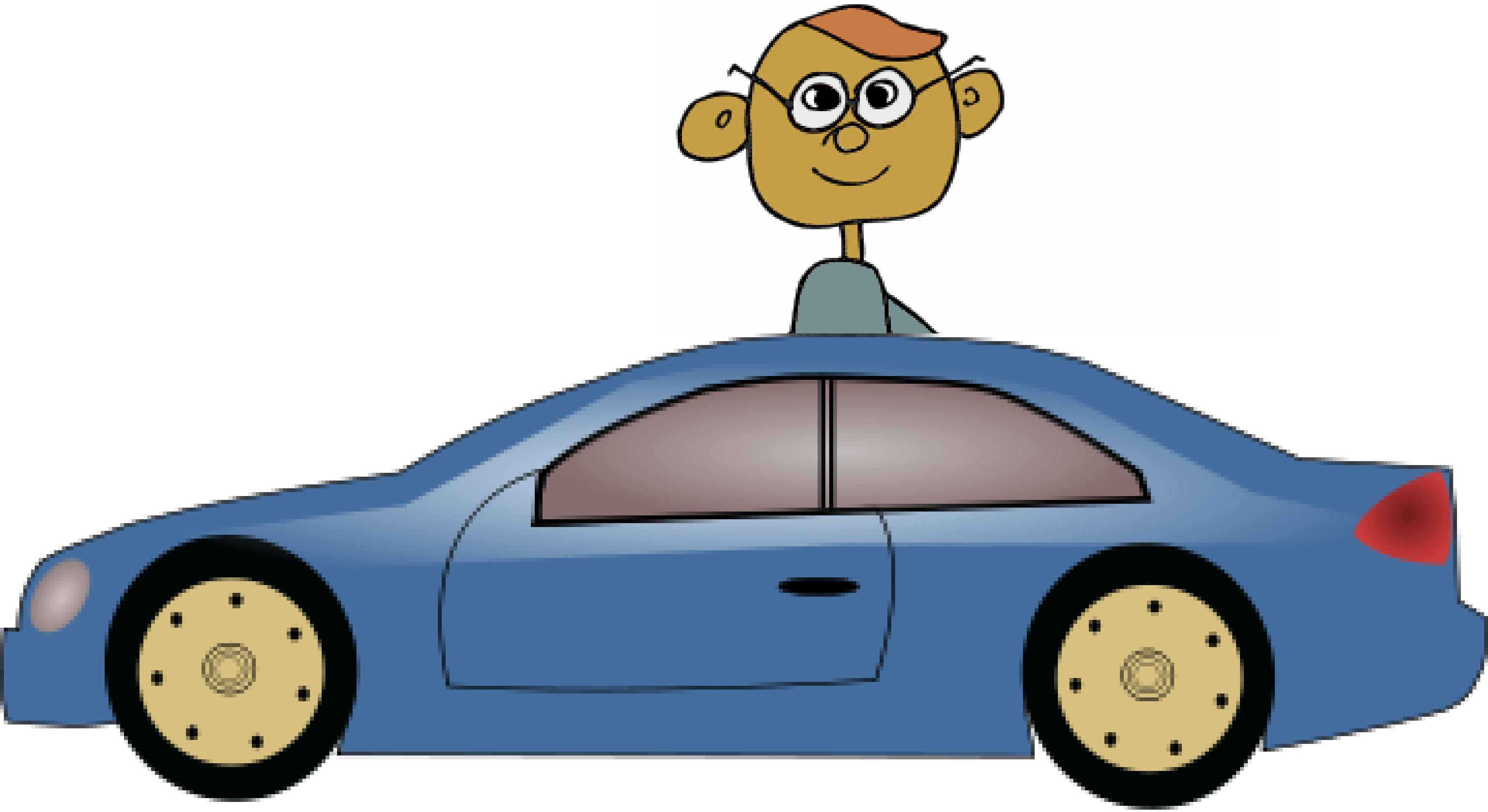
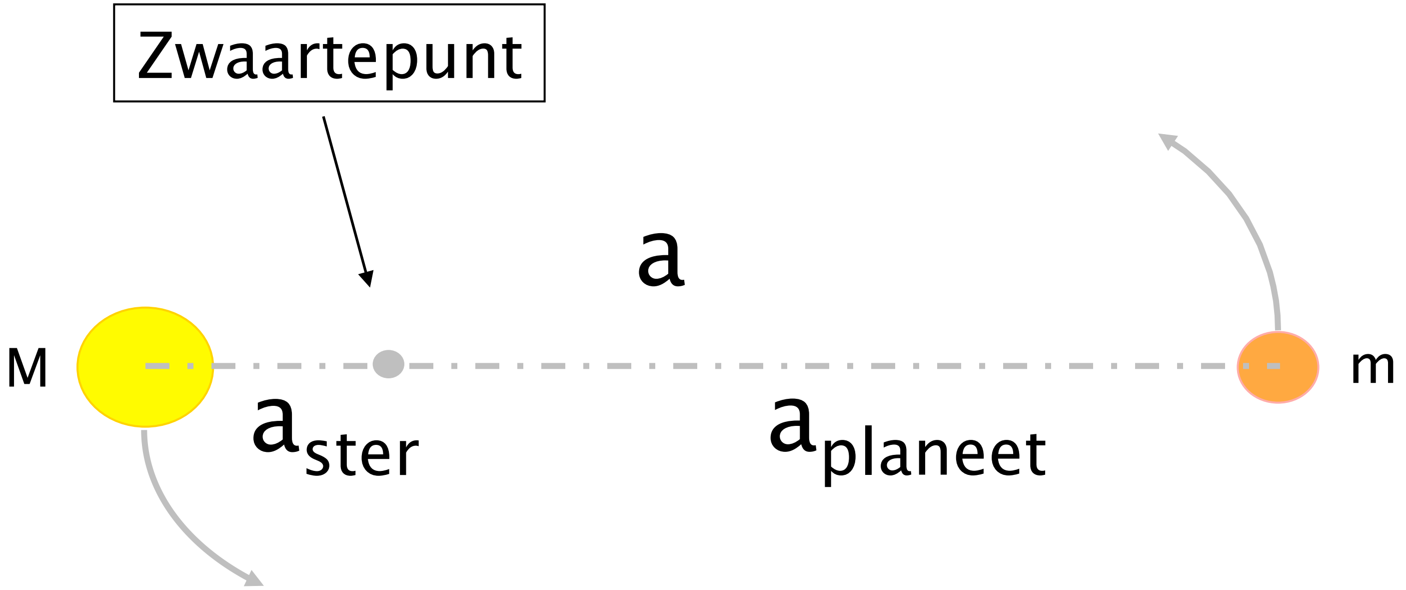
Radial Velocity Planets

Gijs Mulders
Universiteit van Amsterdam



Beweging ster aan de hemel



$$\frac{a_{\mathrm{ster}}}{m} = \frac{a_{\mathrm{planeet}}}{M} \qquad a_{\mathrm{ster}} = \frac{m}{M} a_{\mathrm{planeet}} \approx \frac{m}{M} a$$

Zwaartepunt Zonnestelsel

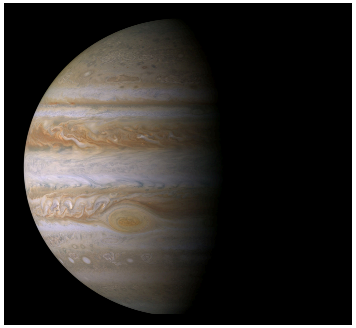
$m = 6*10^{24}$ kg
$M = 2*10^{30}$ kg
$a = 150*10^{6}$ km

$a_{ster} = m/M\ a$
$= 450$ km

$m = 2*10^{27}$ kg
$M = 2*10^{30}$ kg
$a = 780*10^{6}$ km

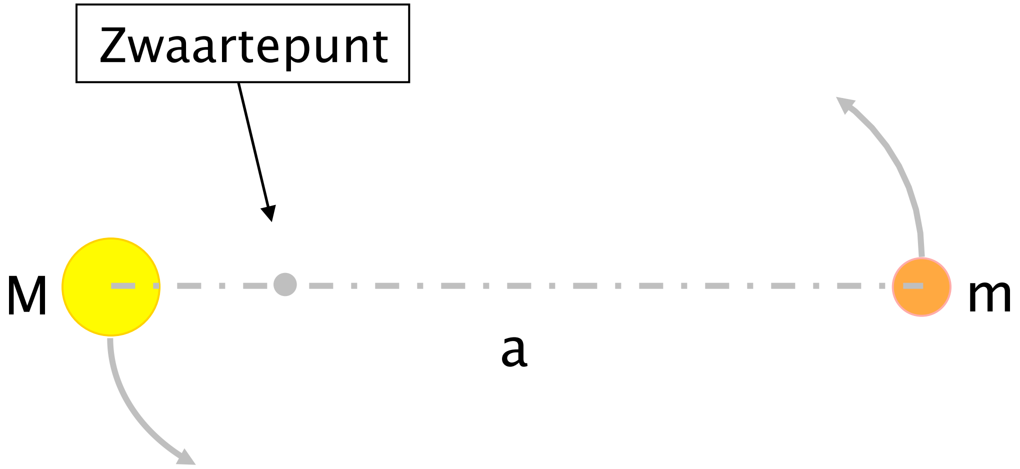
$a_{ster} = 780*10^{3}$ km

$R_{ster} = 690*10^{3}$ km



Baan Periode

Newton's versie van Kepler's derde wet



Twee massa's bewegen om elkaar, de periode P is dan:

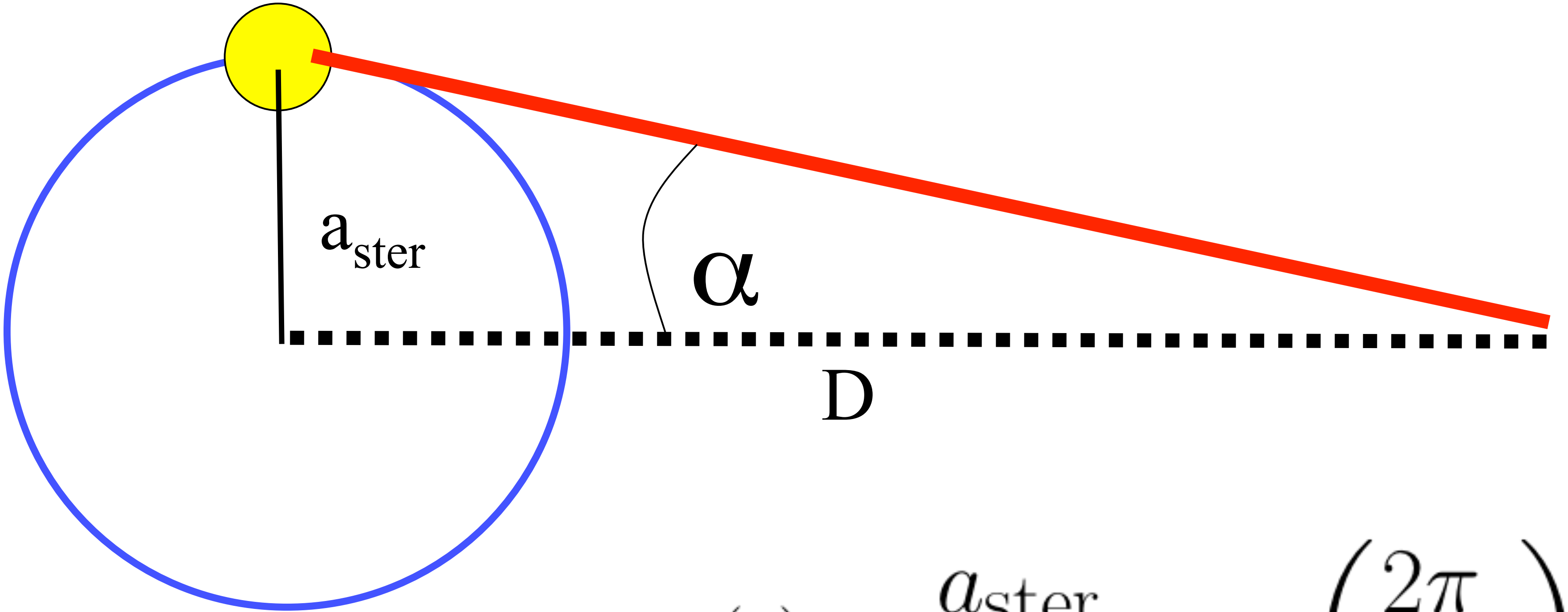
$$\boxed{P^2} = \frac{4\pi^2 a^3}{G \cdot (M+m)} \approx \text{const} \cdot \boxed{a^3}$$

Beweging aan de hemel

$$x(t) = a_{\text{ster}} \cdot \sin\left(\frac{2\pi}{P}t\right)$$

$$y(t) = a_{\text{ster}} \cdot \cos\left(\frac{2\pi}{P}t\right)$$

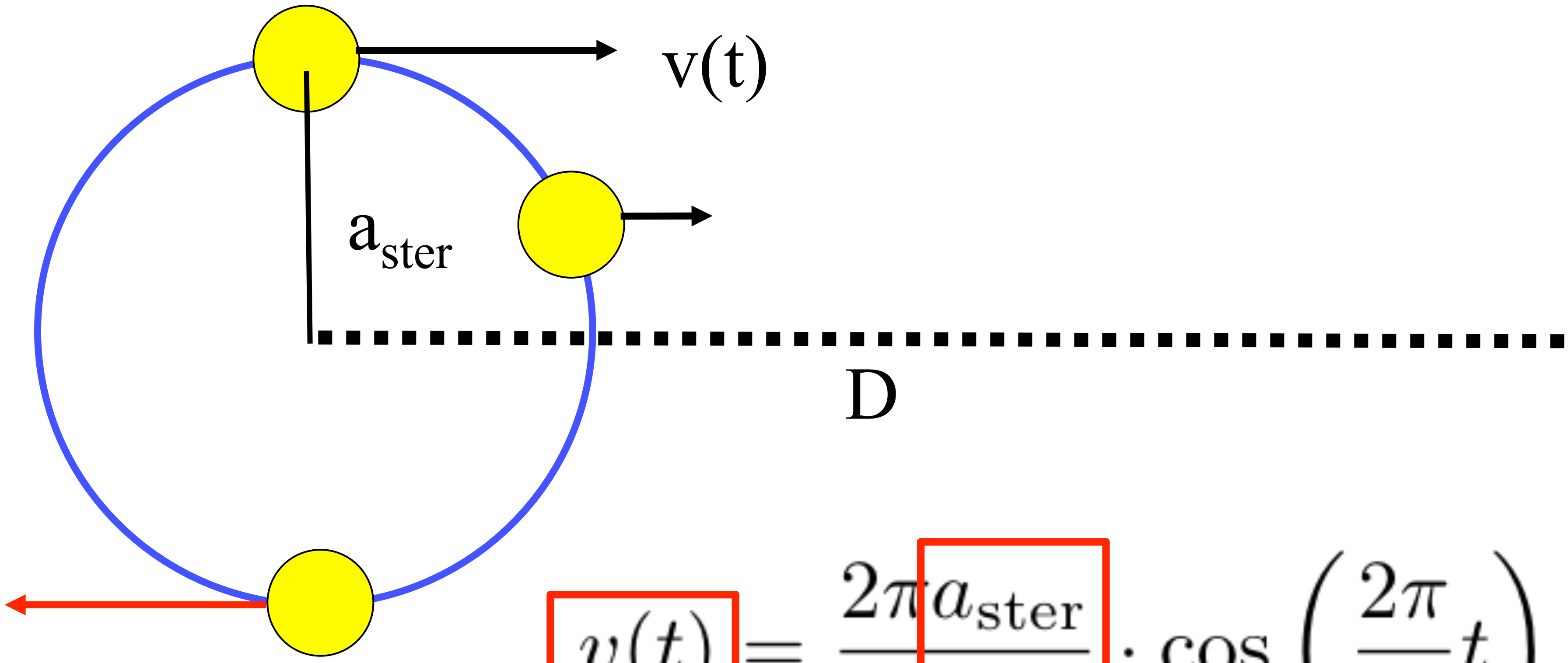
Beweging aan de hemel



$$\alpha(t) = \frac{a_{\text{ster}}}{D} \cdot \cos\left(\frac{2\pi}{P} t\right)$$

$$y(t) = a_{\text{ster}} \cdot \cos\left(\frac{2\pi}{P} t\right)$$

Beweging aan de hemel



$$\boxed{v(t)} = 2\pi\,\boxed{\frac{a_{\text{ster}}}{P}} \cdot \cos\left(\frac{2\pi}{P}t\right)$$

$$x(t) = a_{\text{ster}} \cdot \sin\left(\frac{2\pi}{P}t\right)$$

Snelheden in Zonnestelsel

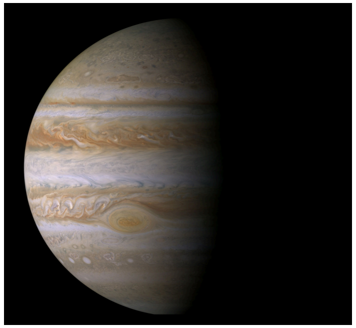
a_{ster} = 450 km
P = 1 jaar

$v_{ster} = 2\pi\, a_{ster} / P$
$= 0.09$ m/s

a_{ster} = 780 $*10^3$ km
P = 11.8 jaar

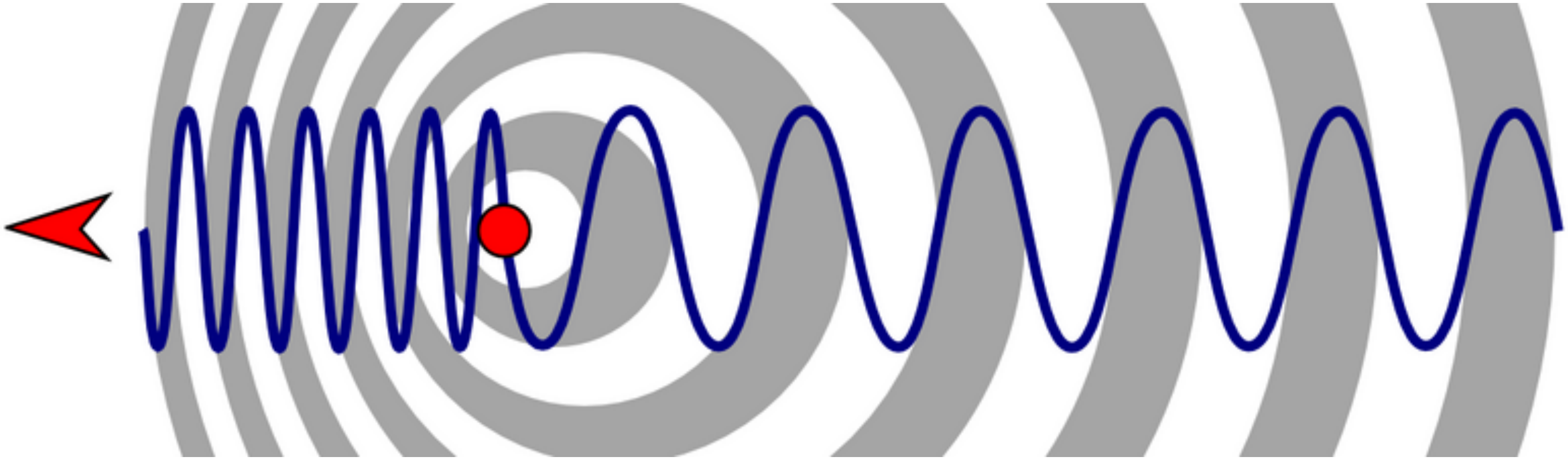
v_{ster} = 13.1 m/s

v_{ster} = 50 km/h



Hoe meet je de snelheid van een ster?

Het Doppler effect



Bewegen naar waarnemer toe: Golven komen sneller achter elkaar -> hogere frequentie

Bewegen van waarnemer af: Golven komen later achter elkaar -> lagere frequentie.

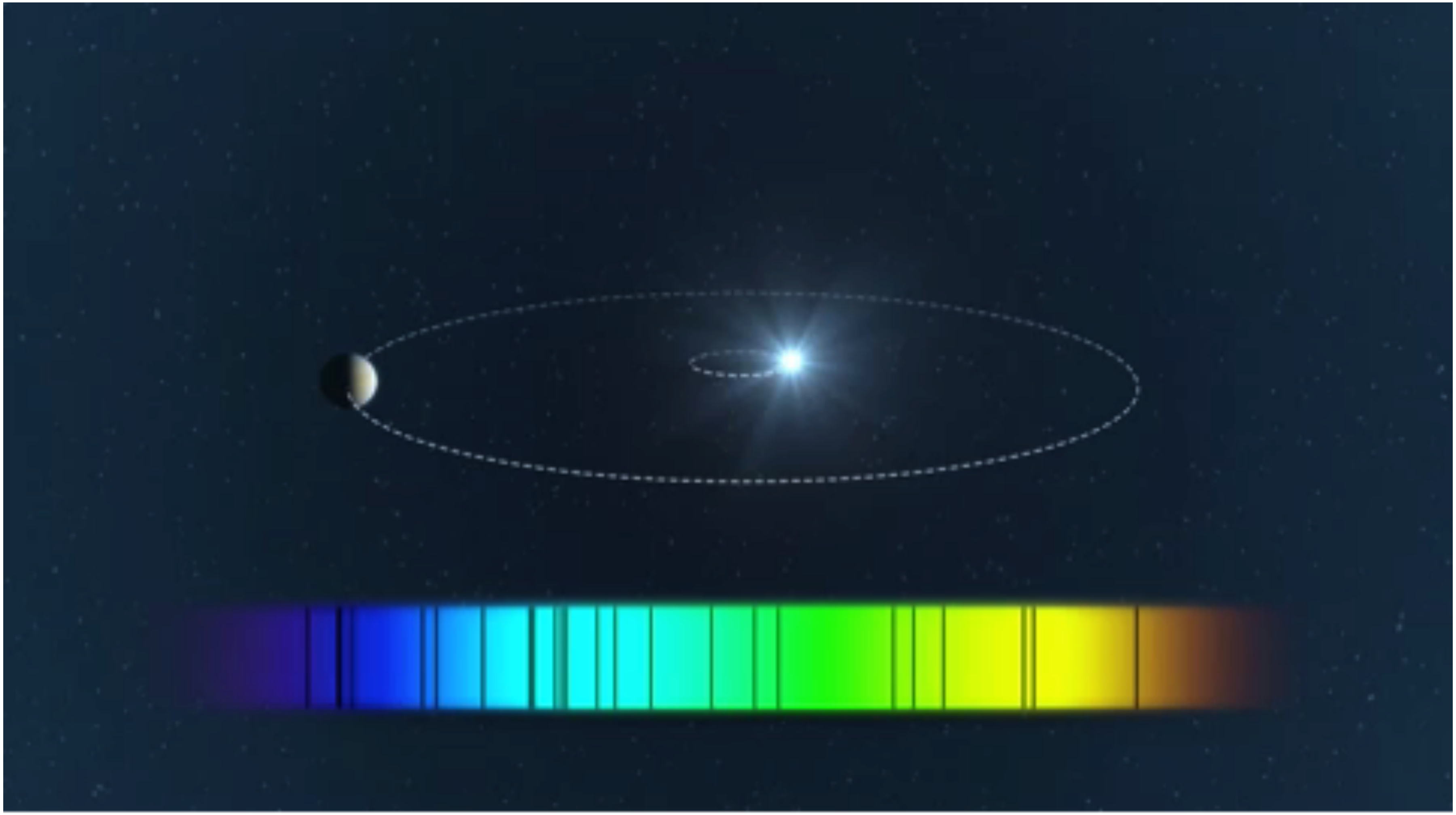
Het Doppler effect

Licht rood
Toon laag

Licht blauw
Toon hoog

Zelfde kleur
Zelfde Toonhoogte

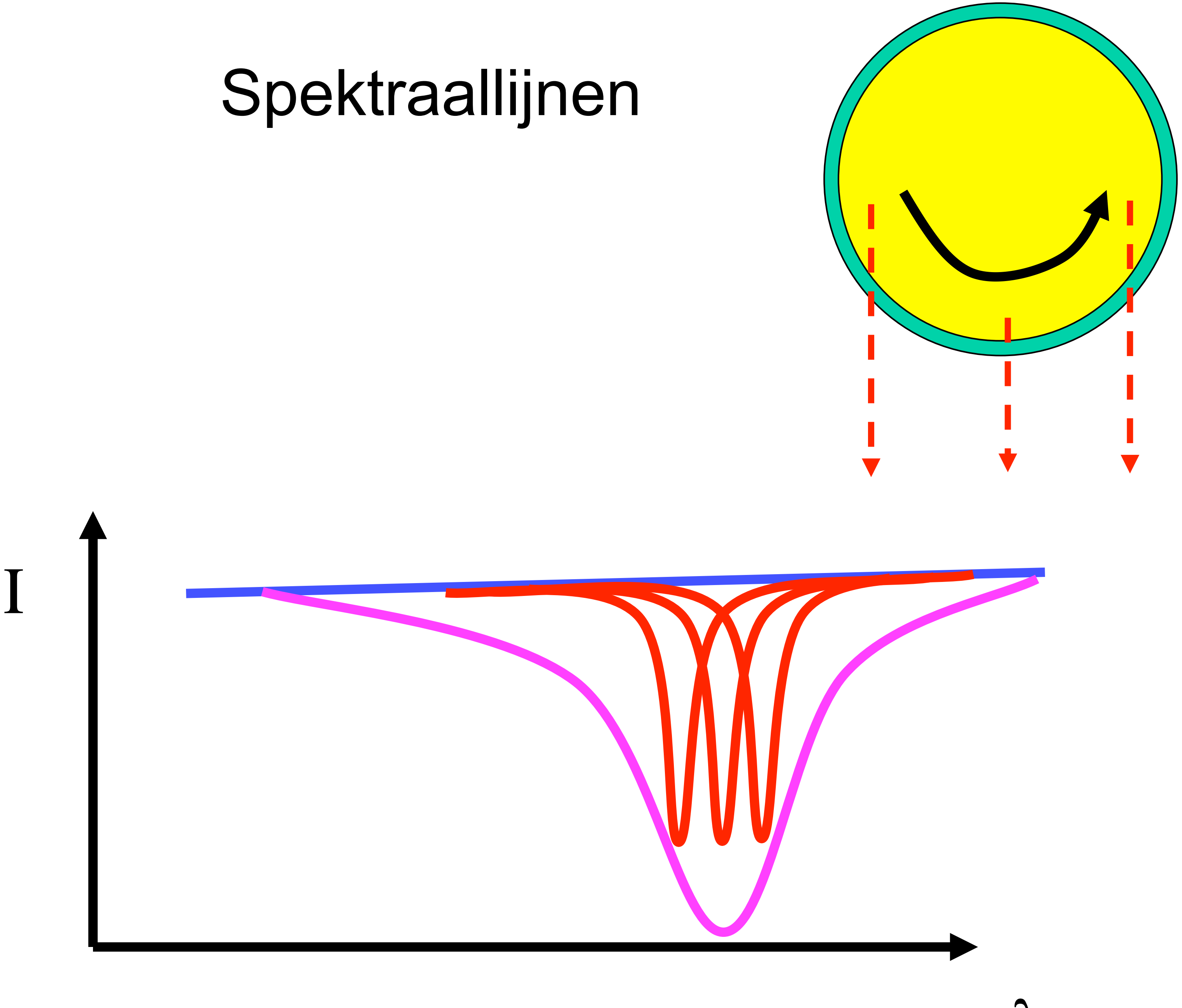
Doppler Methode



Korte samenvatting

- Ster en planeet draaien om elkaar heen
- Snelheid en periode ster = massa en baan planeet
- Radiele snelheid ster te meten met dopplereffect

Spektraallijnen



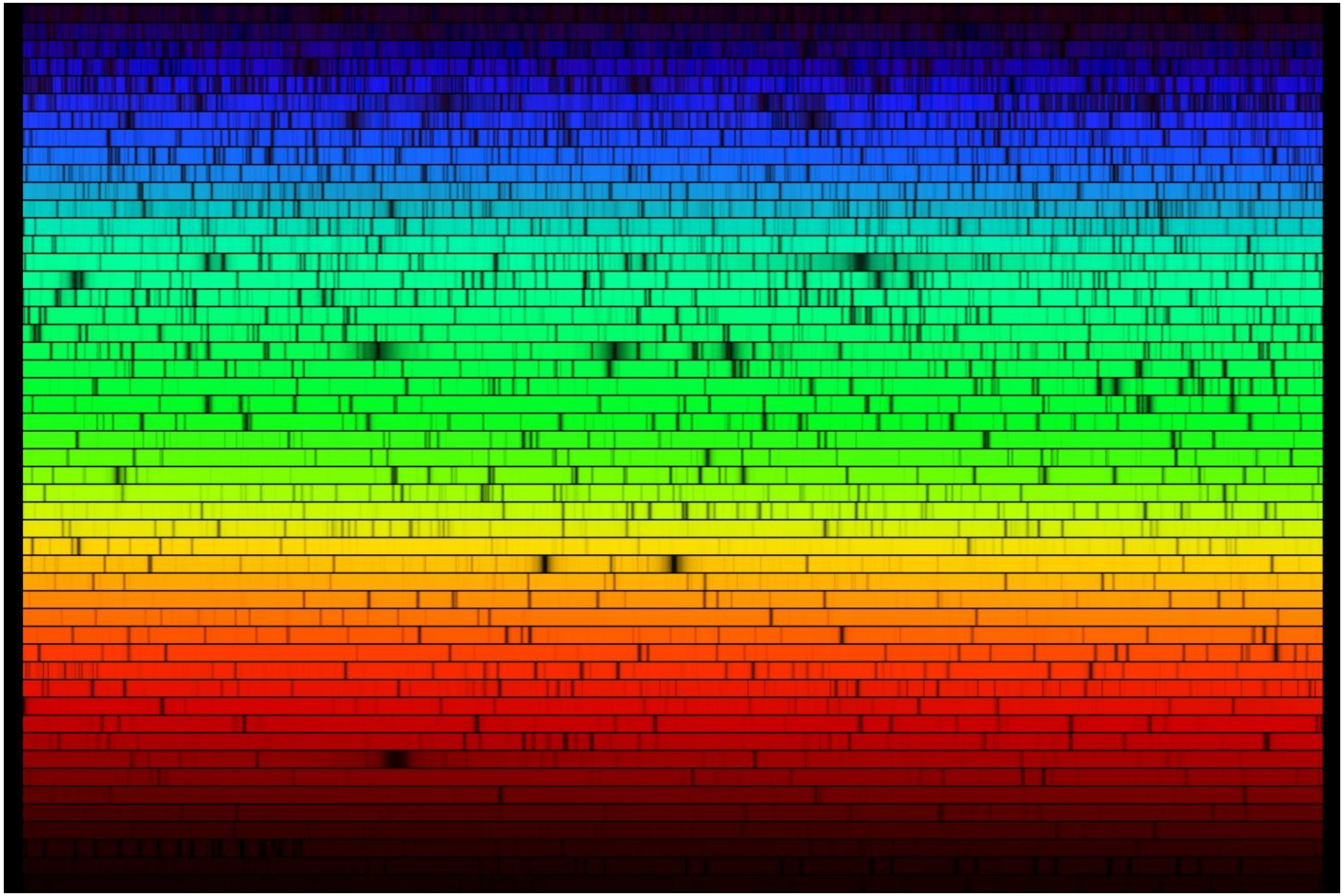
Waarom dopplermethode moeilijk is

- Lijnen verbreden door ster+telescoop
- Lijnen verschuiven door telescoopbeweging

Oplossing

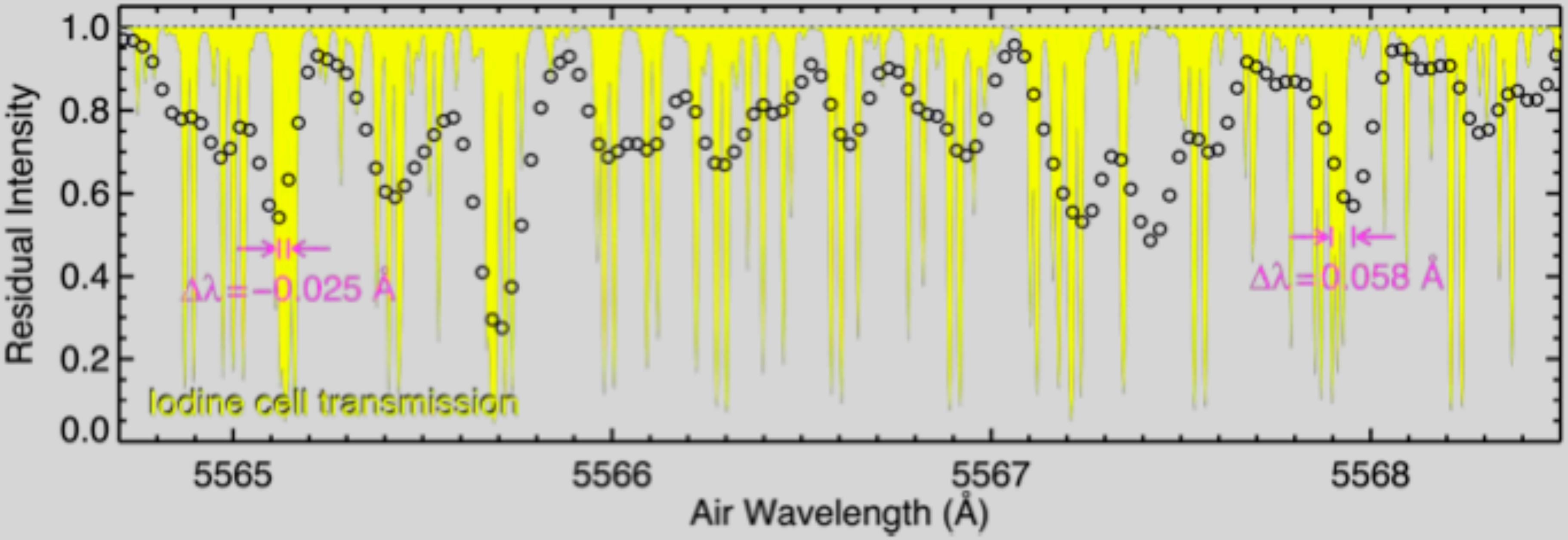
- Calibratie met Jodium cel
- Veel lijnen tegelijk

Duizenden lijnen nodig!

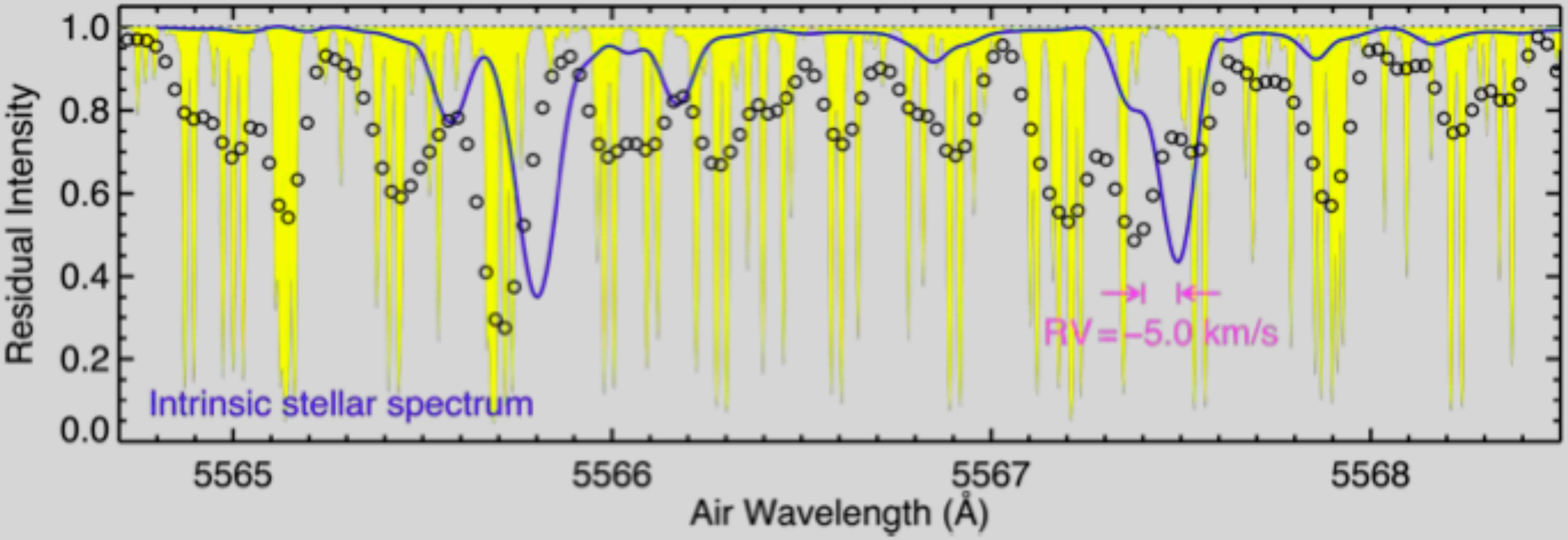


The HARPS iodine cell

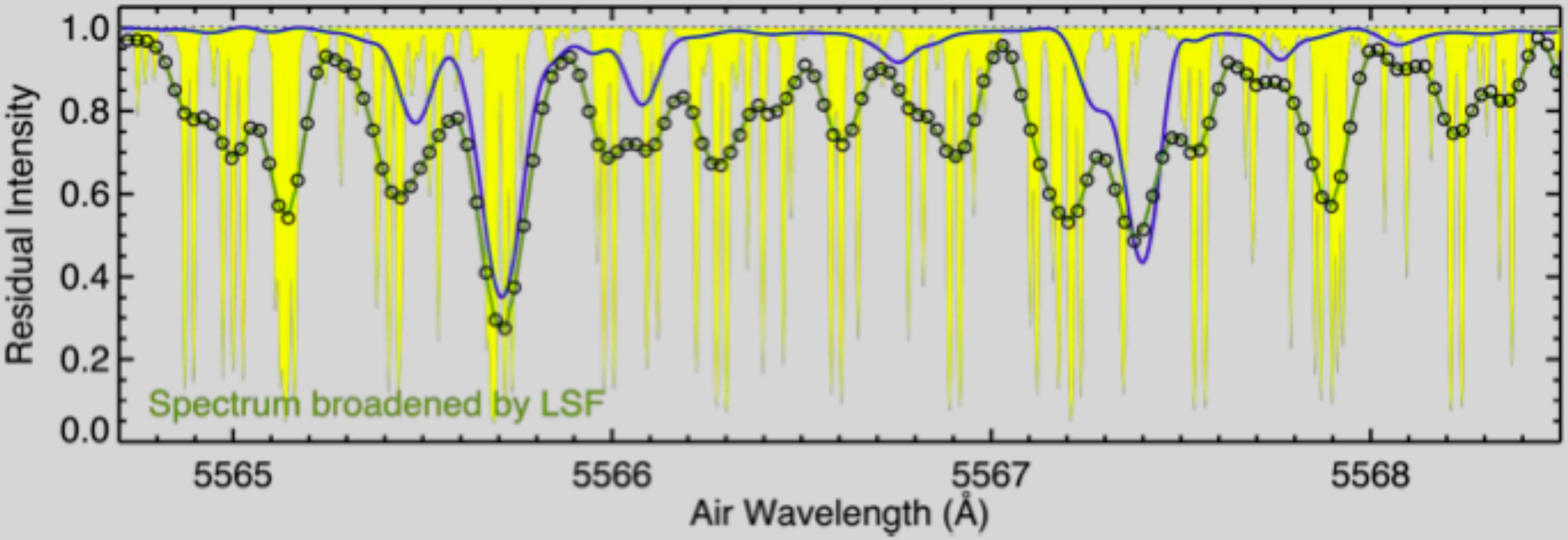
Wavelengths from Iodine Cell Absorption Lines



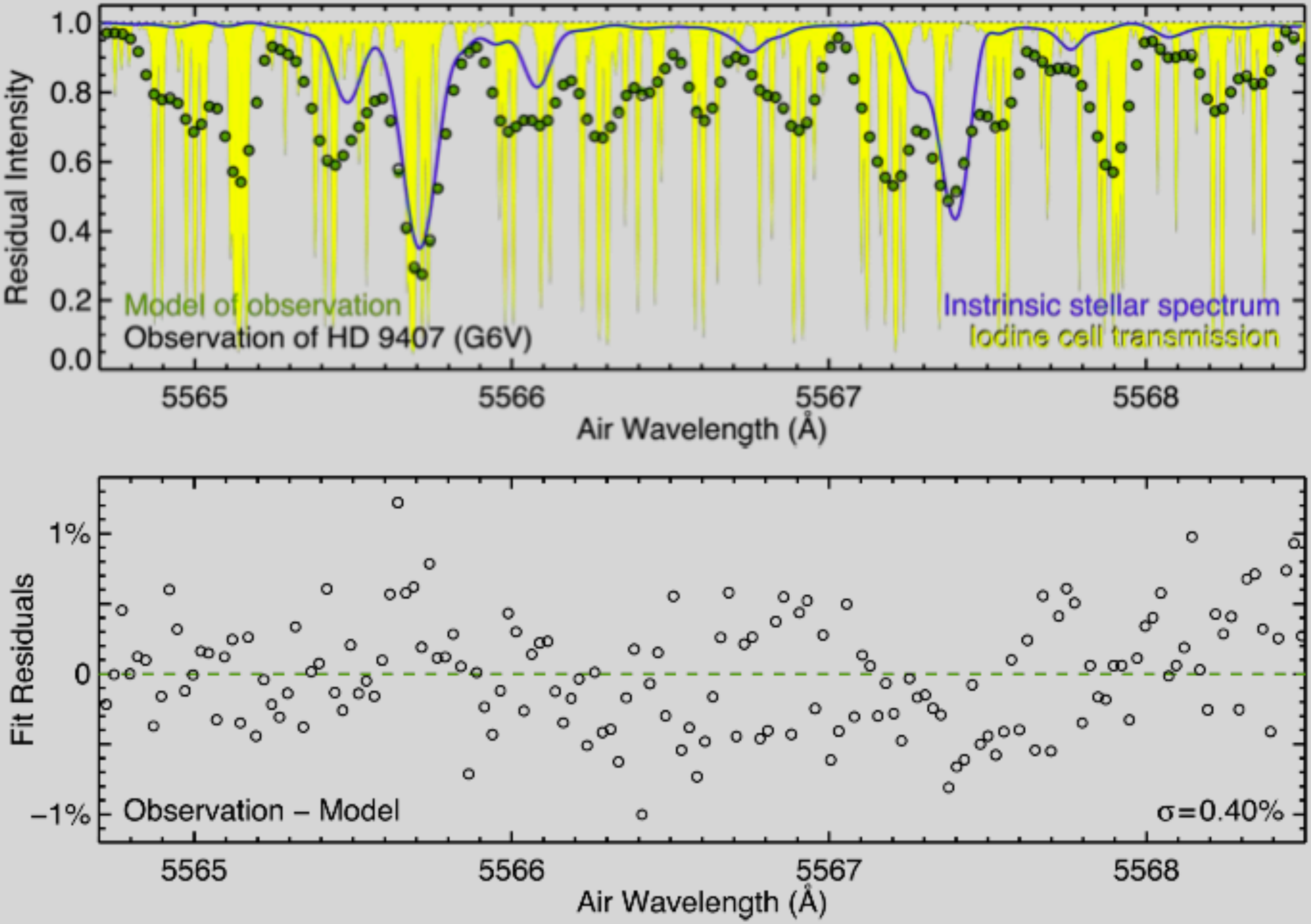
Velocity Shift of Intrinsic Stellar Sepctrum



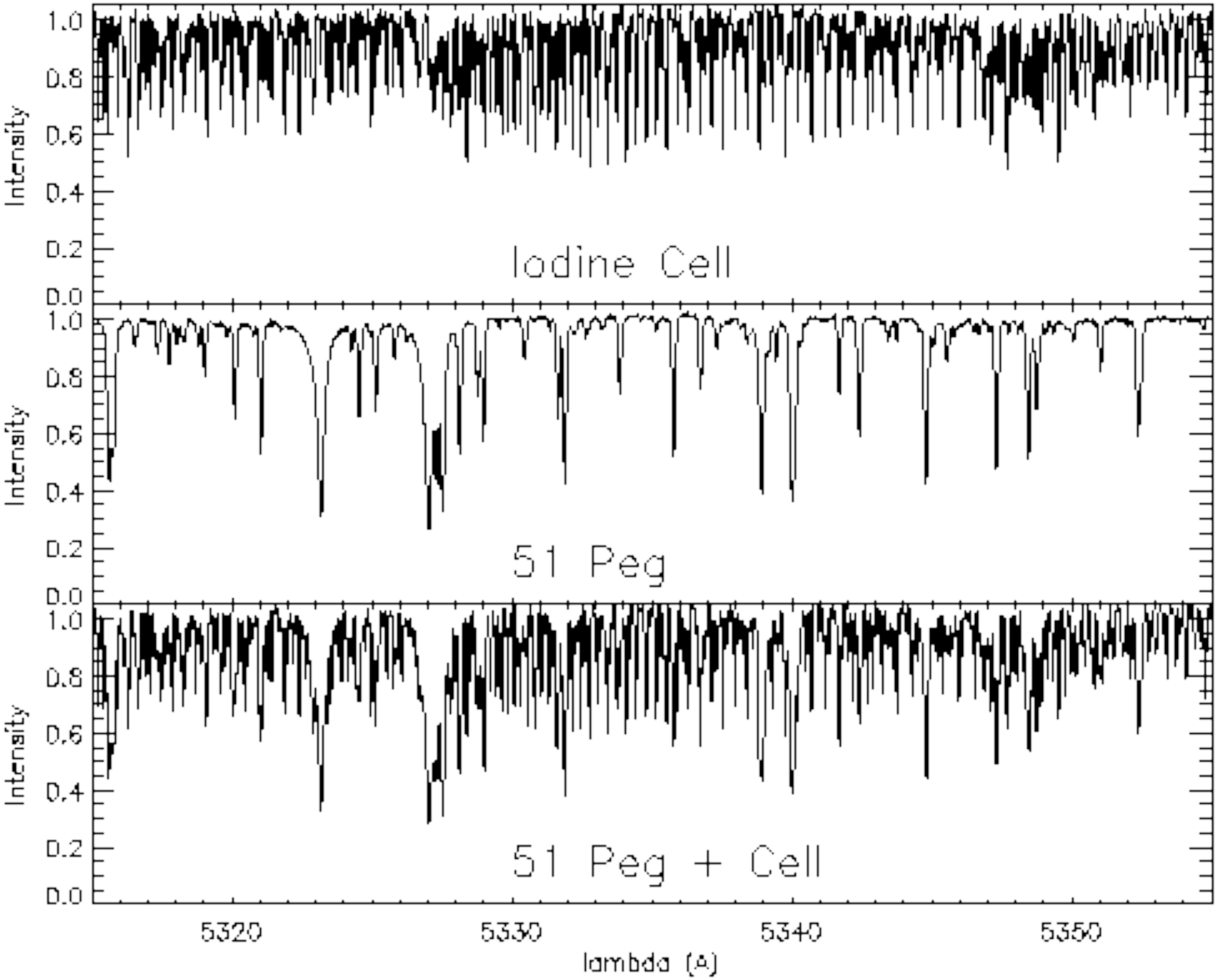
Line Spread Function of Spectrograph



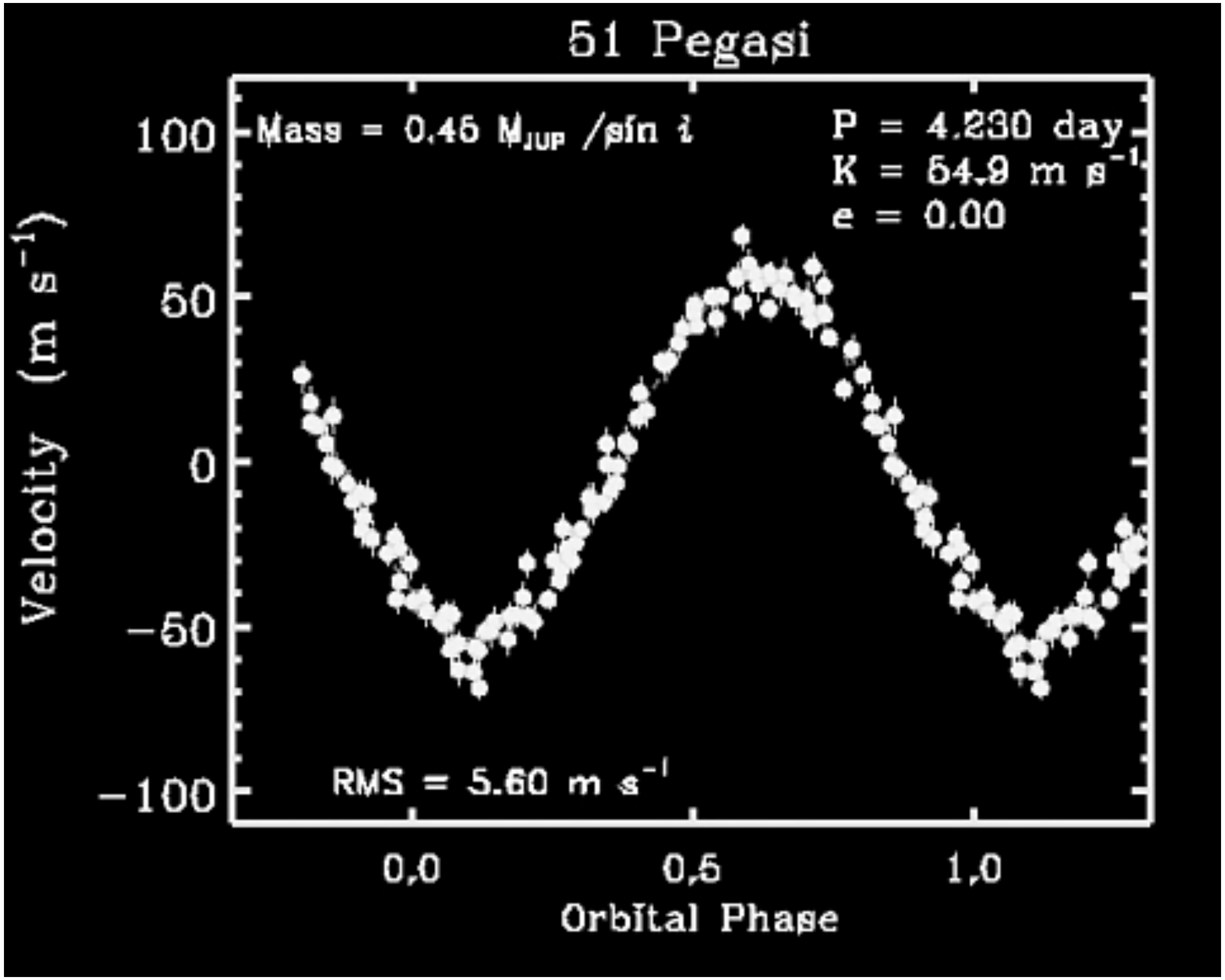
Constructed Model of Observation



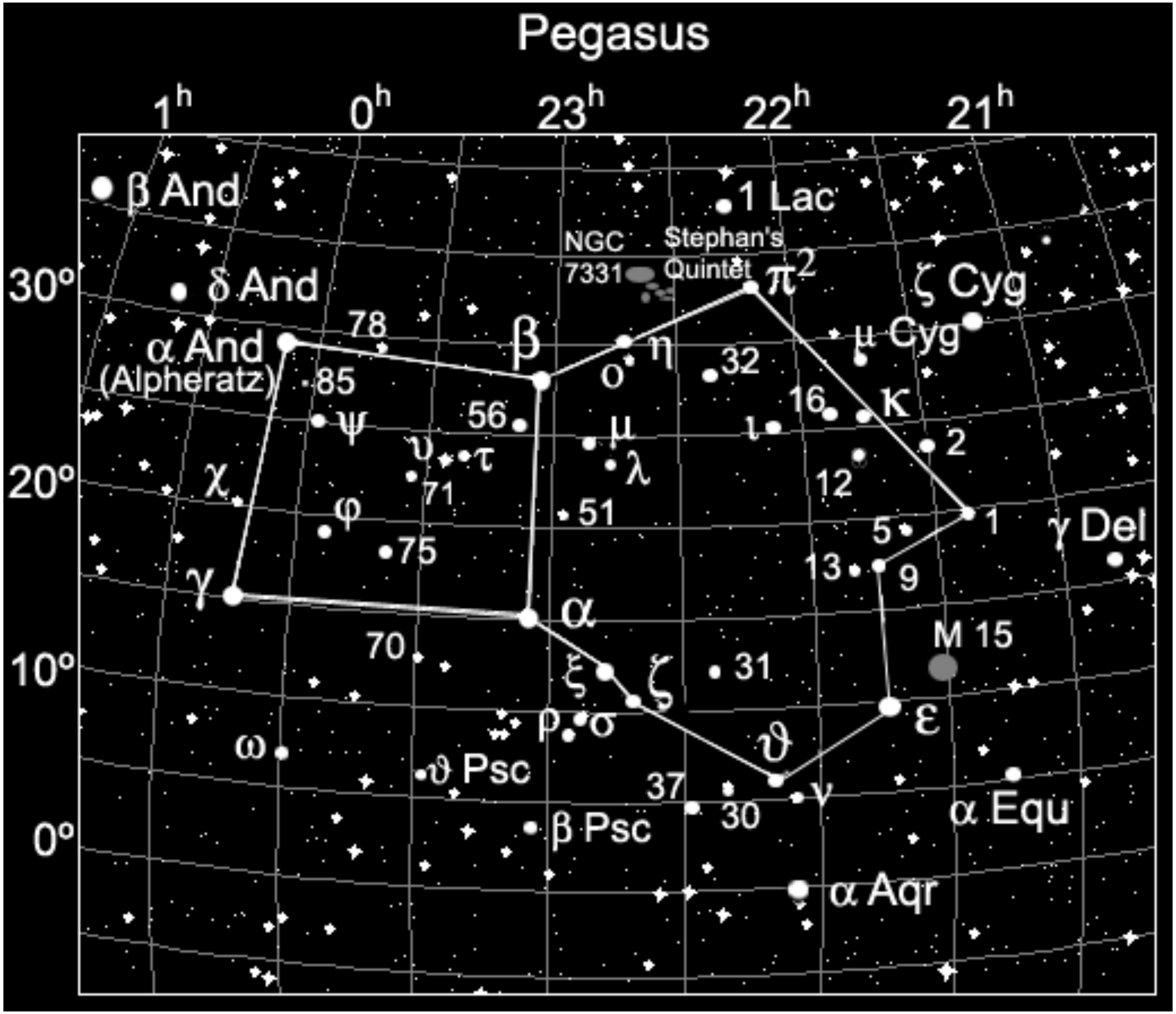
1995: 51 Pegasus

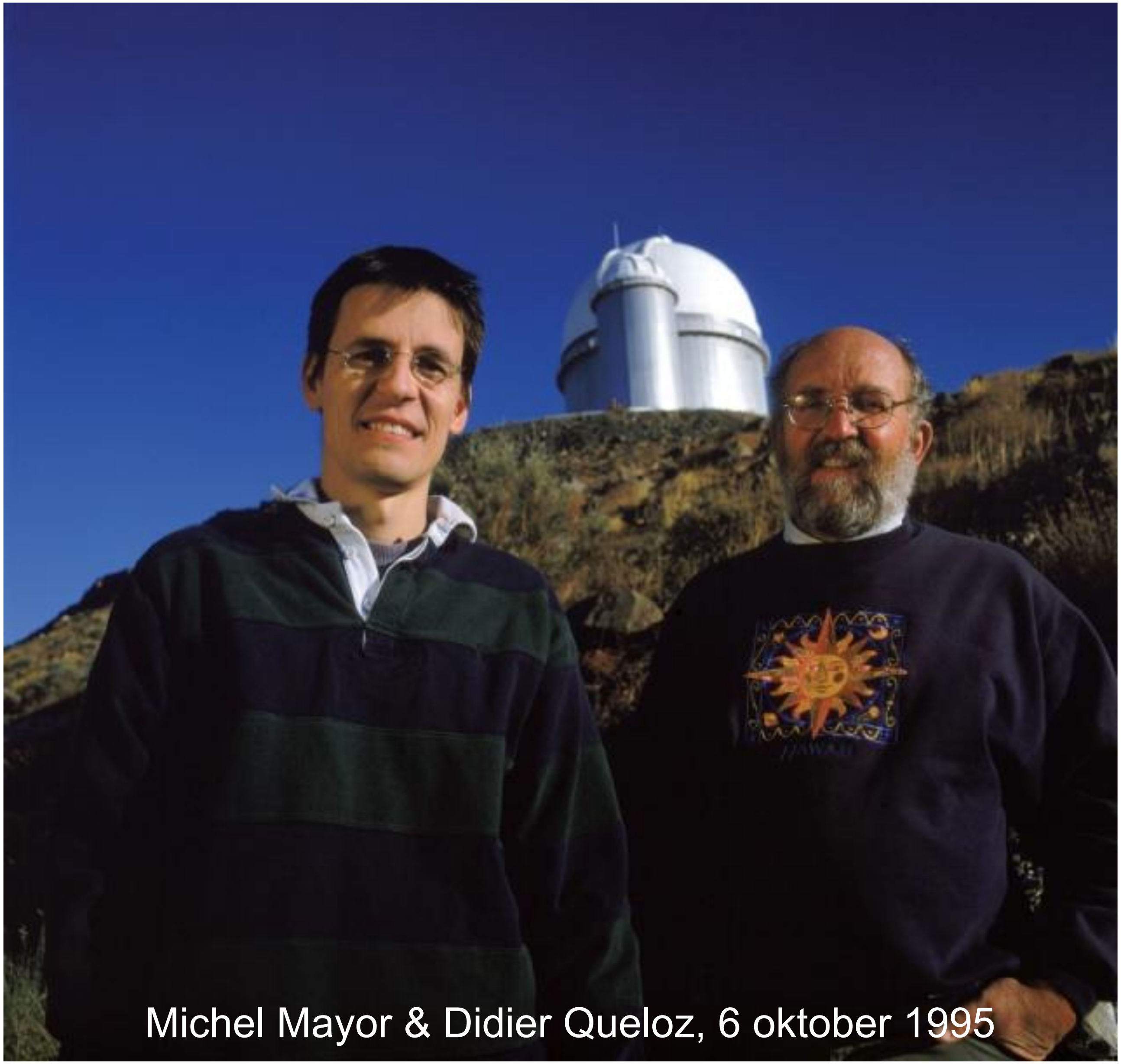


Radiële snelheids variaties 51 Peg



1995: ontdekking eerste exo-planeet


Pegasus
1h
0h
23h
22h
21h
30º
20º
10º
0º
β And
1 Lac
NGC 7331
Stephan's Quintet
δ And
π2
ζ Cyg
μ Cyg
78
α And
(Alpheratz)
85
β
η
ο
32
16
κ
56
ψ
μ
ι
2
υ
τ
λ
12
χ
71
φ
51
1
γ Del
75
5
13
9
γ
α
70
M 15
ξ
ζ
31
ε
ρ
σ
ω
ϑ
ϑ Psc
37
ν
30
α Equ
β Psc
α Aqr



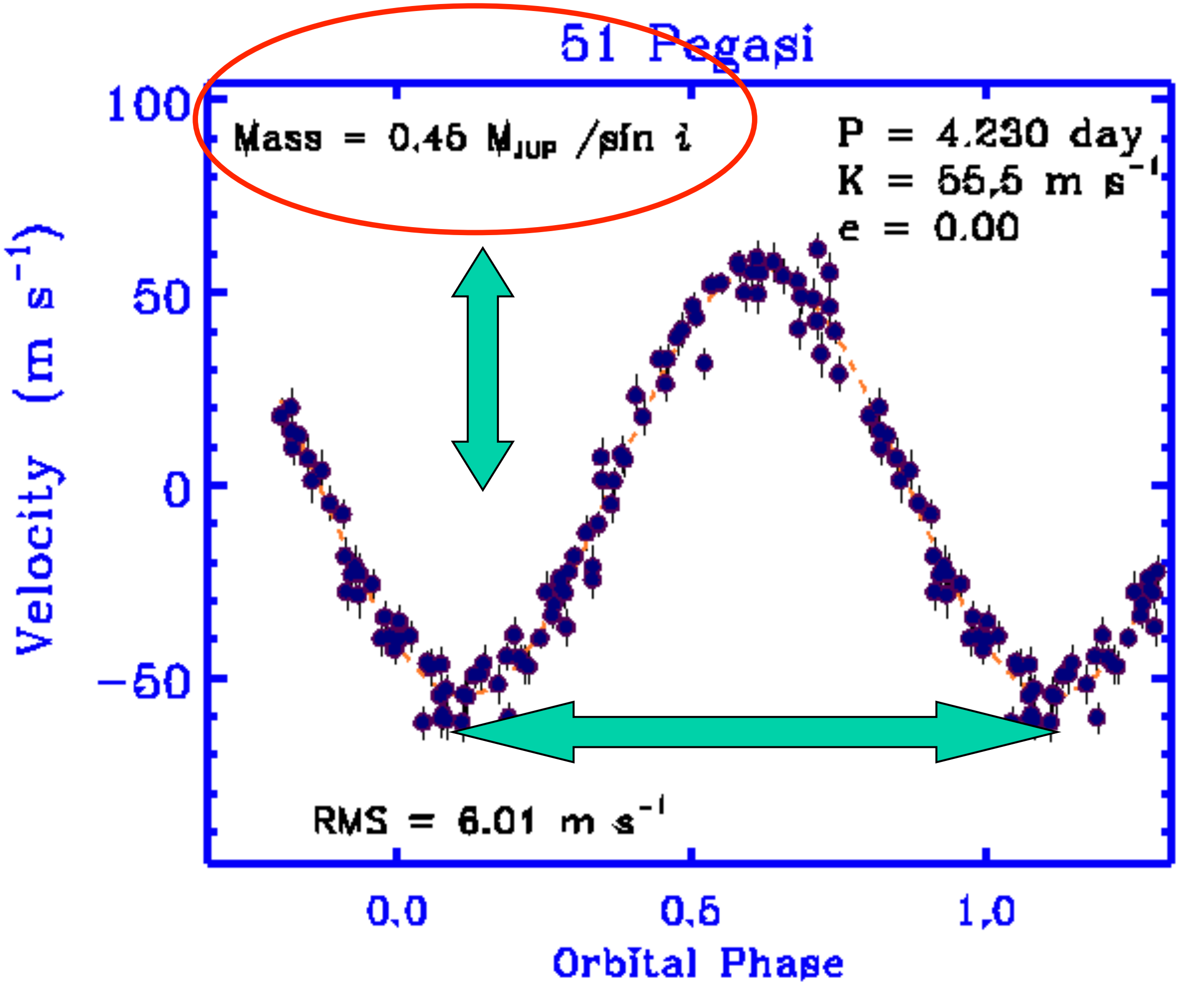
Michel Mayor & Didier Queloz, 6 oktober 1995

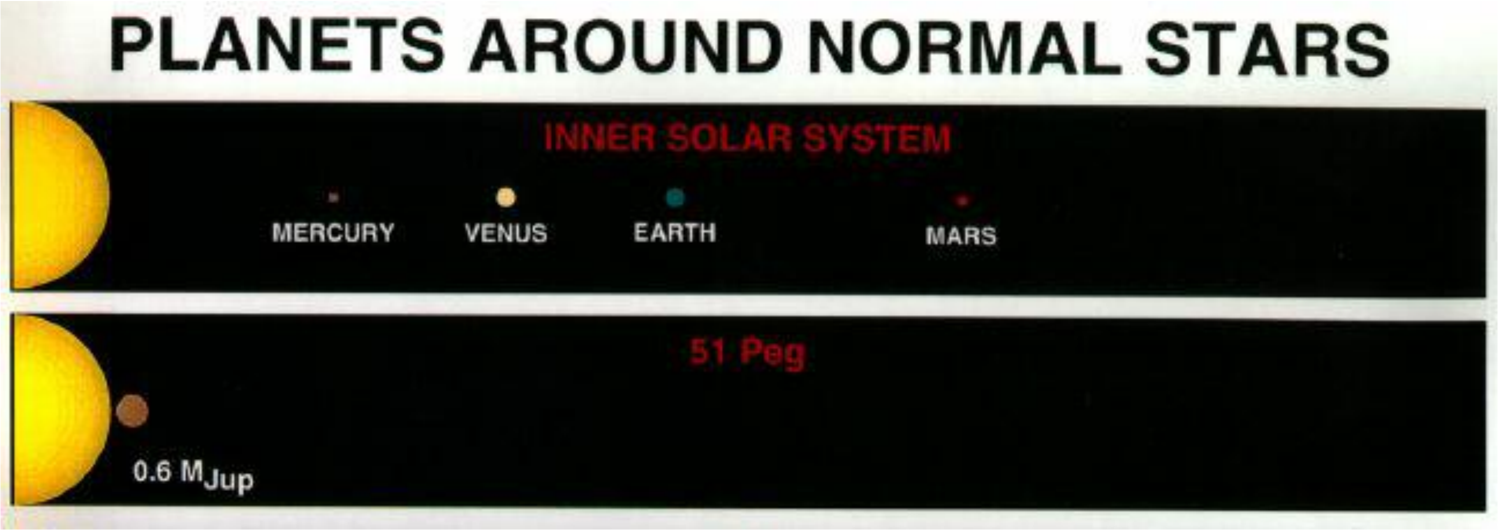
Just one planet (so far) around 51 Peg

Get mass! That easy

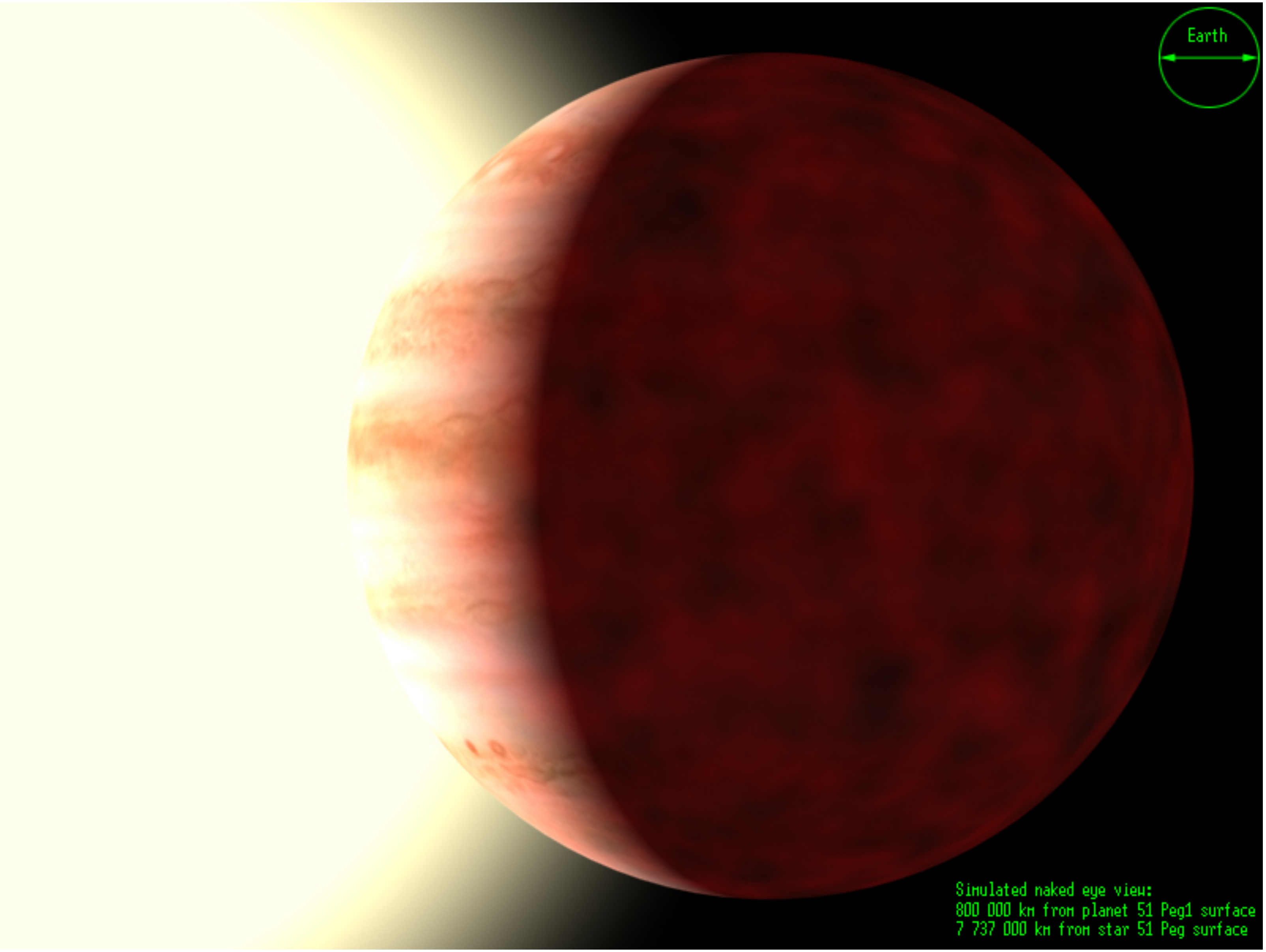
Measure K

Measure P

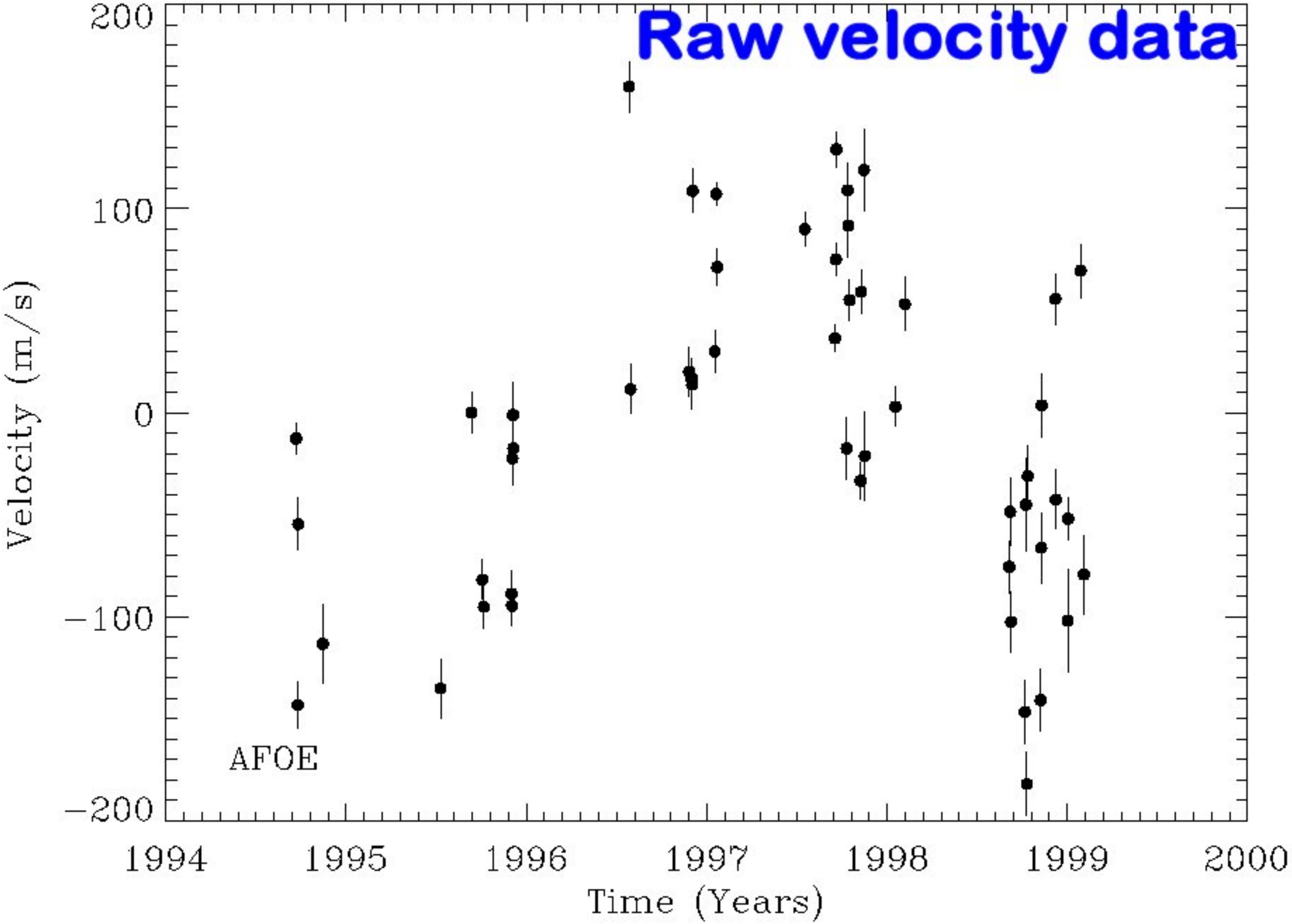




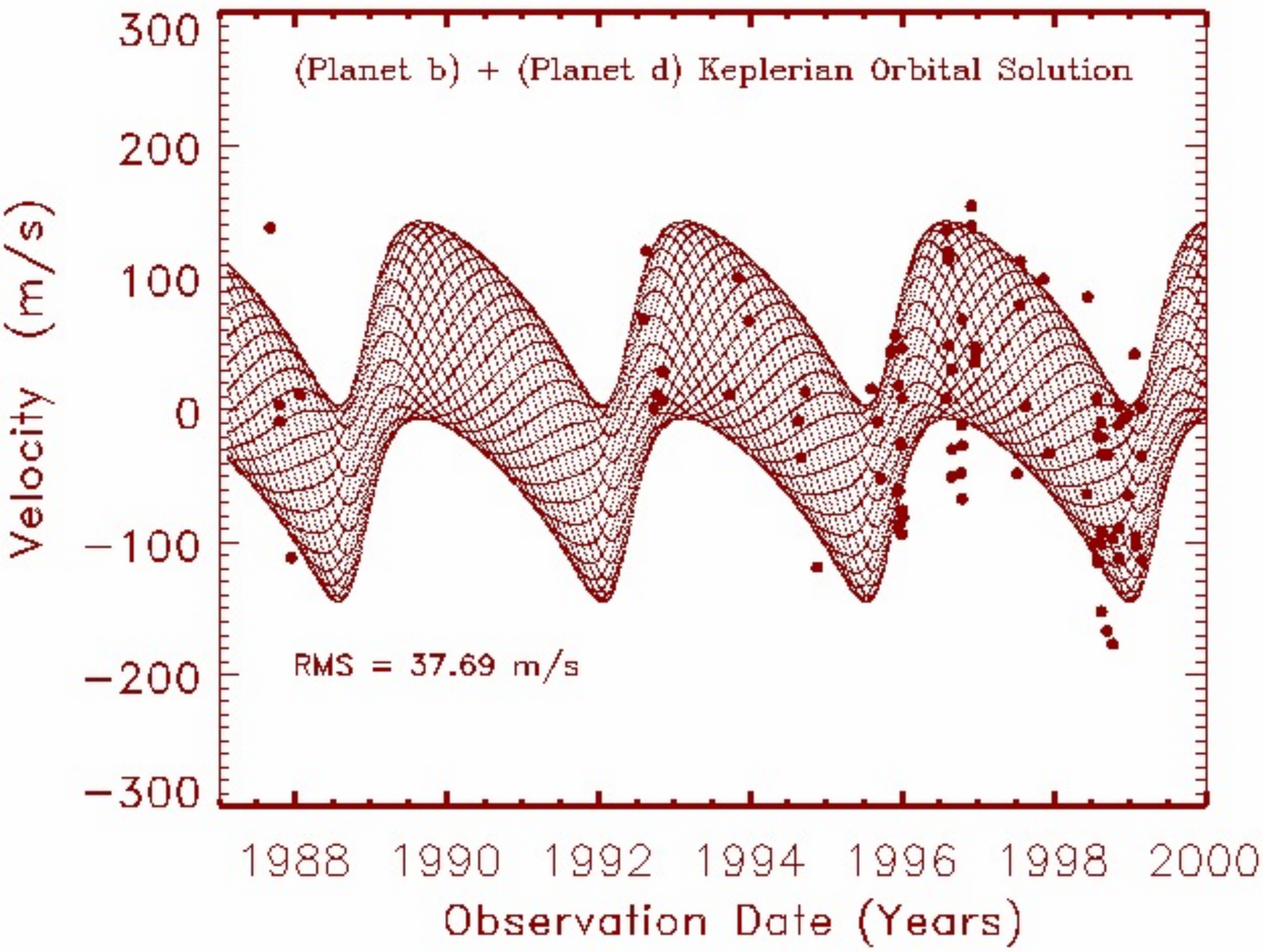
G2 ster. Planeetmassa > 0.45 $M_{jupiter}$. Periode 4.23d a=0.0512 AE


Earth
Simulated naked eye view:
800 000 km from planet 51 Peg1 surface
7 737 000 km from star 51 Peg surface

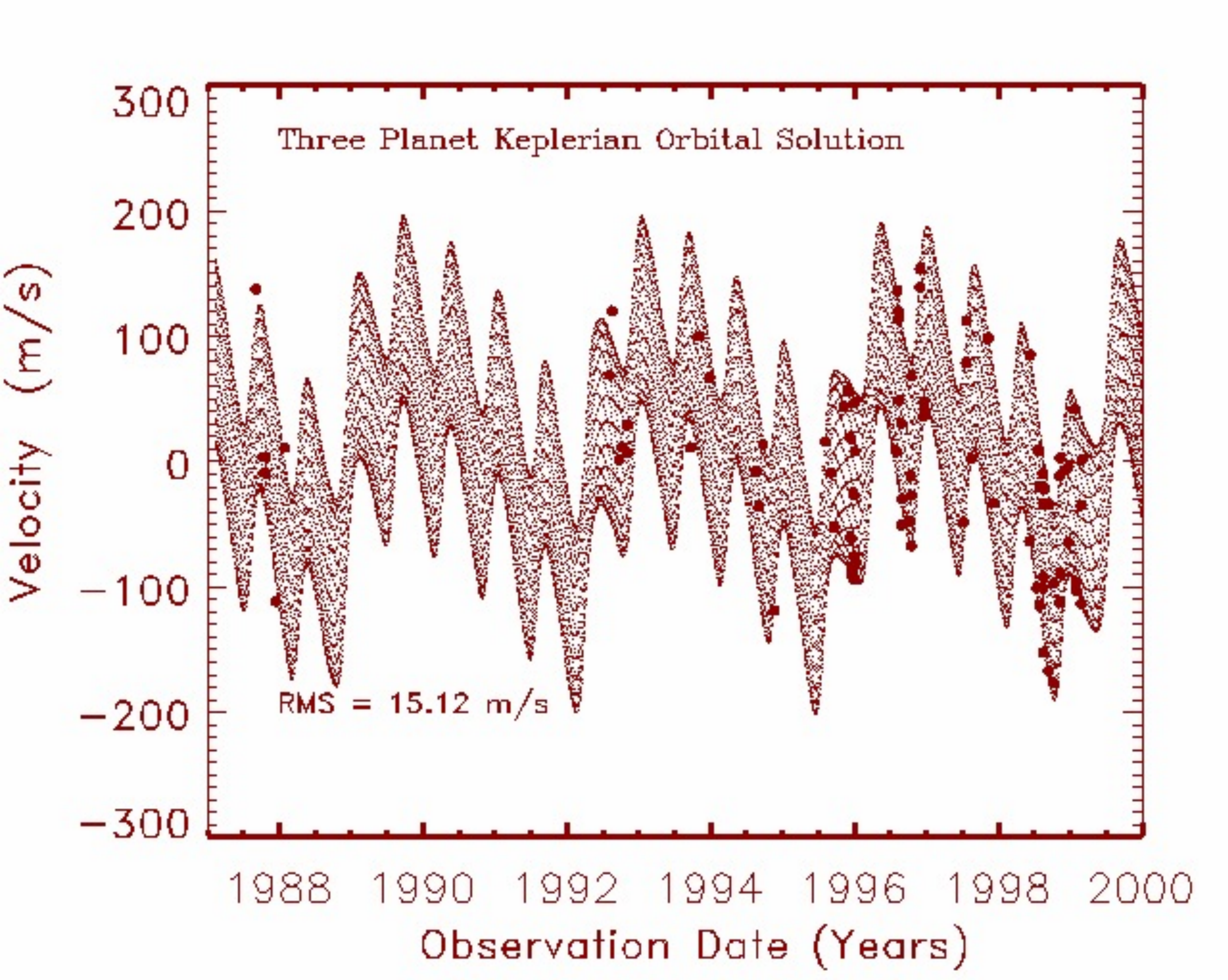
Een gecompliceerd voorbeeld: υ Andromeda


Raw velocity data
Velocity (m/s)
200
100
0
−100
−200
Time (Years)
1994
1995
1996
1997
1998
1999
2000
AFOE

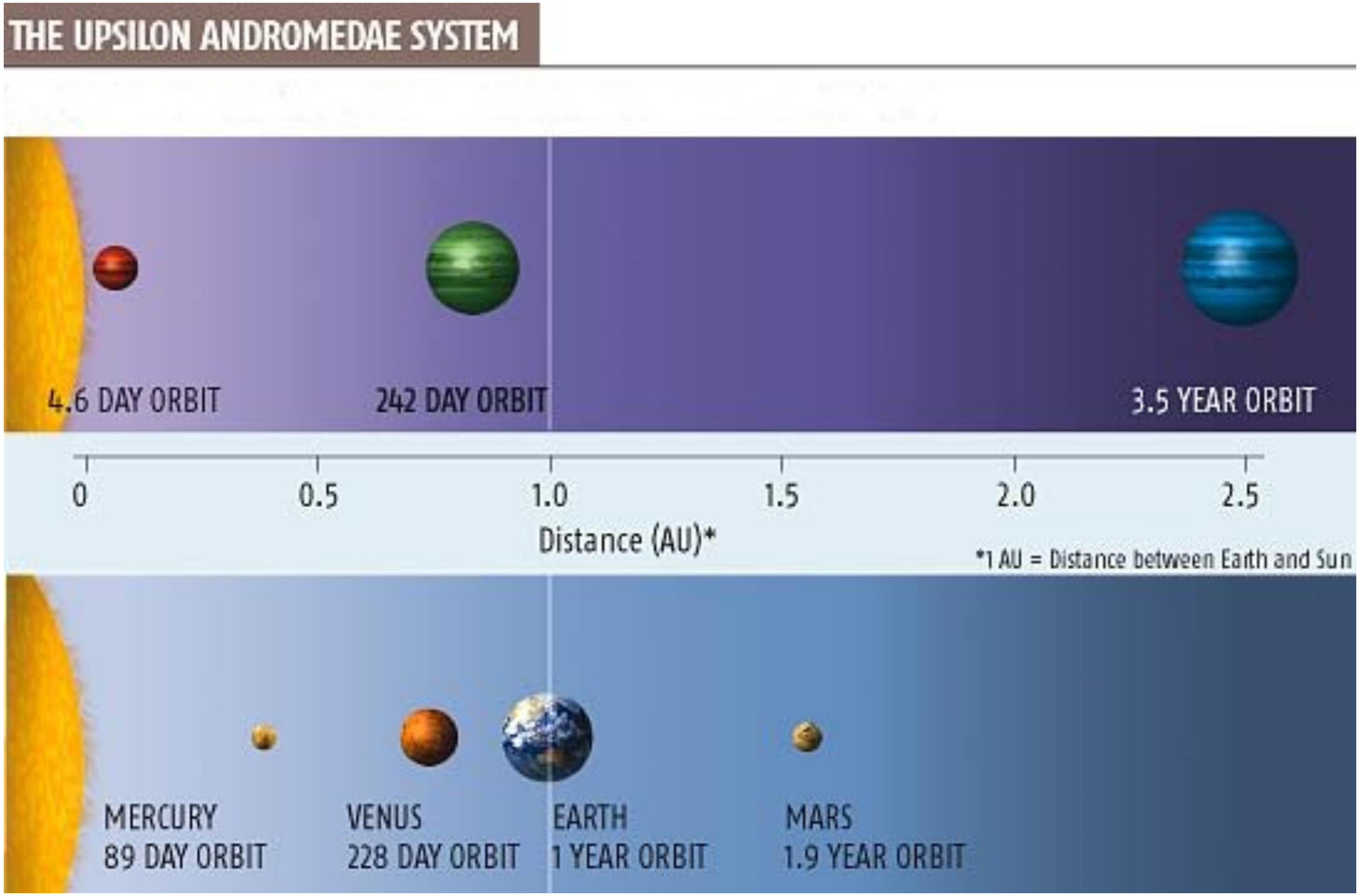
Two planet solution?



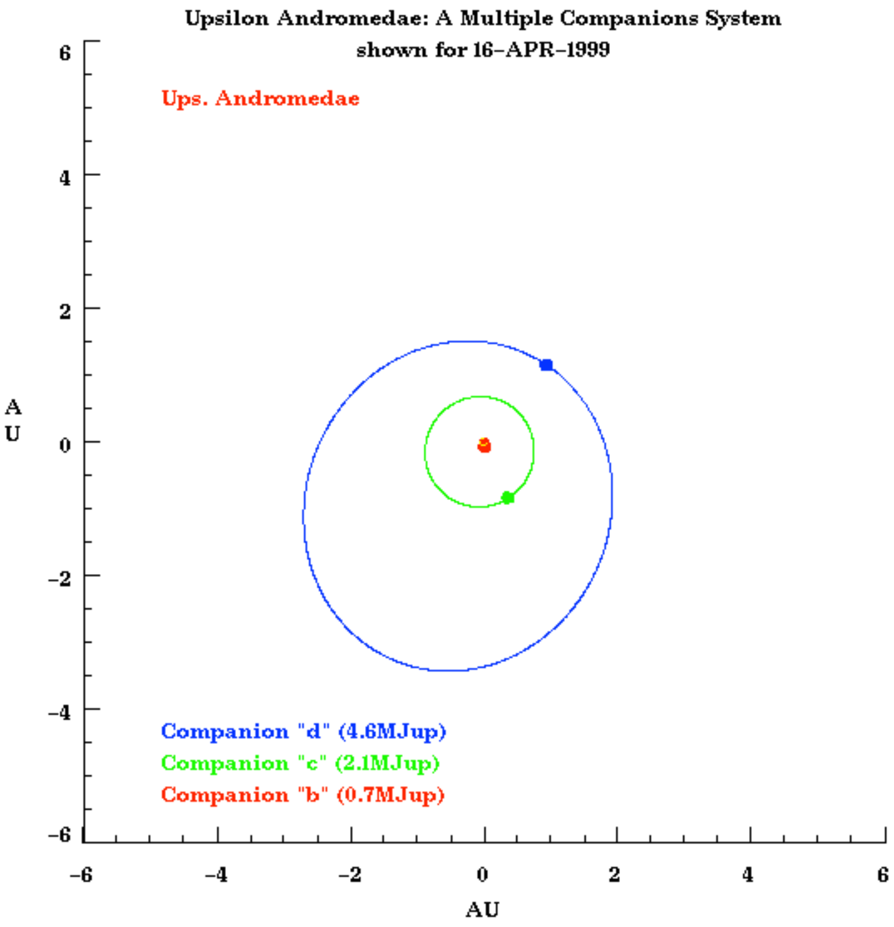
3 planet solution!



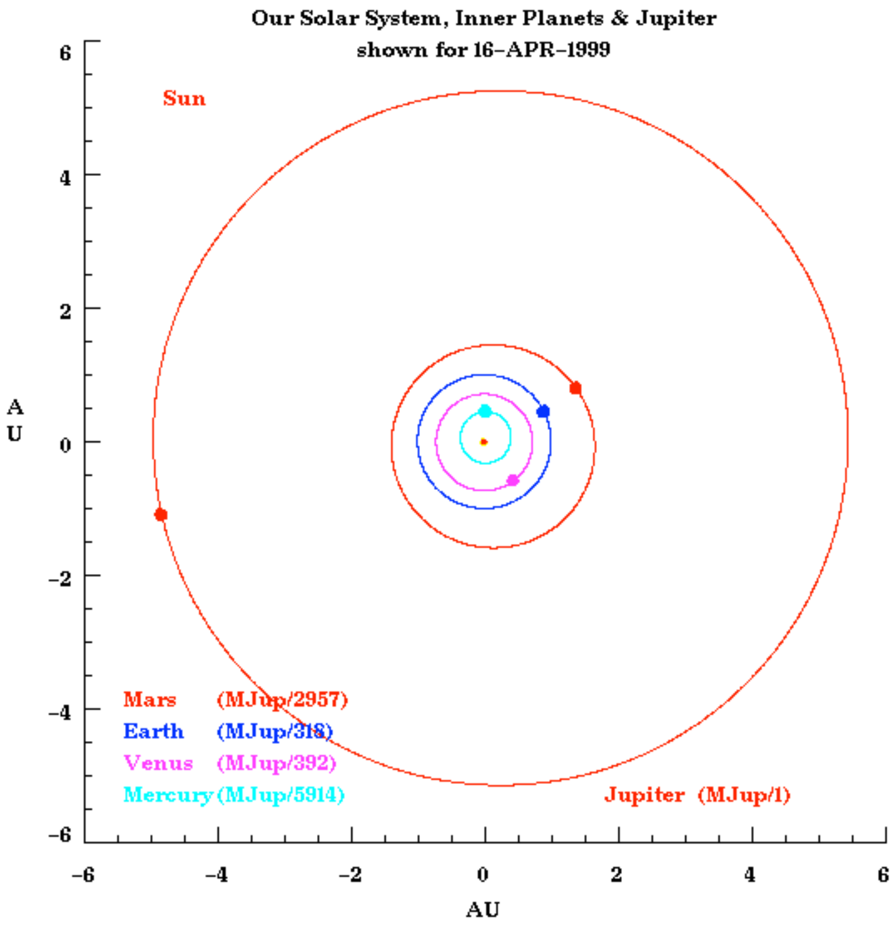
Upsilon Andromedae



Vergelijking met zonnestelsel

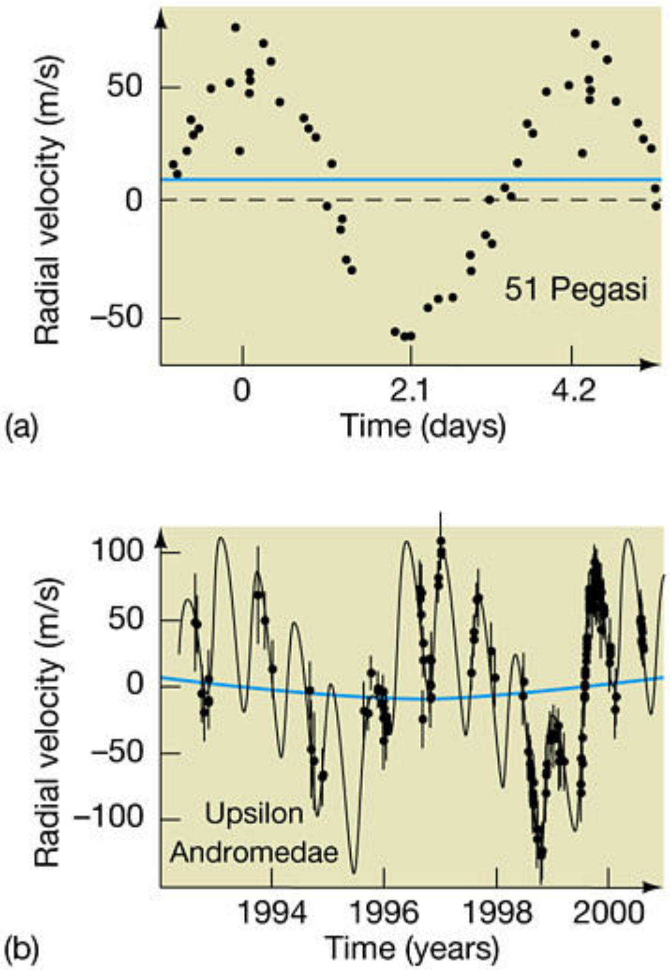


Upsilon Andromedae: A Multiple Companions System
shown for 16-APR-1999

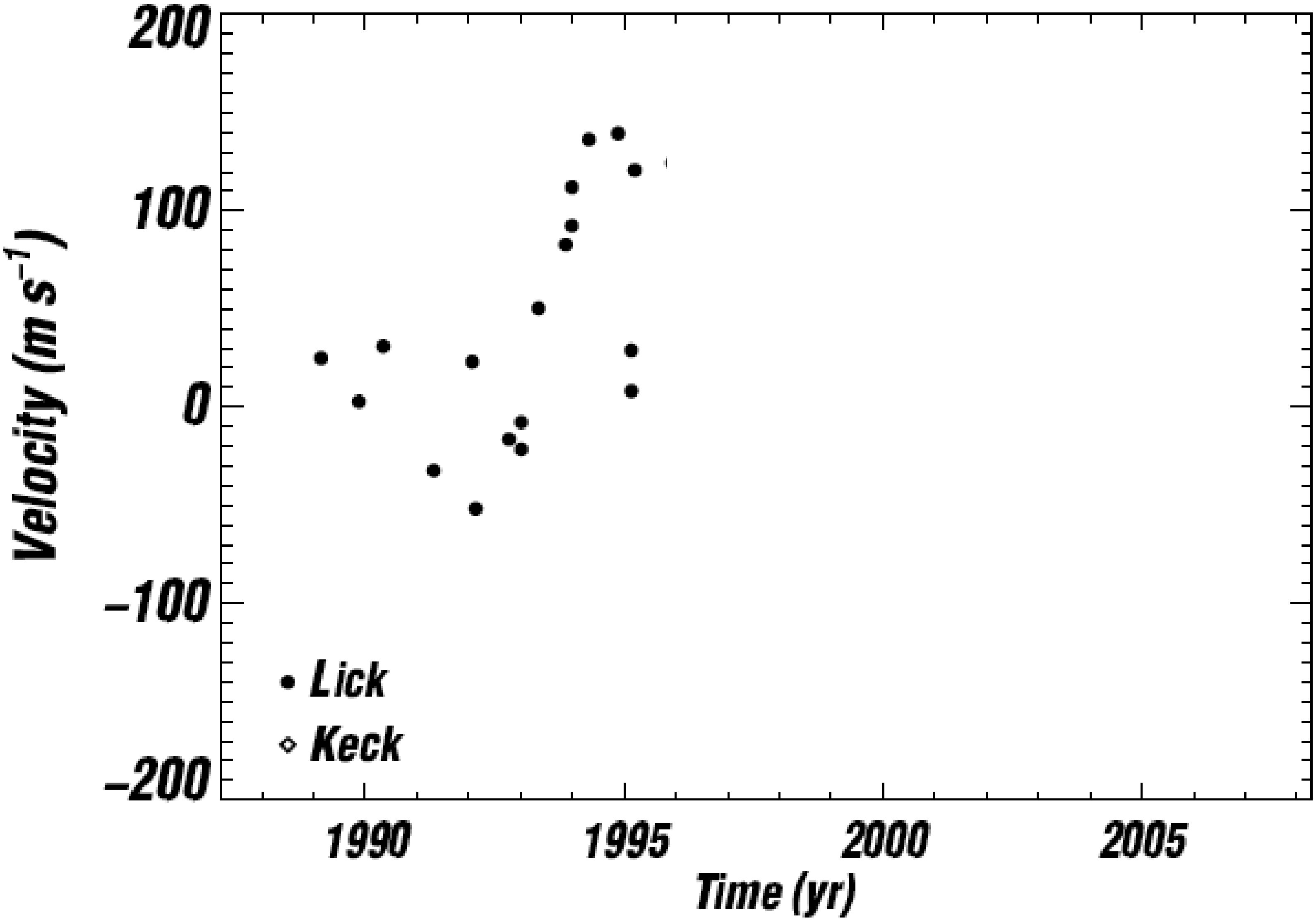


Our Solar System, Inner Planets & Jupiter
shown for 16-APR-1999

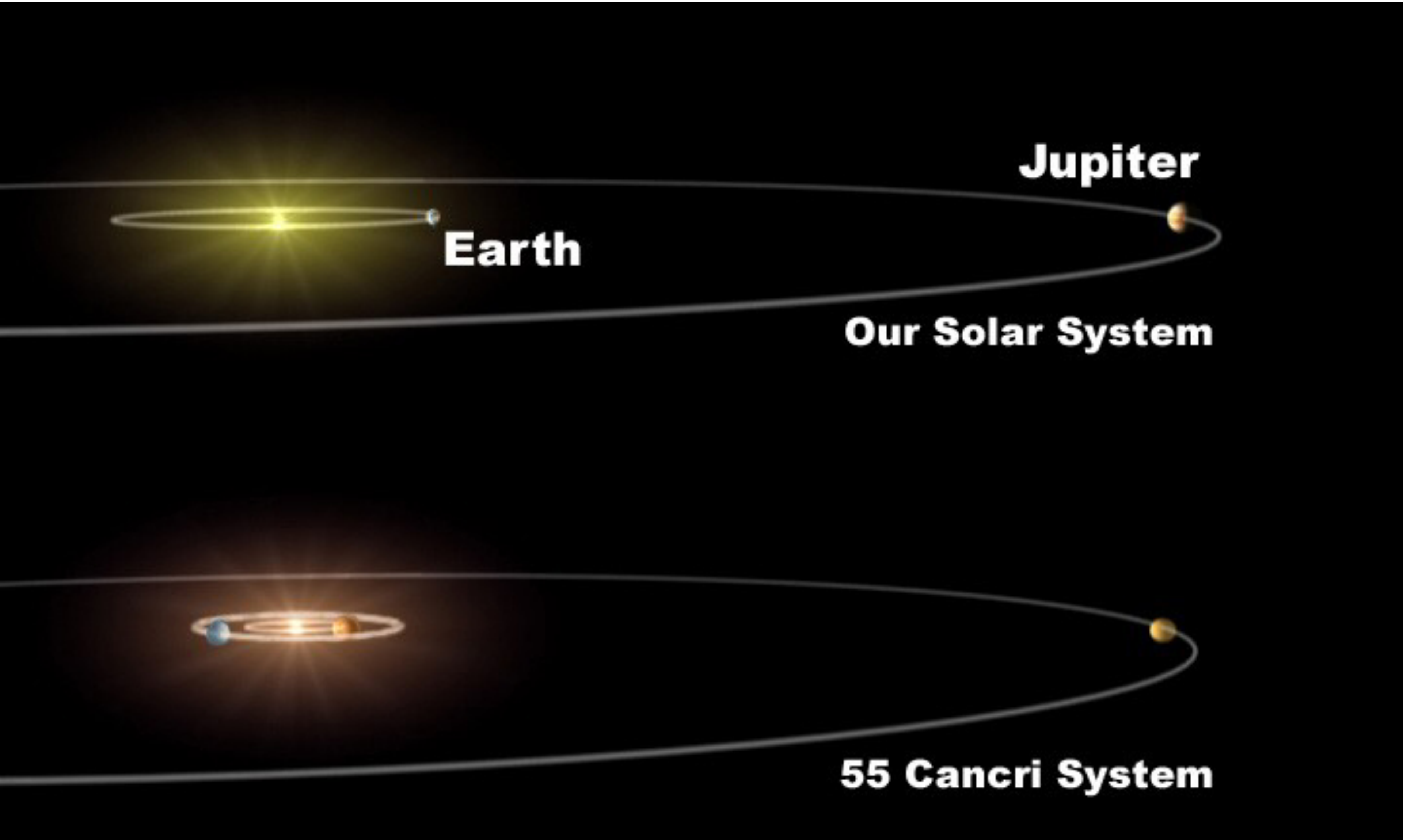
Upsilon Andromedae



55 Cancri

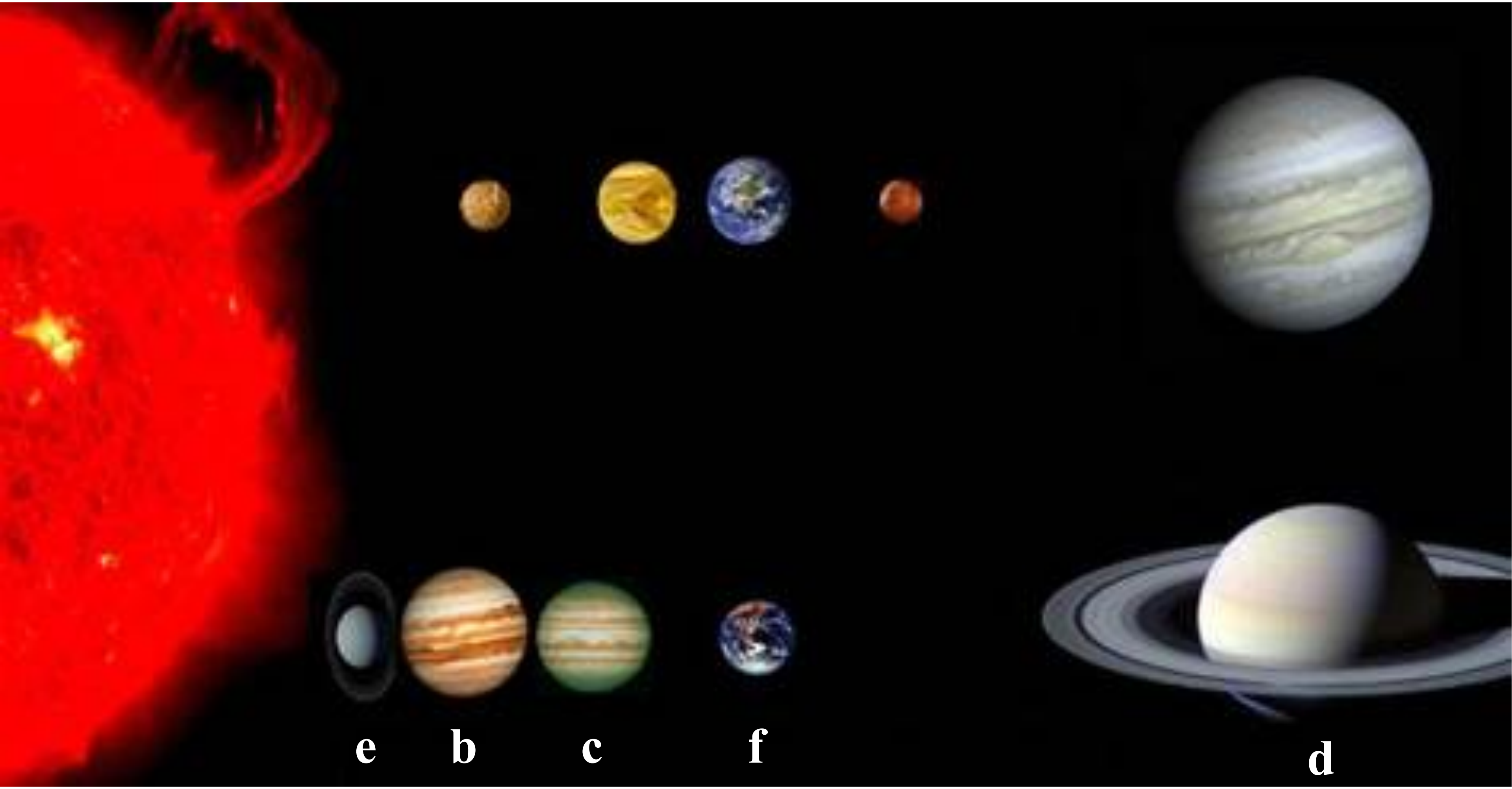

200
100
0
−100
−200
Velocity (m s^{-1})
● Lick
◇ Keck
1990
1995
2000
2005
Time (yr)

55 Cancri: 3 planeten?



Fischer, Marcy et al. (2007)

55 Cancri: 5 planeten!



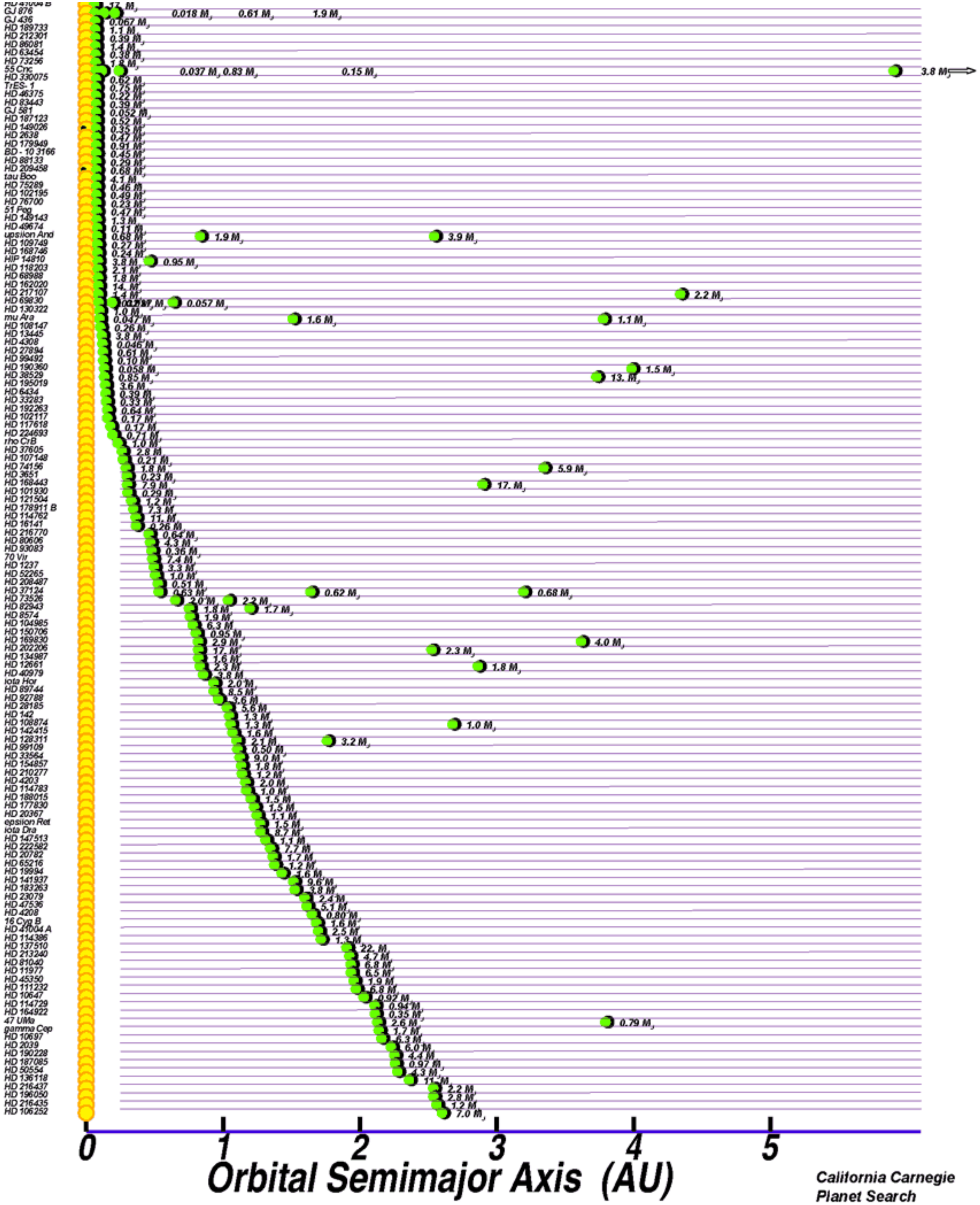
e: M = 8 M_{earth} P=18 uur

f: M = 12 M_{earth} P=260 dagen

Statistiek gebaseerd op Doppler methode

Lijken exoplaneten op ons zonnestelsel?

The first 178 Planets



California Carnegie Planet Search

Exoplanets discovered

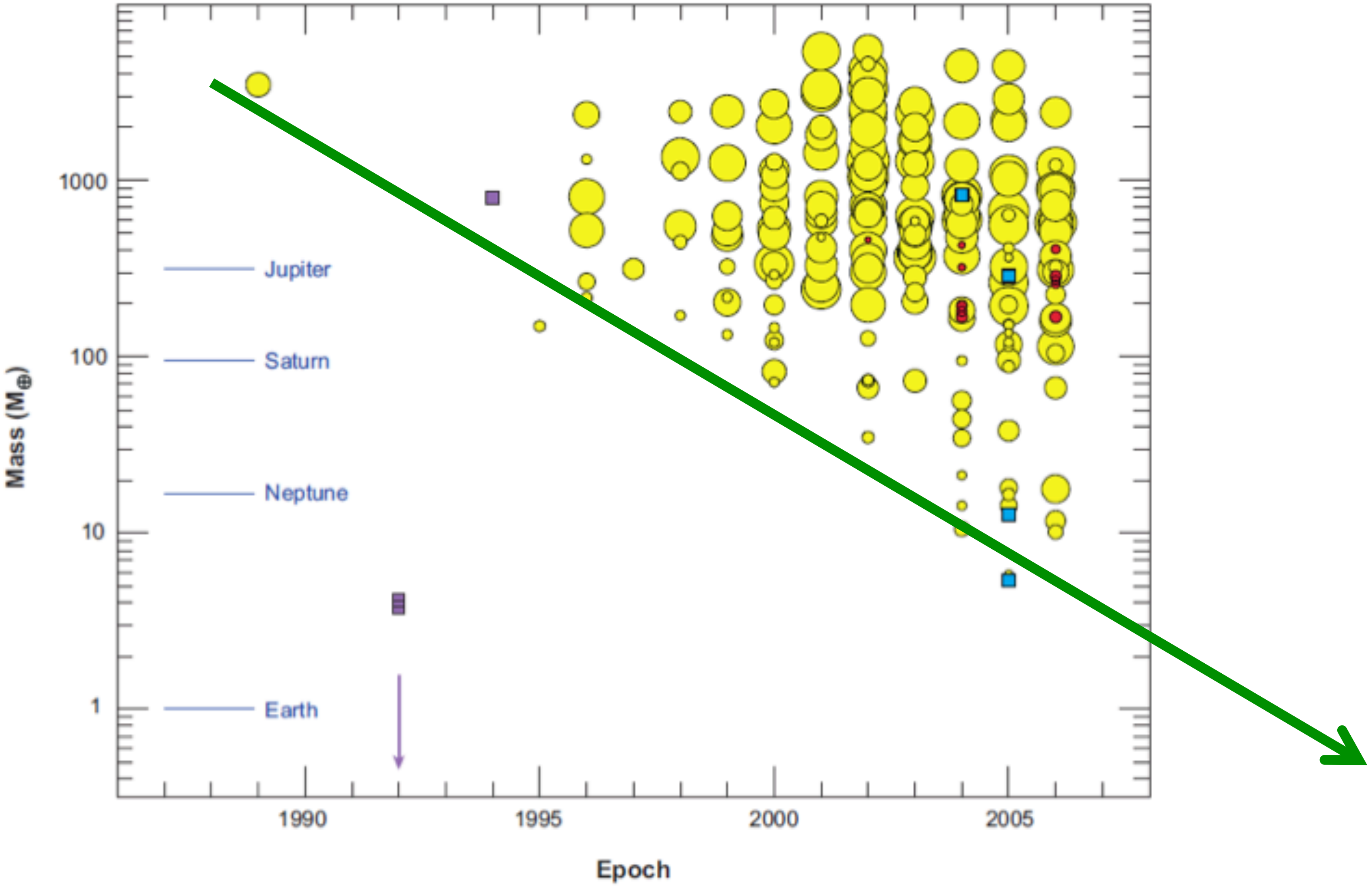


Figure: Mass vs year of discovery, circle size indicates semi-major axis. Yellow=Radial Velocity, red=transit technique, blue=microlensing and purple=pulsartiming.

Exoplanets discovered

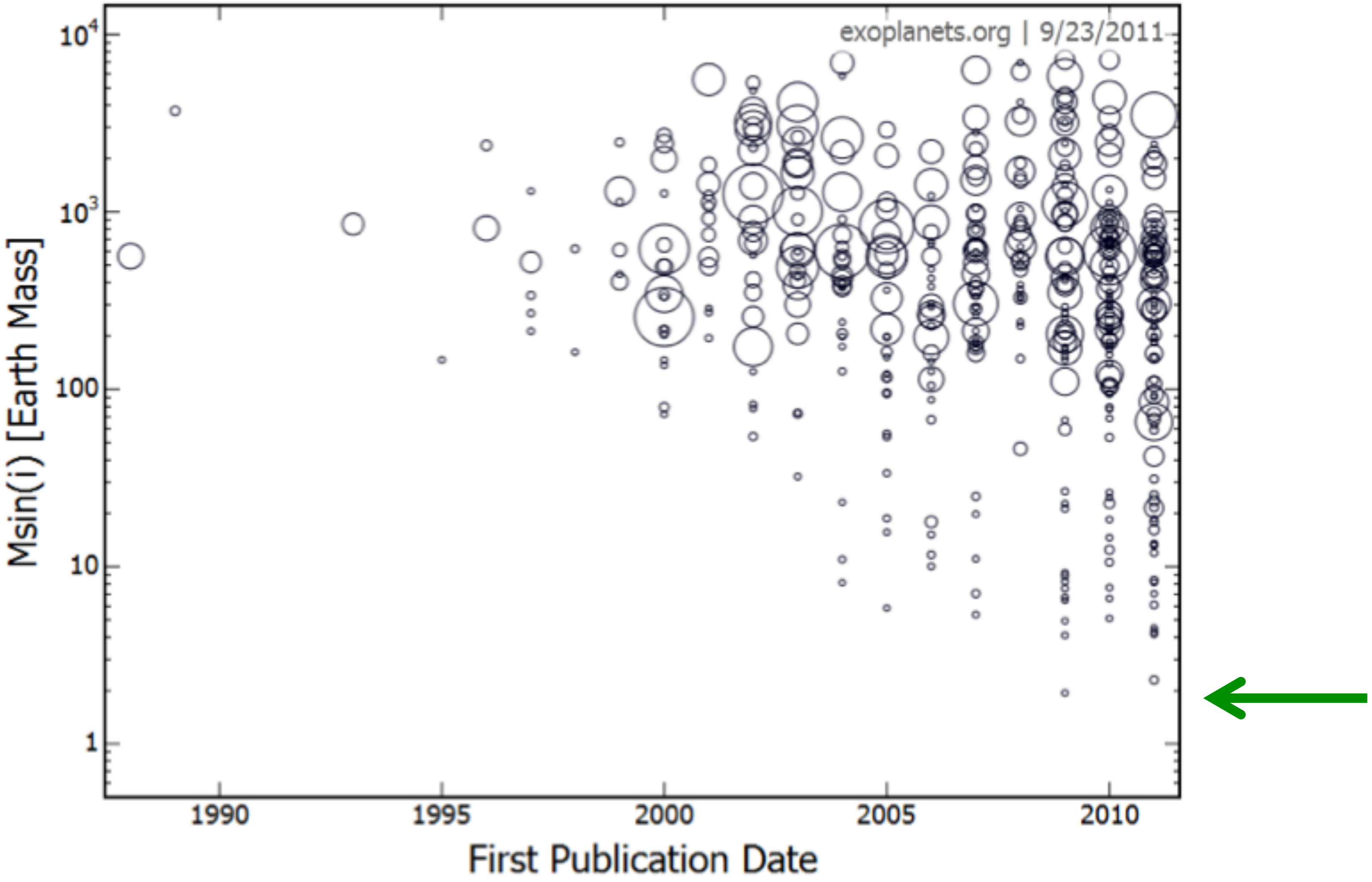
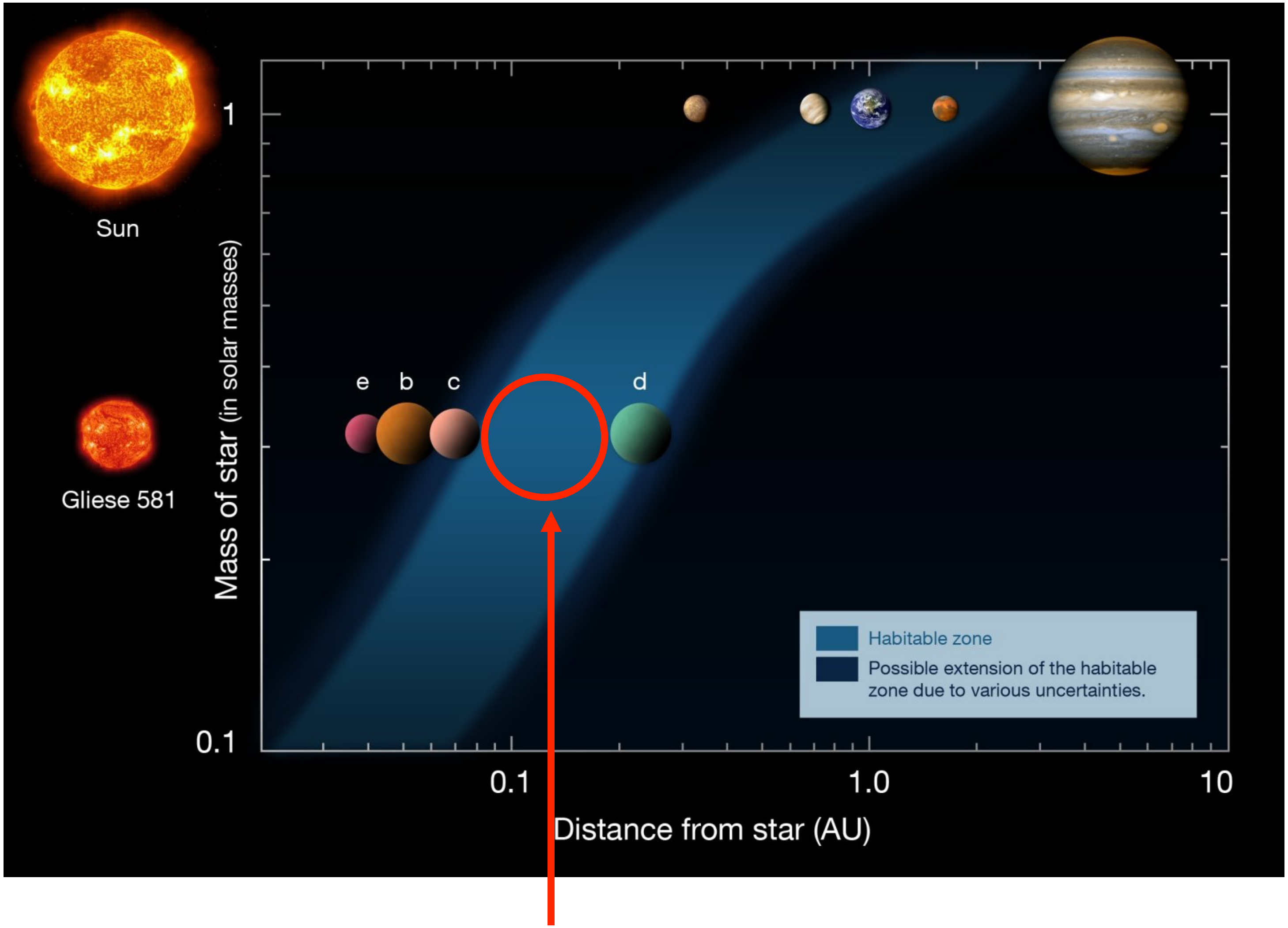


Figure: Mass vs year of discovery, circle size indicates semi-major axis.

Gliese 581e

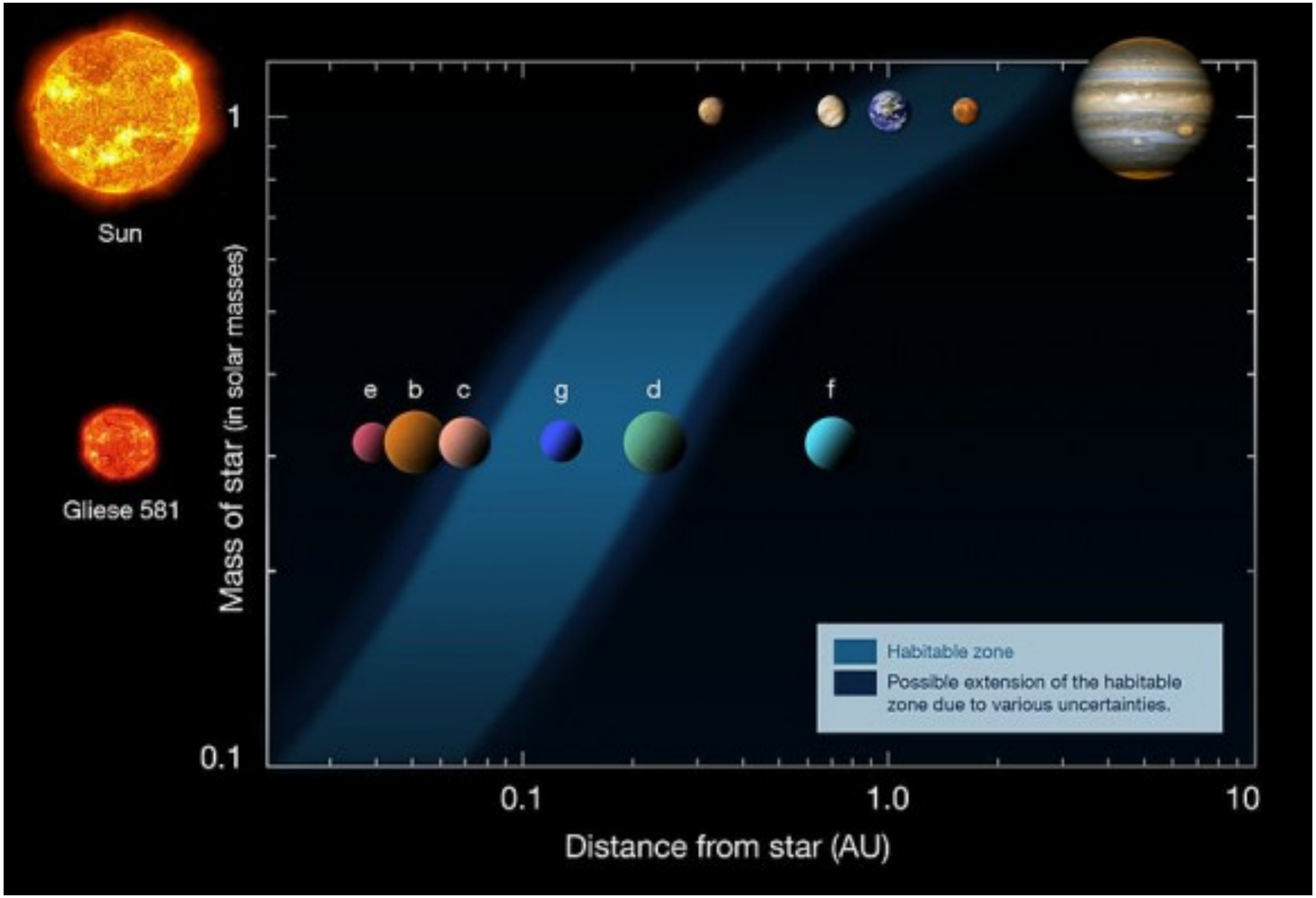
Lichtste exoplaneet tot nu toe:
twee aardmassa's

Gliese 581 b,c,d: 16, 5, 8 aardmassa's: Superaardes



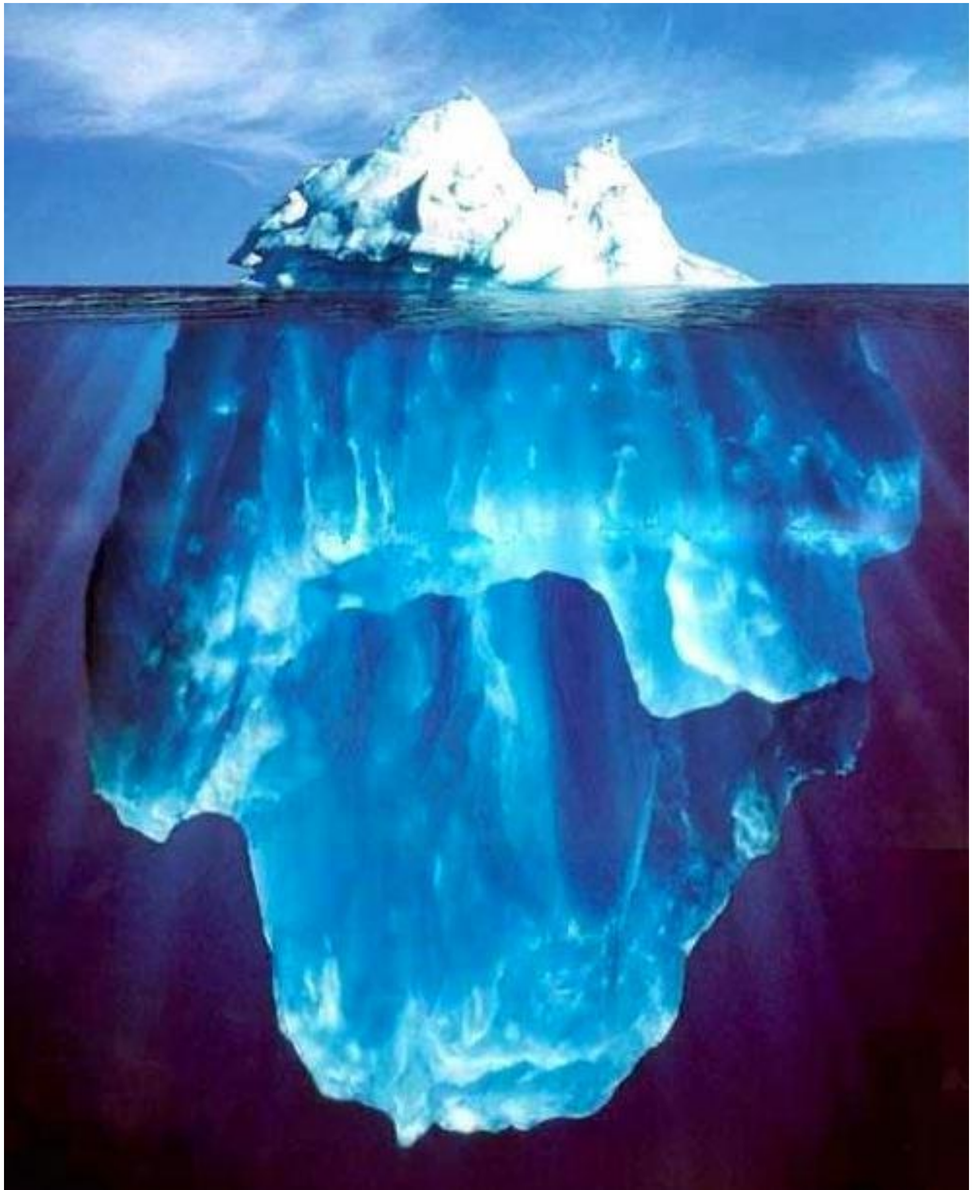
Ruimte voor planeet in bewoonbare zone?

Gliese 581 g: Superaarde in bewoonbare zone?

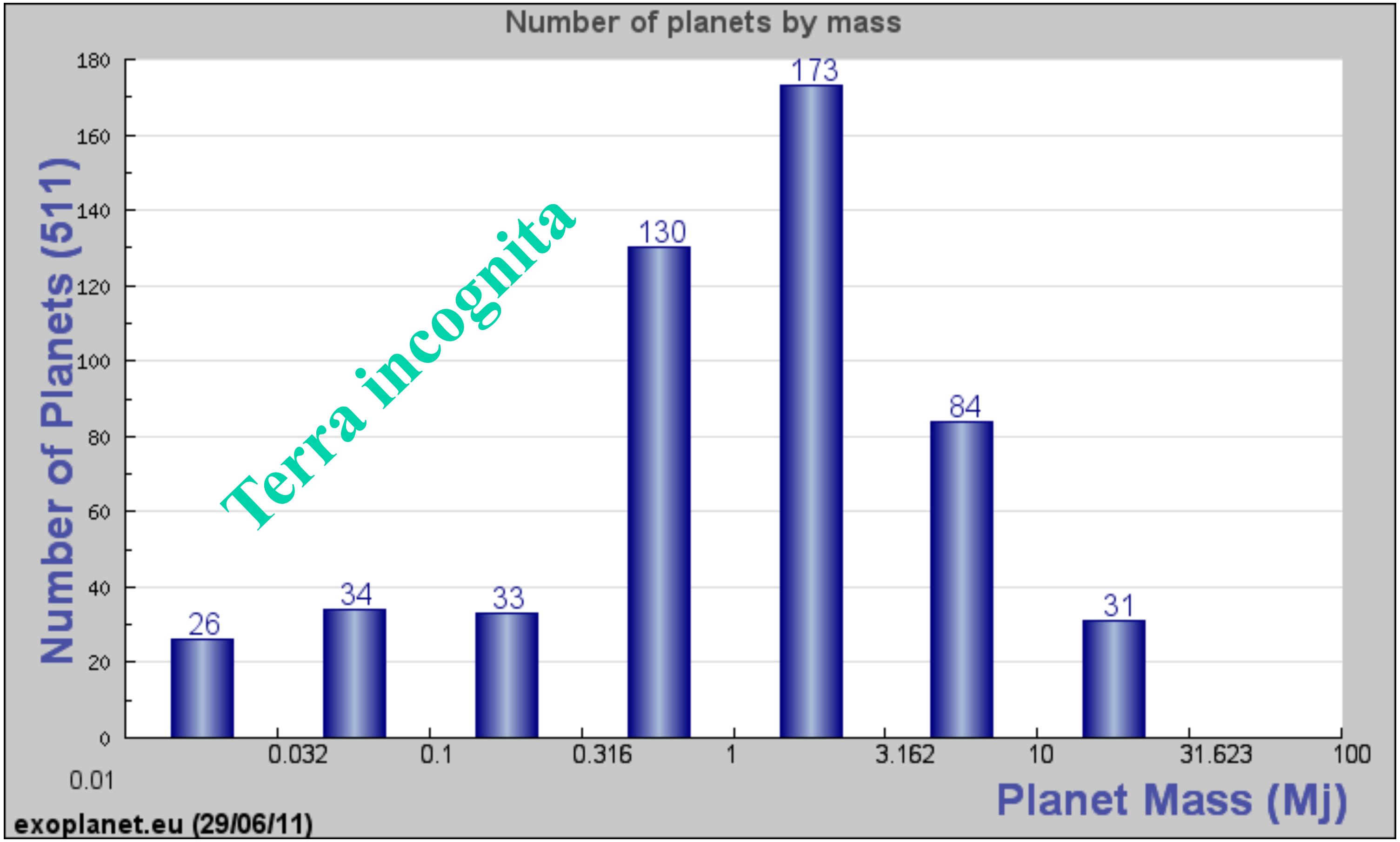


Controversieel: 3 aardmassa's

Topje van de ijsberg?



15 jaar doppler-methode:



Veel planeten zwaarder dan Jupiter

Mass distribution

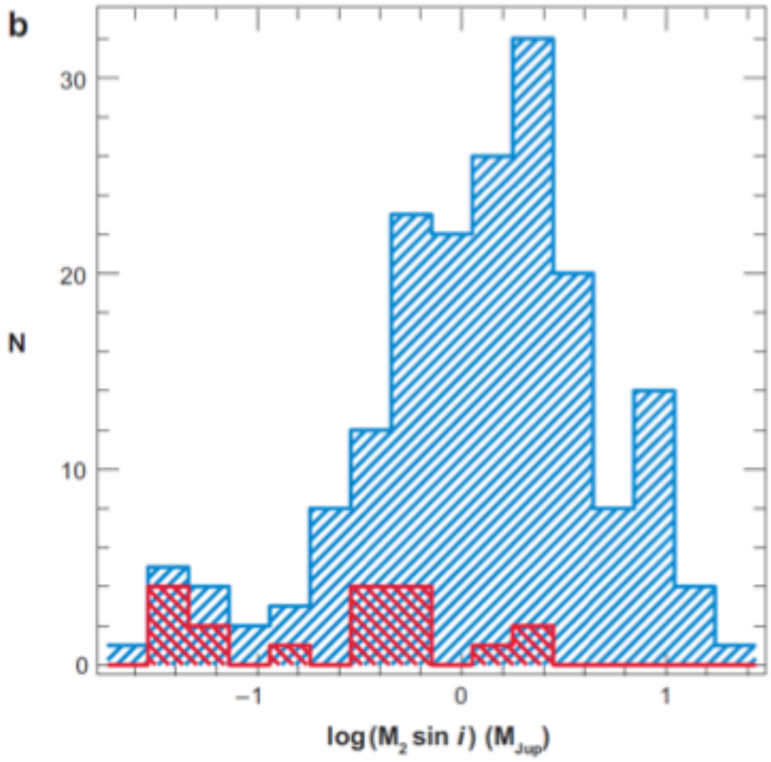
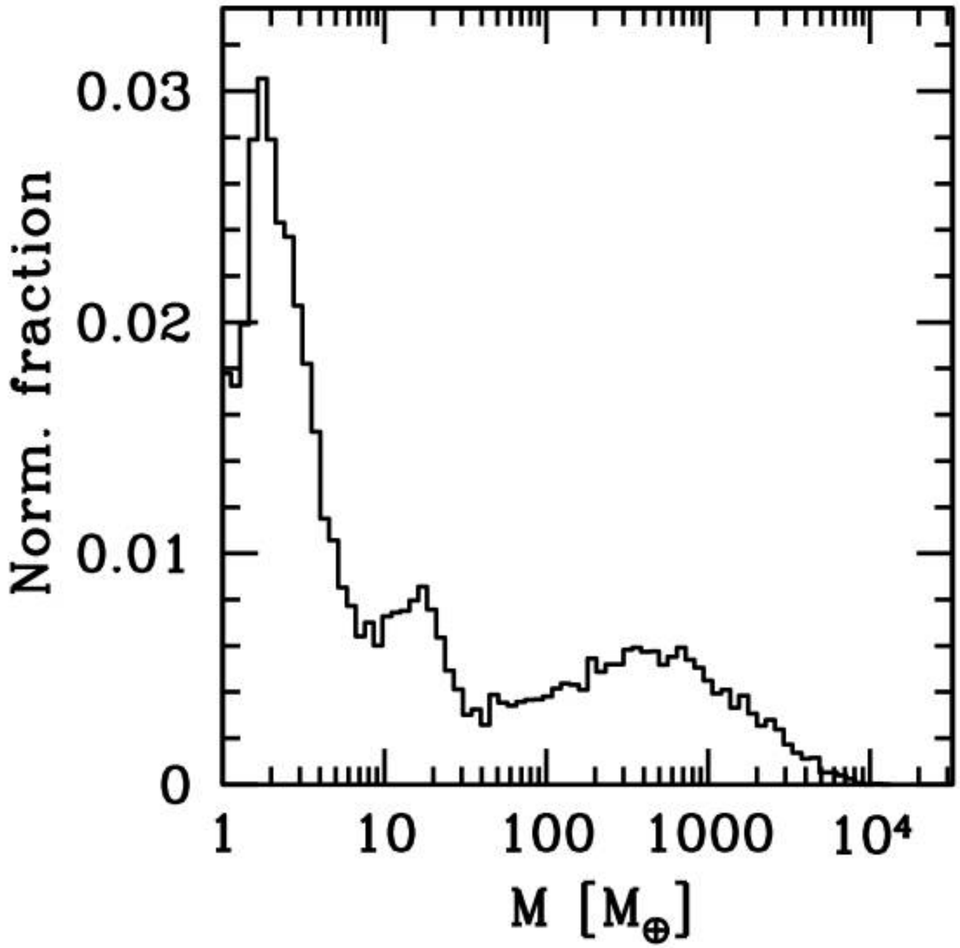


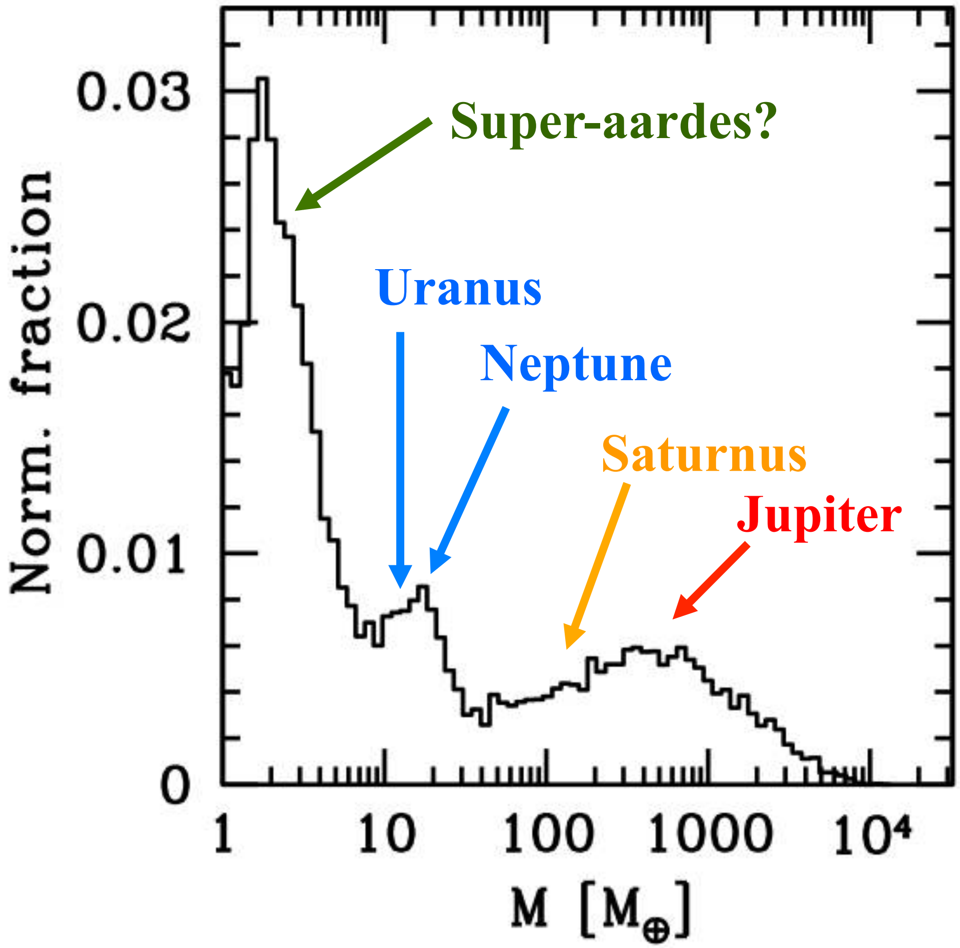
Figure: Number of planets vs log(Msin i), blue is data from Lick+Keck+AAT, red is HARPS data.

- Strong detection bias for planets below the mass of Saturn ($0.3M_{Jup}$)
- Smallest planet has $6M_\oplus$, and the smallest amplitude is 2.2m/s (at the moment 1m/s)
- Not many small-mass planets because of detection limit, however because many were found in a short time, they seem te be quite common. This also agrees with pulsartiming detections
- Neptune mass planets ($0.054M_{Jup}$) seem to have a distribution of their own, seperated at $0.1M_{Jup}$

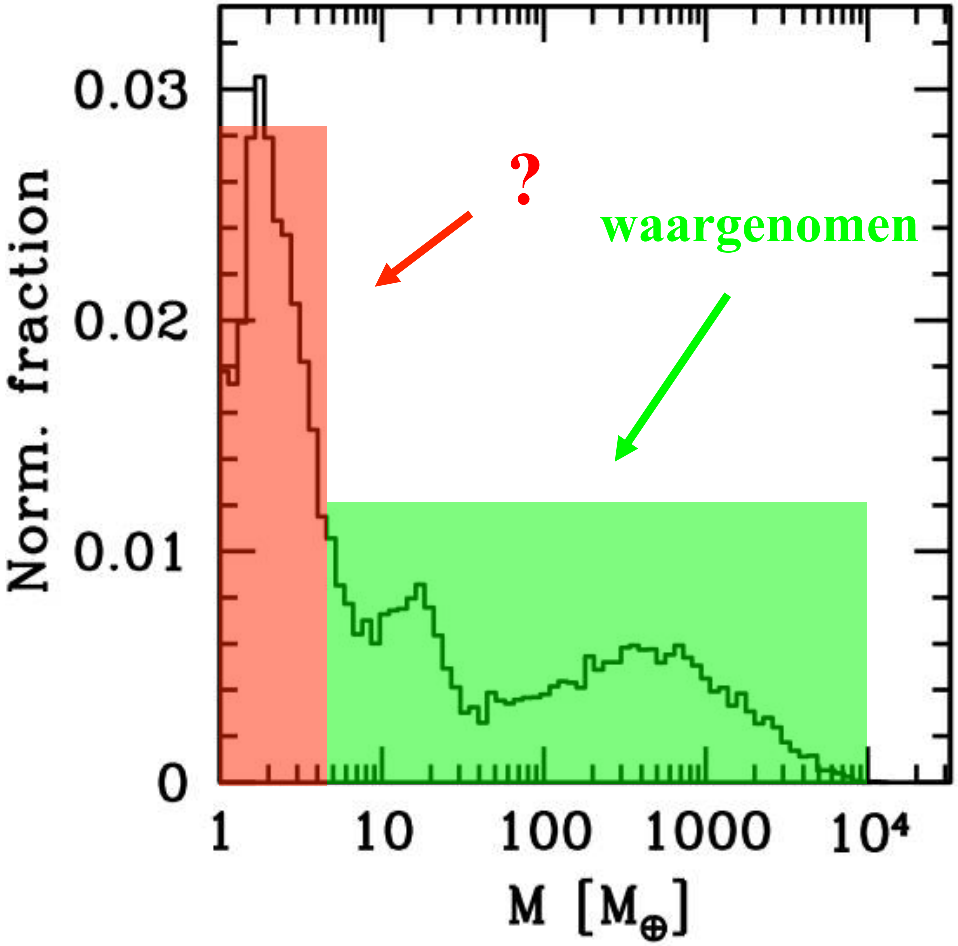
Welke planeten worden gevormd?



Klopt dit met ons zonnestelsel?

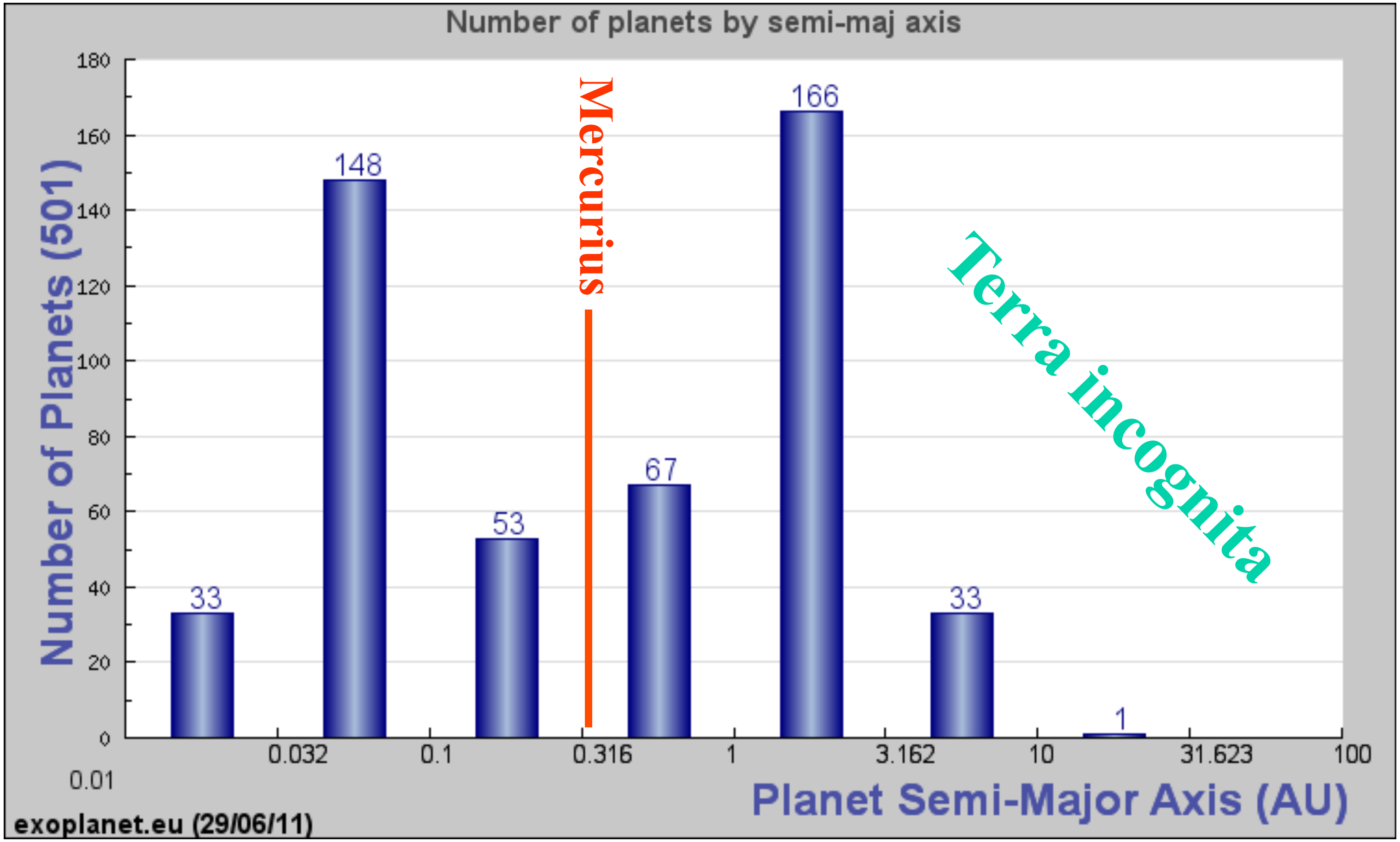


Klopt dit met exoplaneten?



Rond 70-80% van de sterren

15 jaar doppler-methode:



exoplanet.eu (29/06/11)

Nieuwe klasse: ‘hete Jupiters’

Orbital distribution

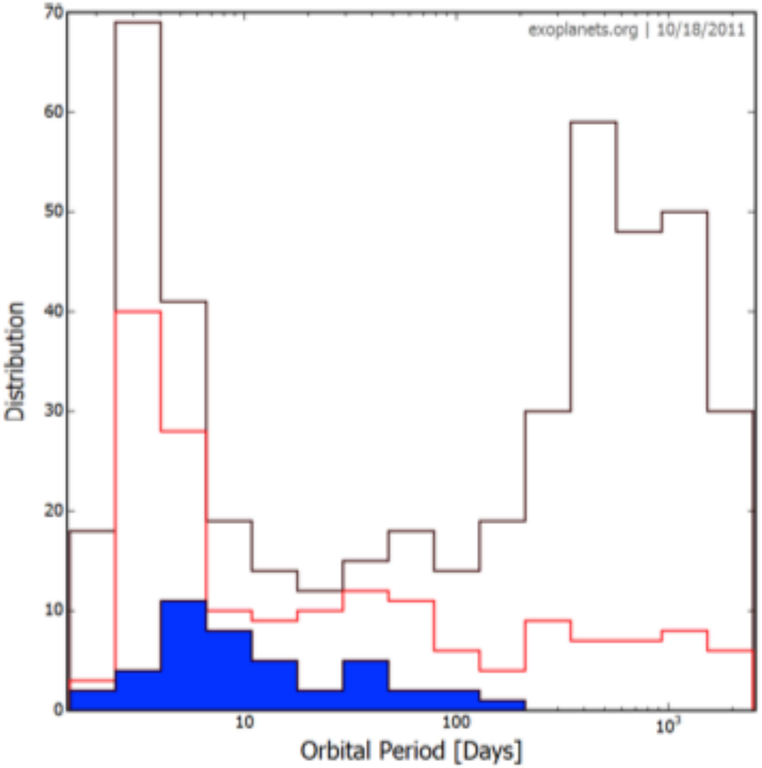
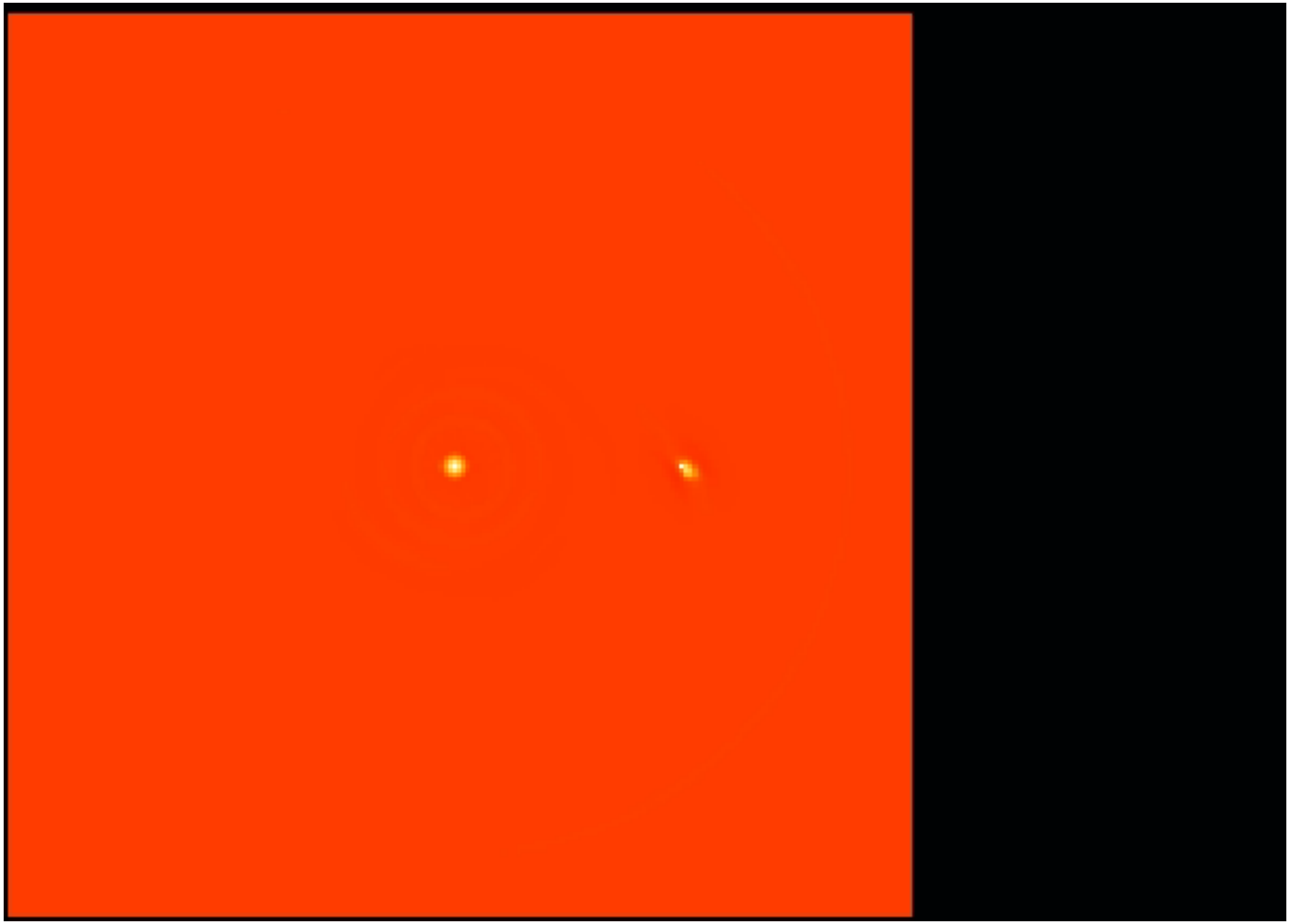


Figure: Open is distribution of gaseous giants, red is planets with mass below 0.75 M_{Jup}, and blue is the distribution of Neptune mass planets ($0.065 M_{Jup}$).

Neptune mass planets:

- Udry et. al. suggest a flat distribution towards 30 days, although only a few planets within this mass range have been found, and it is strongly biased because planets are near the detectionlimit.
- Current data from exoplanets.org suggest a peak at 3 days, but this could be due to detection bias.

Migrerende planeten



Msin *i* vs Period

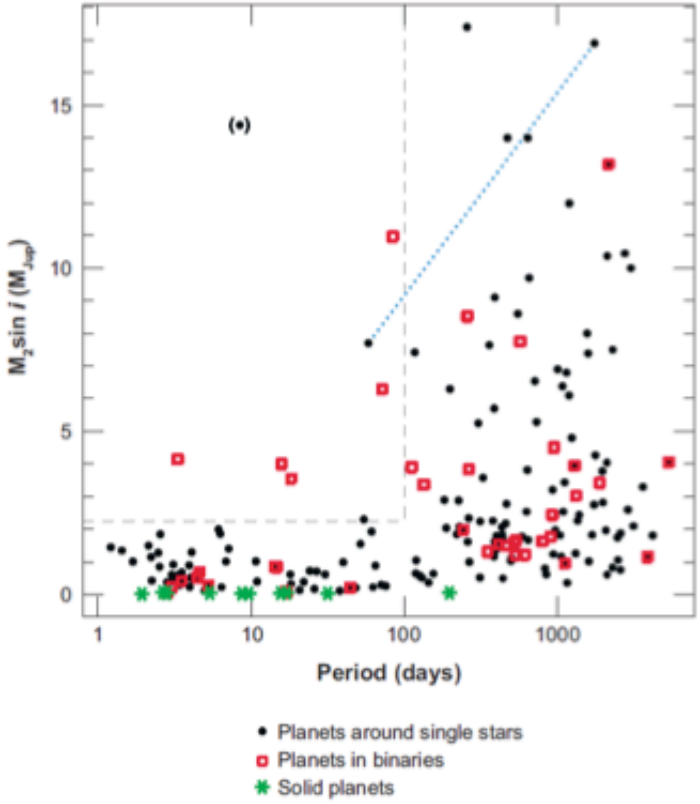
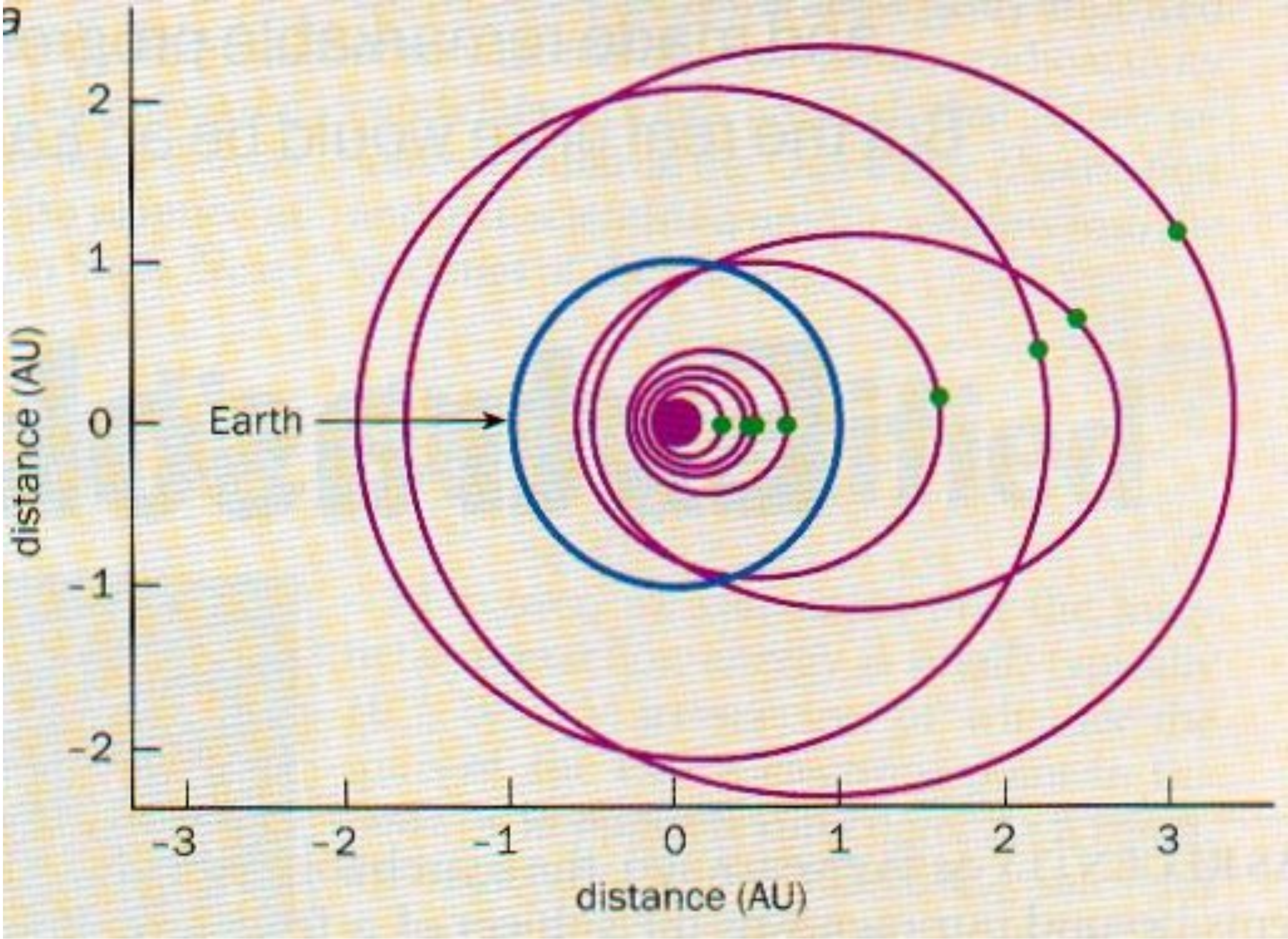


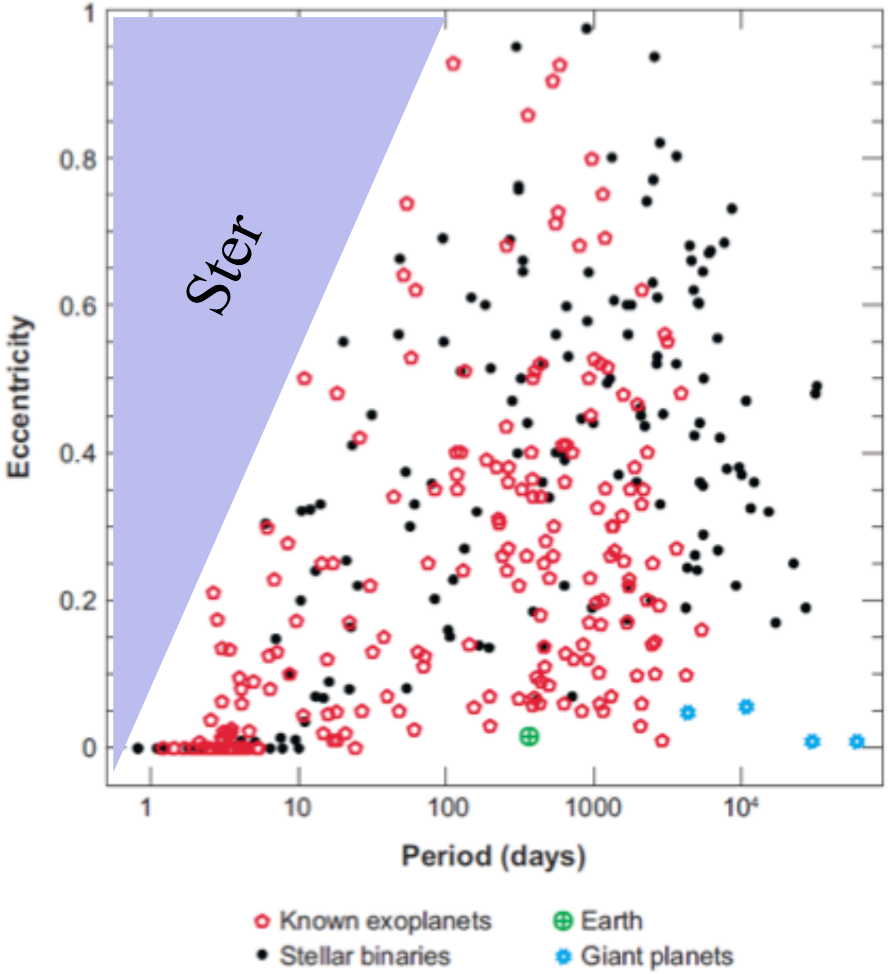
Figure: M sin i vs Period, dashed line both in the same systems, parenthesis indicate possible brown dwarf.

- Lack of heavy planets on short periods; despite the bias towards these planets. Could be that type 2 migration is less effective for heavy planets, or mass transfer shrinks heavy planets that are close to the star.
- Heavy planets need more mass that's just not available close to the star. Heavy stars are harder to dislodge from their formation site.
- Low mass planets far away are just to hard to detect.



Earth's orbit compared to several extrasolar planetary orbits.

Eccentricity vs Period



N vs [Fe/H]

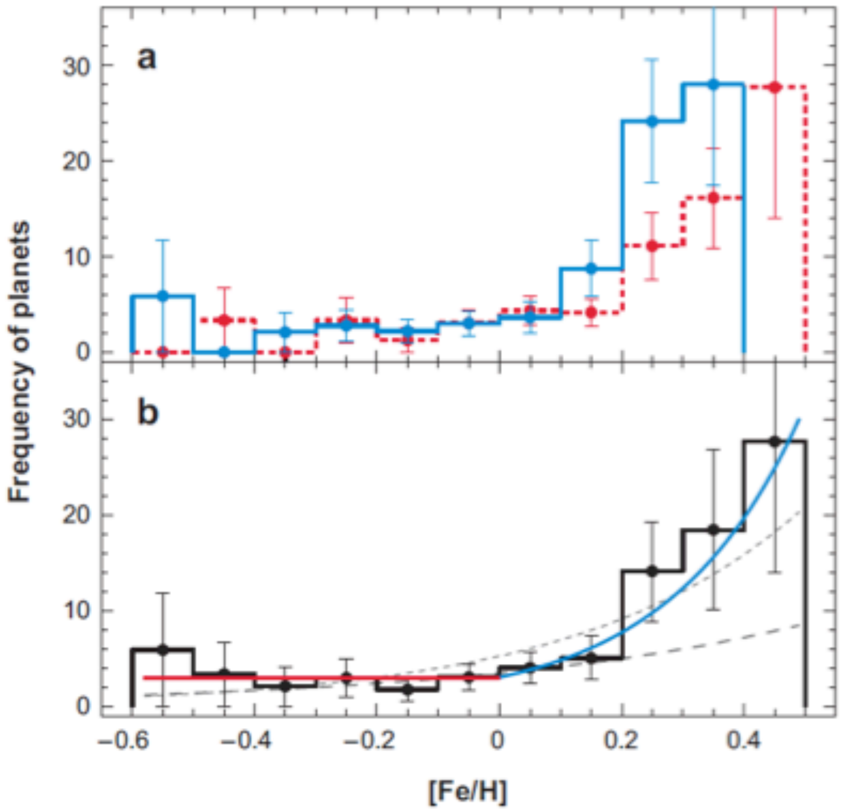


Figure: upper panel: CORALIE (blue) and Lick-Keck (red). Lower panel: average of both, blue line is a fit: freq$=3.01 \times 10^{2.04[Fe/H]}$

- Planet formation occurs more often in high metallicity stars, but it is still possible to form giant planets near low-metallicity stars.
- External origin; planetformation pollutes the star, however this requires a large amount of metals.
- Interstellar origin; the cloud which formed the star was also metall rich, and makes the formation of planets easier.
- High metallicity favors Core-accretion model; more dust means it's easier to build metal cores. However it is unkown how gas-to-dust ratio, timescales and other processes are affected by high metallicity content.

Systemen met meer dan een planeet

- Resonanties belangrijk?

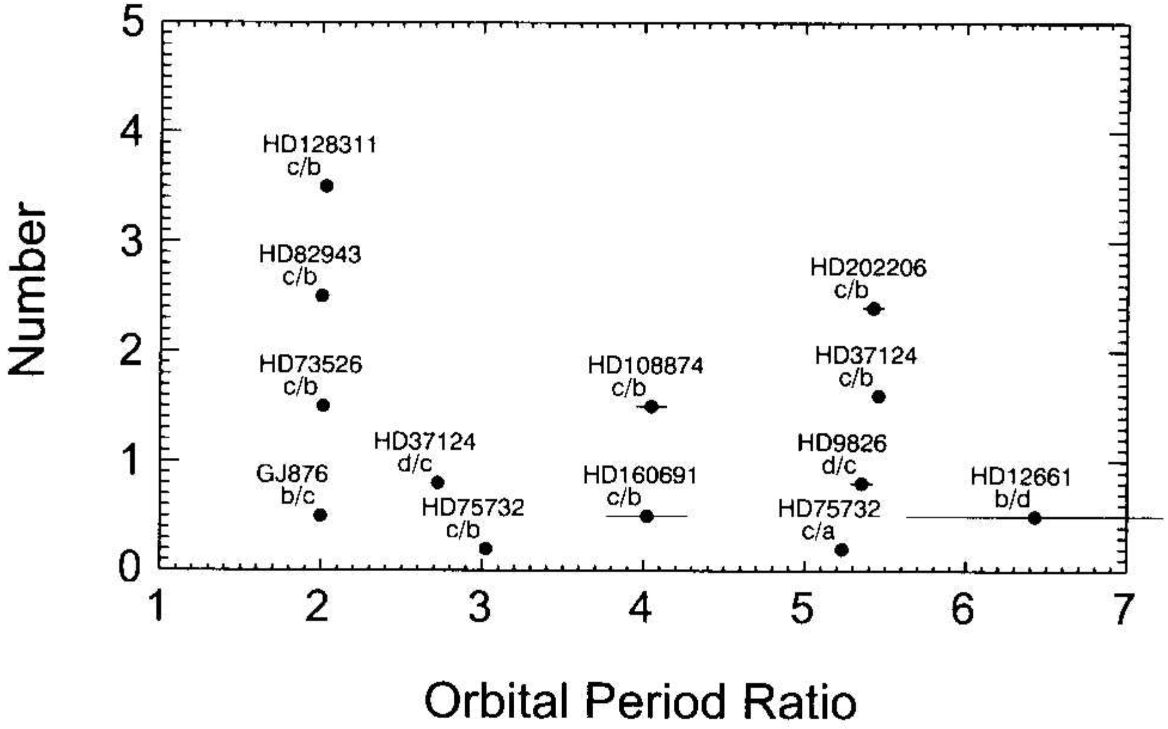


Fig. 9. The ratio of longer to shorter orbital periods is shown for multiplanet systems in Table 2. Uncertainties in the orbital periods are propagated as error bars in the period ratio. The low-order MMR at 2:1 appears to be quite narrow with 2 ± 0.01:1. Four of the 18 systems (including uncovered periods) reside in a 2:1 resonance.

Conclusie

- Radial velocity vind veel planeten (700+)
- Goede spectrograaf (HARPS)
- Dopplereffect: meet radiele snelheid
- Indirect: massa en periode
- Hete Jupiters, ook superaardes
- Veel planeten lijken niet op zonnestelsel!
- Toekomst: aardachtige planeten

Planet density

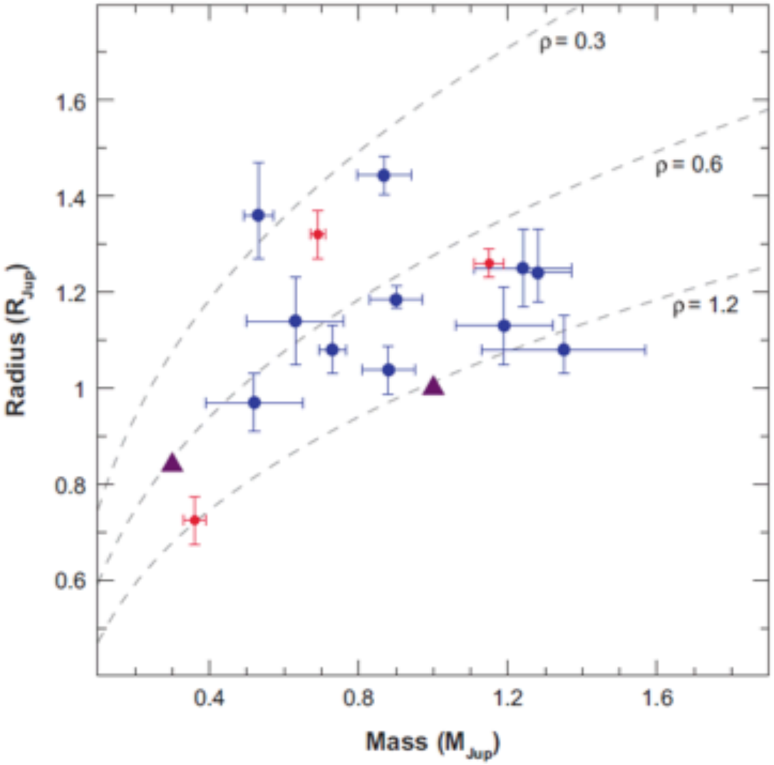


Figure: Red are planets discovered using RV, blue are planets discoverd by transit method, purple are Saturn and Jupiter.

- Very low densities, up the a third of the Jupiter density.
- However many transiting planets are very close to the star.