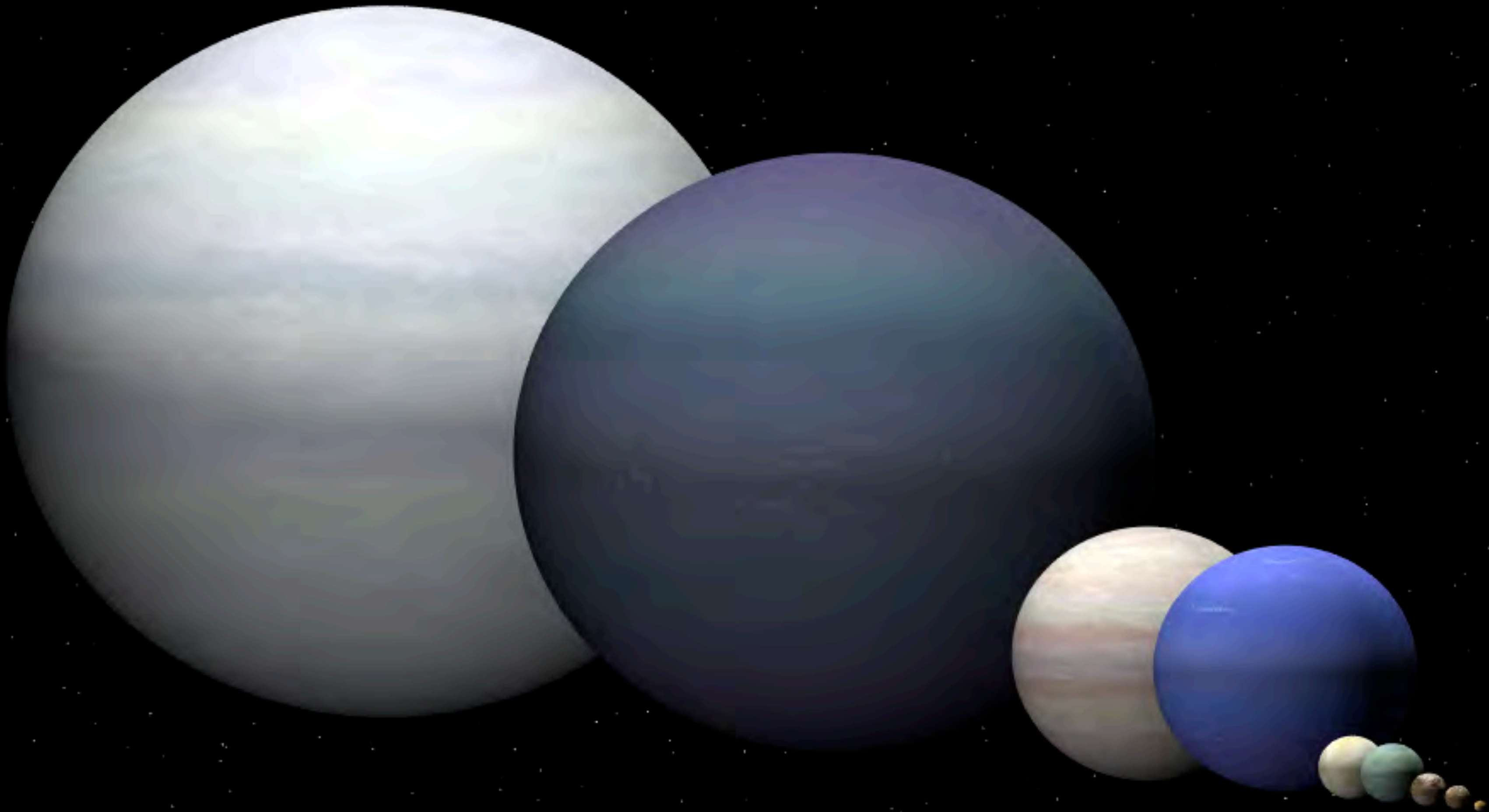


Planets and Exoplanets

Exoplanet Detections

Outline

1. Introduction
2. Radial velocity
3. Transits
4. Microlensing
5. Imaging
6. Astrometry
7. Comparison

What is a Planet?

	Jupiter	Brown Dwarf	Sun
Solar Diameters	0.1	0.2	1
Jupiter Masses	1	55	1000
Convection	partial	full	outer 30%
Fusion	none	deuterium	hydrogen

Planet Definition

- Object with mass too small for fusion of deuterium (~13 Jupiter masses) that orbits star or stellar remnant
- Same minimum mass/size requirement for exoplanets and solar system planets
- Free-floating objects below 13 Jupiter masses are not planets

Detection vs. Observationzation

Detection:

- Detect presence of exoplanet around a star
- Determine mass to distinguish from brown dwarfs
- Determine orbit around star

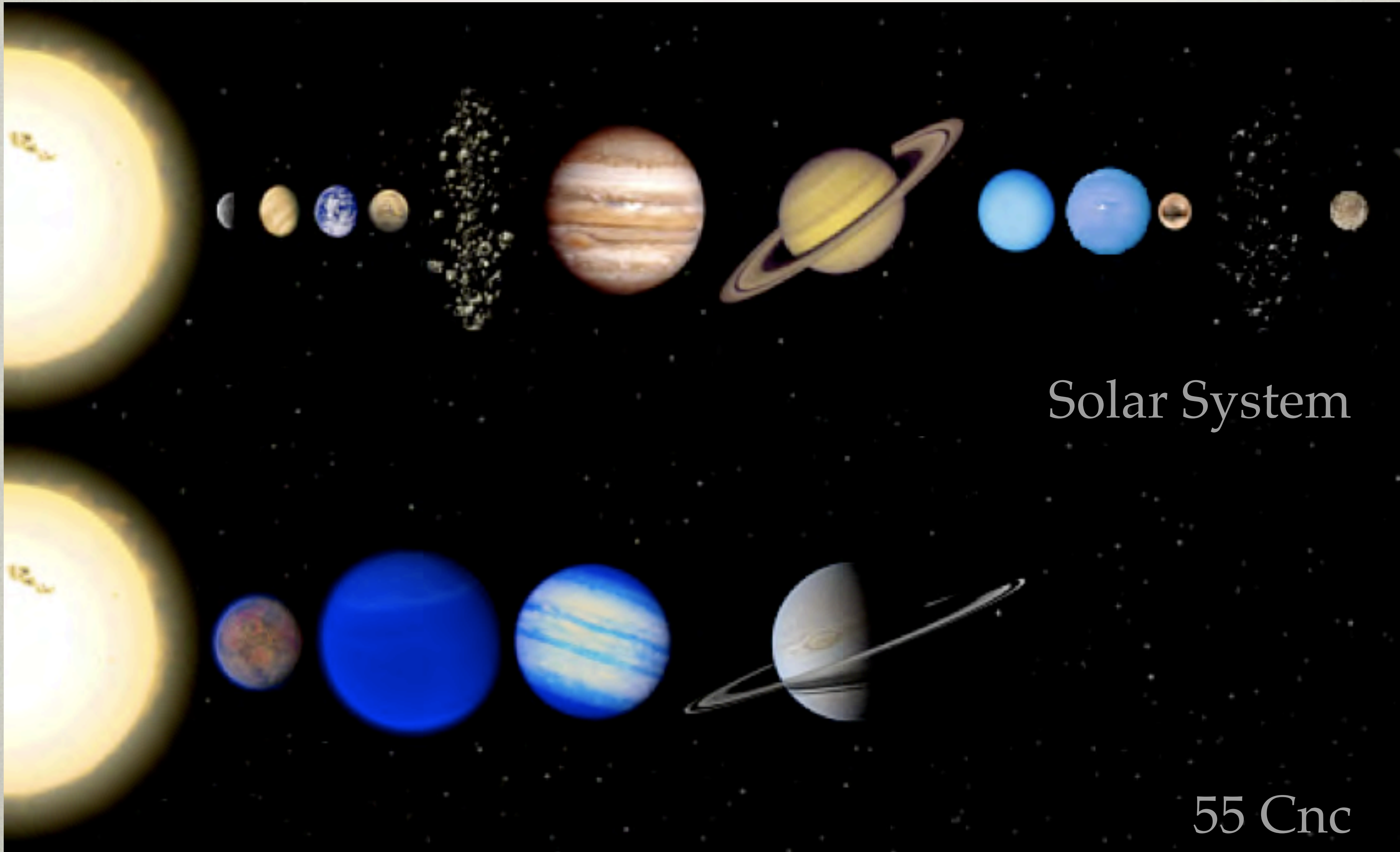
Observation (Characterization):

- Determine radius
- Determine surface properties
- Determine atmosphere properties

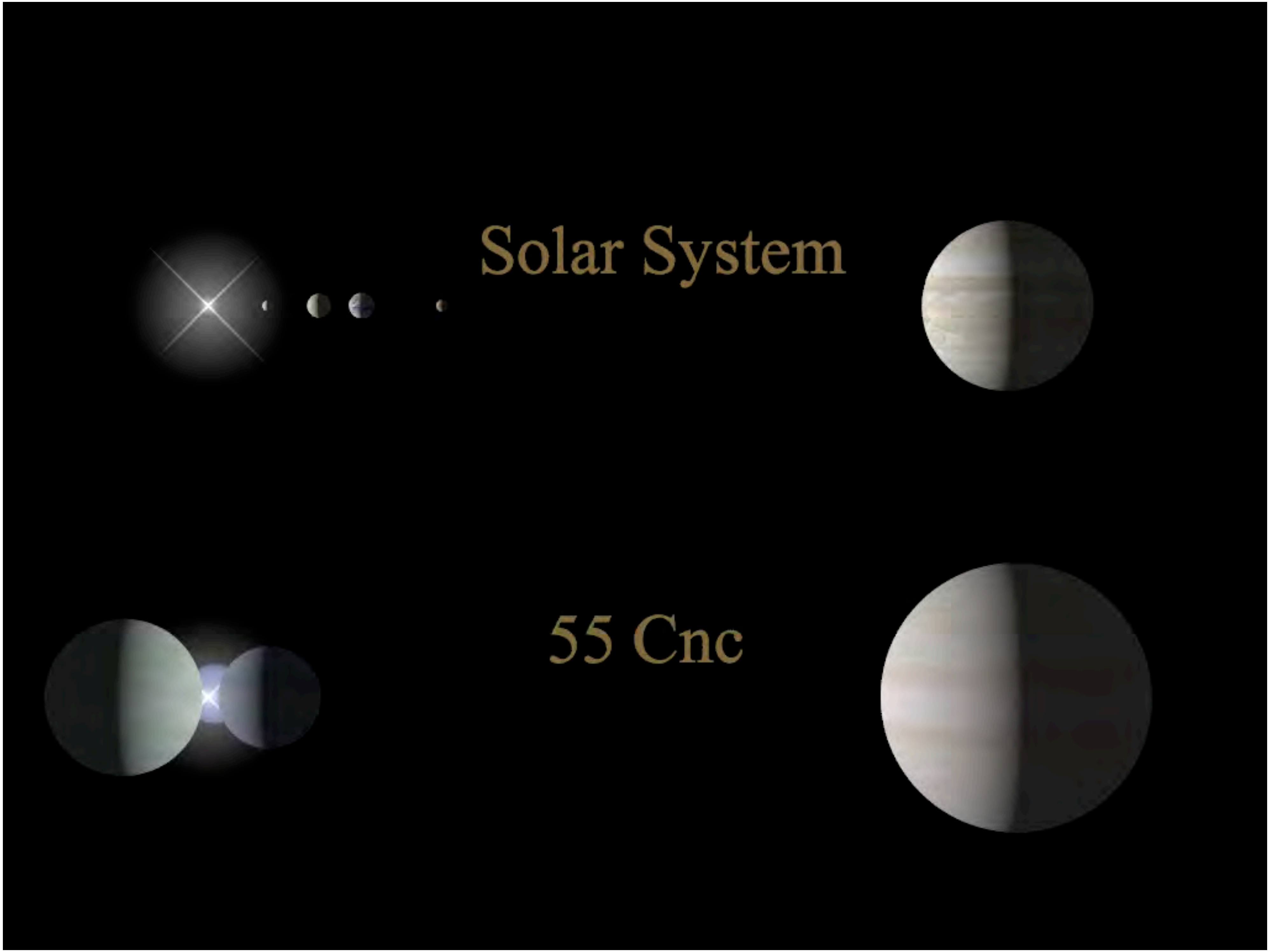
Exoplanetary Systems

- Past and Present: Detection -> Discovery
  - Detecting planetary systems
  - Limited information: orbit, lower limit for mass, evidence for disks, images of outer disks
- The Future: Observation -> Understanding
  - Characterizing extrasolar planetary systems
  - Detailed information: images of inner disks and planets, mass, atmospheres, surfaces, comets
  - Test theories and numerical models
  - Understand formation and evolution of planetary systems

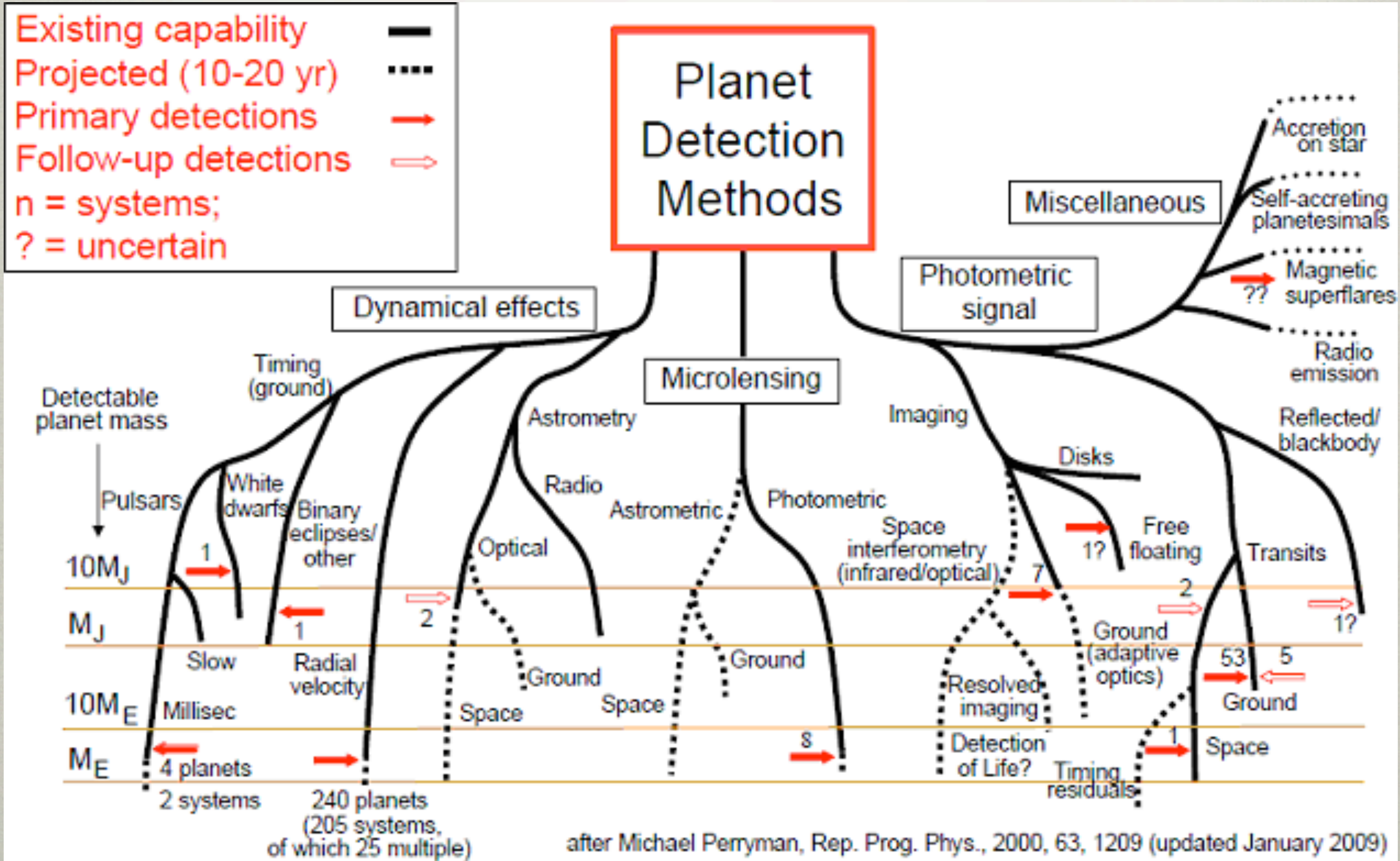
Solar vs. Exoplanetary Systems

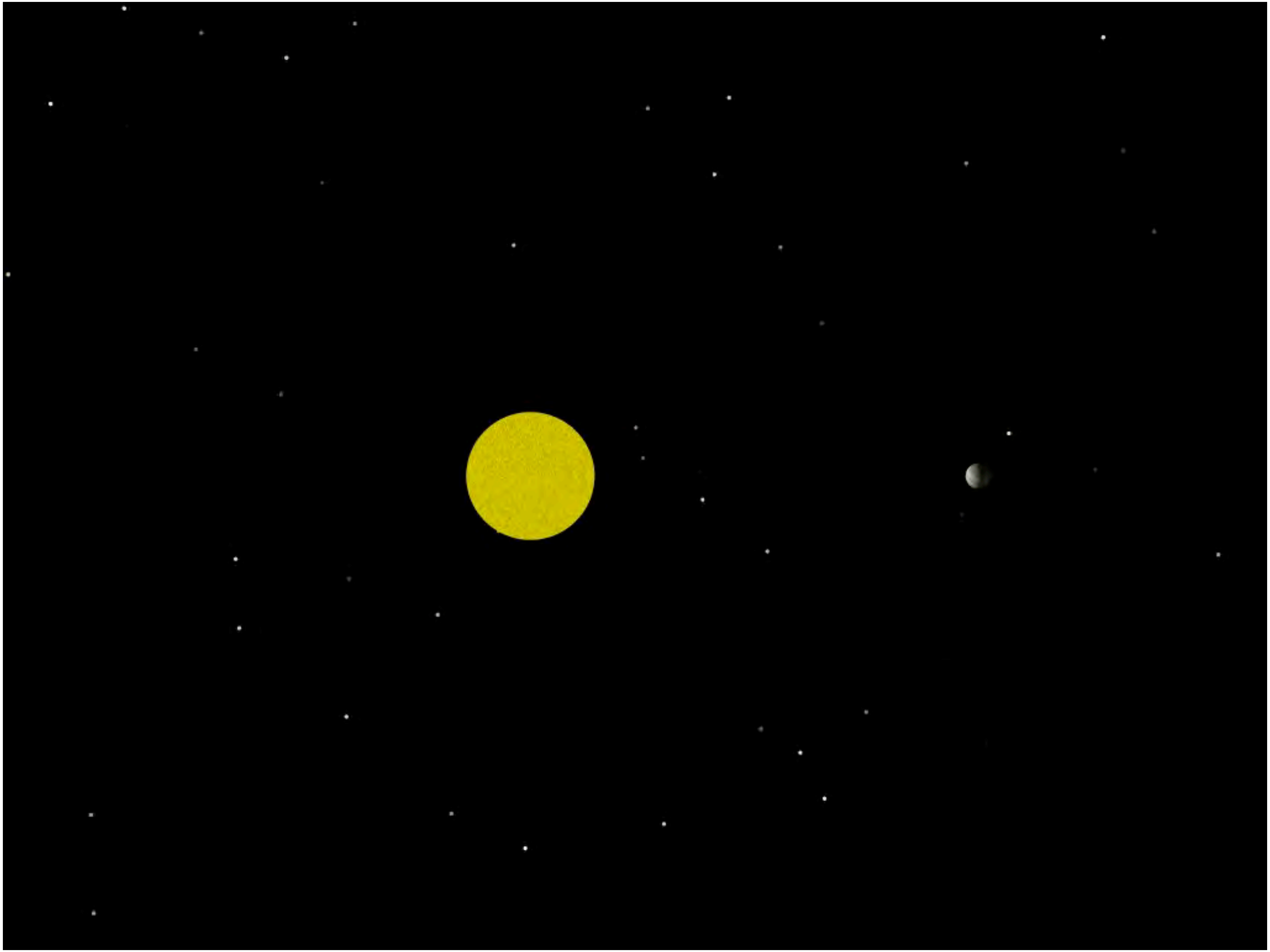


http://www.extrasolar.net/mostinteresting.asp

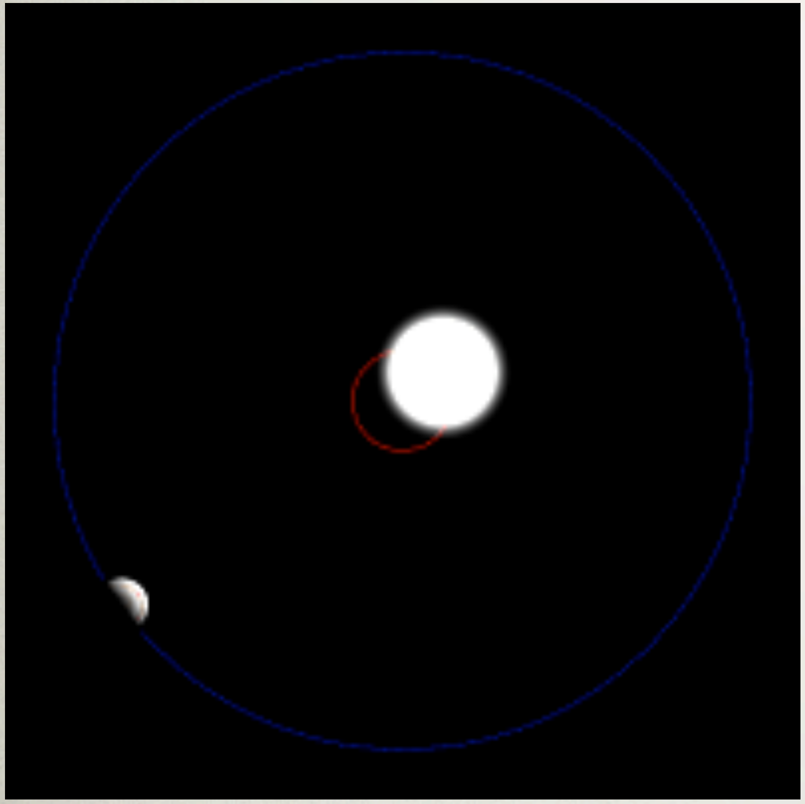

Solar System
55 Cnc

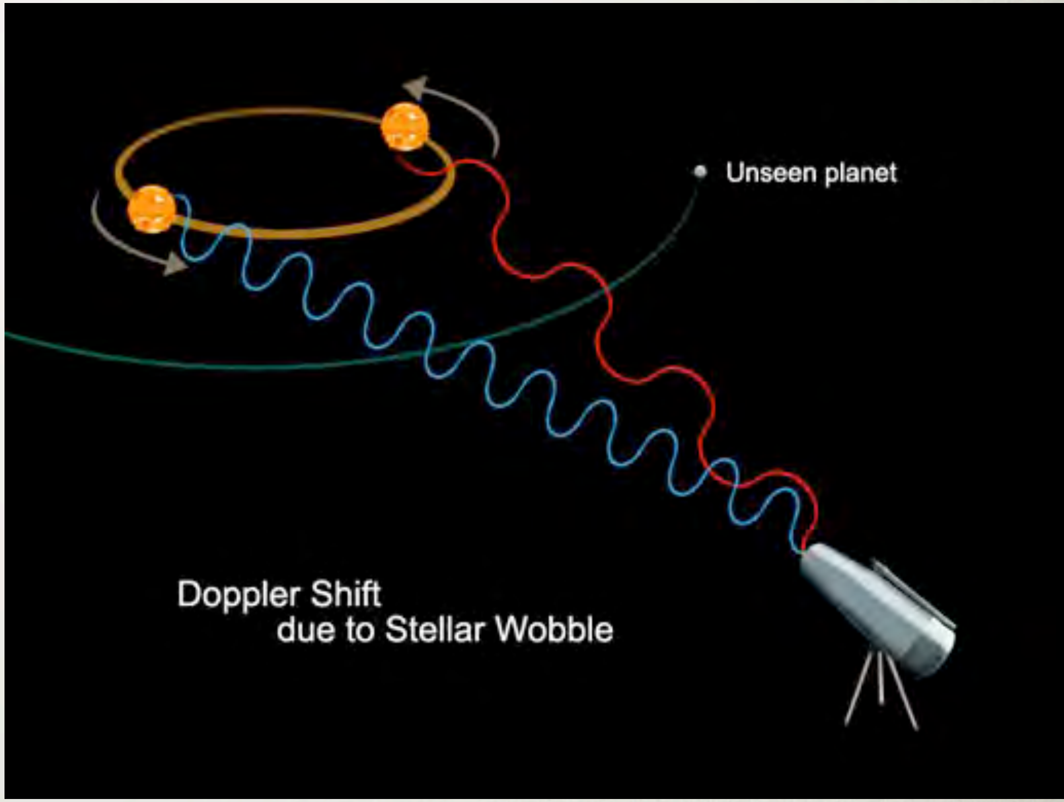
Exoplanet Detection Methods





Radial Velocity





en.wikipedia.org/wiki/Extrasolar_planet

- Star, planet move around common center of mass
- Doppler effect: $\frac{\delta\lambda}{\lambda} = \frac{v}{c}$
- Look for periodic variations in stellar velocity

Radial Velocity Signal

Semi-amplitude of radial velocity given by

$$K = \left(\frac{2\pi G}{P_{\text{orb}}}\right)^{\frac{1}{3}} \frac{M_P \sin i}{(M_* + M_P)^{\frac{2}{3}}} \frac{1}{\sqrt{1-e^2}}$$

- P_{orb}: orbital period
- M_*: mass of star
- M_P: mass of planet
- i: inclination, angle between normal to orbital plane and line of sight
- e: excentricity

Radial Velocity Signal

For circular orbits with $M_P << M_*$ in meter/second:

$$v_{\mathrm{obs}} = 28.4 \frac{M_P \sin i}{P_{\mathrm{orb}}^{1/3} M_*^{2/3}}$$

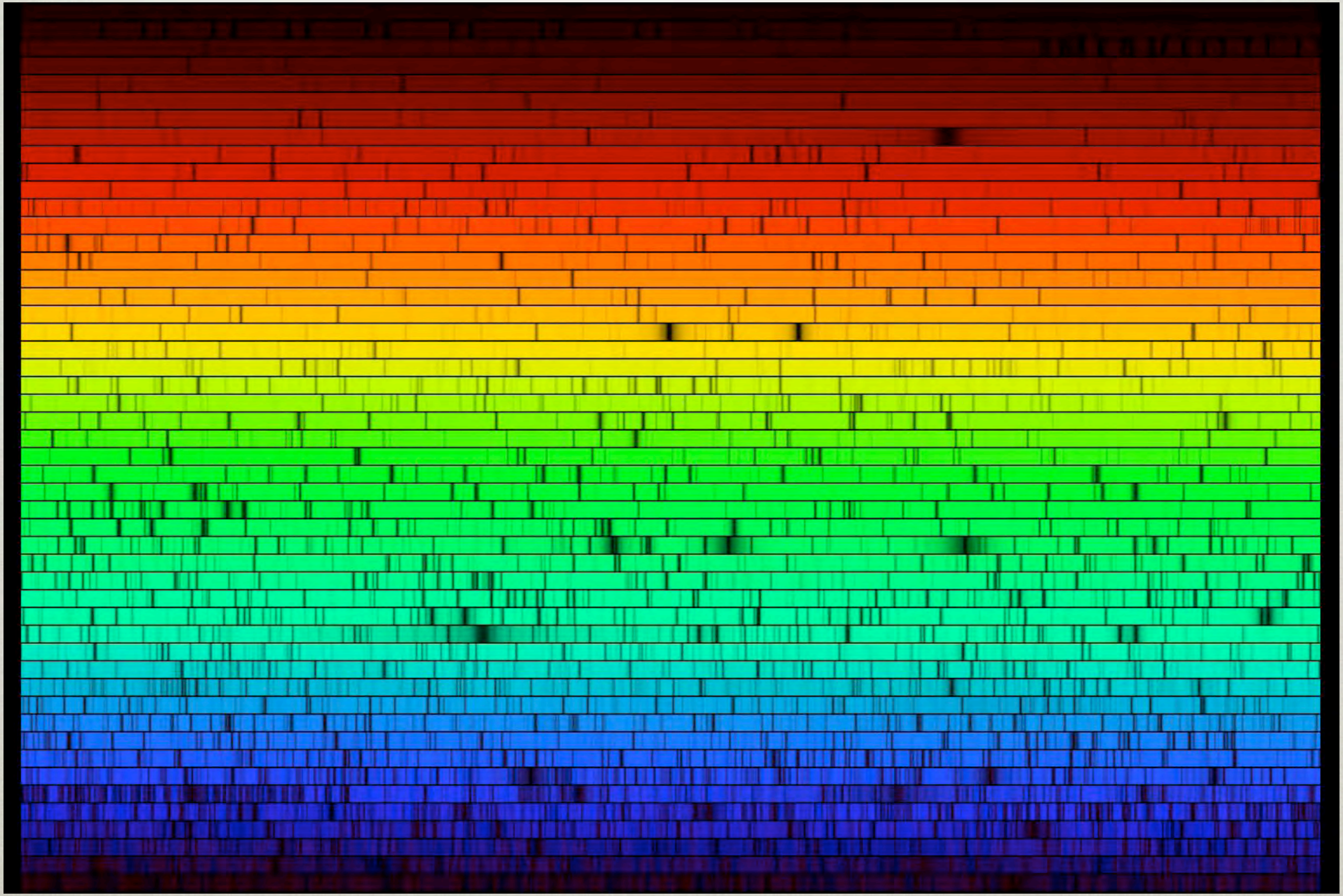
- M_P in Jupiter masses
- P_{orb} in years
- M_* in solar masses

Radial Velocity Signal Amplitude

$$K = \left(\frac{2\pi G}{P_{\mathrm{orb}}}\right)^{\frac{1}{3}} \frac{M_P \sin i}{(M_* + M_P)^{\frac{2}{3}}} \frac{1}{\sqrt{1-e^2}}$$

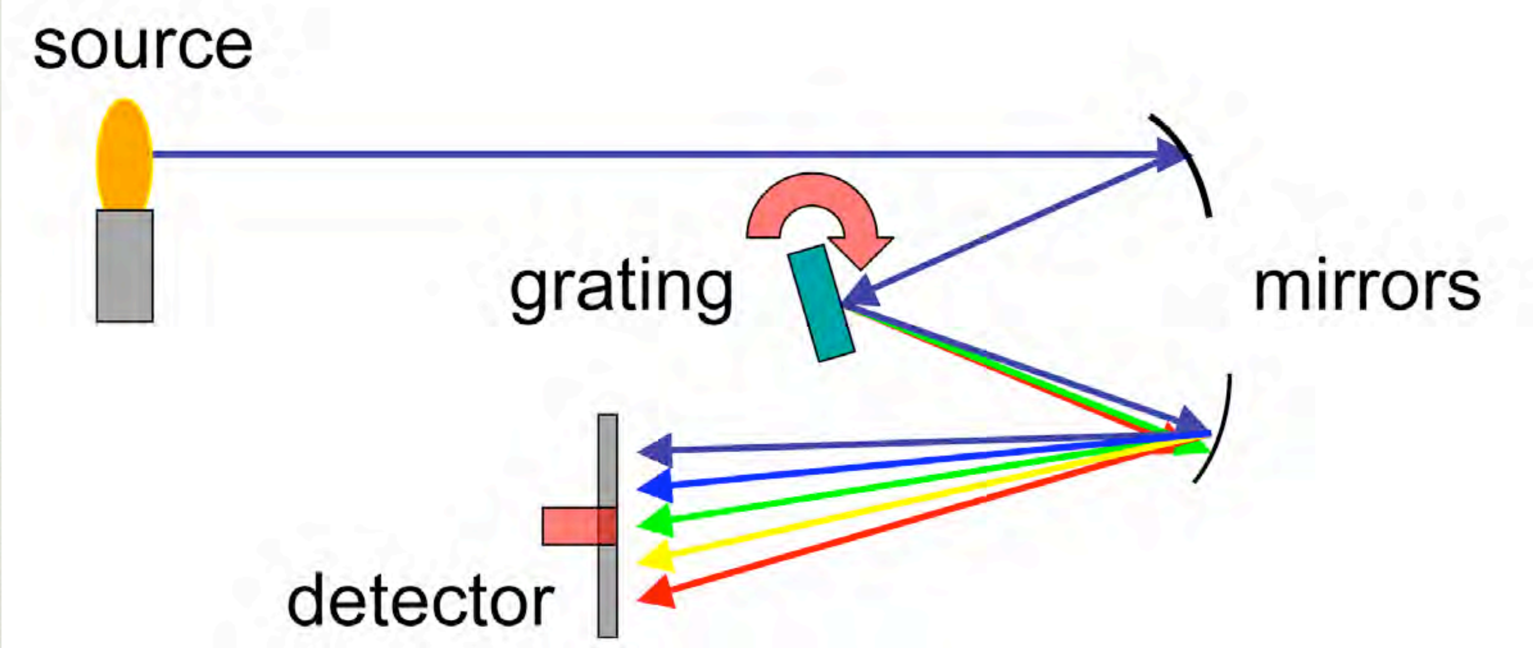
- Observe: period, velocity amplitude and shape
- Stellar mass unknown, but good estimate from stellar spectrum
- Jupiter: 12.4 m/s maximum velocity
- Saturn: 2.8 m/s
- Earth: 9 cm/s
- Heavier stars reduce the signal
- Lighter stars increase the signal

Solar Spectrum



www.noao.edu/image_gallery/images/d5/suny.jpg

Spectrometer



en.wikipedia.org/wiki/Extrasolar_planet

- Wavelength cannot be measured directly
- Spectrograph transforms wavelength into position information
- Must measure spatial location of spectral lines

Positional Stability Requirement

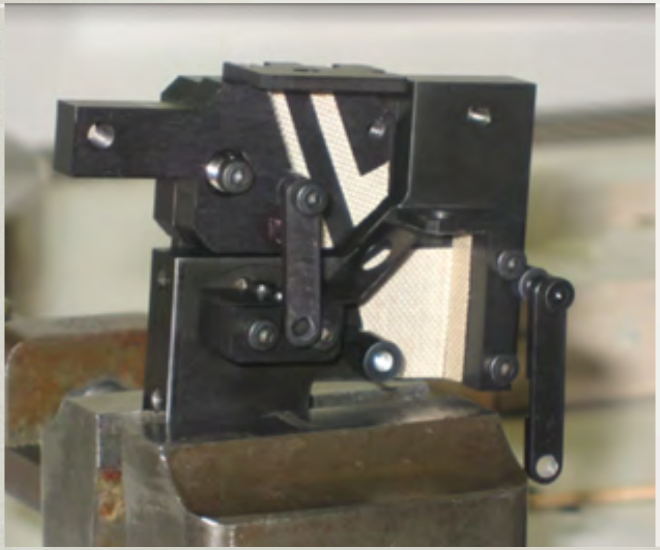
- Visible spectrum: ~ 500 nm
- Typical high-resolution spectrograph: 0.005 nm per camera pixel
- One pixel in velocity: $3*10^8$m/s/10^5 = 3000 m/s
- Typical CCD camera pixel size: 15 μm
- 1 m/s is 15000/3000 nm = 5 nm
- Need to keep this stability over years
- 1-meter aluminum bar expands 24 μm per deg C

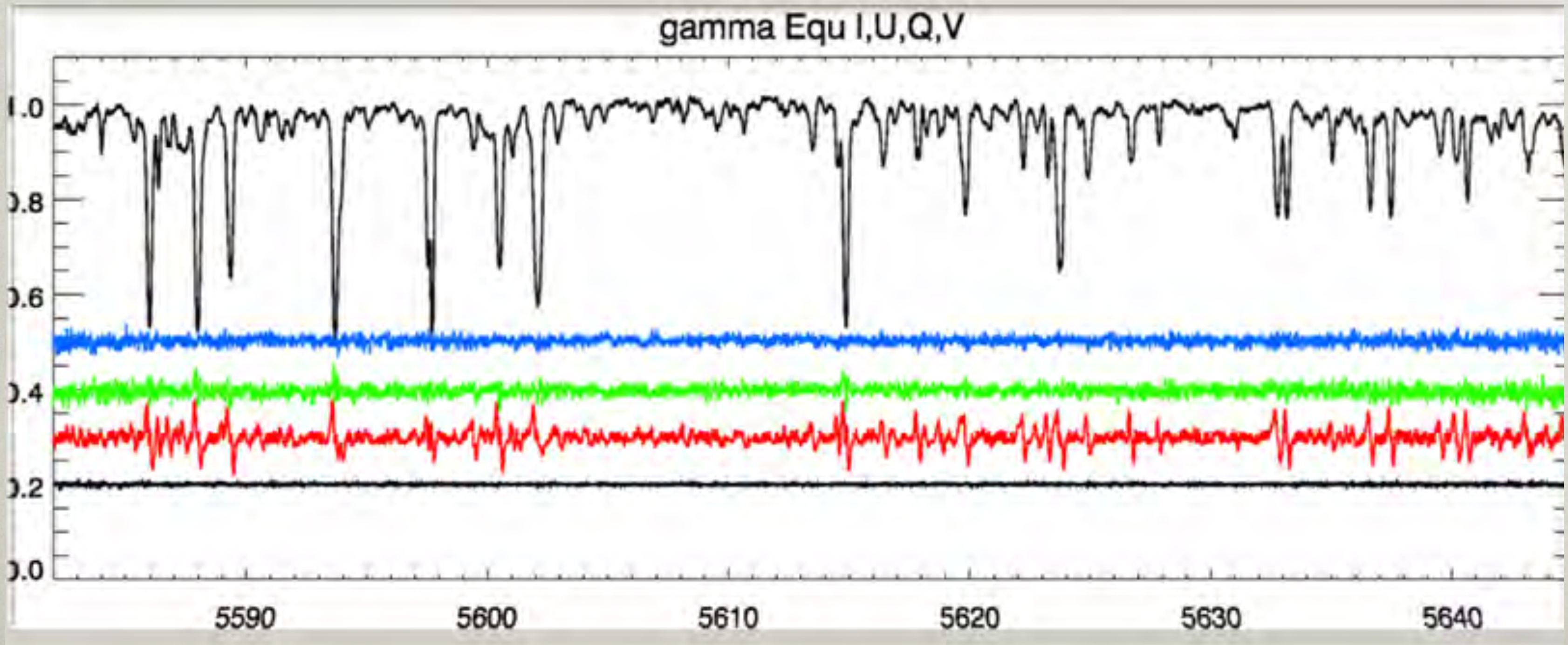
HARPS

obswww.unige.ch/Instruments/Harps/gallery/Integration_LSO/

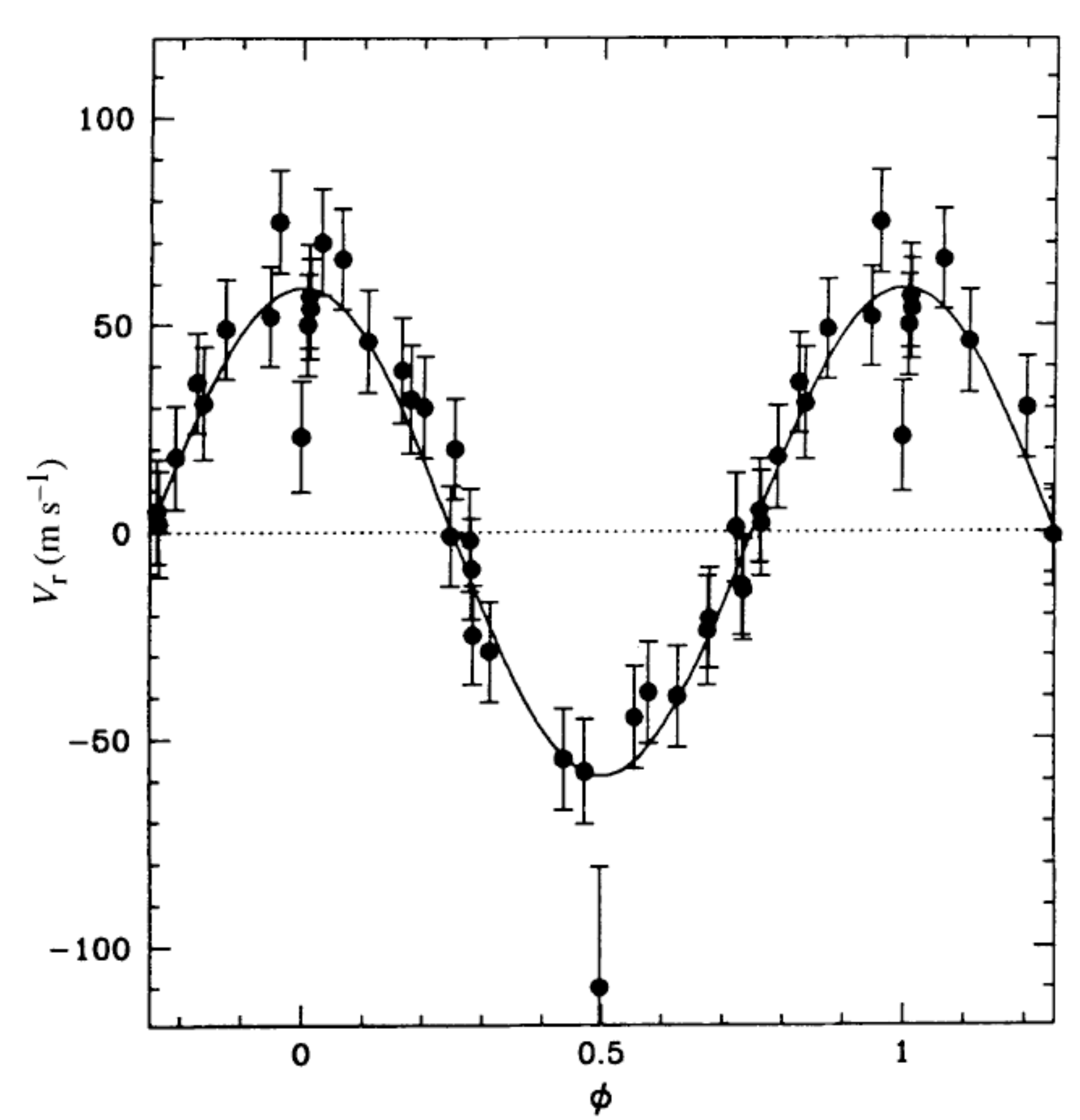
- Velocity noise 0.7 - 2 m/s over many years
- Thorium-Argon calibration source simultaneous with stellar spectrum

HARPS Polarimeter



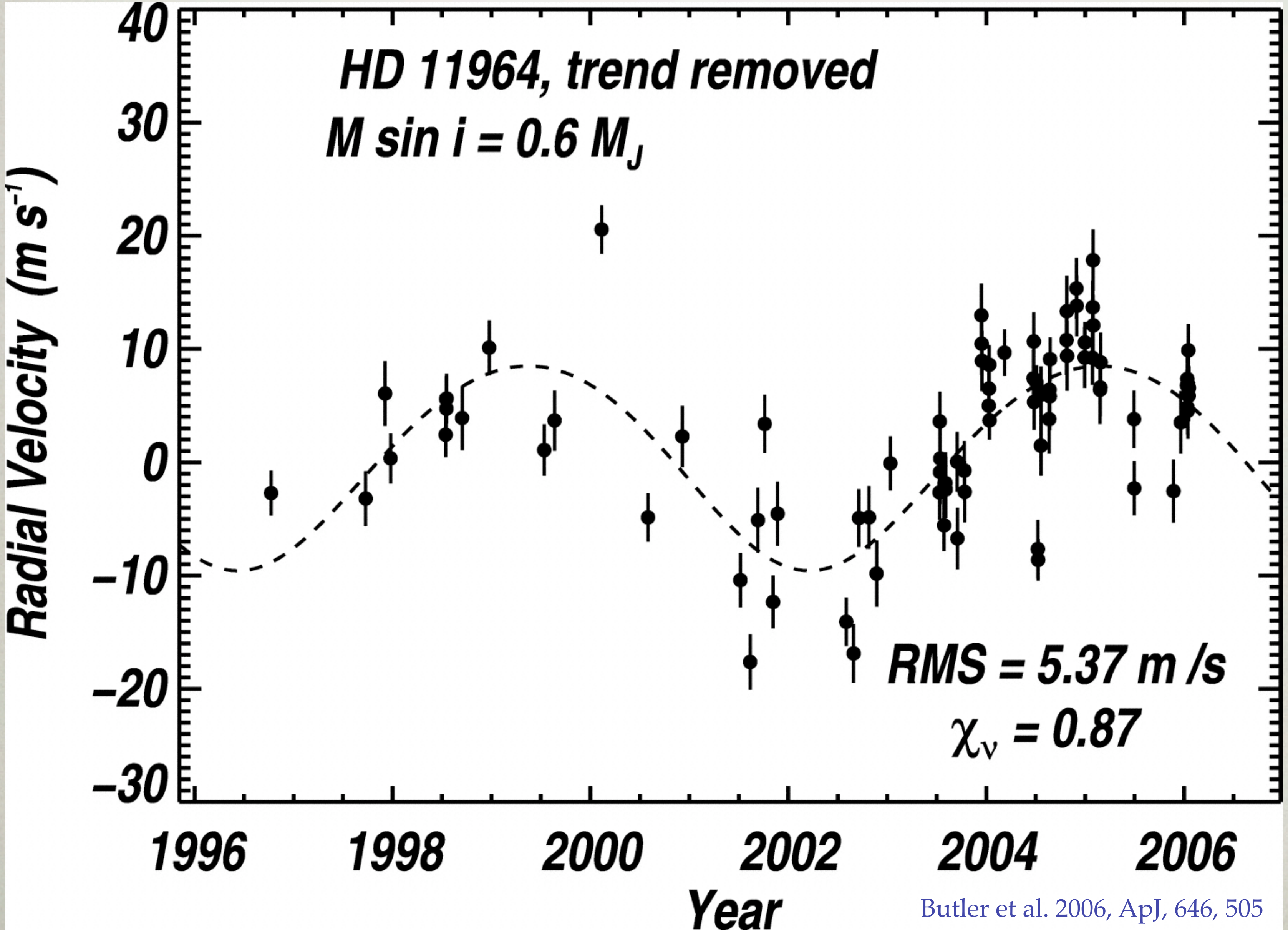


Example 1: 51 Pegasi b



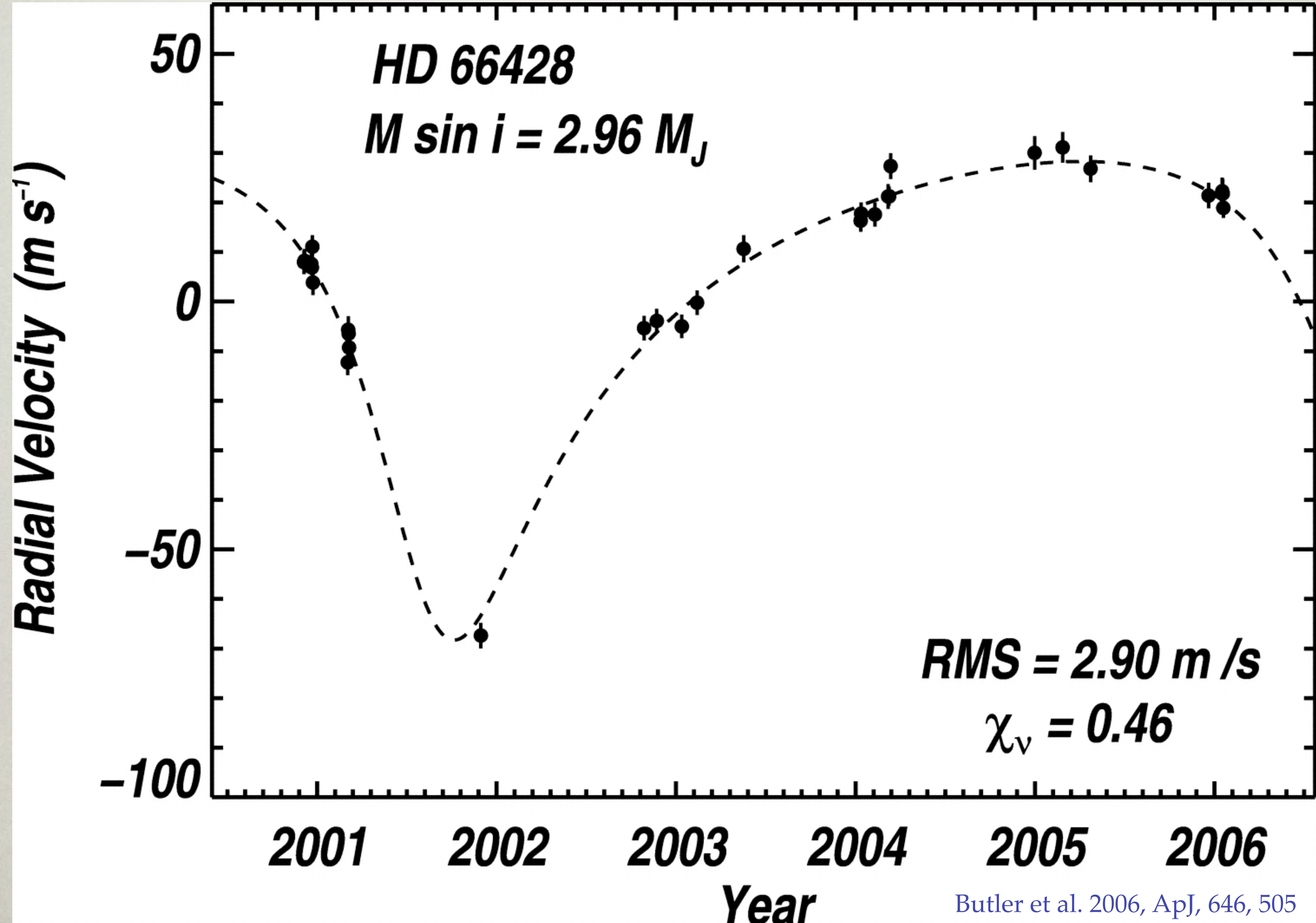
Mayor and Queloz 1995 Figure 4

Example 2: e=0



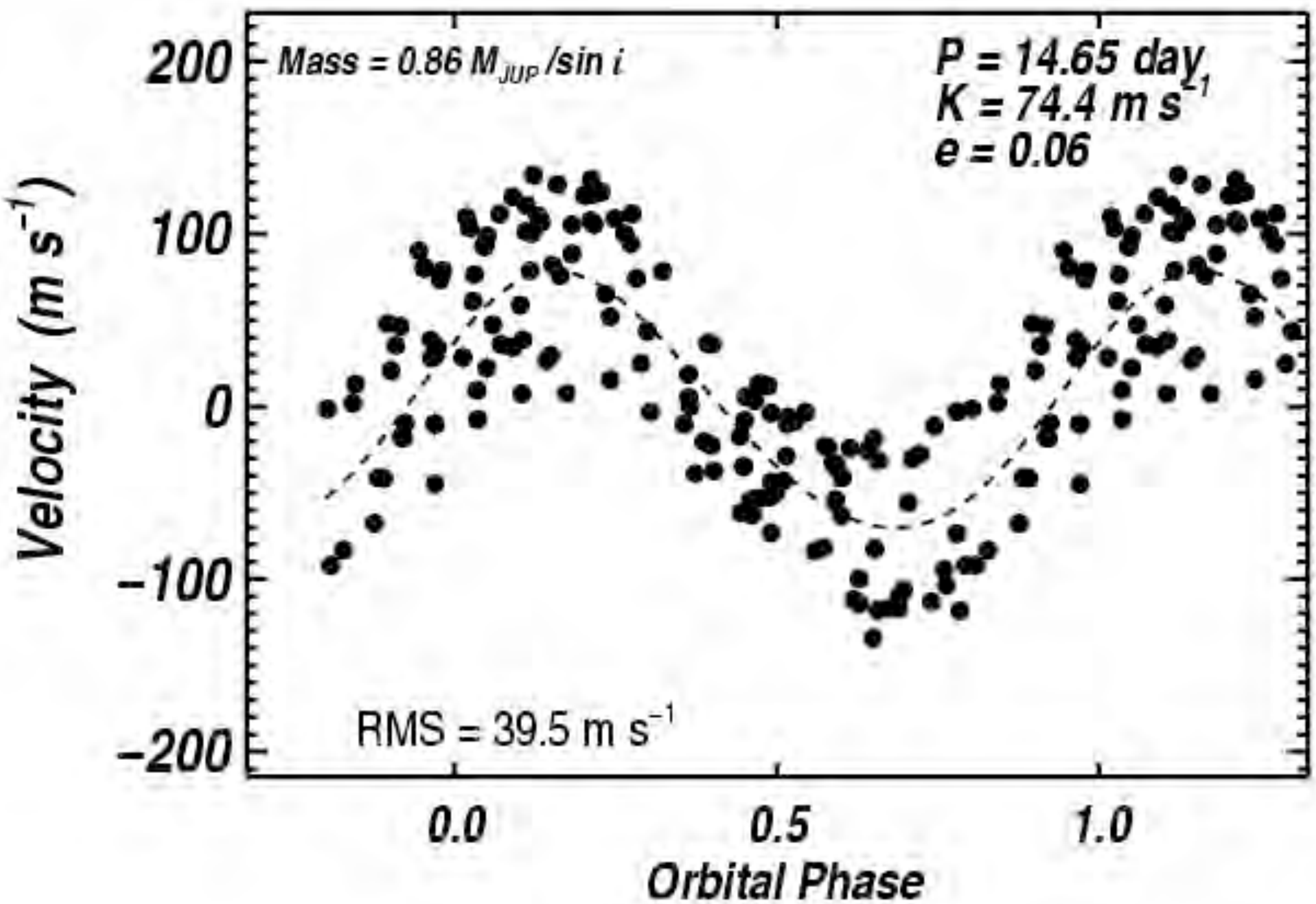
Butler et al. 2006, ApJ, 646, 505

EXAMPLE 3: e=0.5



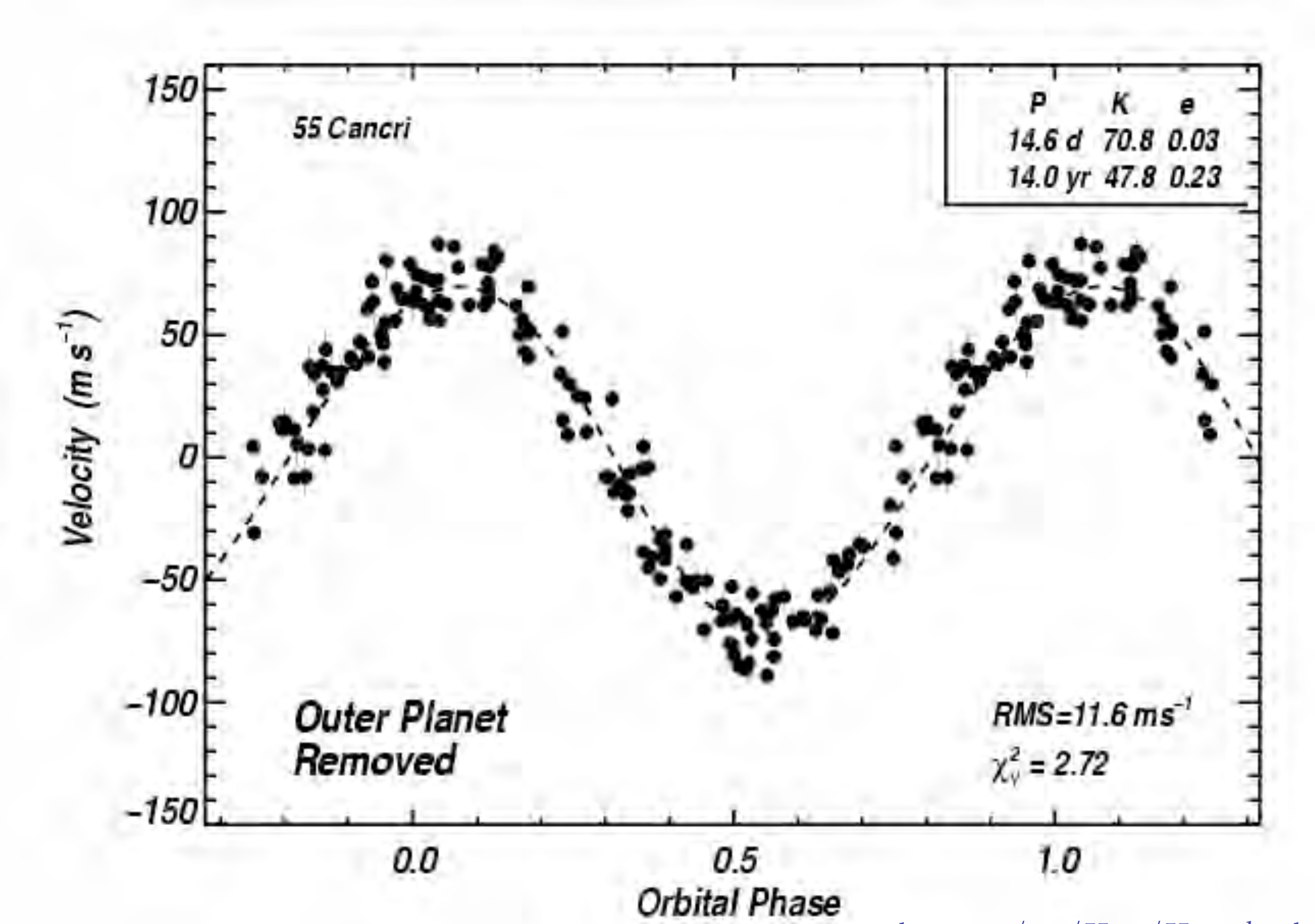
Butler et al. 2006, ApJ, 646, 505

Multiple Planets: One-Planet Fit



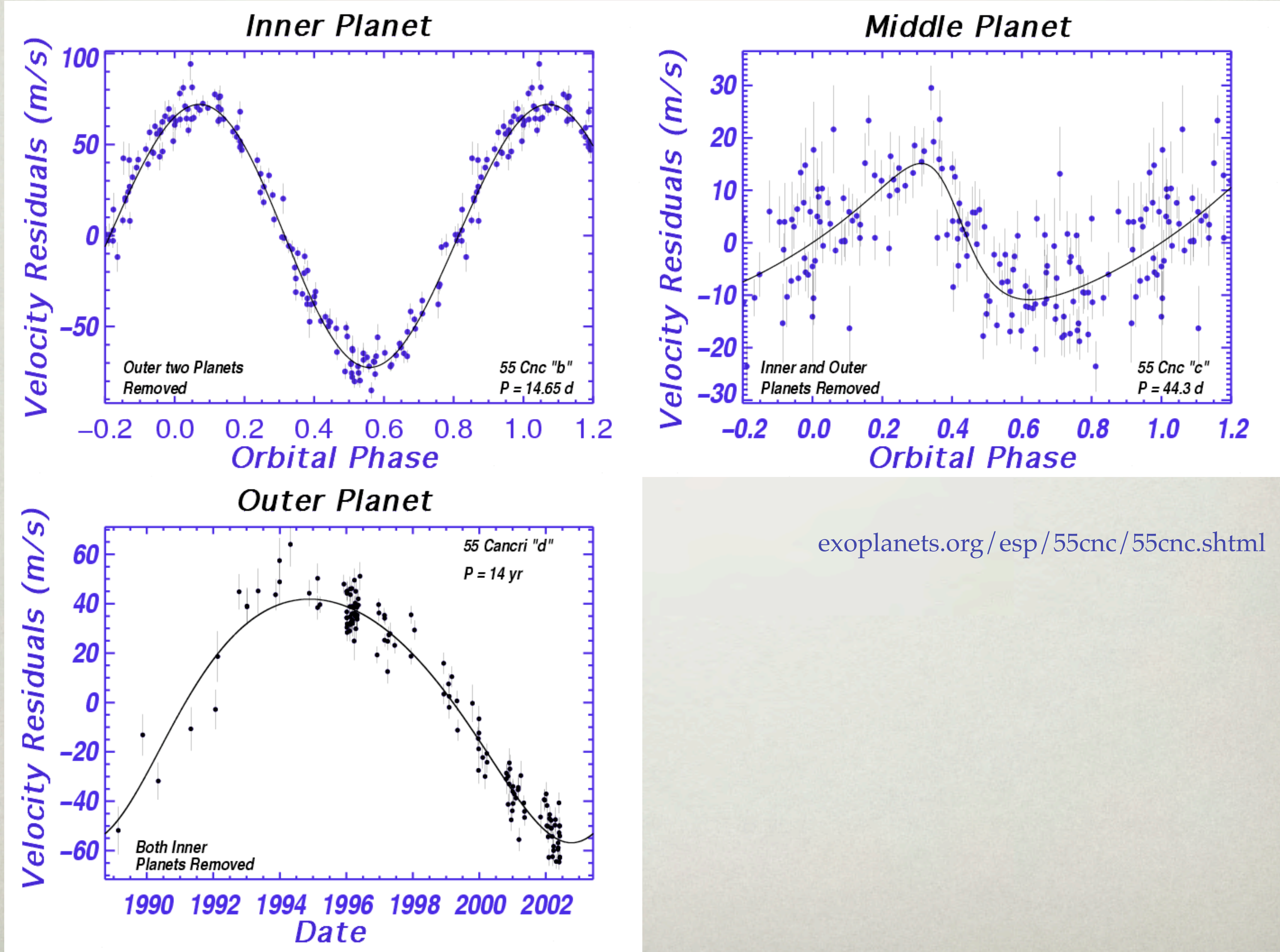
exoplanets.org/esp/55cnc/55cnc.shtml

Multiple Planets: Two-Planet Fit



exoplanets.org/esp/55cnc/55cnc.shtml

Multiple Planets: Three-Planet Fit



exoplanets.org/esp/55cnc/55cnc.shtml

Radial Velocity Observables

- Period
- Lower limit to mass: ($M_P \sin i$)
- Eccentricity of orbit

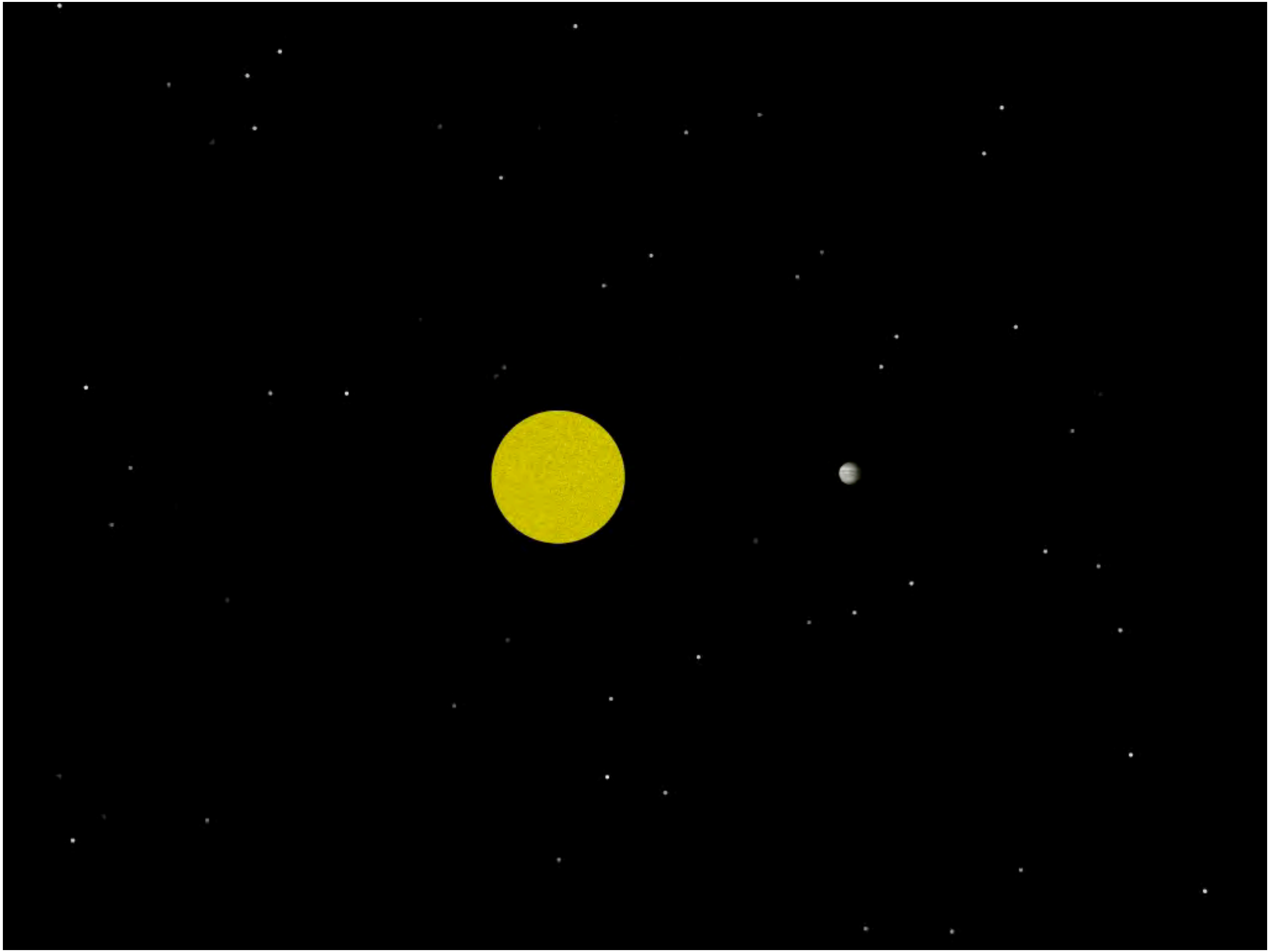
Problems with Radial velocity

- Correction of earth orbital motion (up to 30 km/s) and earth rotation (0.5 km/s)
- Period analysis (see Astronomical Data Analysis)
- Only good for cool stars such as the Sun
- Hot stars (O,B,A) do not have enough narrow, spectral lines
- Stellar rotation, starspots, oscillations, convection impact Doppler signal

Radial Velocity Limits

$$v_{\rm obs} = 28.4 \frac{M_P \sin i}{P_{\rm orb}^{1/3} M_*^{2/3}}$$

- Kepler's 3rd law: $P_{\rm orb}{}^{1/3} \sim a^{1/2}/M_*{}^{1/6}$
- Limit given by $M_P \sin i \sim a^{1/2}$
- Need to observe at least one full orbit
- Detection limit proportional to $a^{1/2}$

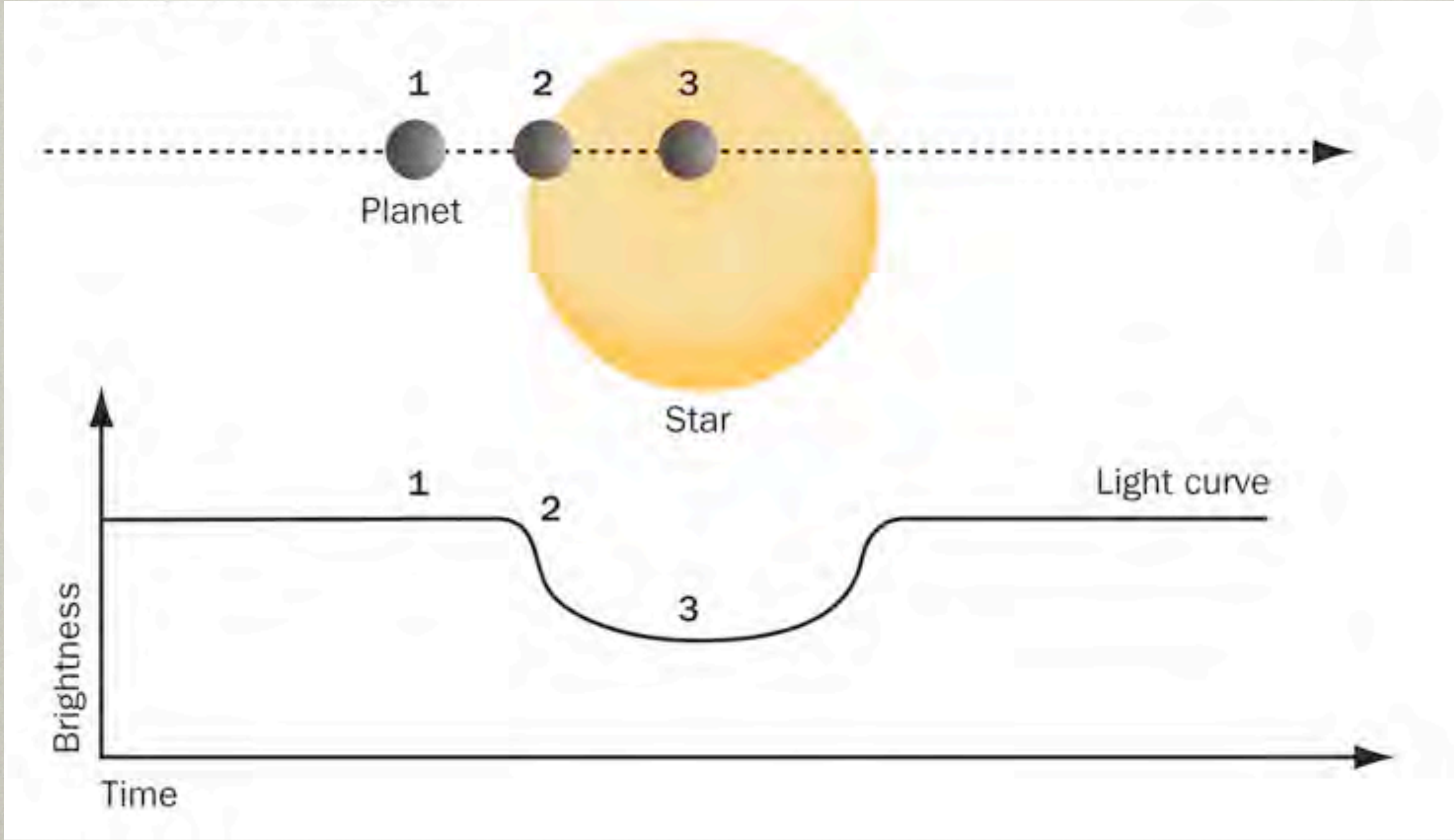


Transits

- Can use small telescopes (<1 m diameter)
- Space missions avoid problems with Earth's atmosphere
- Transit timing variations may reveal hidden exoplanets

sci.esa.int/science-e/www/object/index.cfm?fobjectid=35225

Transits



www.sciencenews.org/view/feature/id/39031/title/The_Hunt_for_Habitable_Planets

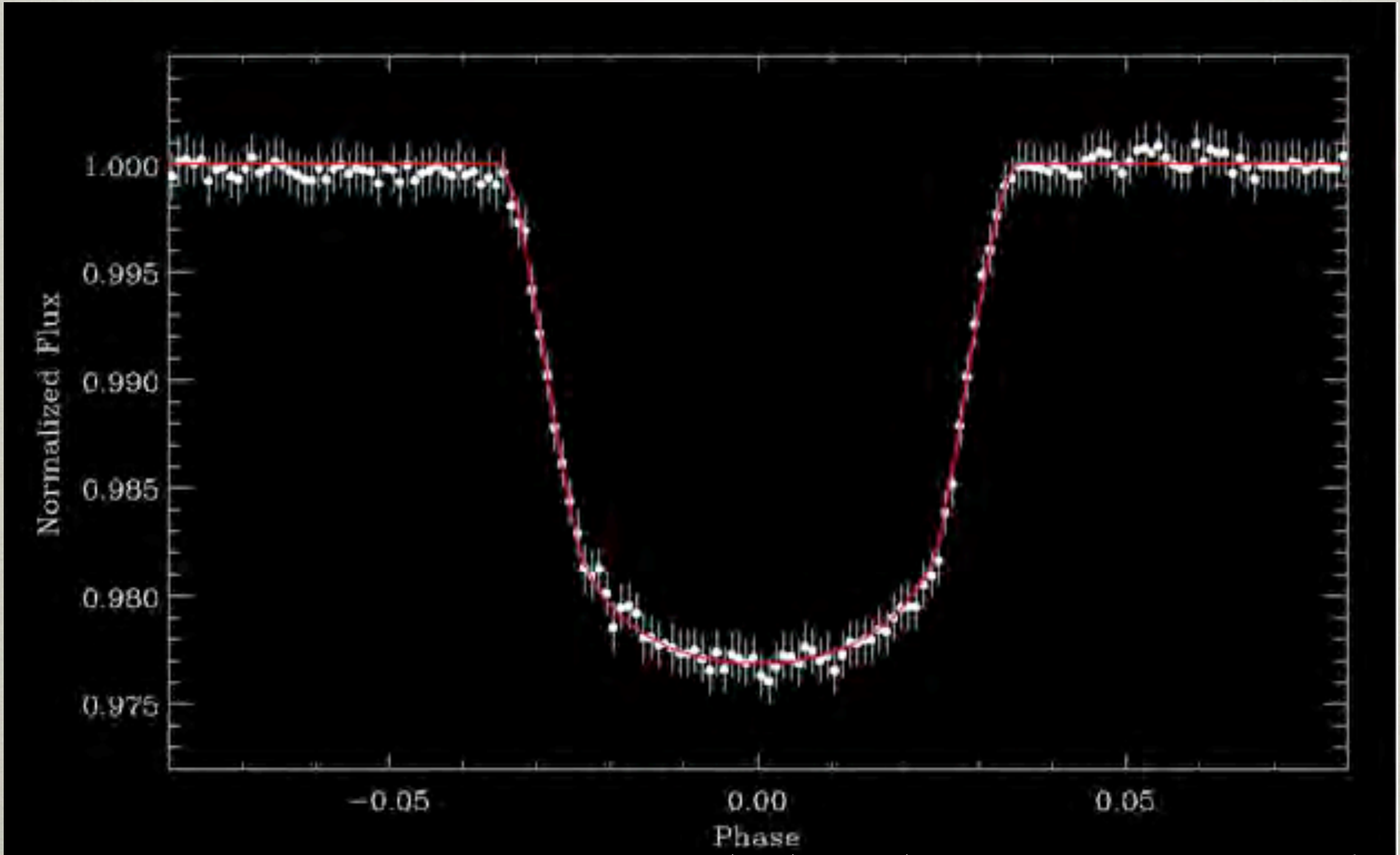
Transit Signals

- Intensity signal

$$\frac{\Delta I}{I} = \left(\frac{R_P}{R_*}\right)^2$$

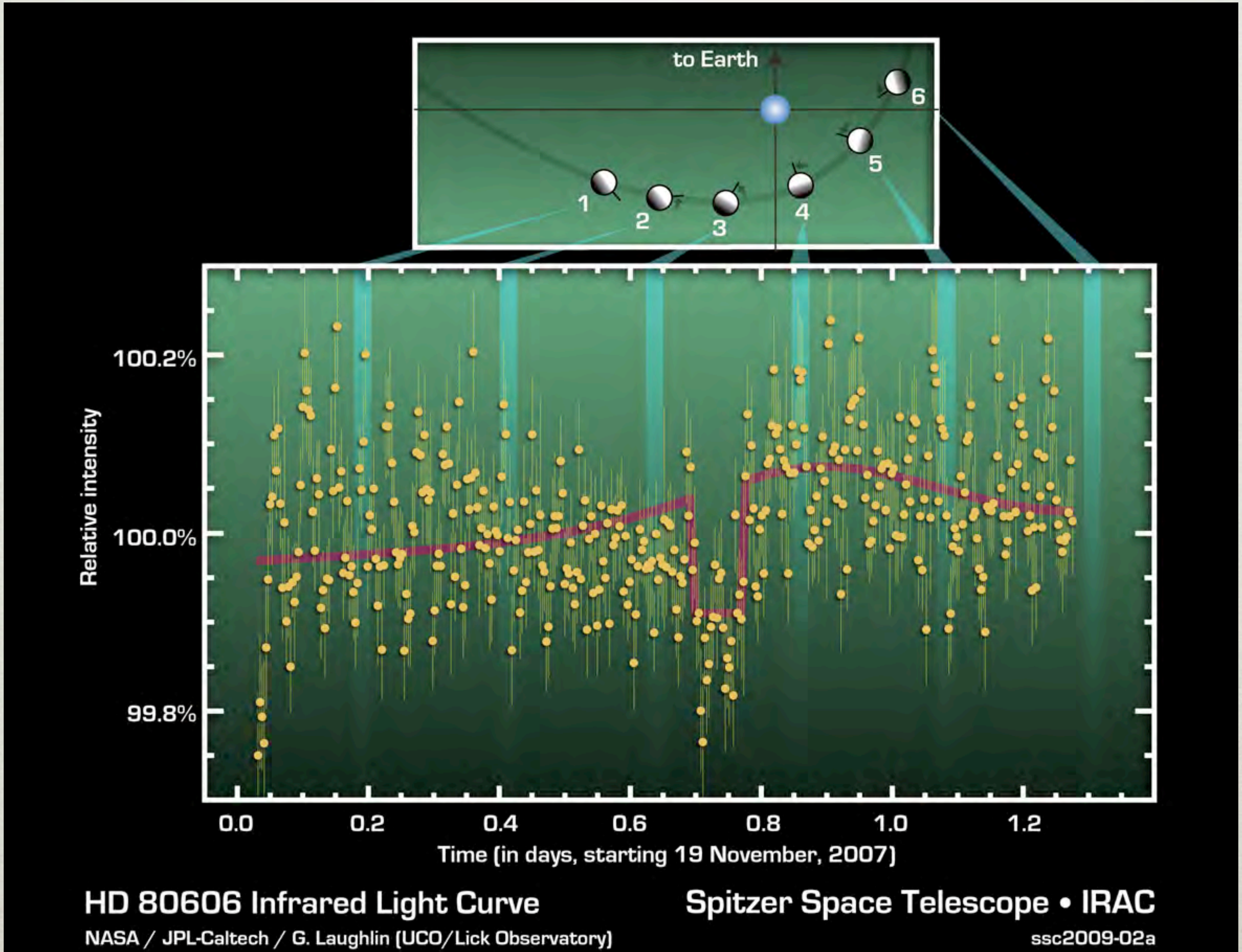
- R_* stellar radius; R_p planet radius
- About 1% for Jupiter and Sun
- Transit duration proportional to $P_{orb}^{1/3} R_* / M_*^{1/3}$
- Transit duration provides estimate of stellar radius
- Intensity change then provides planetary radius

Transit Example (Corot)



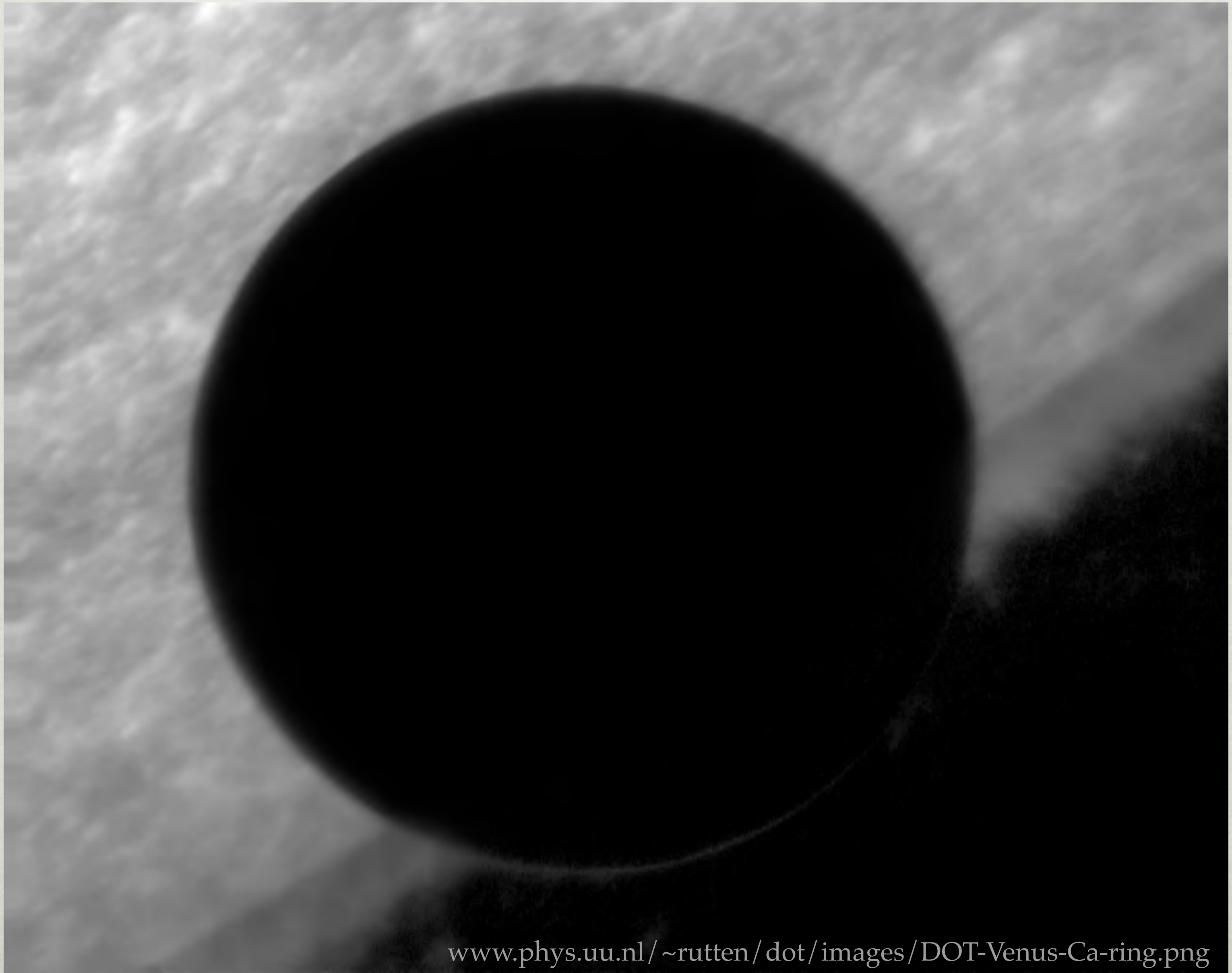
www.cnes.fr/web/CNES-en/5918-corot-discovers-its-first-exoplanet.php

Secondary Eclipse



photojournal.jpl.nasa.gov/catalog/PIA11390

Atmospheric Transmission



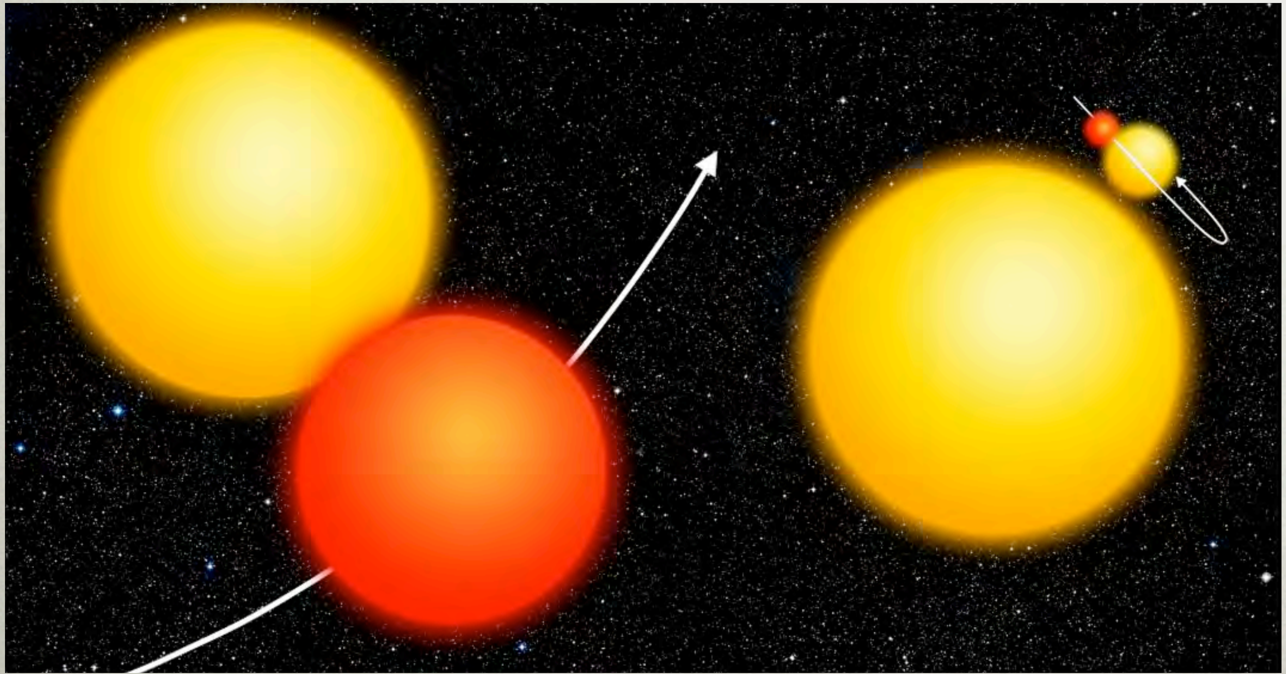
Transit Observables

- Period
- Orbit inclination ($i \approx 90°$)
- Planet radius
- Planet temperature from secondary eclipse
- Stellar limb darkening

- Good for large planets close to the star

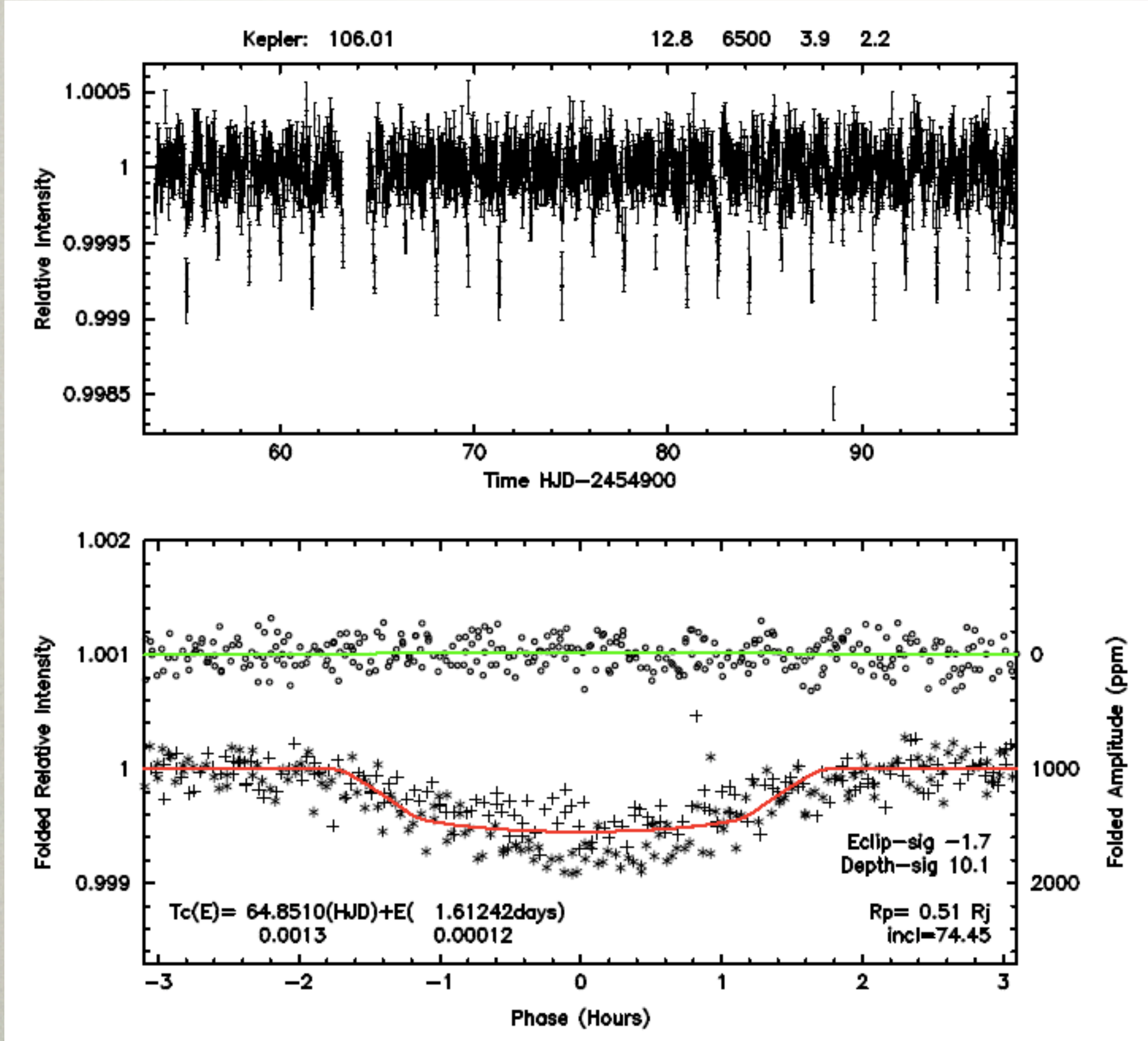
Problems with Transits

- Low probability, but simple observation
- Many false positives:
  - Grazing eclipse from main-sequence star
  - Eclipsing binary (giant and main-sequence)
  - Eclipsing binary close by (foreground or background)



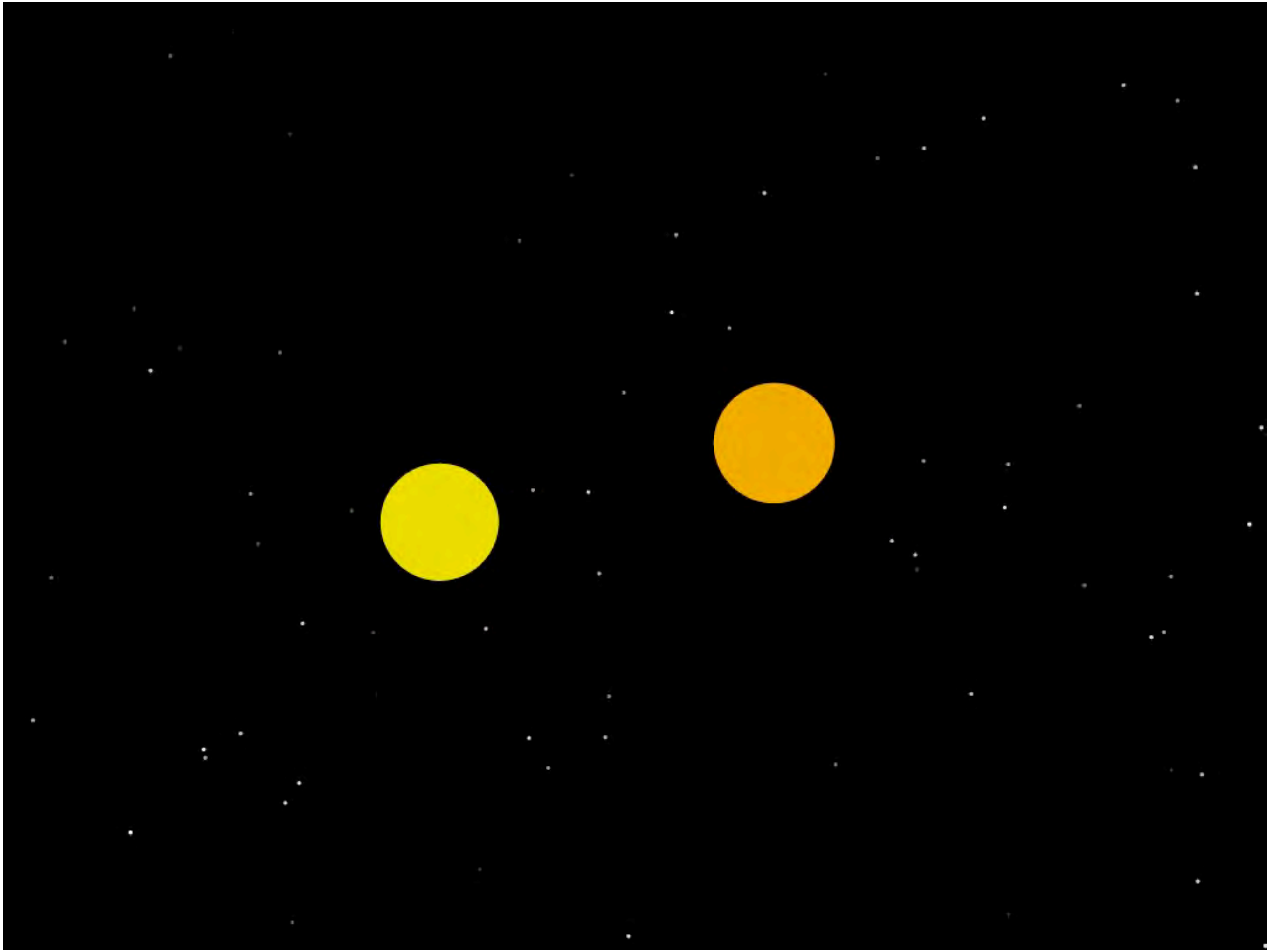
kepler.nasa.gov/files/mws/aas2010-5nbFalsePositives.jpg

Kepler Object of Interest 106

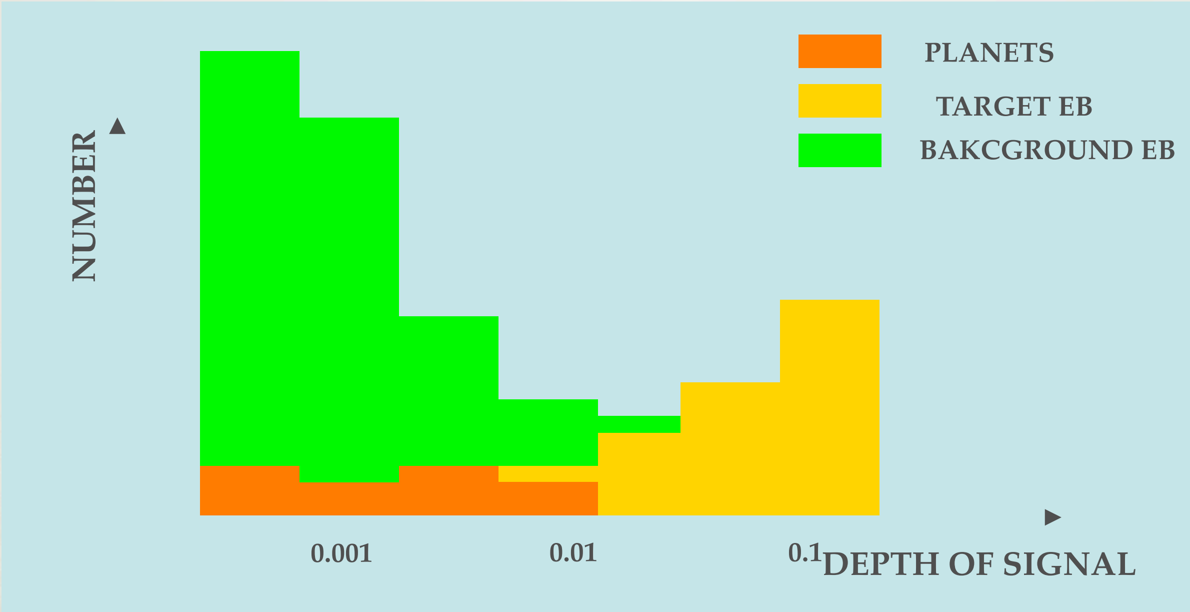


- Eclipsing binary in background
- Odd and even transits are different

Batalha et al. 2010



Problems with Transits



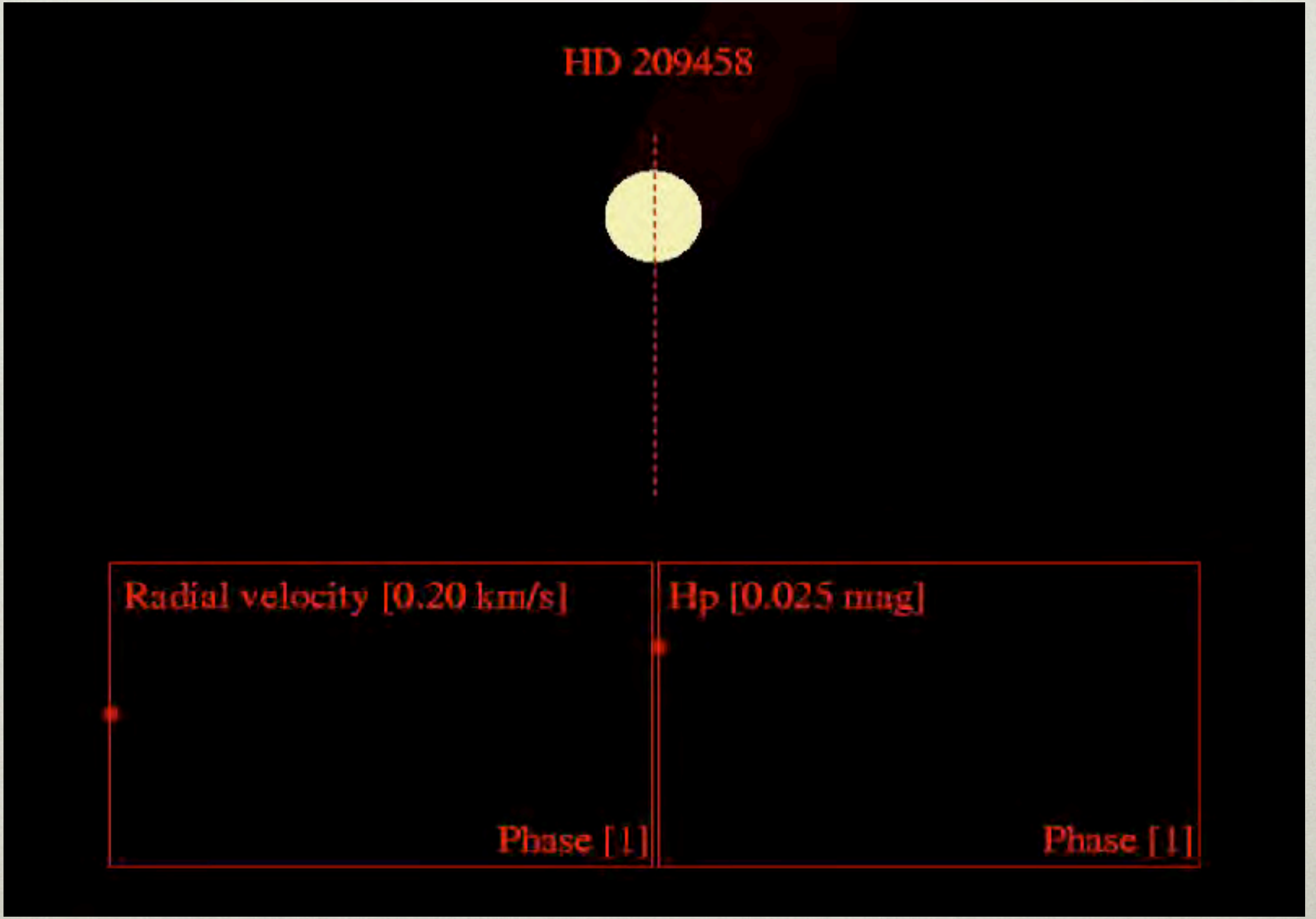
www.oca.eu/cassiopee/COROTWeek10/Communications/F_Pont.pdf

- Only few percent of candidates are real exoplanet
- Need radial velocity confirmation with large telescopes (≥4m)

Transit Limits

- Need to observe more than one transit, best at least 3 (short periods)
- Transit requires that cos $i < (R_* + R_P)/a$
- Detection threshold therefore proportional to a

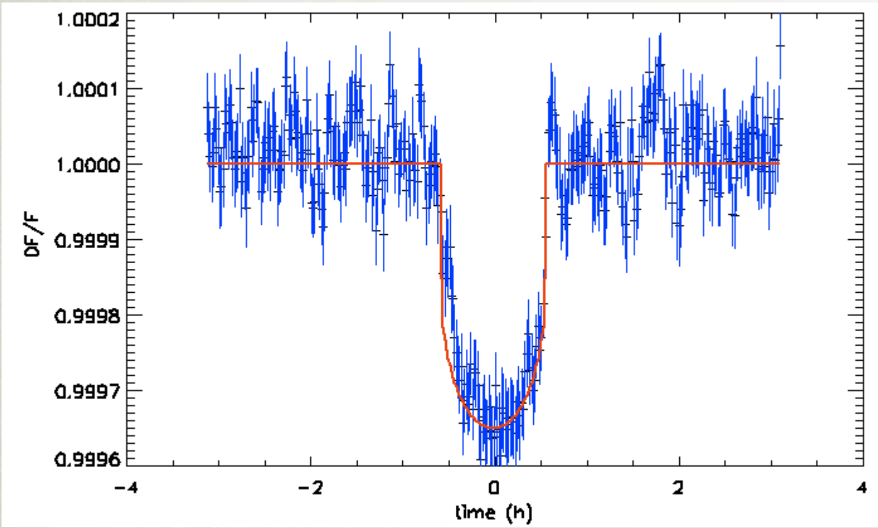
Transit + radial velocity = planet density



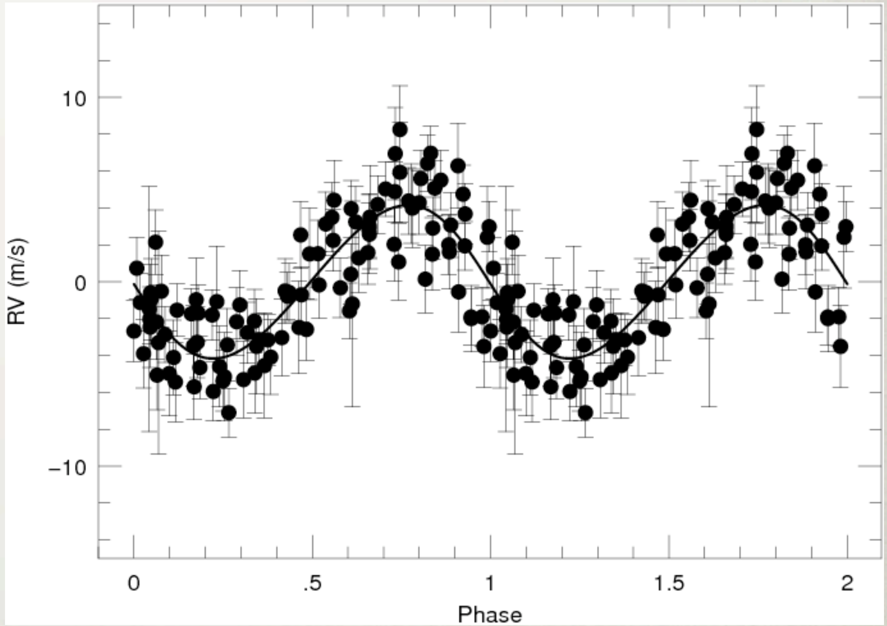
www.rssd.esa.int/SA-general/Projects/Staff/perryman/planet3d.mpg

First Rocky Exoplanet

CoRoT (Leger et al. 2009)

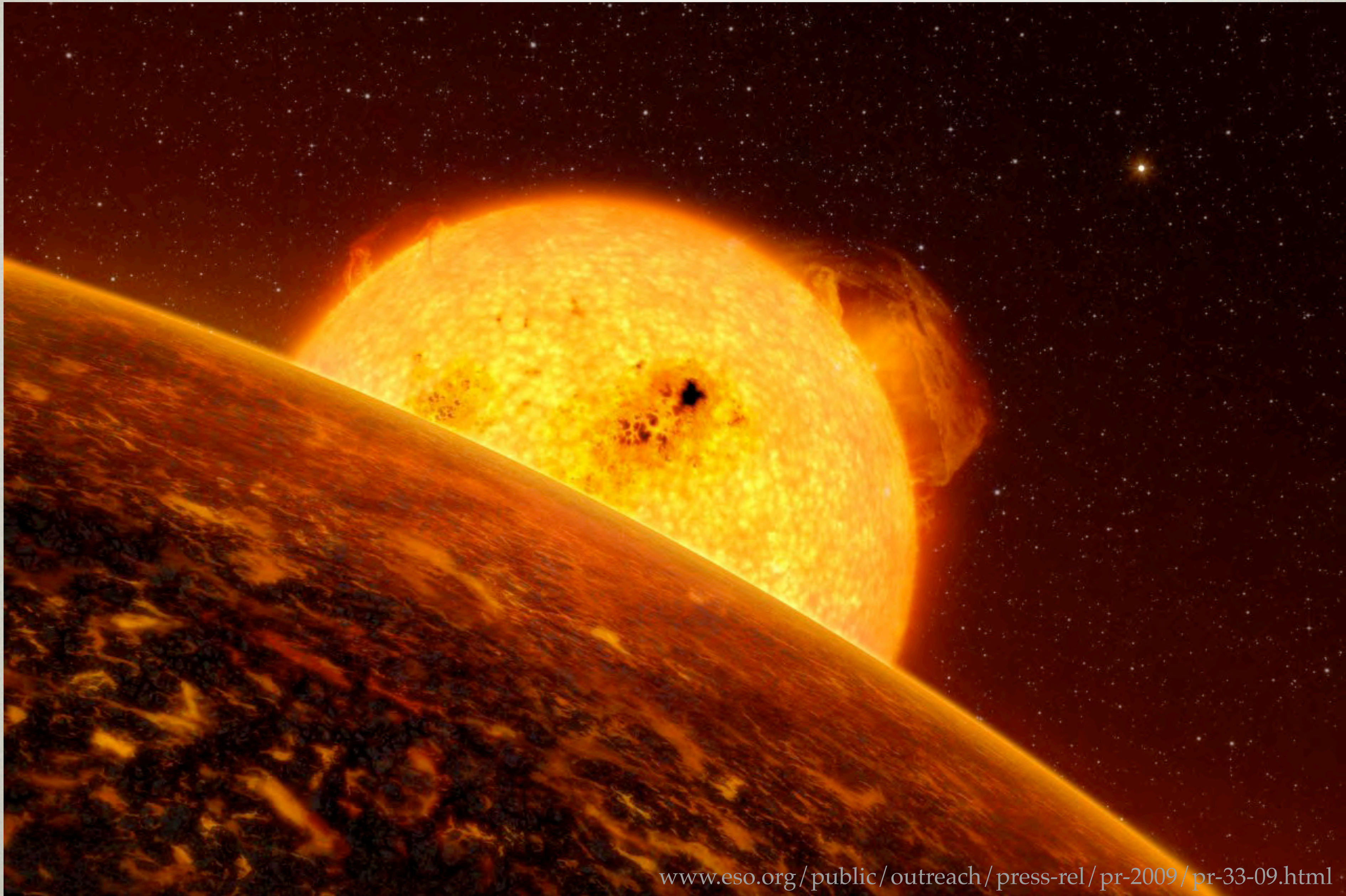


HARPS (Queloz et al. 2009)



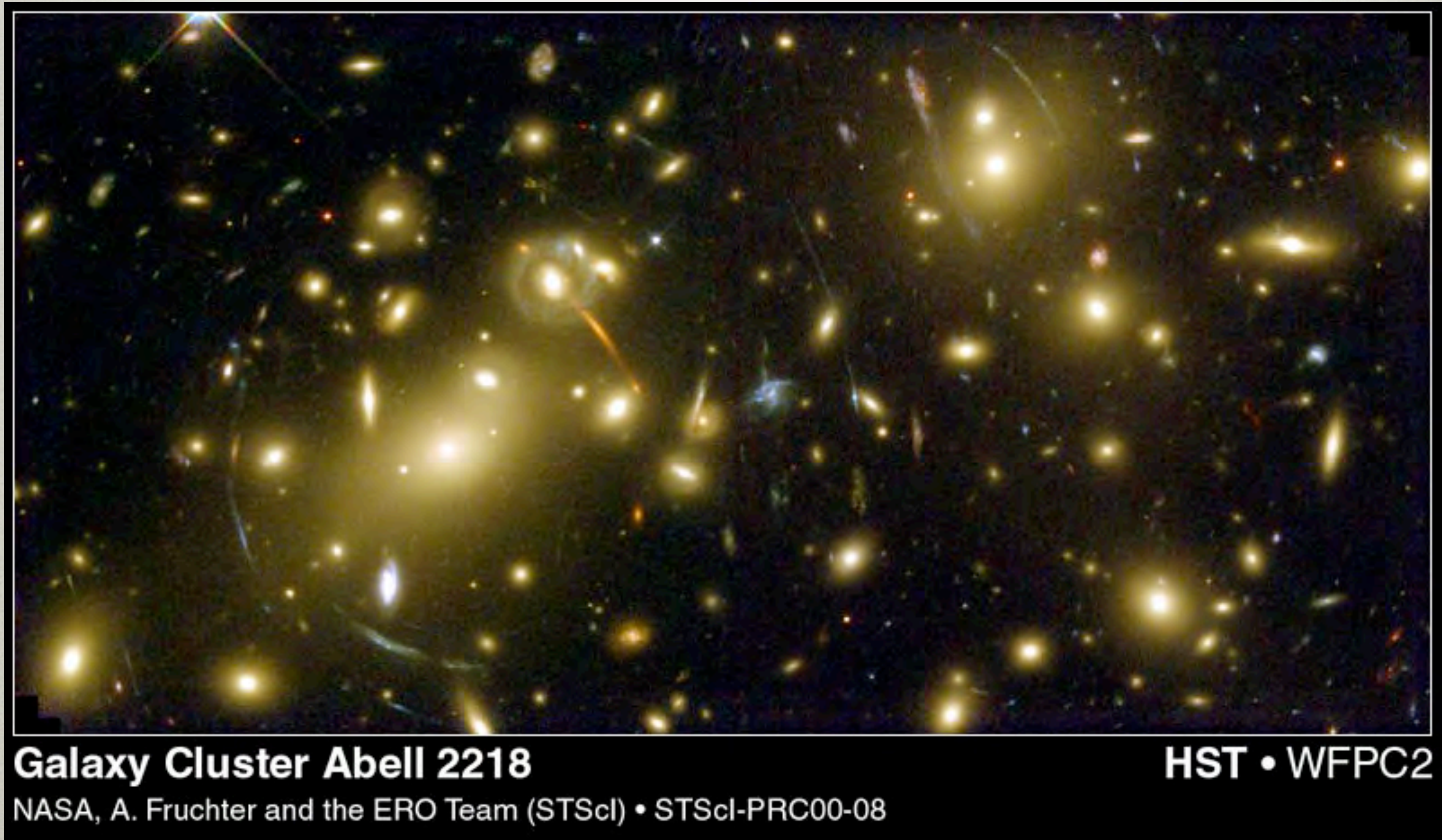
- 4.8 Earth masses
- density 5.6 g/cm^3

CoRoT-7b



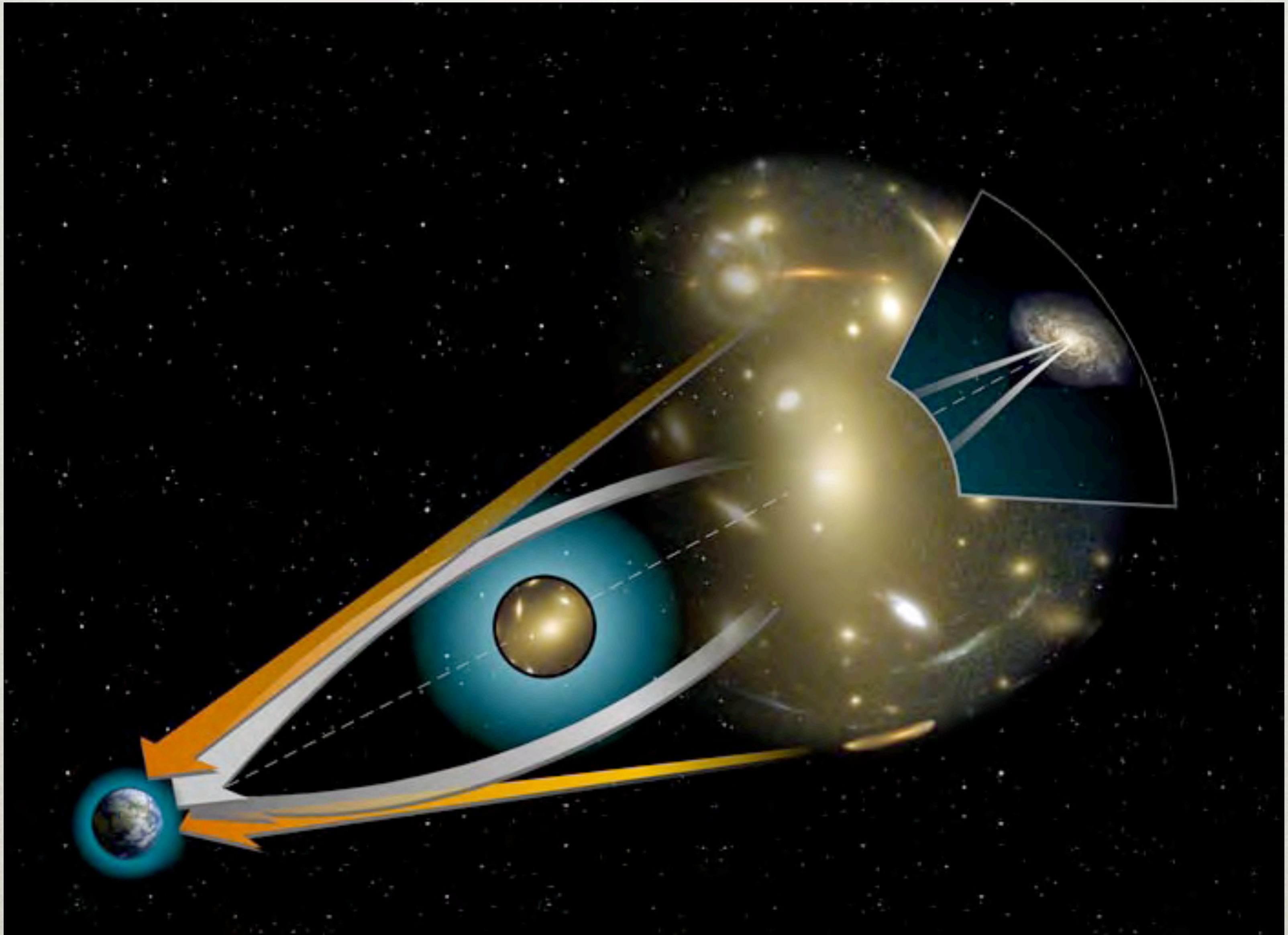
www.eso.org/public/outreach/press-rel/pr-2009/pr-33-09.html

Gravitational Lensing



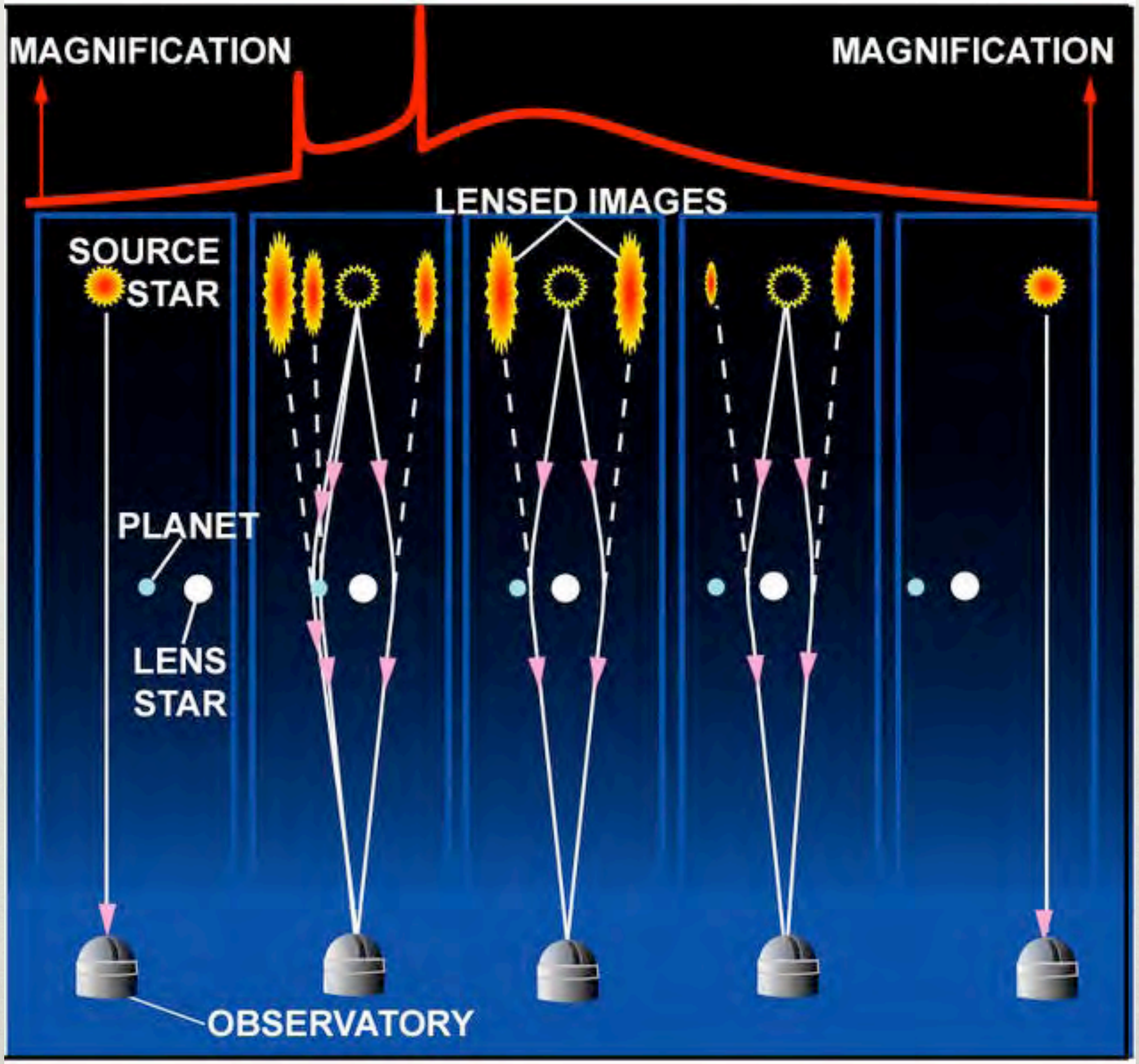
apod.nasa.gov/apod/image/0110/a2218c_hst_big.jpg

Gravitational Lensing Explained



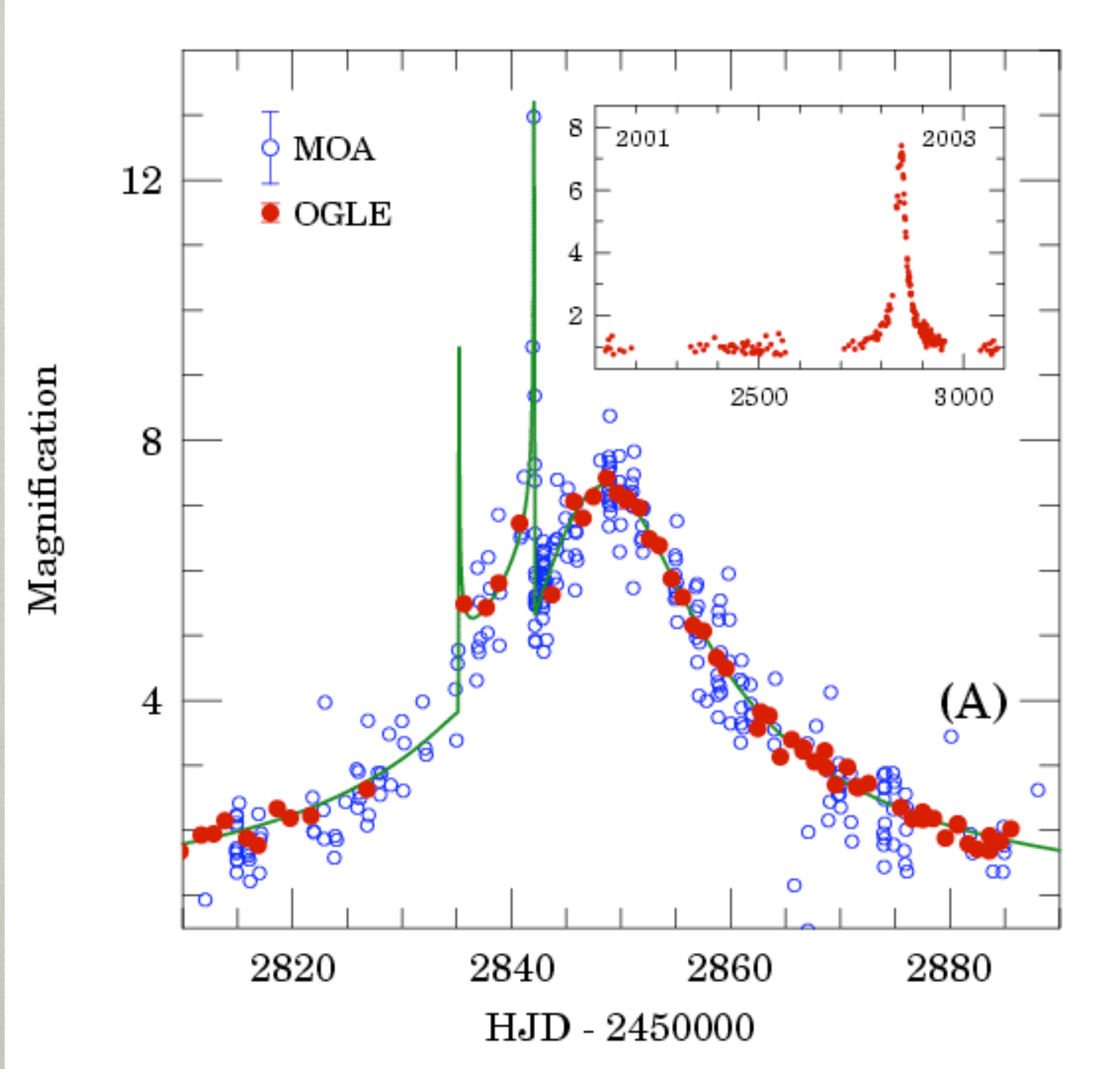
hubblesite.org/newscenter/archive/releases/2000/07/image/c/

Microlensing



ogle.astrouw.edu.pl/cont/4_main/epl/blg235/blg235.html

Microlensing Event



- $M_* = 0.36\ M_{Sun}$
- $M_P = 1.5\ M_{Jupiter}$
- a = 3.0 AU
- d = 5.2kpc

ogle.astrouw.edu.pl/cont/4_main/epl/blg235/blg235.html

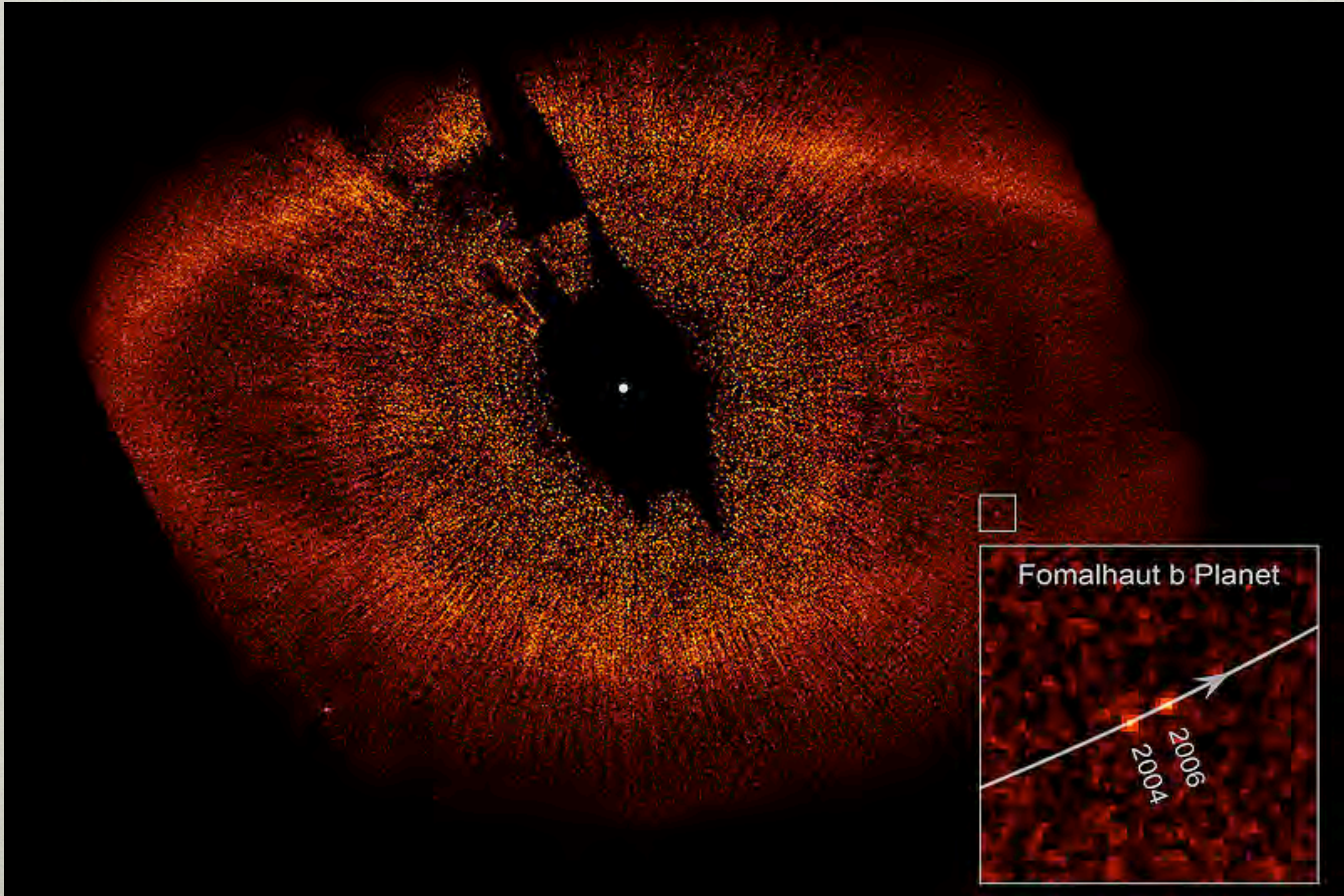
Problems with Microlensing

- One-time observation
- Cannot be repeated
- Solutions to light curves are not necessarily unique
- Small number of detections (<10)

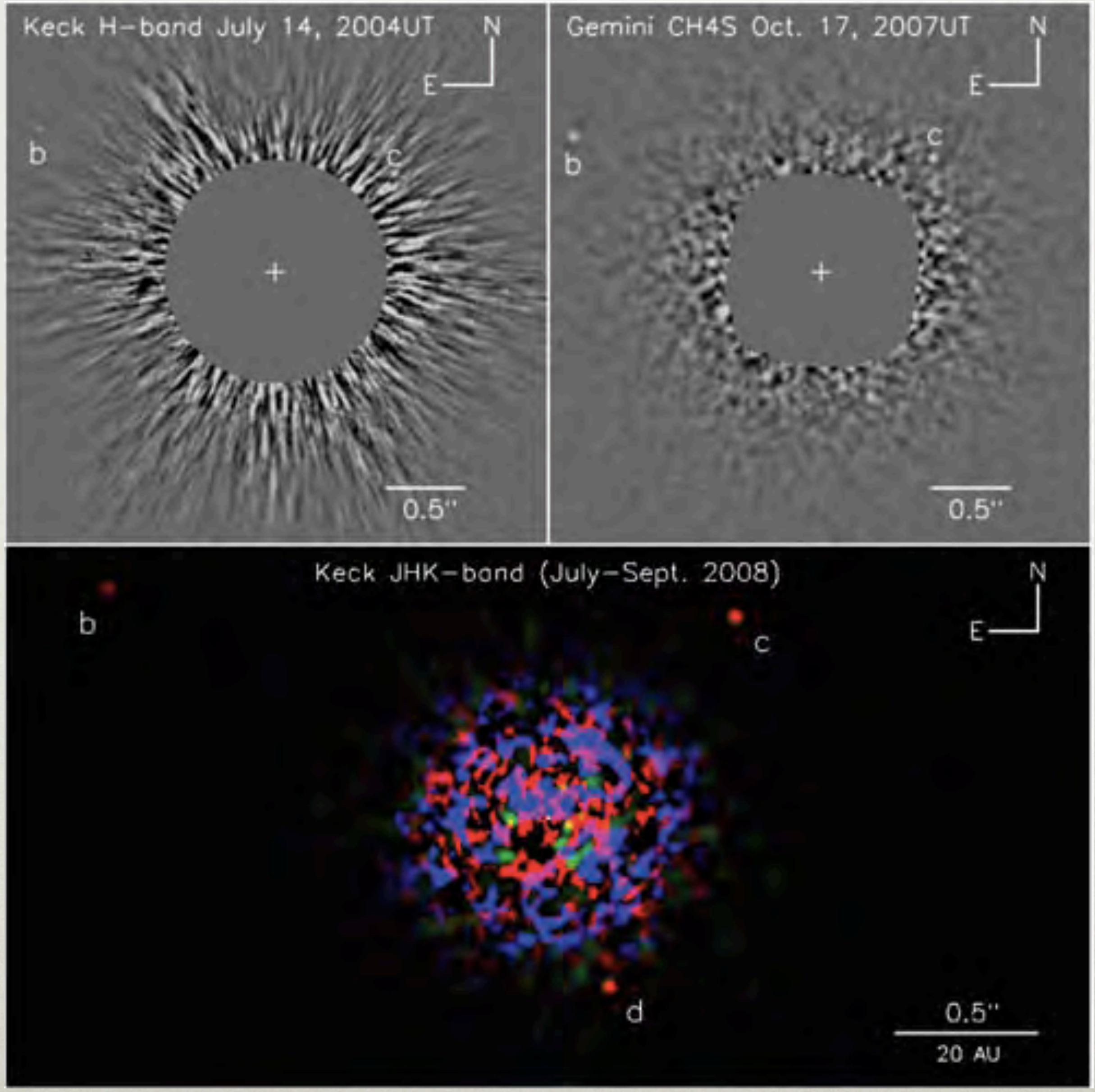
Direct Imaging

- Central star much brighter than disks and planets
  - Disks: at least 10^4 times fainter than central star
  - Jupiter: 10^9 times fainter than Sun
- Telescope optics, Earth atmosphere make halo
  - halo: 10^2 to 10^6 times fainter than central star
- Space telescopes show significant halos

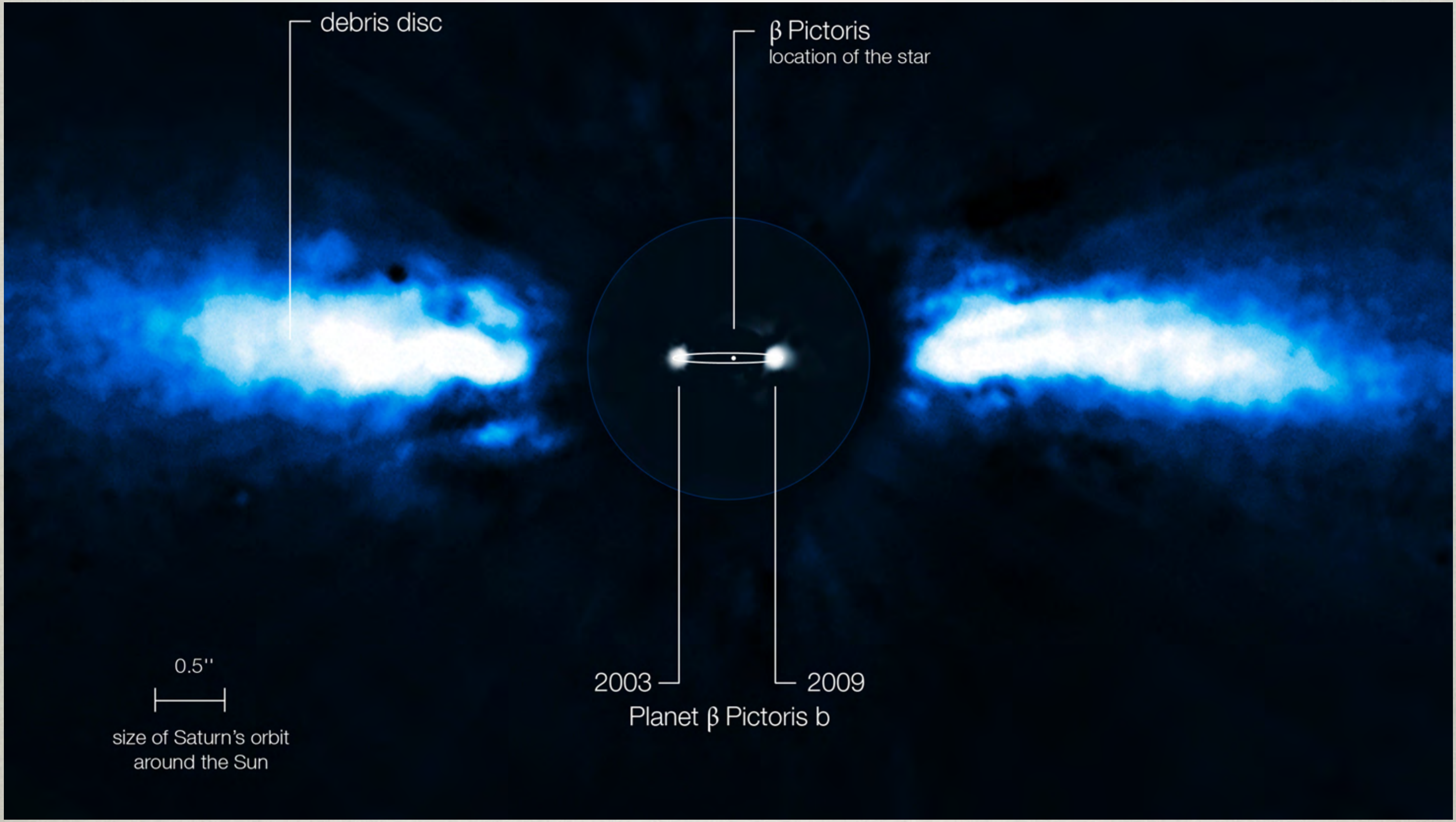
Fomalhaut b (Kalas et al. 2008)



HR 8799 (Marois et al. 2008)

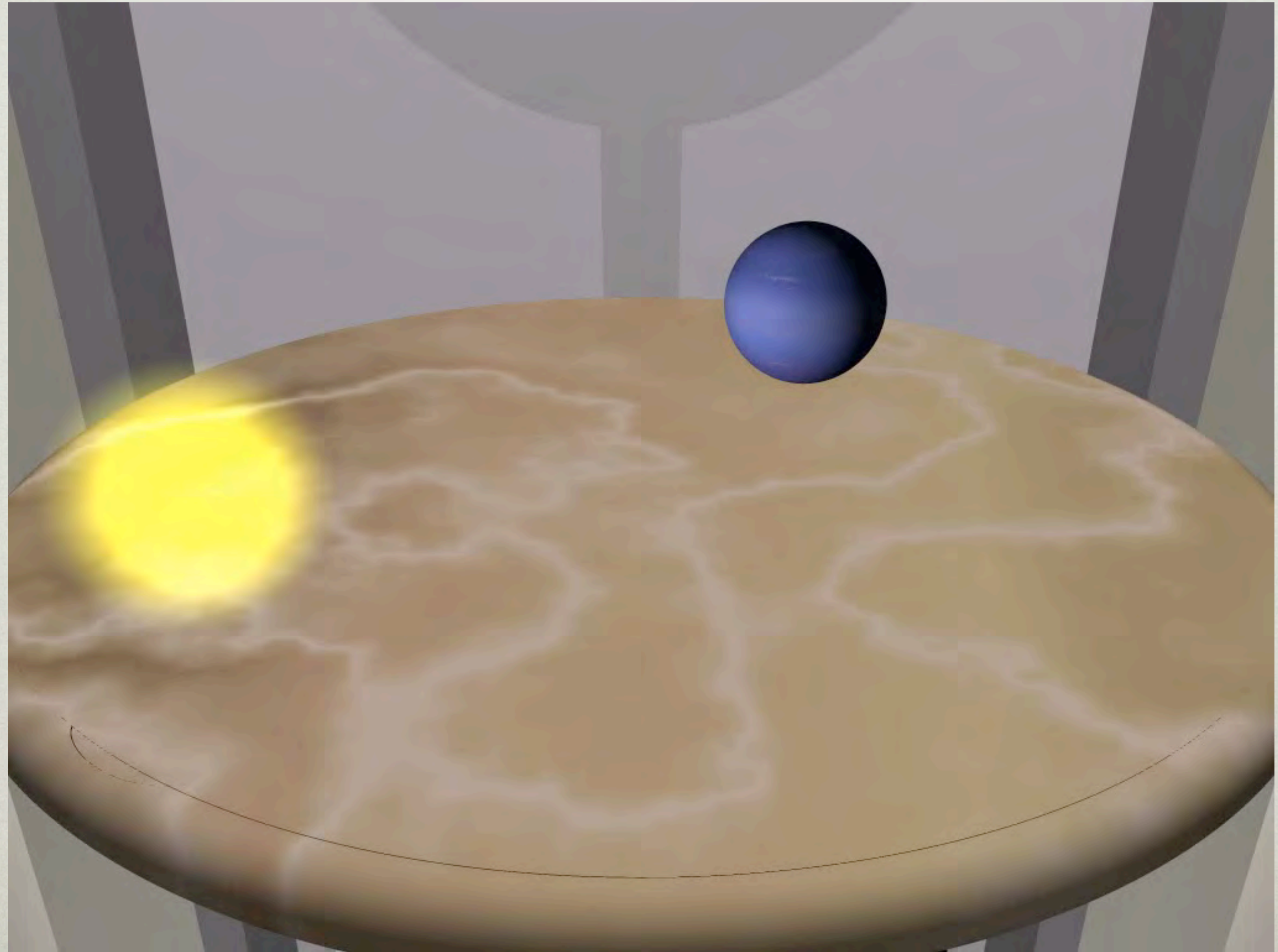


Beta Pic

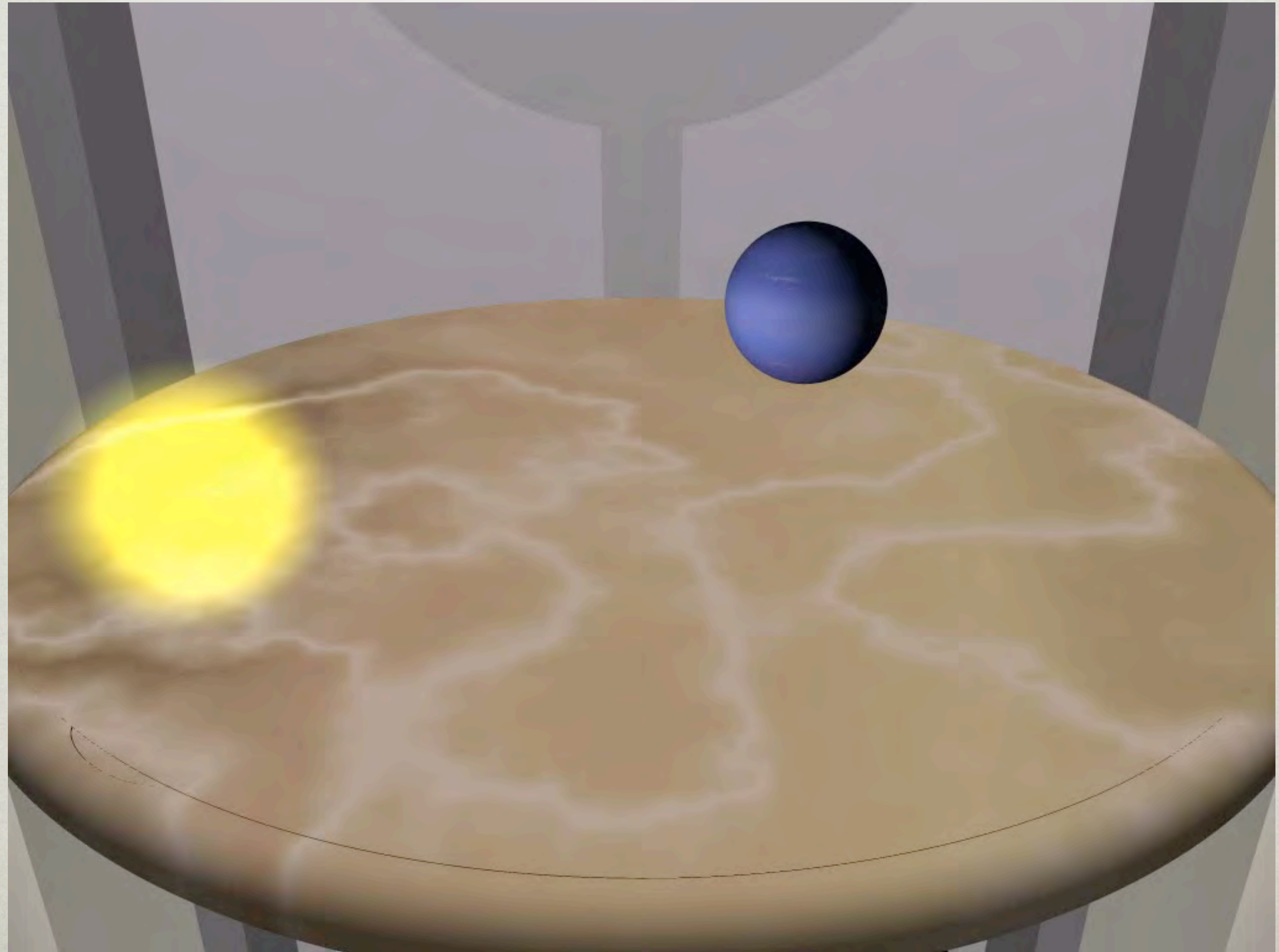


www.eso.org/public/images/eso1024c/

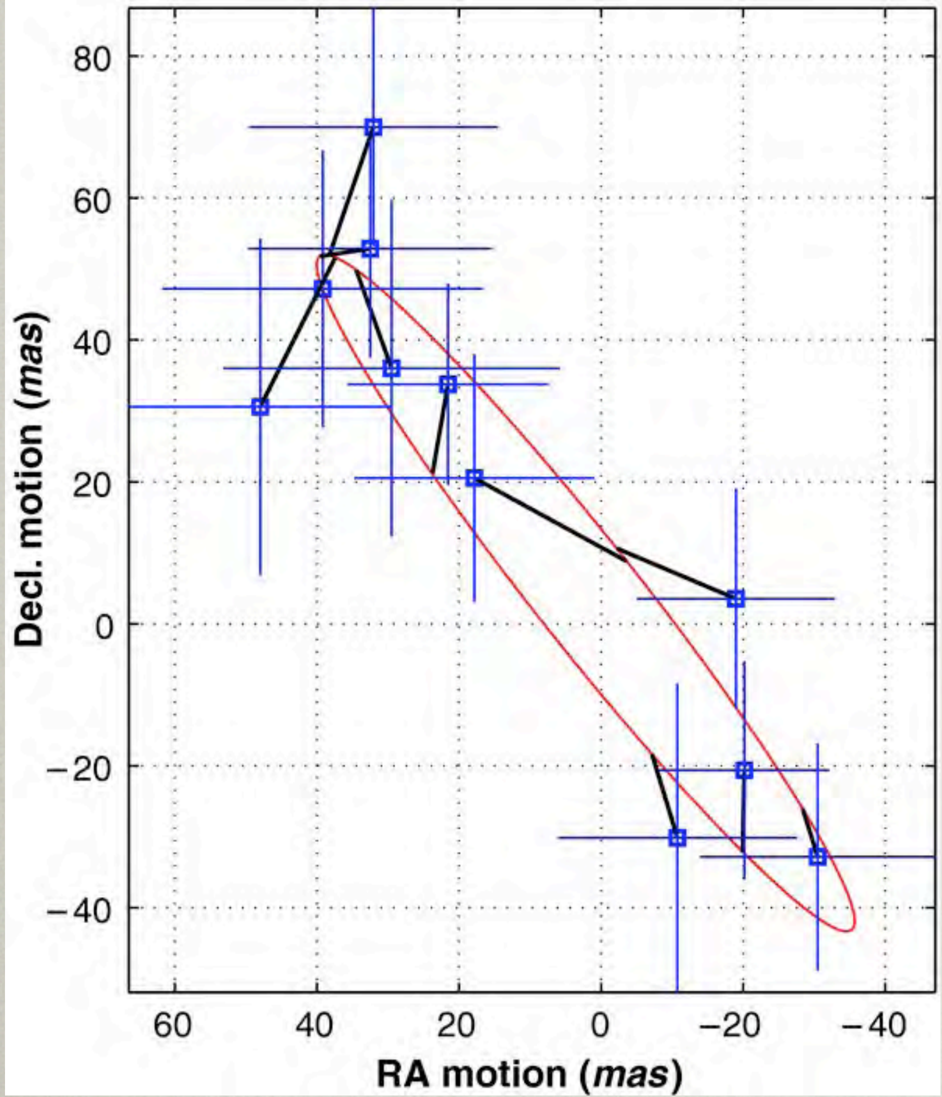
Scattering Polarization

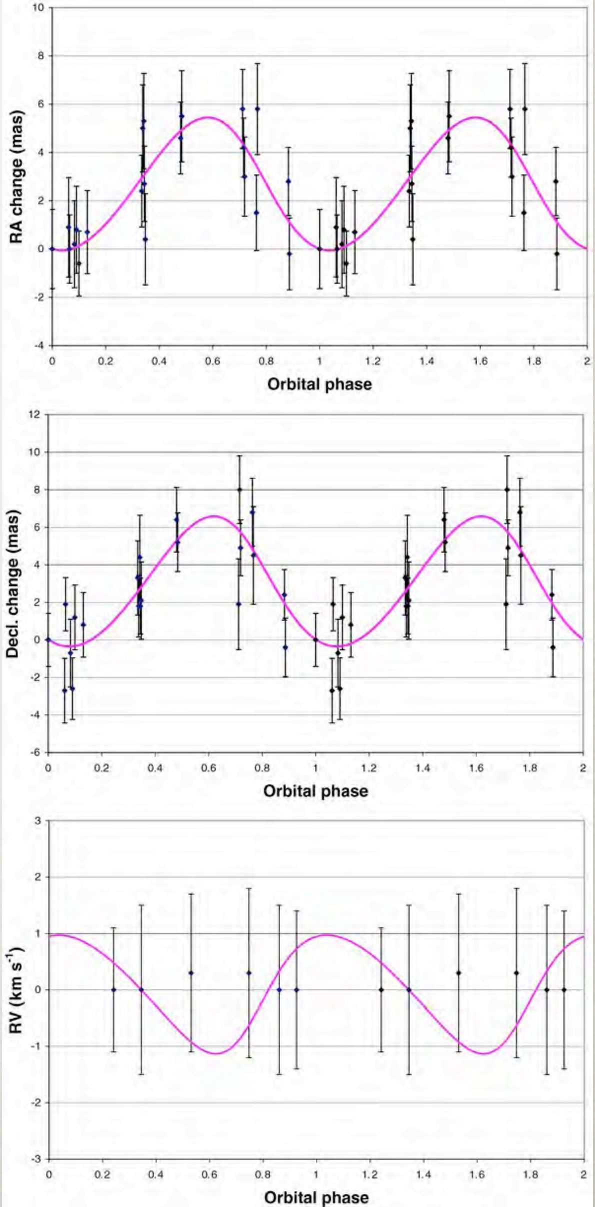


Scattering Polarization



Astrometry

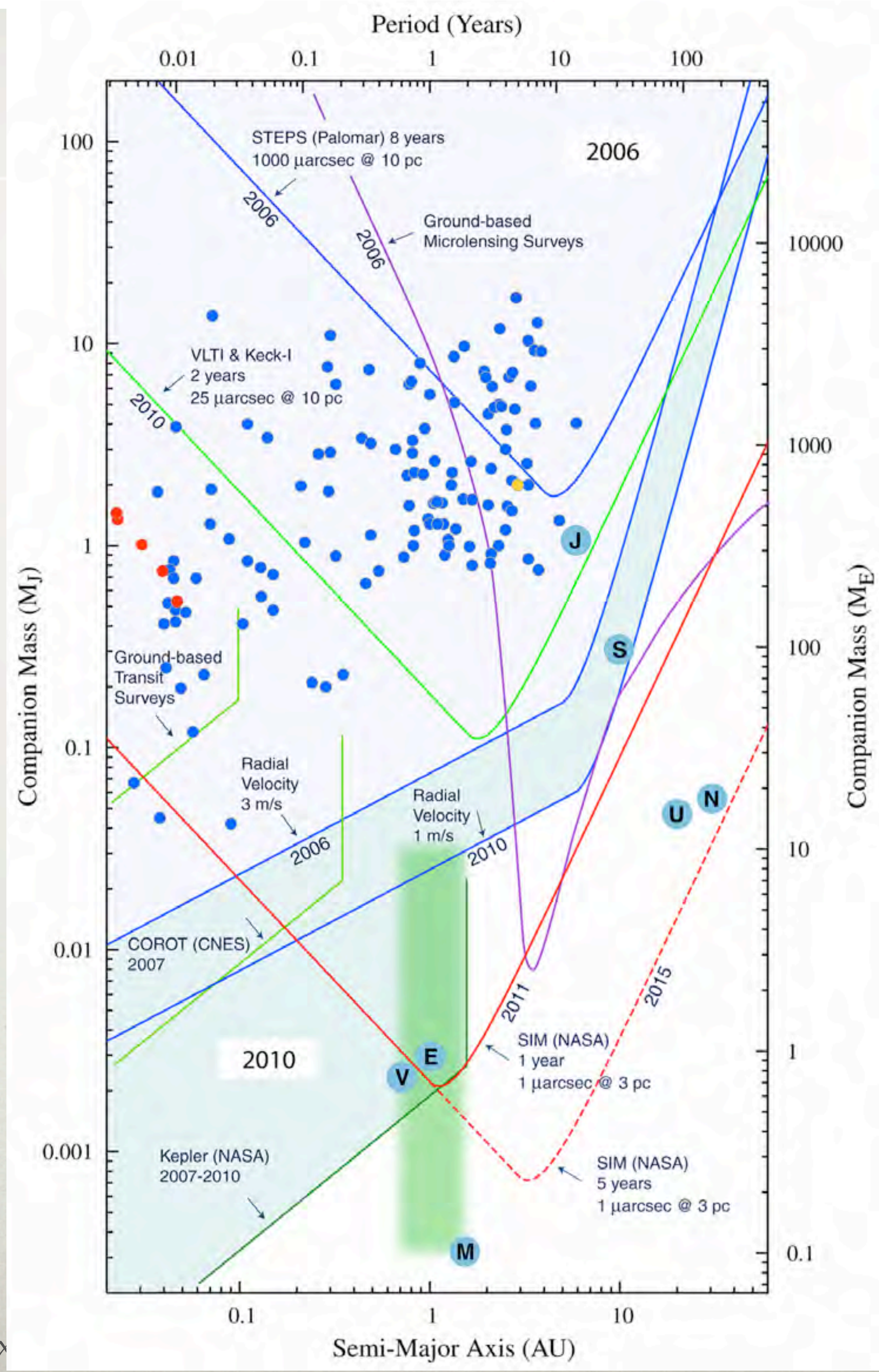




www.iop.org/EJ/article/0004-637X/700/1/623/apj_700_1_623.figures.html

Astrometry Detection Limit

- Size of circle on sky given by $M_P/M_* \times a/d$
- Detection limit given by fixed product $M_P \times a$
- Need to observe at least one full orbit
- No confirmed detection


Period (Years)
0.01
0.1
1
10
100
STEPS (Palomar) 8 years
1000 µarcsec @ 10 pc
2006
2006
2006
Ground-based
Microlensing Surveys
VLTI & Keck-I
2 years
25 µarcsec @ 10 pc
2010
Ground-based
Transit
Surveys
Radial
Velocity
3 m/s
2006
Radial
Velocity
1 m/s
2010
COROT (CNES)
2007
2010
Kepler (NASA)
2007-2010
2011
2015
SIM (NASA)
1 year
1 µarcsec @ 3 pc
SIM (NASA)
5 years
1 µarcsec @ 3 pc
J
S
U
N
E
V
M
Companion Mass (MJ)
100
10
1
0.1
0.01
0.001
Companion Mass (ME)
10000
1000
100
10
1
0.1
0.1
1
10
Semi-Major Axis (AU)