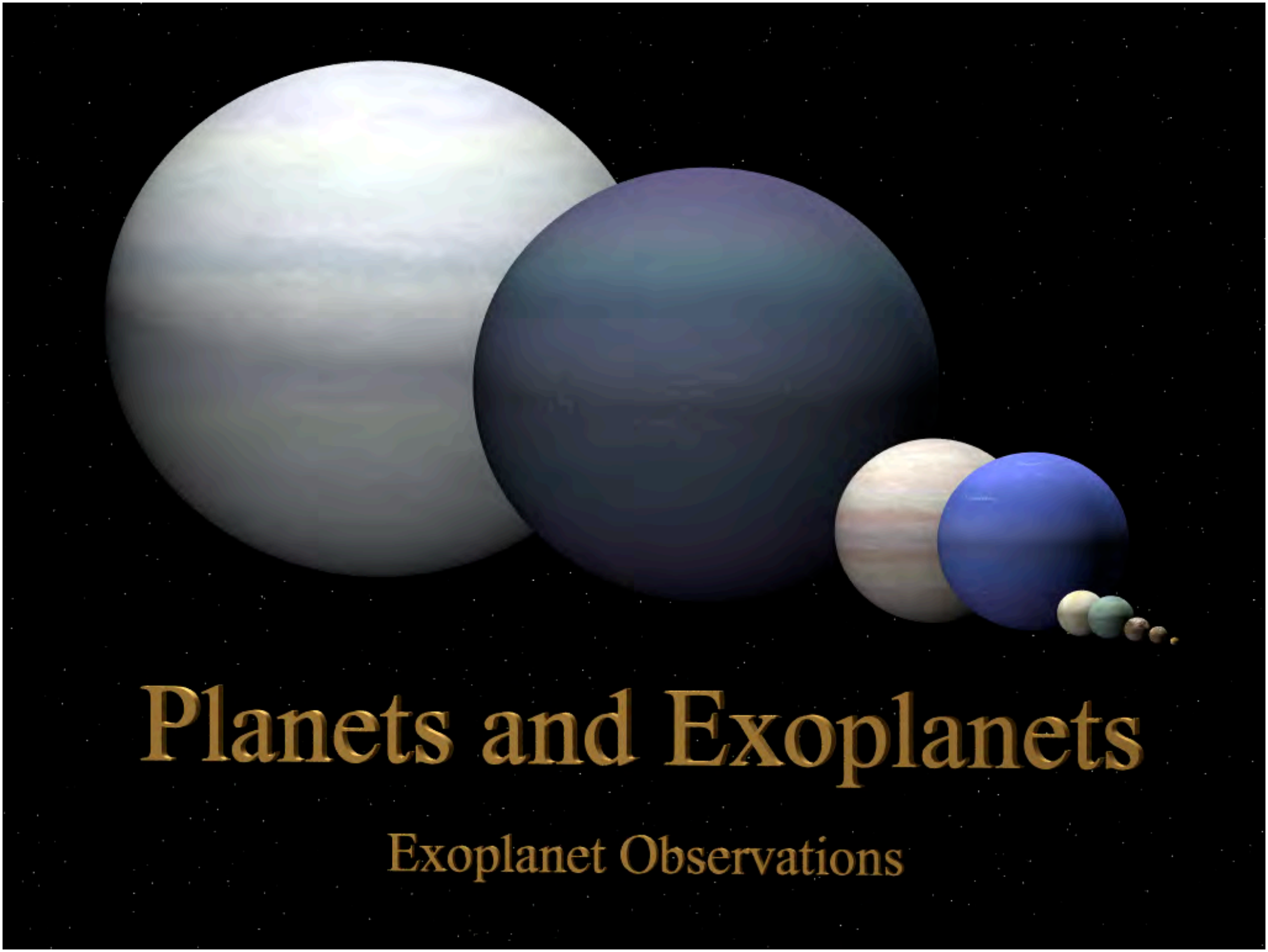

Planets and Exoplanets
Exoplanet Observations

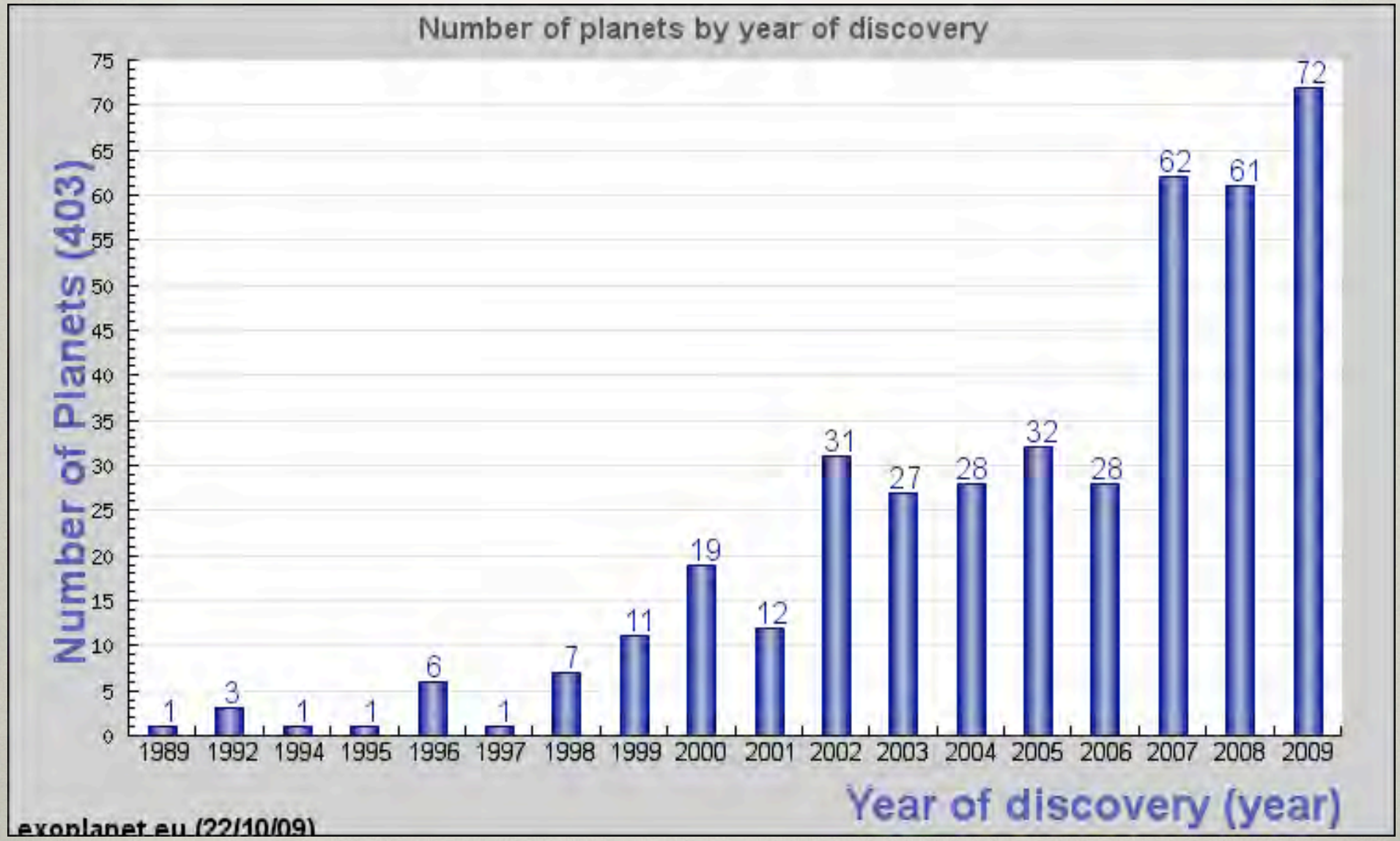
Outline

1. Introduction
2. Exoplanet Masses
3. Exoplanet Orbits
4. Exoplanet Radii
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



Detection vs. Characterization

Detection:

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

Characterization:

- Determine radius
- Determine surface properties
- Determine atmospheric properties

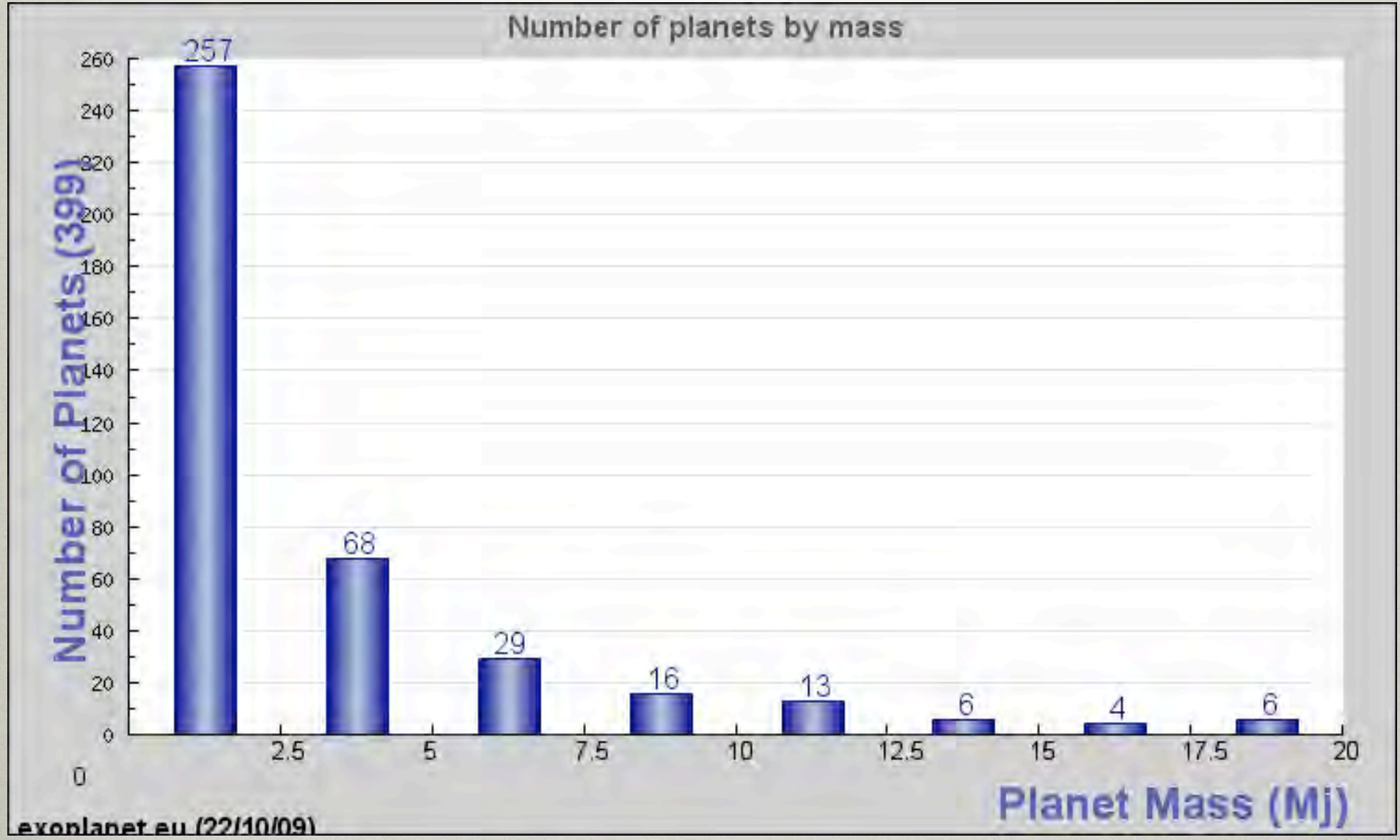
Planet Detections as of 19.10.2009

- Radial velocity : 320 planetary systems with 376 planets and 38 multiple planet systems
- Transits: 62 planetary systems with 62 planets and 3 multiple planet systems
- Microlensing: 8 planetary systems with 9 planets and 1 multiple planet systems
- Imaging: 9 planetary systems with 11 planets and 1 multiple planet system
- Timing: 4 planetary systems with 7 planets and 2 multiple planet systems
- Source: exoplanet.eu

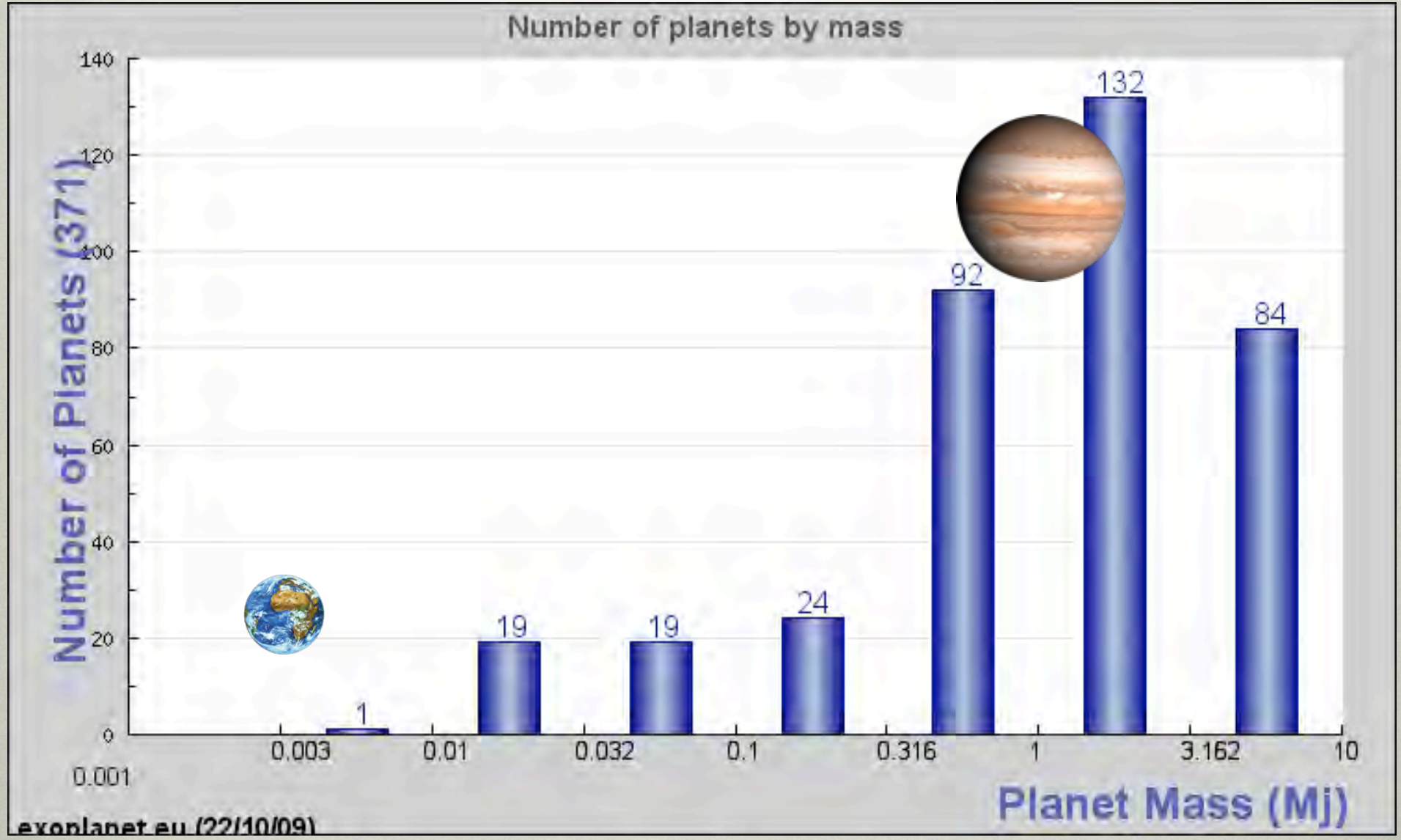
Problems with Statistics

- Selection effects:
  - some aspects of observed distributions are inconsistent with real population of exoplanets
  - Are different for different exoplanet search programs
- Mass is mostly a lower limit to the mass

Exoplanet Masses



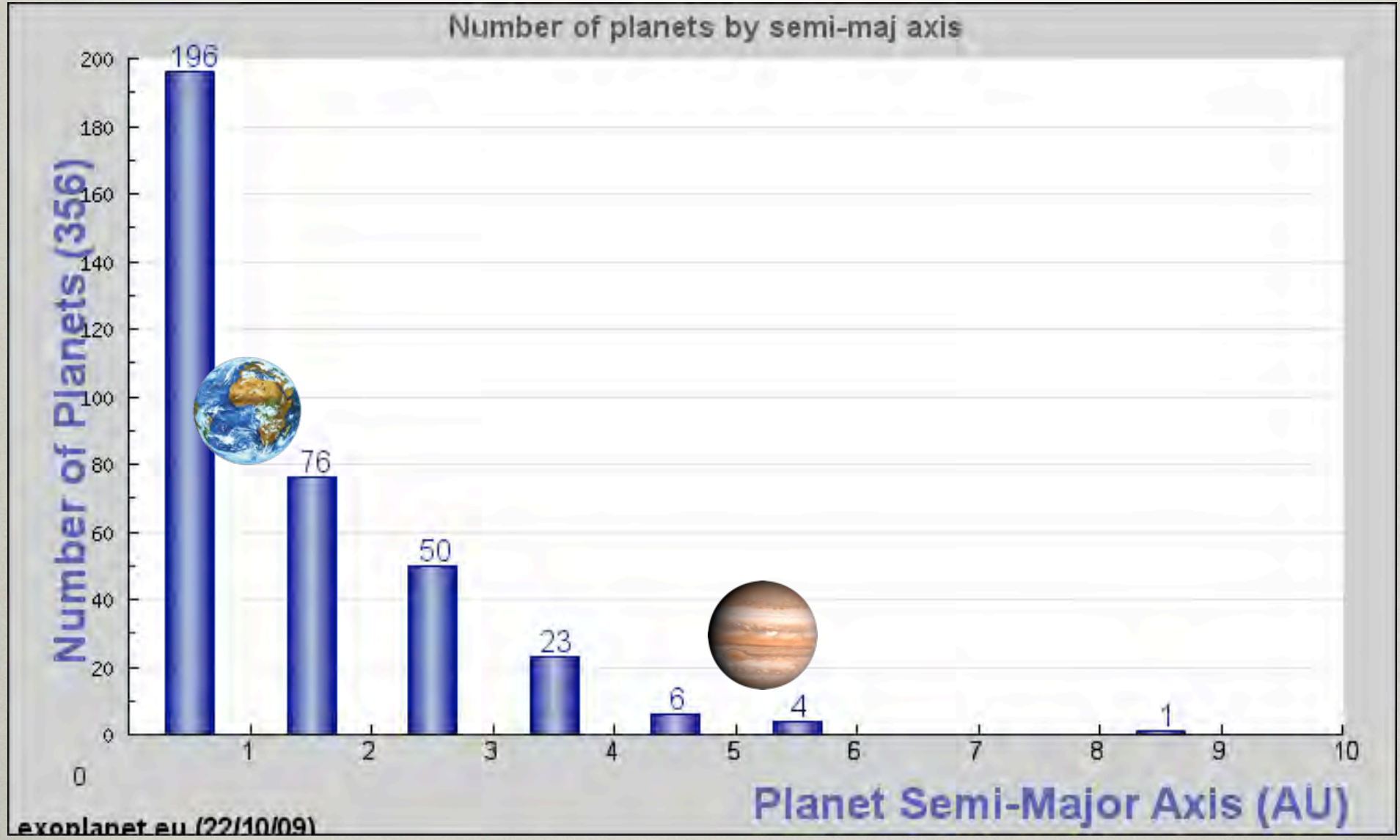
Exoplanet Masses



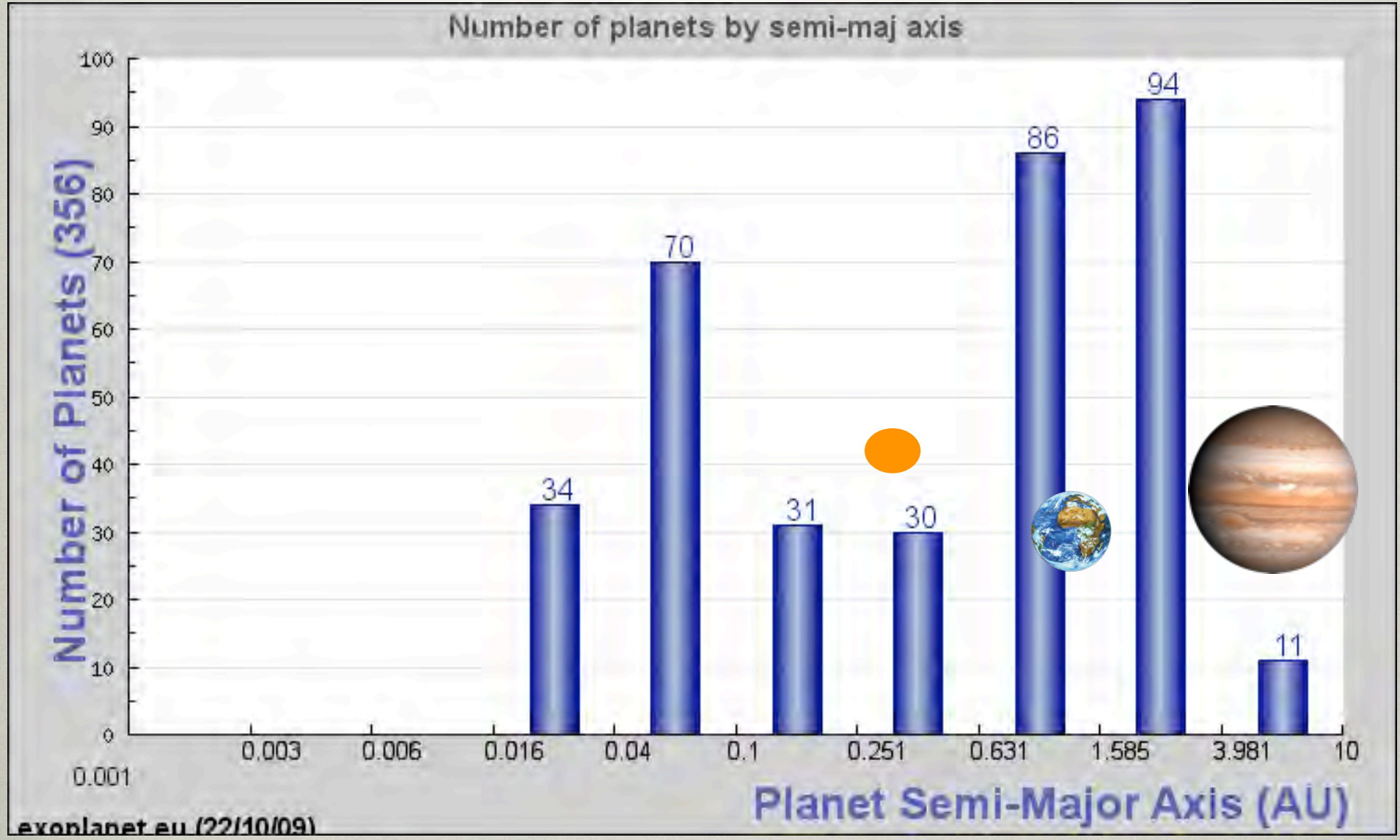
Mass Distribution Interpretation

- 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



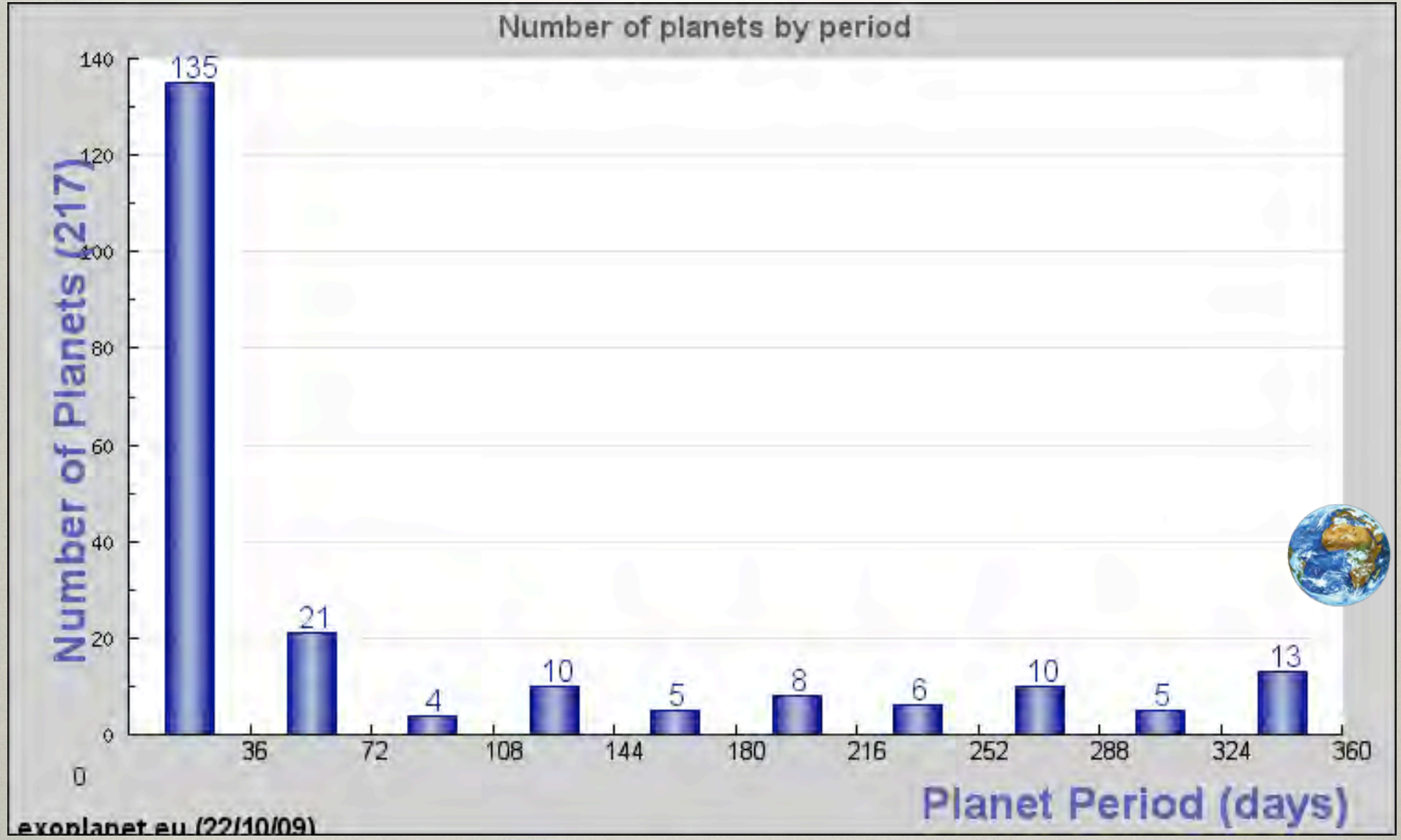
Exoplanet Orbital Distances



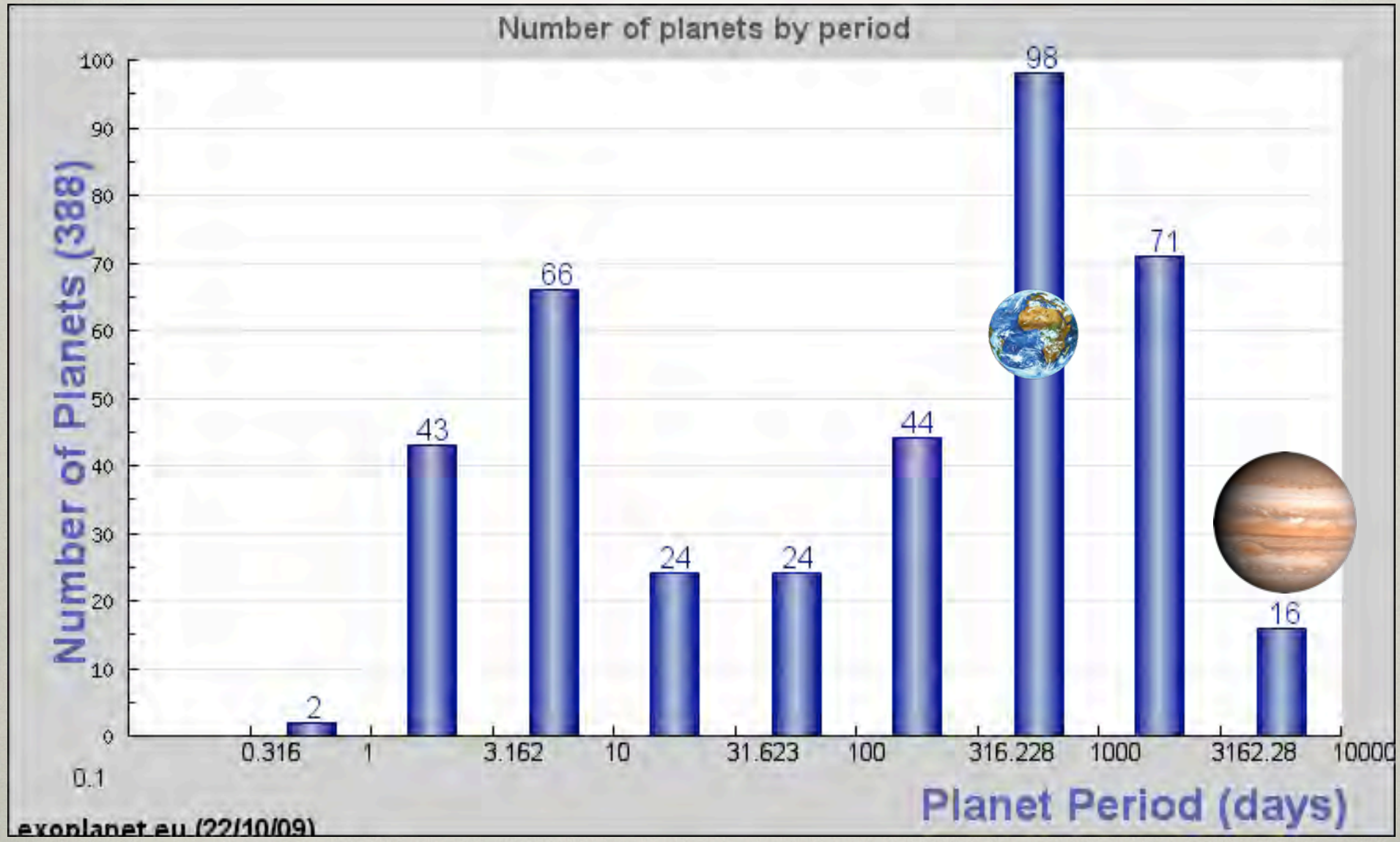
Orbit Interpretation

- Planets with a > 3AU have periods ≥ length of Doppler surveys
- Incomplete distribution beyond ~ 3 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



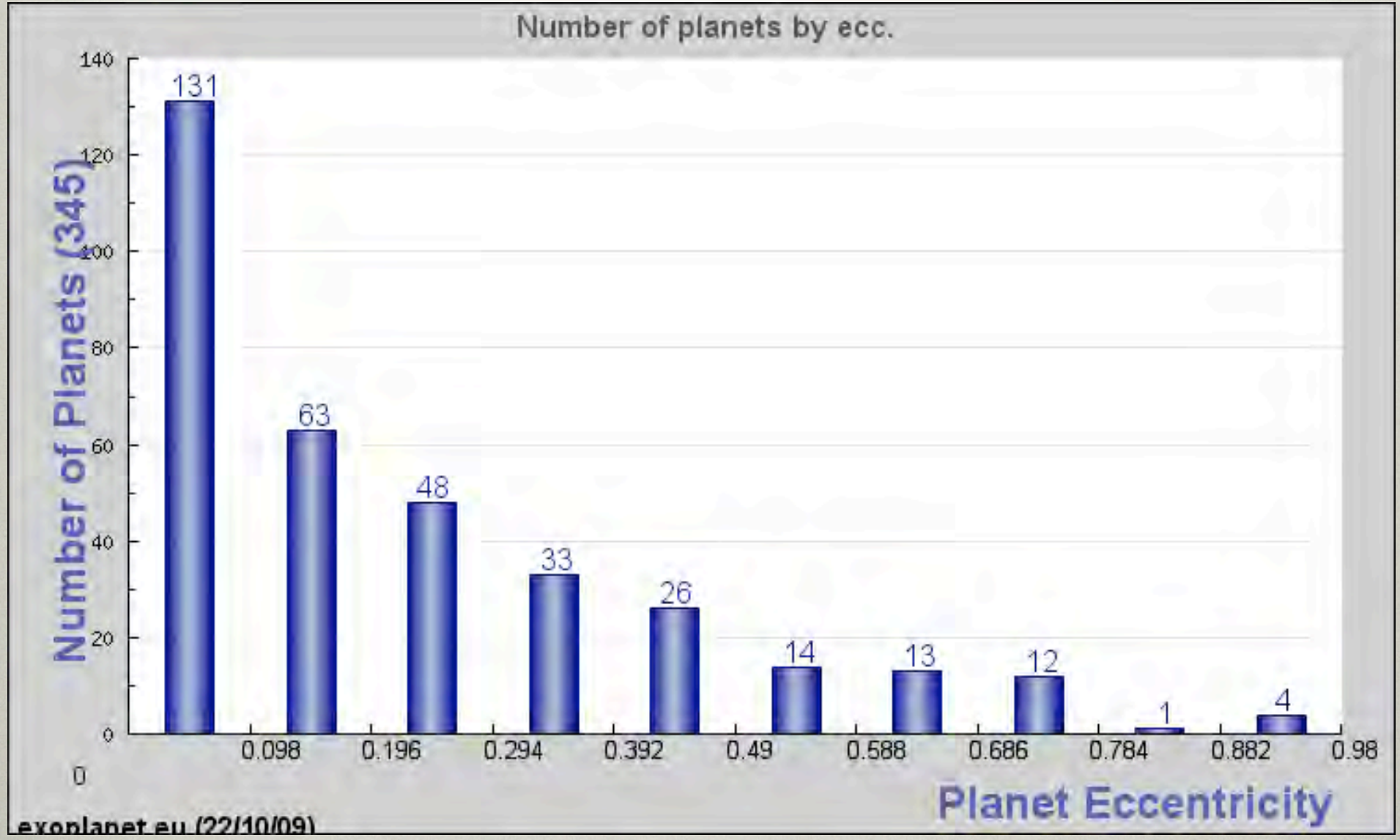
Exoplanet Orbital Periods



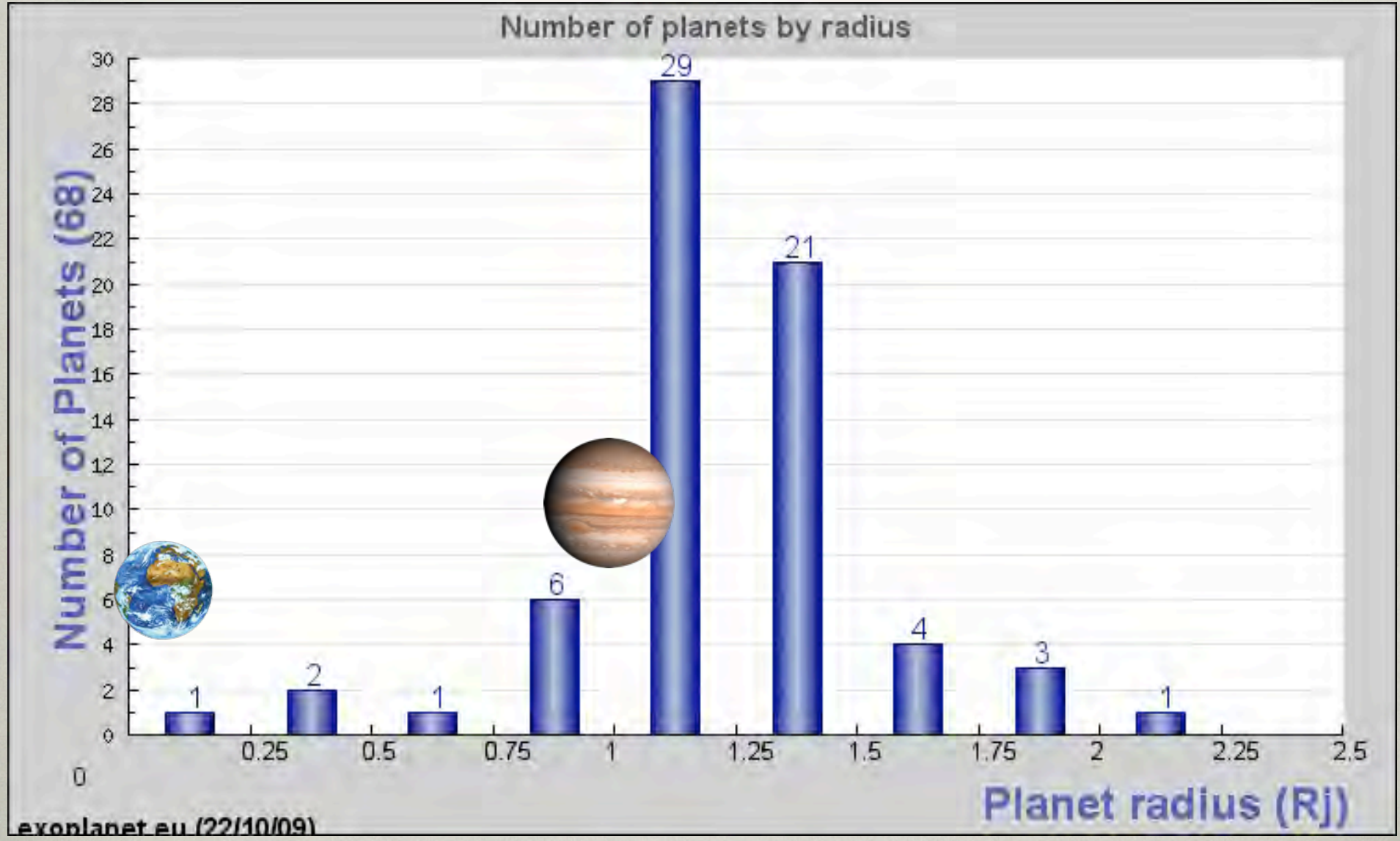
Orbital Period Interpretation

- 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

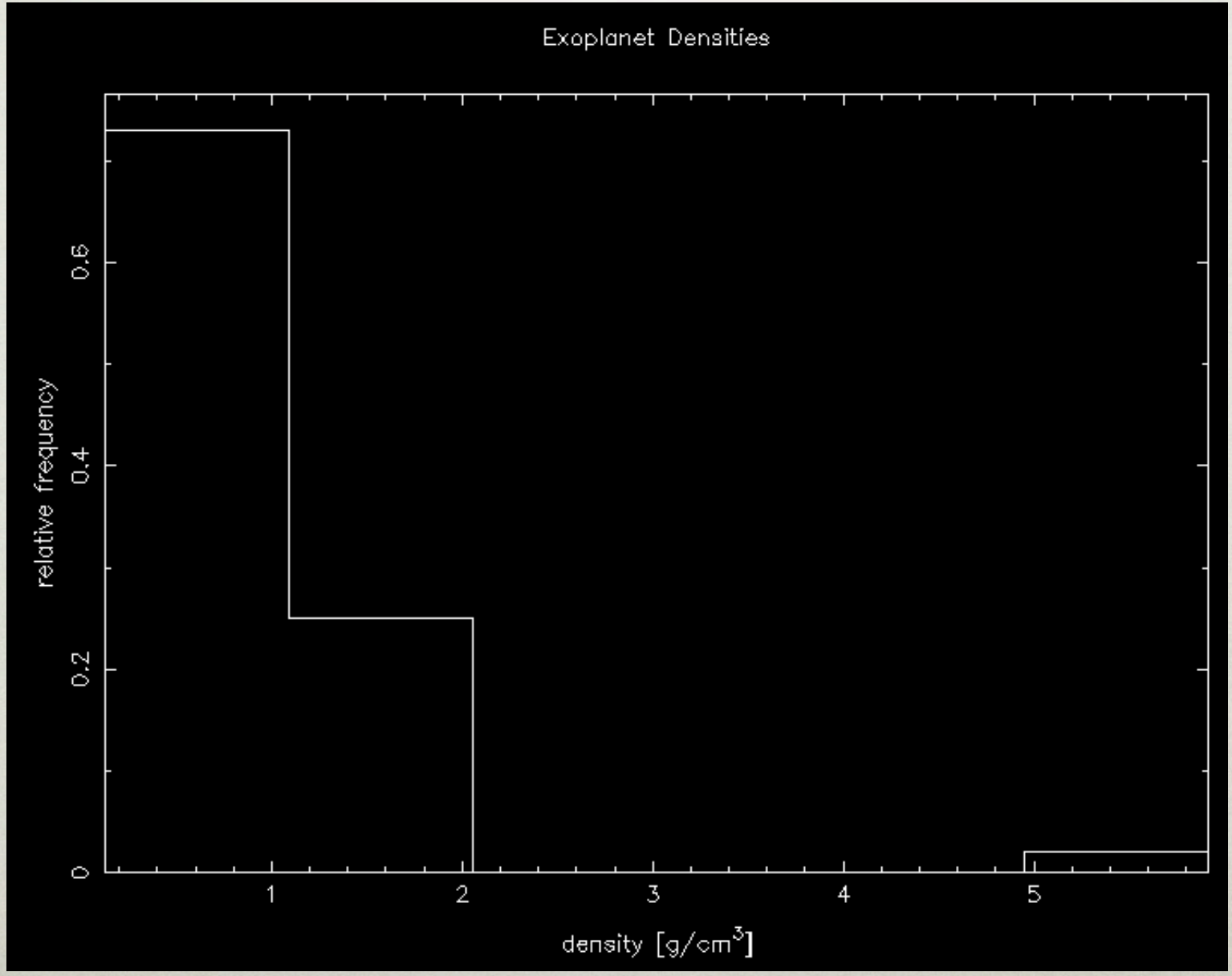
Exoplanet Eccentricities



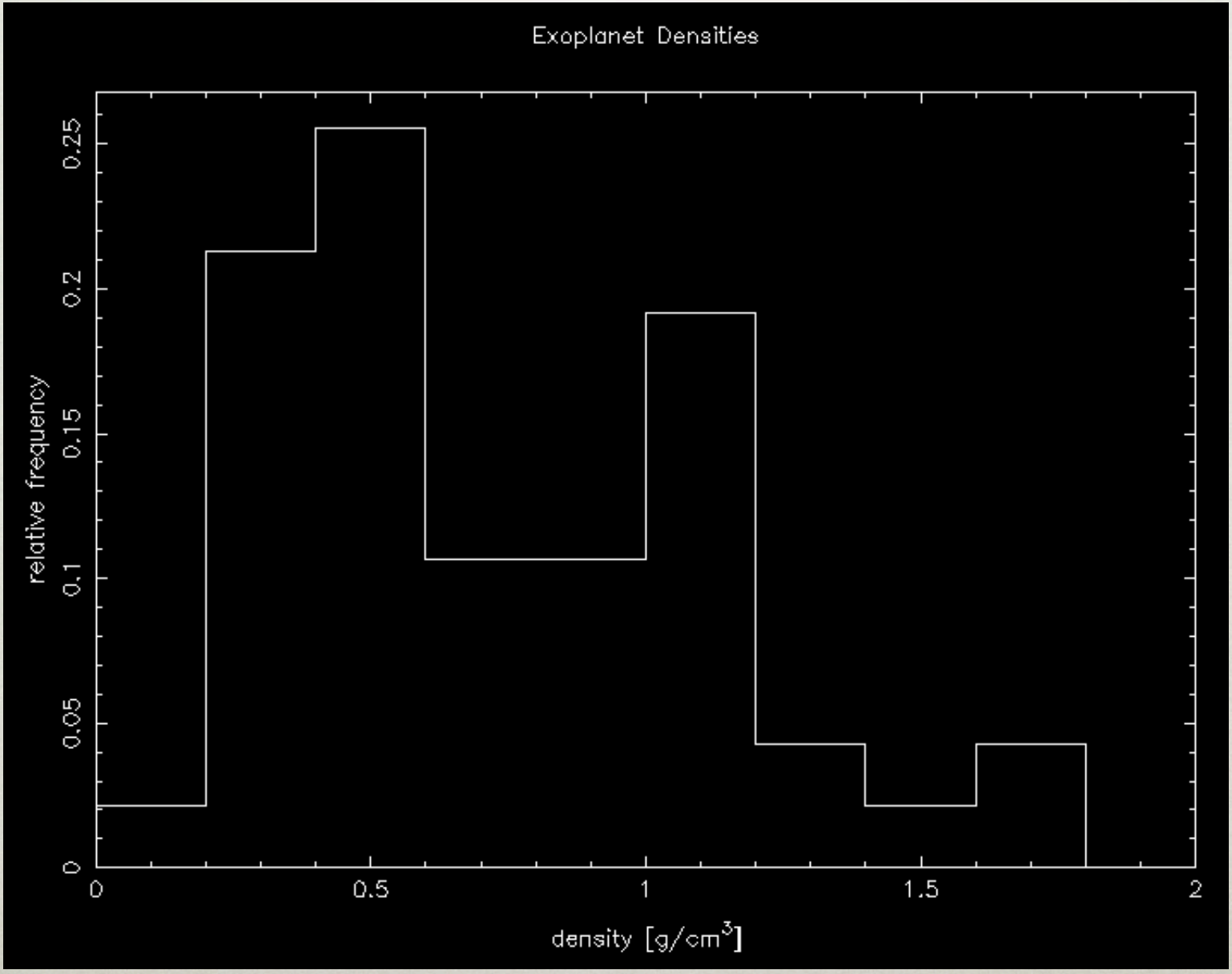
Exoplanet Radii



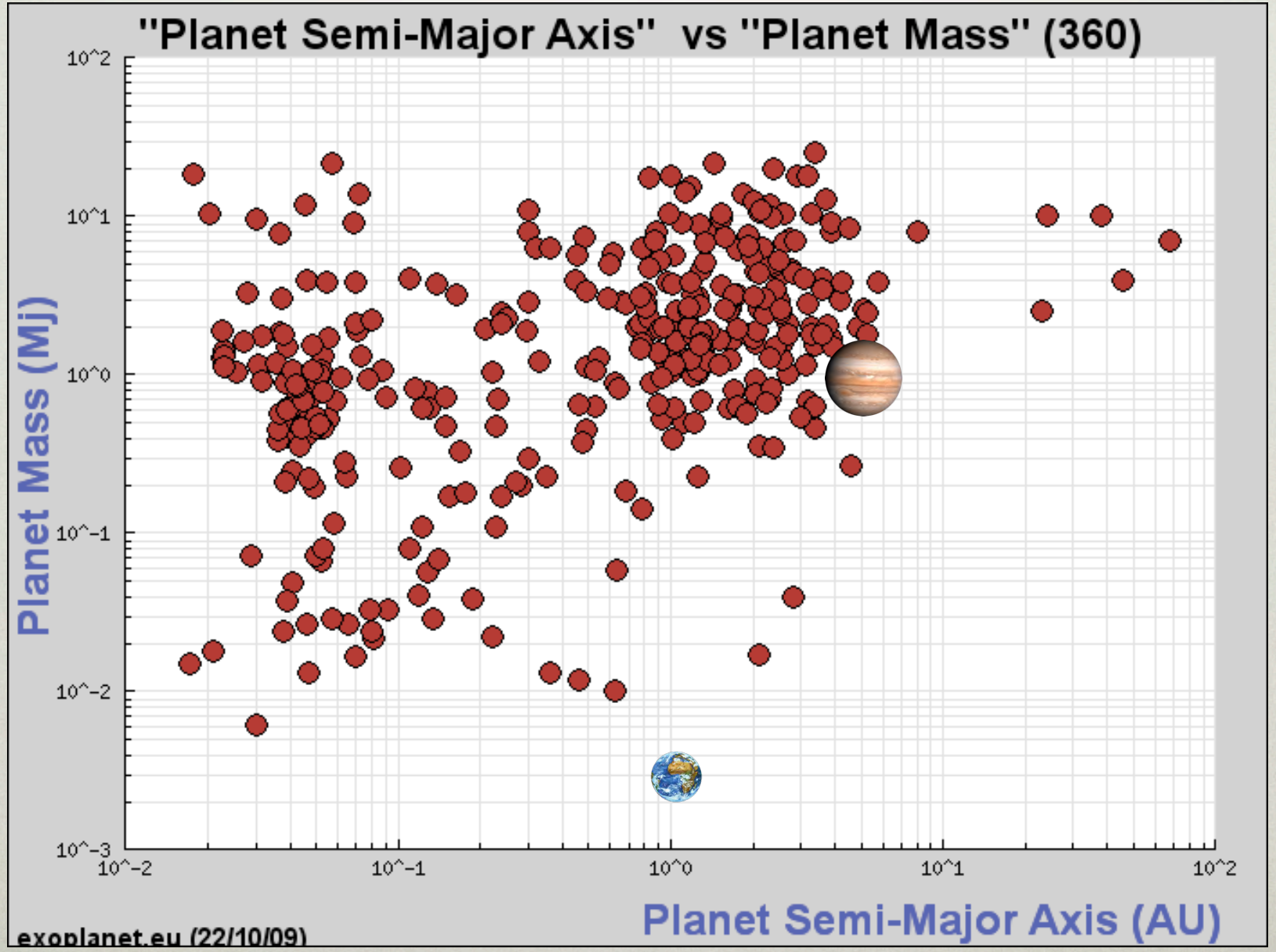
Exoplanet Densities



Exoplanet Densities



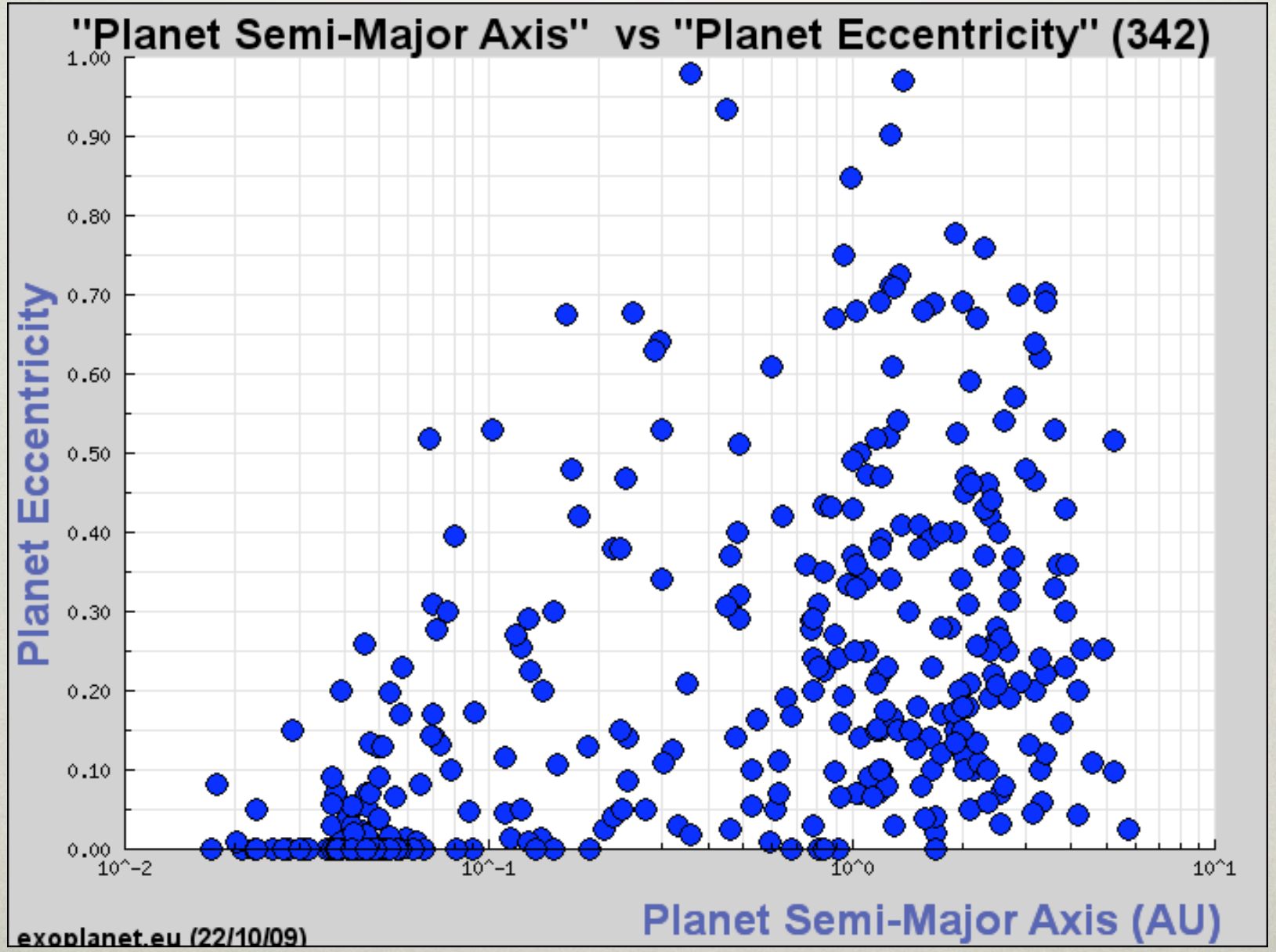
Mass vs. Semi-Major Axis



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

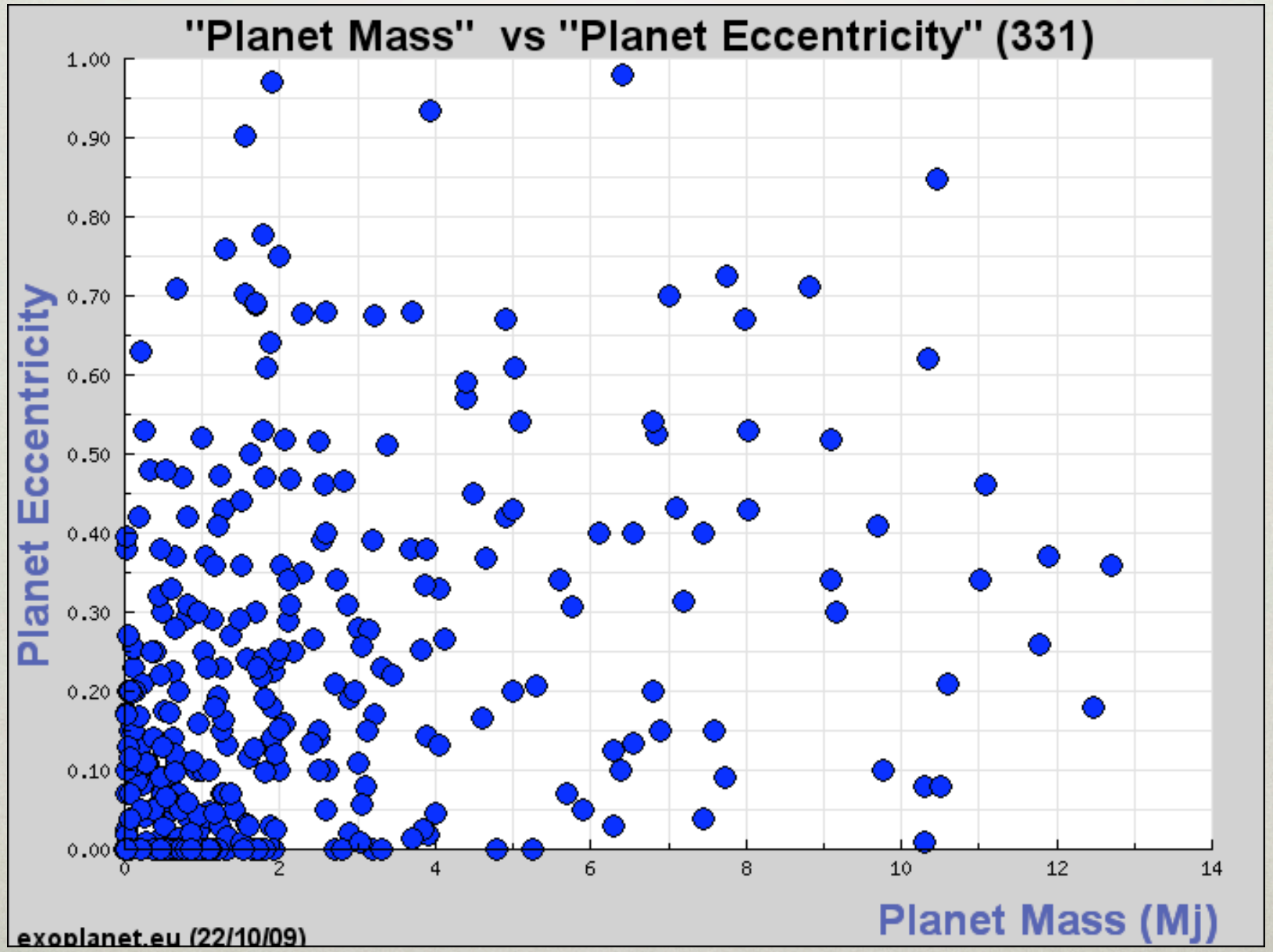
Eccentricity



Eccentricity

- Exoplanets within 0.1 AU on nearly circular orbits, presumably due to tidal circularization
- 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



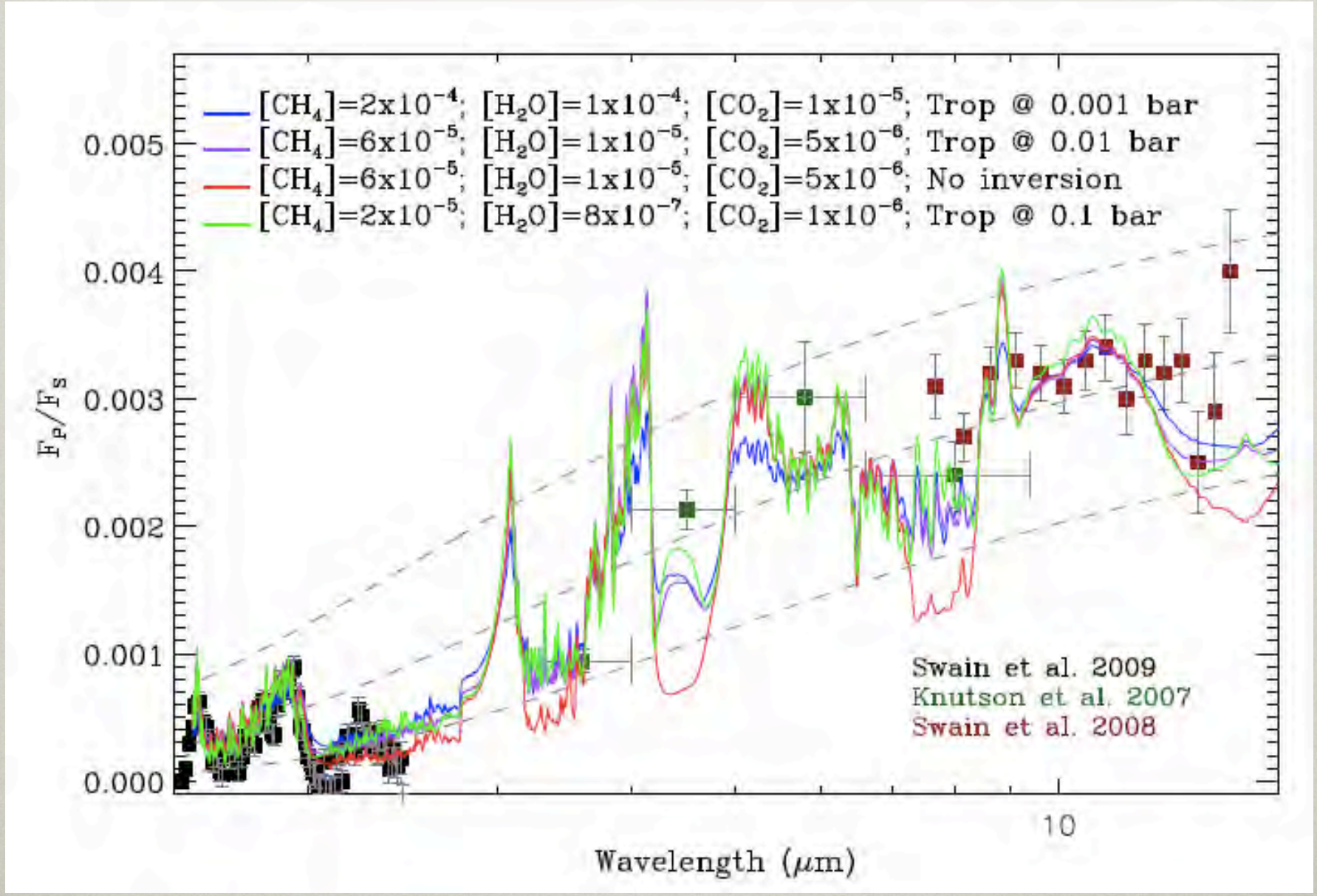
Eccentricity

- Tidally circularized orbits at a < 0.1 AU
- No clear correlation between eccentricity and mass
- But high-mass exoplanets (M sin i > $5M_J$) have higher median eccentricity than lower mass exoplanets

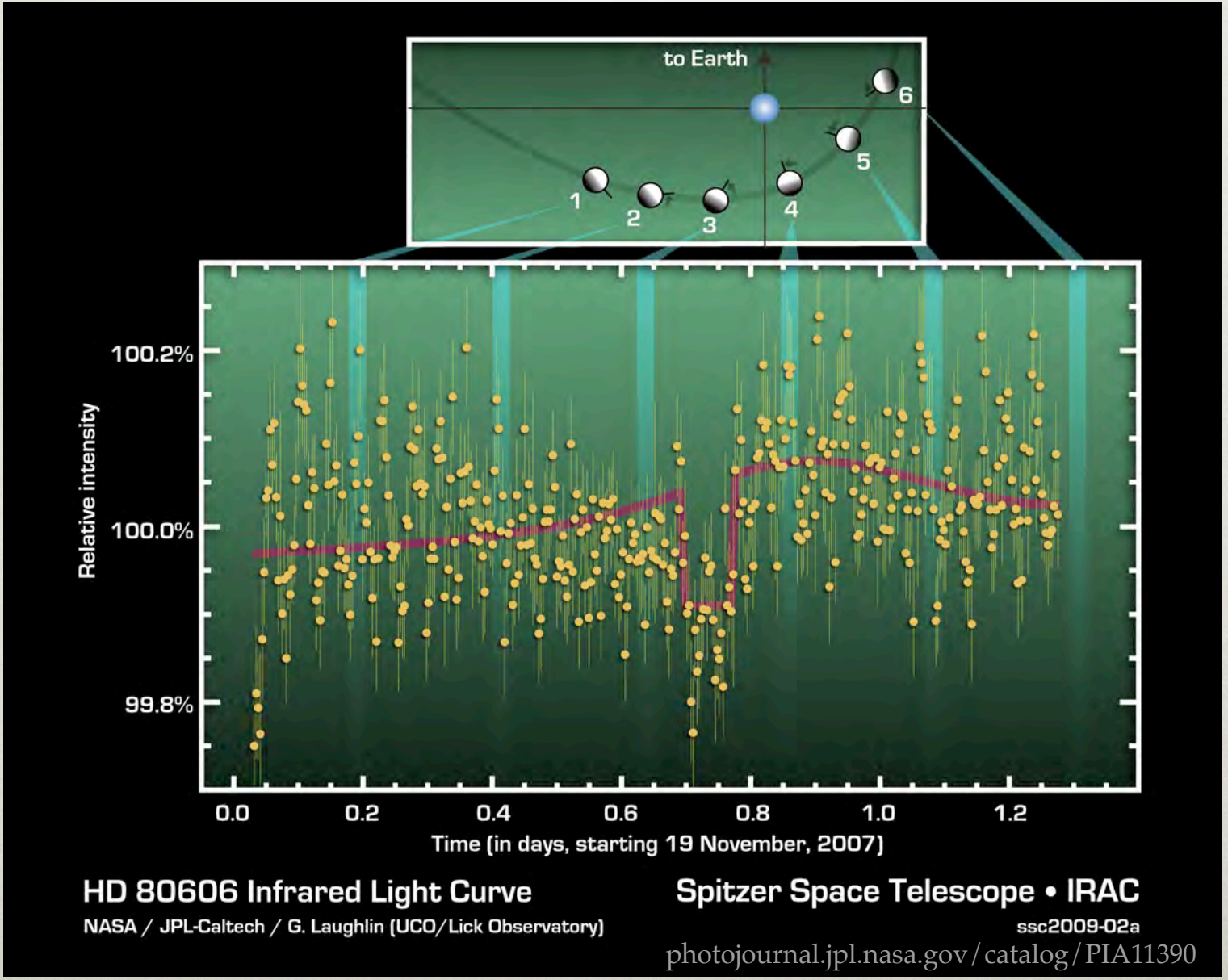
ExoPlanet Atmosphere Observations

- 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

Exoplanet Atmospheres (Swain et al. 2009)

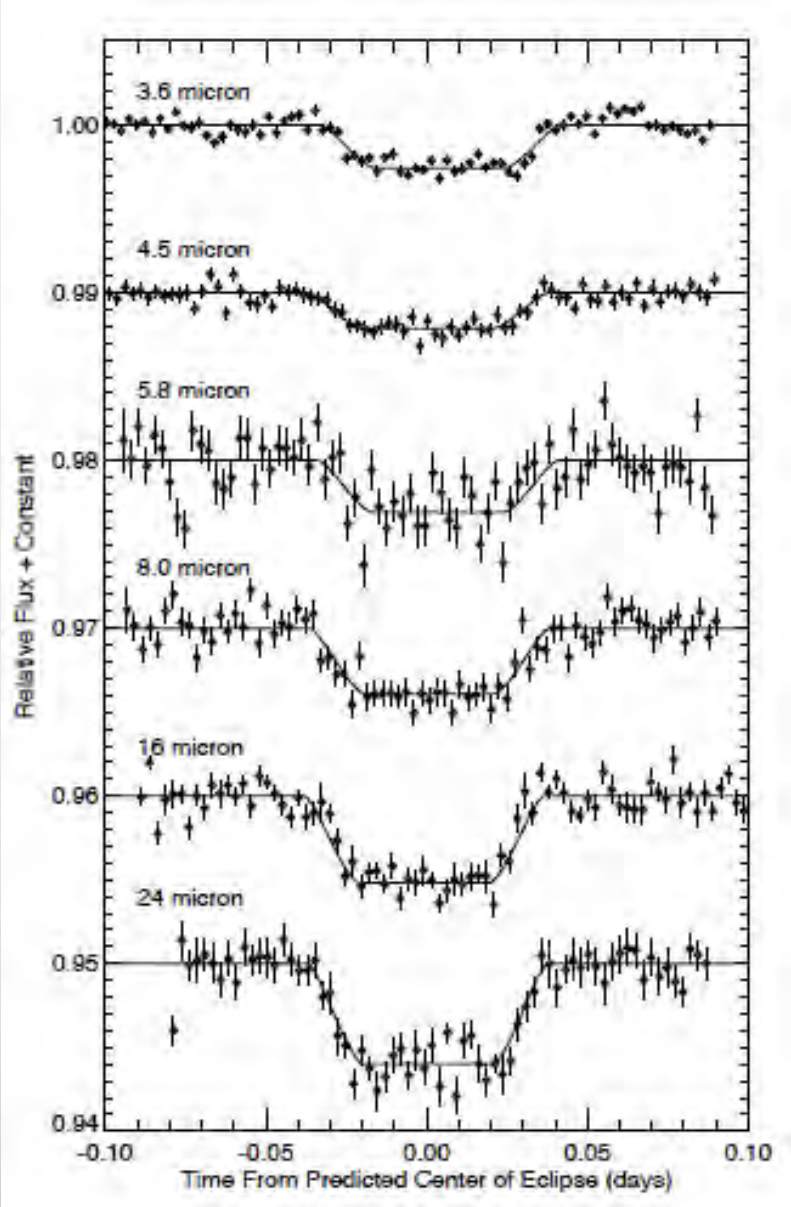


Secondary Eclipse



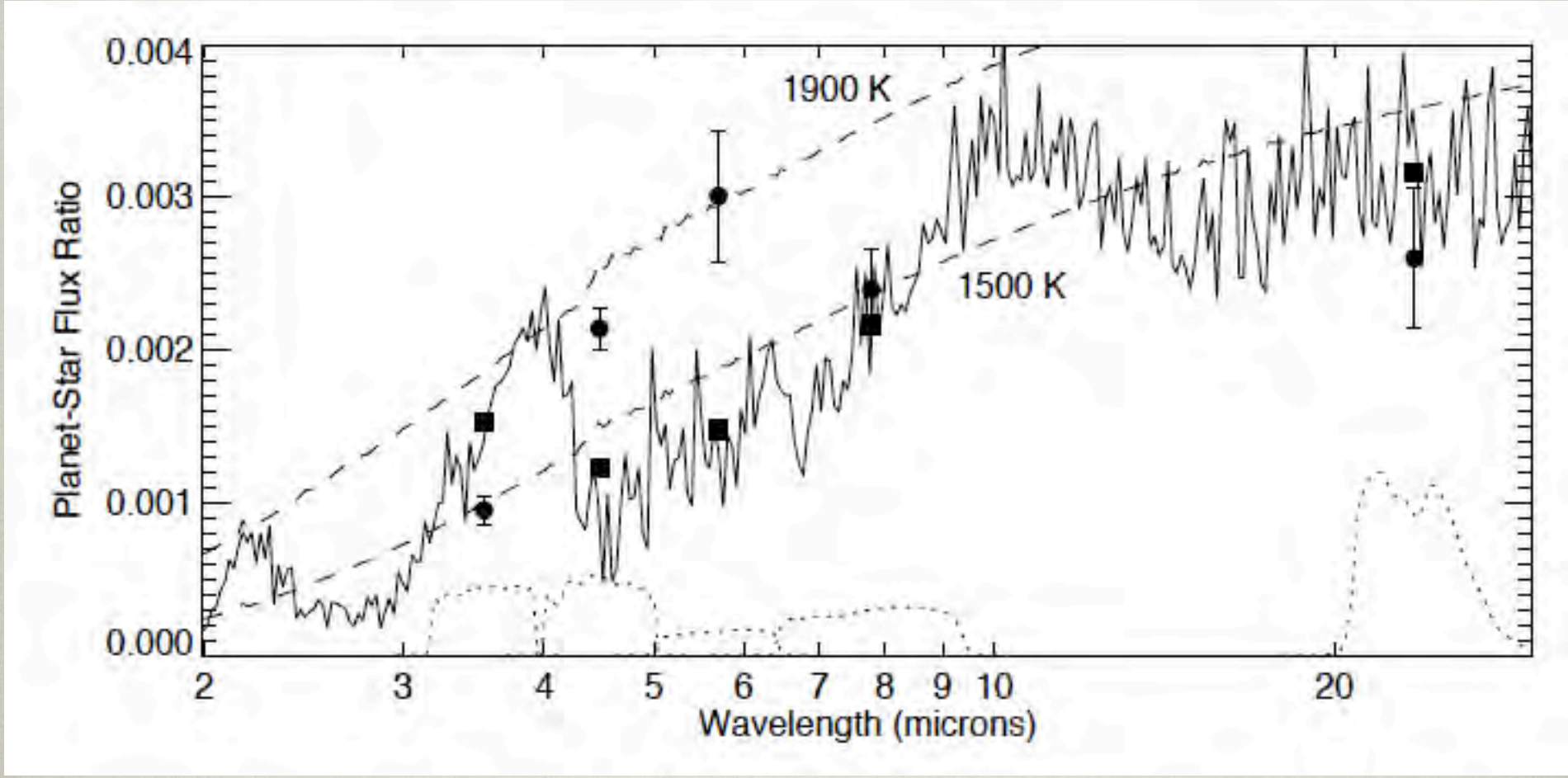
photojournal.jpl.nasa.gov/catalog/PIA11390

λ-Dependence of Secondary Eclipse



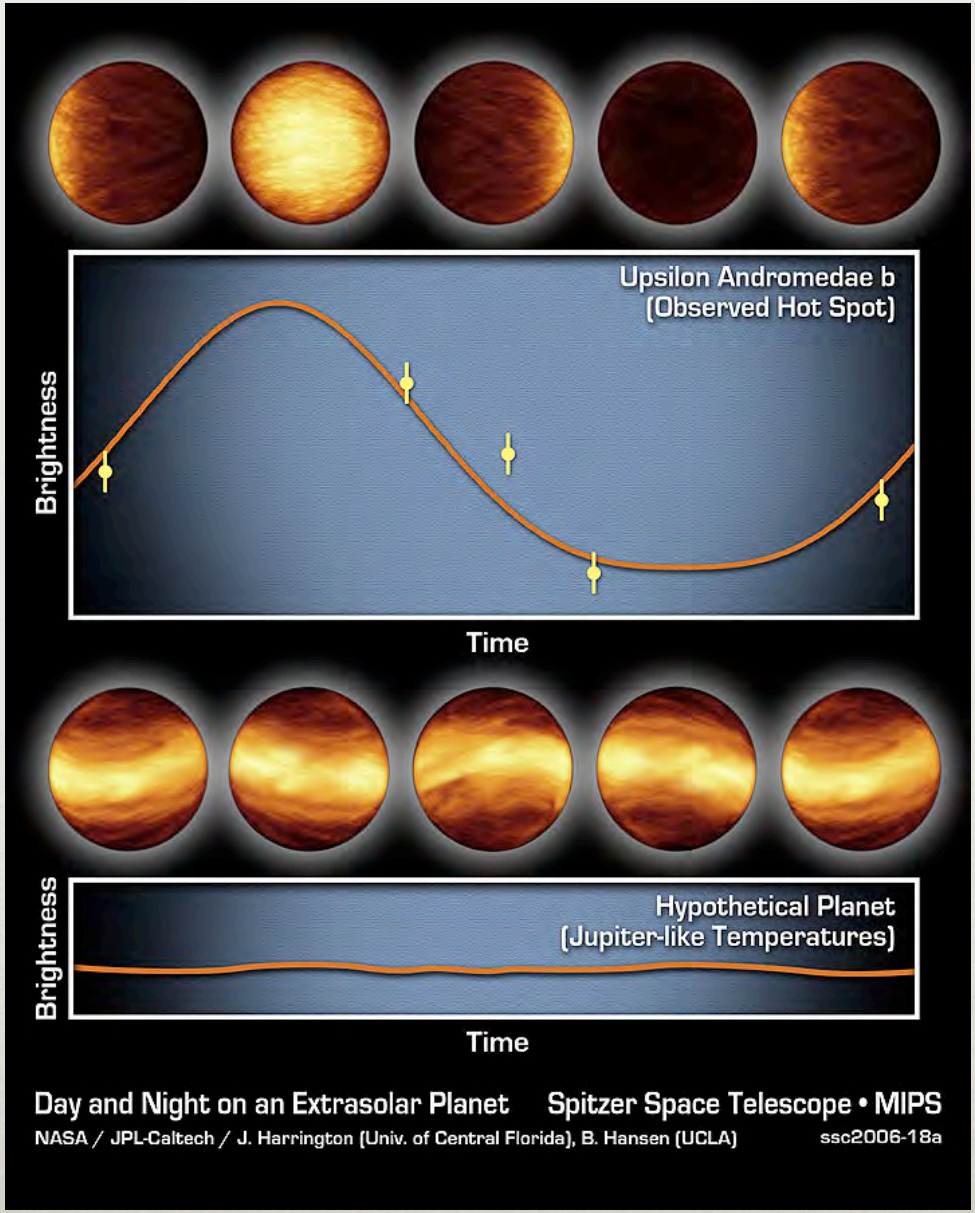
Charbonneau et al. 2008

Thermal Inversion



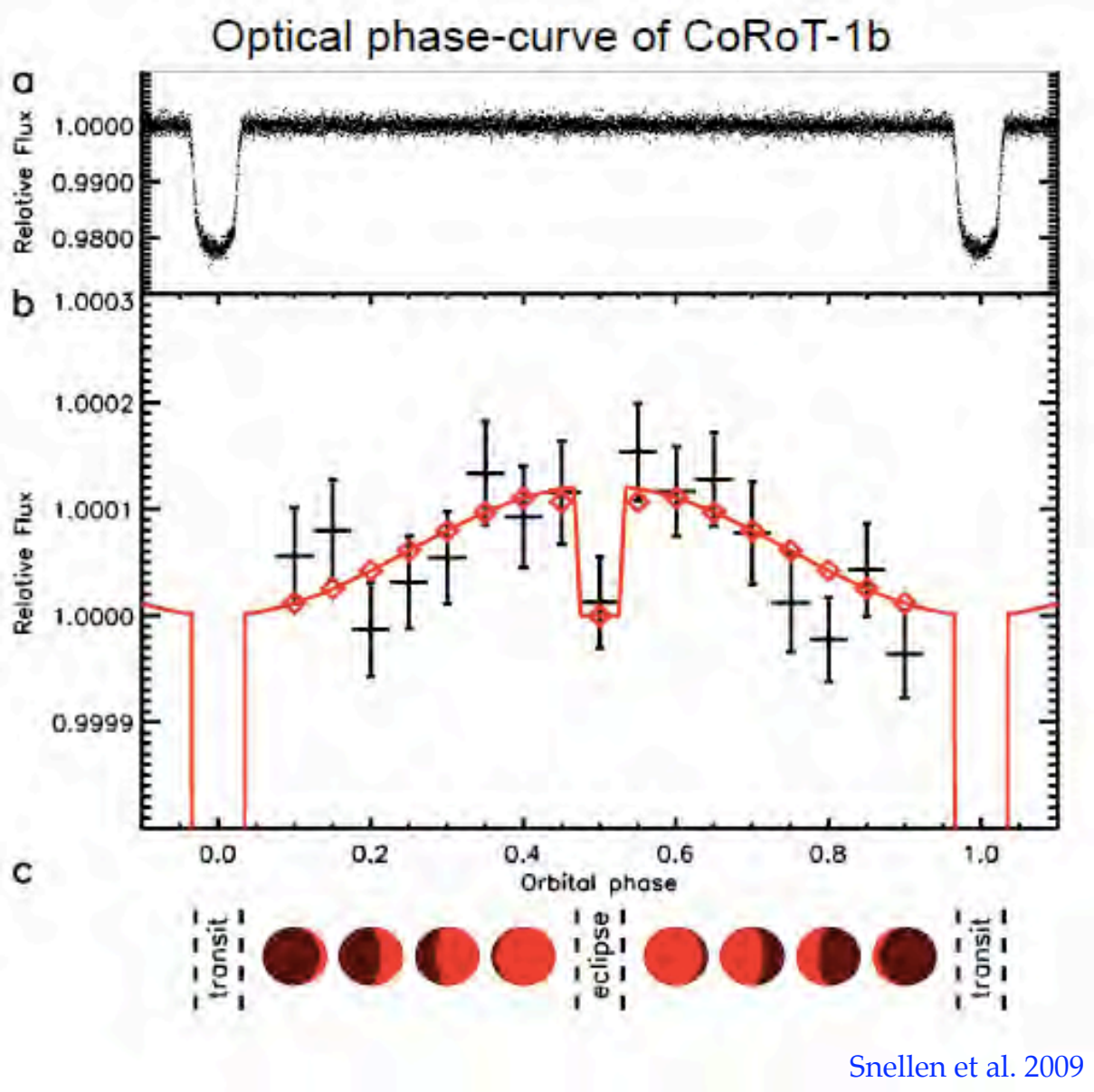
Knutson et al. 2008

Atmospheric Inhomogenouities



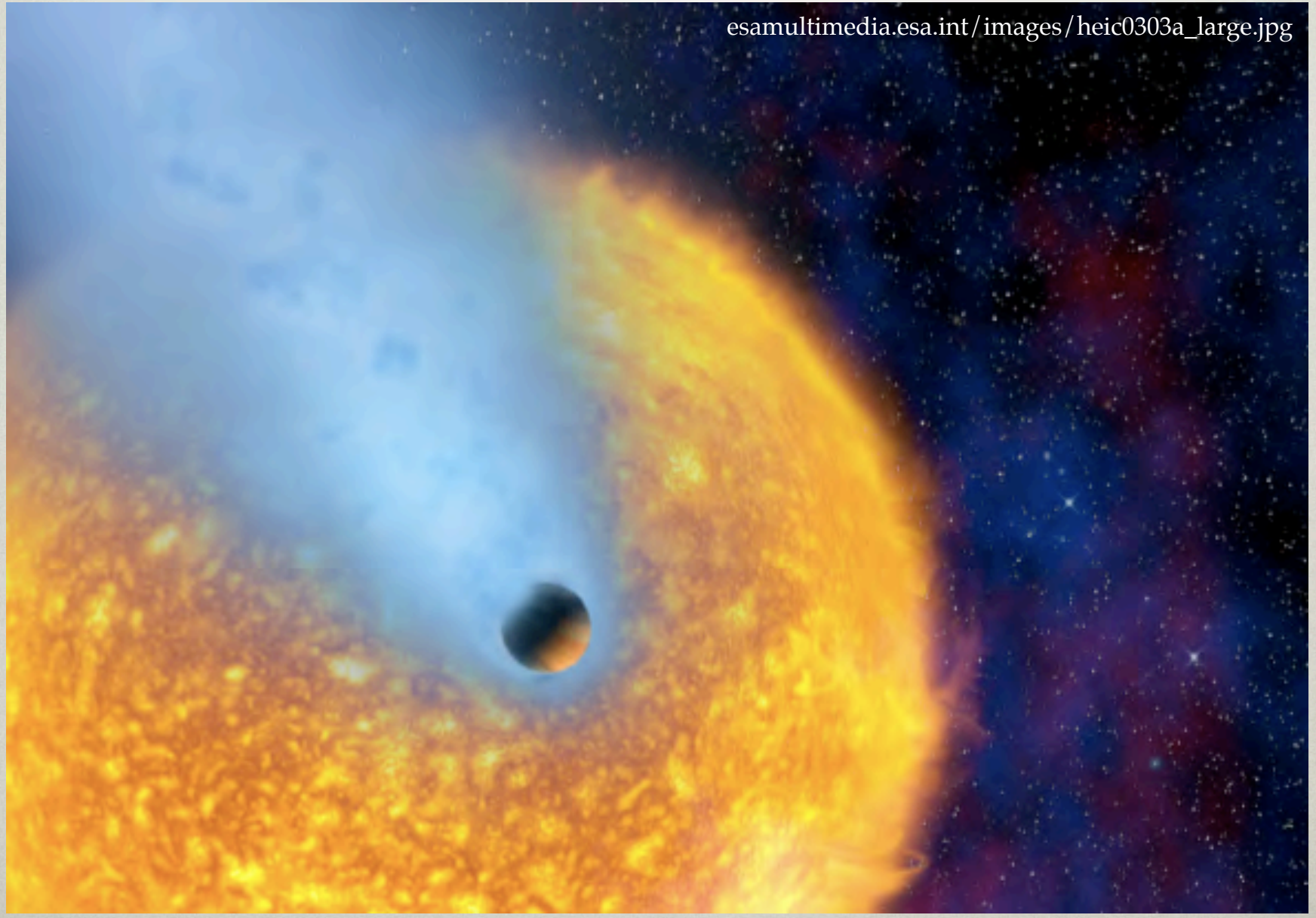
ipac.jpl.nasa.gov/media_images/ssc2006-18a_medium.jpg

Secondary Eclipse from CoRoT

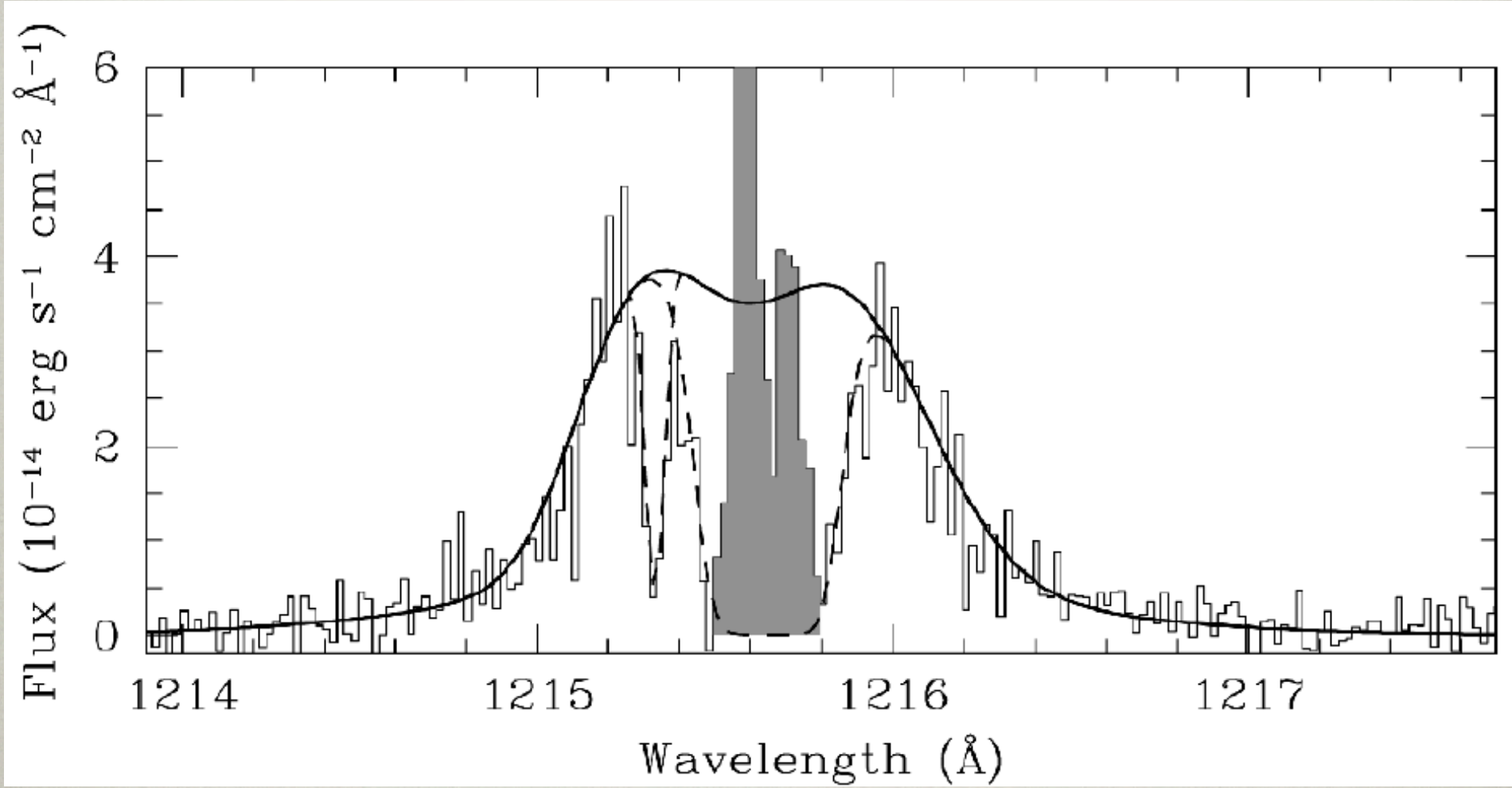


Snellen et al. 2009

Atmospheric Escape

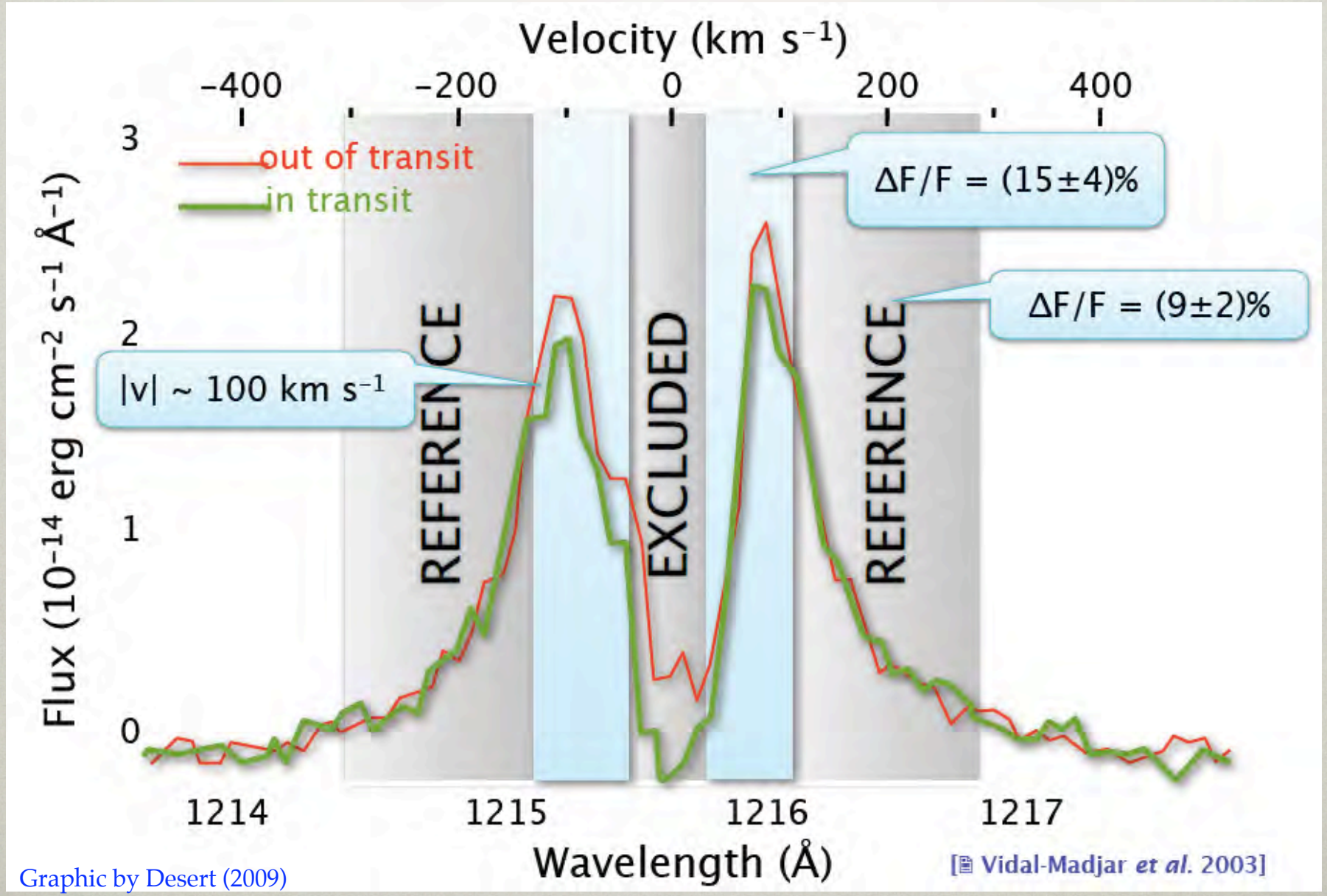


Atmospheric Escape

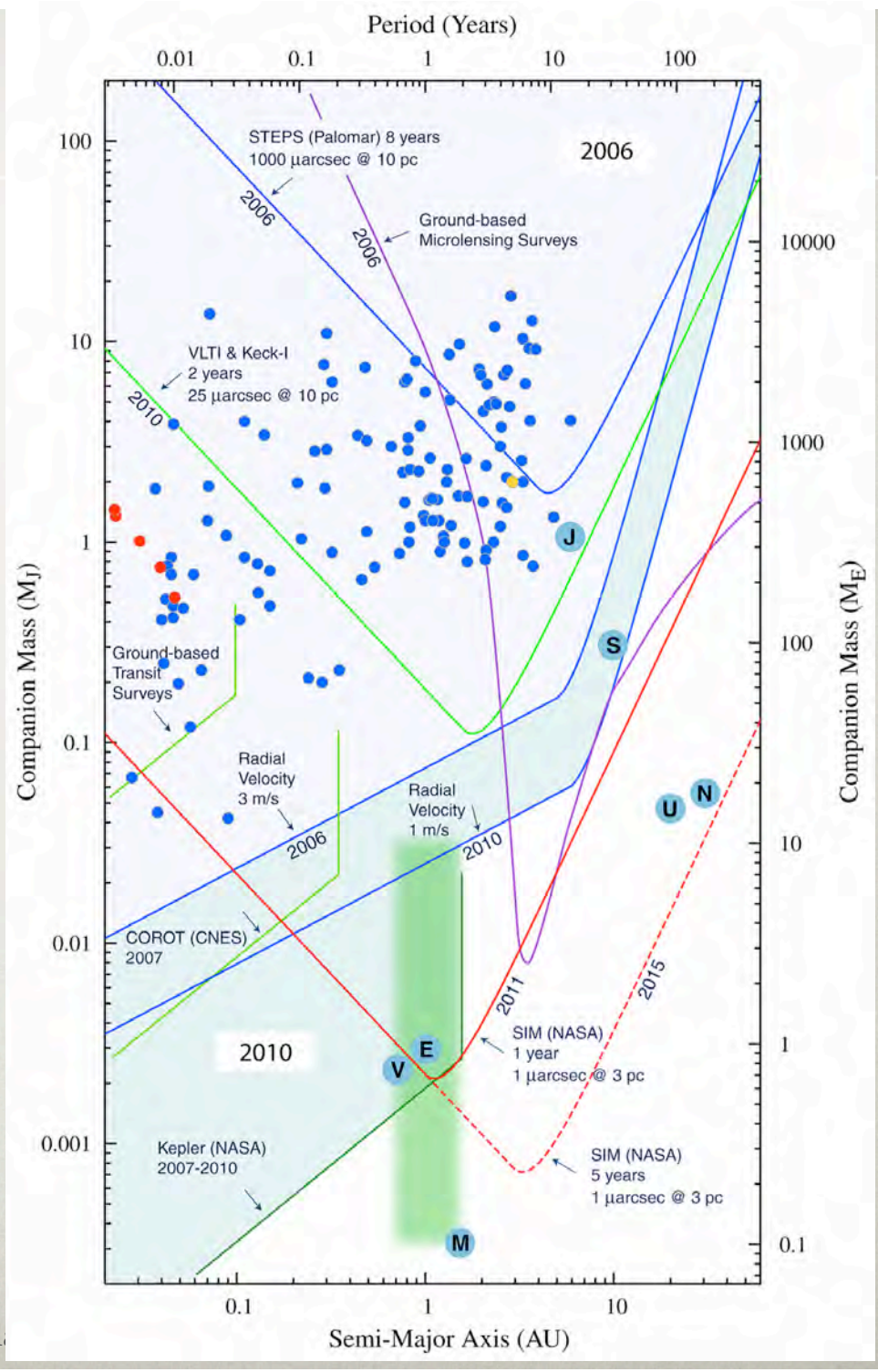


Vidal-Madjar et al. 2003

Atmospheric Escape



Graphic by Desert (2009)


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
V
E
M
Companion Mass (M_J)
Companion Mass (M_E)
Semi-Major Axis (AU)
100
10
1
0.1
0.01
0.001
10000
1000
100
10
1
0.1