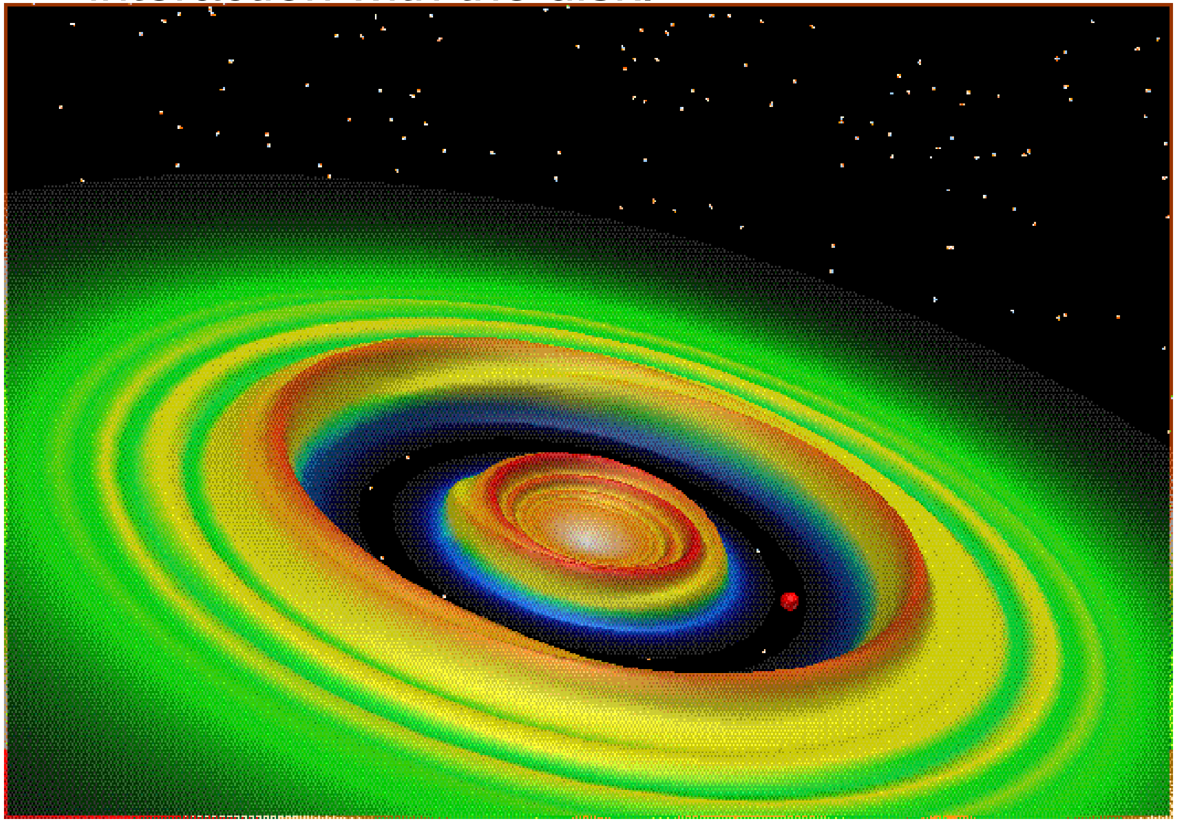
Planetesimal formation

- The Solar nebula was made of H y He, with a small fraction of heavy elements.
- About 4500 million years ago these heavy elements condensed as dust in the inner disk, and as ice + dust in the outer disk.
- According to the Solar system formation theory, Jupiter must form beyond the ice line, at 5 AU.



Hot Jupiters

Solution for hot giant extrasolar planets: inward migration mechanism during the formation. The planet is formed far away from the star, but migrates inwards by interaction with the disk.



Massive planet in formation sweeps the proto-planetary disk around its orbit

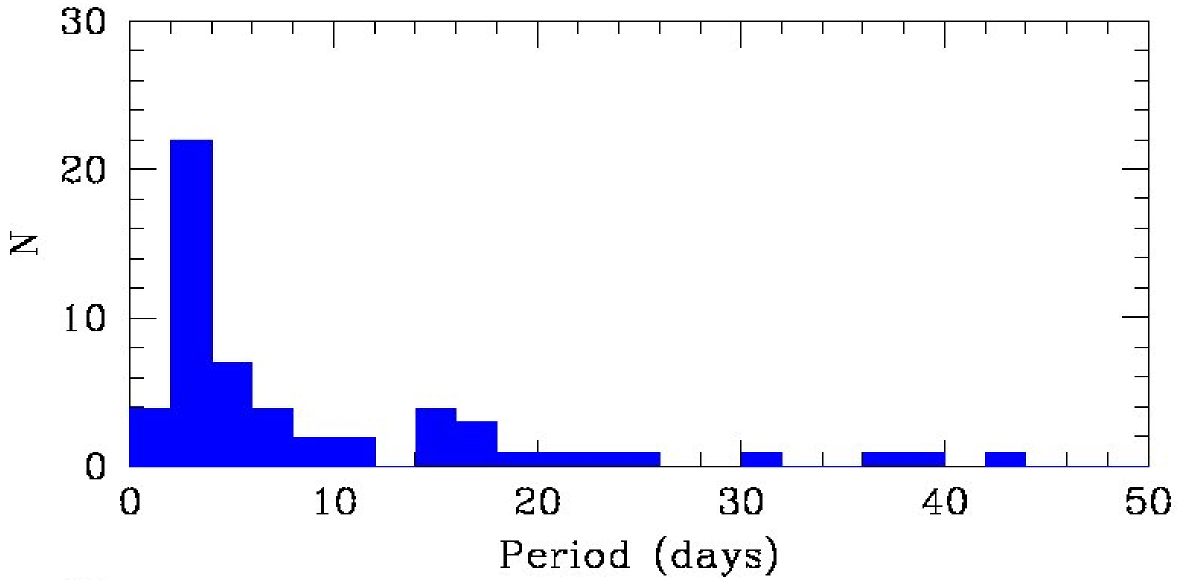
Drag with the disk material causes migration

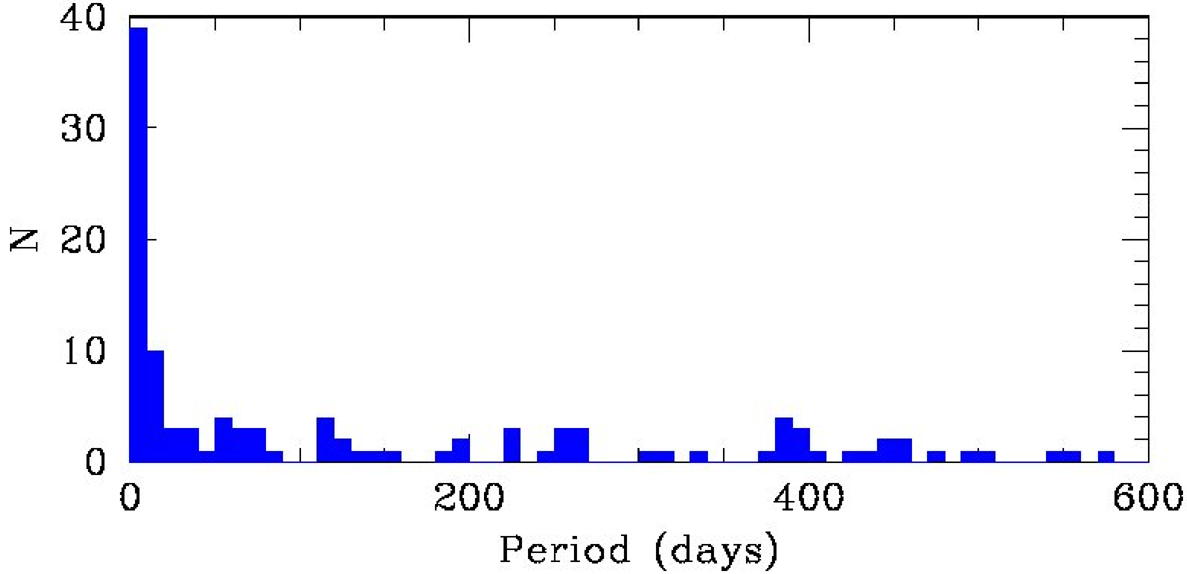
Problems:

1. Apparently the orbits of these planets piled up at P = 3 d. Hard to find a “parking” mechanism.

2. Disk timescale short, then $\tau_{MIG} = 1$ Myr. No time to form some lower mass planets.

Hot Jupiters





Very easy to find.

The Roche limit for solar mass stars is:

$$R_R = 2.44\ R_* (\rho_*/\rho_p)^{1/3}$$

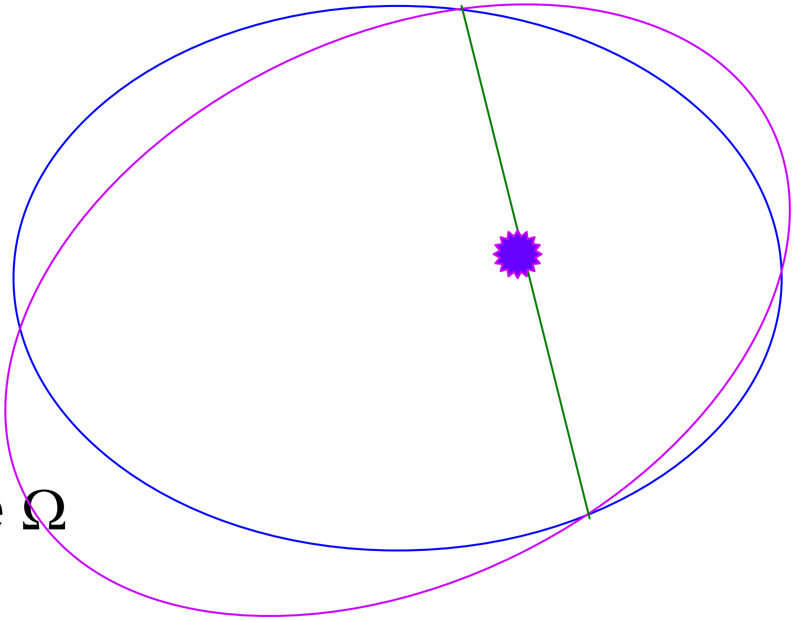
corresponding to

P~1d

Orbital Elements

Parameters necessary to define an orbit

- Semimajor axis a
- Period P
- Eccentricity ε
- Inclination i
- Longitude of the ascending node Ω
- Argument of perihelium ω
- Time of passage by perihelium τ



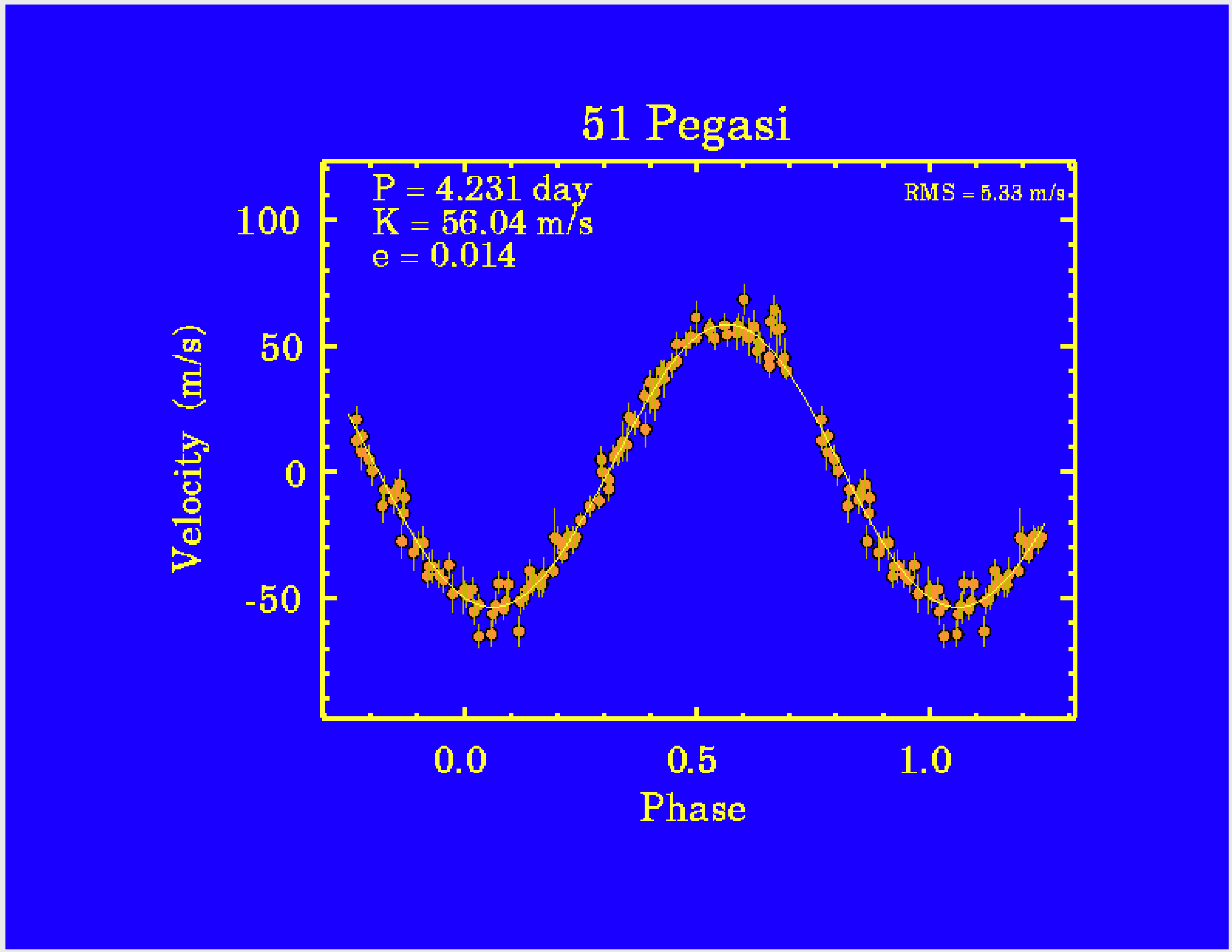
Aside from the M sin i and P, the radial velocities give the orbital eccentricity.

Radial velocity results

- The orbits of planets with a<<1AU must be circularized

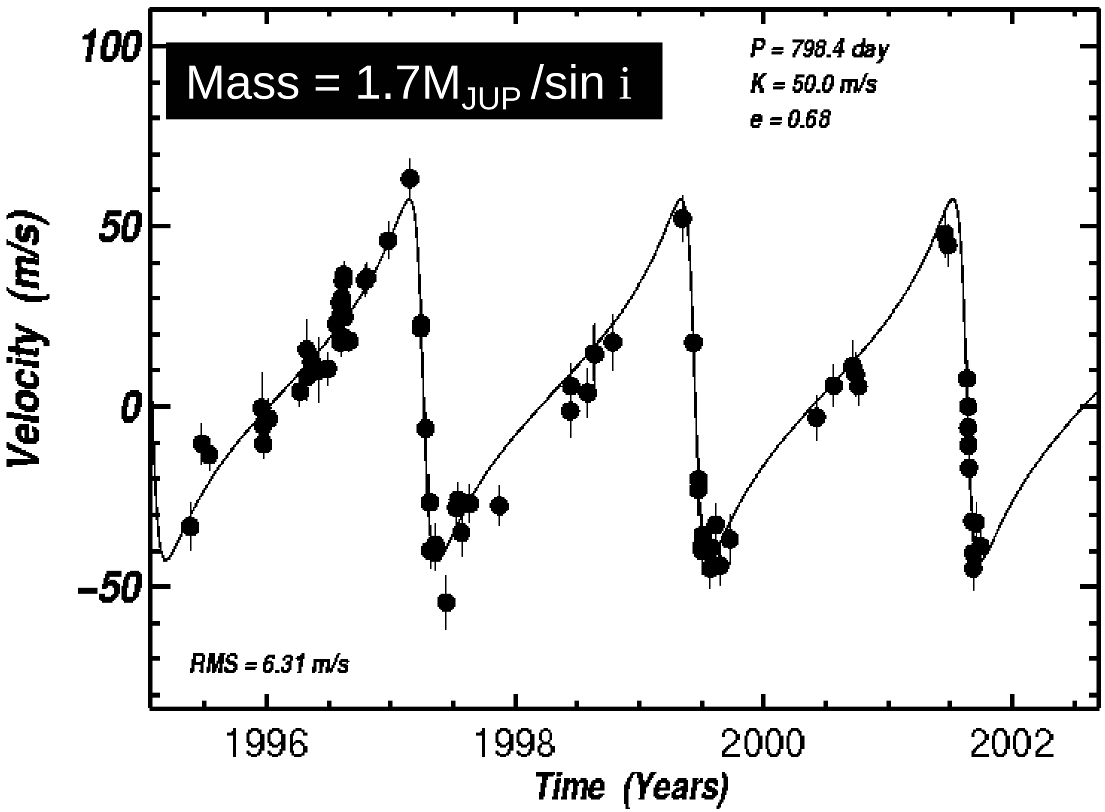
$\Delta F = -2GM_* / D^3$

Butler & Marcy 1995



16 Cyg B

- 2nd surprise: eccentric planets
- Problem for theory: if in the disk the orbits were circular, what is the origin of the eccentricities?
  - Planet-planet interactions
  - Gravitational scattering of the planetesimals
  - Multiple star systems



Cochran et al. 1997

The most eccentric planet: HD80606

Naef et al. (2001)

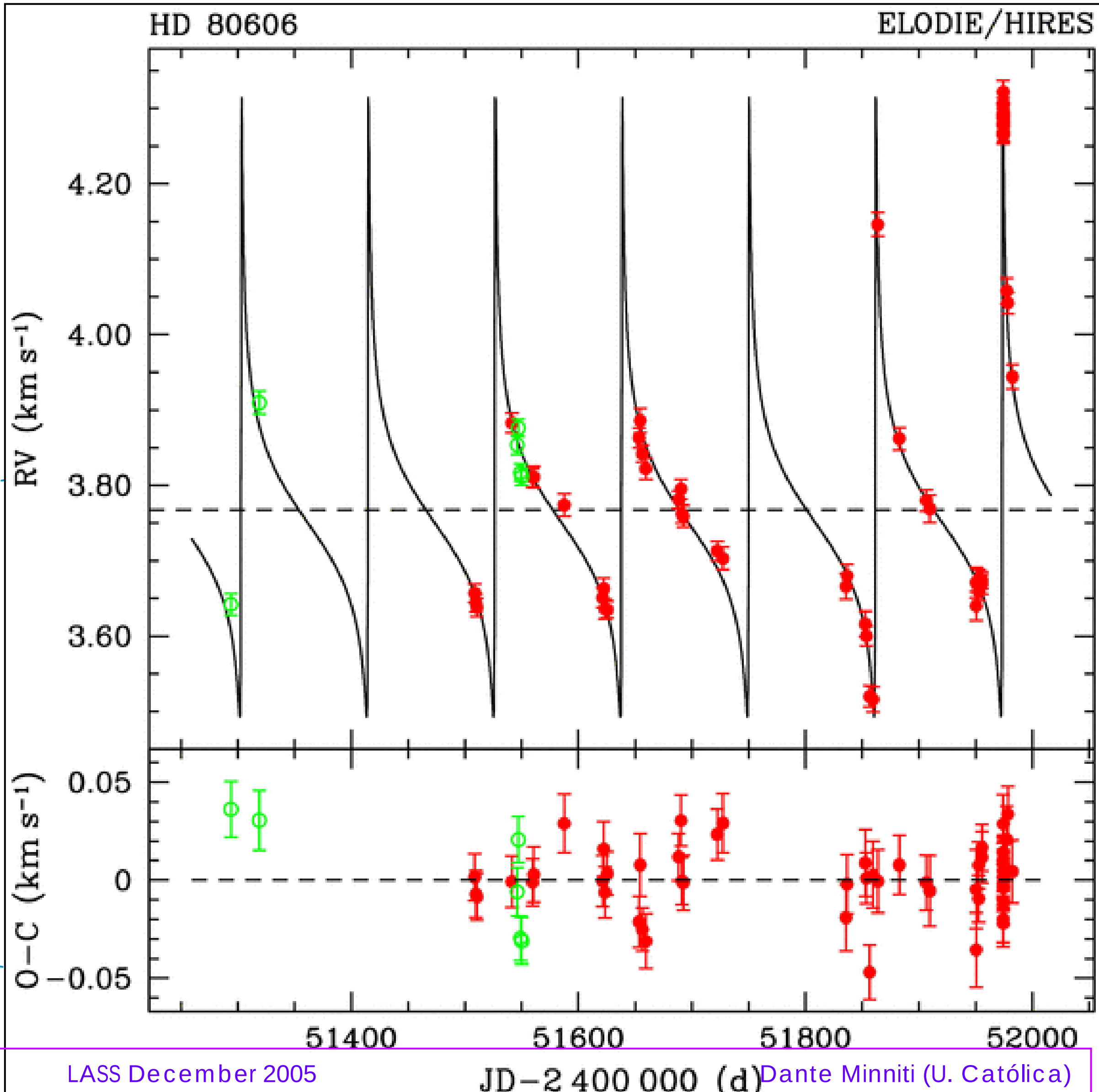
Type *G5V*

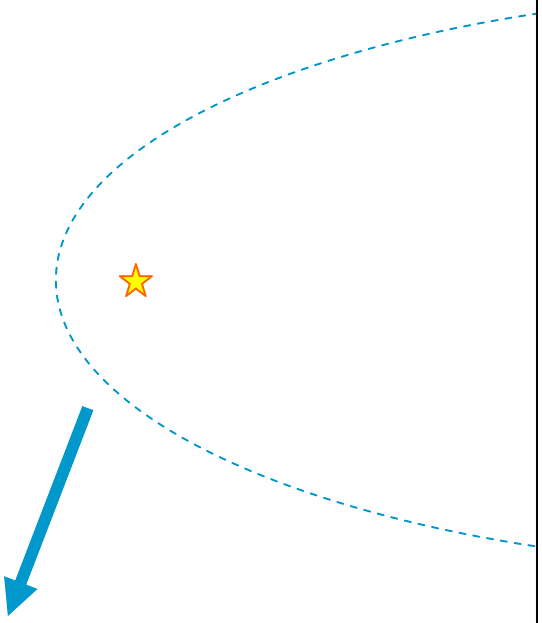
Distance = *58 pc*

V = 9.06

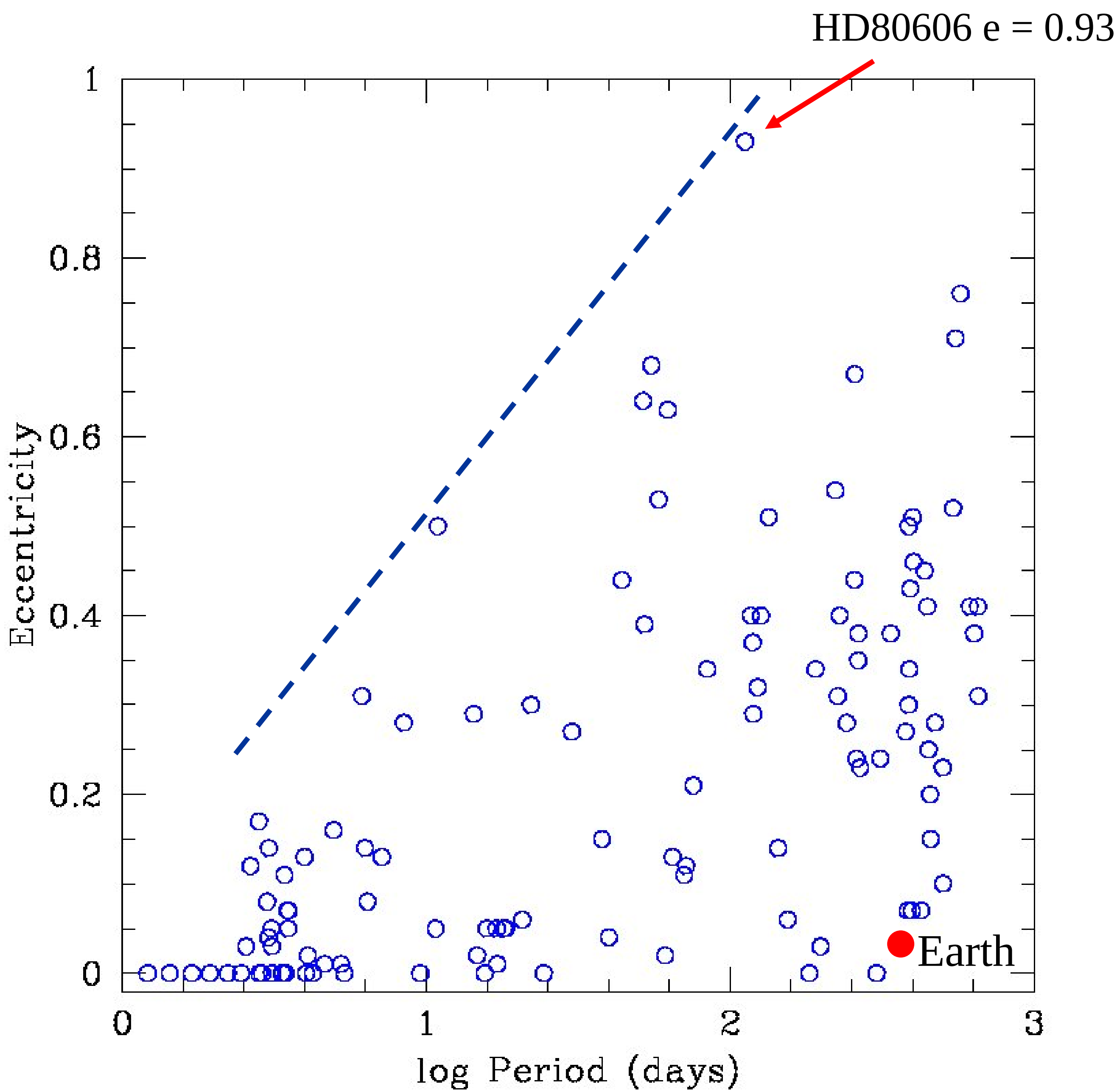
[Fe/H]=+0.43

$r_{mín}$ = 7 R_o → transits ?





e *vs* P



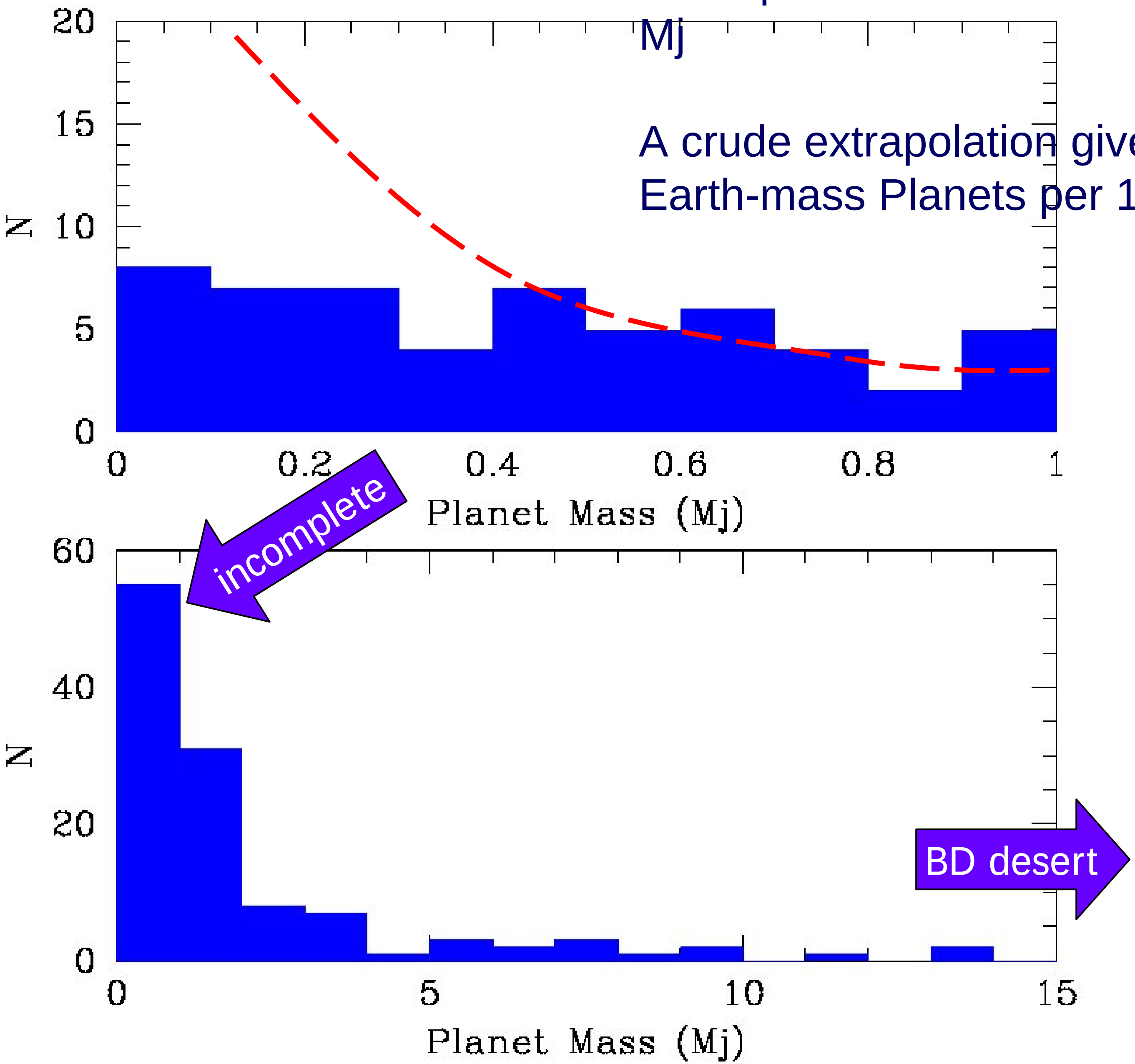
There is a non - random distribution of periods and eccentricities.

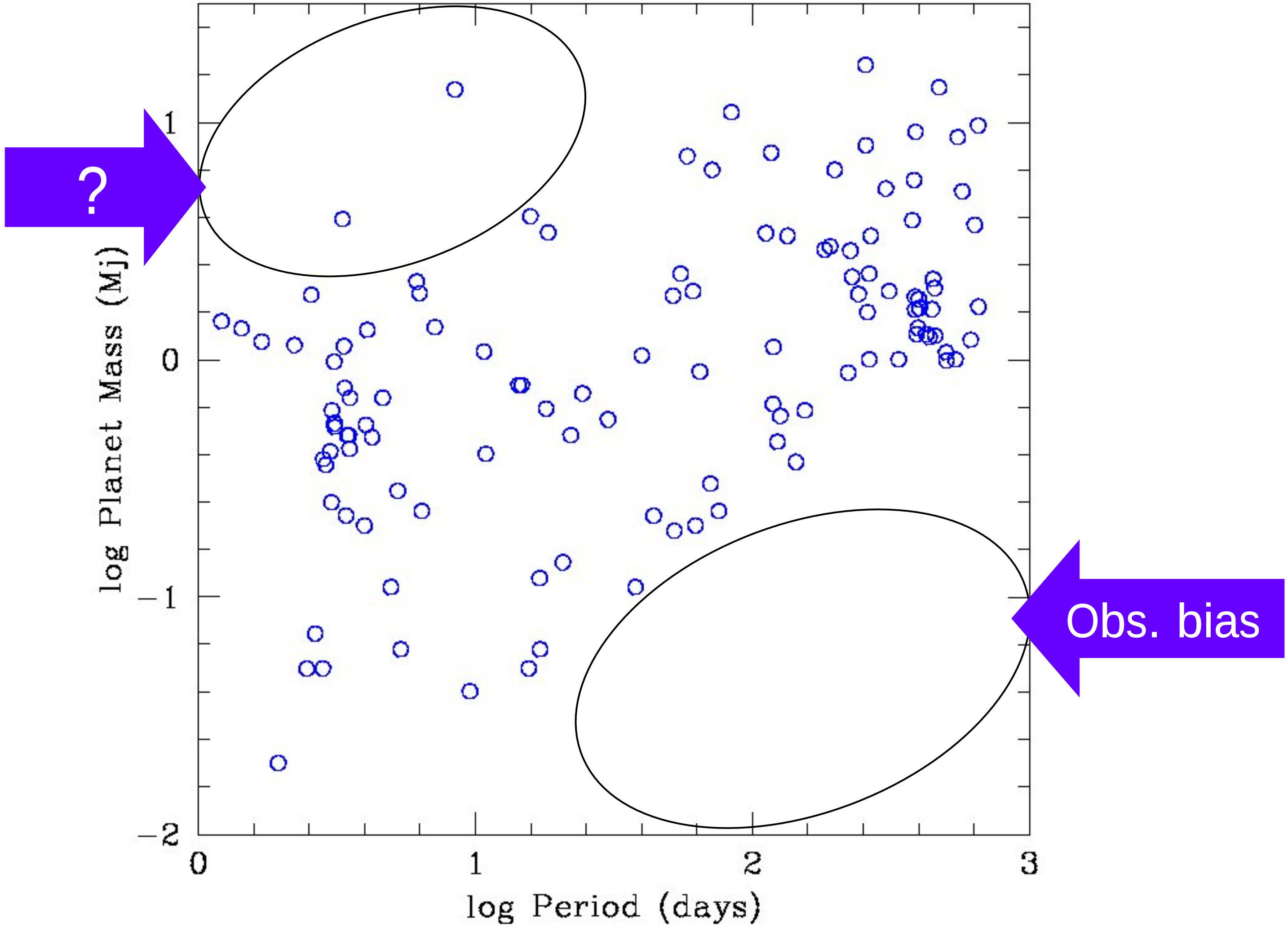
Almost all planets with P > 10 d are eccentric.

Almost all planets with P < 10 d have circular orbits.

Incompleteness severe for M < 1 Mj

A crude extrapolation gives a few Earth-mass Planets per 100 Stars





- There is a lack of planets in the upper left (with M sin i > 4 Mj inside of 0.3 AU), in spite of the better detectability.
- But many of the extrasolar planets beyond 1 AU have M sin i > 4 Mj
- This suggests that more massive planets (with M > 4 Mj) do not migrate inside of 1 AU, or they migrate but are swallowed by the star.

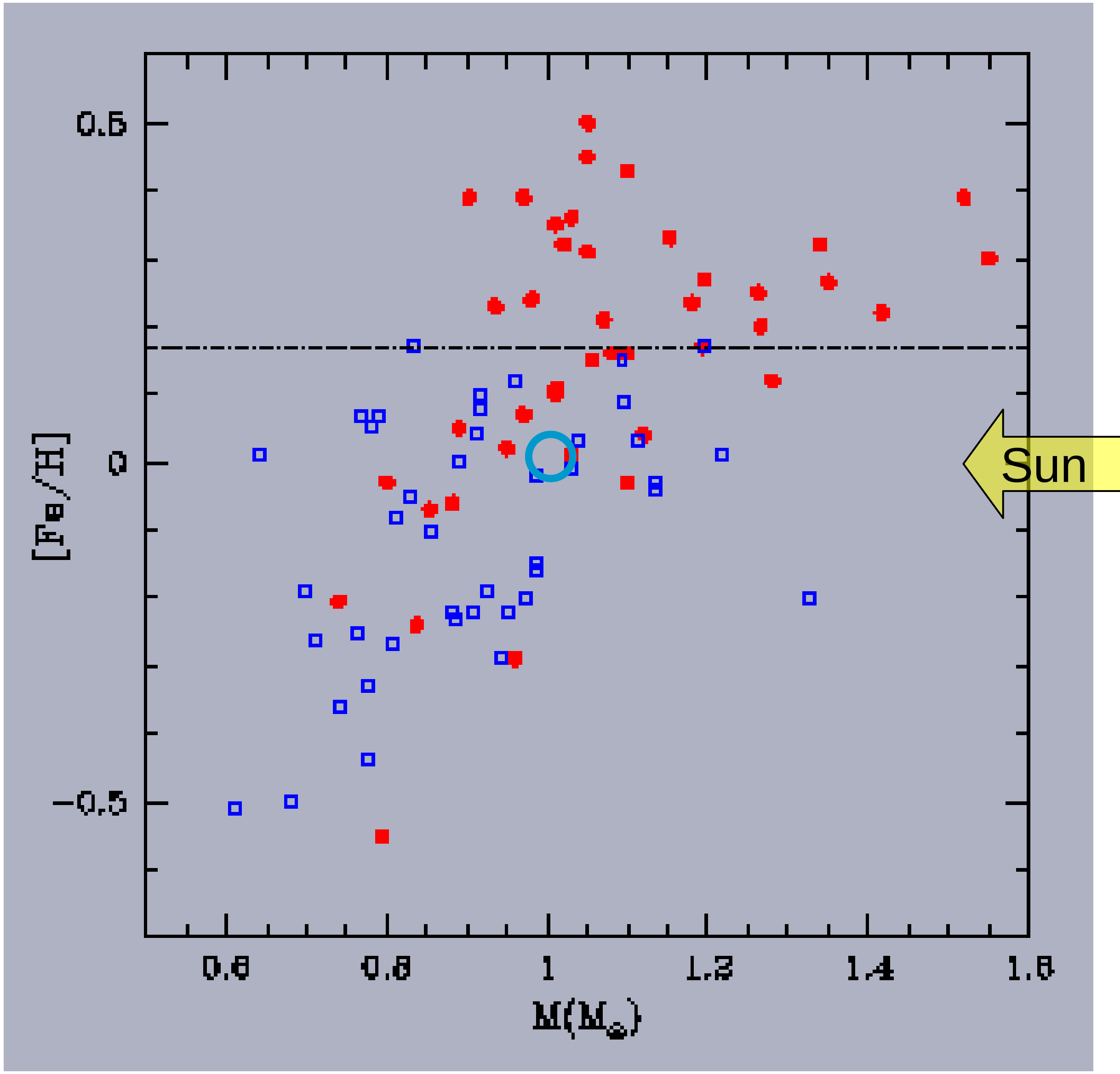
Metallicities

Metallicities vs masses for stars with planets (red circles) and without planets (blue squares).

Conclusion: stars with planets are metal rich.

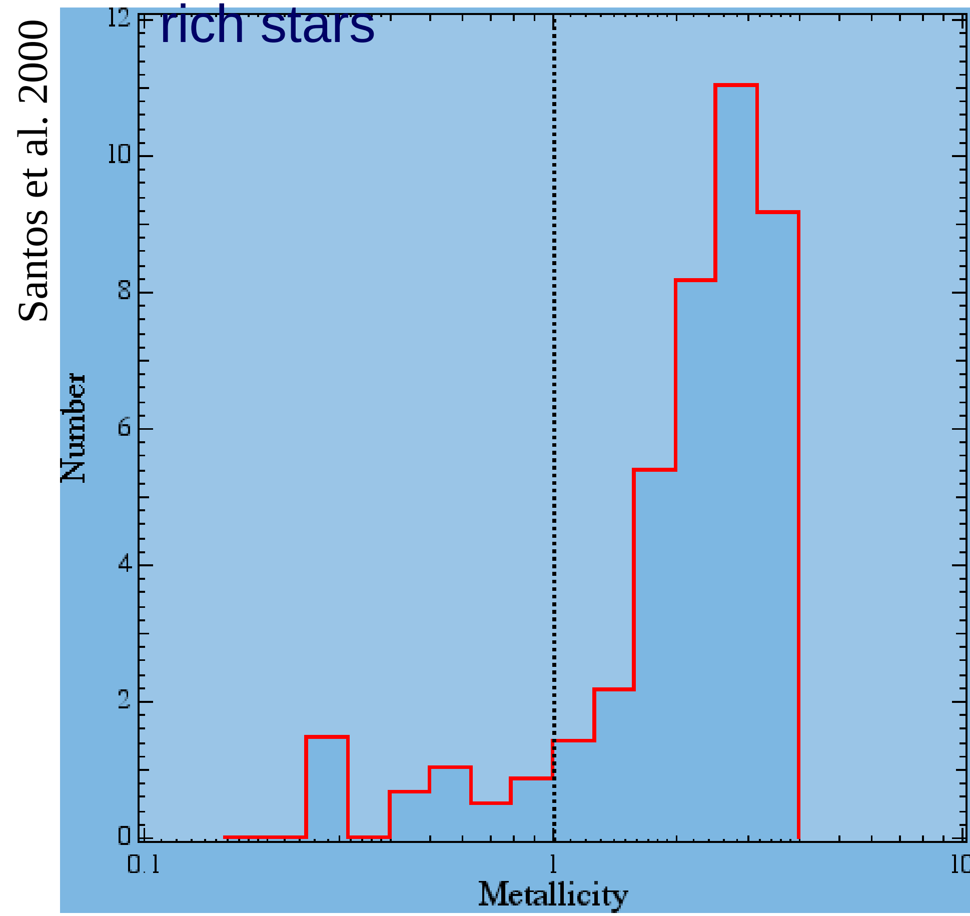
Change the strategy: select the more metal-rich objects.

N2K program: next 2000 stars with 7 < V < 9
(Fischer et al. 2005)



Metallicities

Normalized metallicity distribution: planets favor metal-rich stars



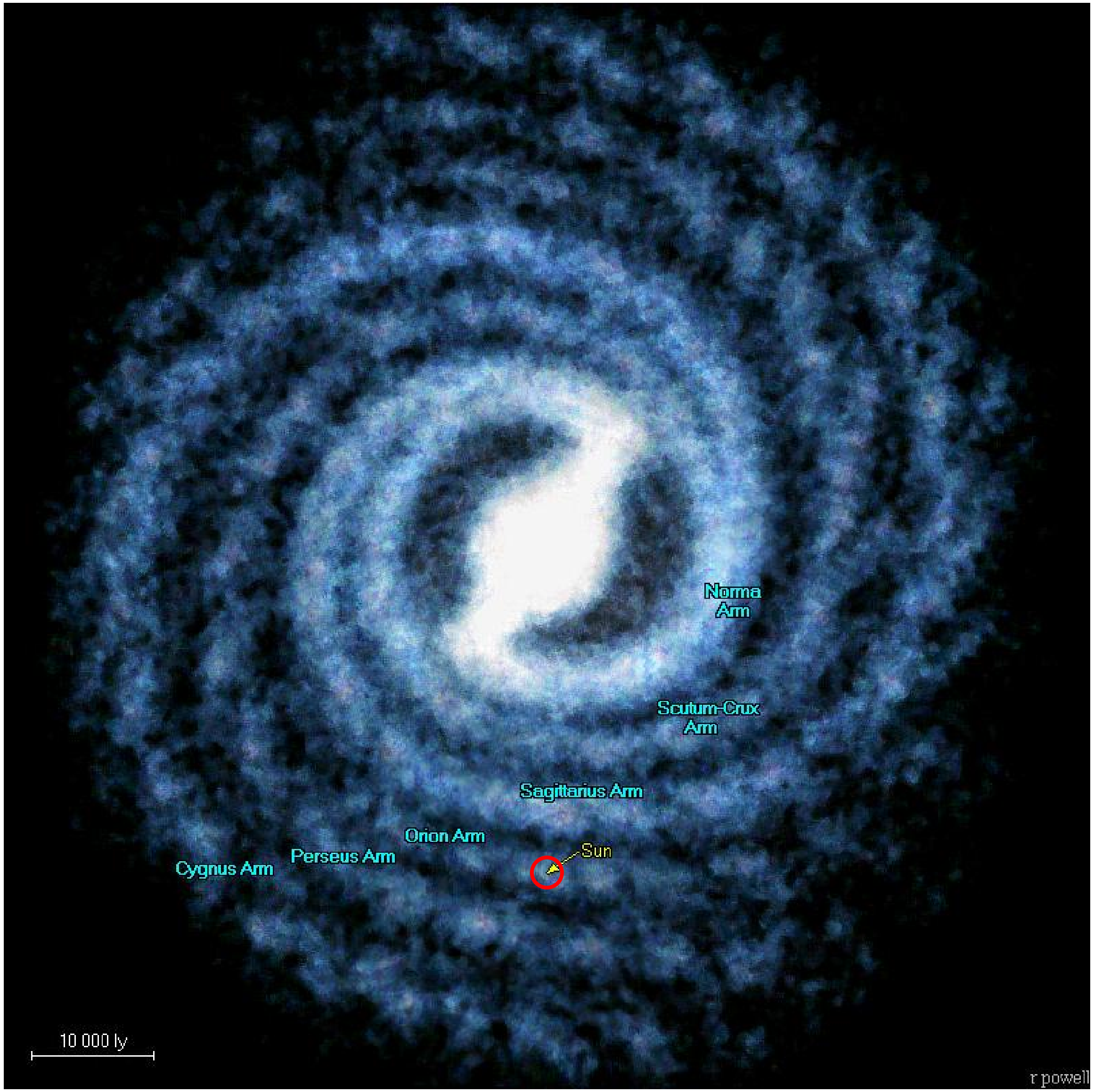
Why are stars with planets more metal-rich?

1. The high metallicities are primordial, and favor the formation of planets simply because there is more heavy material for them.

2. The high metallicities are a result of pollution by the same planetary material.

The answer may be found by studying different stellar population

Exoplanets in the Milky Way



How is the distribution of planets throughout the Galaxy? We do not know, but it must be different according to the metallicity.

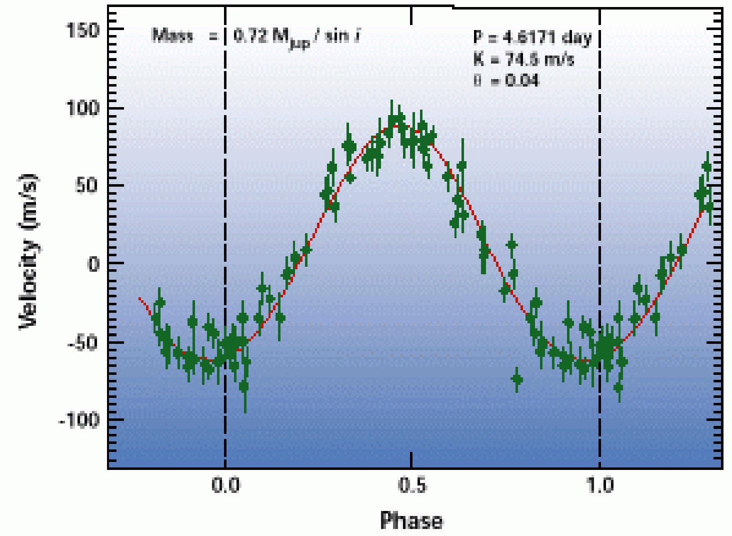
Searches in:

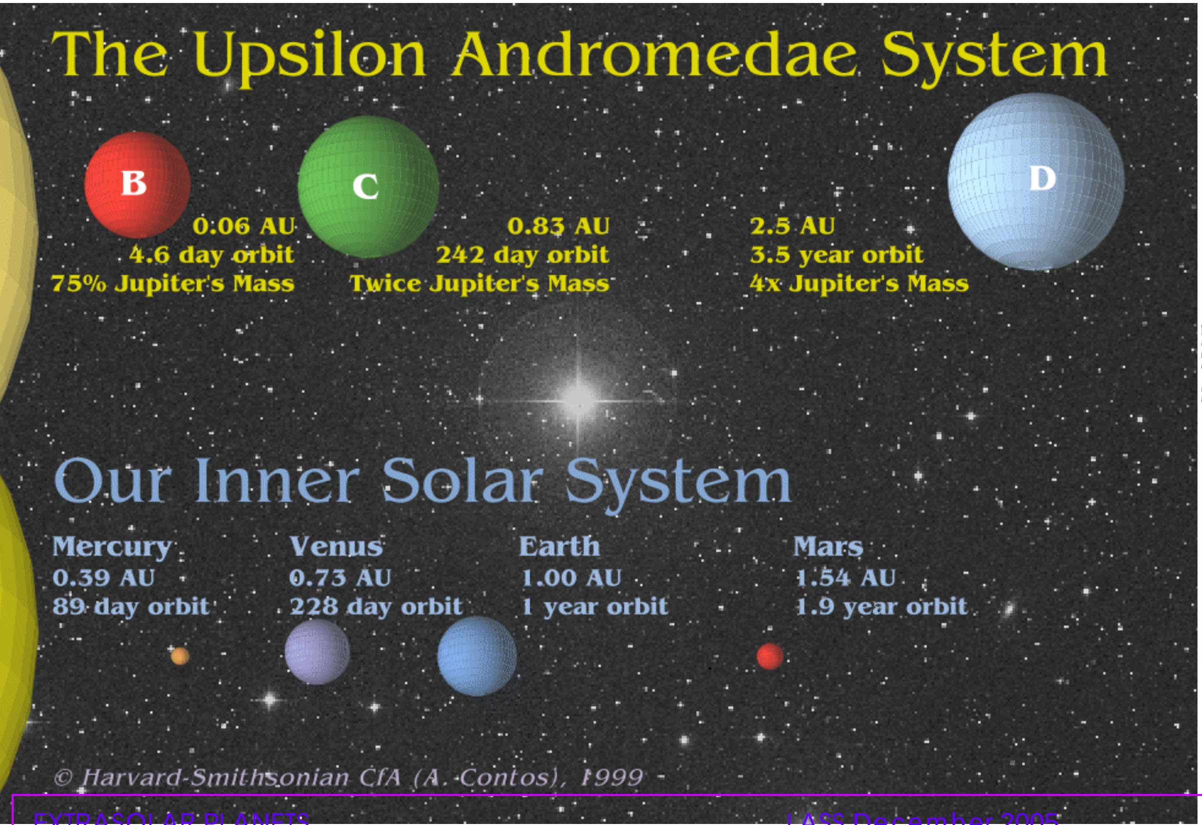
- The Solar vicinity
- The disk (Car, Nor, Scl)
- The bulge
- Globular clusters (47 Tuc)
- Open clusters

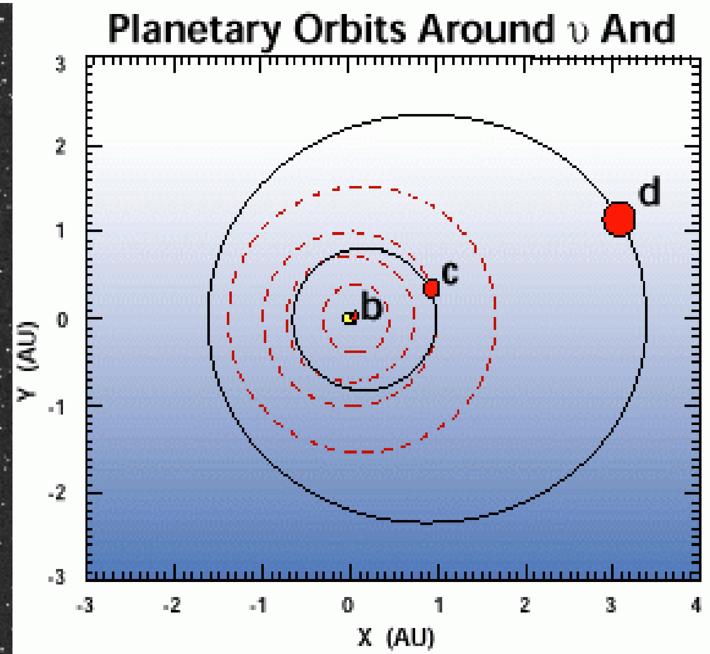
Planetary systems

- υ And:
  - a multiple planetary system.
  - Orbits barely stable, in secular resonance – same ω (Lin et al., Laughlin et al., Lee & Peale)

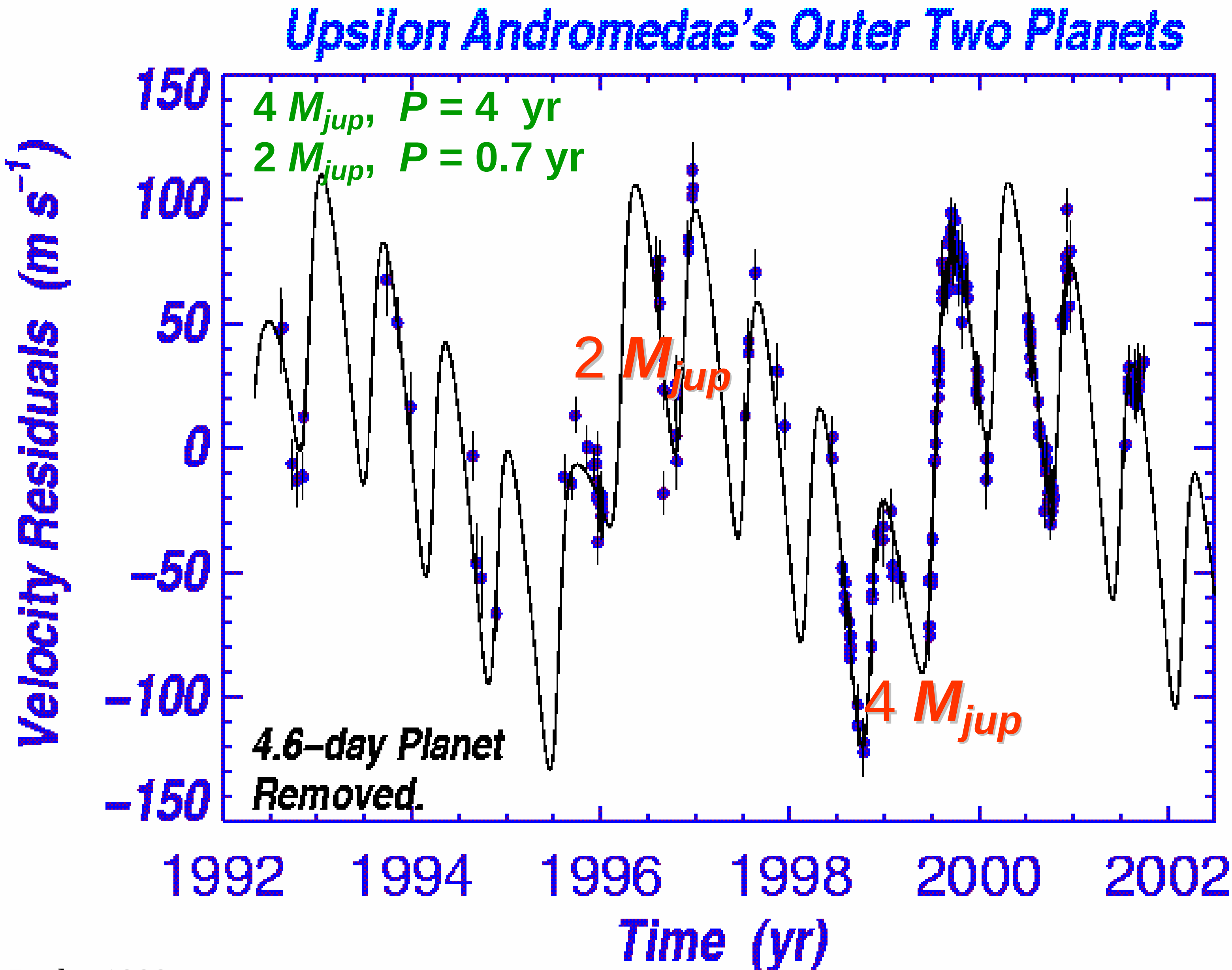
Marcy & Butler 1999







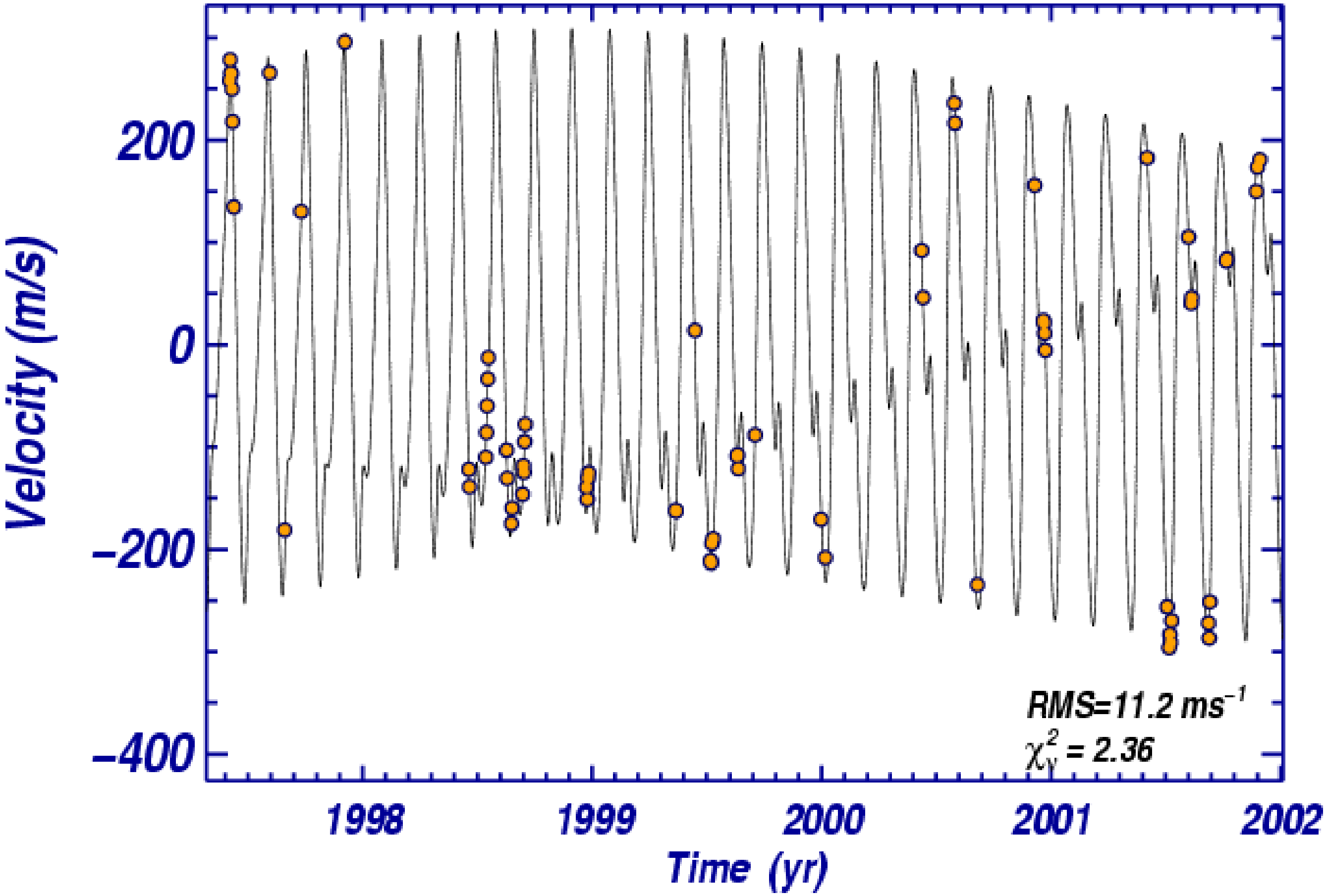
Also binary with P_{orb} = 10000 yr



Marcy & Butler 1999

Planetary systems

Gliese 876 (M4V)



Marcy & Butler

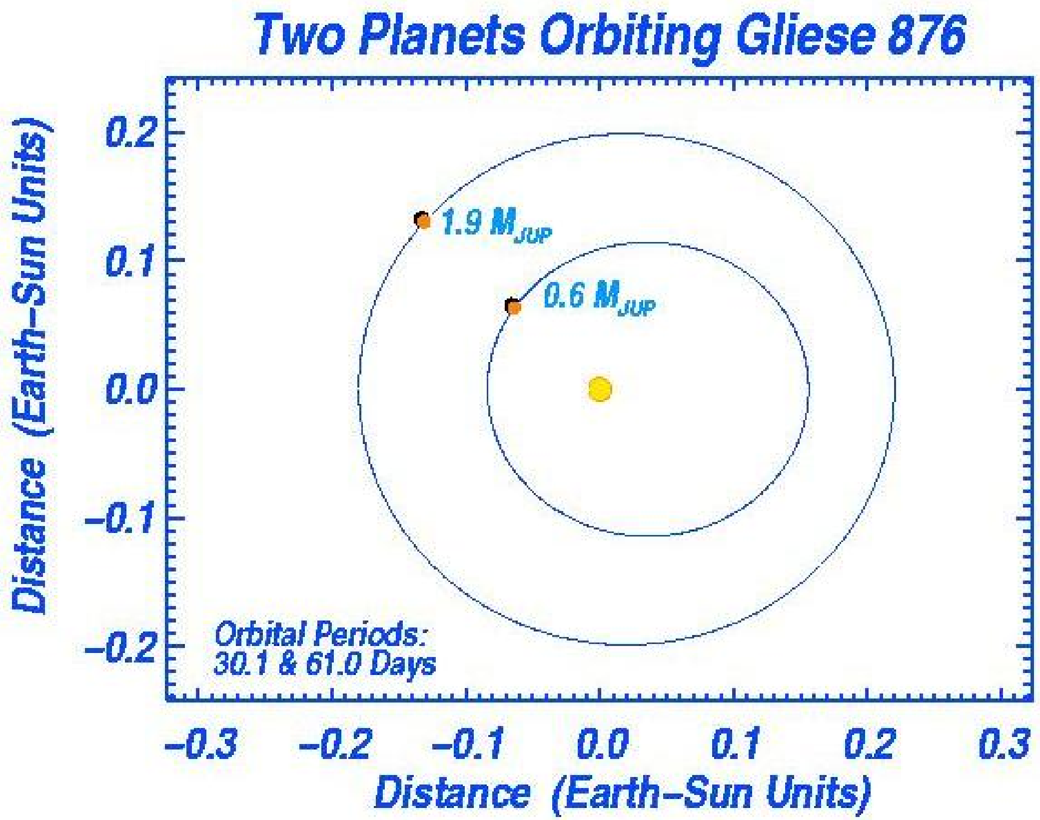
V=10.17

P = 61 d
P = 30 d

M sin***i*** = 1.9 M_J
M sin***i*** = 0.56 M_J

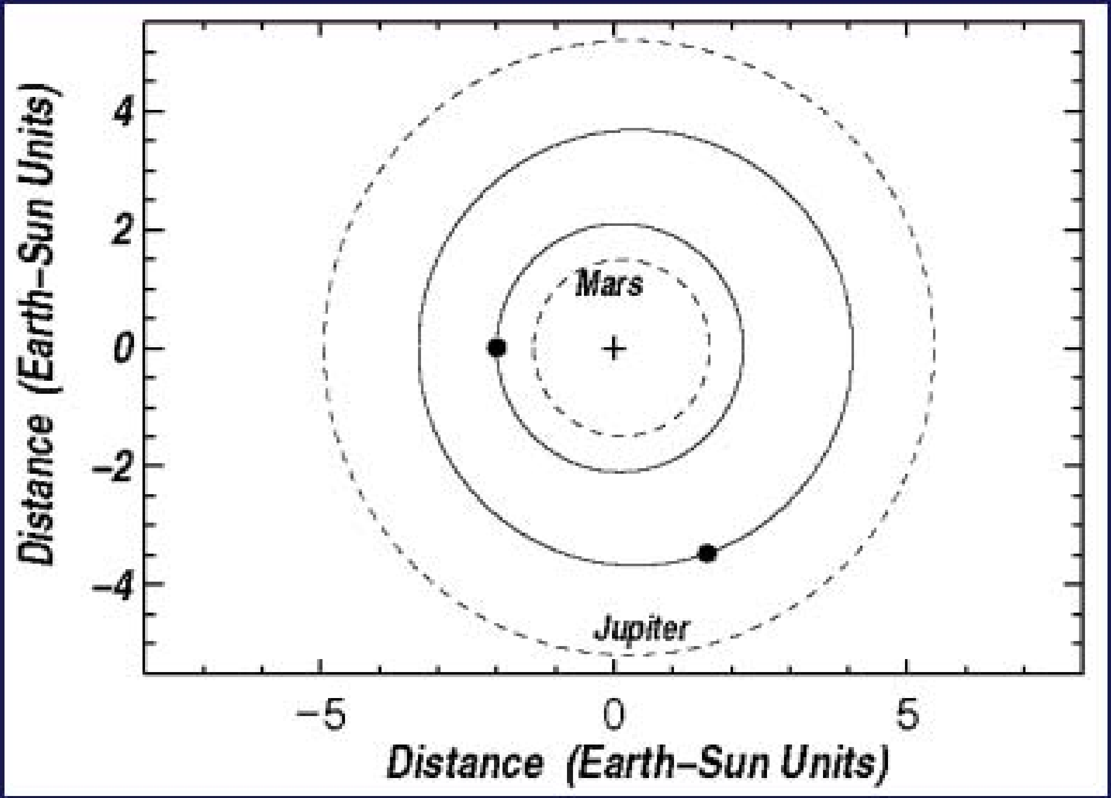
e = 0.10
e = 0.27

GL 876
2:1 mean-motion resonance



Mean resonance 2:1
and secular resonance
(orbital axes aligned)

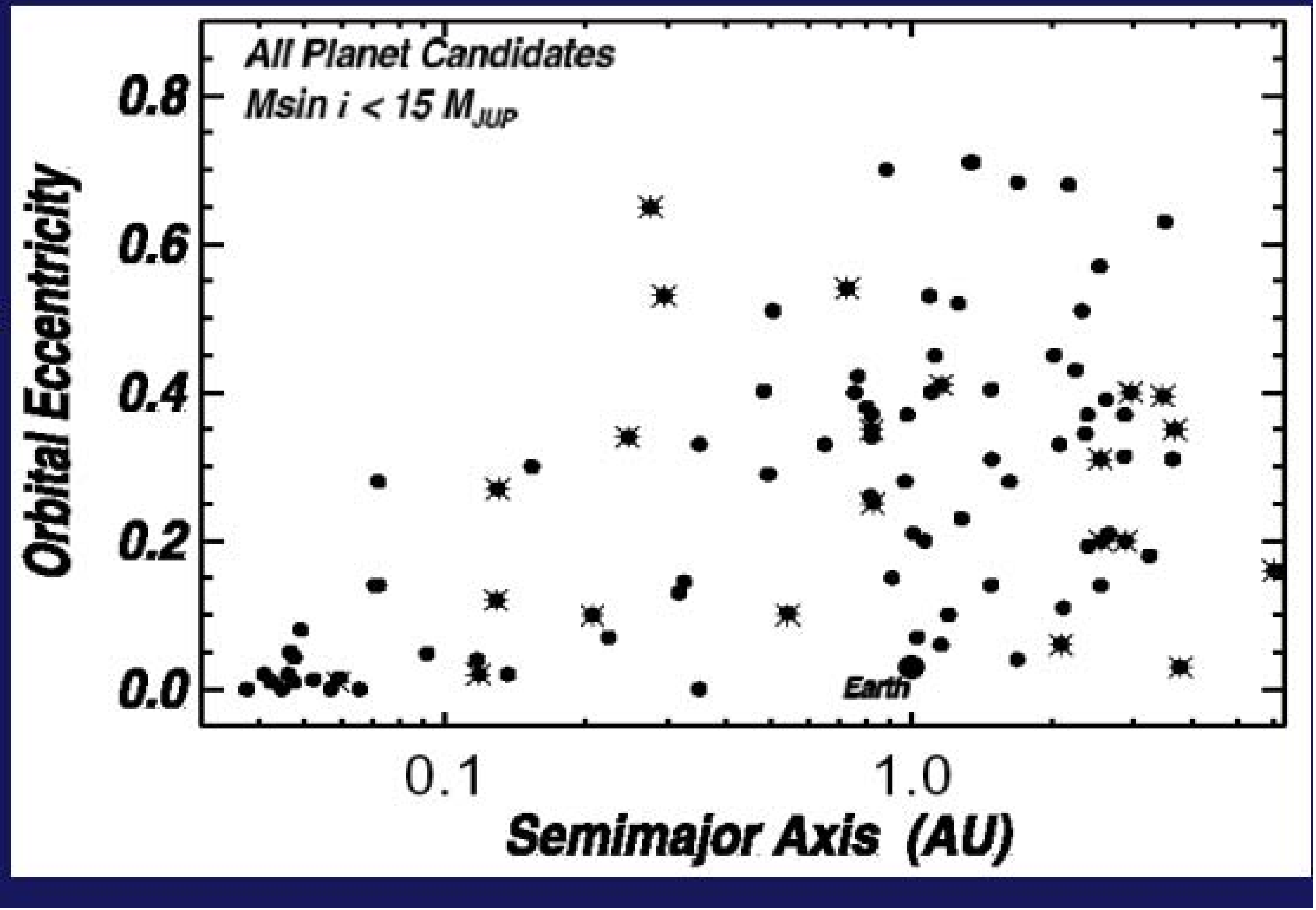
Marcy & Butler
Rivera & Lissauer
Laughlin & Chambers
Lee & Peale



• 3 planets in Ups And, 55 Cnc and Gl876
• 2 planets in Gl876 in resonance 2:1
• 2 massive planets in HD168443: 7.2 & 15.1 Mj
• 2 planets in circular orbits in 47UMa: Solar

Planetary resonances: Ferraz-Melo et al. (2004, 2005)

Planetary systems: 47 UMa



- The planets in multiple systems (asteriscs) apparently do not differ from the general population: there are multiple planets with varied eccentricities.

Latest radial velocity statistics

Web page that contains the data for known extrasolar planets. Very complete. It allows to explore through different parameters.

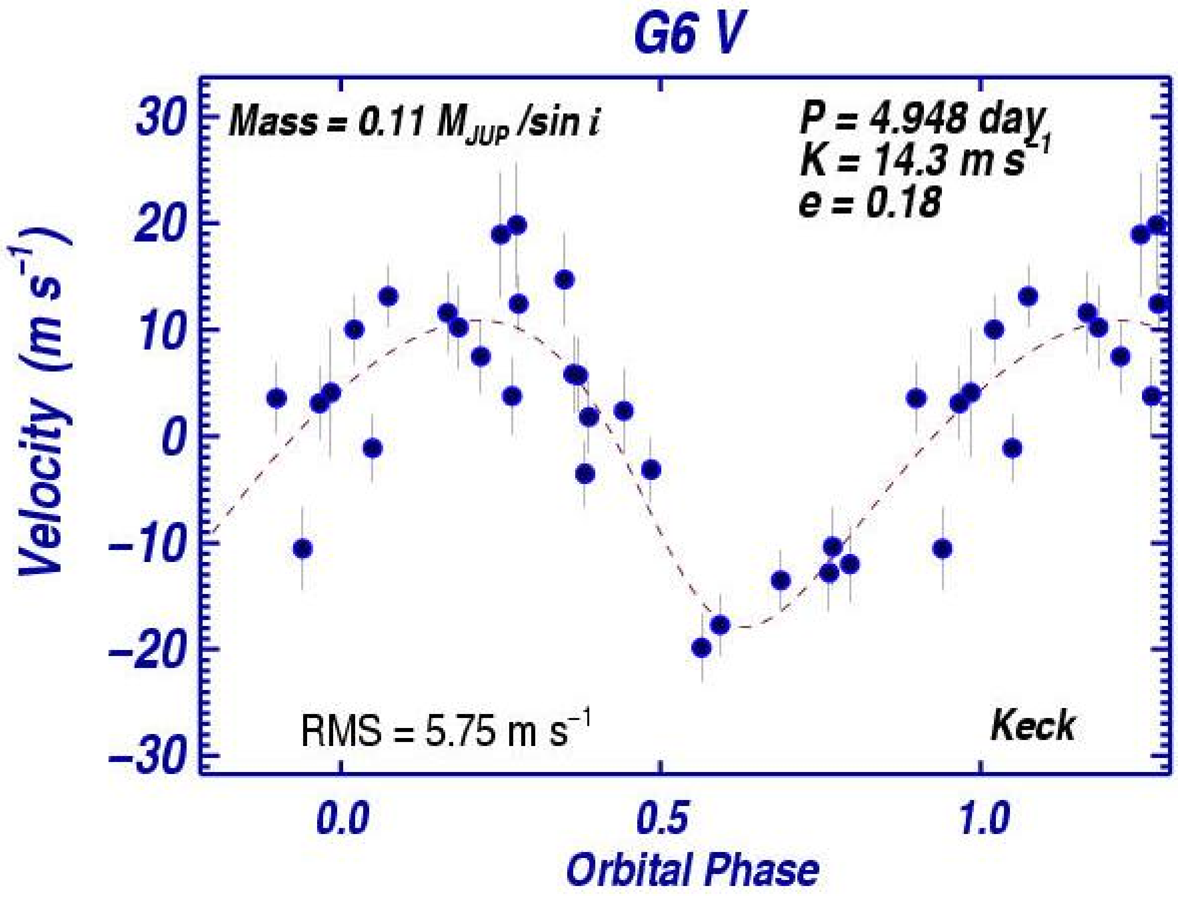
- Jean Schneider (Obs. de Paris Meudon):
  - Extrasolar Planets Encyclopaedia
  - www.obspm.fr/planets
  - Results from RV till Dec 2005
  - 170 planets
  - 18 multiple planetary systems
- Incompleteness:
  - Planets with M < 0.1 Mj
  - Planets with a > 3 AU (P > 10 yr)
  - Multiple planets

$a = 0.04 – 5.0$ AU

$P = 3 – 3000$ d

$M = 0.1 – 15\ M_{JUP}$

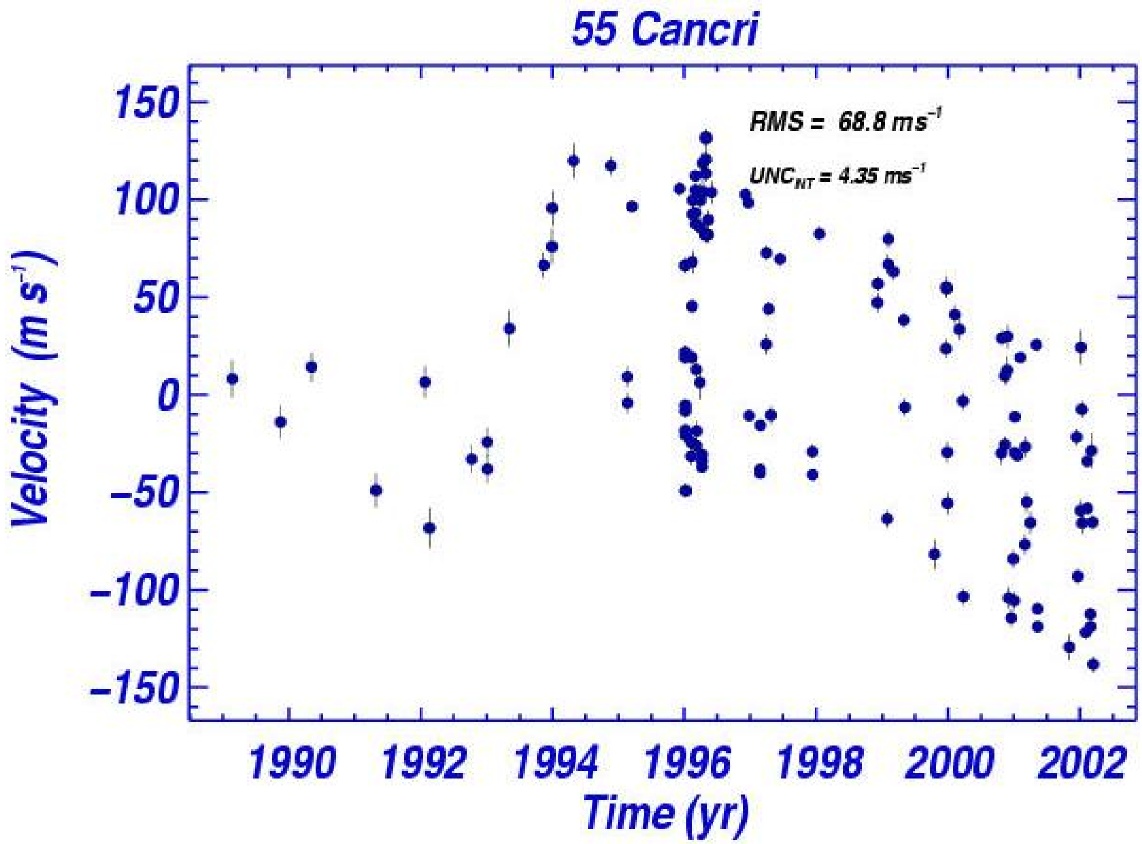
The future: Neptune mass planets



Butler et al. 2005

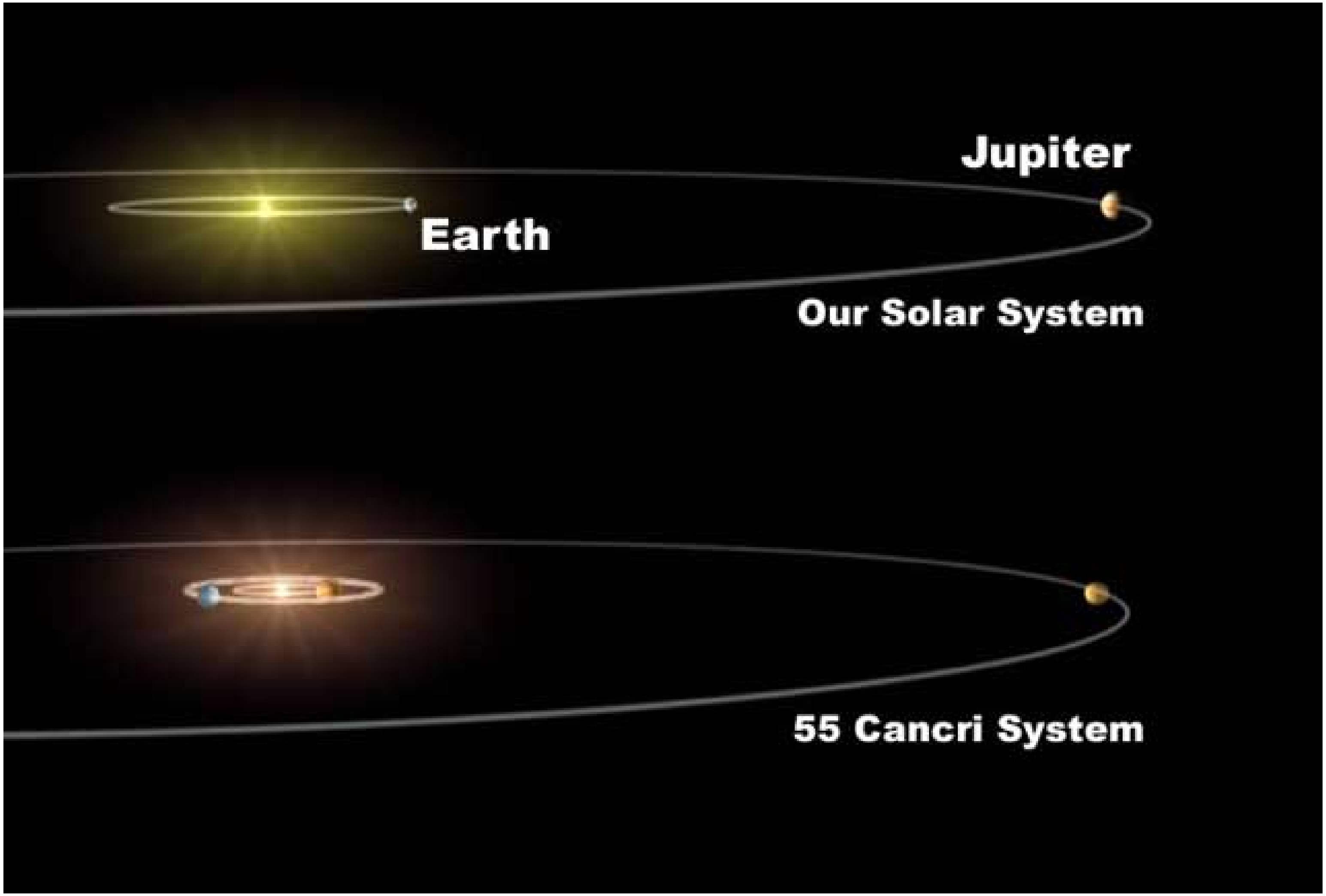
4 low mass planets discovered so far this year (2005)

The future: planets with a > 5 AU



Butler & Marcy

As time span increases, long RV trends turn into real orbits



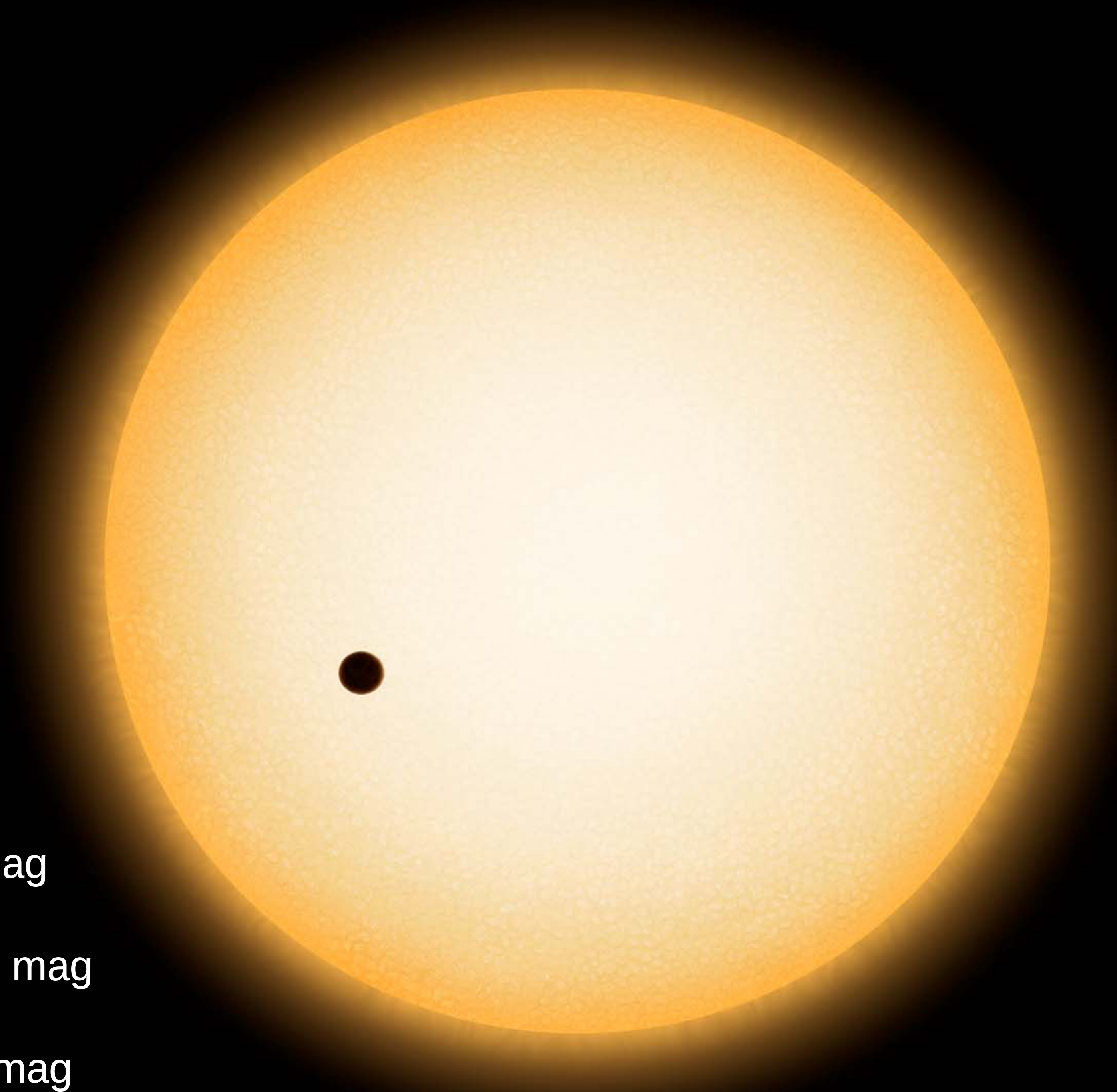
Planetary systems: 55 Cnc

Extrasolar Planets

- Radial velocities
- Transits
- Astrometry
- Microlensing
- Timing
- Direct detections

Extrasolar planets

- Transits
  - Technique
  - Results
    1. HD209458: the 1st transit
    2. Problems
    3. Very hot Jupiters
    4. Latest statistics



Lynnette Cook

$A_{Jupiter} = 0.01$ mag

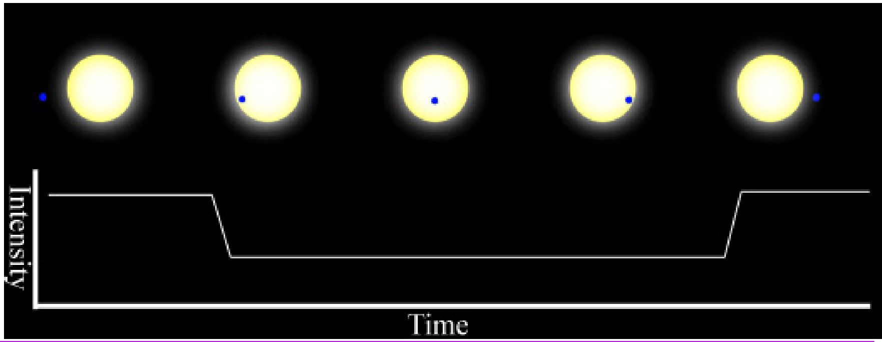
$A_{Neptune} = 0.001$ mag

$A_{Earth} < 0.0001$ mag

Extrasolar planets 10 years later

- 160 exoplanets discovered so far (Schneider 2005)
- The majority were found using precise radial velocities, which give ***M sin i***
- A few of them transit in front of their parent stars
- Importance of transiting extrasolar planets: they give

R, i ➔ ρ



Transits

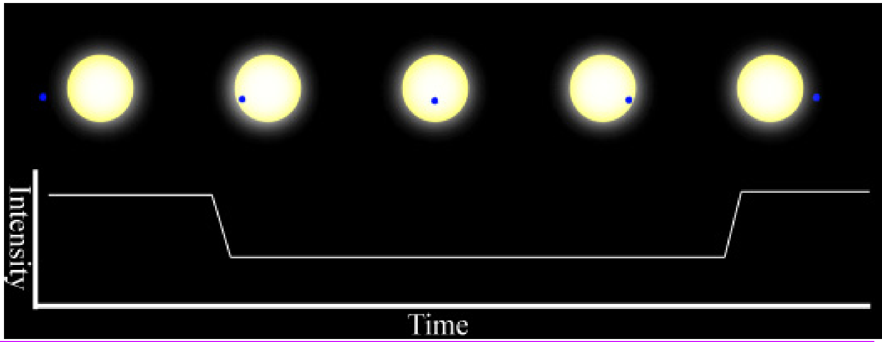
- Measure the brightness of the stars, searching for transiting planets
- Giant planets in small stars can be detected.
- Knowing the dependence of R_* with M_* for MS stars, the transit time depends on the orbital period and the star mass as:

$$t_T = 13(M_*/M_o)^{1/2}(a/1AU)^{1/2} \text{ hours}$$

- The transit depth depends on the relative planet and star sizes:

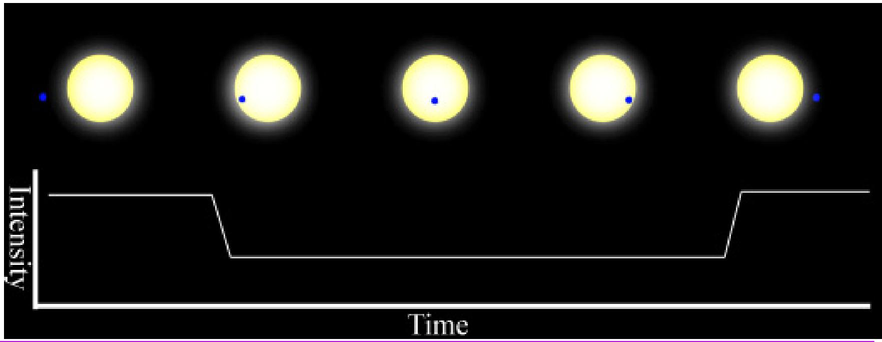
$$\Delta V = (R_p/R_*)^2$$

- Sensitive to giant planets, terrestrial planets much more difficult to detect.
- For typical main sequence stars:
  - Transit durations: 2h – 20 h
  - Transit depths: 0.0001 - 0.01 mag

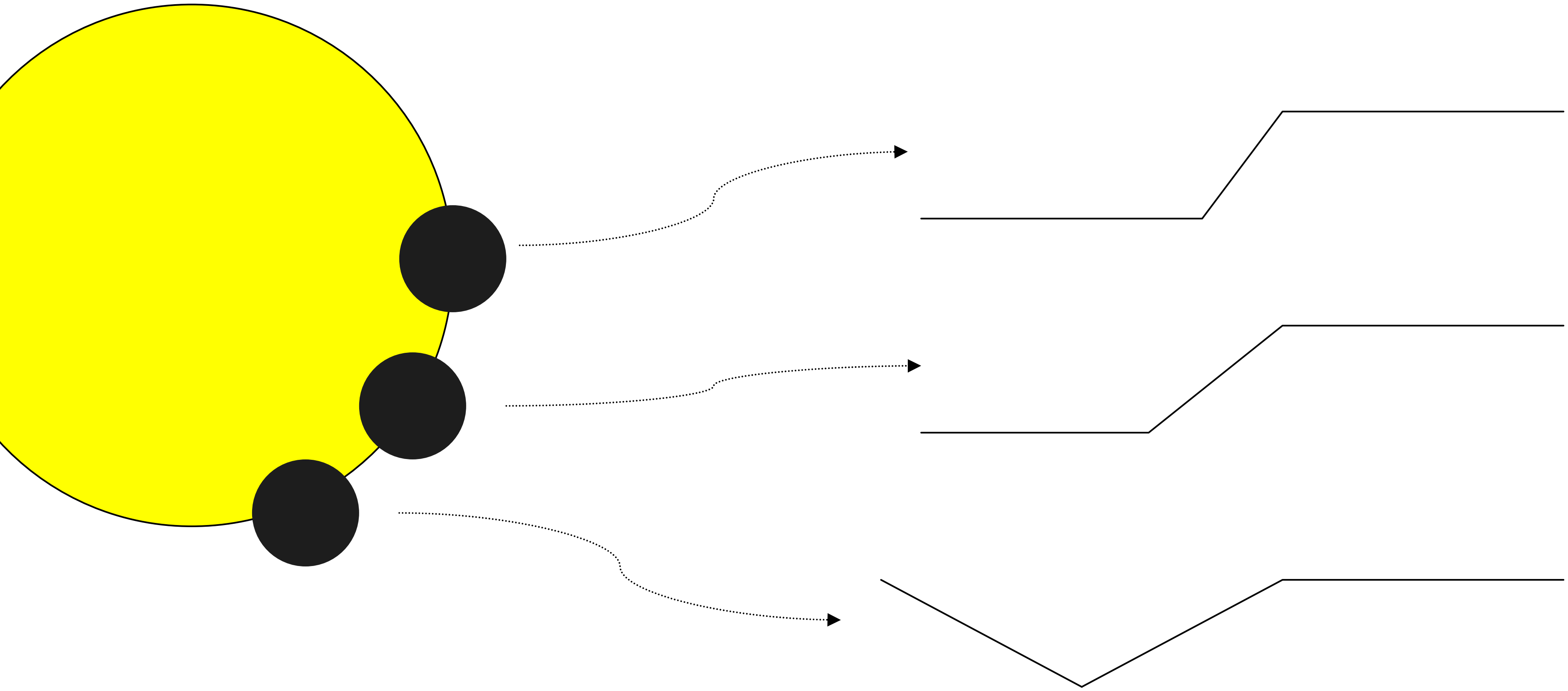


Transit information

- Multiple transit observations give:
  - Orbital period P → orbital semimajor axis a
  - Transit depth → planet radius Rp
  - Transit shape → orbital inclination i
  - Transit time → i, Rs+Rp



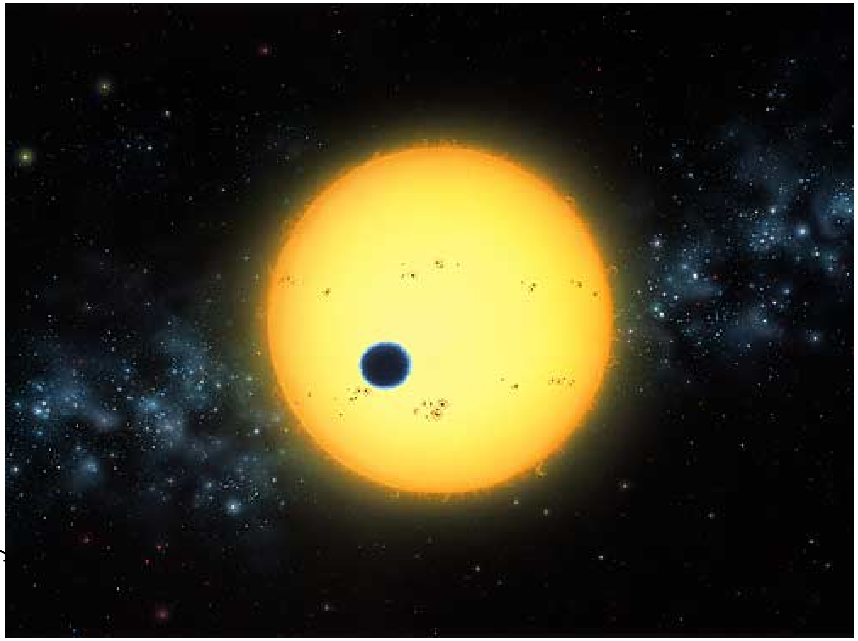
Transit shape



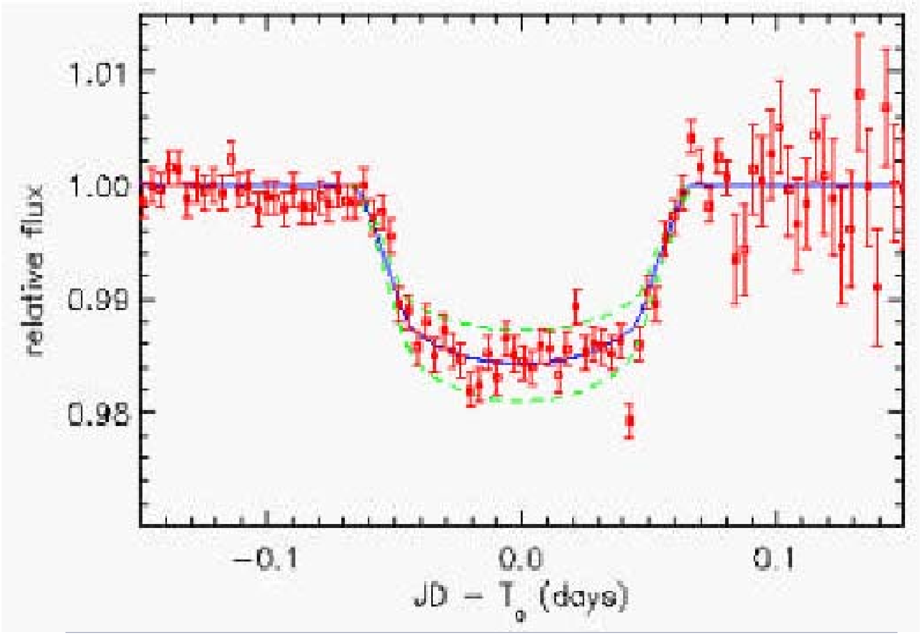
→ Dependence with the orbital inclination: we know the inclination angle i from the shape of the light curve at ingress and egress.

HD209458 transit

- Tested method: Charbonneau et al. (2000) and Henry et al. (2000) found transits in a planet previously discovered by radial velocities.

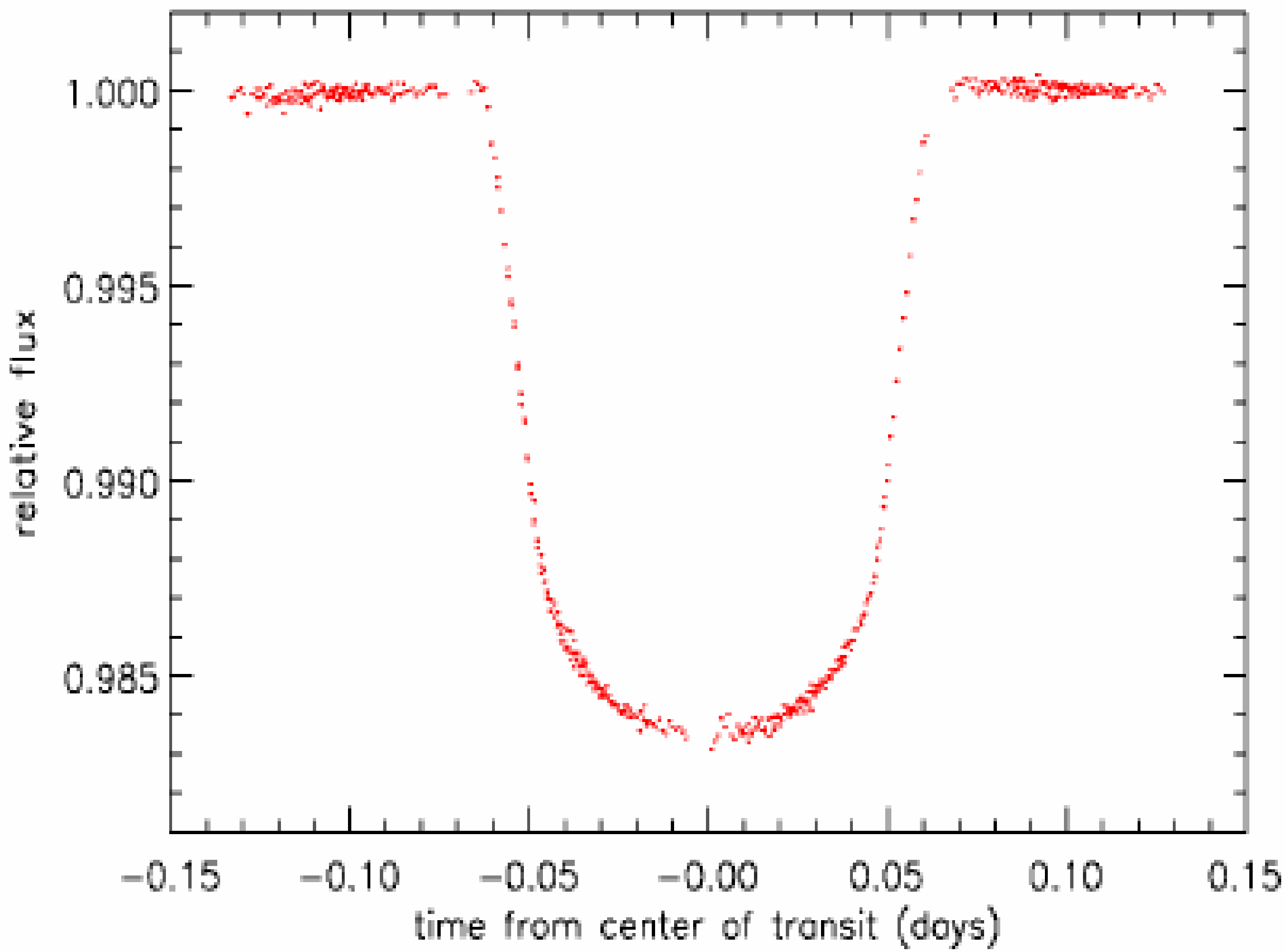


Lynette Cook



A = 1.5 %, $t_T = 3^h$ for the giant planet around HD209458.

HD209458 transit



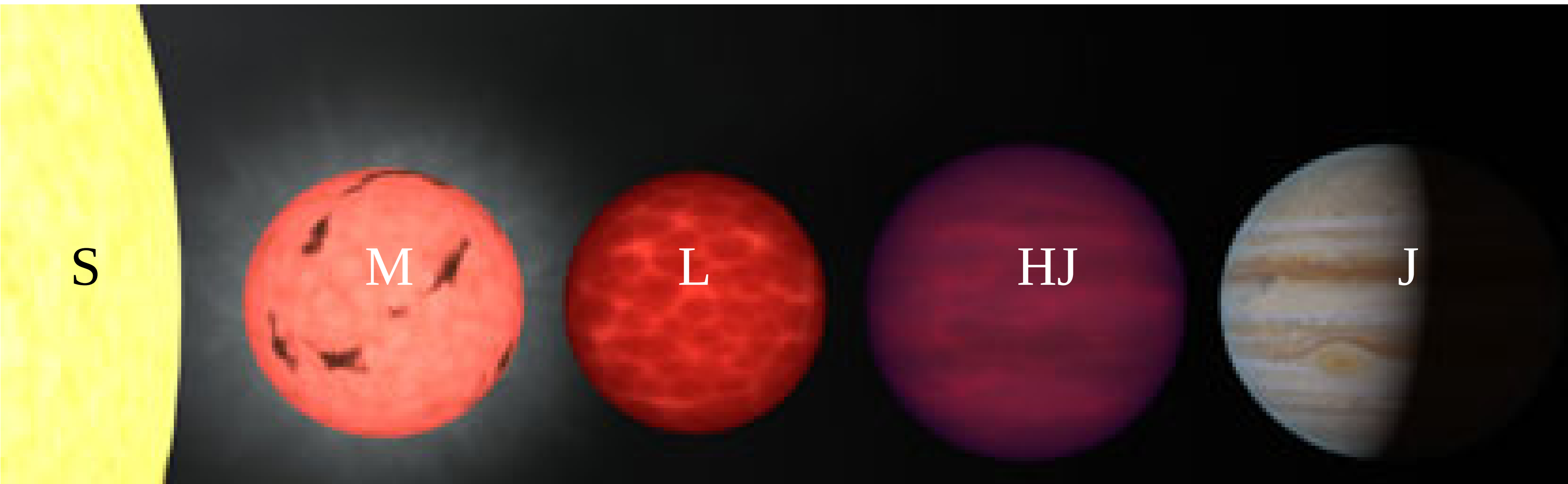
Brown et al. 2001: detailed shape of the eclipse using HST+STIS as a photometer.

M=0.63 MJUP
R = 1.4 RJUP
ρ = 0.4 g/cm3

➔Gas giant

Problems

- Contamination by other small stellar and substellar objects: the radii of small stars, brown dwarfs and giant planets are similar



Sol	Gliese 229	Gliese 229b	HD209458	Jupiter
T=5800K	T~3400K	T~1500K	T~1000K	T~200K
M=1000Mj	M~300Mj	M~50Mj	M~1Mj	M=1Mj
R=10Rj	R~3Rj	R~1Rj	R~1.5Rj	R=1Rj

Problems

- A large fraction (95%) of OGLE transits are not due to planets. Impostors mimicking planetary transits:
  - Blended binary stars in dense fields. Could be discriminated using ellipsoidal modulations of the light curve or secondary transits.
  - Grazing binaries. Could be discriminated using the shape of the light curve or secondary transits.
  - MS star in orbit around a giant star. Could be discriminated using spectral type.
  - False positives

False positive (no transit)
Single planet transit
Single planet with rings
Single planet with moon(s)
Binary planets
Multiple planets
Grazing binary, same colors
Grazing binary, different colors
Binary, red giant primary
Binary, M or BD secondary
Triple, MS binary (same color)+background star
Triple, star+background MS binary (same color)
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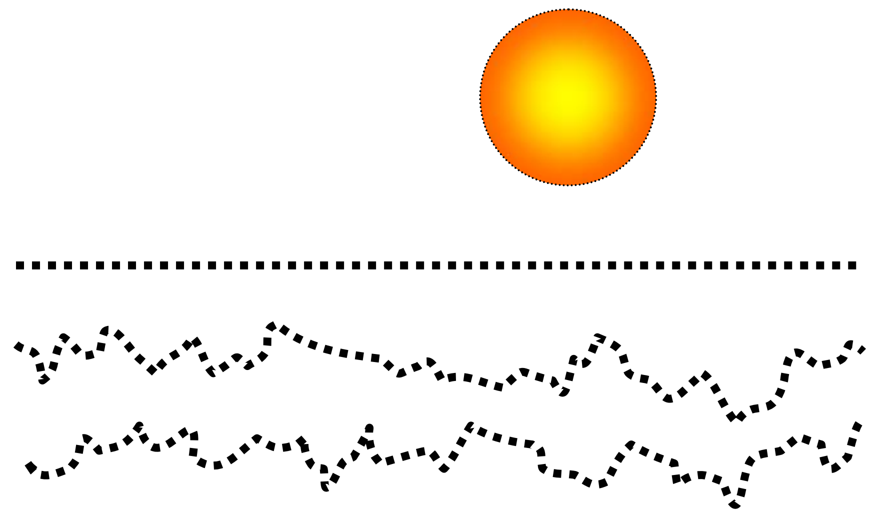
Triple, binary (RG+MS)+foreground star
Quadruples...



Sometimes just "red noise" or star spots can mimic periodic low amplitude transits

Transit zoo

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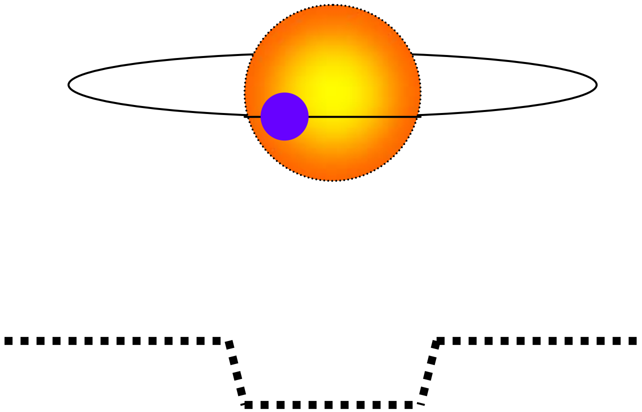
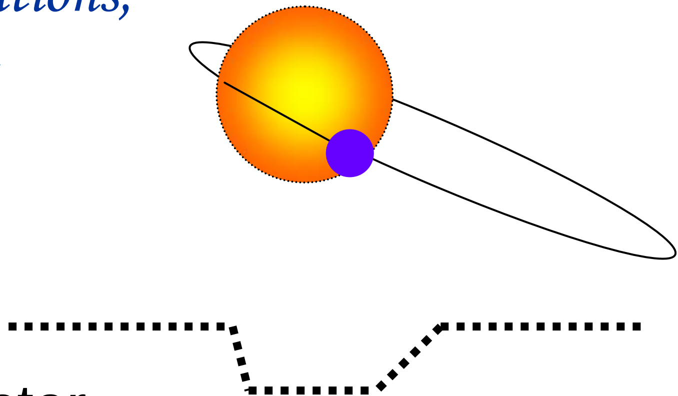


Different durations, depths, shapes



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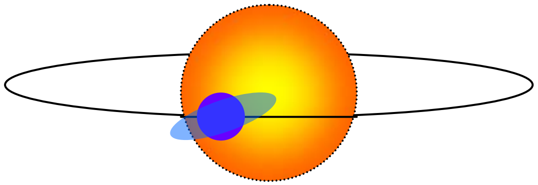
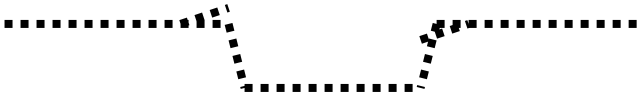
Quadruples...





Different effects, not necessarily symmetric

Arnold & Schneider 2004, Barnes & Fortney 2004

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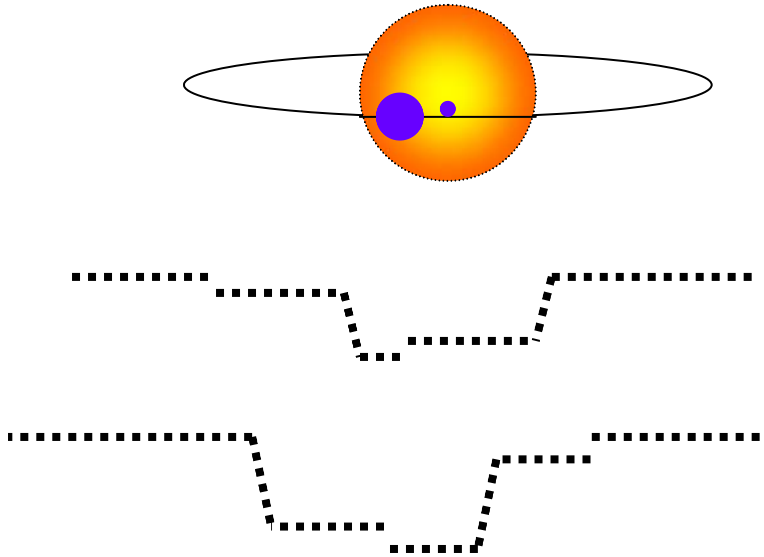

Many different possible shapes

Sartoretti & Schneider 1999,
Barnes & O'Brien 2002

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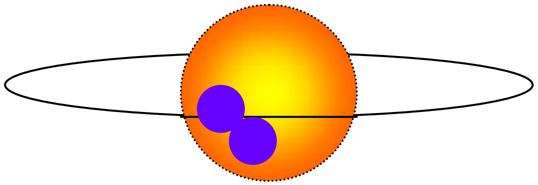

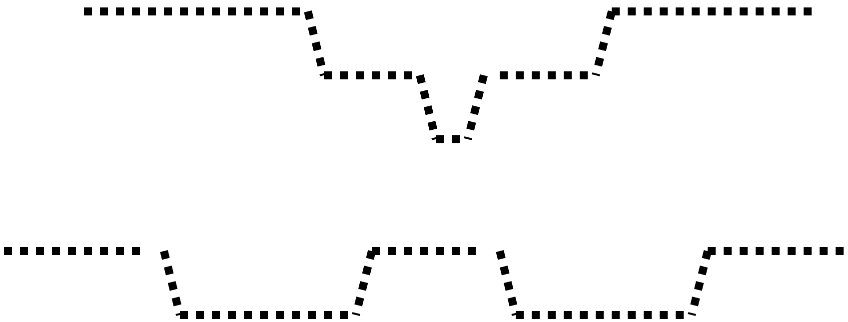

Many different possible shapes

Transit zoo

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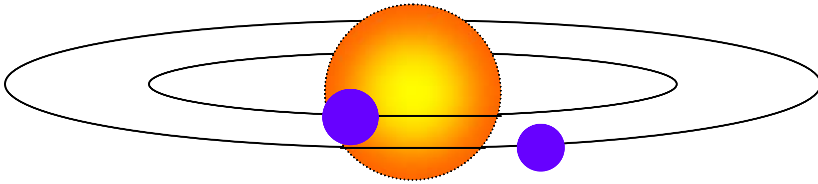
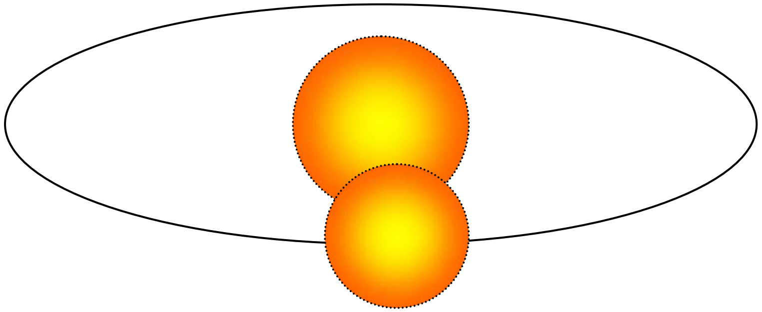
Quadruples...



Many different possible durations and depths

Transit zoo



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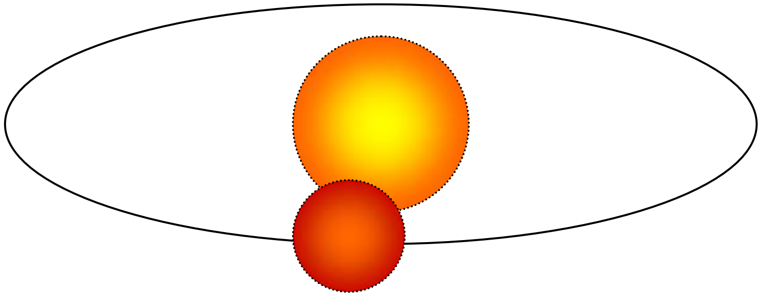
Quadruples...

Very common, low amplitudes, serious contaminants



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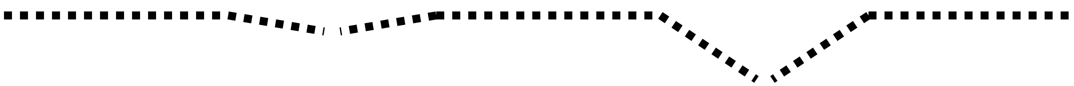
Quadruples...



Very common, low amplitudes, serious contaminants, but the color difference helps

Transit zoo

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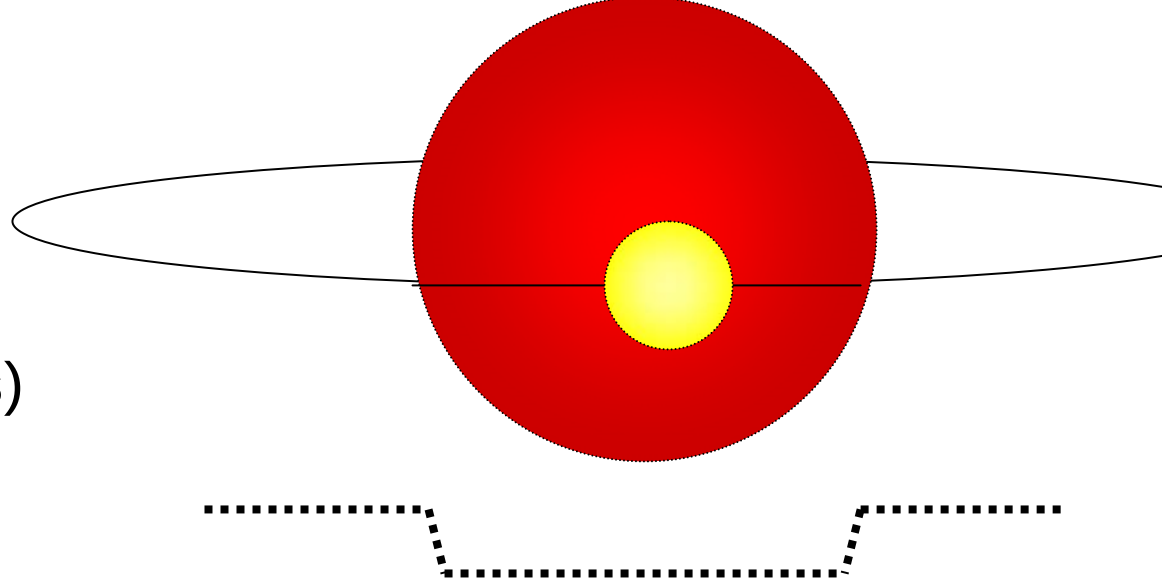
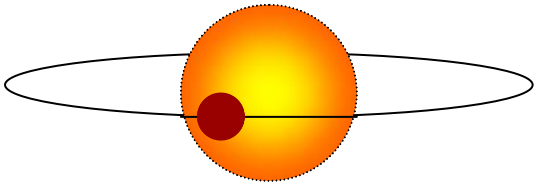
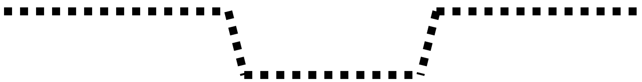


Low amplitudes, but long duration of transits helps

Transit zoo





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Quadruples...

Very common in the MW, low amplitudes, check for ellipsoidal modulation, serious contaminants

Transit zoo

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Single planet with moon(s)
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Multiple planets
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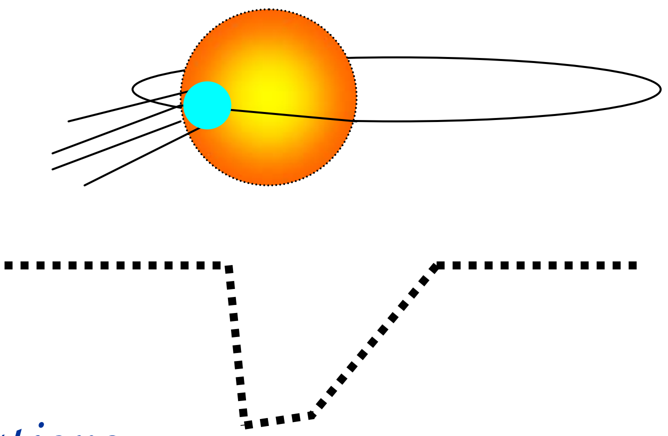
Quadruples… And comets!



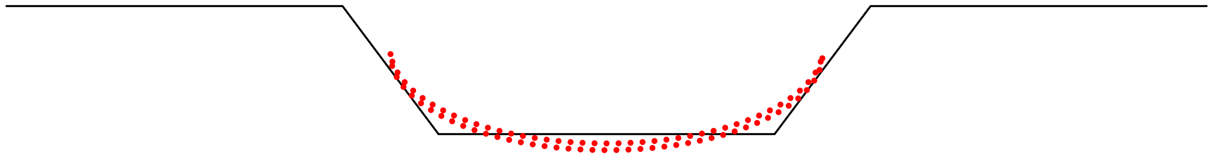
Different durations, depths, shapes

Lecavelier des Etangs et al. 1999

Transit zoo

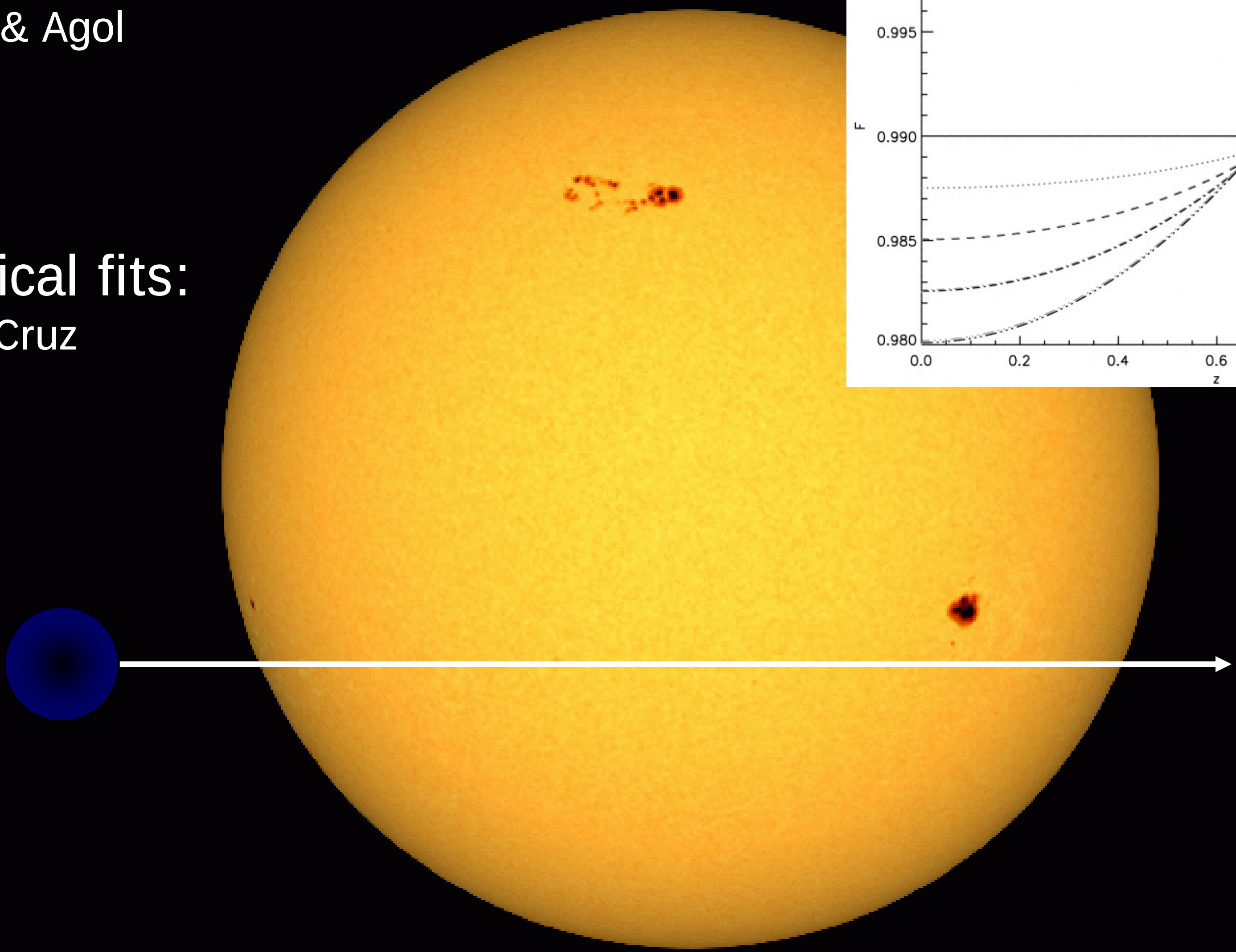
Problems

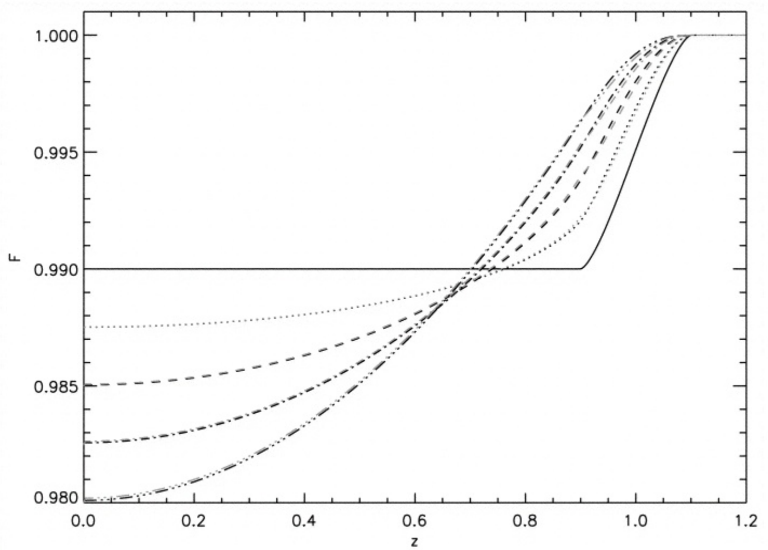
- Limb darkenning:
  - Extrasolar planetary transits are not flat.
  - The eclipse shape changes due to limb darkenning.
  - The inclination cannot be determined unless a limb darkenning law is assumed.
  - Luckily, most stars are Solar type, and we can use a Solar limb darkenning or a simple quadratic law.
  - Limb darkenning depends on λ: it is larger in the blue than in the red.



Transit fits:
Mandel & Agol (2002)

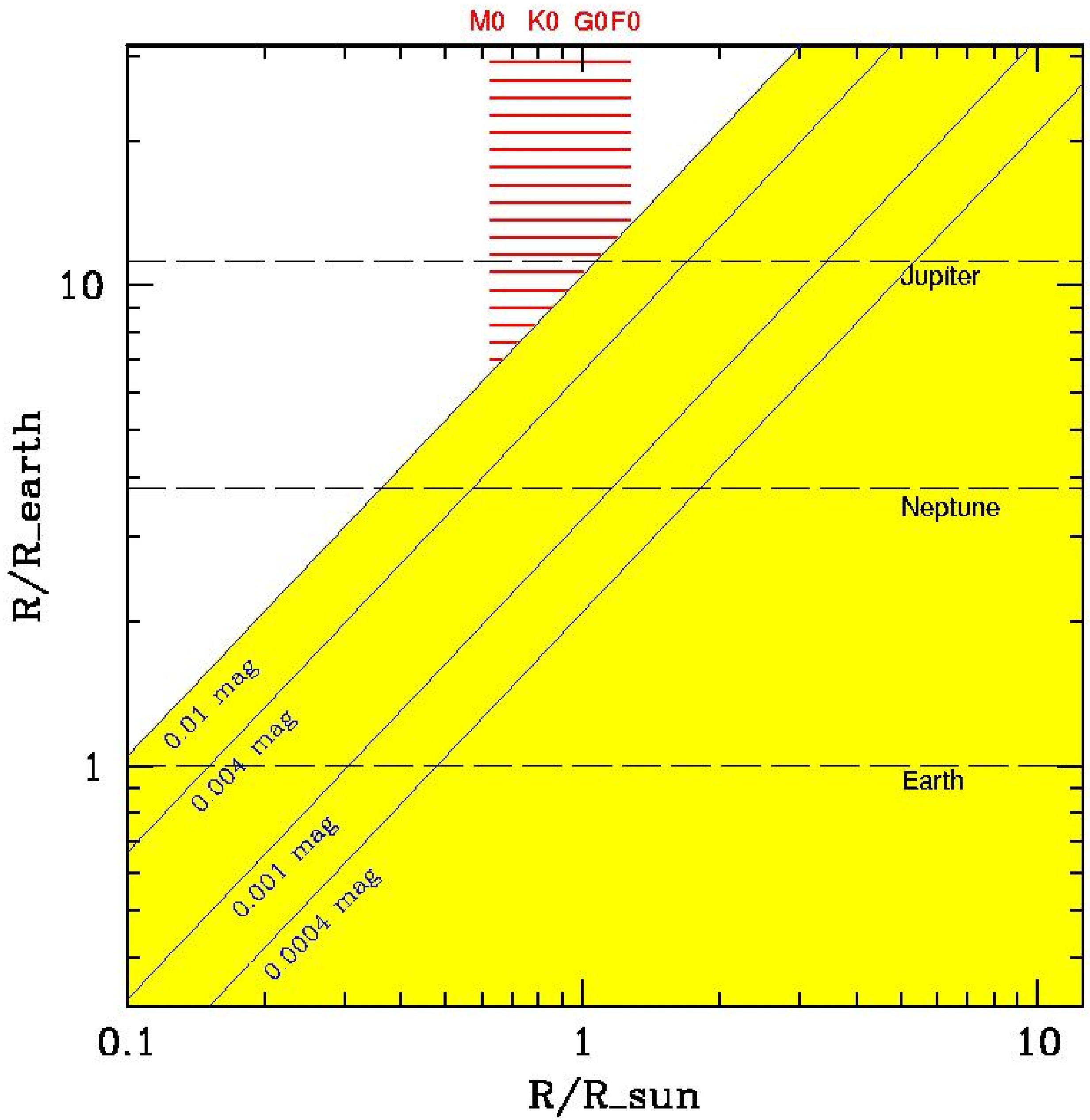
Empirical fits:
Silva & Cruz (2005)





Sensitivity

- Depending on the photometric accuracy, this technique is potentially sensitive to detect planets of all sizes.
- From the ground, if we can reach 0.001 mag we can detect hot Neptunes.
- From space, future missions will reach 0.0001 mag, being able to detect Earth size planets.

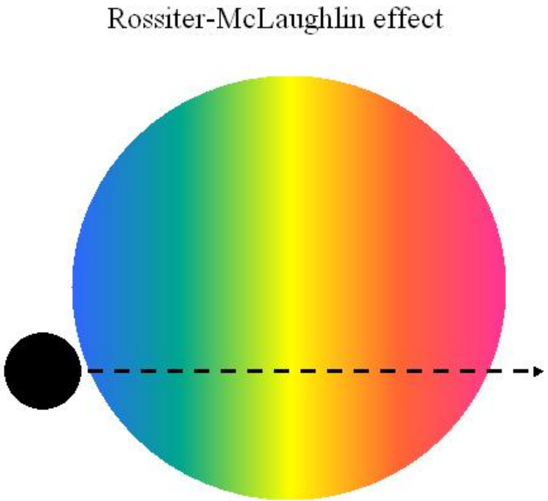


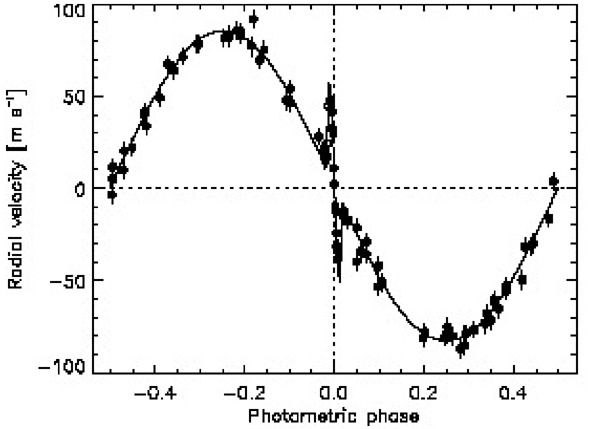
Rossiter-McLaughlin effect

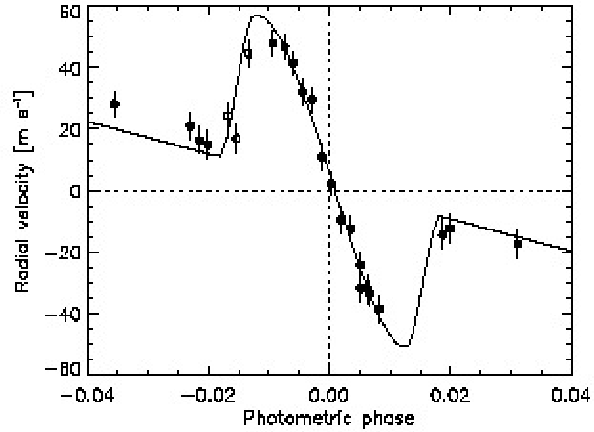
This effect is due to the transiting planet occulting part of a rotating star. In general, one can assume that the star equator matches the plane of the orbit, specially for short period planets. The radial velocity curve shows deviations during the planetary transit.

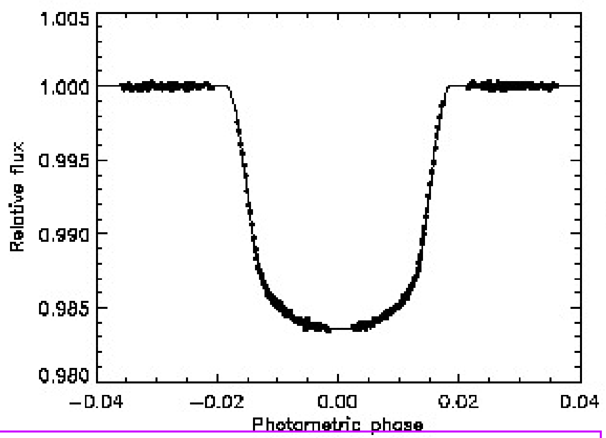
It allows to determine the rotation axis and limb darkenning accurately.

(Queloz et al. 2000, Marcy et al. 2005, Charbonneau et al. 2005)

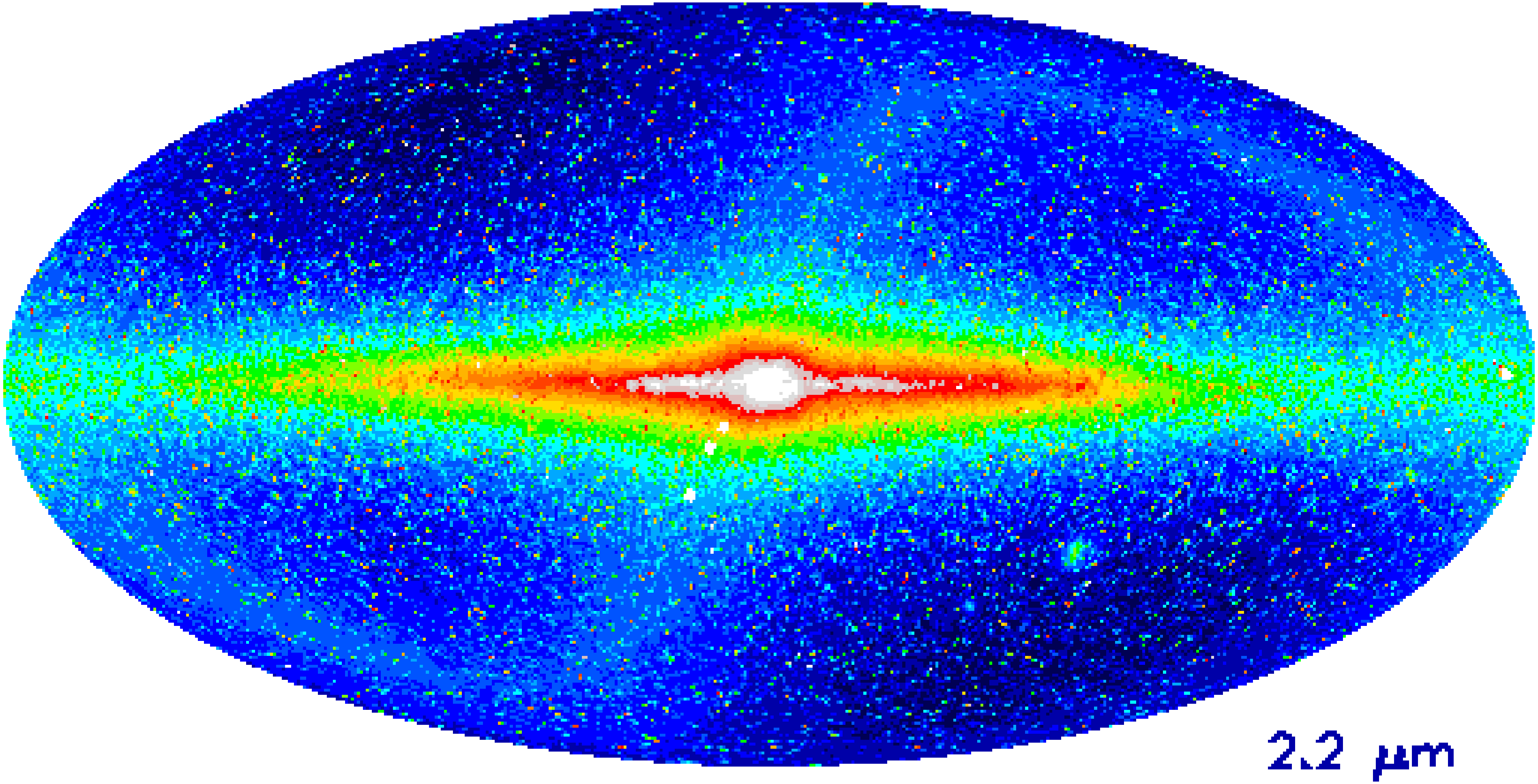








The OGLE Transit search

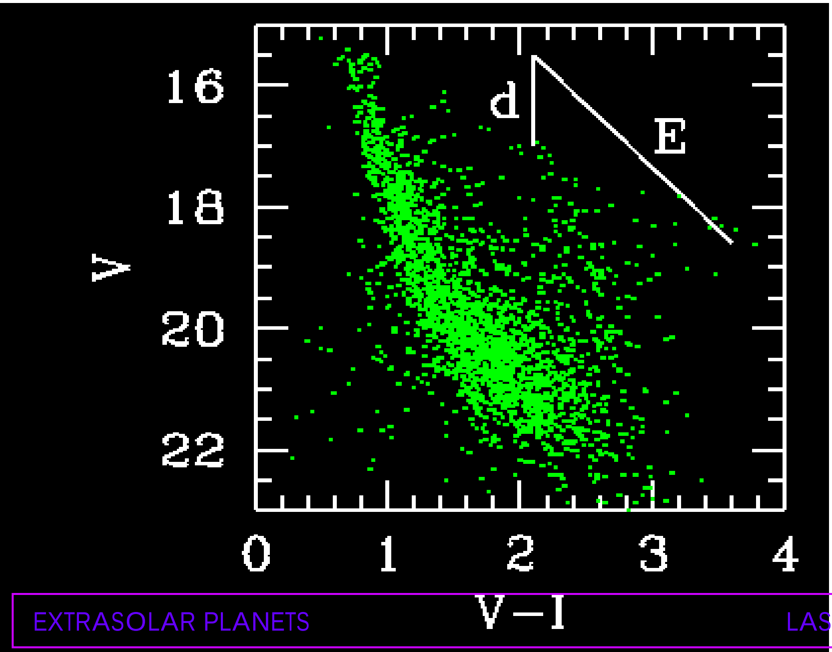


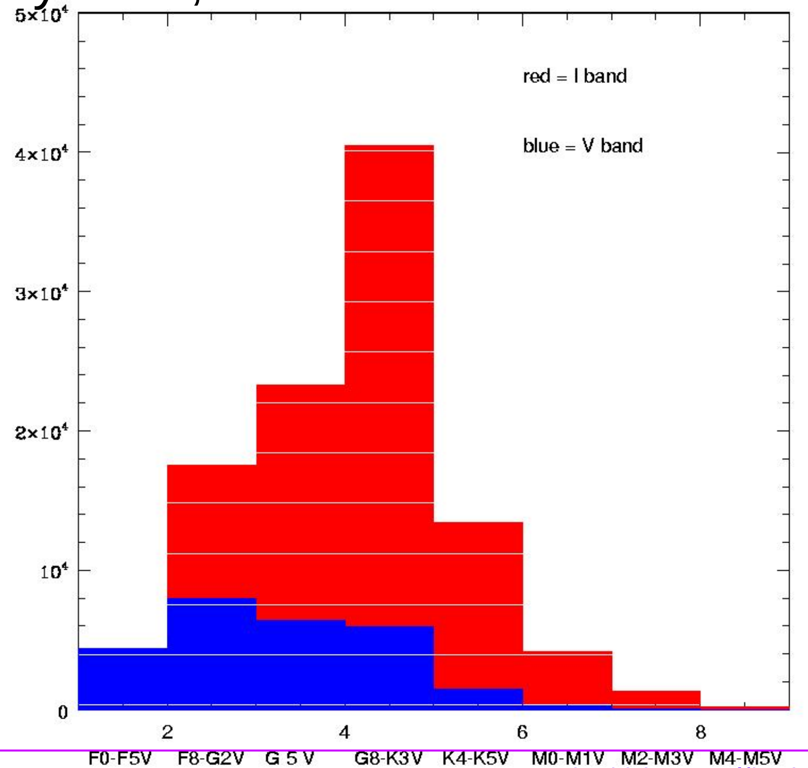
OGLE: 177 low amplitude transit candidates in the Milky Way disk and bulge Udalski et al. (2002-2004). But ~95% are not real planets.

OGLE fields

A. Mallenhof

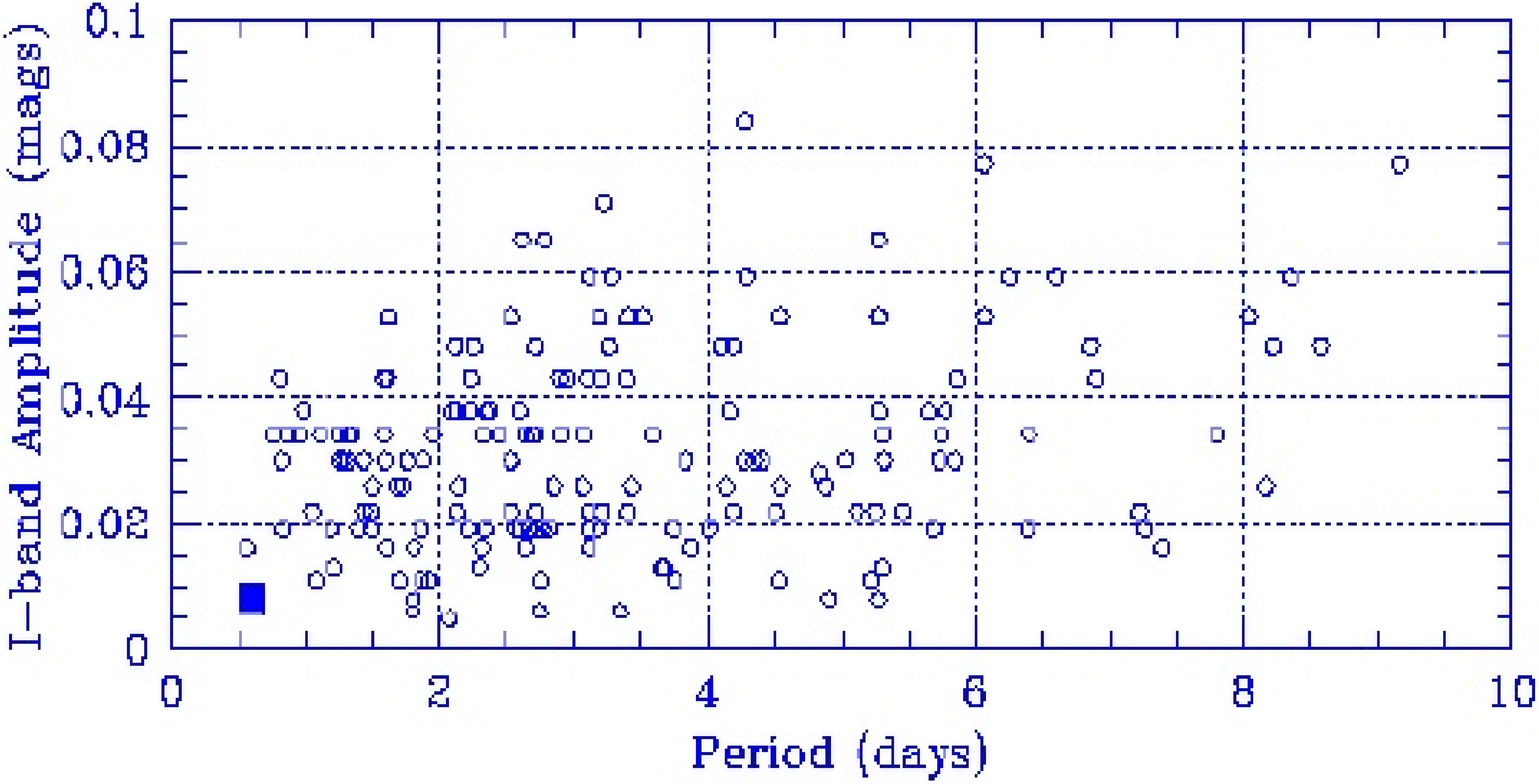
- Targets: galactic plane (Car, Scl, Cen, Nor) and bulge (Sgr)
- Many other searches
- Results: OGLE is the most successful, 177 candidates so far
- Big field of view → optical search (I), many stars, >1000000
- Many nights, >30
- MS star, no giants





OGLE transits

Udalski et al. (2002a,b, 2003, 2004)



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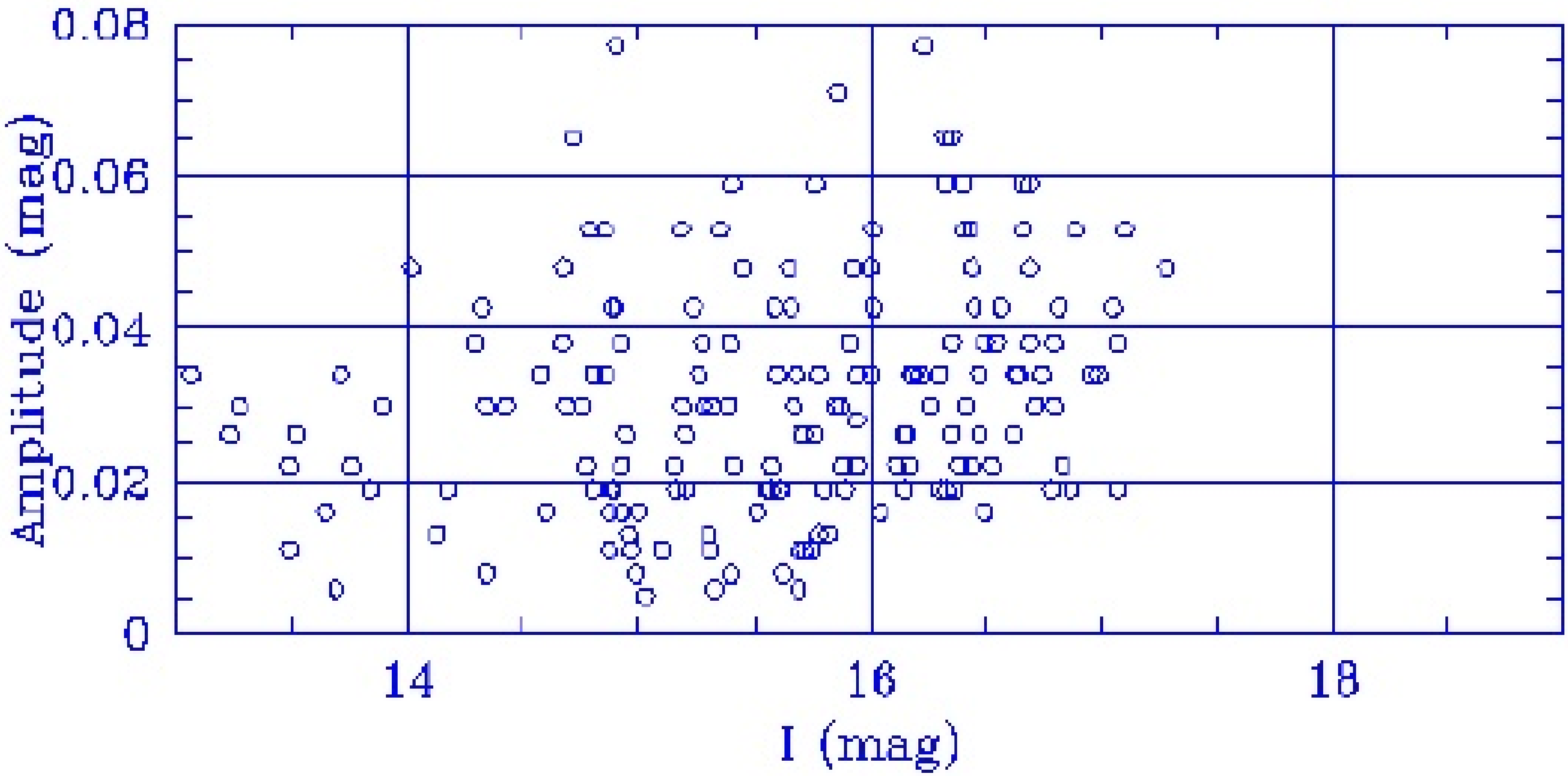
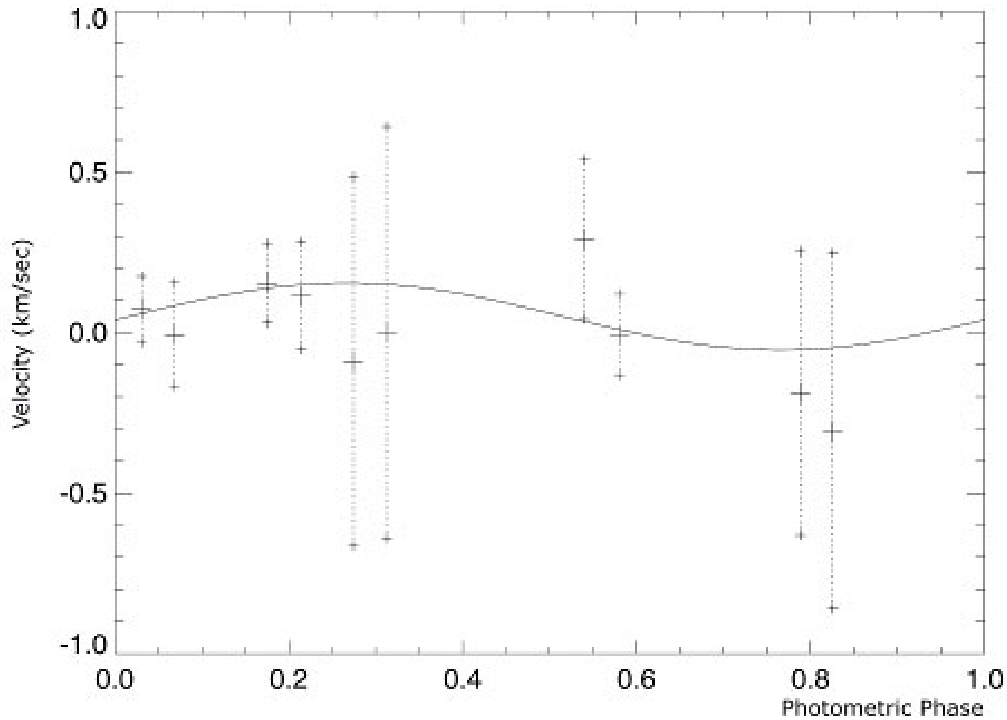


Problems:

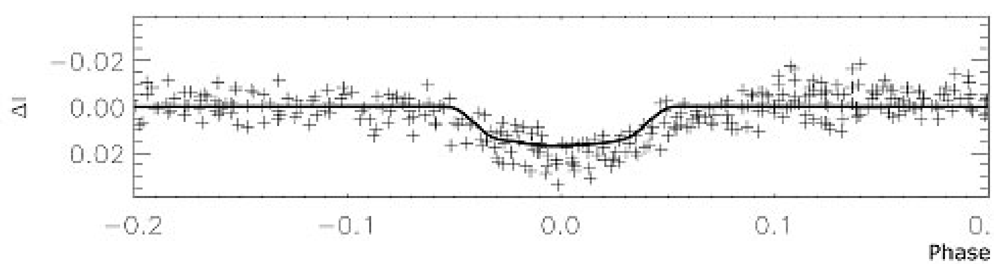
- OGLE-TR-3 was discovered in 2003, but it was not confirmed. In fact, it is a blend, as shown by the more detailed spectroscopy. Line bisector analysis can in principle discriminate some binary blends.



Velocity Curve of OGLE-TR-3
(VLT KUEYEN + UVES)

ESO PR Photo 10d/03 (22 April 2003)

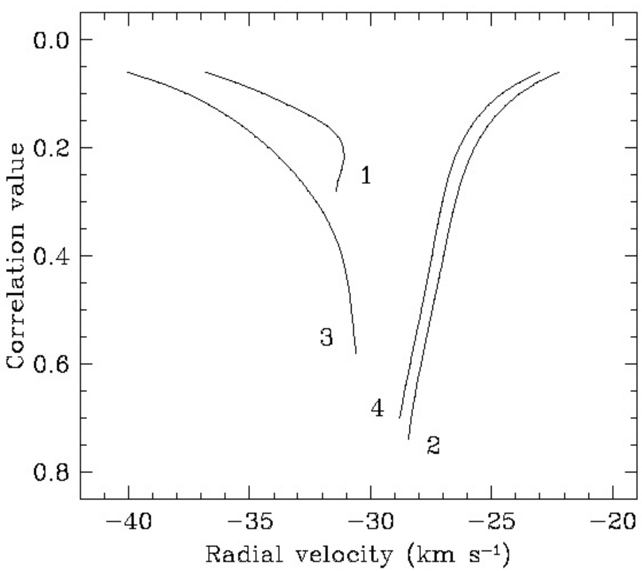
©European Southern Observatory



Brightness Dip Due to Planetary Transit at OGLE-TR-3
(OGLE Project)

ESO PR Photo 10e/03 (22 April 2003)

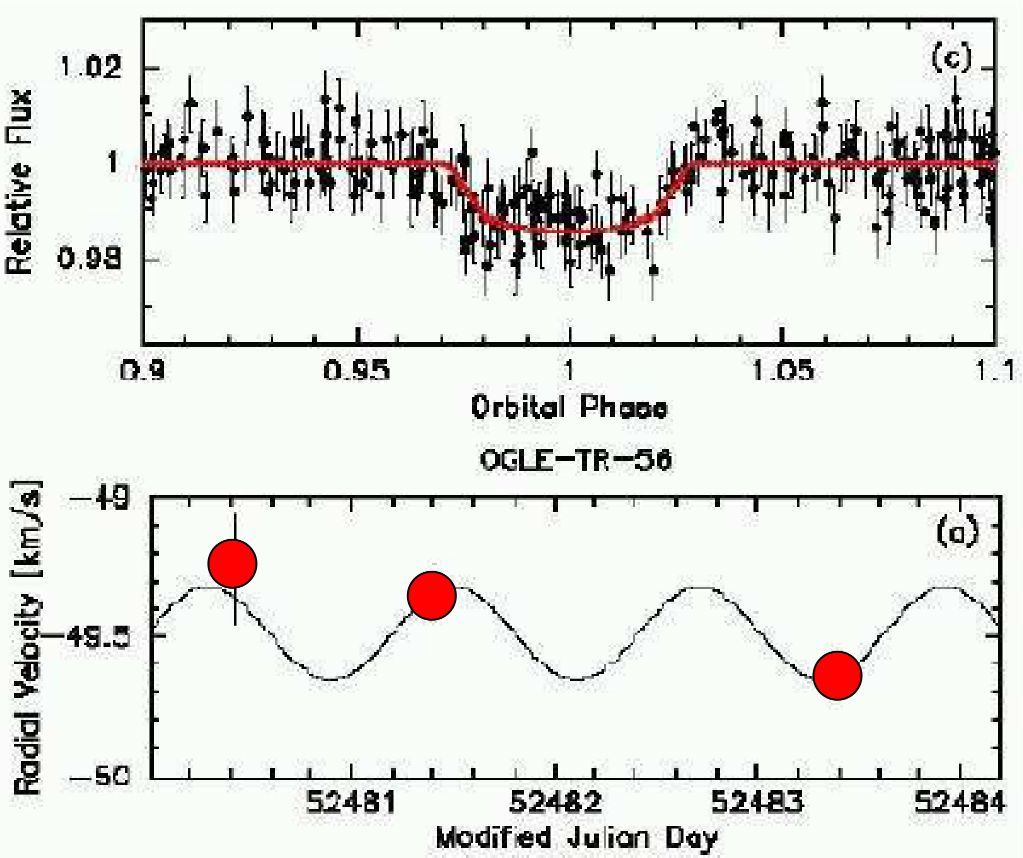
©European Southern Observatory



A new class of planets

- OGLE-TR-56 was the first planet discovered by transits. But it was resisted because it has a very short period.

P=1.2d, R=1.25Rj, M=1.43Mj

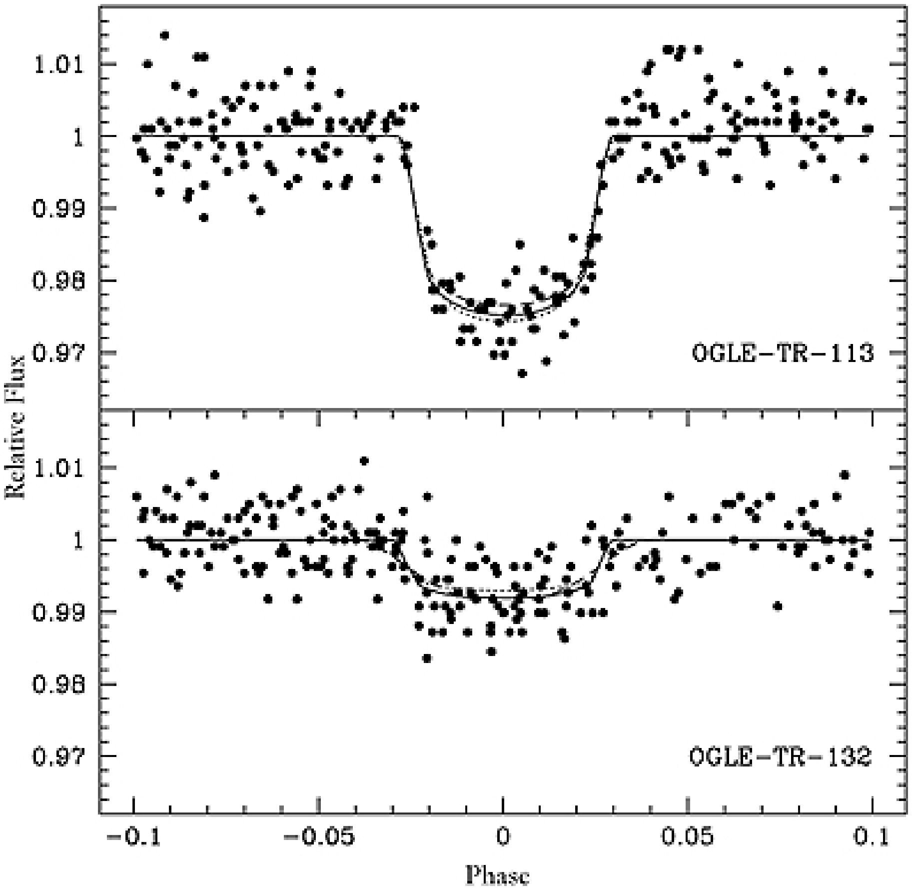


OGLE-TR-56 was confirmed by radial velocities, the observations are hard because it is a faint star V=15 (Konacki et al. 2003, Torres et al. 2003).

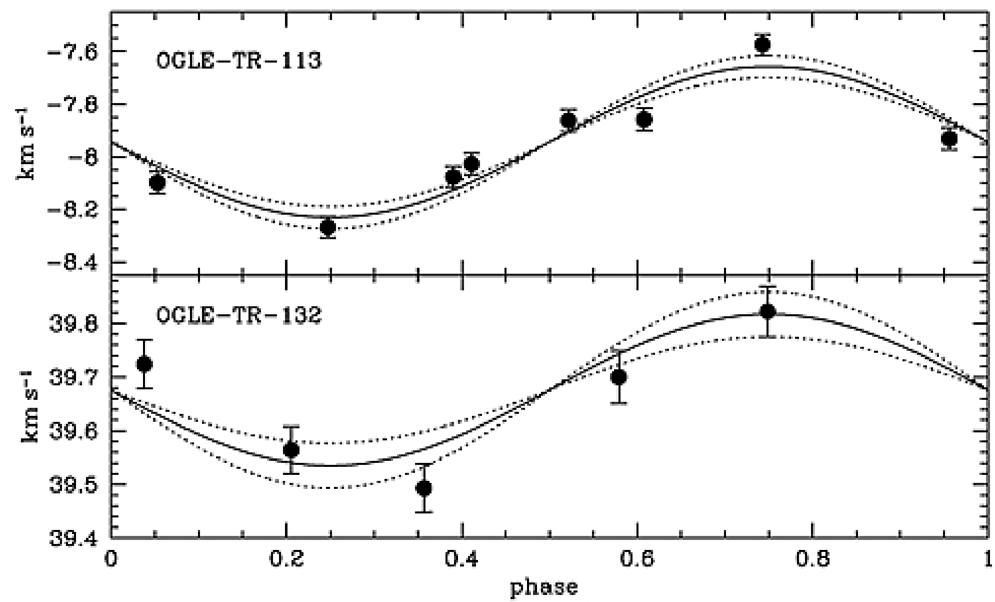
A new class of planets

- OGLE-TR-113, OGLE-TR-132: two planets similar to OGLE-TR-56 discovered shortly afterwards: very hot Jupiters!

Bouchy et al. 2004



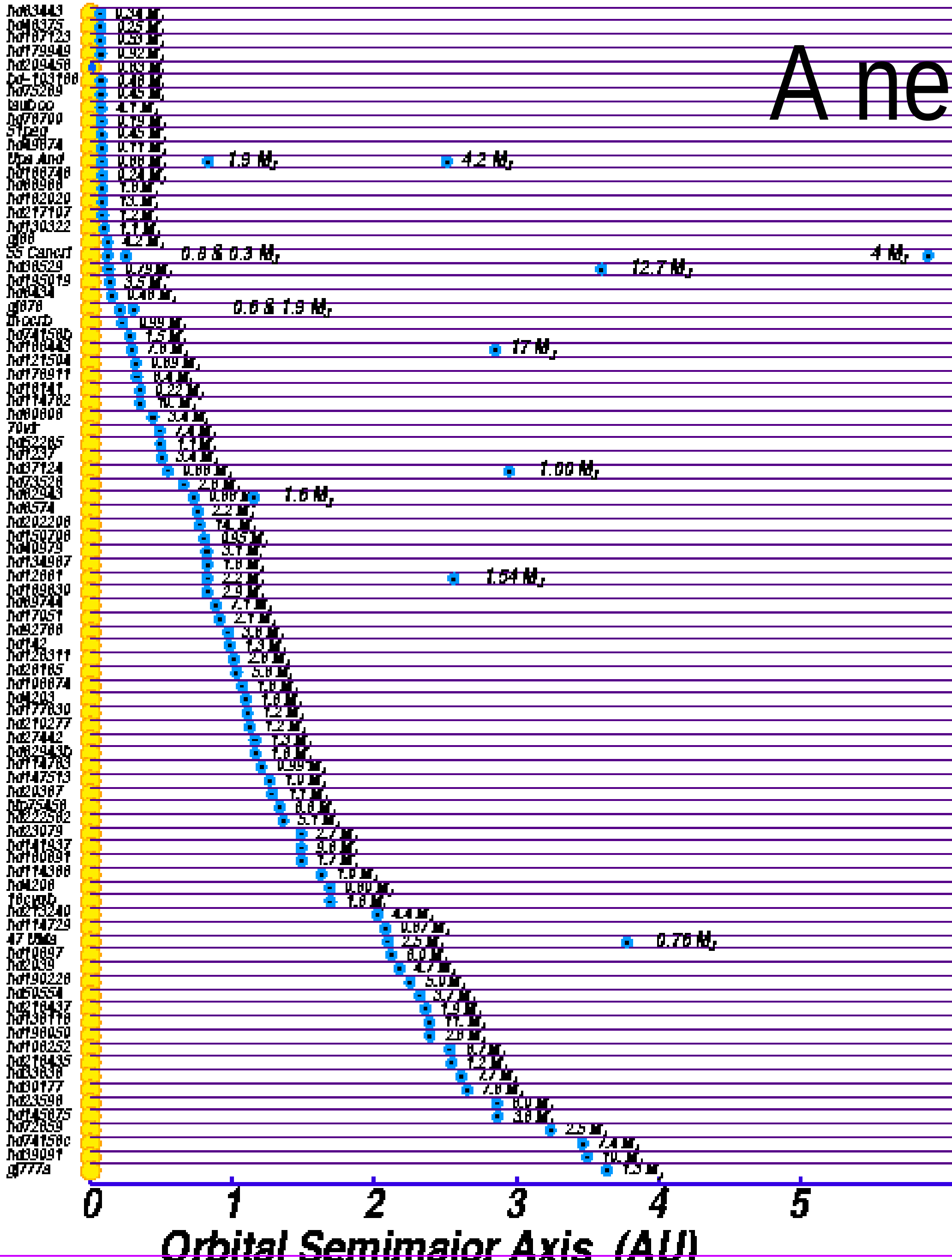
Brightness Variations of Two Stars with Transiting Exoplanets
(OGLE Survey)



Velocity Variations of Two Stars with Transiting Exoplanets
(VLT KUEYEN + FLAMES)

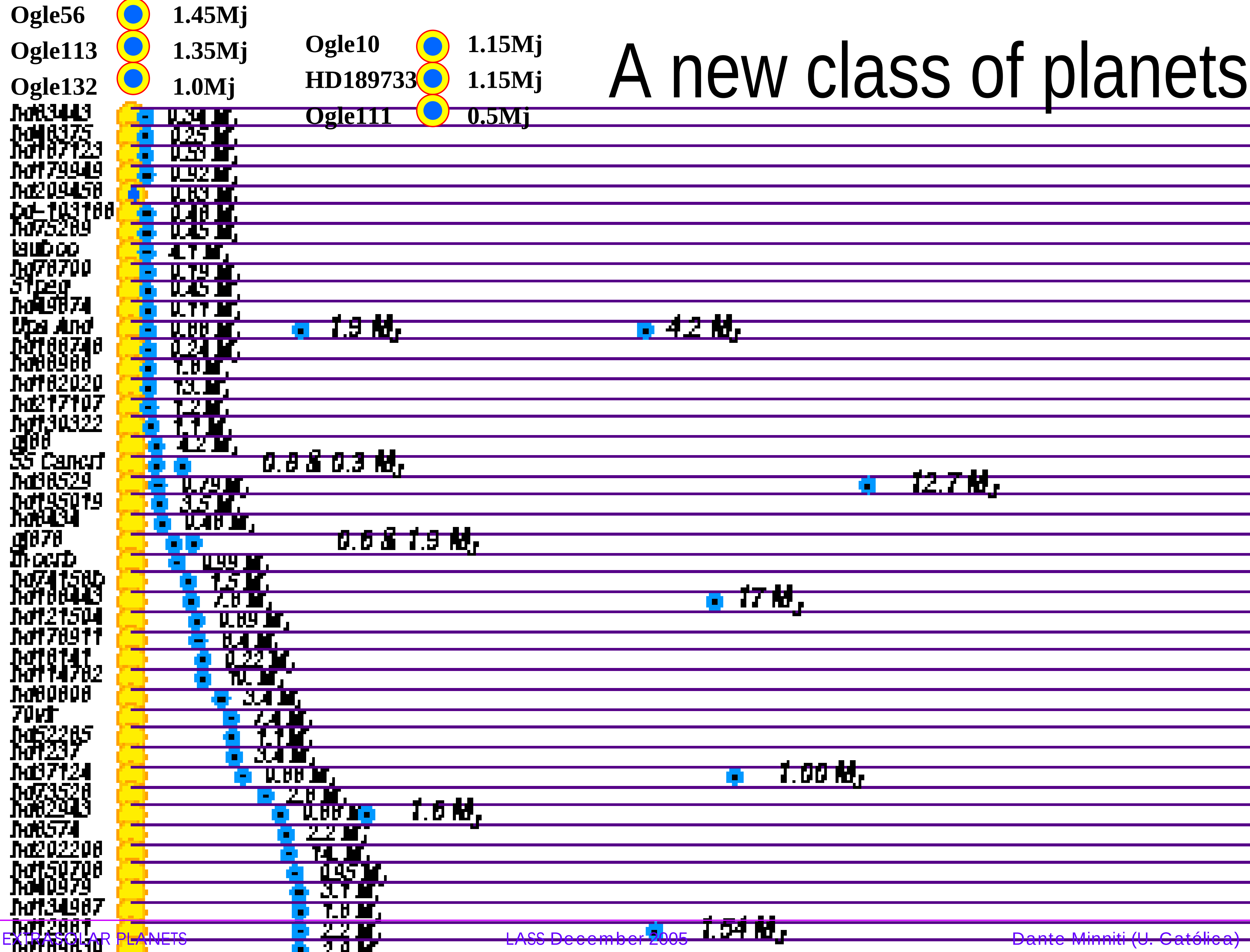
ESO PR Photo 14d/04 (7 May 2004)

A new class of planets

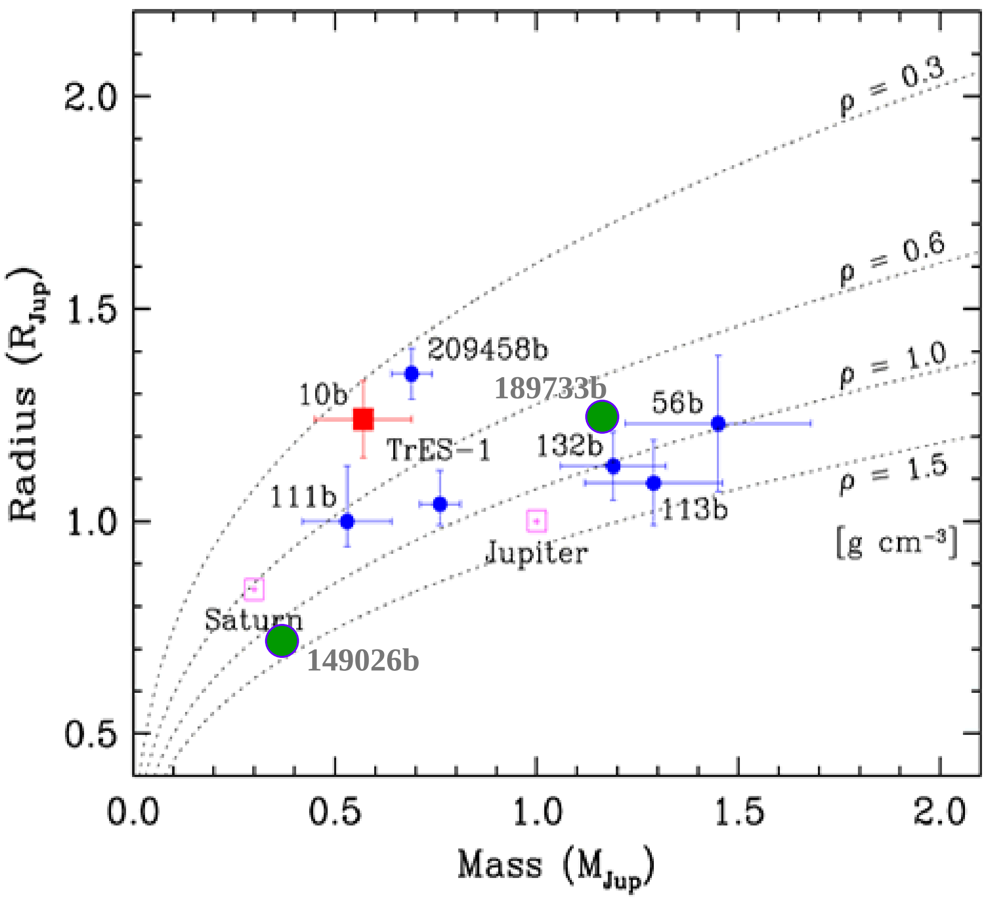


- OGLE planets have shorter periods than RV planets.
- Transit searches find a different population because the selection effects are different.
- Will the other techniques surprise us by revealing other new kinds of planets?

A new class of planets



Transiting extrasolar planets



There are 9 transiting exoplanets known. These are important because we know their mean densities and can test models.

Some of them have radii inflated due to the stellar irradiation:

- Models without irradiation →1Rj
- Models with irradiation → >1Rj

PLANETARY MODELS: Allard et al. 2003, Sudarsky et al. 2003, Baraffe et al. 2003, 2005, Burrows et al 2002, 2003, Chabrier et al. 2004, Bohdenheimer et al. 2005.

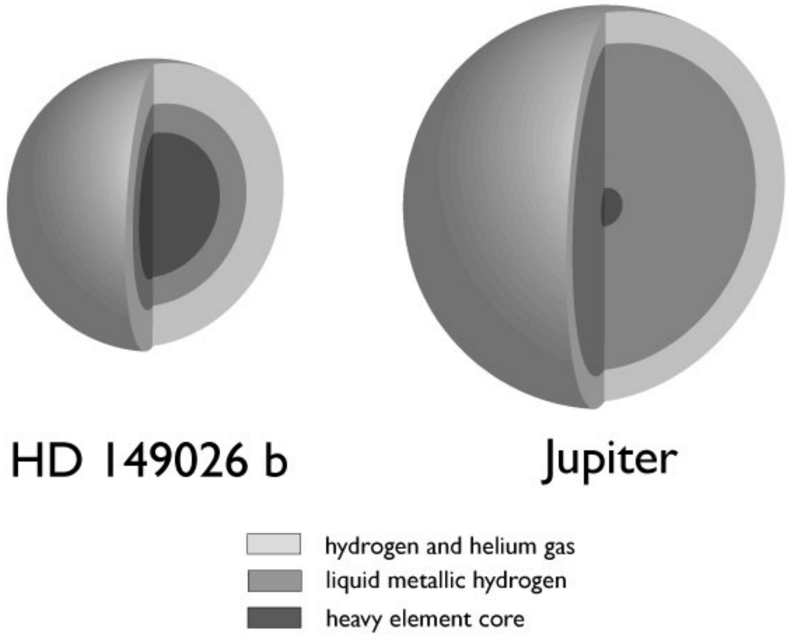
The models are complicated because they have several ingredients: composition, albedo, irradiation, atmospheric structure, particle condensation, clouds, rain, snow, solid core, etc.

Transiting extrasolar planets

The mean densities also allow us to test models of planet formation:

I. Core accretion where planets begin as small rocky-icy cores that grow by collisions gravitationally acquiring more and more mass.

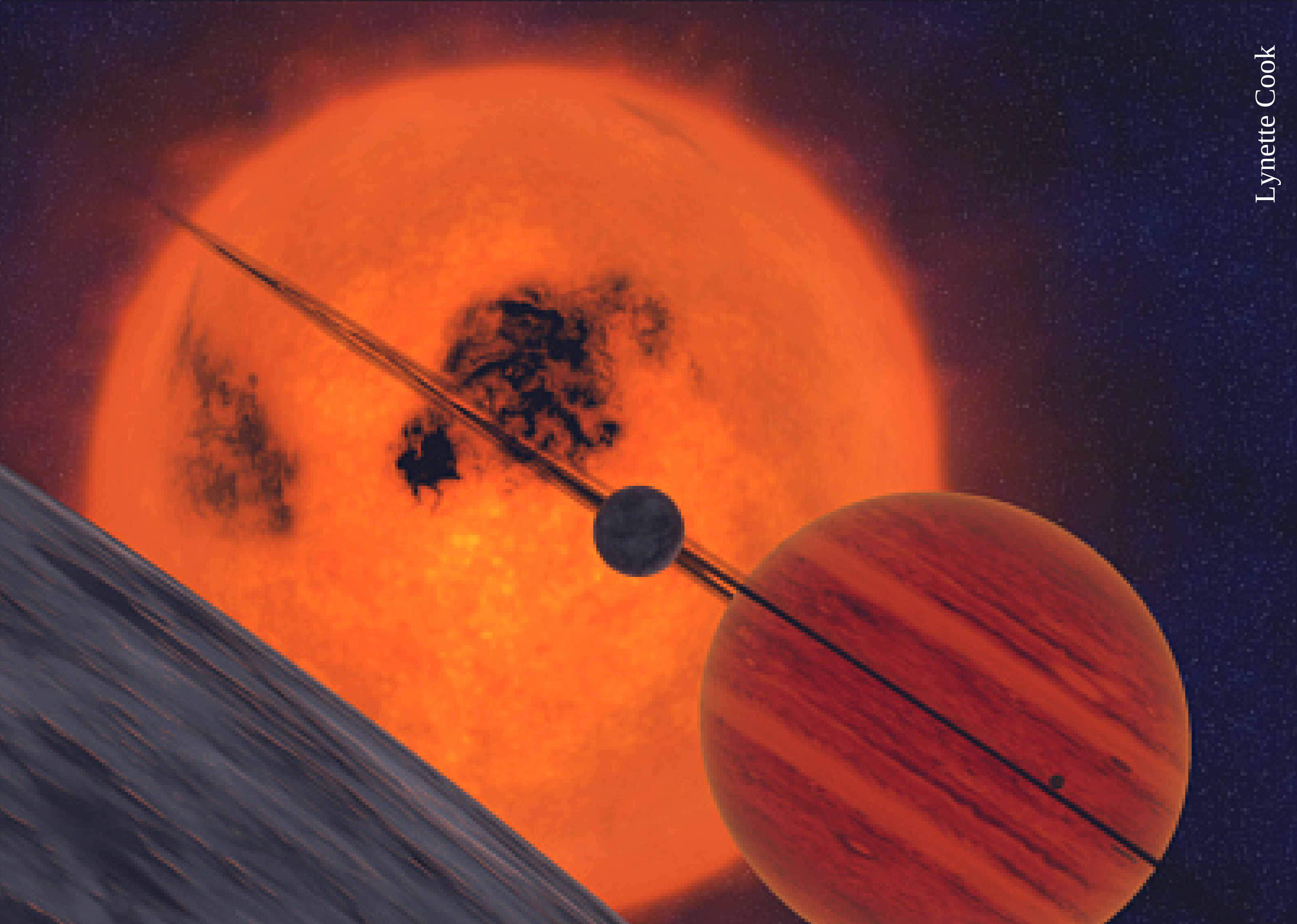
II. Gravitational instability in the disk where planets from by a rapid collapse of a dense gas cloud.



Fischer et al. 2005

E.g. HD209458 is gaseous with $\rho < 1$ (Charbonneau et al. 2000), ~~I~~

and HD149026 has a heavy core with ~70ME (Sato et al. 2005). ~~II~~


Lynette Cook

Transits

$$\left\{ \begin{array}{l} \sin i \rightarrow M_p \\ P \rightarrow a \\ R_p \\ \rho \end{array} \right.$$

- Incompleteness:
  - Planets with $R<R_N$
  - Only planets with a<<1UA (P<<1yr)
  - Many contaminants (WDs, BDs, M*s)
- OGLE transit survey
  - All sky searches & MW bulge and disk
    bulge.astro.princeton.edu/~ogle/ogle3/transits
  - Ephemerides: www.transitsearch.org
- Transit results till Oct 2005:
  >200 transit candidates
  9 confirmed planets

Radial Velocities

$$\left\{ \begin{array}{l} M \sin i \\ P \rightarrow a \\ \varepsilon \end{array} \right.$$

- Incompleteness:
  - Planets with $M<1M_J$
  - Planets with a>3UA (P>10yr)
  - Multiple planets
- Extrasolar planets encyclopaedia
  - Jean Schneider *(Obs. de Paris Meudon):*

    www.vo.obspm.fr/exoplanetes/encyclo/encycl.html
  - RV results till Oct 2005:

    170 planets discovered

    18 planetary systems
- http://exoplanets.org , http://obswww.unige.ch/planet