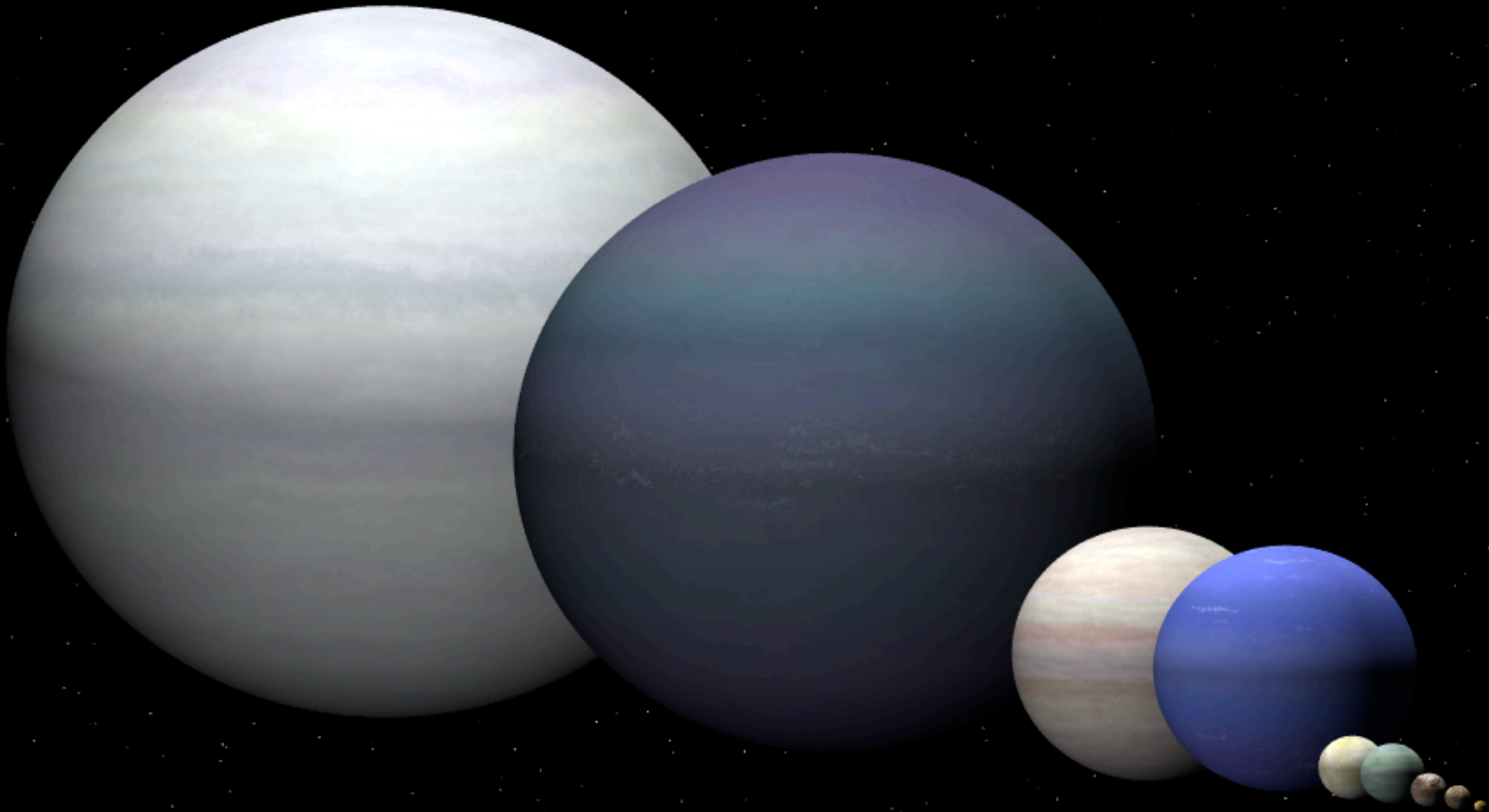


Planets and Exoplanets

Exoplanet Observations

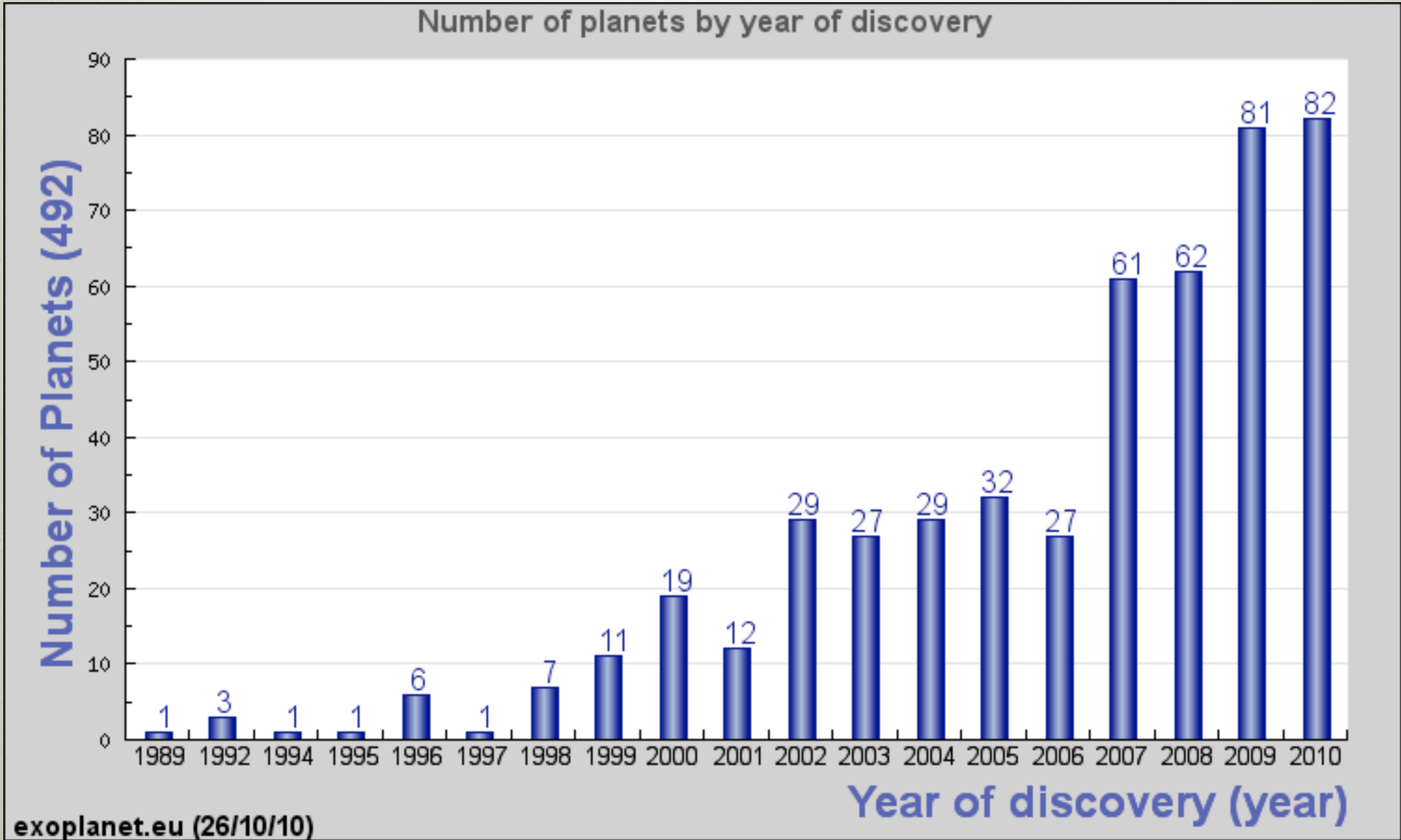
Outline

1. Introduction
2. Exoplanet Masses
3. Exoplanet Orbits
4. Exoplanet Radii and Densities
5. Exoplanet Atmospheres

Exoplanet Detection

- **Planet**: Object with mass too small for fusion of deuterium (~13 Jupiter masses) that orbits star or stellar remnant
- Main detection methods, derived properties:
  - **Radial velocity**: period, semi-major axis, eccentricity, lower limit to mass
  - **Transits**: period, semi-major axis, inclination, radius, planet temperature, planet atmosphere

Exoplanet Detection Rate



Planet Detections as of 26.10.2010

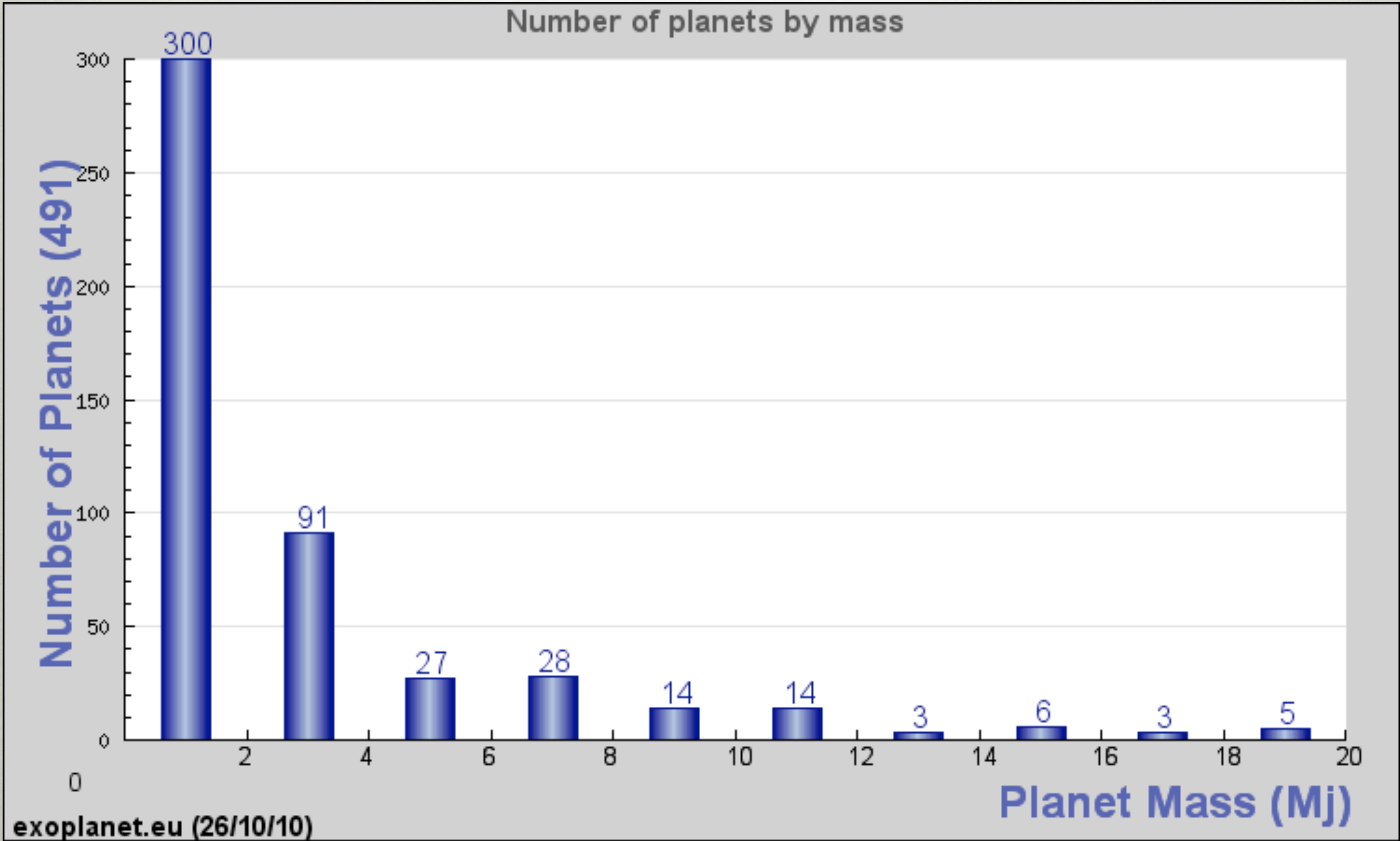
- Radial velocity : 390 planetary systems with 461 planets and 45 multiple planet systems
- Transits: 105 planetary systems with 106 planets and 7 multiple planet systems
- Microlensing: 10 planetary systems with 11 planets and 1 multiple planet systems
- Imaging: 10 planetary systems with 12 planets and 1 multiple planet system
- Timing: 6 planetary systems with 10 planets and 3 multiple planet systems

Source: exoplanet.eu

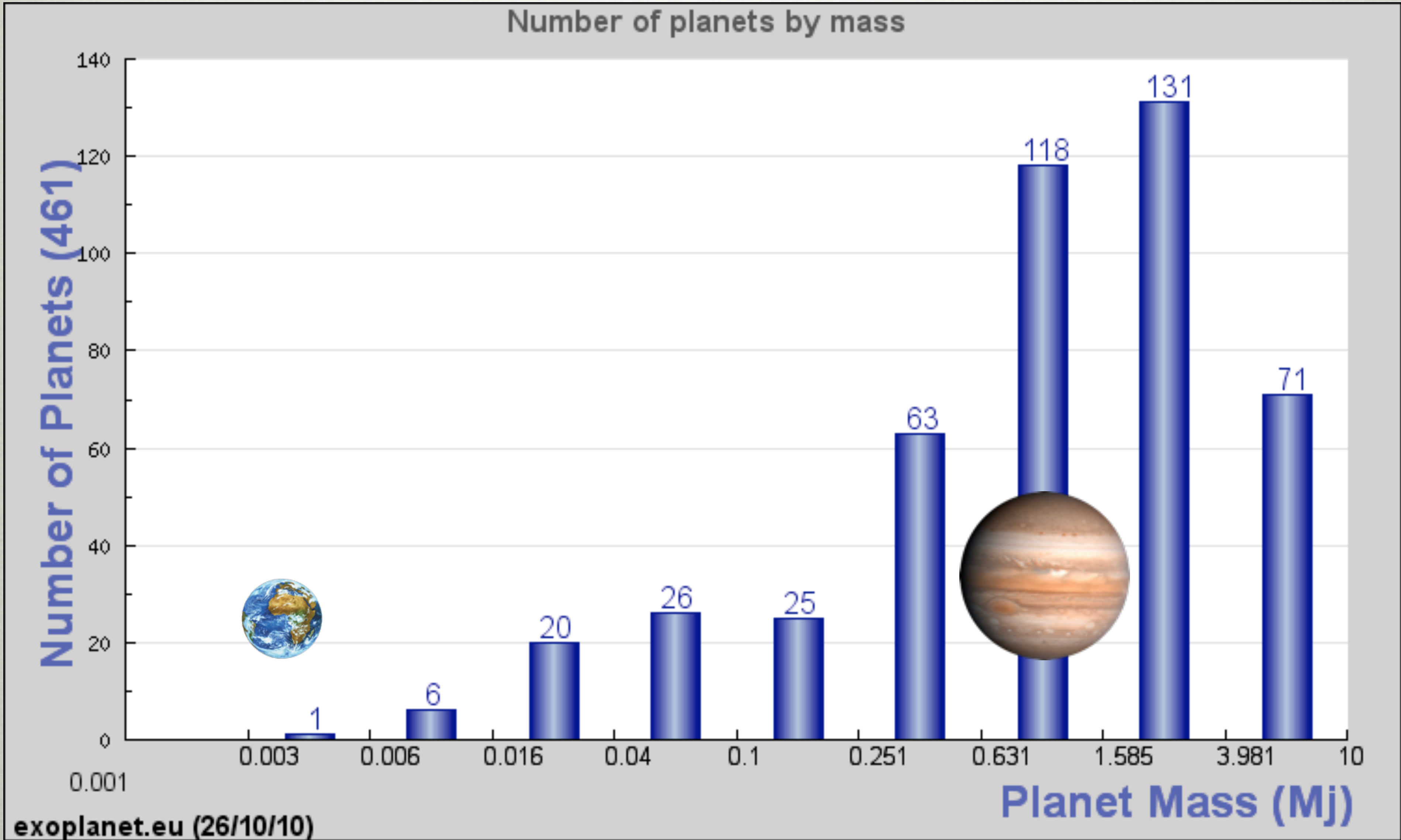
Problems with Statistics

- Selection effects:
  - some aspects of observed distributions are inconsistent with real population of exoplanets
  - depend on exoplanet detection approach
- Mass is mostly a lower limit to real mass

Exoplanet Masses



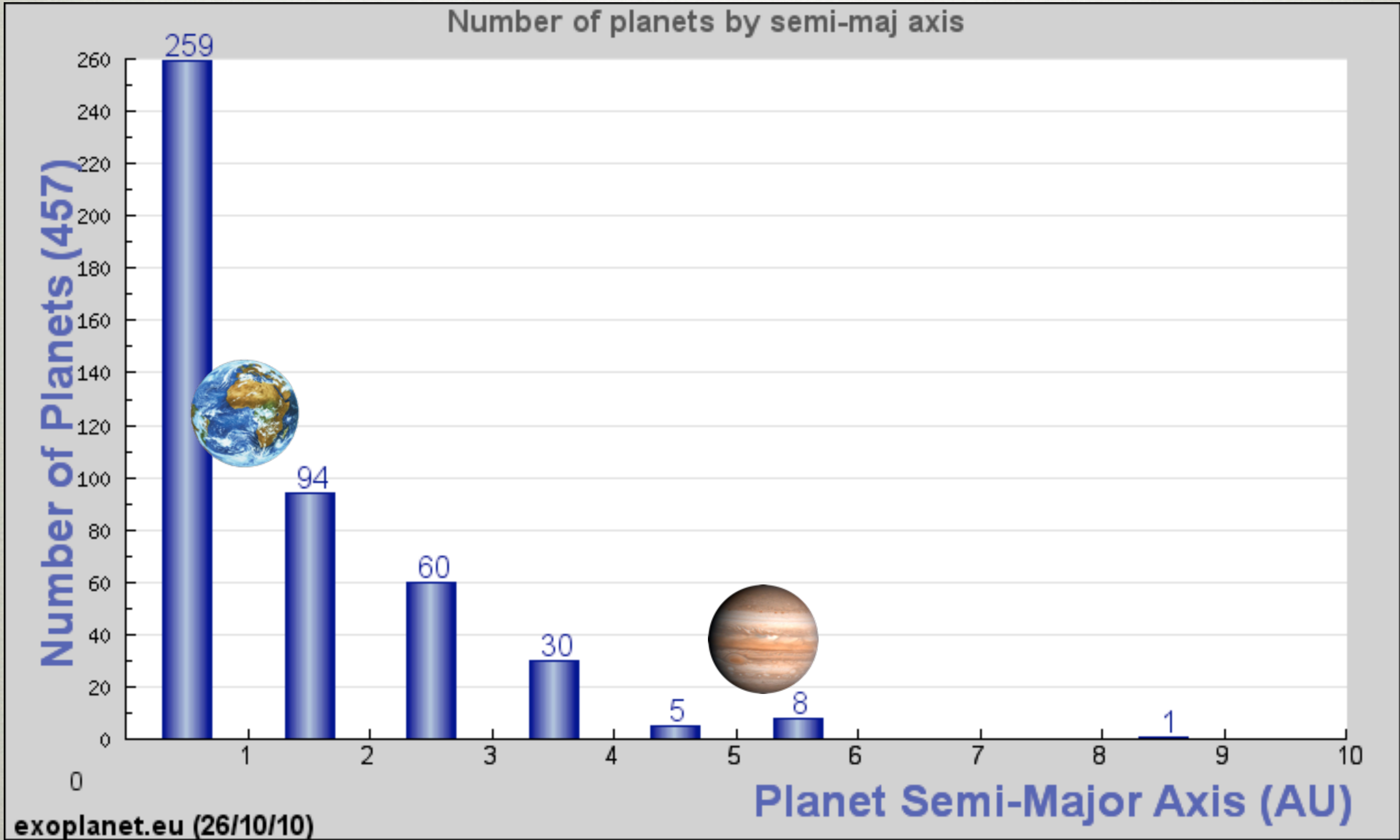
Exoplanet Masses



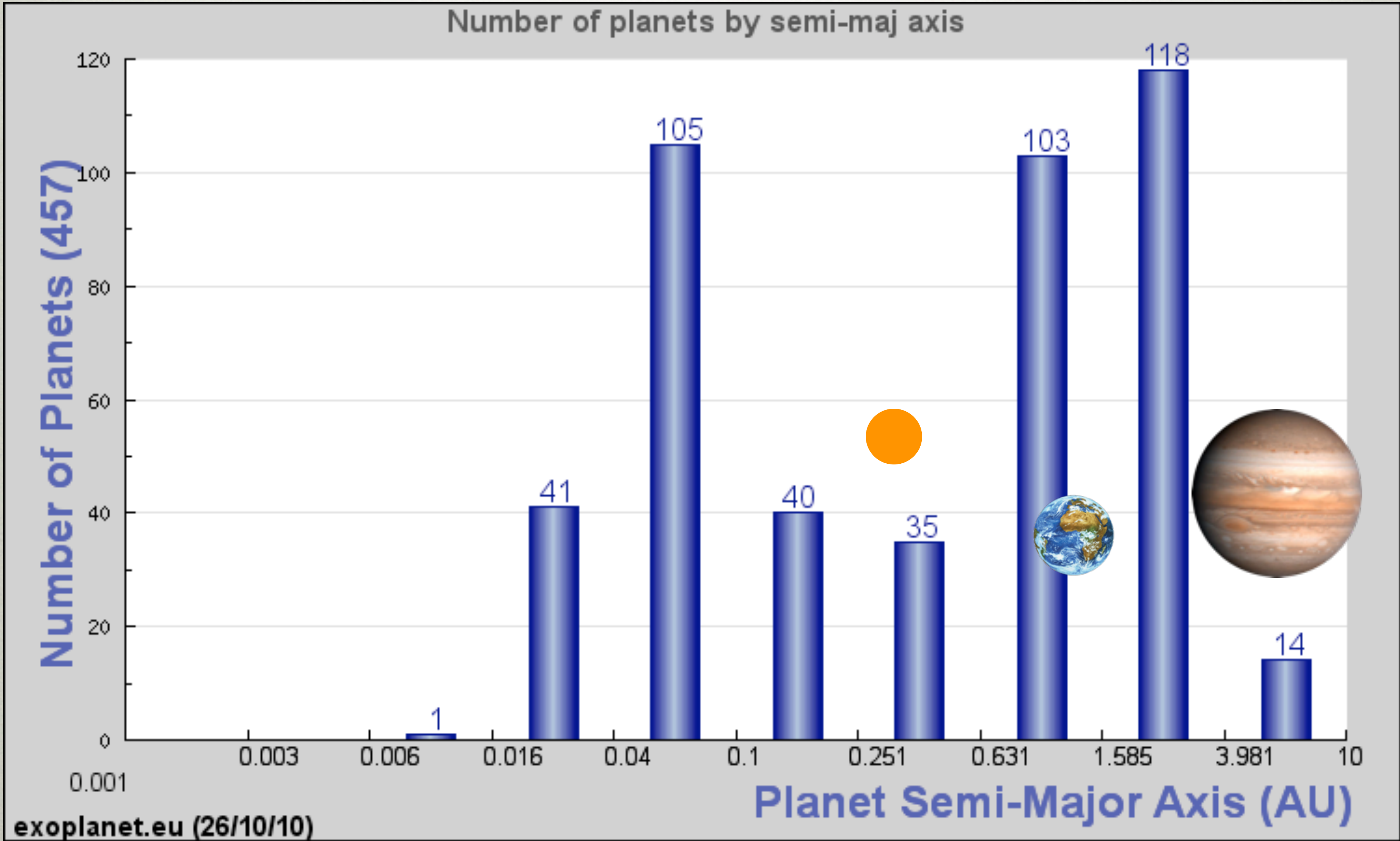
Mass Distribution Interpretation

- Low end of mass distribution:
  - Heavily affected by selection
  - low-mass planets induce small velocity variations, difficult to detect, underrepresented
- High end of mass distribution:
  - Massive planets easier to detect
  - Apparent decrease for $M > 3M_J$ real
  - Apparent decrease for $M > 12M_J$ real, "brown dwarf desert"

Exoplanet Orbital Distances



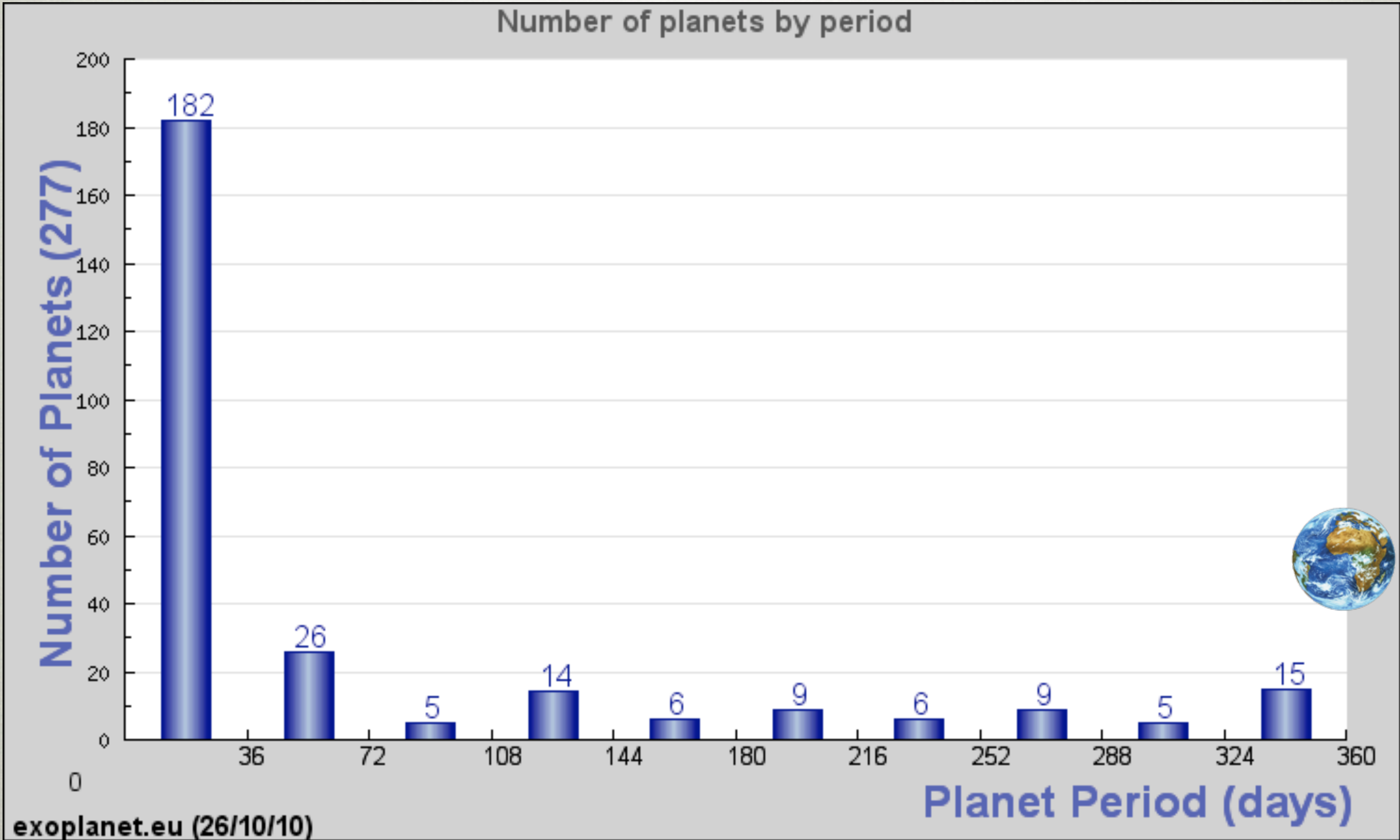
Exoplanet Orbital Distances



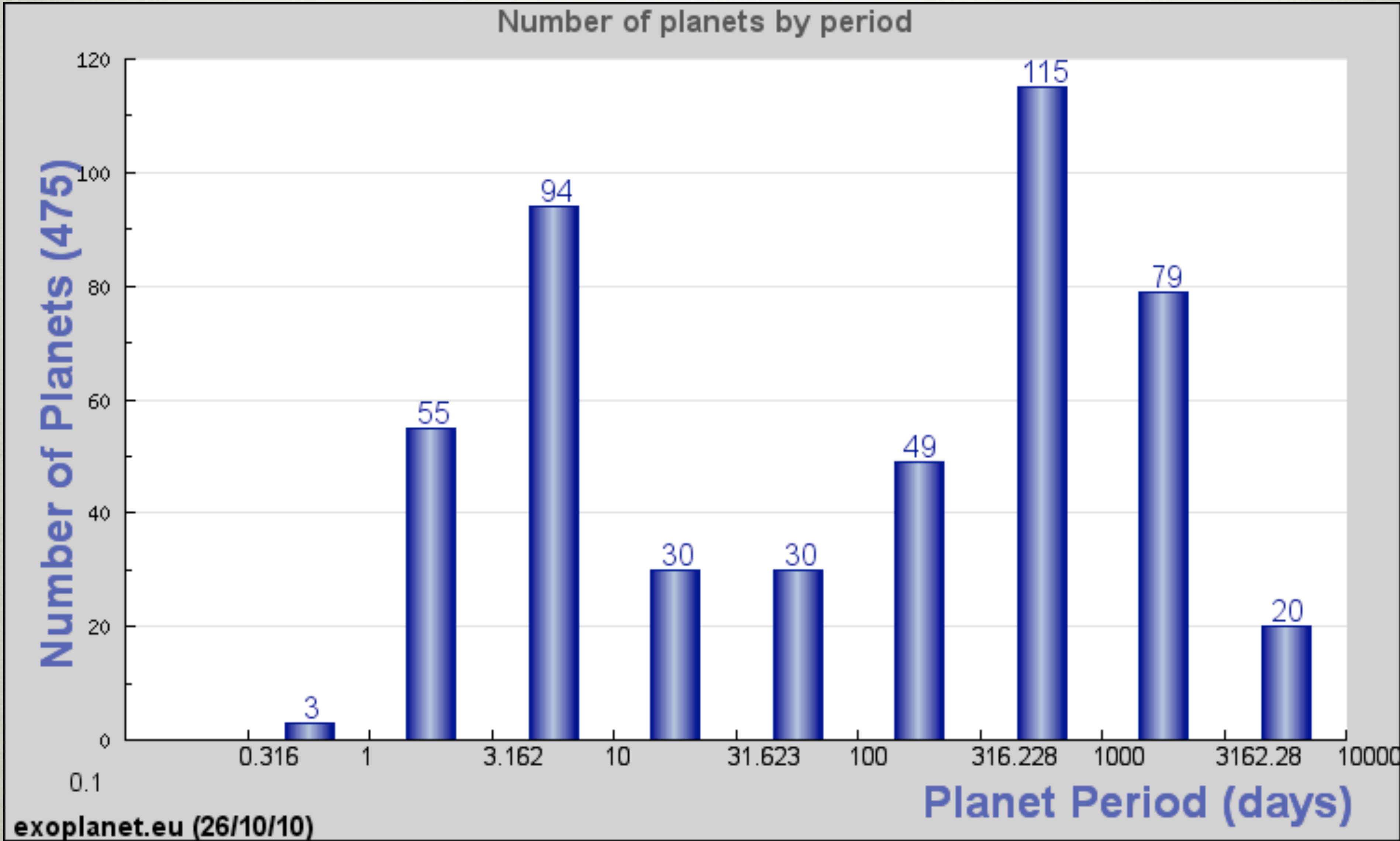
Orbit Interpretation

- Planets with a > 4 AU have periods ≥ length of Doppler surveys
- Incomplete distribution beyond ~ 4 AU
- Occurrence rate of planets within 0.1 AU: 1.2%
- Roughly as many planets at distances between 3 and 30 AU as below 3 AU
- Expected occurrence of giant planets ~12% within 30 AU
- Rapid rise of planet frequency with a > 0.5 AU suggests large population of Jupiter-like planets beyond 3 AU

Exoplanet Orbital Periods



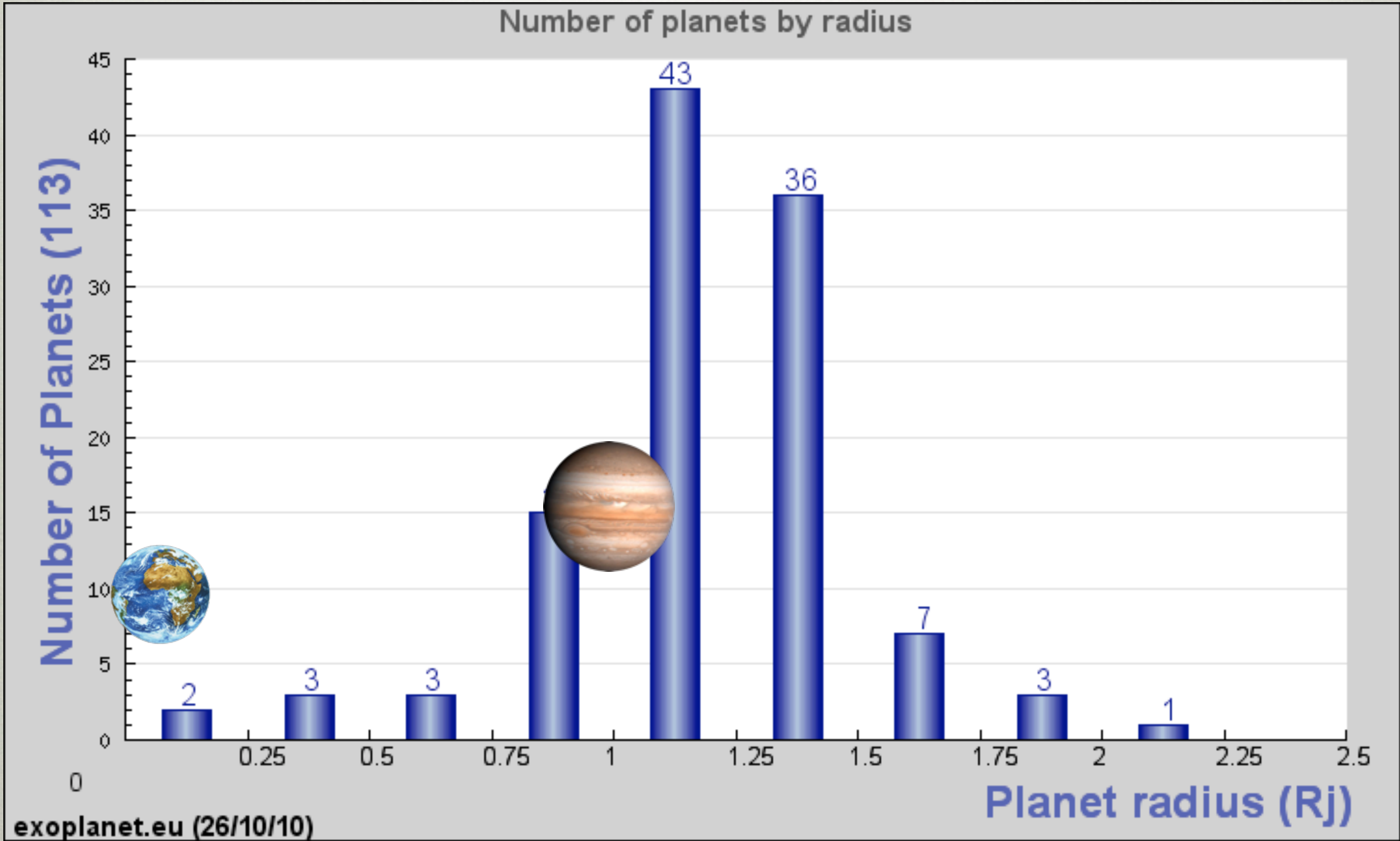
Exoplanet Orbital Periods



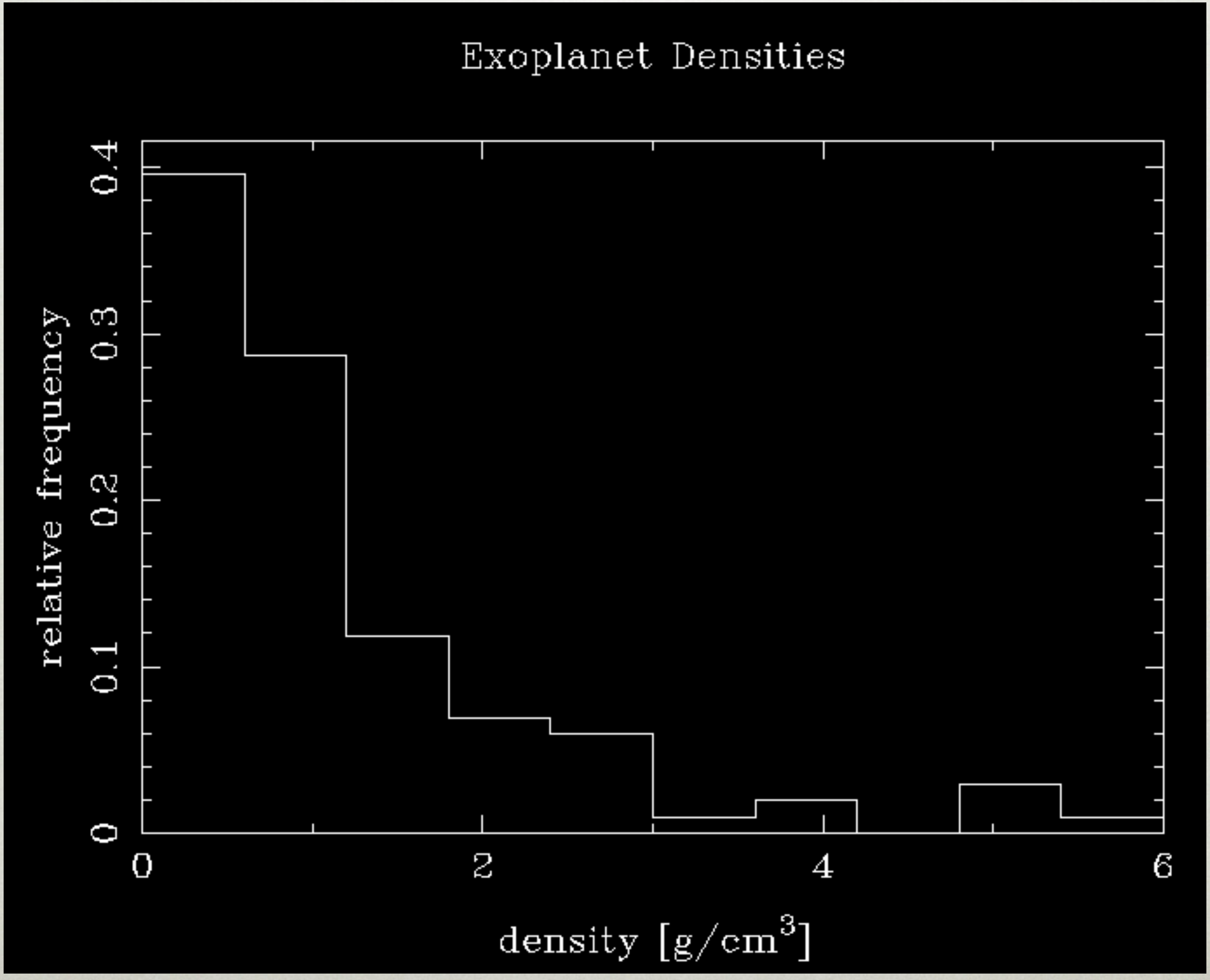
Orbital Period Interpretation

- Peak near 3 days:
  - Orbital migration mechanism stops there
  - Breaking mechanism stops them there
  - Closer planets are “sent” into the star
- Radial velocity surveys generally have uniform sensitivity to hot Jupiters at all orbital distances
- No important selection effect contributing to 3-day peek

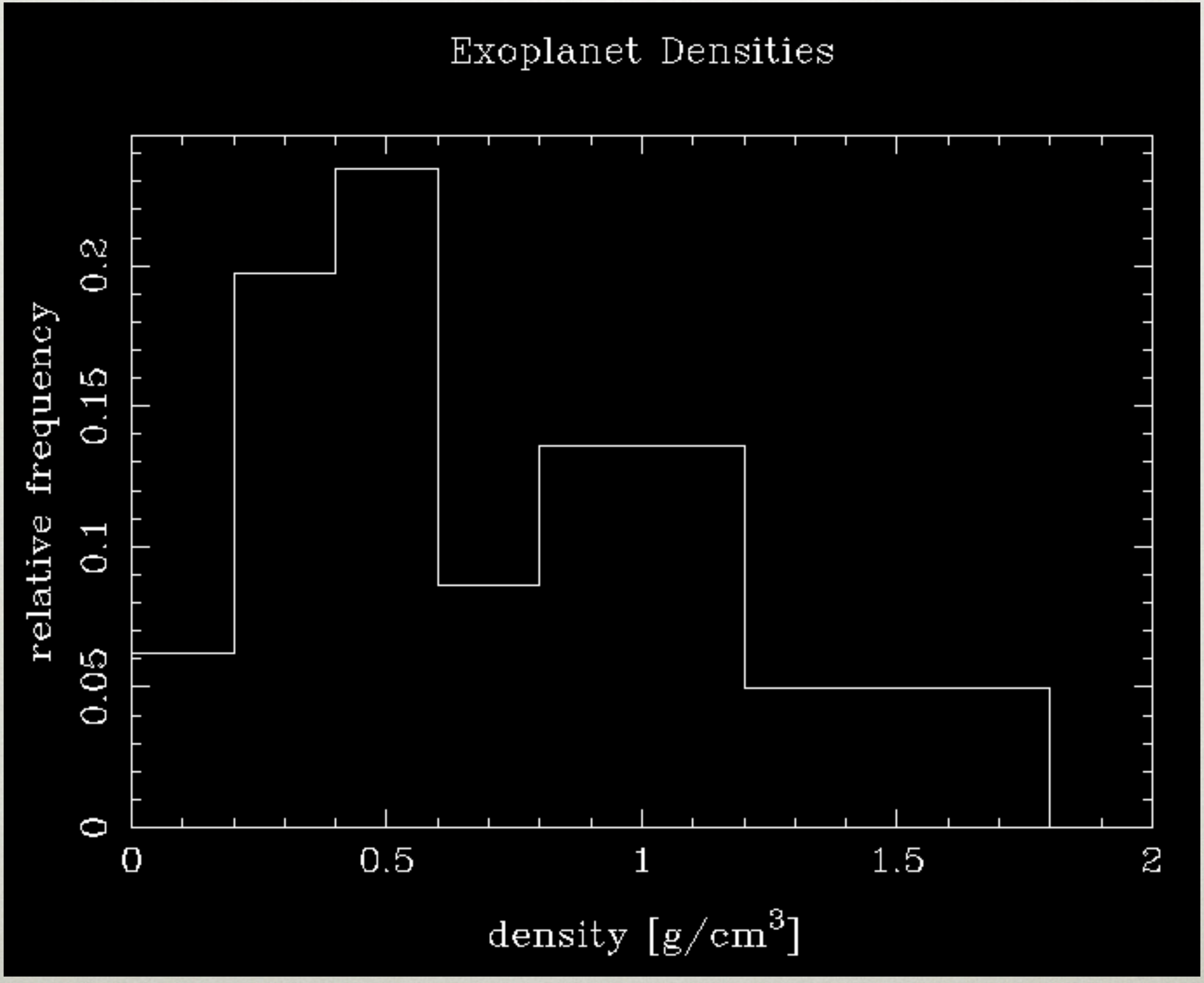
Exoplanet Radii



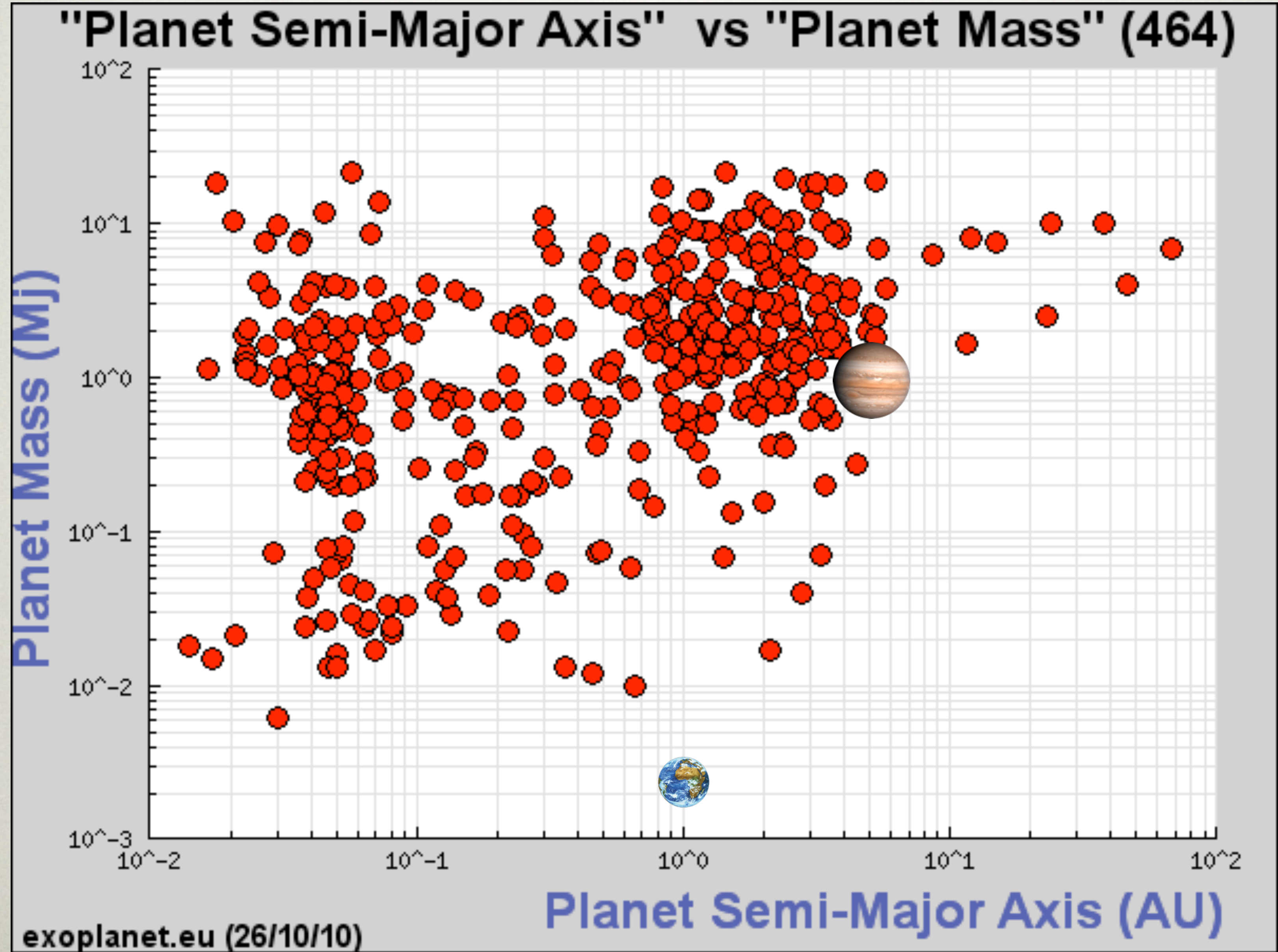
Exoplanet Densities



Exoplanet Densities



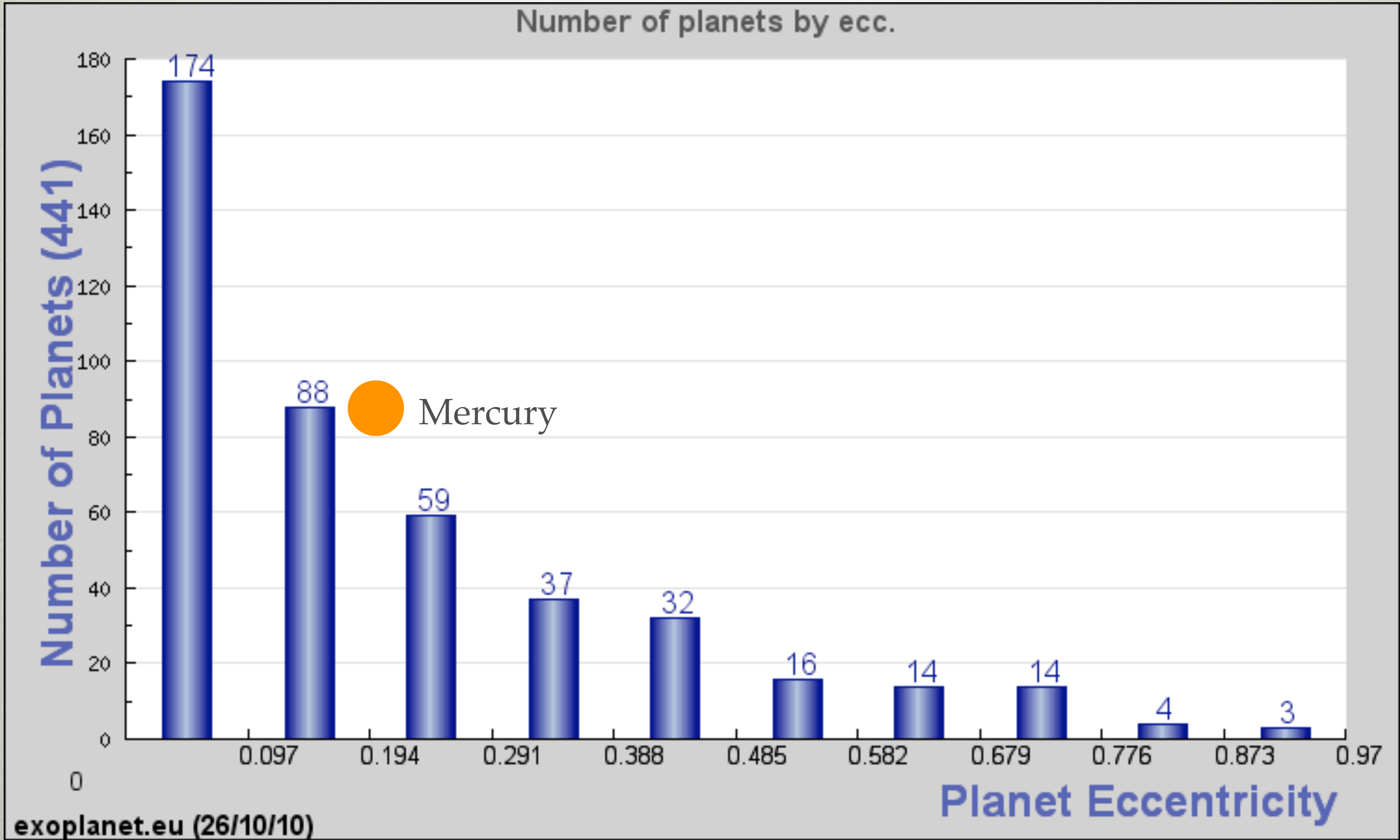
Mass vs. Semi-Major Axis



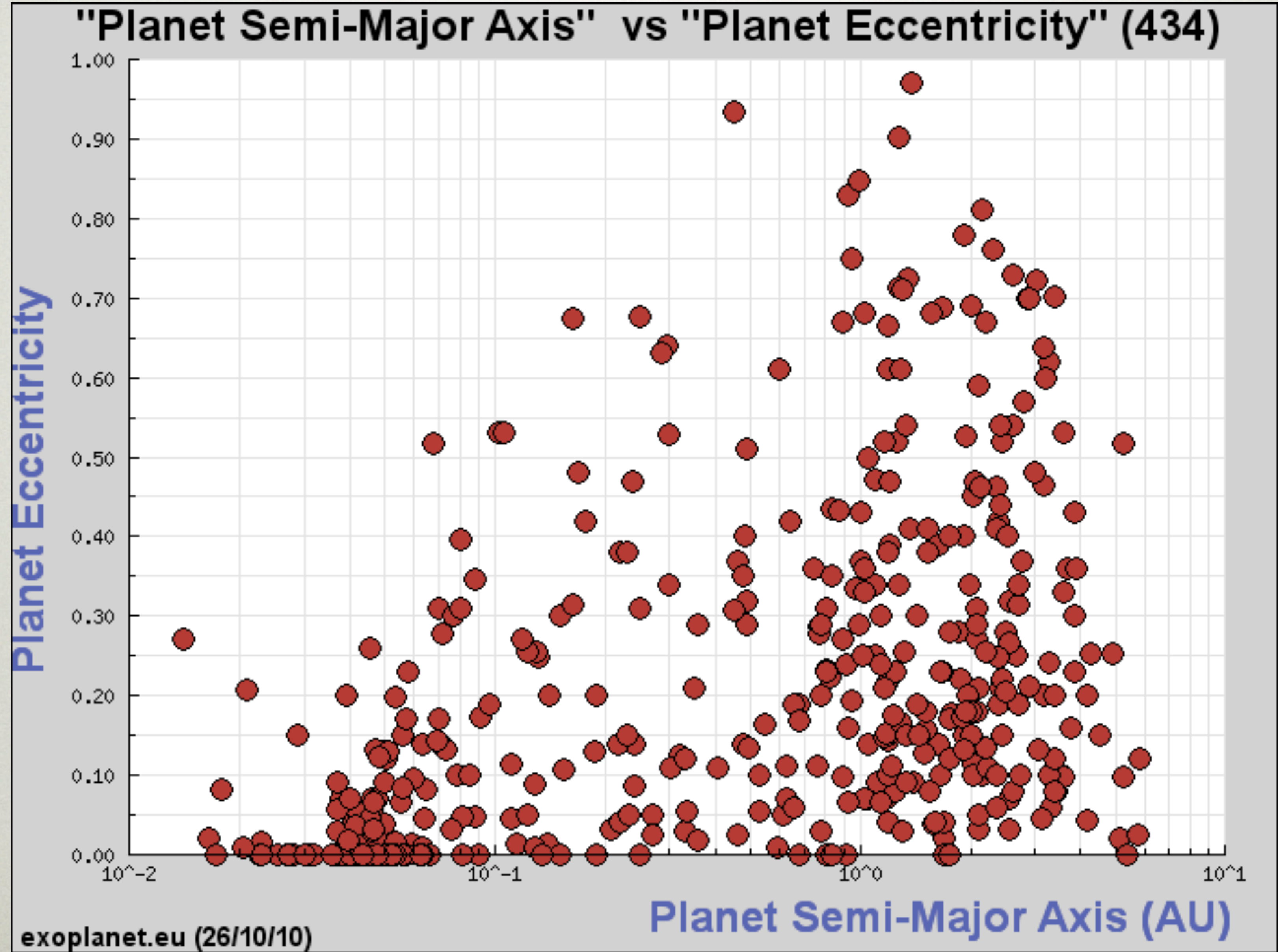
Mass-Orbit Interpretation

- Large number of close-in exoplanets with high mass, cannot be due to a selection
- Selection effects make detection of low-mass planets beyond 1 AU difficult
- Not clear that mass distribution for planets beyond 1 AU is different from that of hot Jupiters

Exoplanet Eccentricities



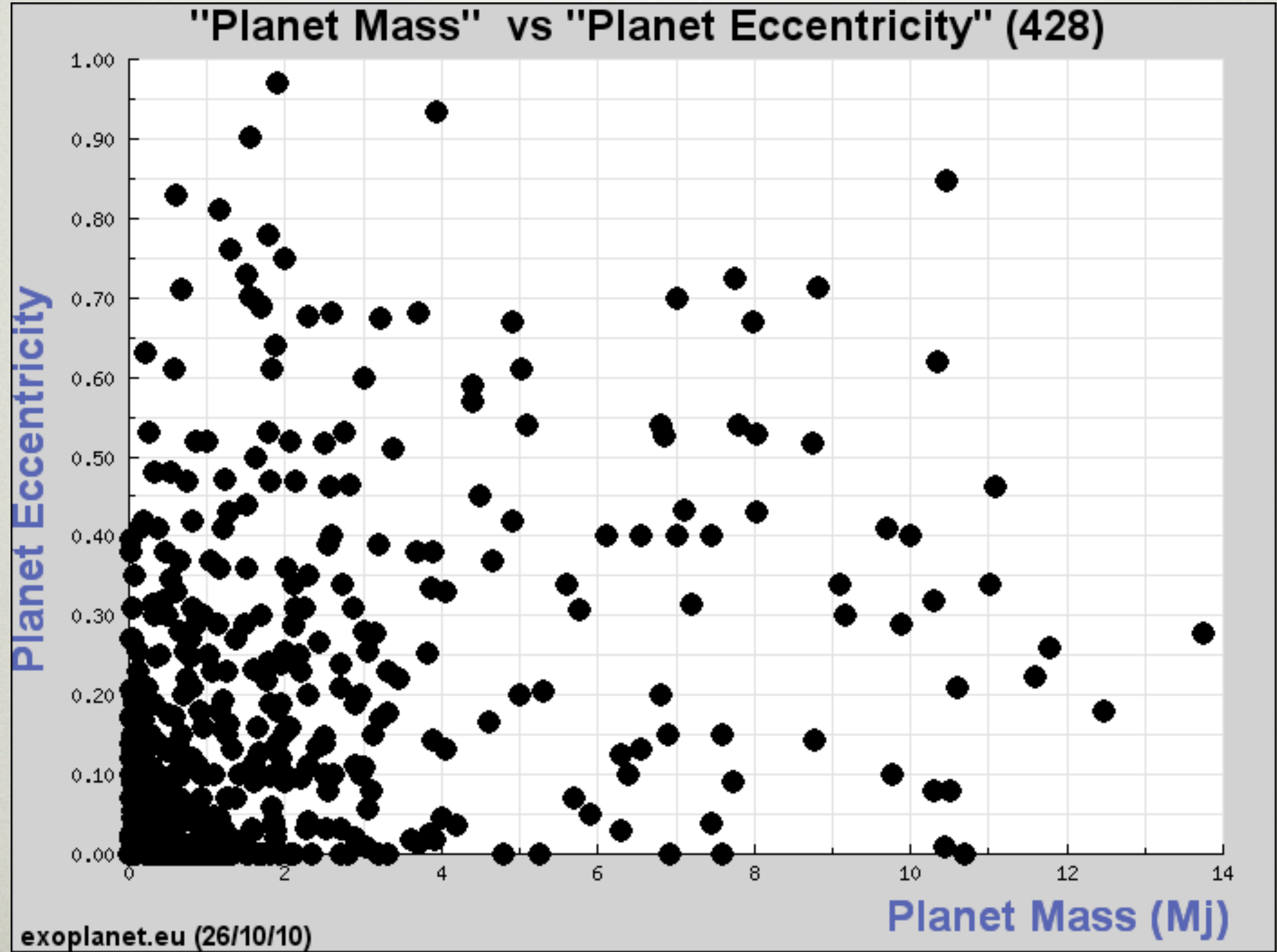
Distance vs. Eccentricity



Eccentricity

- Exoplanets within 0.1 AU on nearly circular orbits
- Beyond 0.3 AU, distribution of eccentricities is essentially uniform between 0 and 0.8
- Radial velocity survey sensitivity not a strong function of eccentricity for $0 < e < 0.7$ and $a < 3$ AU

Eccentricity



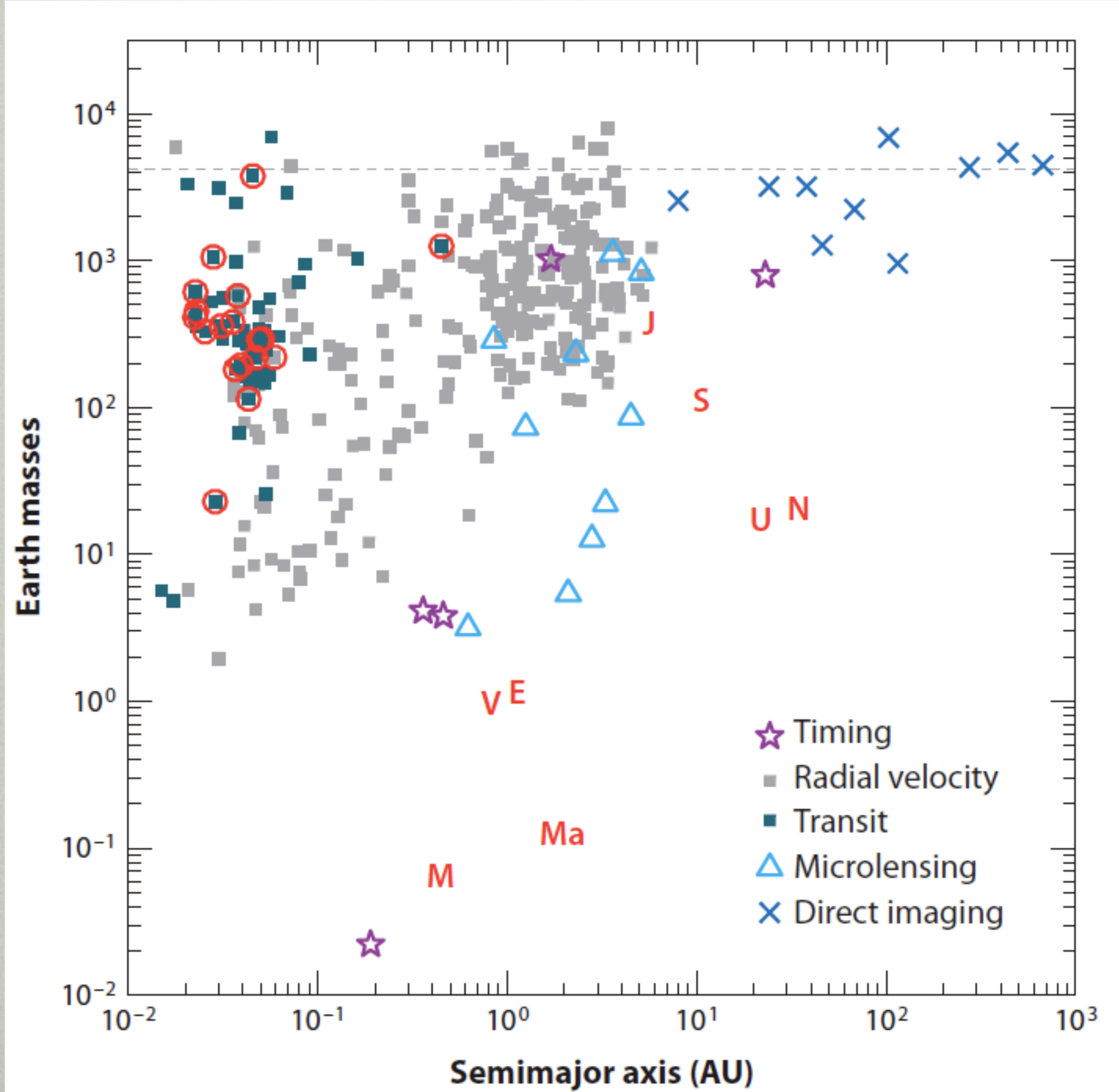
Orbital Eccentricity Interpretation

- Overestimation of eccentricity because of $e > 0$
- Probably 30-40% have $e < 0.05$
- For $a<0.1$ mostly circular orbits due to tidal circularization
- Large eccentricities for more distant exoplanets may be due to
  - Perturbations by other planets
  - Resonances
  - Interactions with protoplanetary disk
- No clear correlation between eccentricity and mass
- But high-mass exoplanets ($M \sin i > 5M_J$) have higher median eccentricity than lower mass exoplanets

ExoPlanet Atmosphere Observations

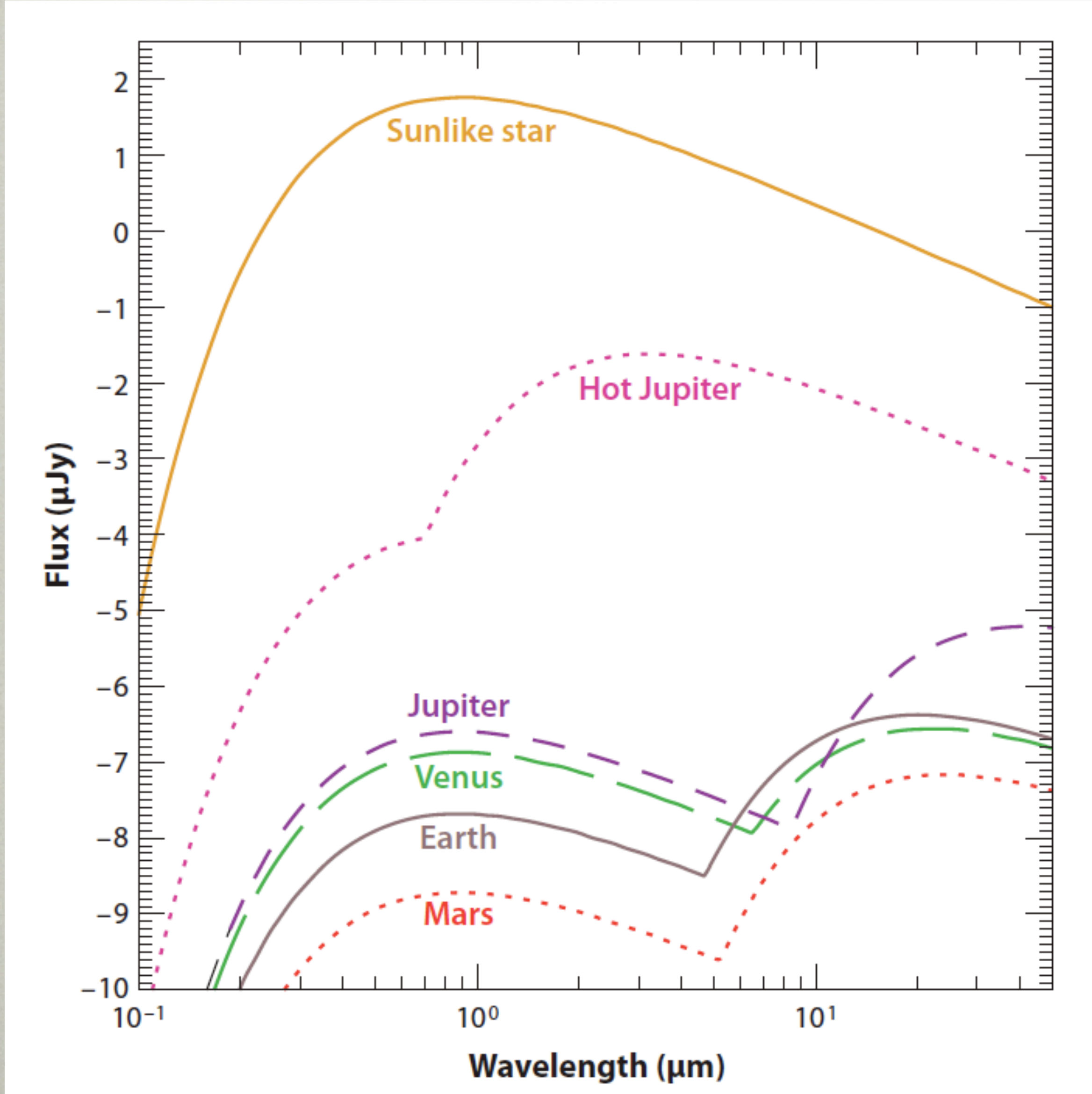
- Transits: planet size
- Thermal emission: emitting atmosphere, temperature and its gradient, thermal phase curve
- Transmission Spectra: upper atmosphere, exosphere
- Reflection: albedo, reflected light phase curve, (polarization), scattering atmosphere

Measured Exoplanet Atmospheres



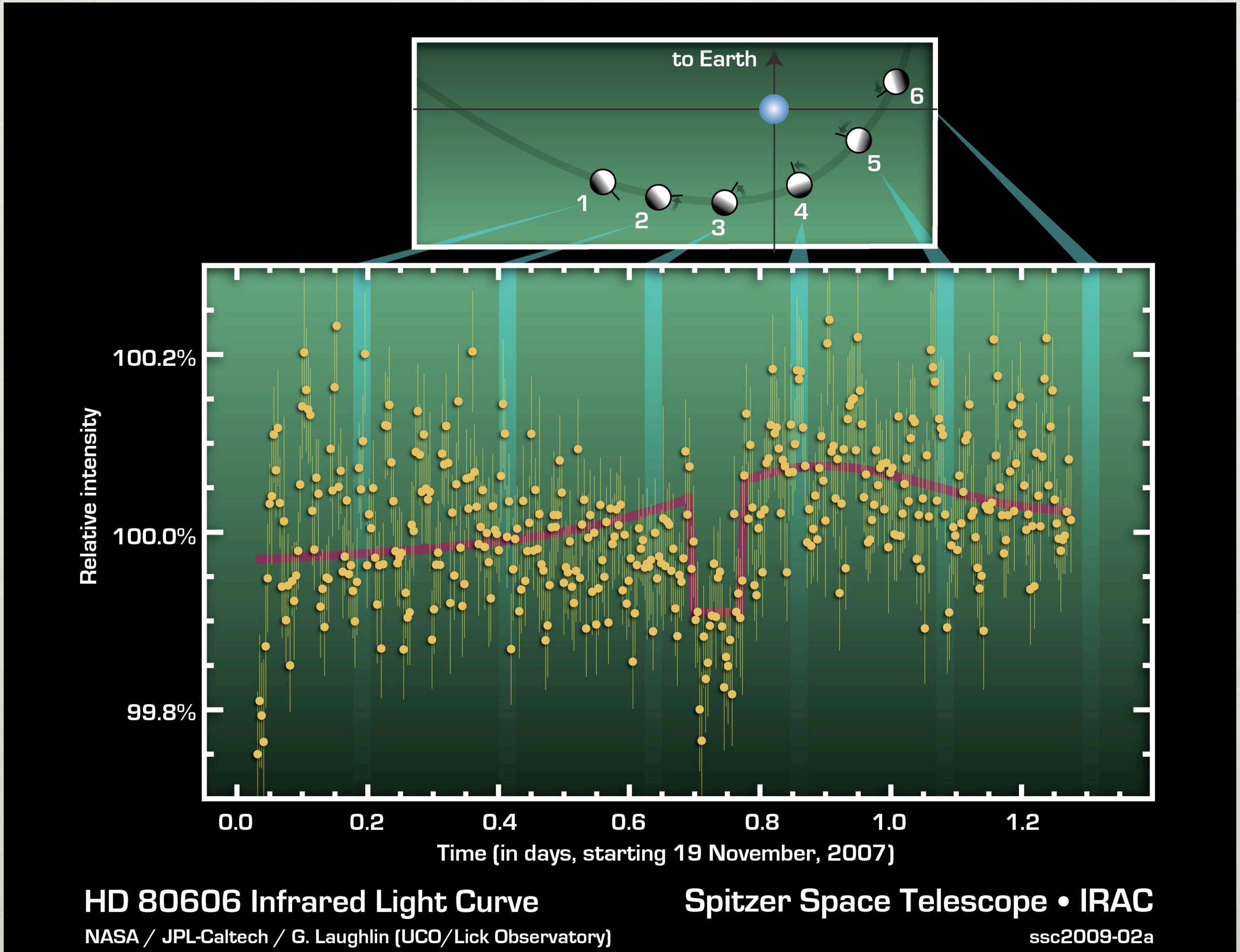
Seager & Deming 2010

Exoplanets as Black Bodies



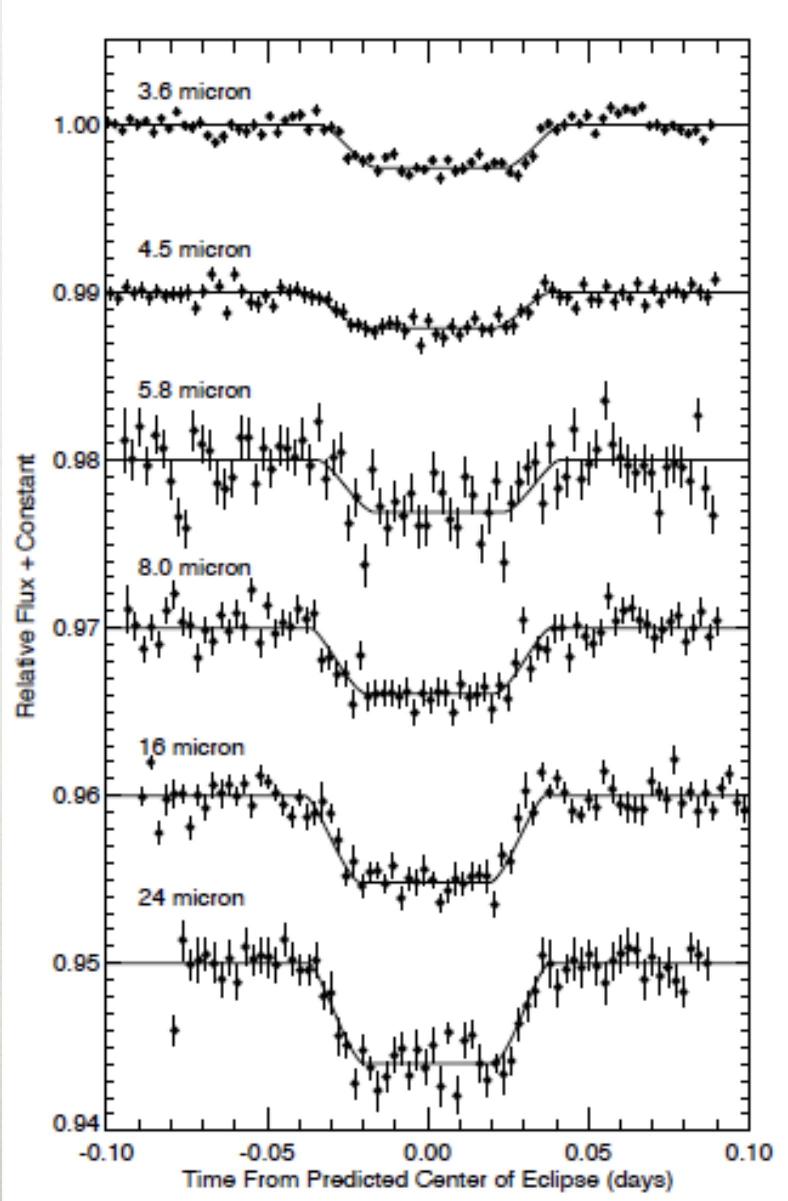
Seager & Deming 2010

Secondary Eclipse



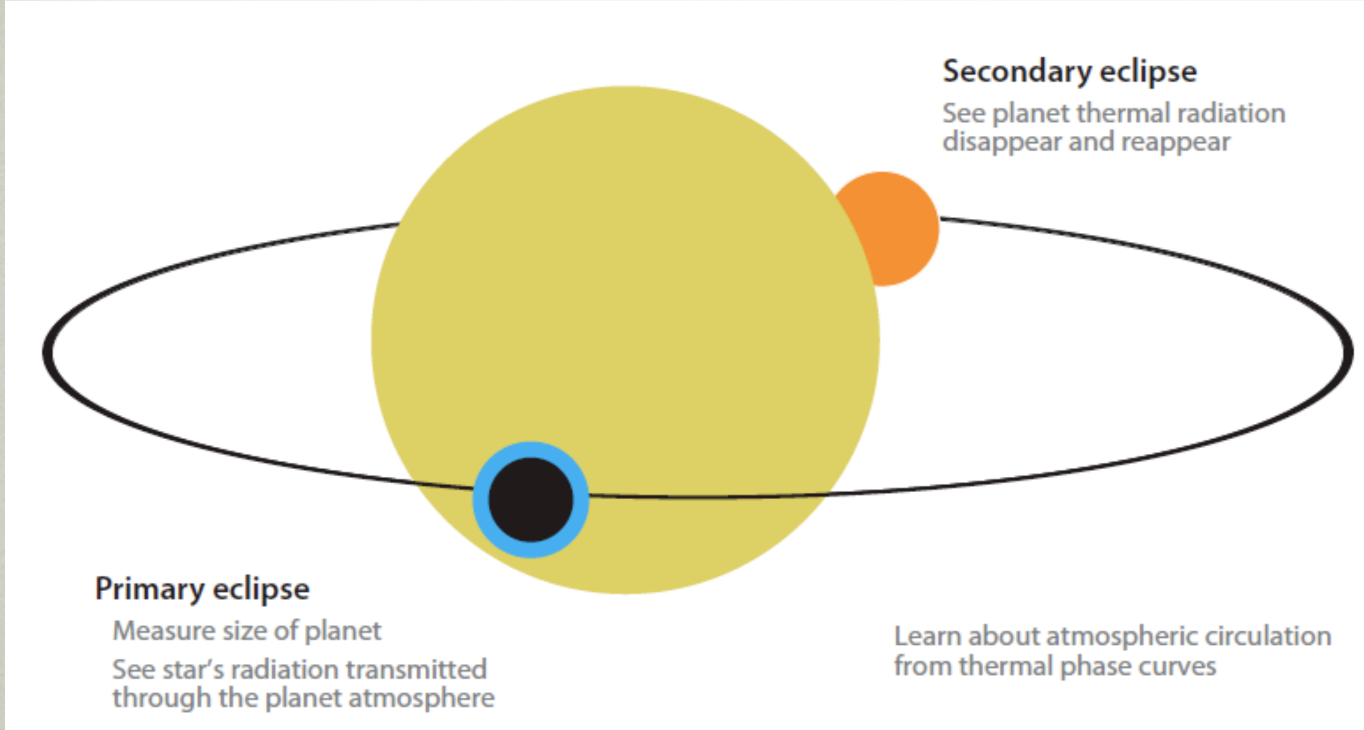
photojournal.jpl.nasa.gov/catalog/PIA11390

λ -Dependence of Secondary Eclipse



Charbonneau et al. 2008

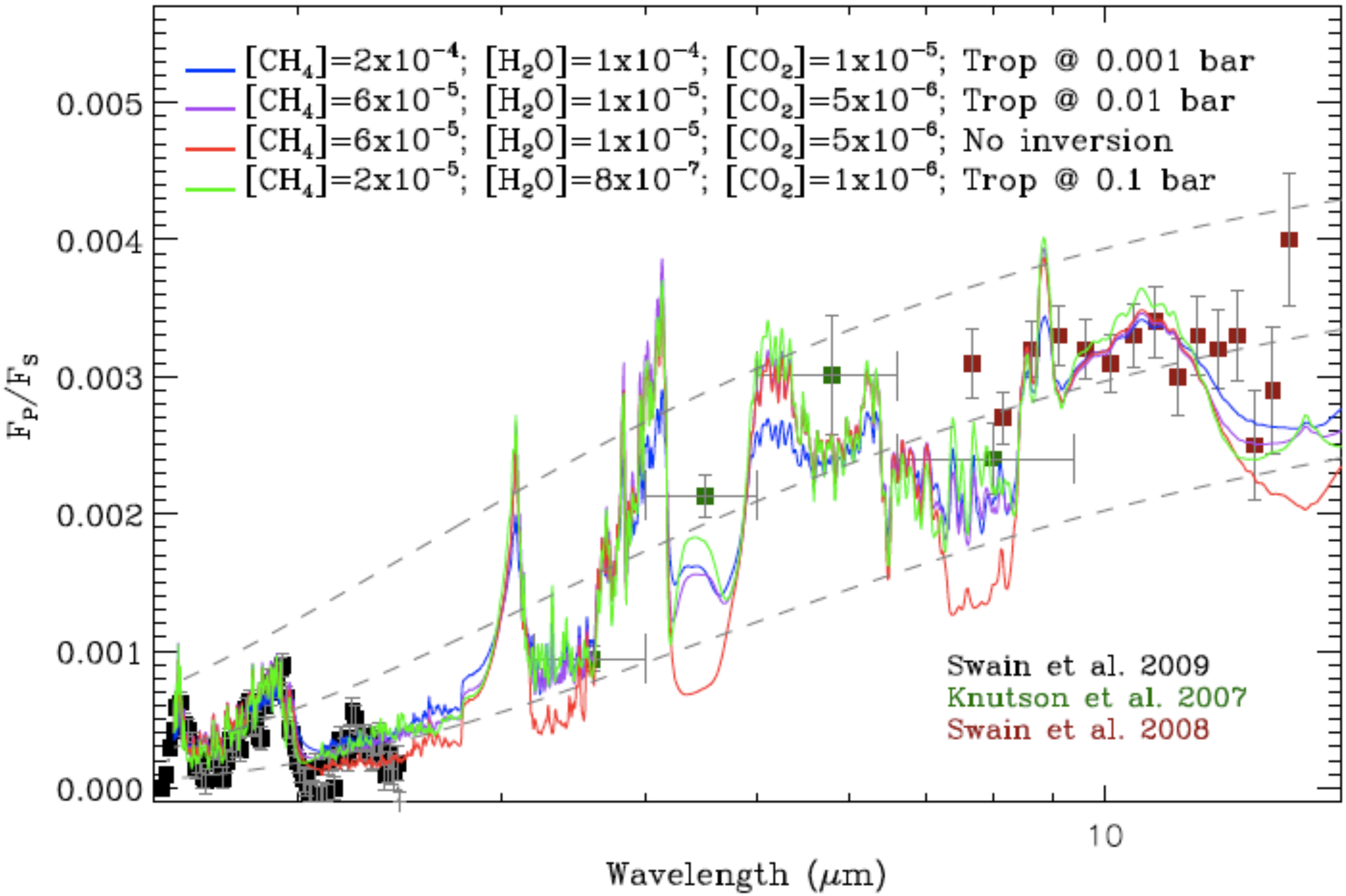
Secondary Eclipse and Phase Curve



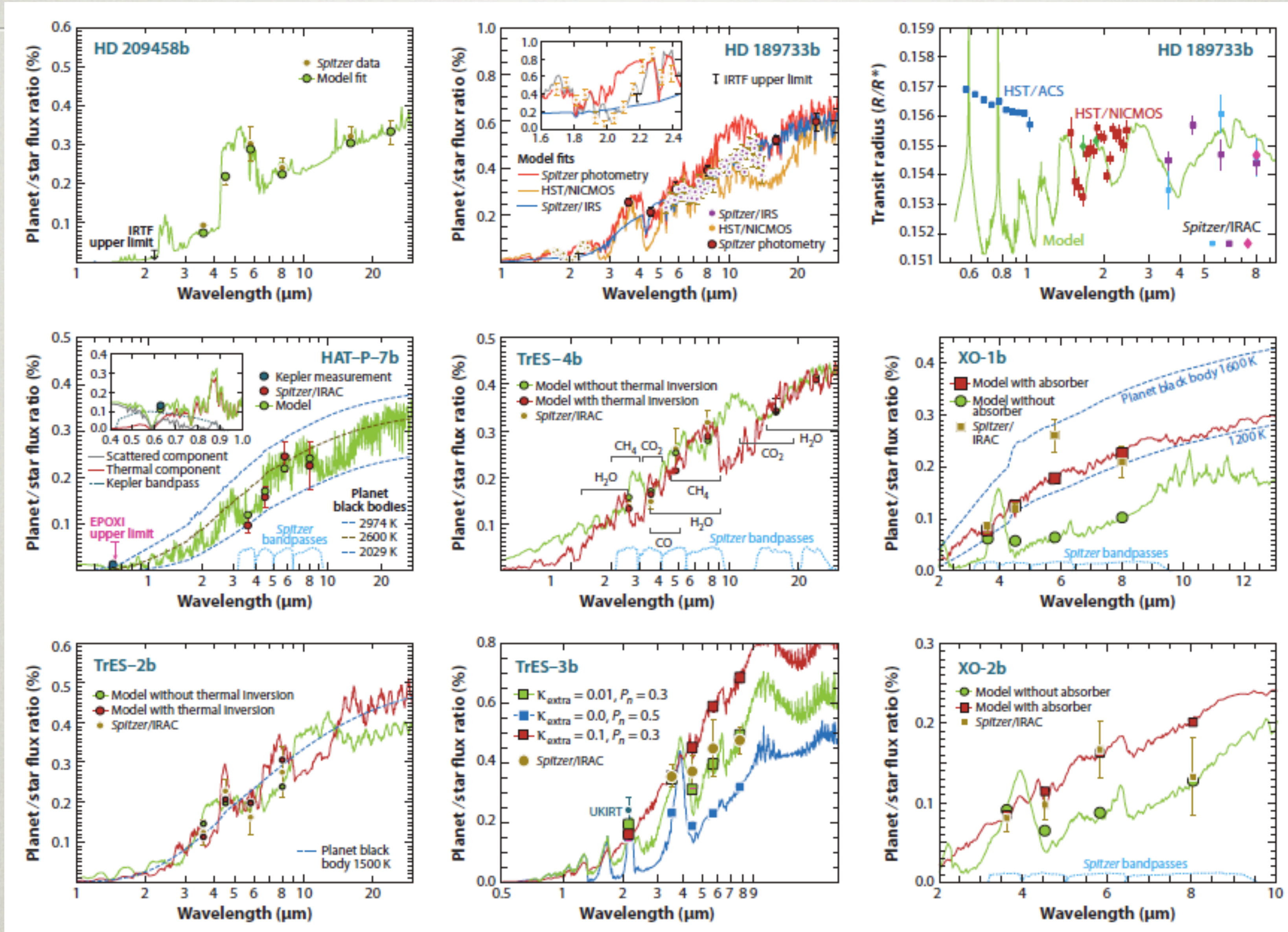
Seager & Deming 2010

- Light curve provides information on star + planet
- Secondary eclipse: no planet light
- Can derive phase curve of planet alone
- Do this at different wavelengths -> exoplanet spectrum
- Exoplanet spectrum -> atmosphere composition

Exoplanet Atmospheres (Swain et al. 2009)

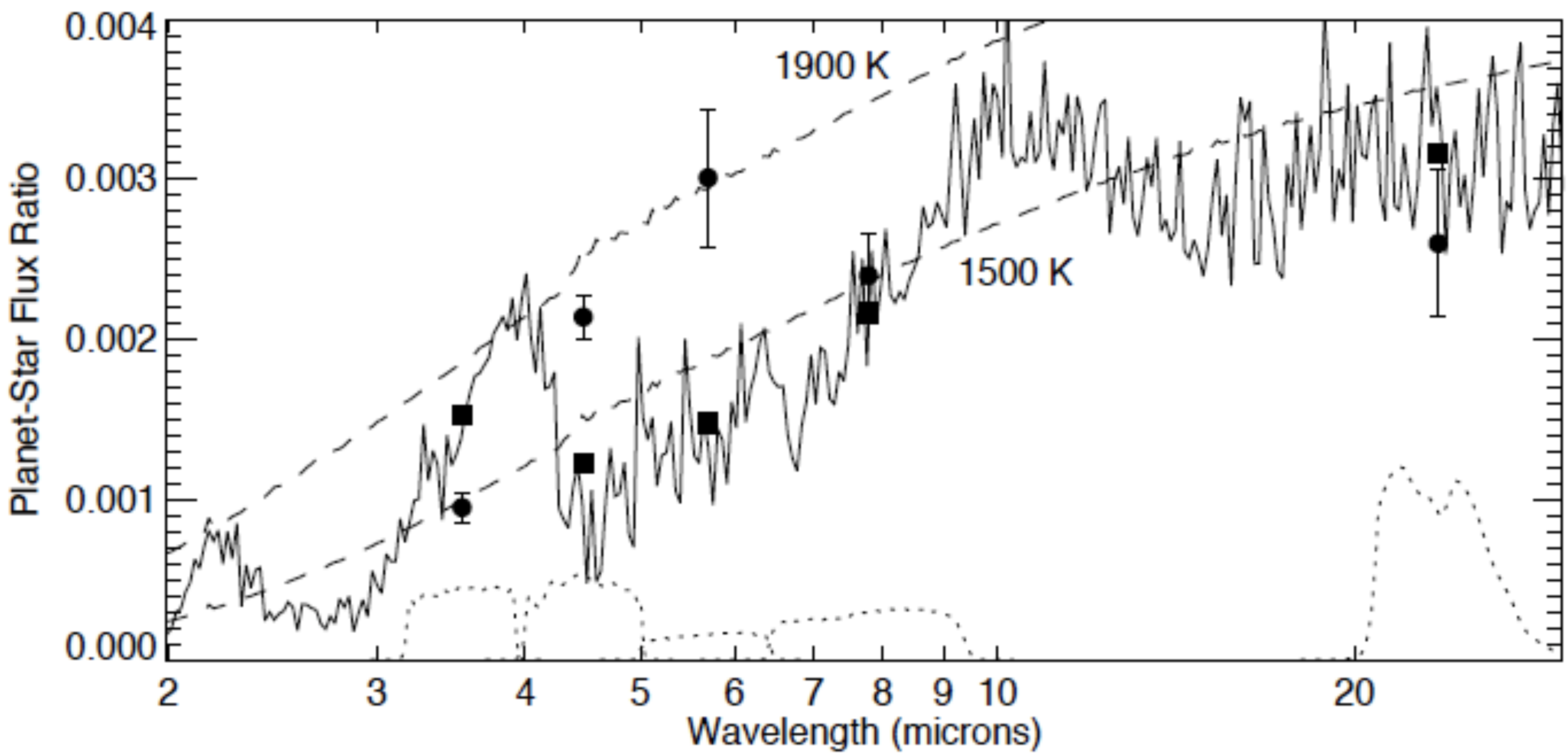


Exoplanet Atmosphere Spectra



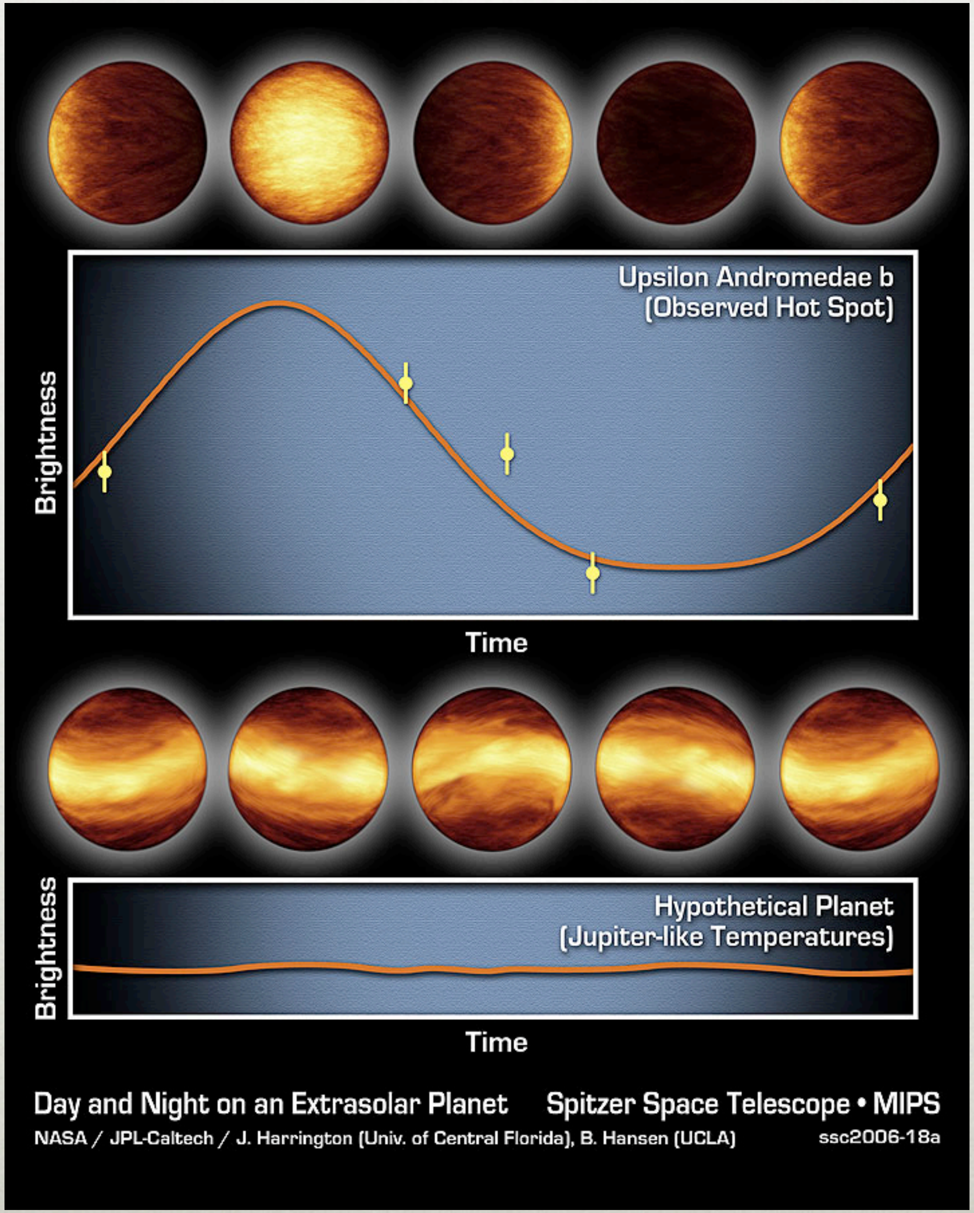
Seager & Deming 2010

Thermal Inversion



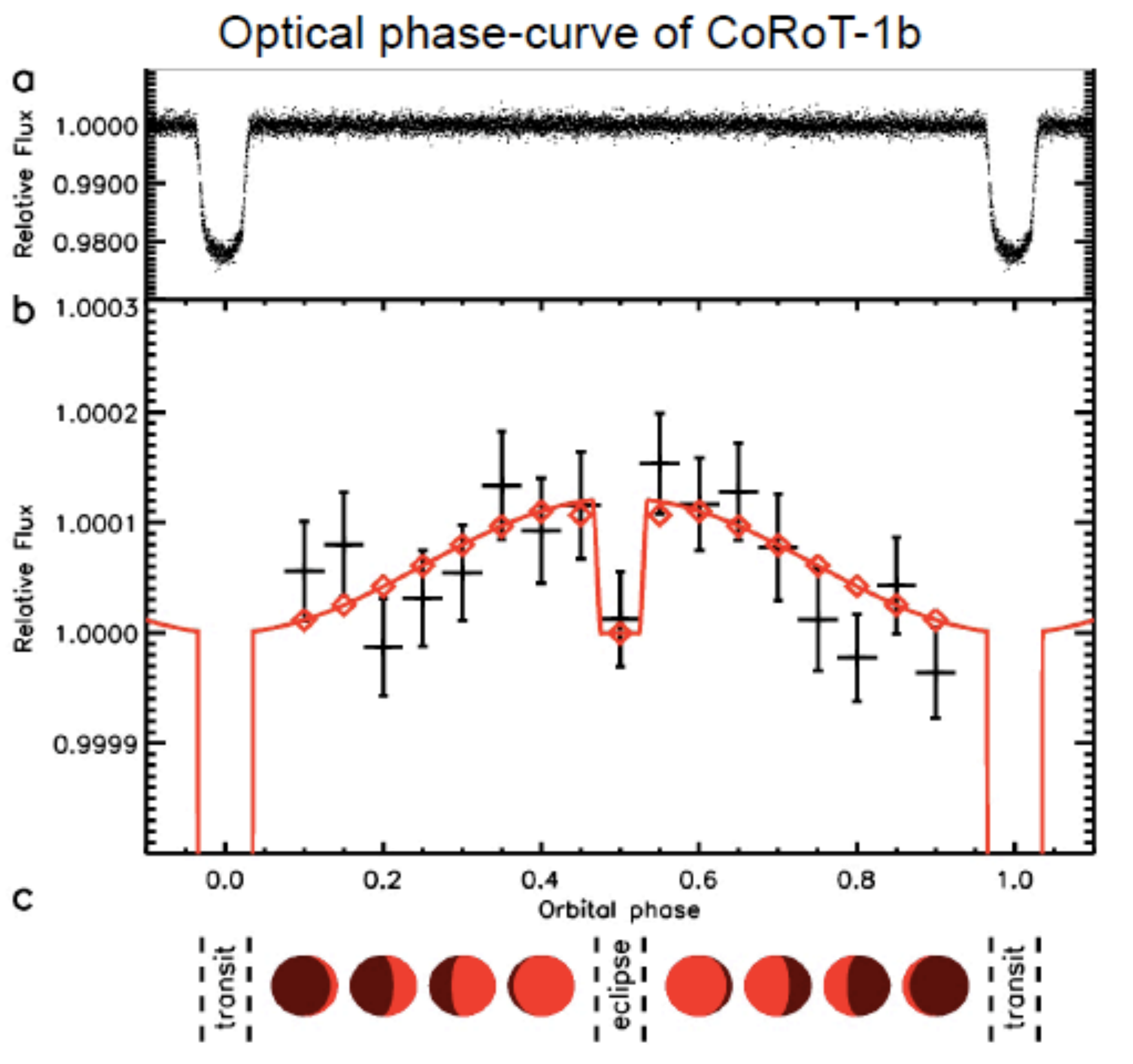
Knutson et al. 2008

Atmospheric Inhomogenouities



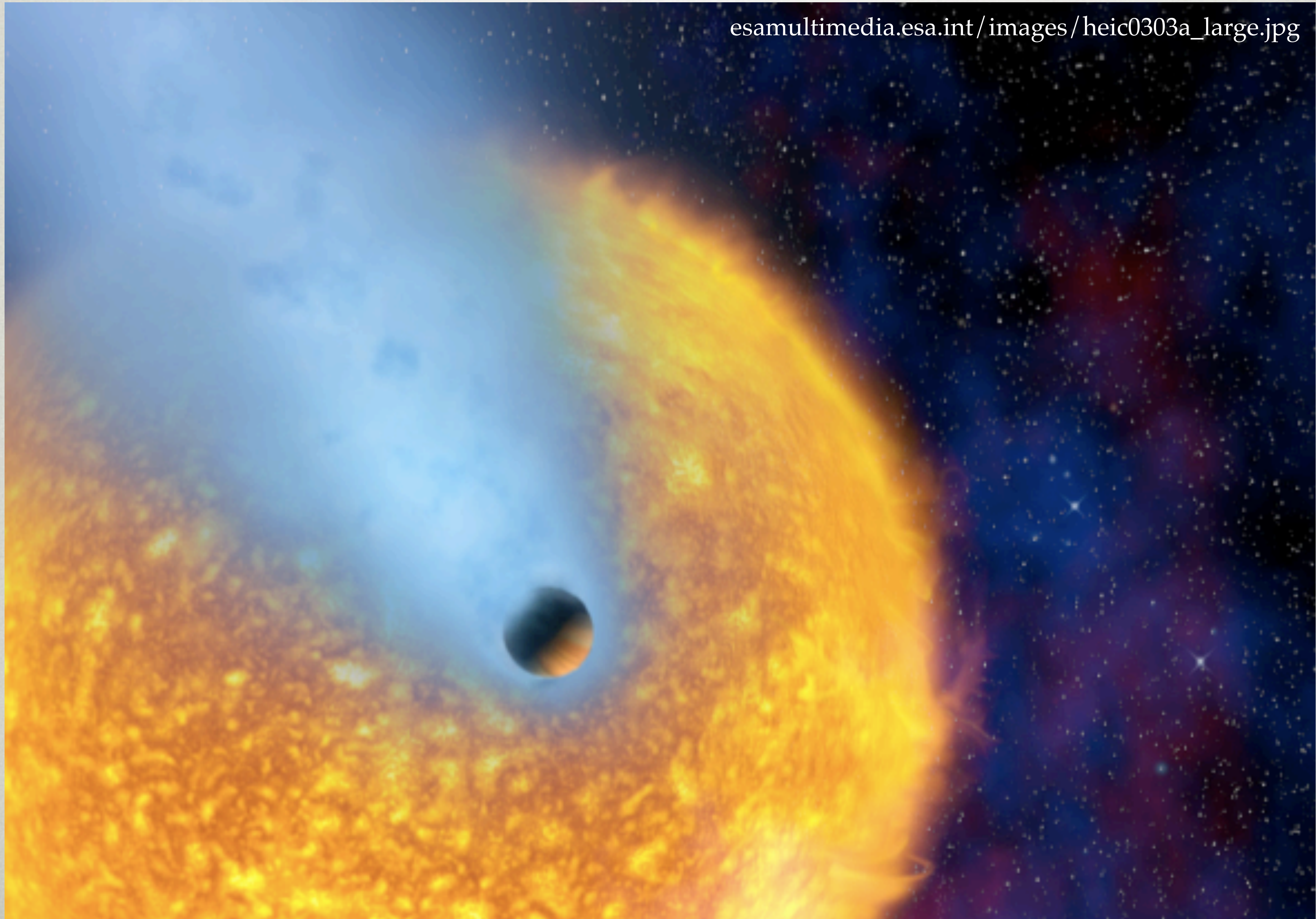
ipac.jpl.nasa.gov/media_images/ssc2006-18a_medium.jpg

Secondary Eclipse from Corot

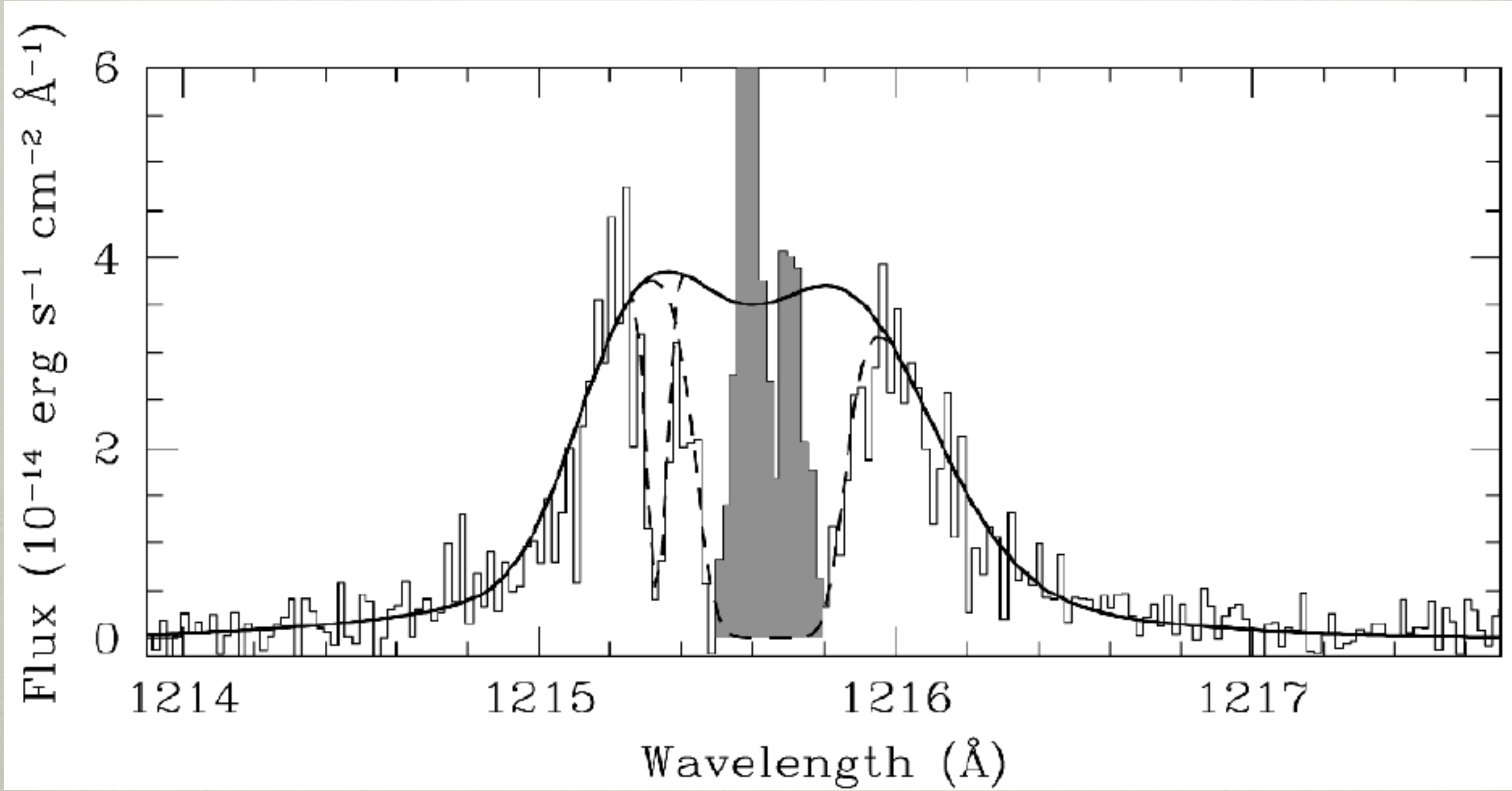


Snellen et al. 2009

Atmospheric Escape

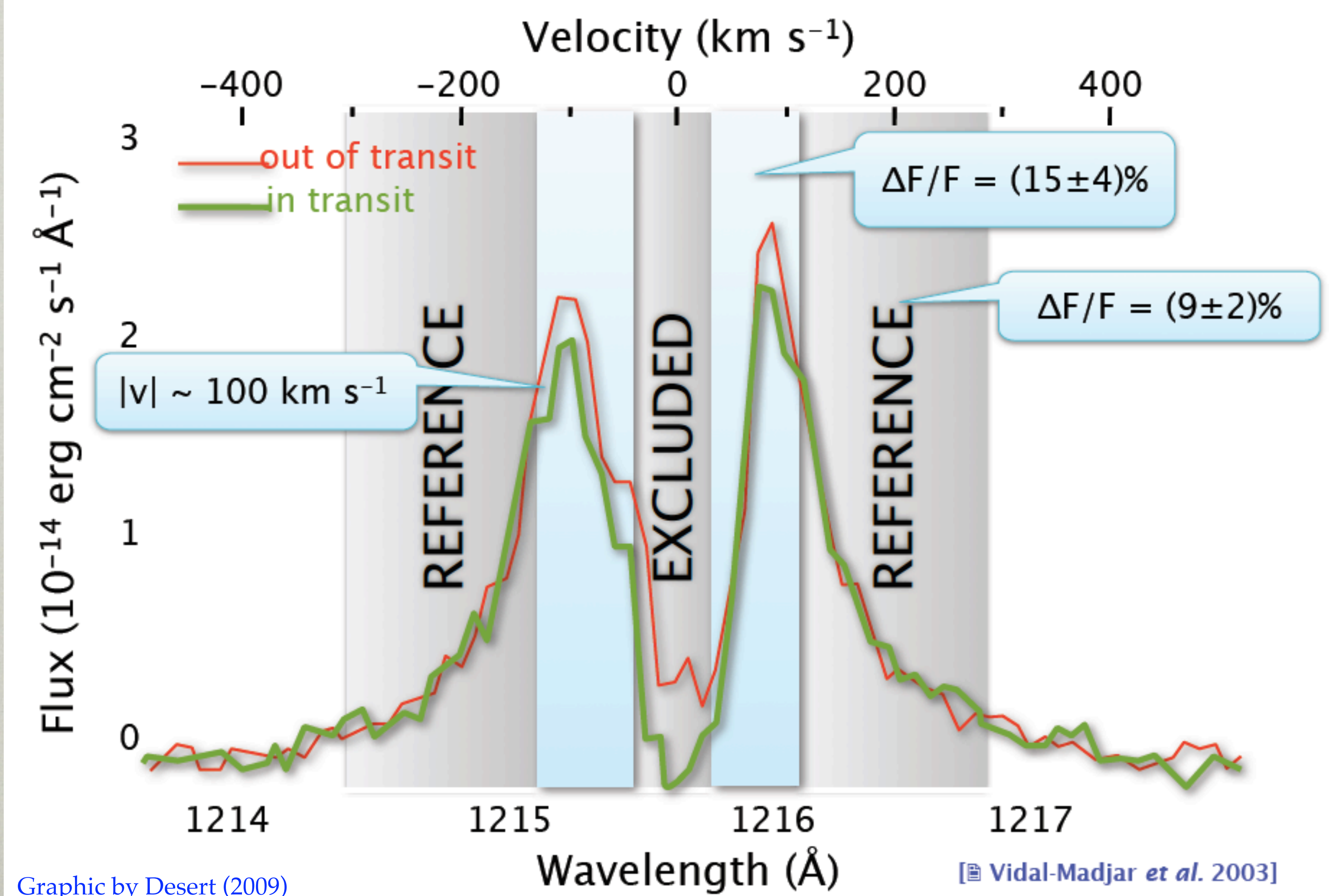


Atmospheric Escape



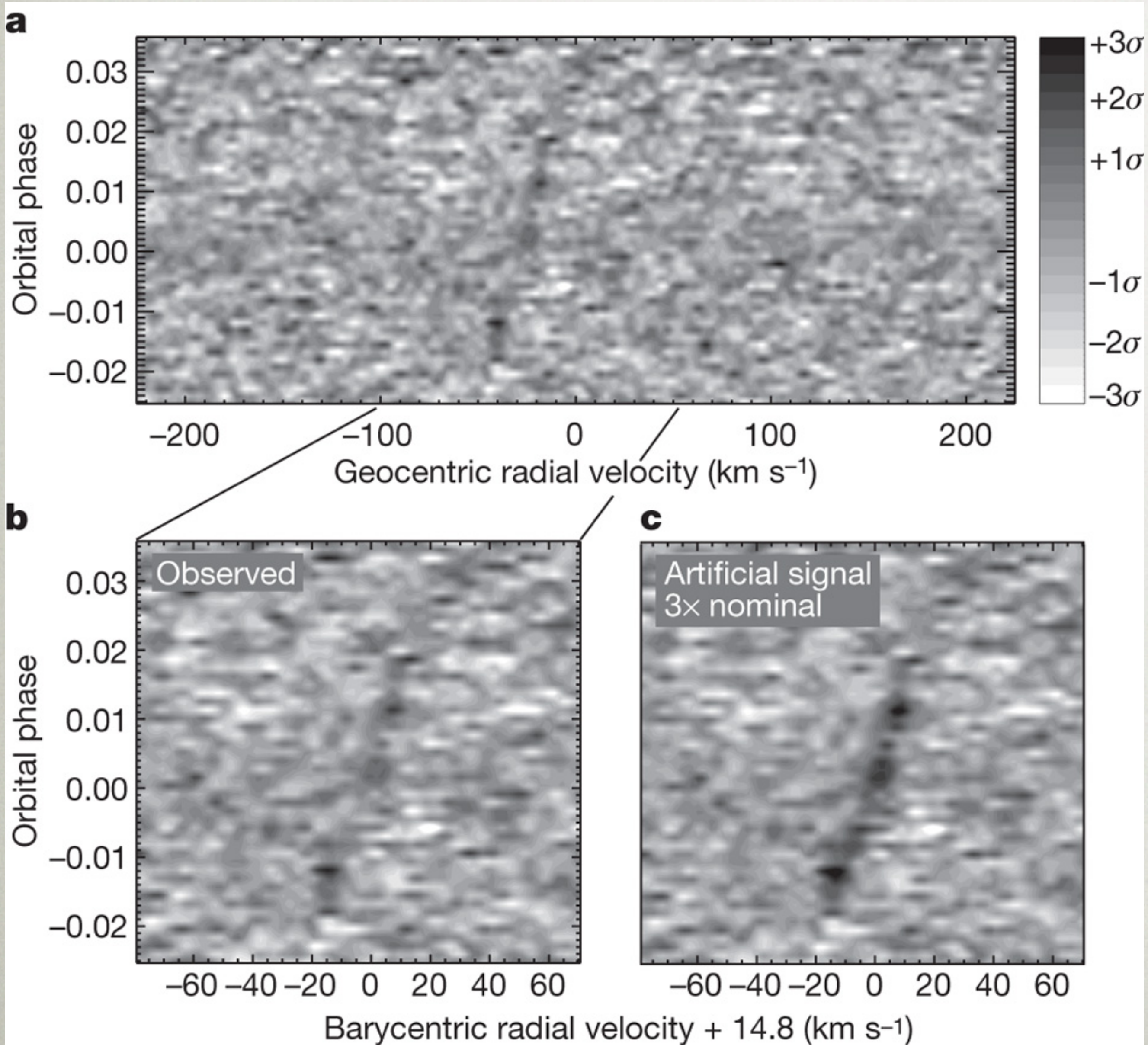
Vidal-Madjar et al. 2003

Atmospheric Escape



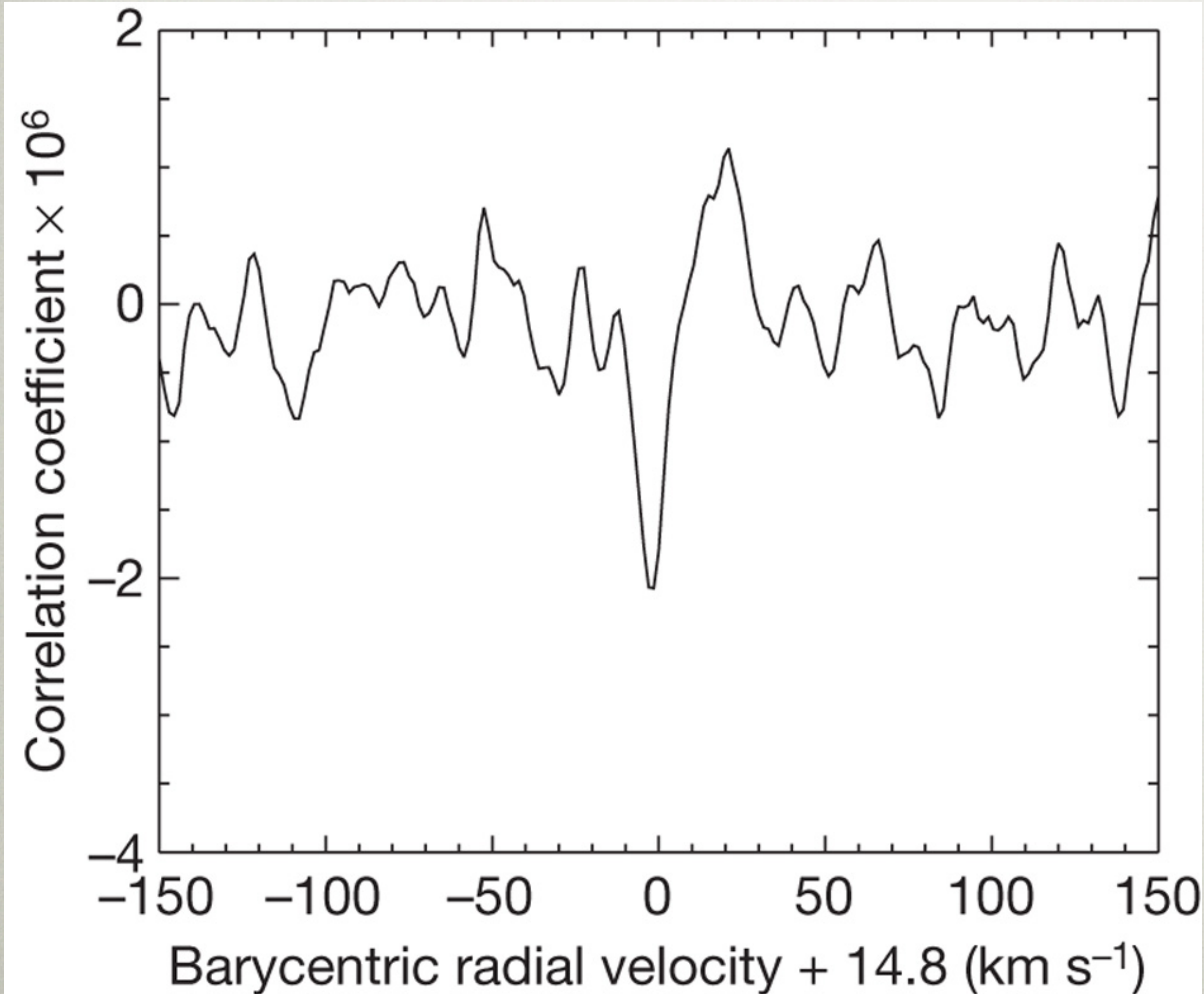
Graphic by Desert (2009)

Carbon Monoxide on Exoplanets



Snellen et al. 2010

Winds on Exoplanets



Snellen et al. 2010