

# Planets and Exoplanets

Exoplanet Detections

# OUTLINE

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

# WHAT IS A PLANET?

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

# PLANET DEFINITION

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- Object with mass too small for fusion of deuterium ( $\sim 13$  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. CHARACTERIZATION

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## Detection:

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

## Characterization:

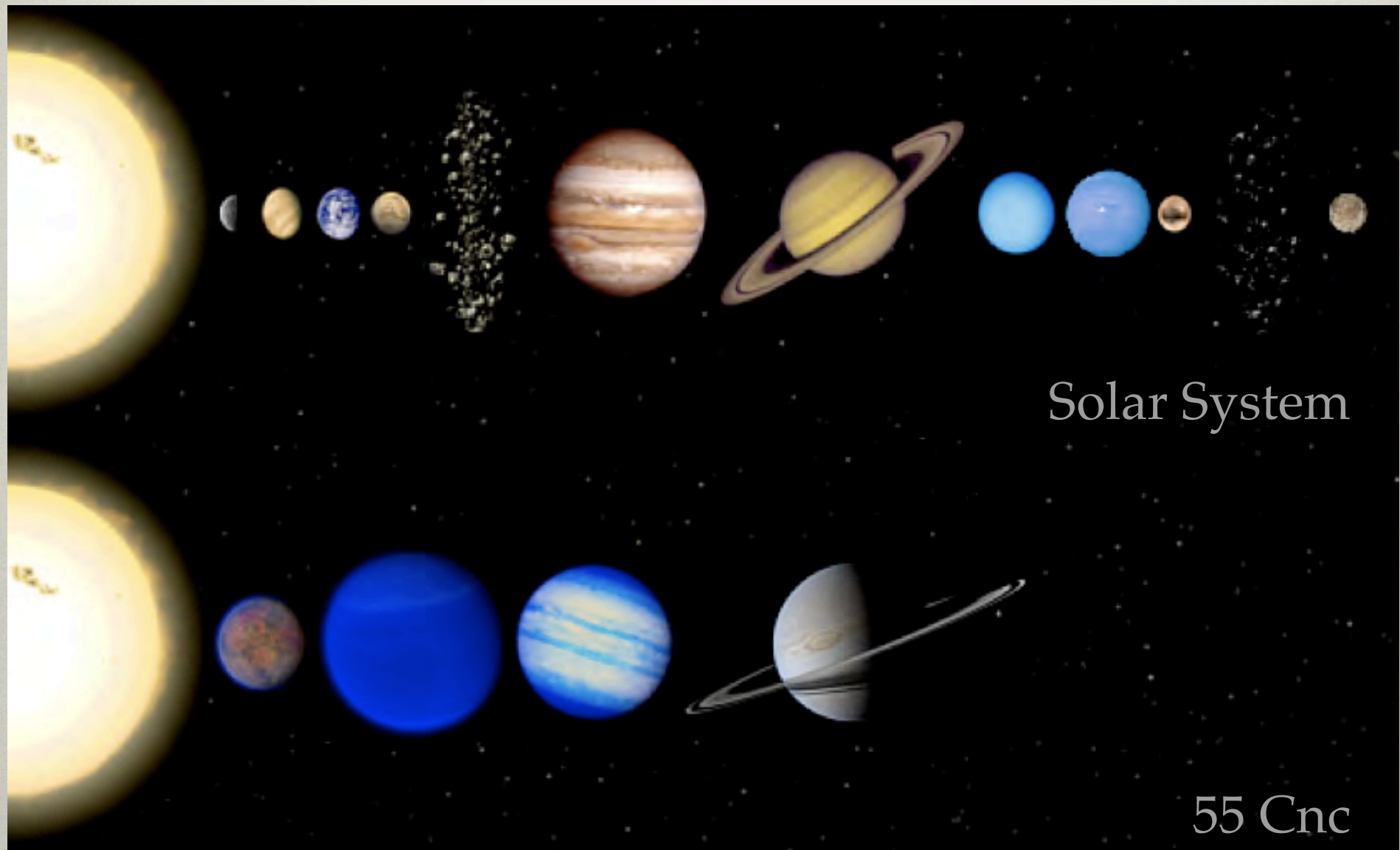
- Determine radius
- Determine surface properties
- Determine atmosphere properties

# EXOPLANETARY SYSTEMS

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- Past and Present: Discovery
  - Detecting planetary systems
  - Limited information: orbit, lower limit for mass, evidence for disks, images of outer disks
- The Future: 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



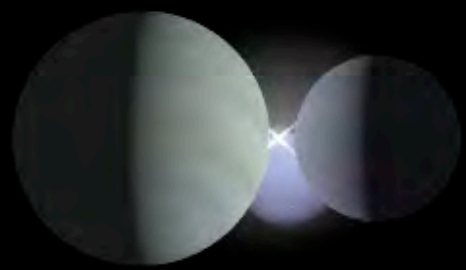
Solar System

55 Cnc

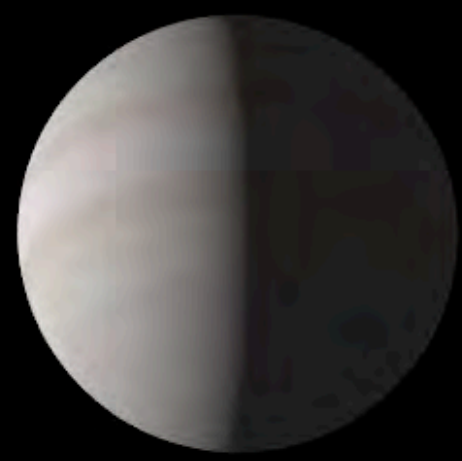
<http://www.extrasolar.net/mostinteresting.asp>



**Solar System**

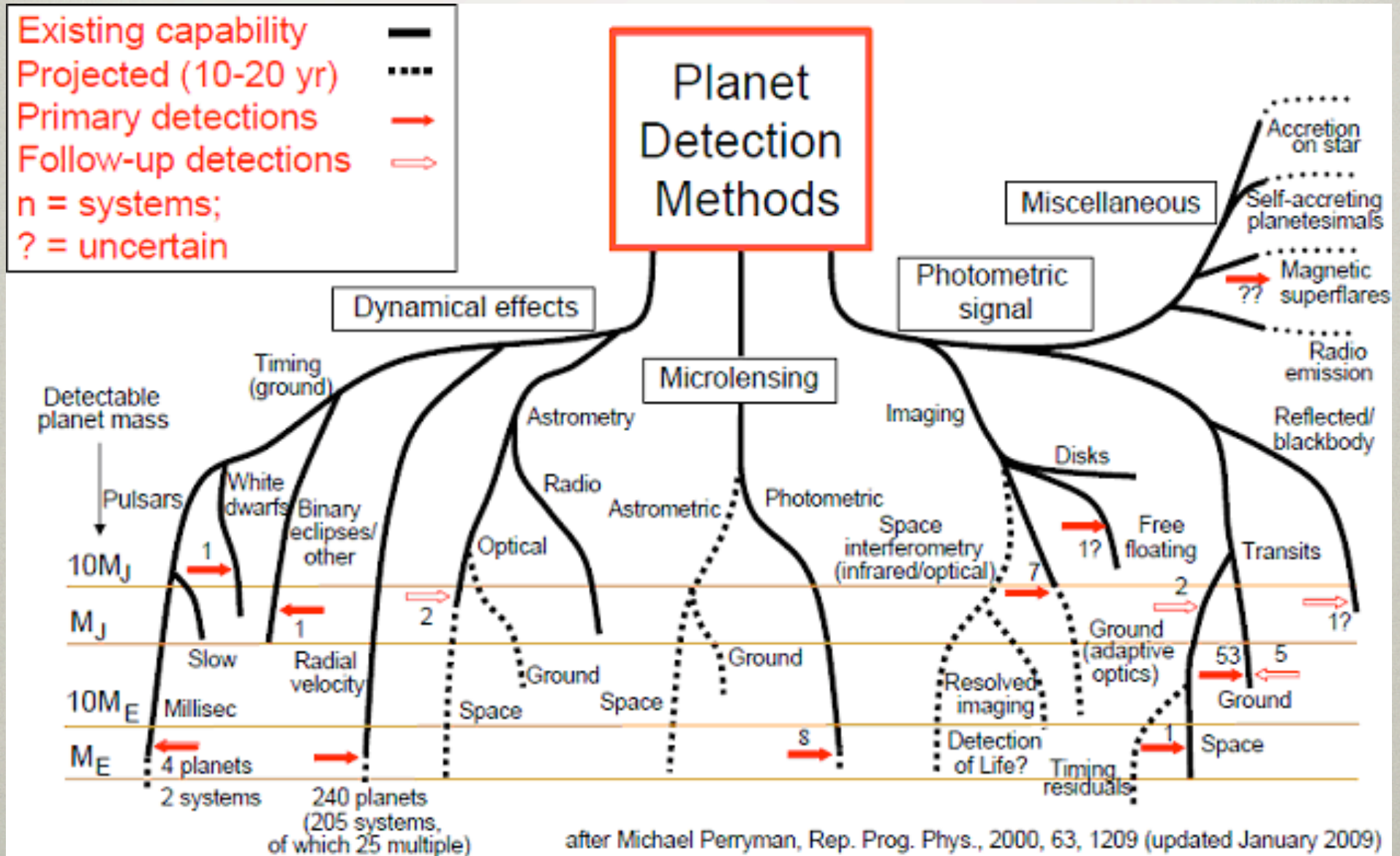


**55 Cnc**

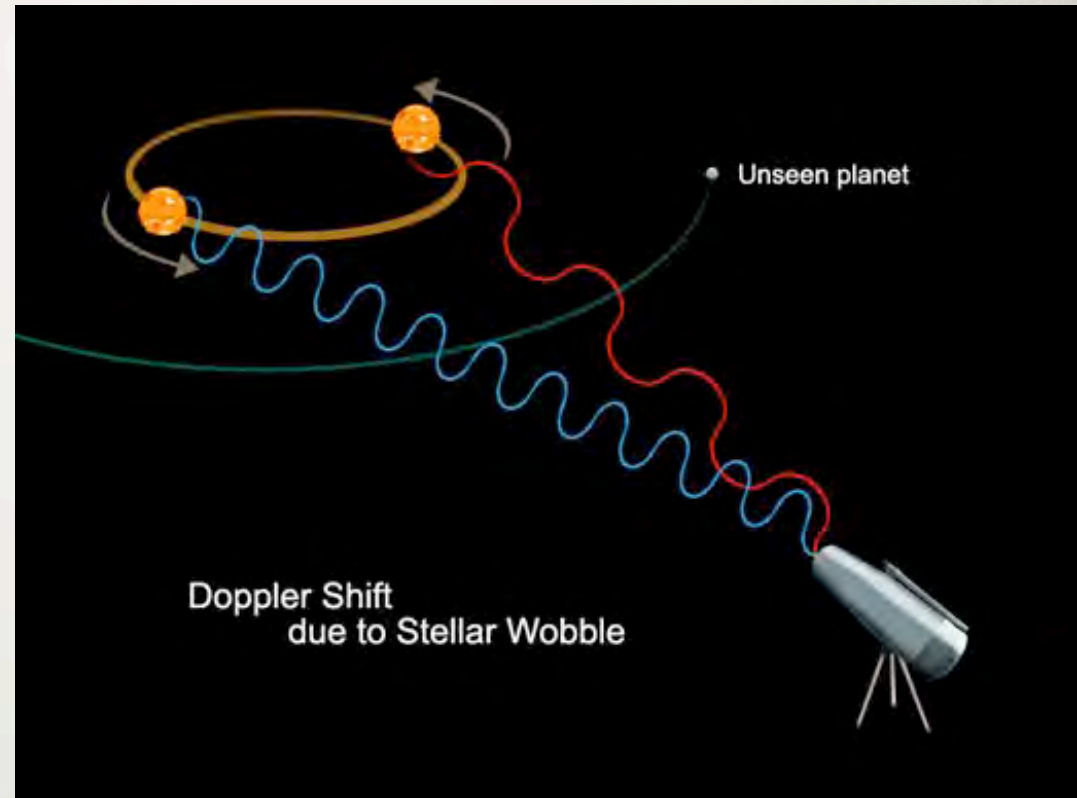
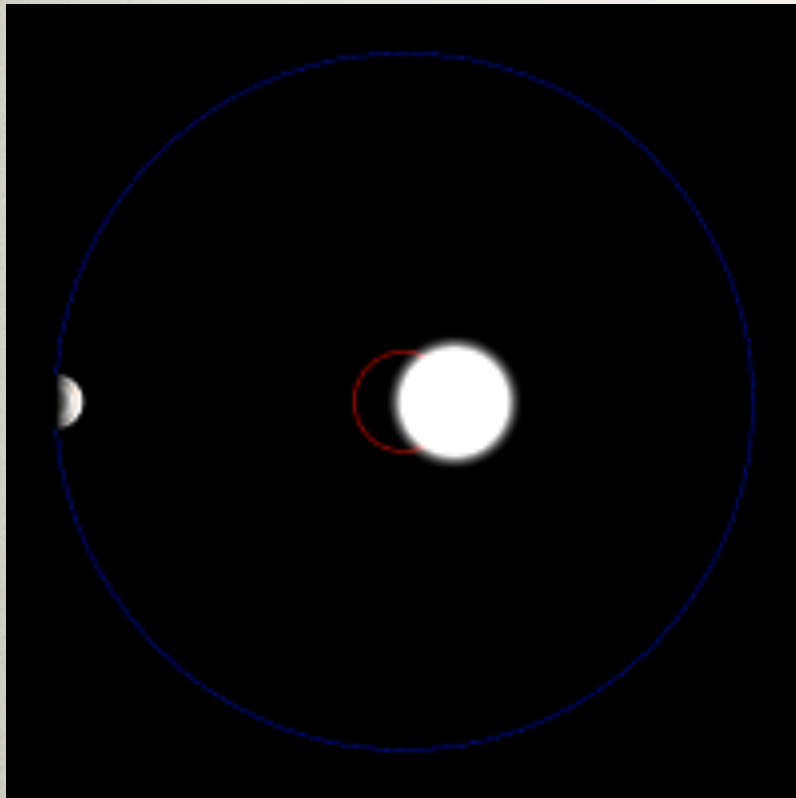




# EXOPLANET DETECTION METHODS



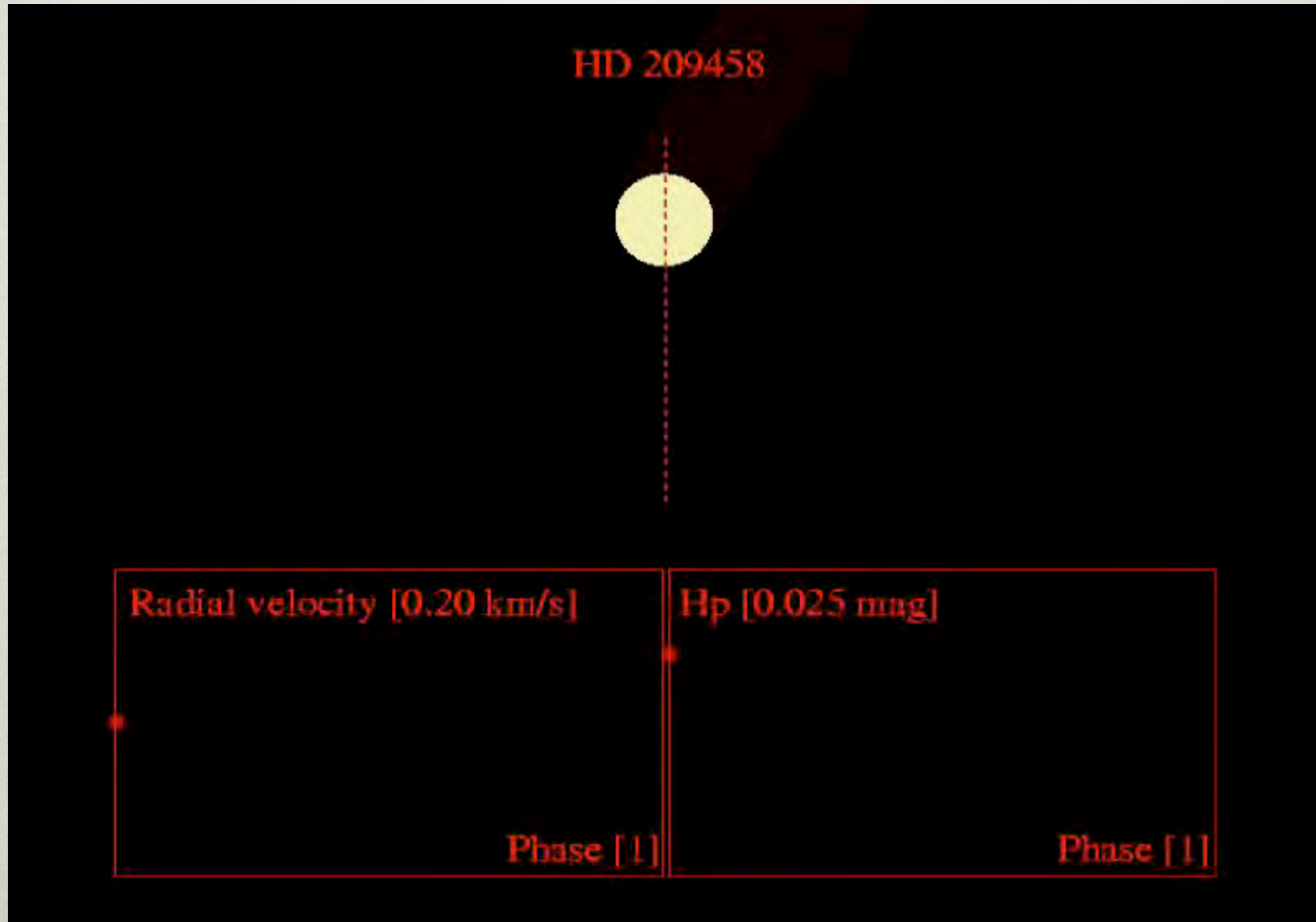
# RADIAL VELOCITY



[en.wikipedia.org/wiki/Extrasolar\\_planet](http://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 & LIGHT CURVE



# RADIAL VELOCITY SIGNAL

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Semi-amplitude of radial velocity given by

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

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

# RADIAL VELOCITY SIGNAL

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

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

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

# RADIAL VELOCITY SIGNAL AMPLITUDE

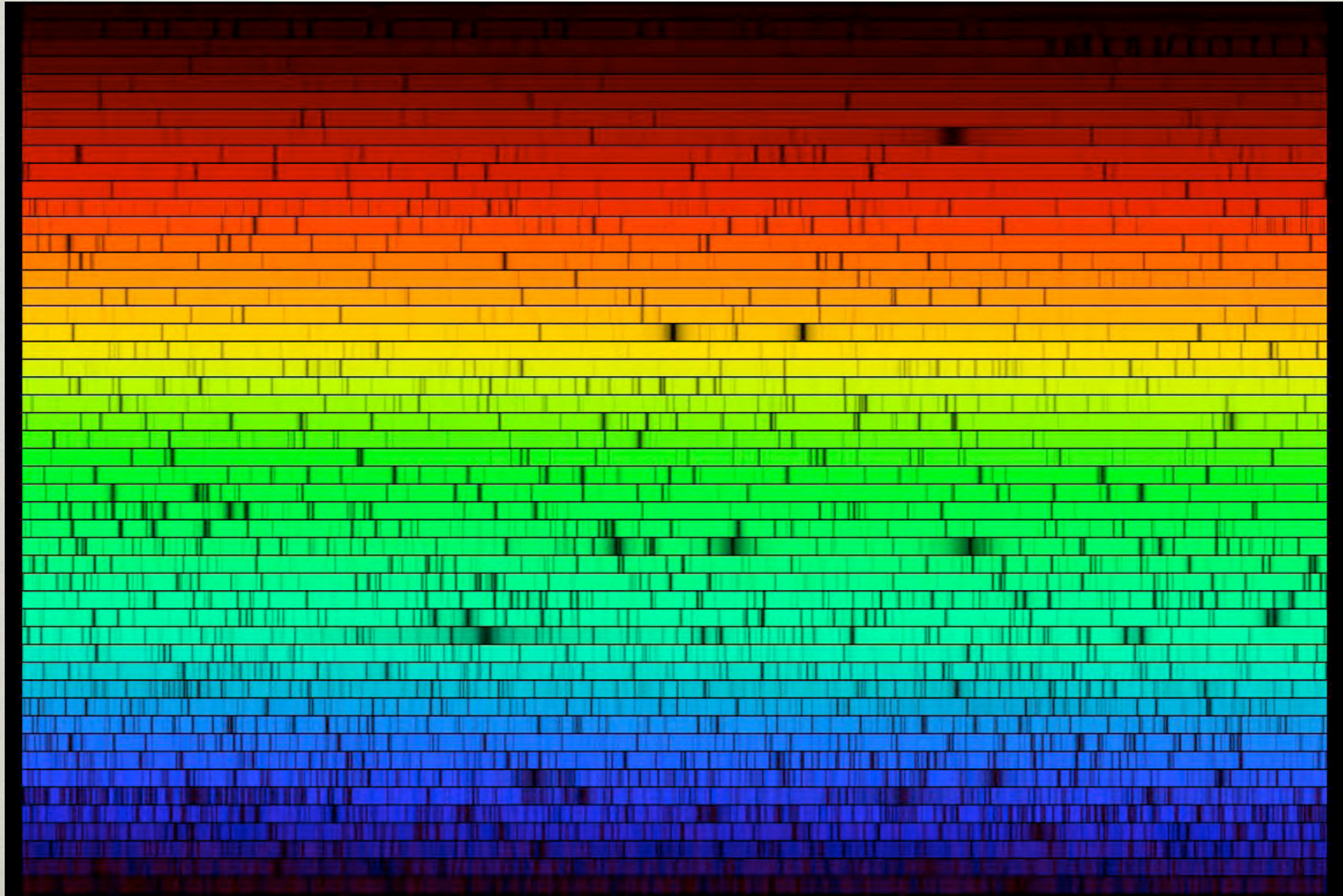
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$$K = \left( \frac{2\pi G}{P_{\text{orb}}} \right)^{\frac{1}{3}} \frac{M_P \sin i}{(M_* + M_P)^{\frac{2}{3}}} \frac{1}{\sqrt{1 - e^2}}$$

- 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

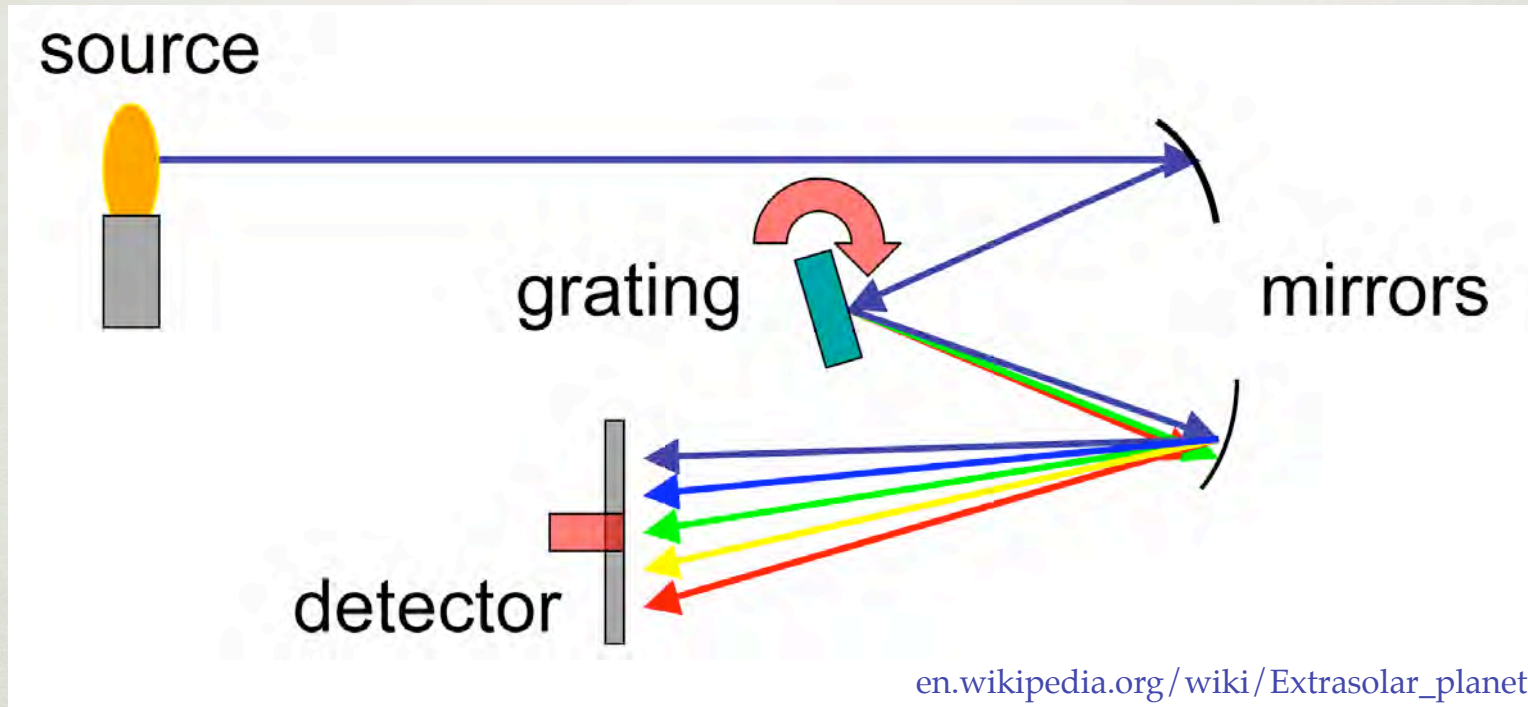
# SOLAR SPECTRUM

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[www.noao.edu/image\\_gallery/images/d5/suny.jpg](http://www.noao.edu/image_gallery/images/d5/suny.jpg)

# SPECTROMETER



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



# POSITIONAL STABILITY REQUIREMENT

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

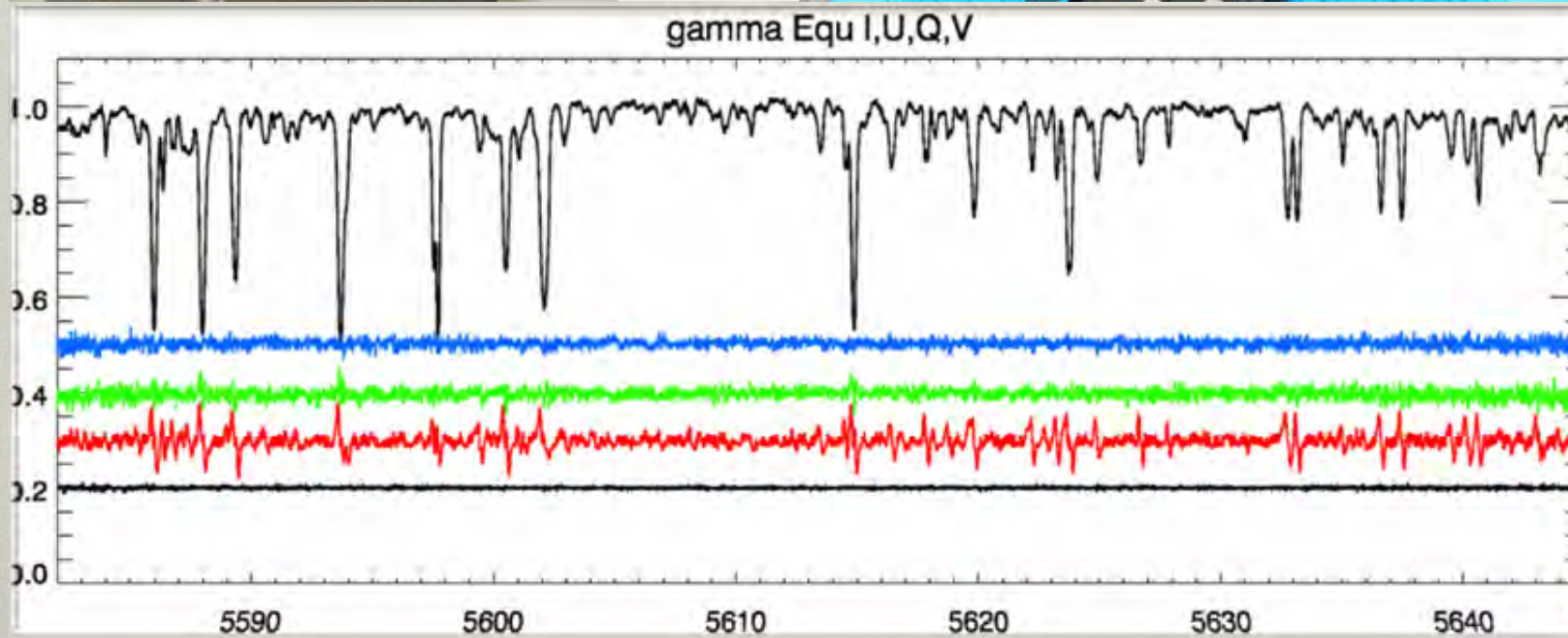
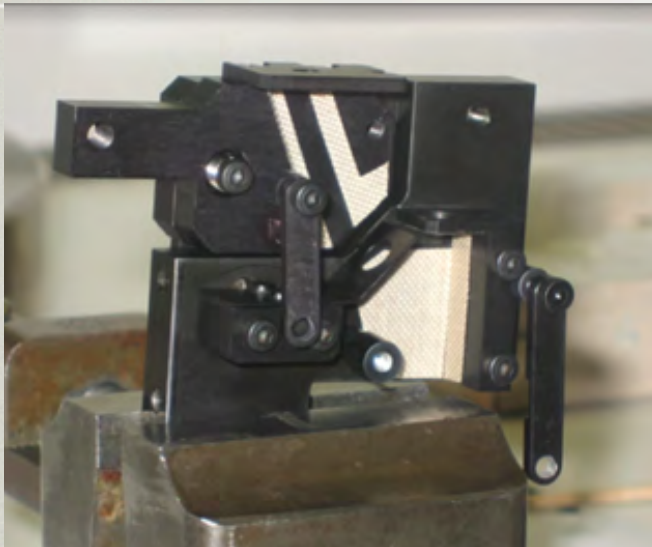
# HARPS



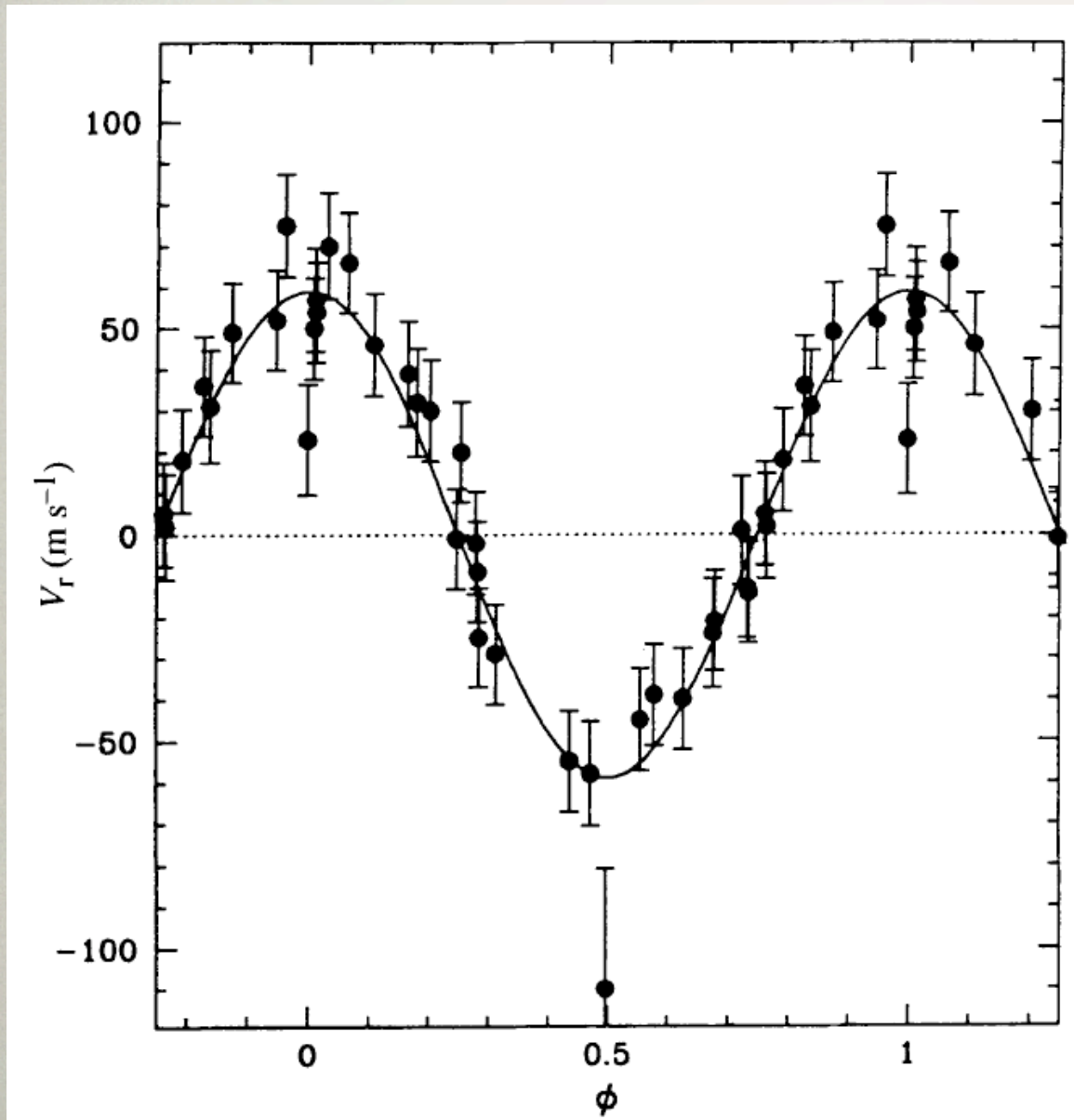
[obswww.unige.ch/Instruments/Harps/gallery/Integration\\_LSO/](http://obswww.unige.ch/Instruments/Harps/gallery/Integration_LSO/)

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

# HARPS POLARIMETER

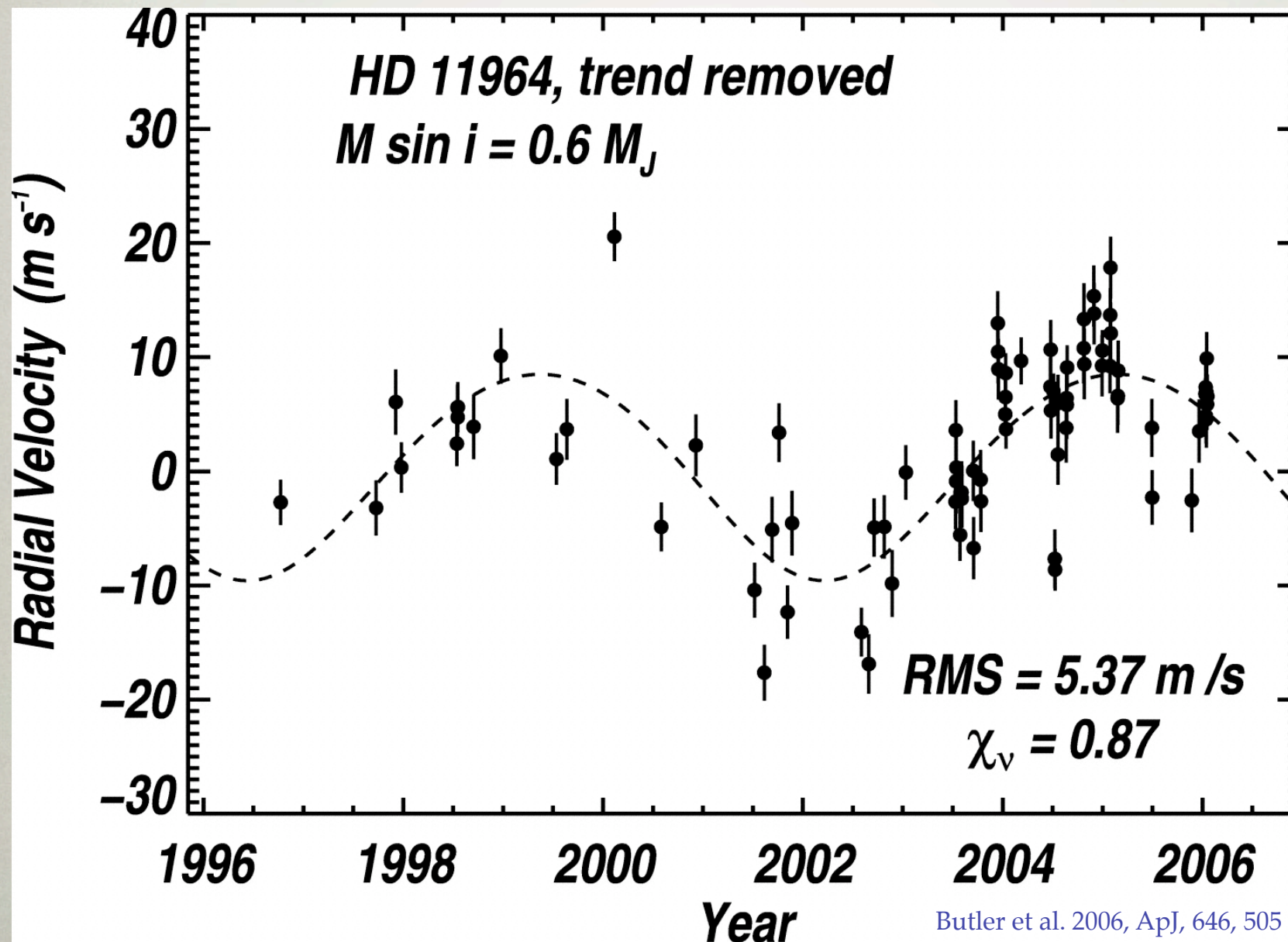


# EXAMPLE 1: 51 PEGASI B

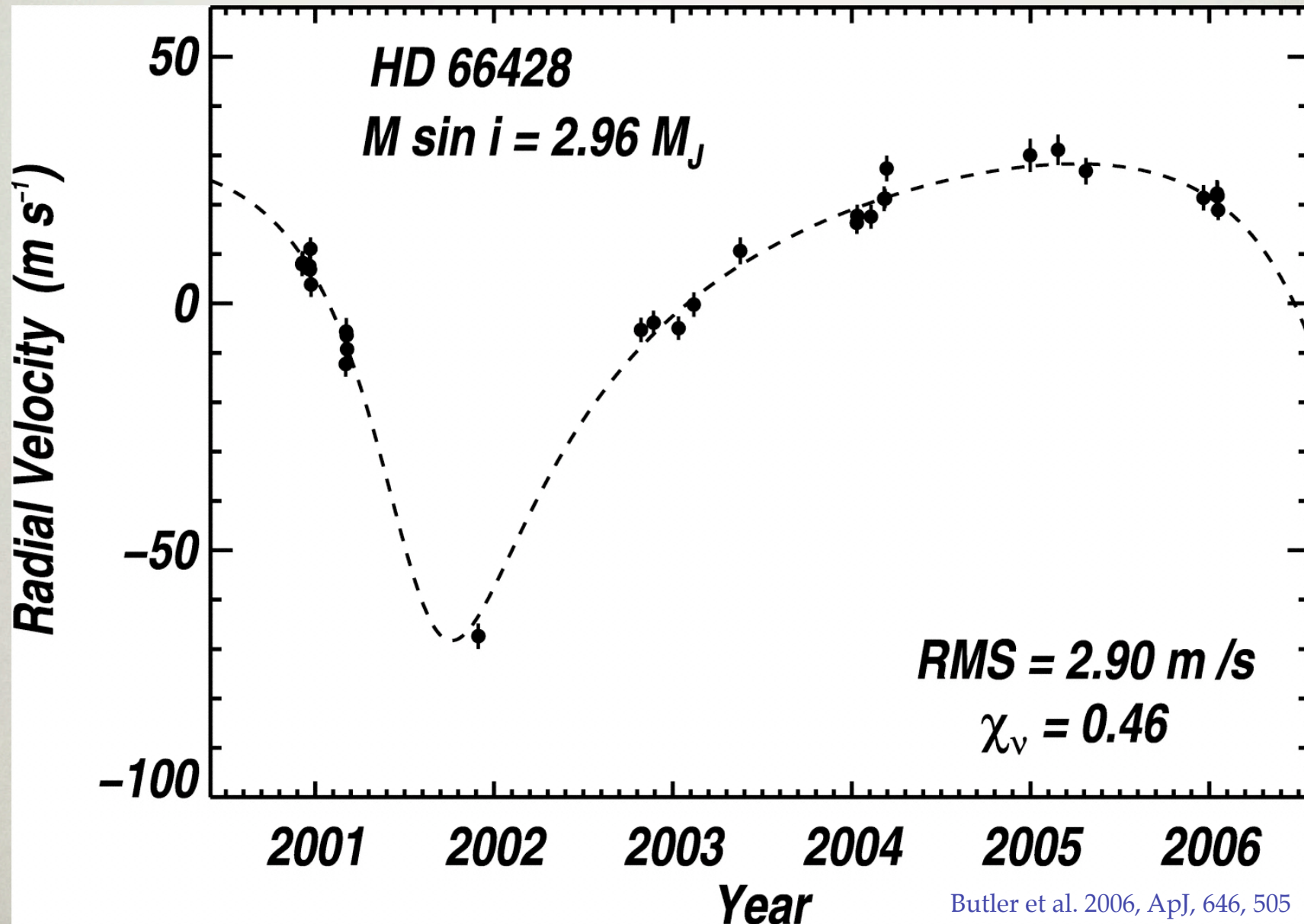


Mayor and Queloz 1995 Figure 4

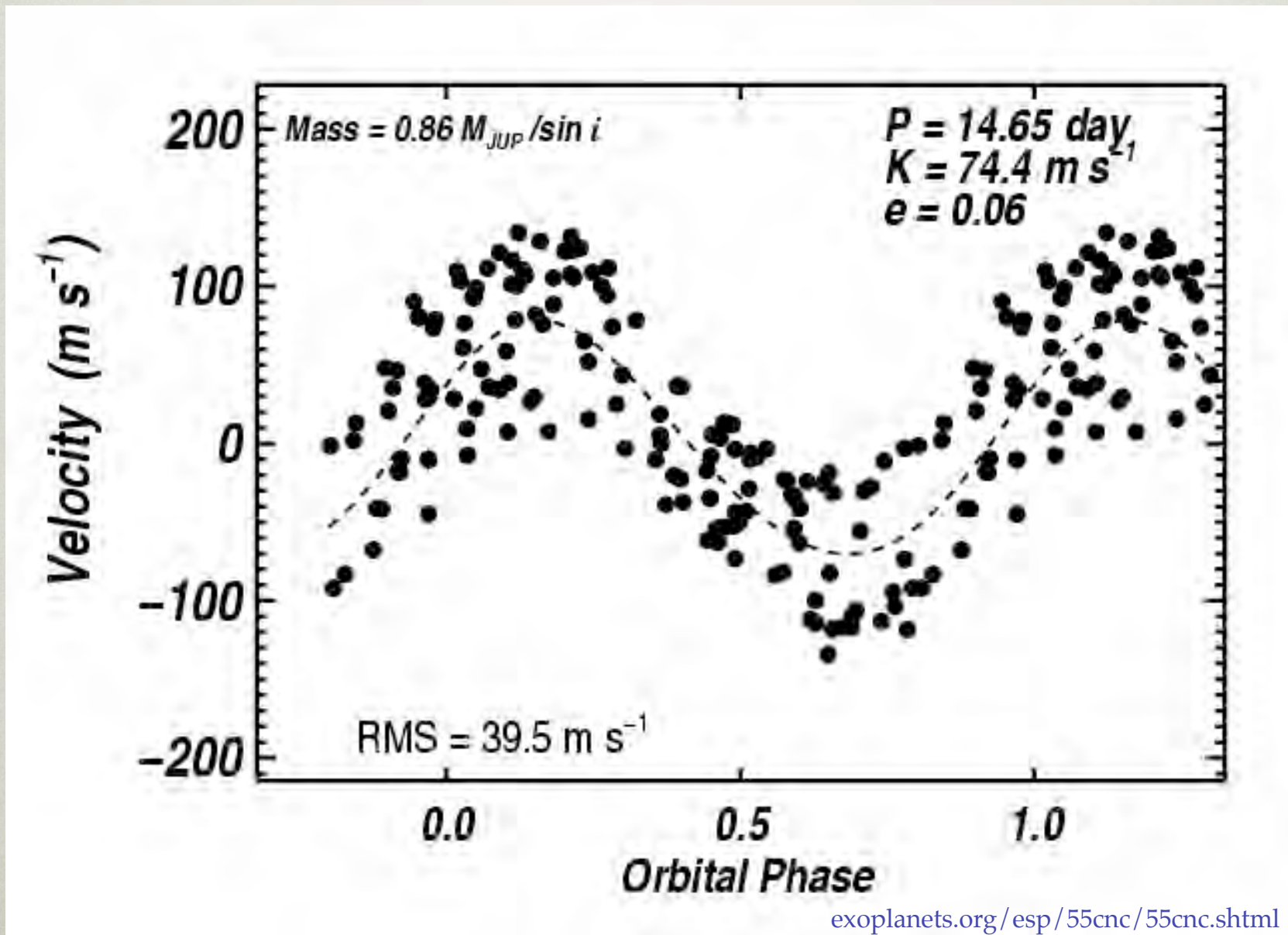
## EXAMPLE 2: $e=0$



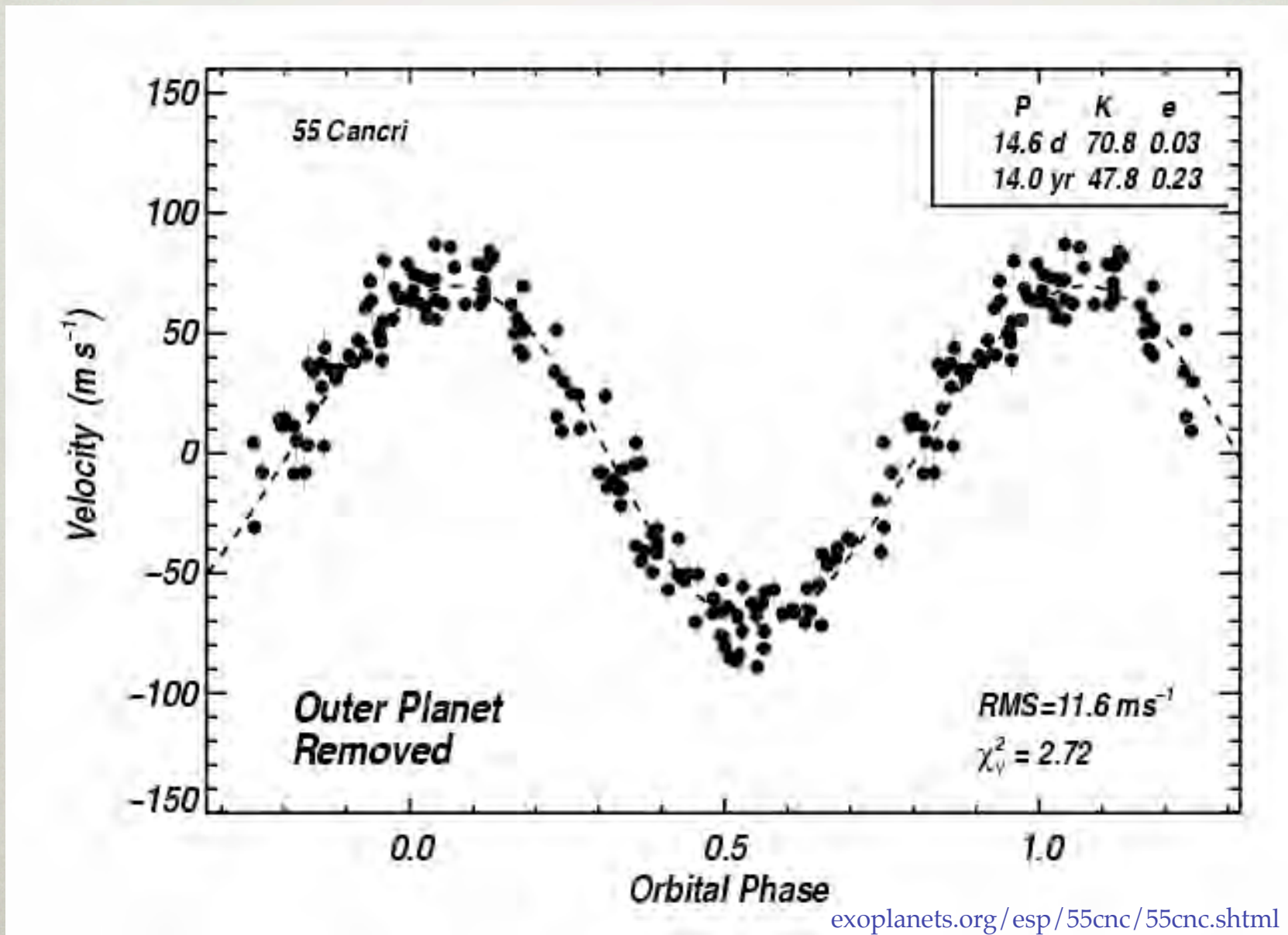
# EXAMPLE 3: $e=0.5$



# MULTIPLE PLANETS: ONE-PLANET FIT

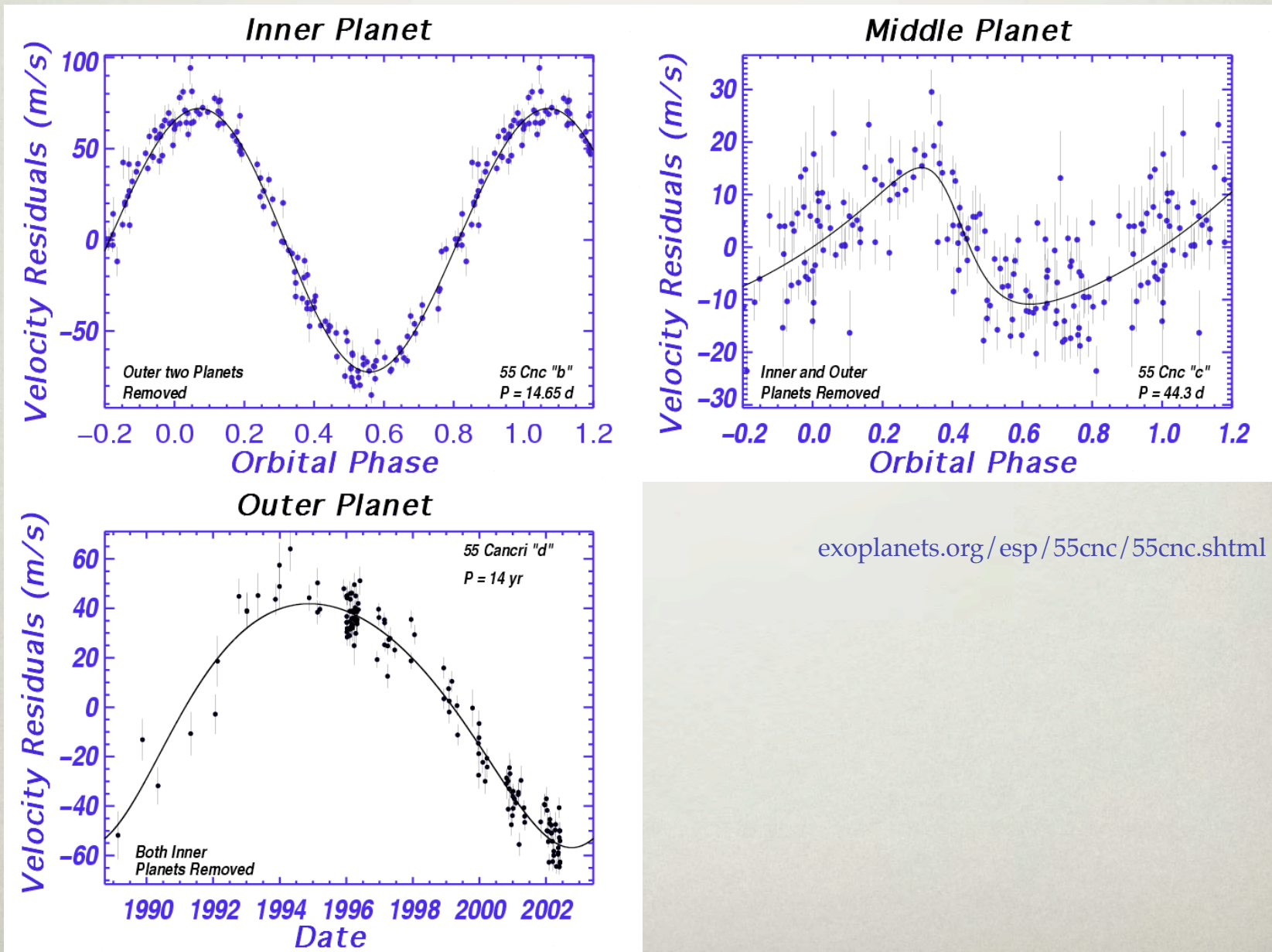


# MULTIPLE PLANETS: TWO-PLANET FIT





# MULTIPLE PLANETS: THREE-PLANET FIT



[exoplanets.org/esp/55cnc/55cnc.shtml](http://exoplanets.org/esp/55cnc/55cnc.shtml)

# RADIAL VELOCITY OBSERVABLES

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

# PROBLEMS WITH RADIAL VELOCITY

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- Correction of earth orbital motion (up to 30 km/s) and earth rotation (0.5 km/s)
- Period analysis (see Observational Astrophysics 2)
- 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 signal

# RADIAL VELOCITY LIMITS

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

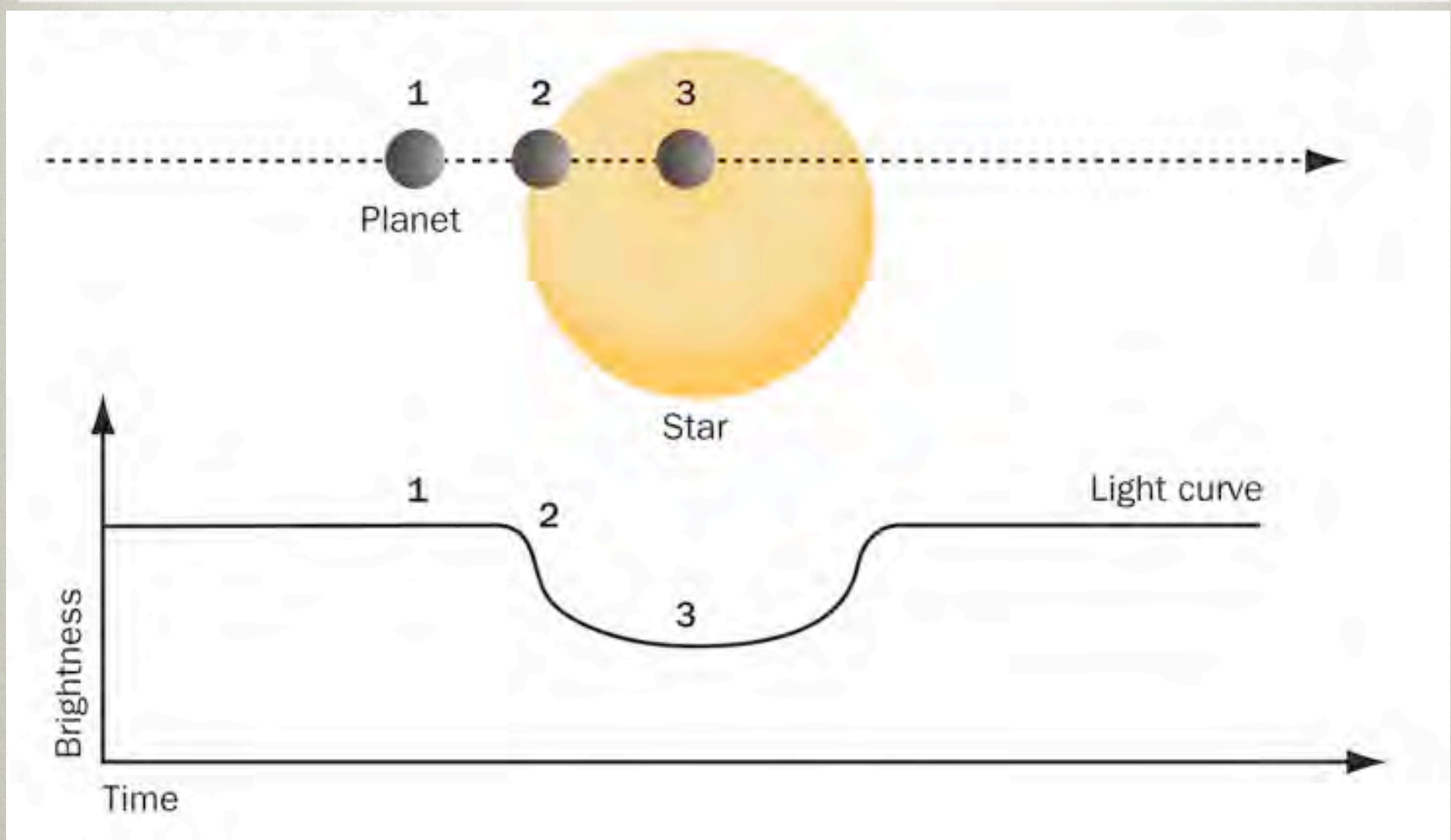
- Kepler's 3<sup>rd</sup> law:  $P_{\text{orb}}^{1/3} \sim a^{1/2}/M_*^{1/6}$
- Limit given by  $M_P \sin i \sim a^{1/2}$
- Need to observe at least one full orbit
- Detection limit proportional to  $a^{1/2}$

# TRANSITS

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

# TRANSITS



[www.sciencenews.org/view/feature/id/39031/title/The\\_Hunt\\_for\\_Habitable\\_Planets](http://www.sciencenews.org/view/feature/id/39031/title/The_Hunt_for_Habitable_Planets)

# TRANSIT SIGNALS

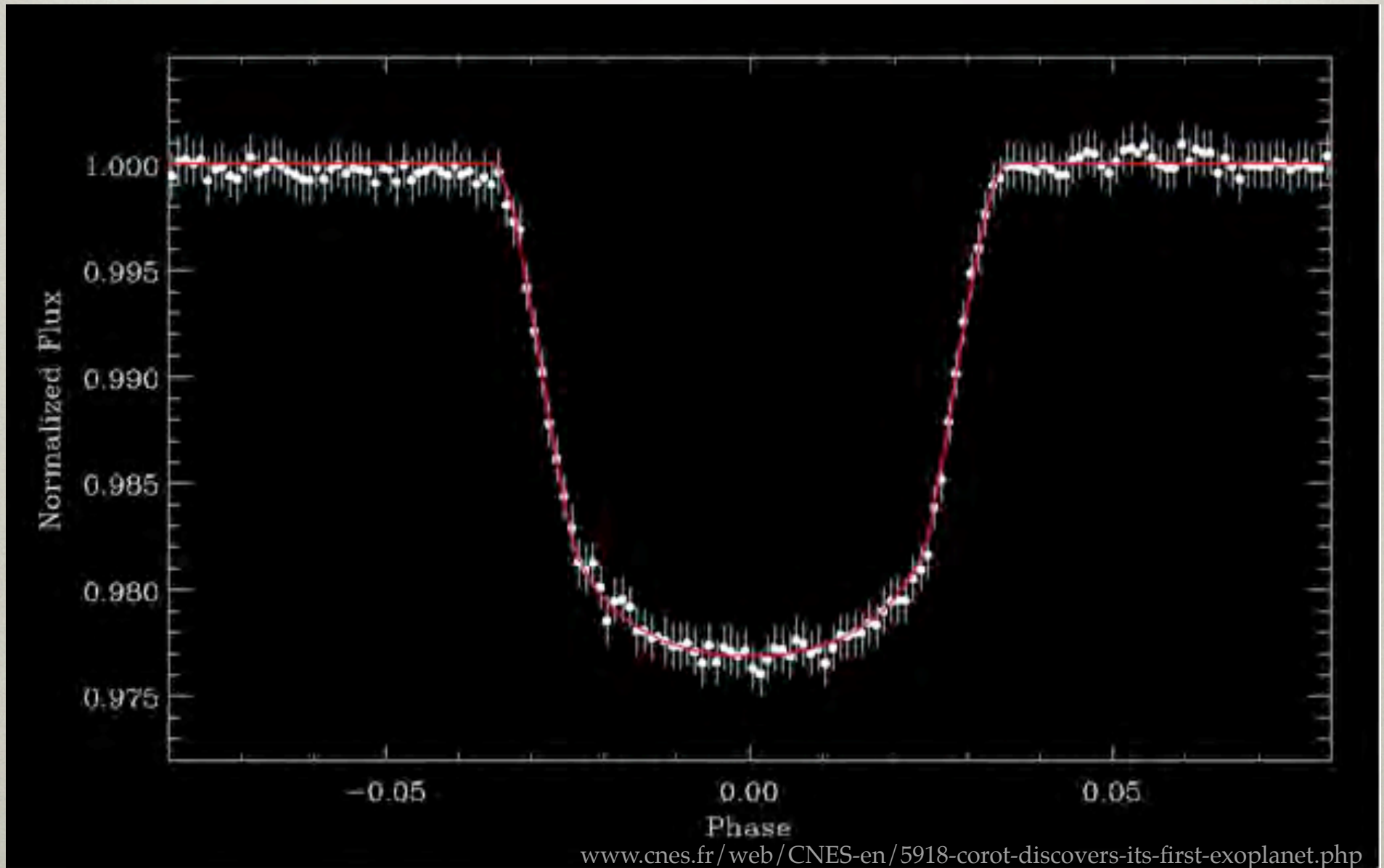
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- Intensity signal

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

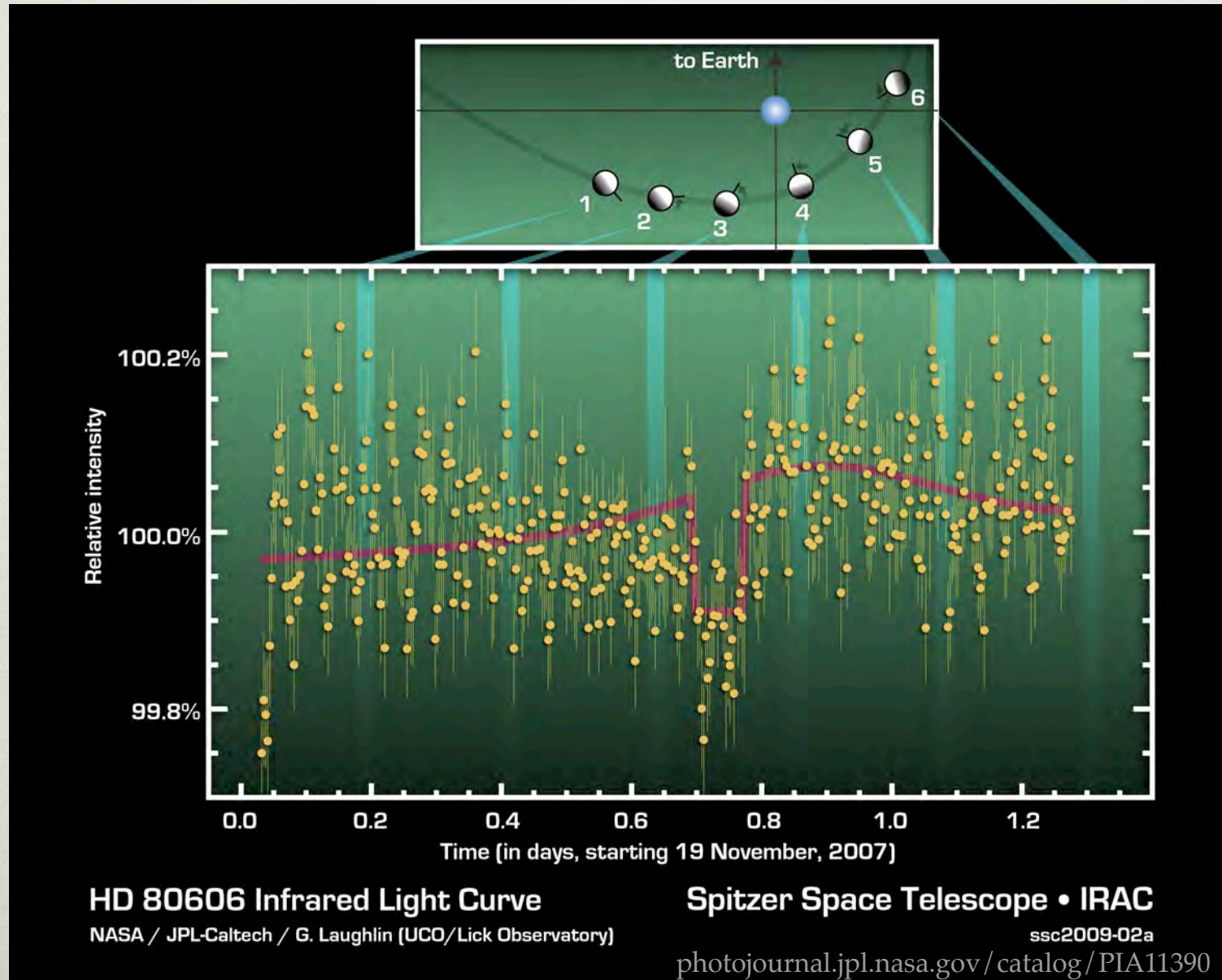
- About 1% for Jupiter and Sun
- Transit duration proportional to  $P_{\text{orb}}^{1/3} R_* / M_*^{1/3}$
- Transit duration provides estimate of stellar radius
- Intensity change then provides planetary radius

# TRANSIT EXAMPLE (COROT)



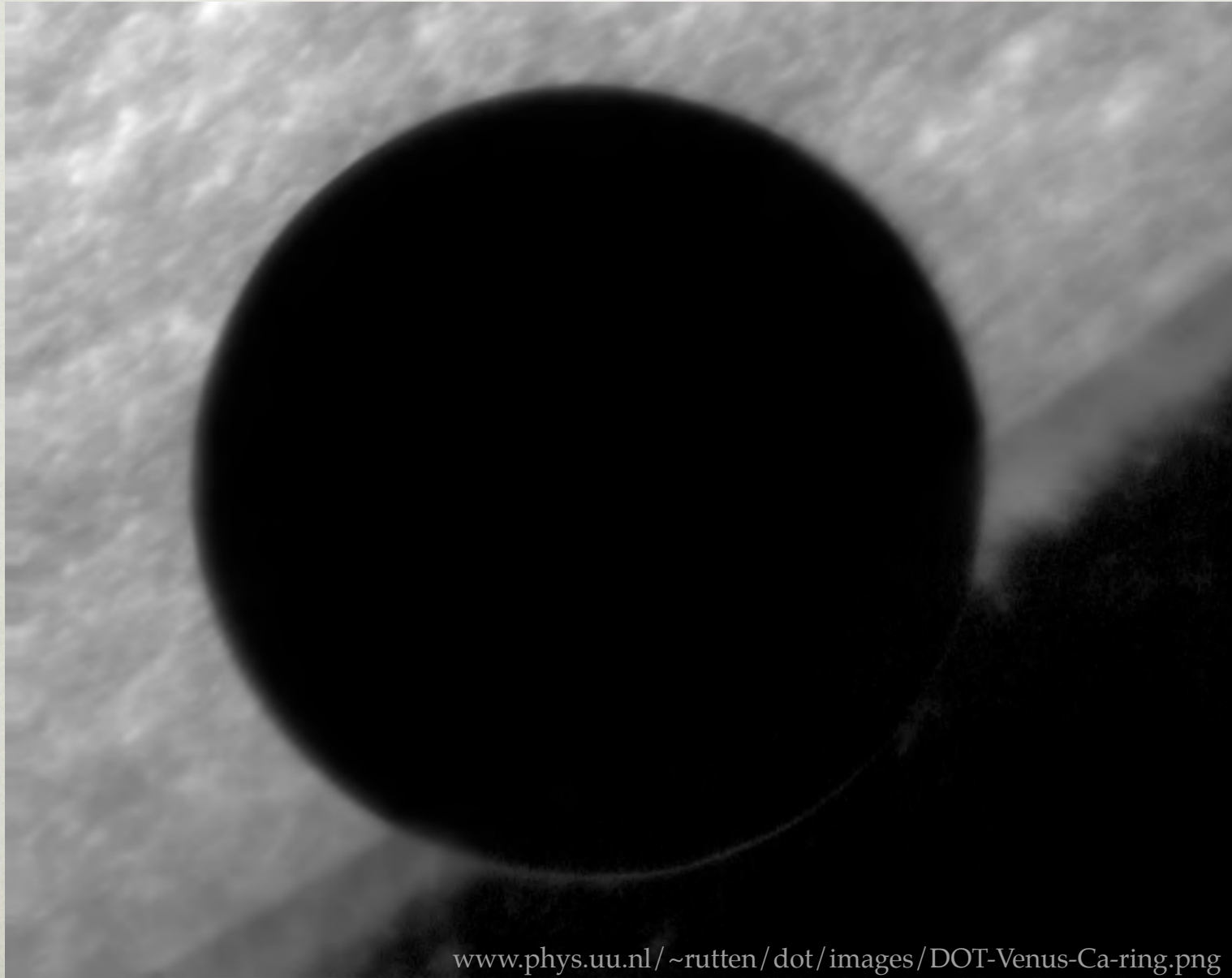


# SECONDARY ECLIPSE



# ATMOSPHERIC TRANSMISSION

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[www.phys.uu.nl/~rutten/dot/images/DOT-Venus-Ca-ring.png](http://www.phys.uu.nl/~rutten/dot/images/DOT-Venus-Ca-ring.png)

# TRANSIT OBSERVABLES

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- Period
  - Orbit inclination ( $i=90^\circ$ )
  - Planet radius
  - Planet temperature from secondary eclipse
  - Stellar limb darkening
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- Good for large planets close to the star

# PROBLEMS WITH TRANSITS

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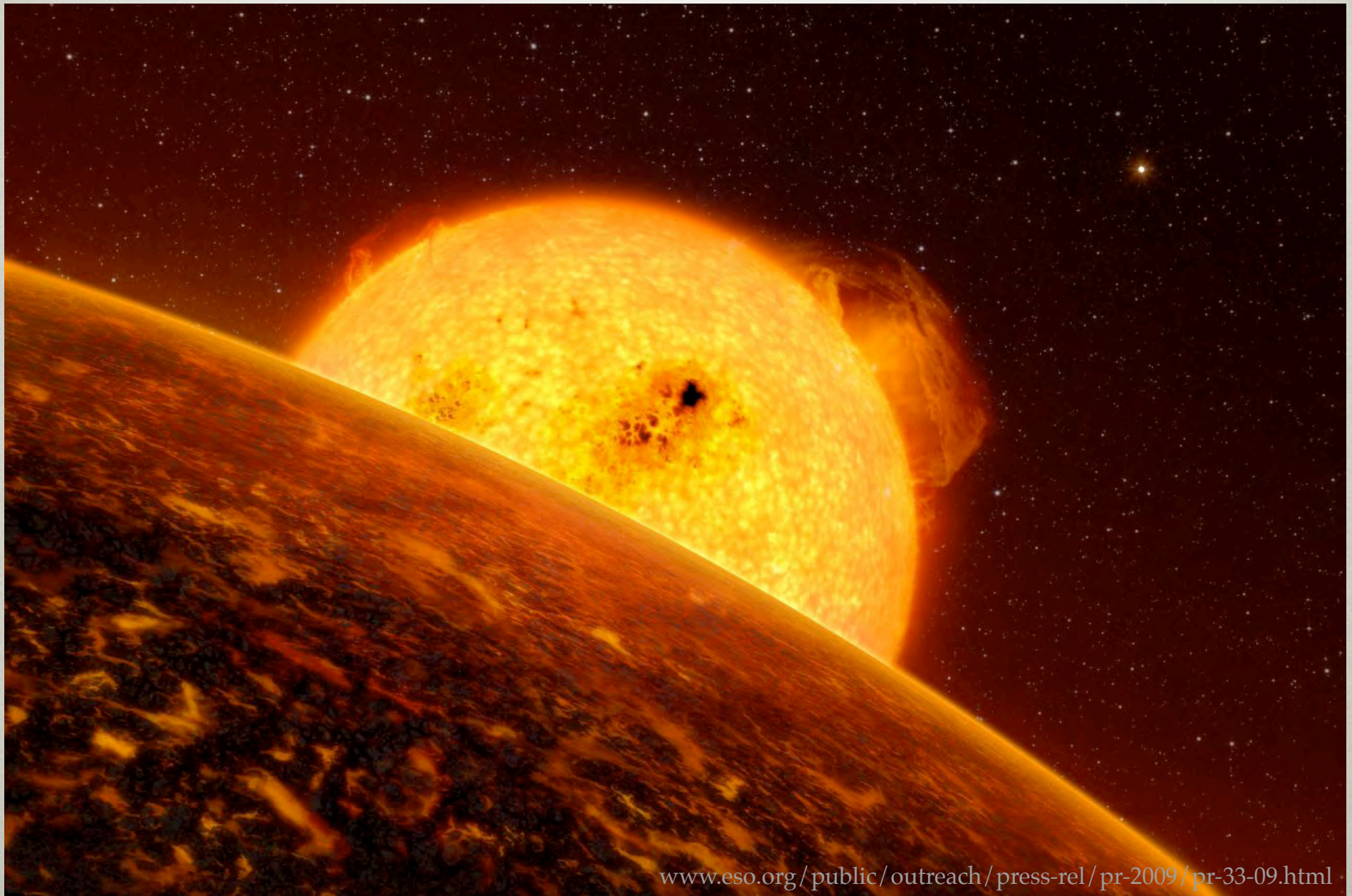
- Low probability, but simple observation
- Many false positives:
  - Grazing eclipse from main-sequence star
  - Eclipsing binary (giant and main-sequence)
  - Eclipsing binary close by (foreground or background)
- Only one in 10 candidates is real exoplanet
- Need radial velocity confirmation with big telescopes
- Transit and radial velocity → planet density

# TRANSIT LIMITS

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- 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  $a$

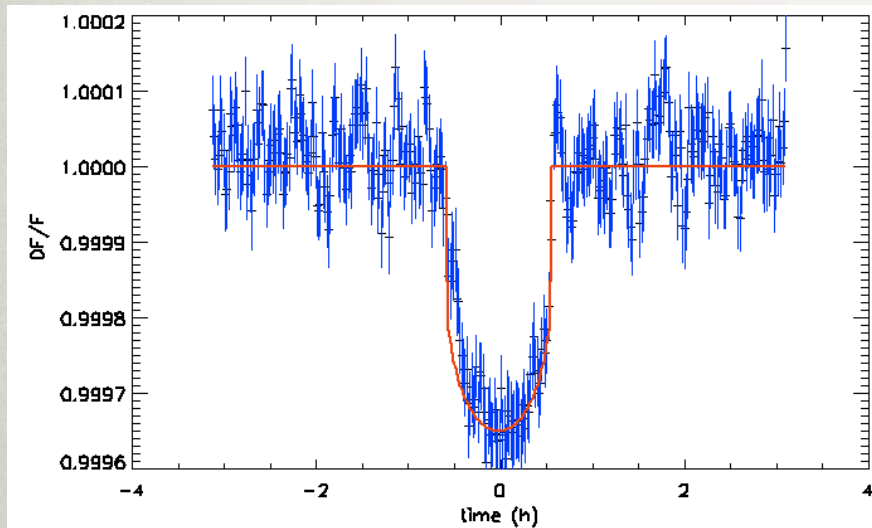
# CoRoT-7B



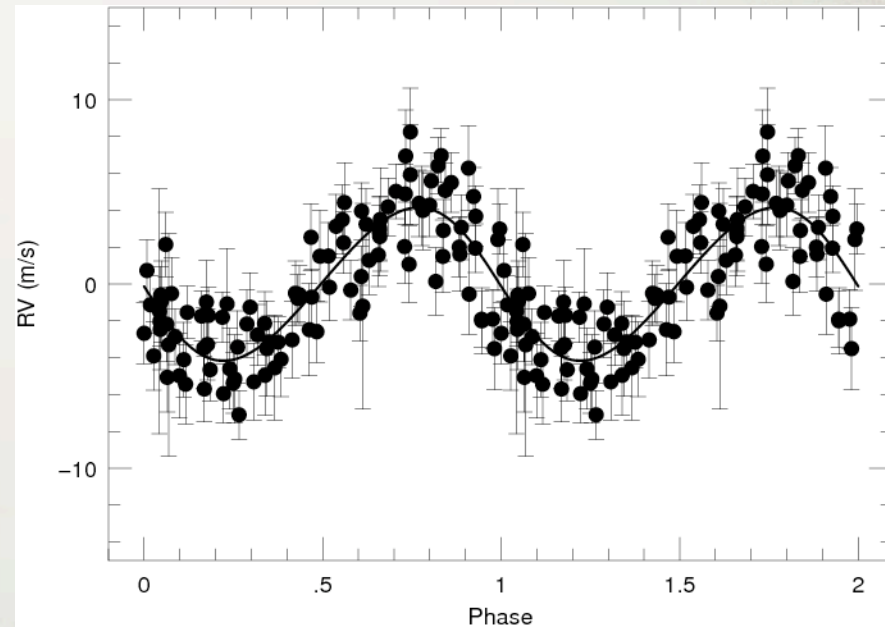
[www.eso.org/public/outreach/press-rel/pr-2009/pr-33-09.html](http://www.eso.org/public/outreach/press-rel/pr-2009/pr-33-09.html)

# FIRST ROCKY EXOPLANET

CoRoT (Leger et al. 2009)



HARPS (Queloz et al. 2009)



- 4.8 Earth masses
- density  $5.6 \text{ g/cm}^3$

# GRAVITATIONAL LENSING



**Galaxy Cluster Abell 2218**

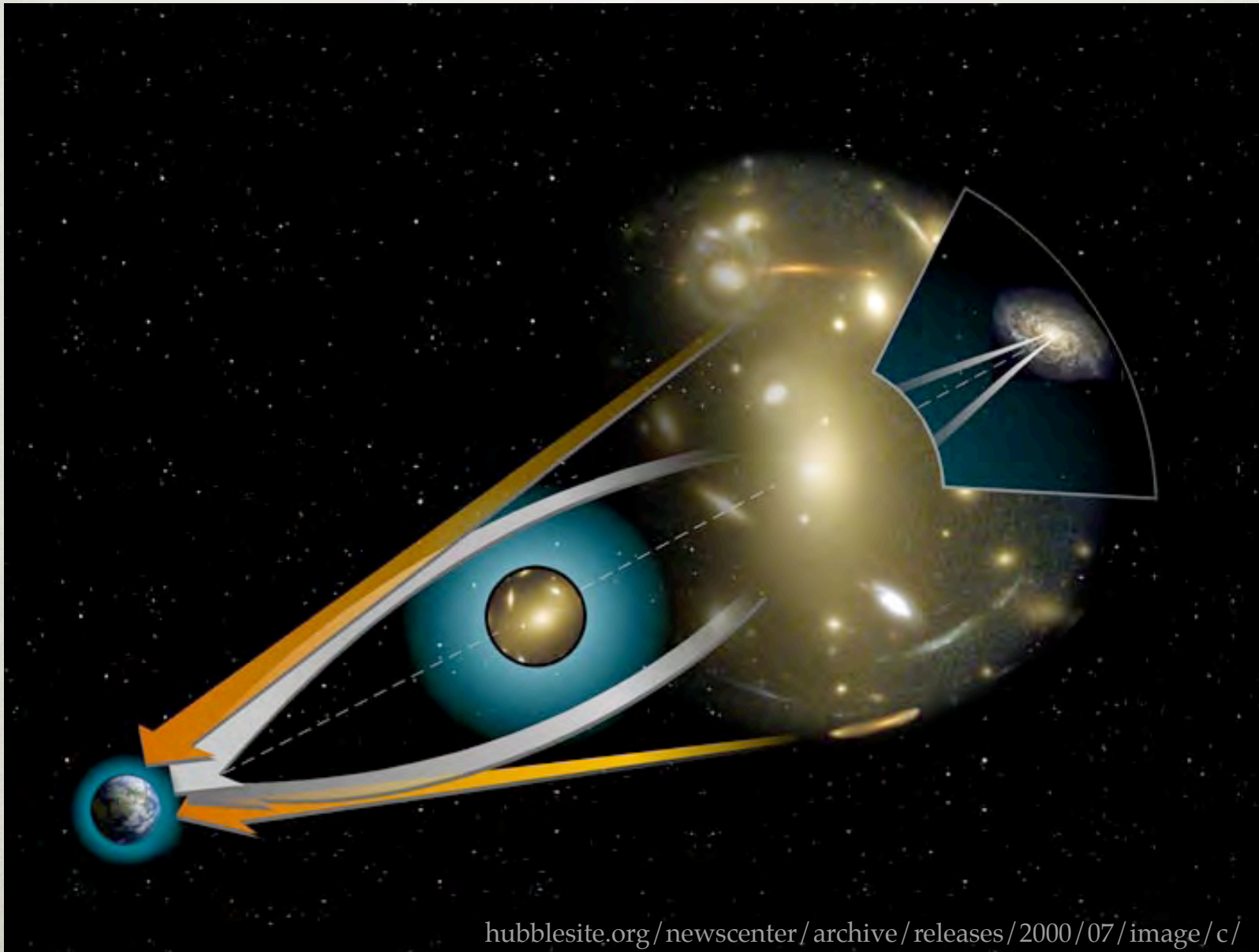
**HST • WFPC2**

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

[apod.nasa.gov/apod/image/0110/a2218c\\_hst\\_big.jpg](http://apod.nasa.gov/apod/image/0110/a2218c_hst_big.jpg)

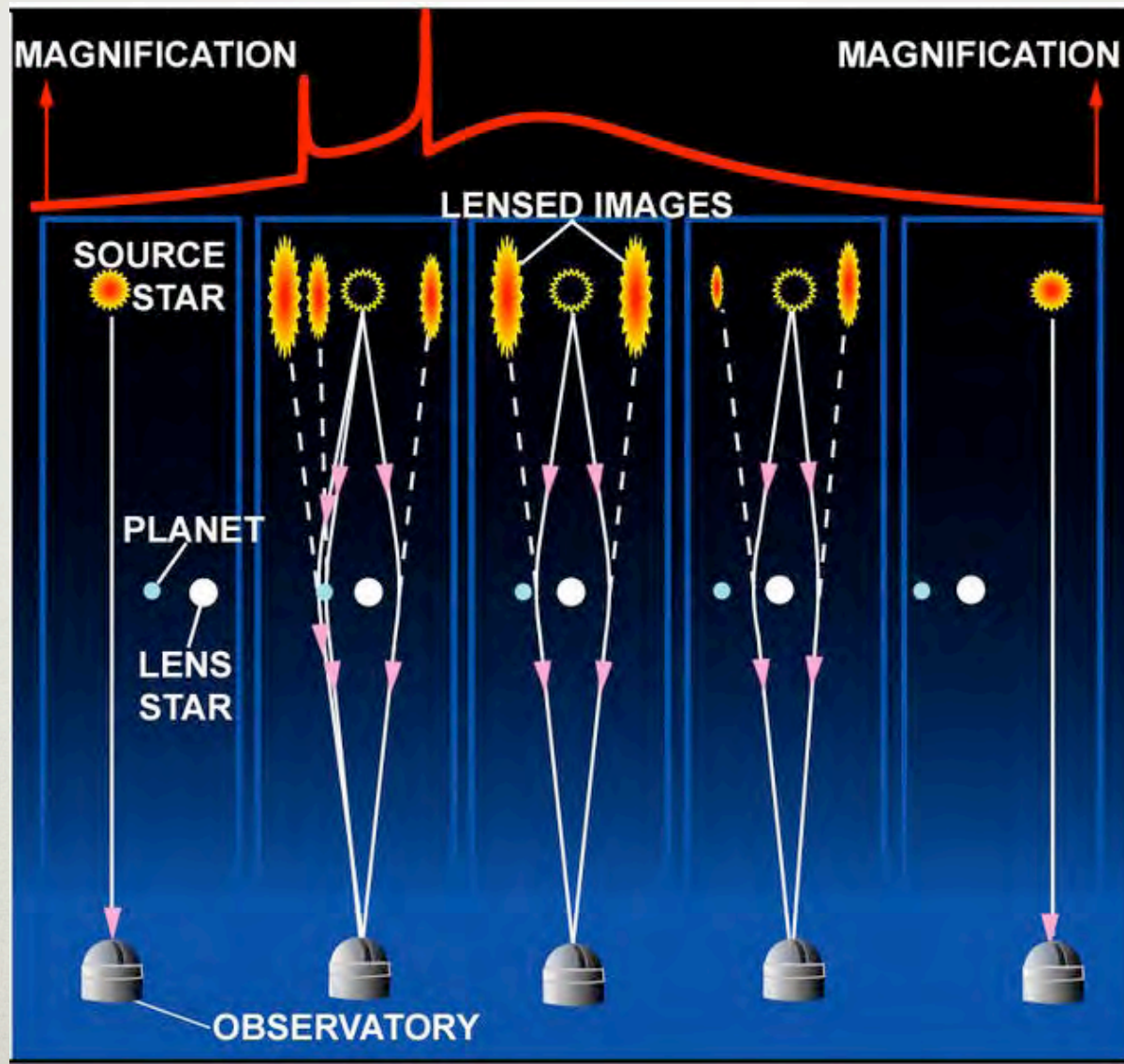


# GRAVITATIONAL LENSING EXPLAINED



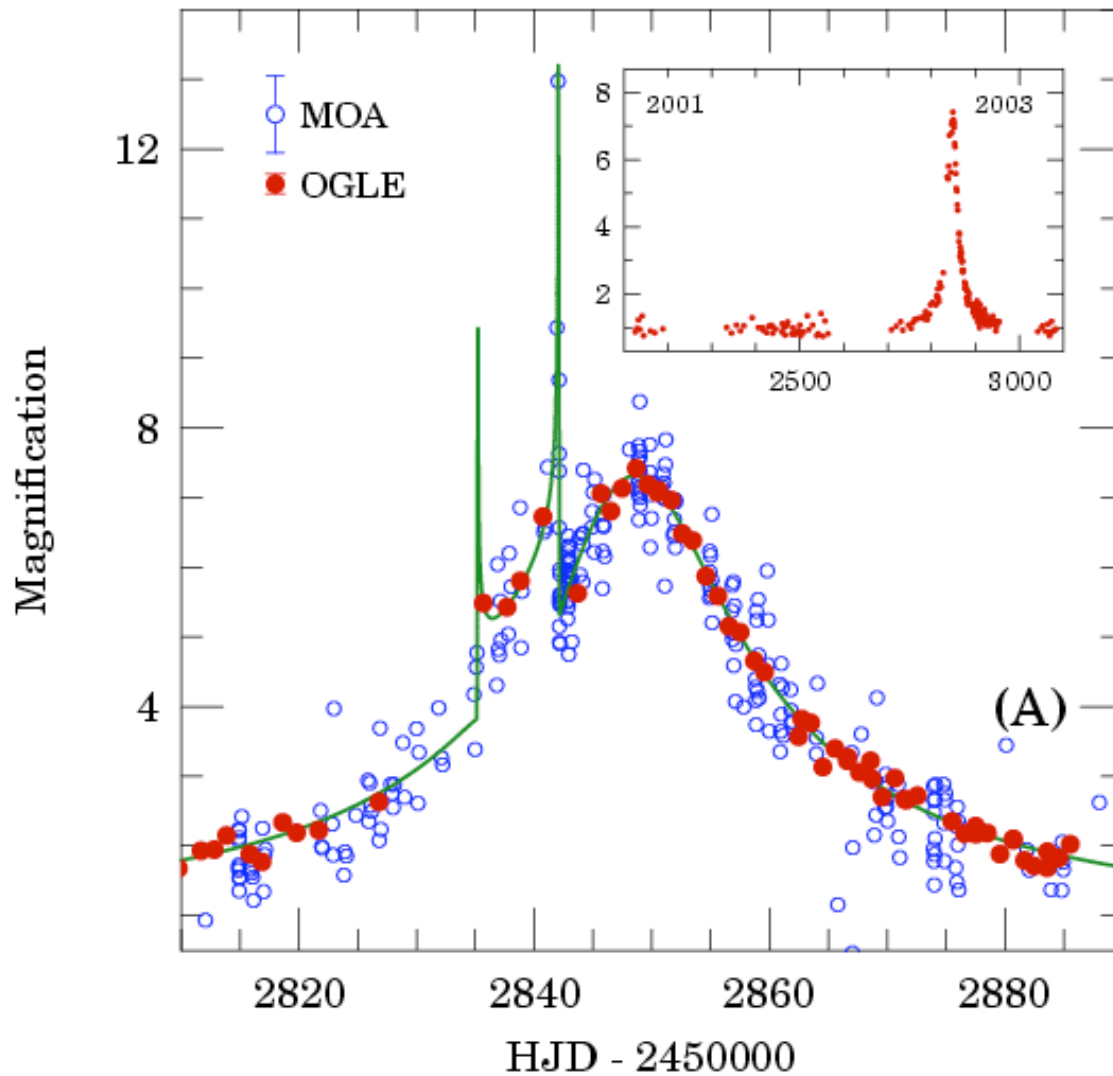
[hubblesite.org/newscenter/archive/releases/2000/07/image/c/](http://hubblesite.org/newscenter/archive/releases/2000/07/image/c/)

# MICROLENSING



[ogle.astrouw.edu.pl/cont/4\\_main/epl/blg235/blg235.html](http://ogle.astrouw.edu.pl/cont/4_main/epl/blg235/blg235.html)

# MICROLENSING EVENT



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

[ogle.astrouw.edu.pl/cont/4\\_main/epl/blg235/blg235.html](http://ogle.astrouw.edu.pl/cont/4_main/epl/blg235/blg235.html)

# PROBLEMS WITH MICROLENSING

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

# DIRECT IMAGING

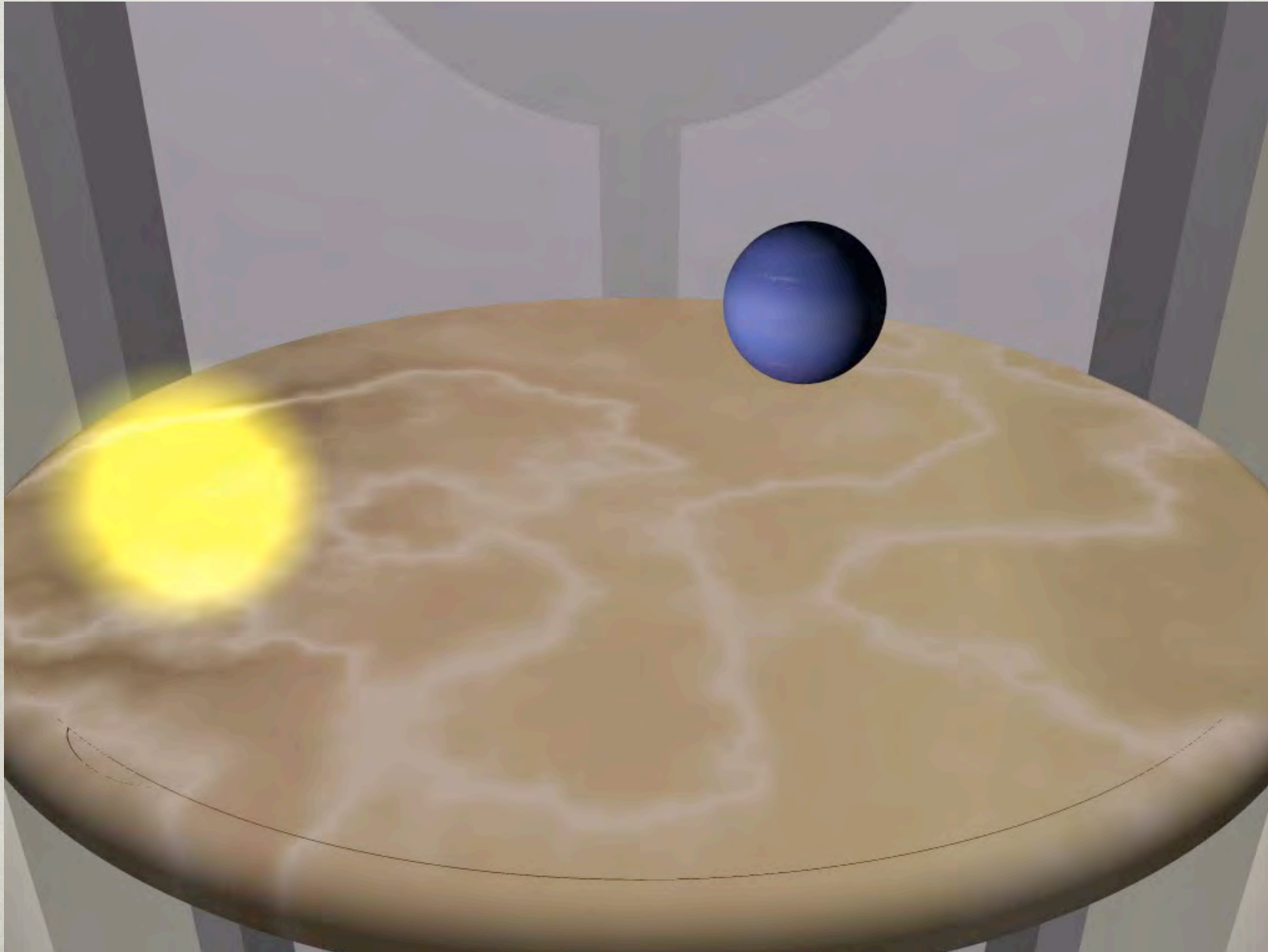
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- Central star much brighter than disks and planets
  - Disks: at least  $10^4$  times fainter than central star
  - Jupiter:  $10^9$  times fainter than Sun
- Telescope optics, Earth atmosphere make halo
  - halo:  $10^2$  to  $10^6$  times fainter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



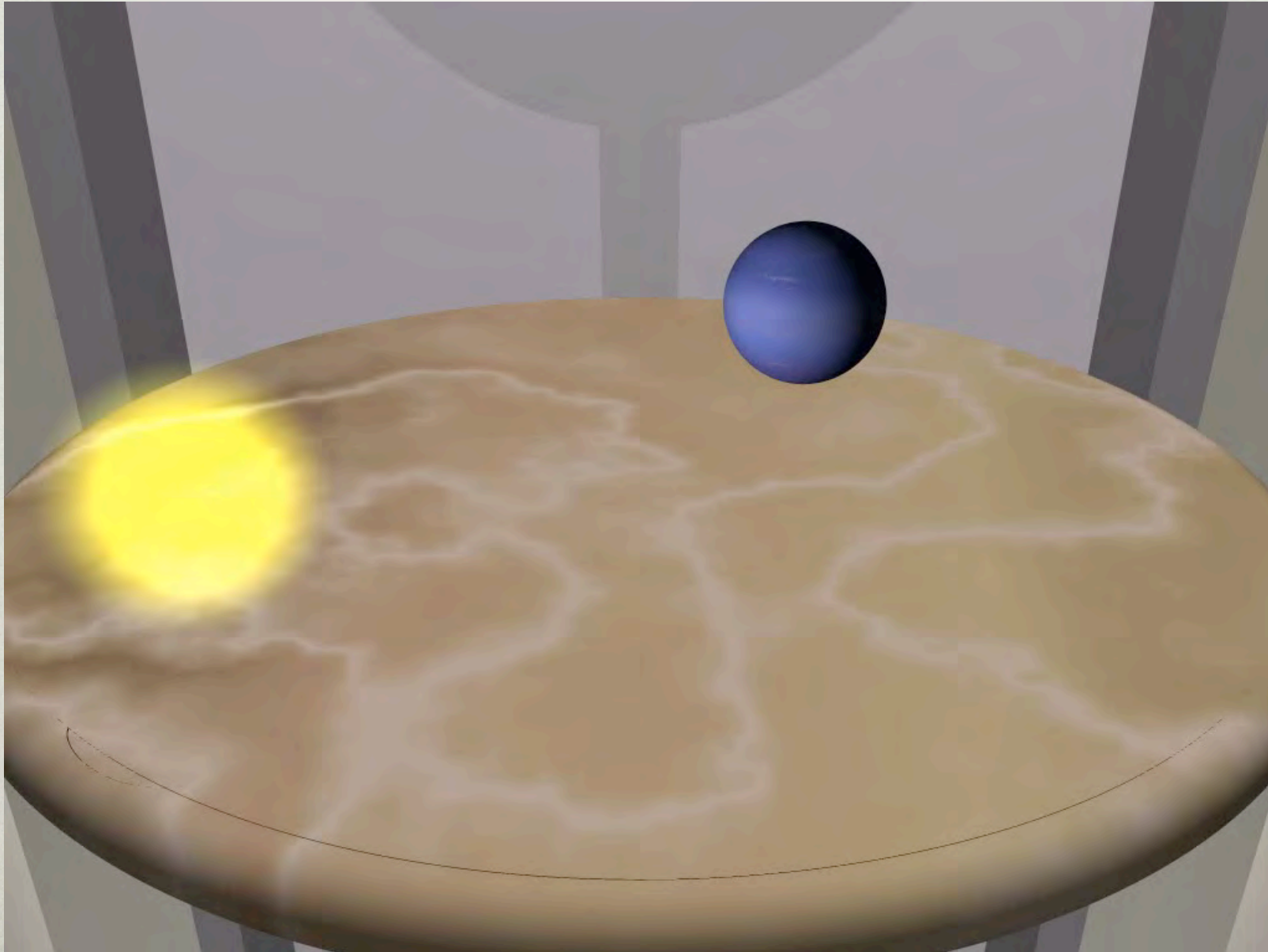
# SCATTERING POLARIZATION

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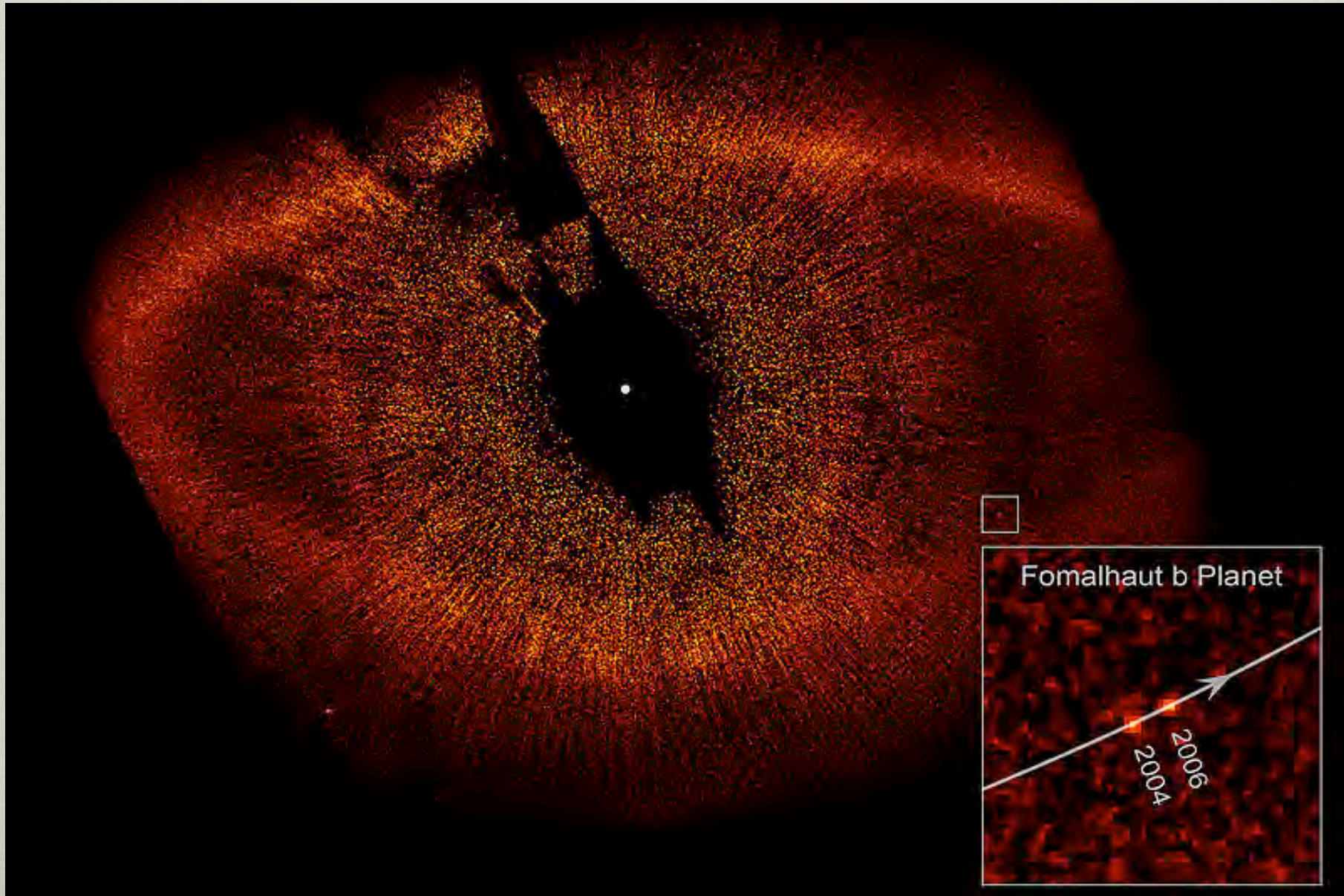


# SCATTERING POLARIZATION

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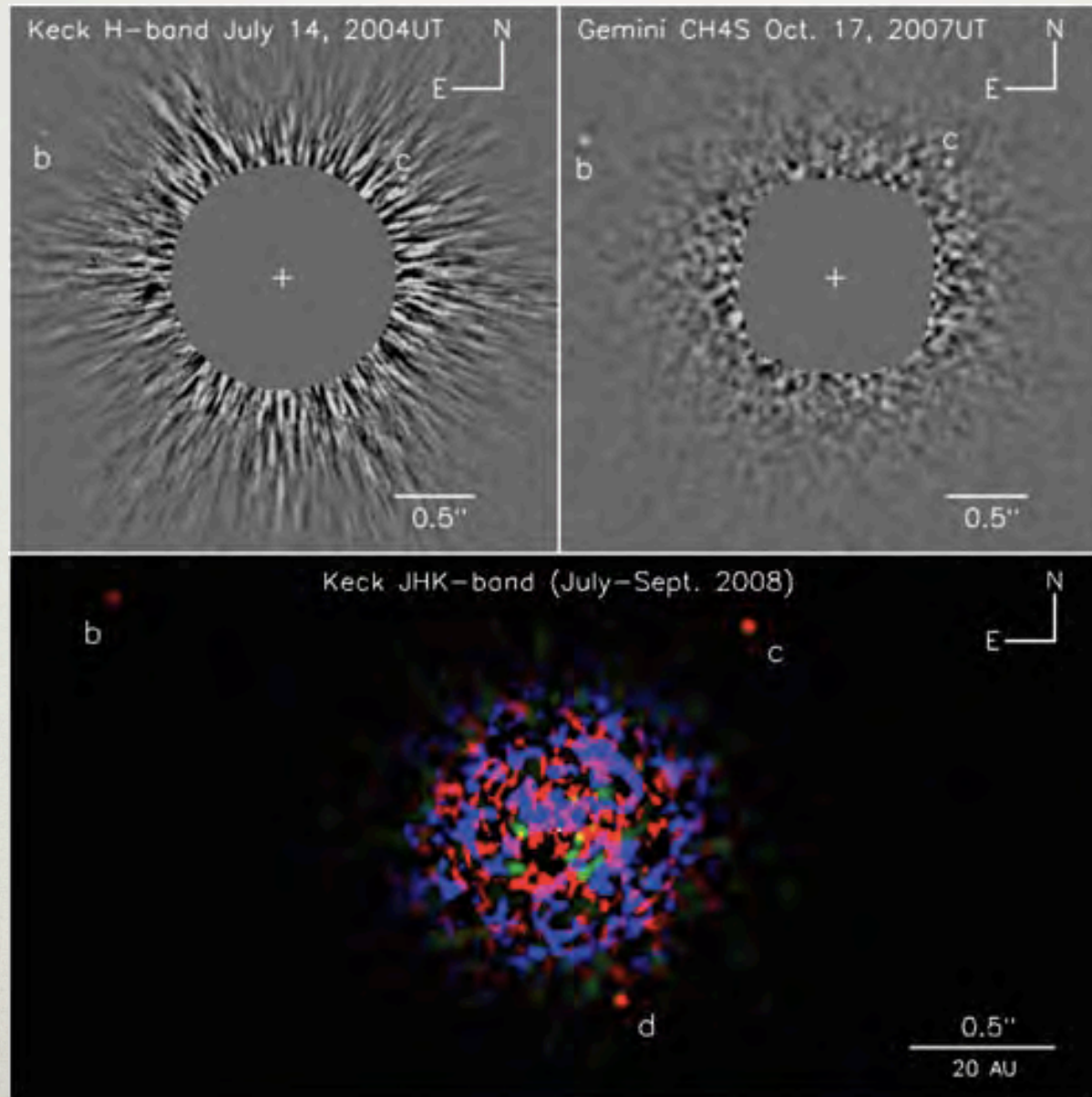


# FOMALHAUT B (KALAS ET AL. 2008)

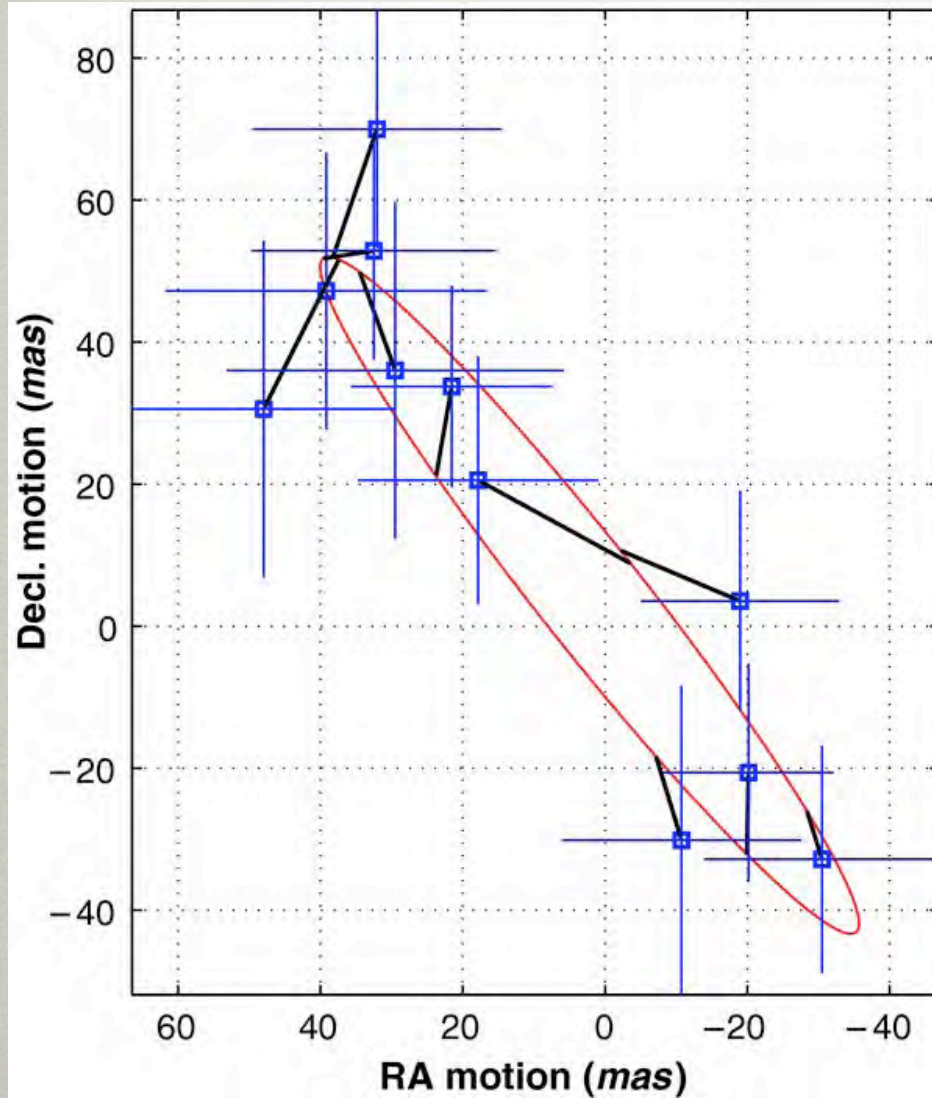




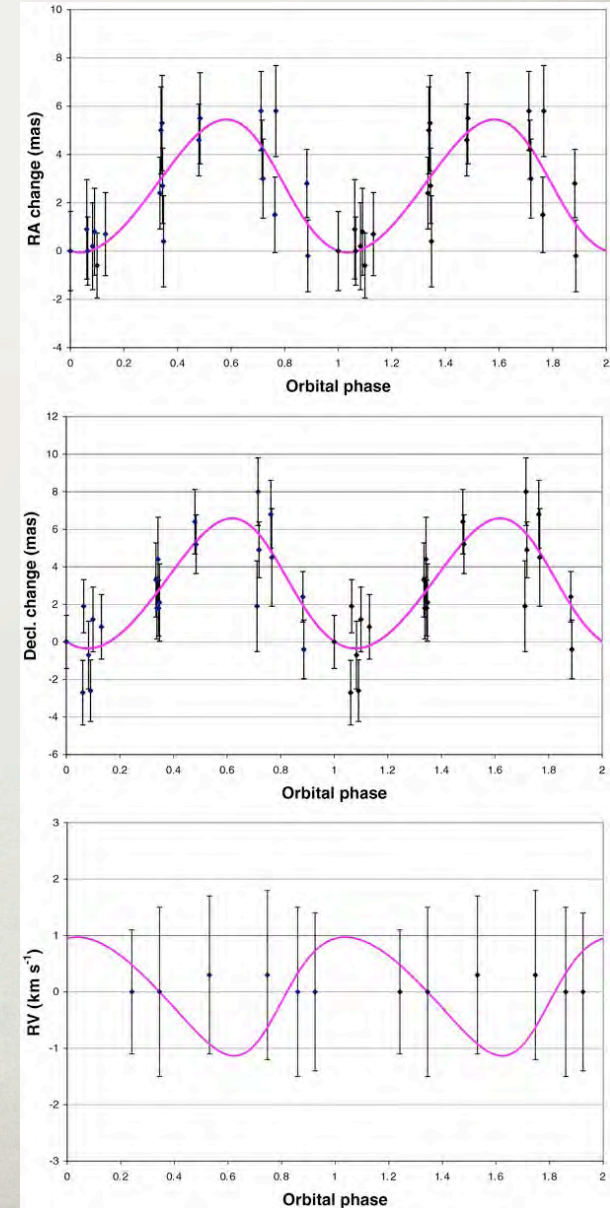
# HR 8799 (MAROIS ET AL. 2008)



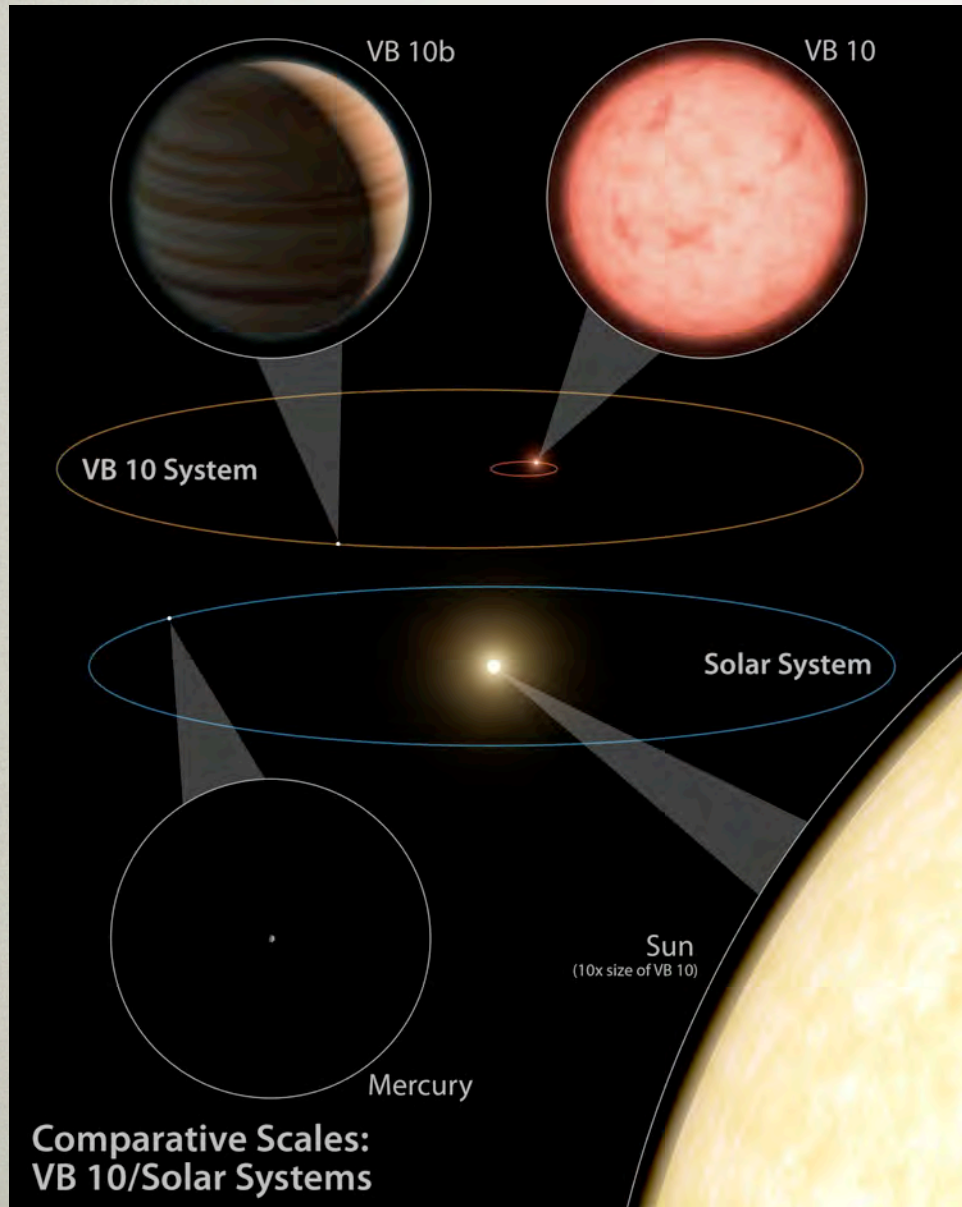
# ASTROMETRY



[www.iop.org/EJ/article/0004-637X/700/1/623/apj\\_700\\_1\\_623.figures.html](http://www.iop.org/EJ/article/0004-637X/700/1/623/apj_700_1_623.figures.html)



# COMPARISON SOLAR SYSTEM – VB 10



[photojournal.jpl.nasa.gov/catalog/PIA12014](http://photojournal.jpl.nasa.gov/catalog/PIA12014)

# ASTROMETRY DETECTION LIMIT

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- 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

