The Future of Exoplanet Characterization

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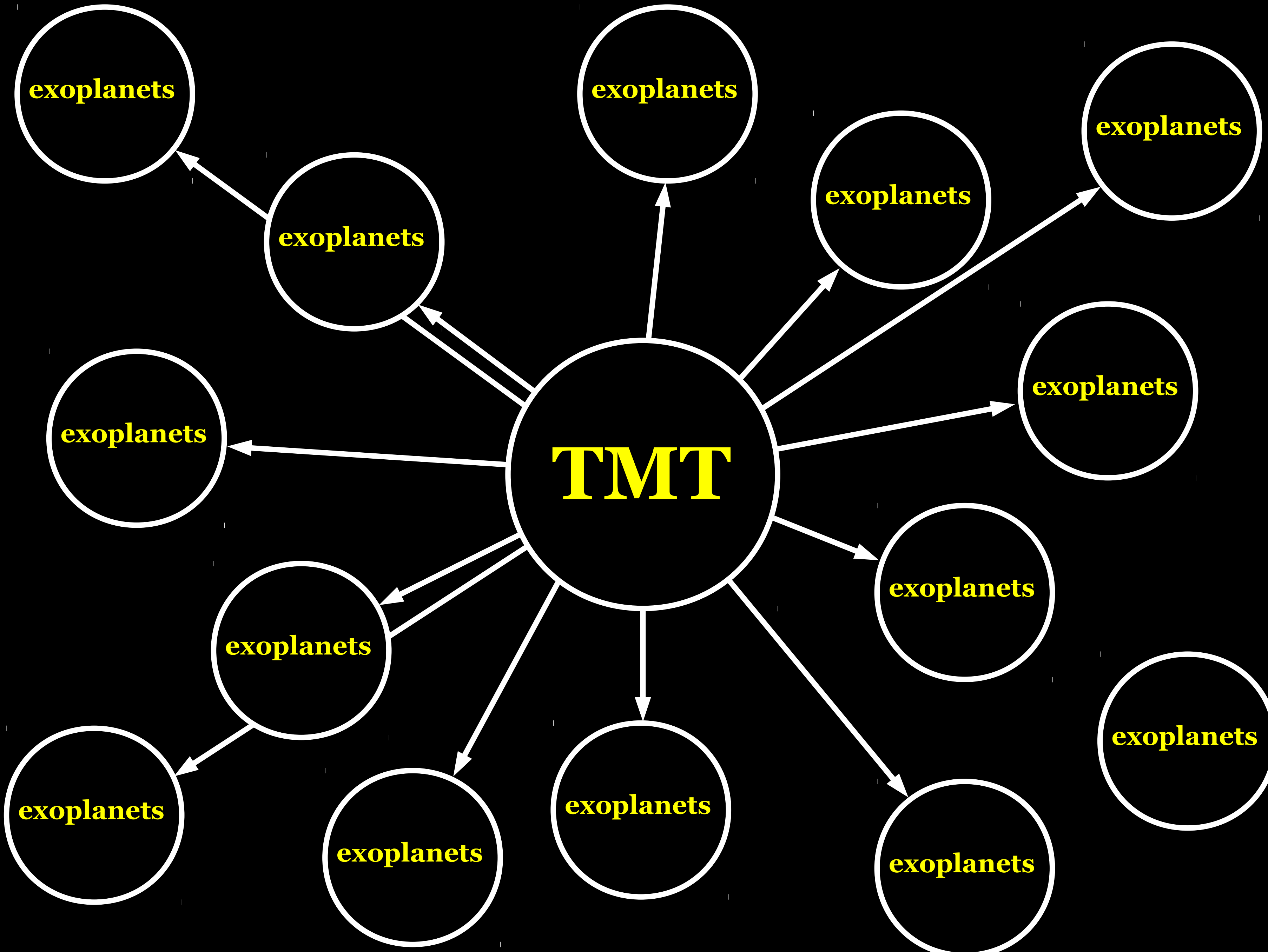

TMT
exoplanets
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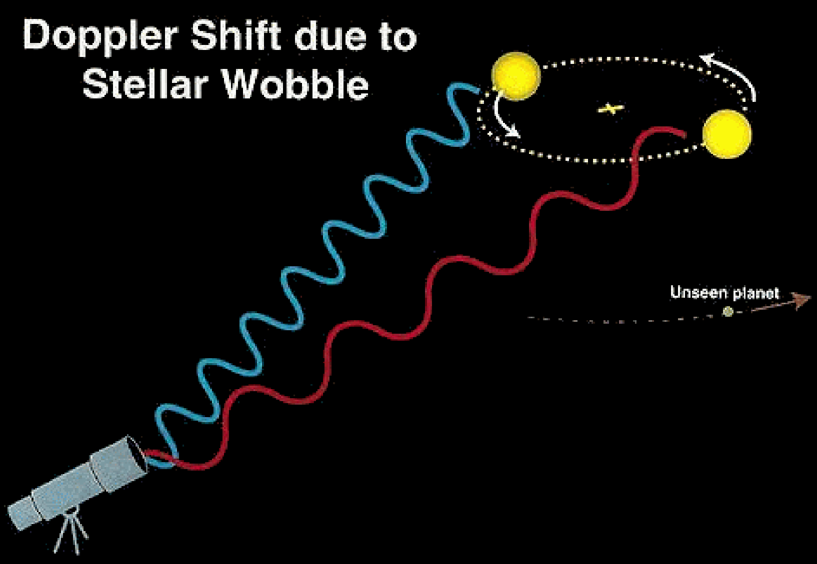
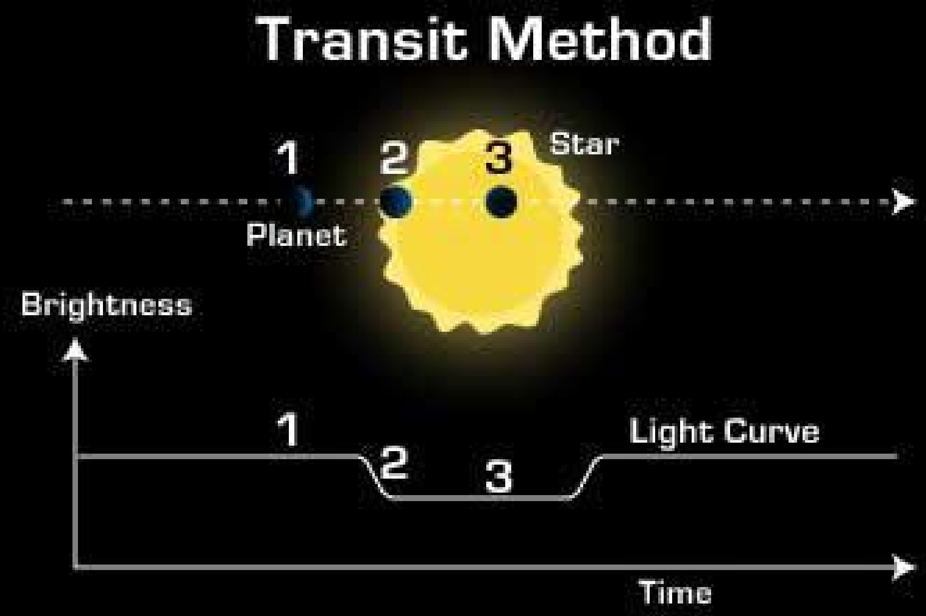
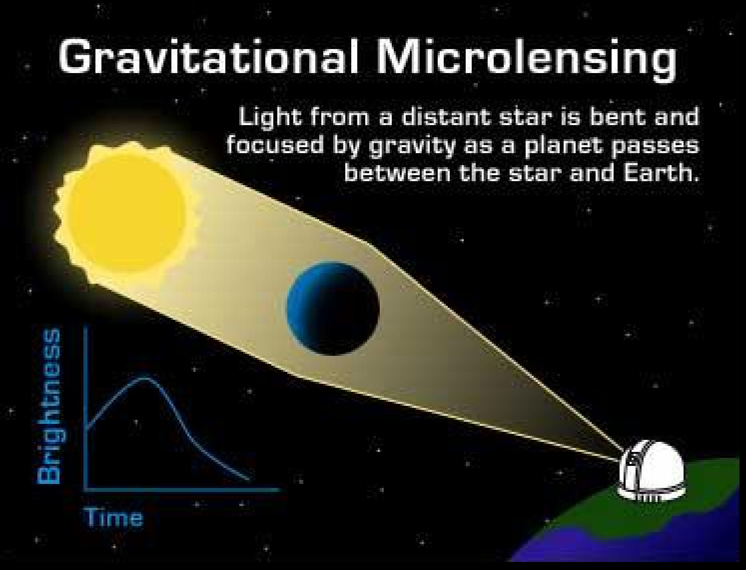
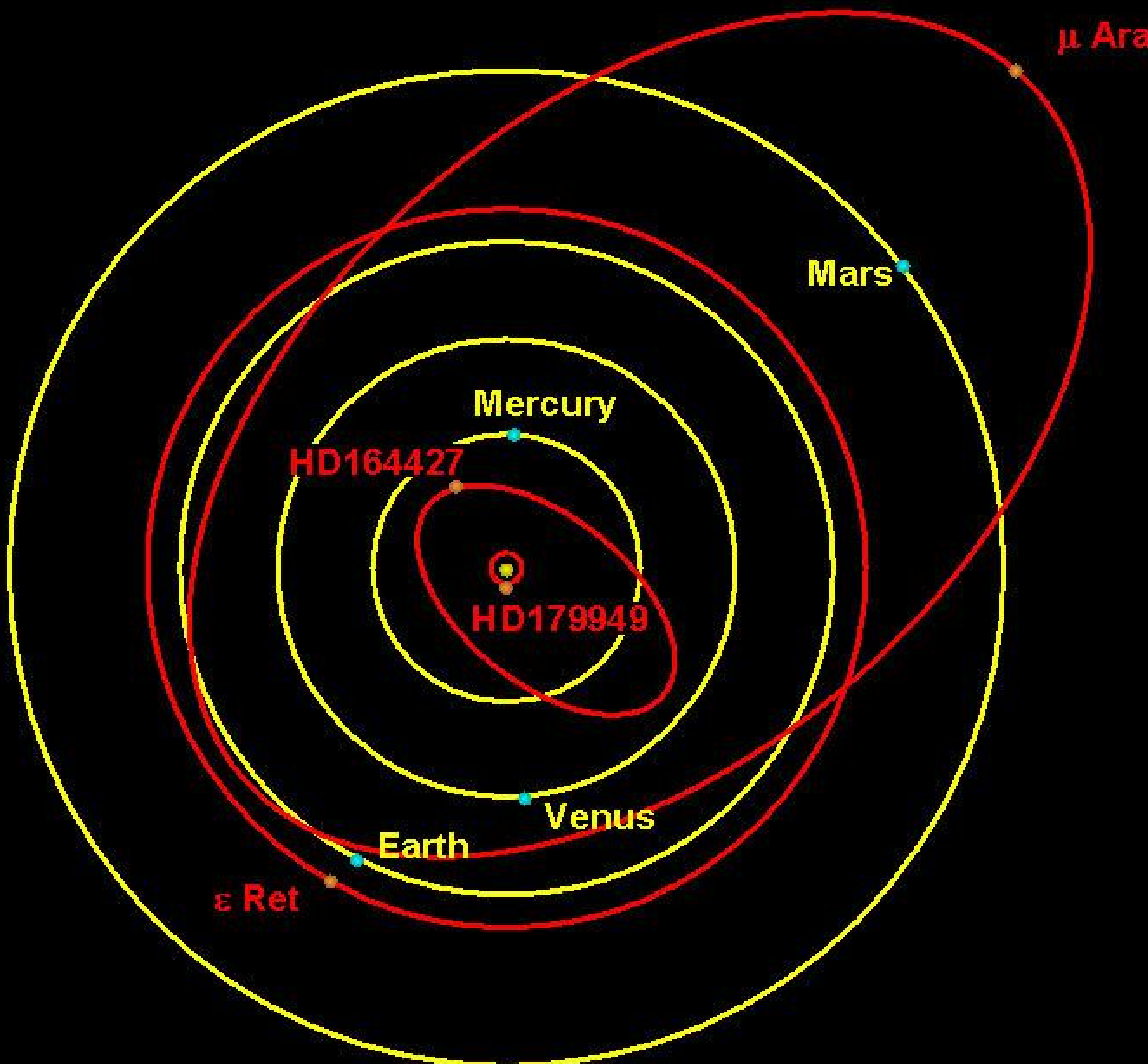
Exoplanet Detection Methods

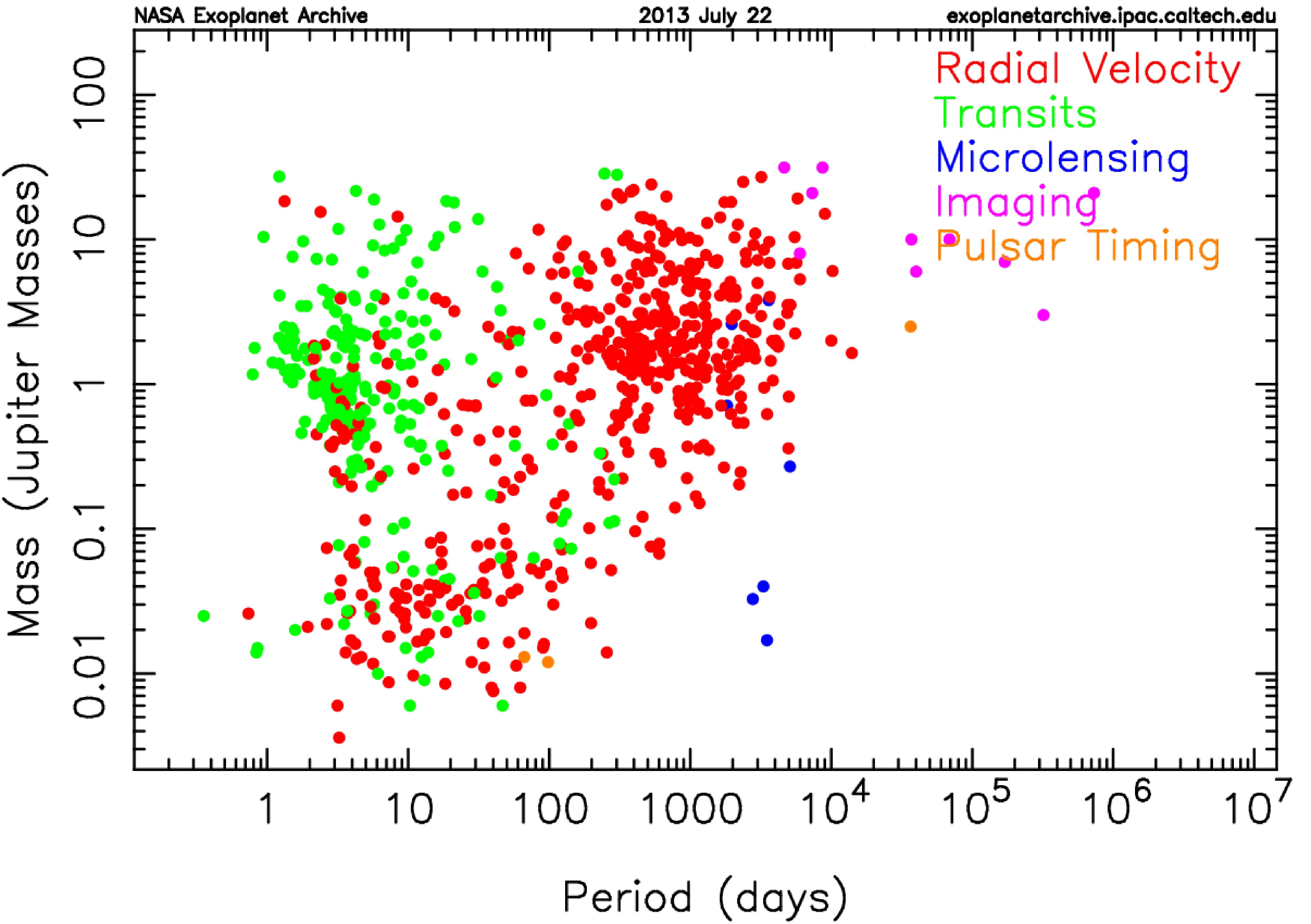
- Radial velocity "Doppler" method
- Transit method
- Microlensing method

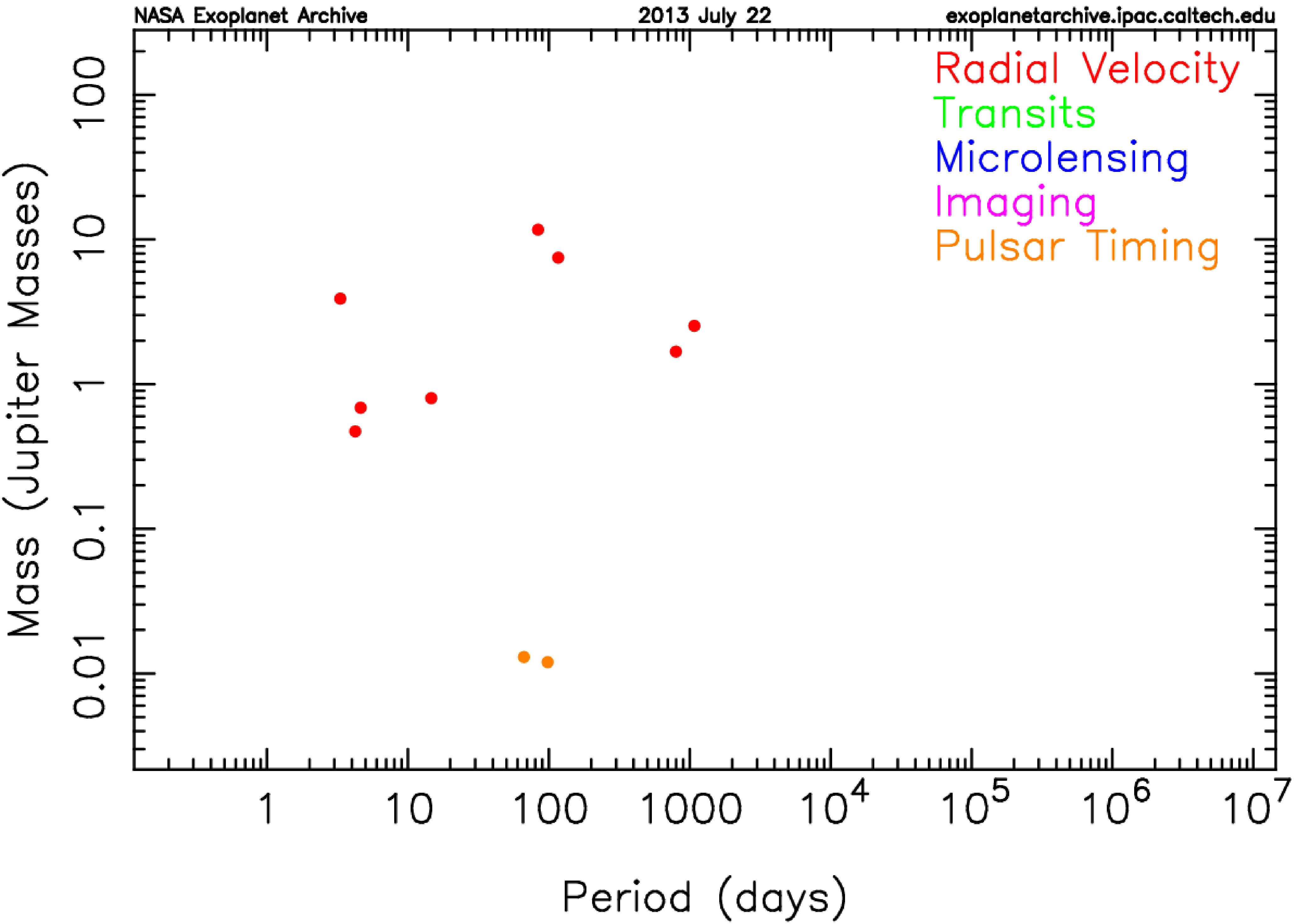







μ Ara
Mars
Mercury
HD164427
HD179949
Venus
Earth
ε Ret


NASA Exoplanet Archive
2013 July 22
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Microlensing
Imaging
Pulsar Timing
Mass (Jupiter Masses)
100
10
1
0.1
0.01
1
10
100
1000
10^4
10^5
10^6
10^7
Period (days)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Radial Velocity
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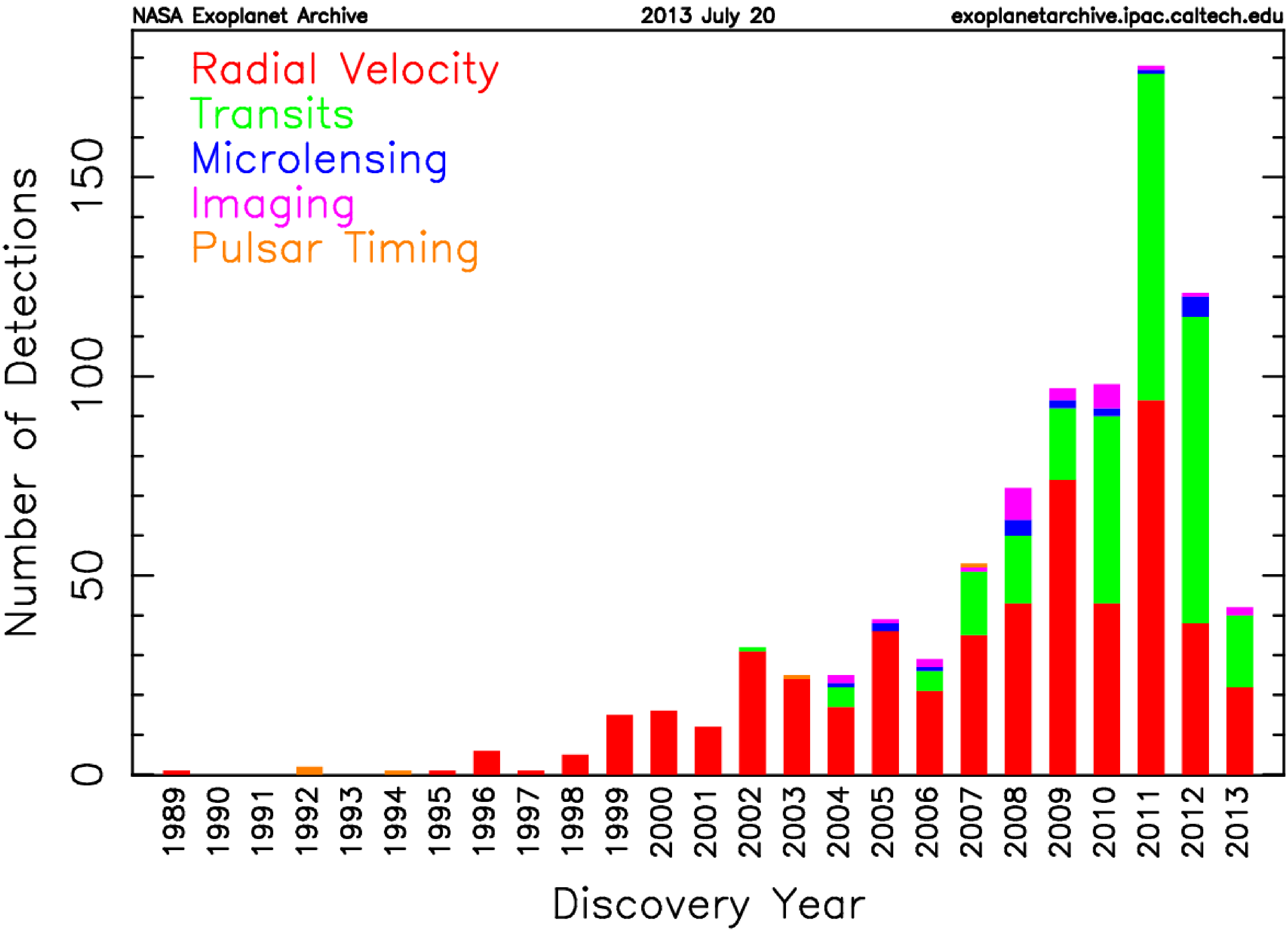
Mass (Jupiter Masses)
100
10
1
0.1
0.01
1
10
100
1000
10^4
10^5
10^6
10^7
Period (days)

Table 7-2. A Decade of Ground-Based Observations

Year	Possible Milestones
1995[1]	First planets discovered through radial velocities
1996[1]	High-mass planets on short-period orbits, detected by astrometric wobble with single telescope and interferometers
1997	Microlensing detects first Earth-like planets
1998	Microlensing detects 10 more planets with first follow-up
1998	Radial velocities find Uranus-mass planets in a 1-year orbit
1999	Five more planets from radial velocity (year three of data)
1999	Microlensing detects 50 planets
1999	Keck or other interferometer detects exo-zodiacal emission
2000	Direct detection of Jupiter-mass planets on 6- to 10-m telescopes in near-IR
2000	High-mass planets on short-period orbits
2002	Earth-mass planets in habitable zone around M stars detected by improved ($<1\ m\ s^{-1}$) radial velocities
2003	Large ground-based interferometer finds hundreds of Jupiters around nearby stars in about 3 years
2006	Microlensing search finds 30 Earth-, 50 Neptune-, 80 Saturn- and 100 Jupiter-mass planets
2006	Radial-velocity search complete. 200 Saturn- and Jupiter-mass planets around 1,000 nearby stars

[1]Already achieved!

"A Road Map for the Exploration of Neighboring Planetary Systems (ExNPS)" (1996)



NASA Exoplanet Archive
2013 July 20
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Microlensing
Imaging
Pulsar Timing
Number of Detections
0
50
100
150
1989
1990
1991
1992
1993
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1996
1997
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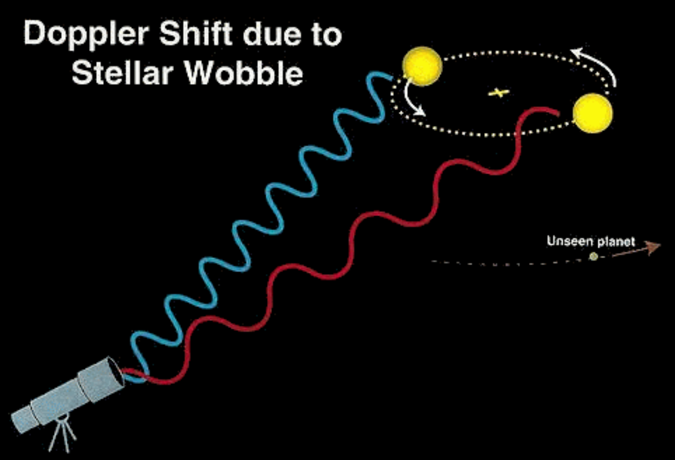
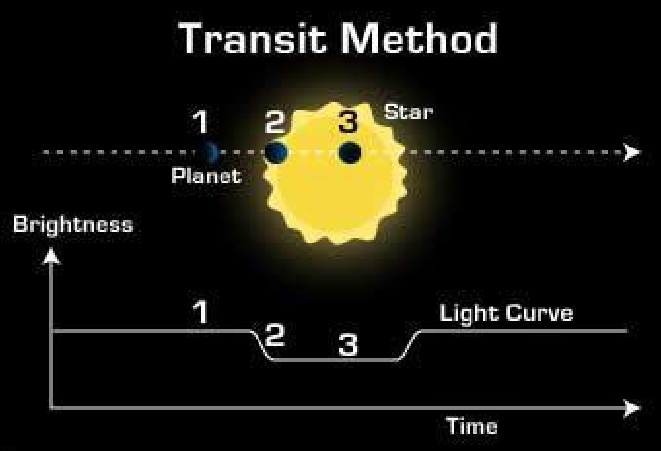
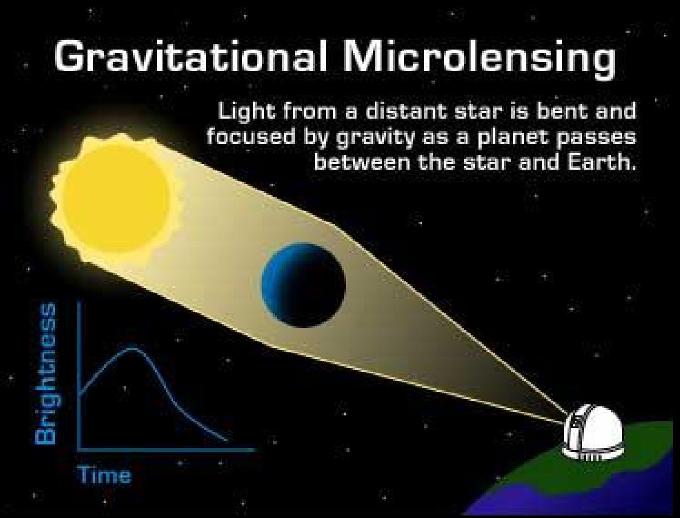
2012
2013
Discovery Year

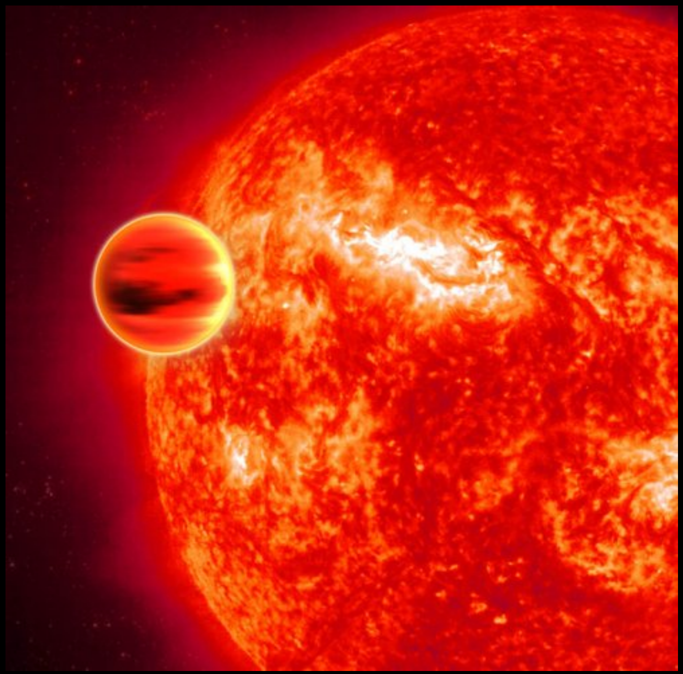
Exoplanet Detection Methods

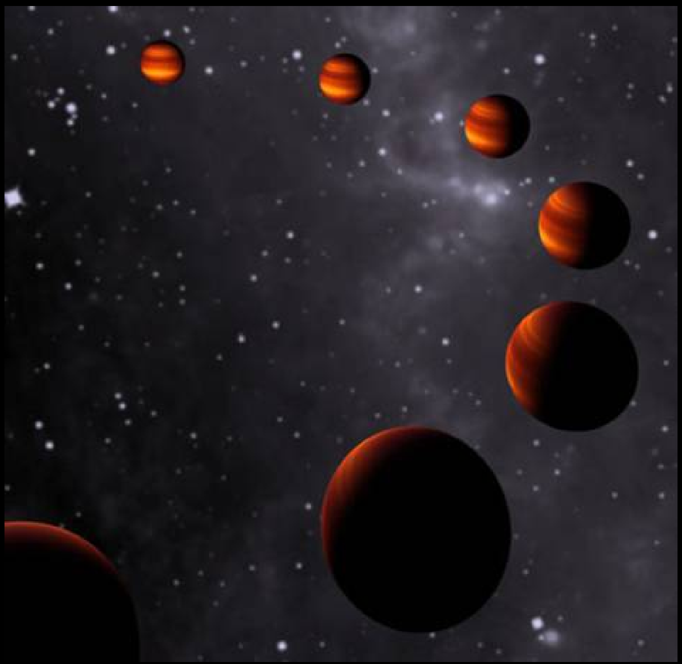


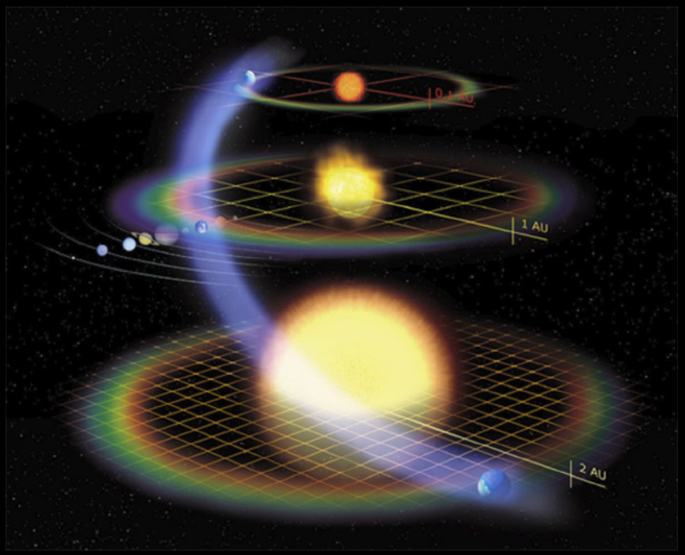




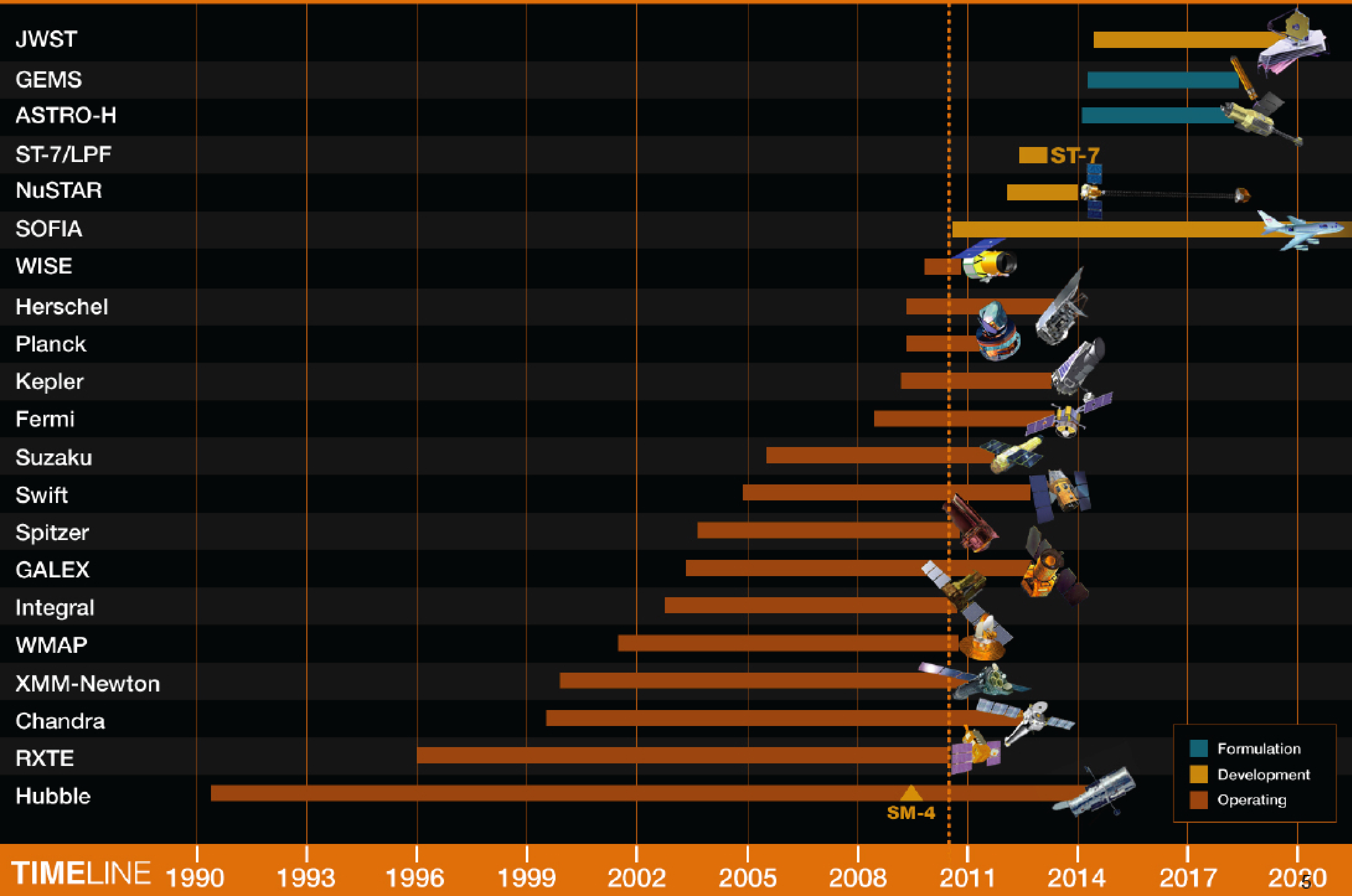
… to characterization





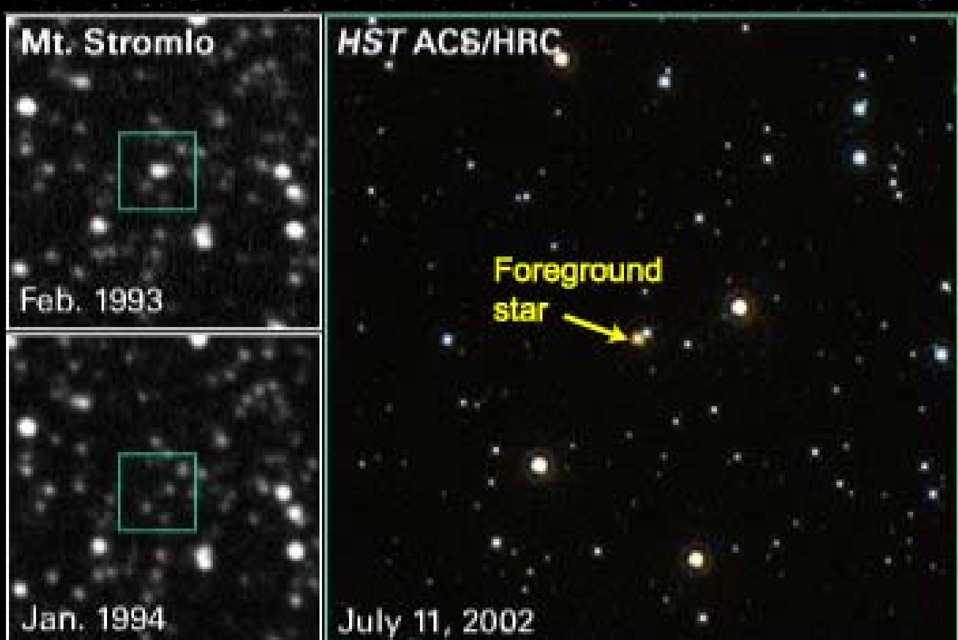


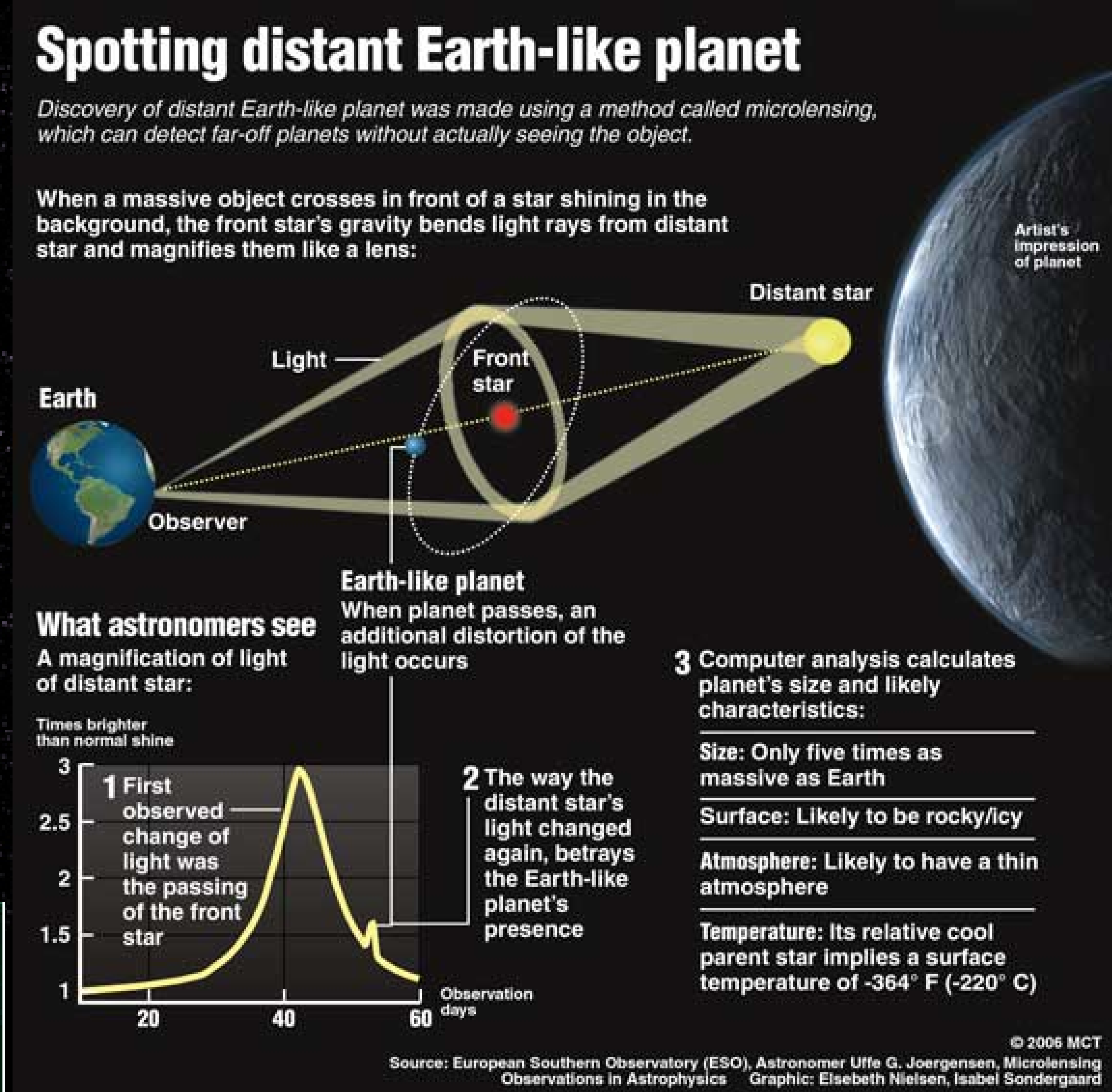
Astrophysics Missions timeline



Microlensing

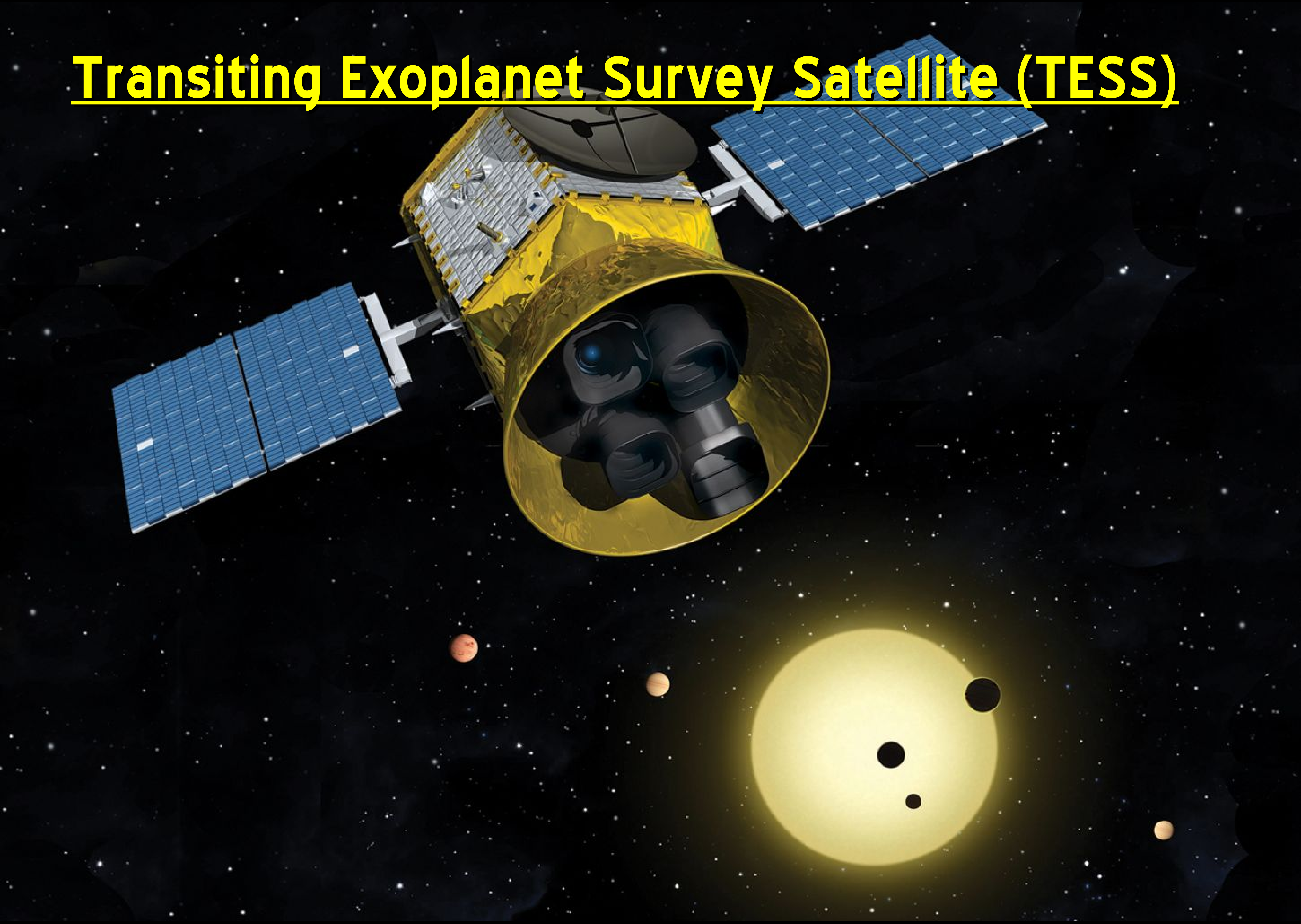
WFIRST
Wide-Field Infrared Survey Telescope





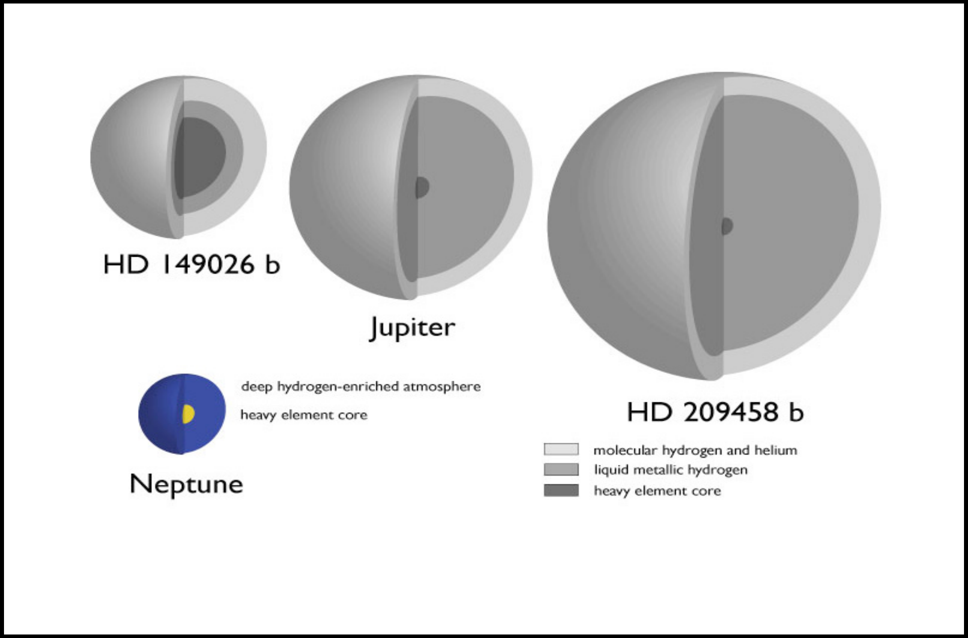
- Microlensing measures the MASS RATIO of the star and planet
- Thus follow-up of the lens star reveals more accurate properties of the planet

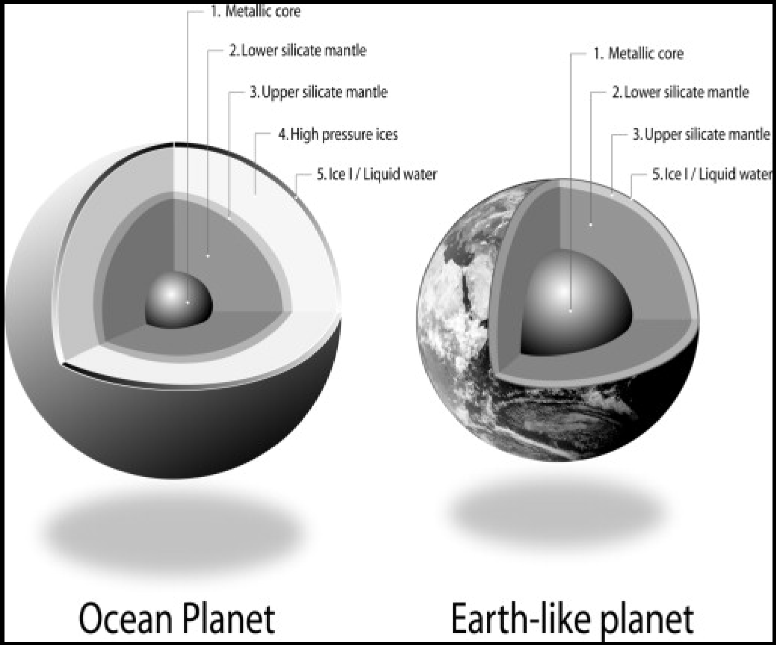
Transiting Exoplanet Survey Satellite (TESS)



Transiting Exoplanets

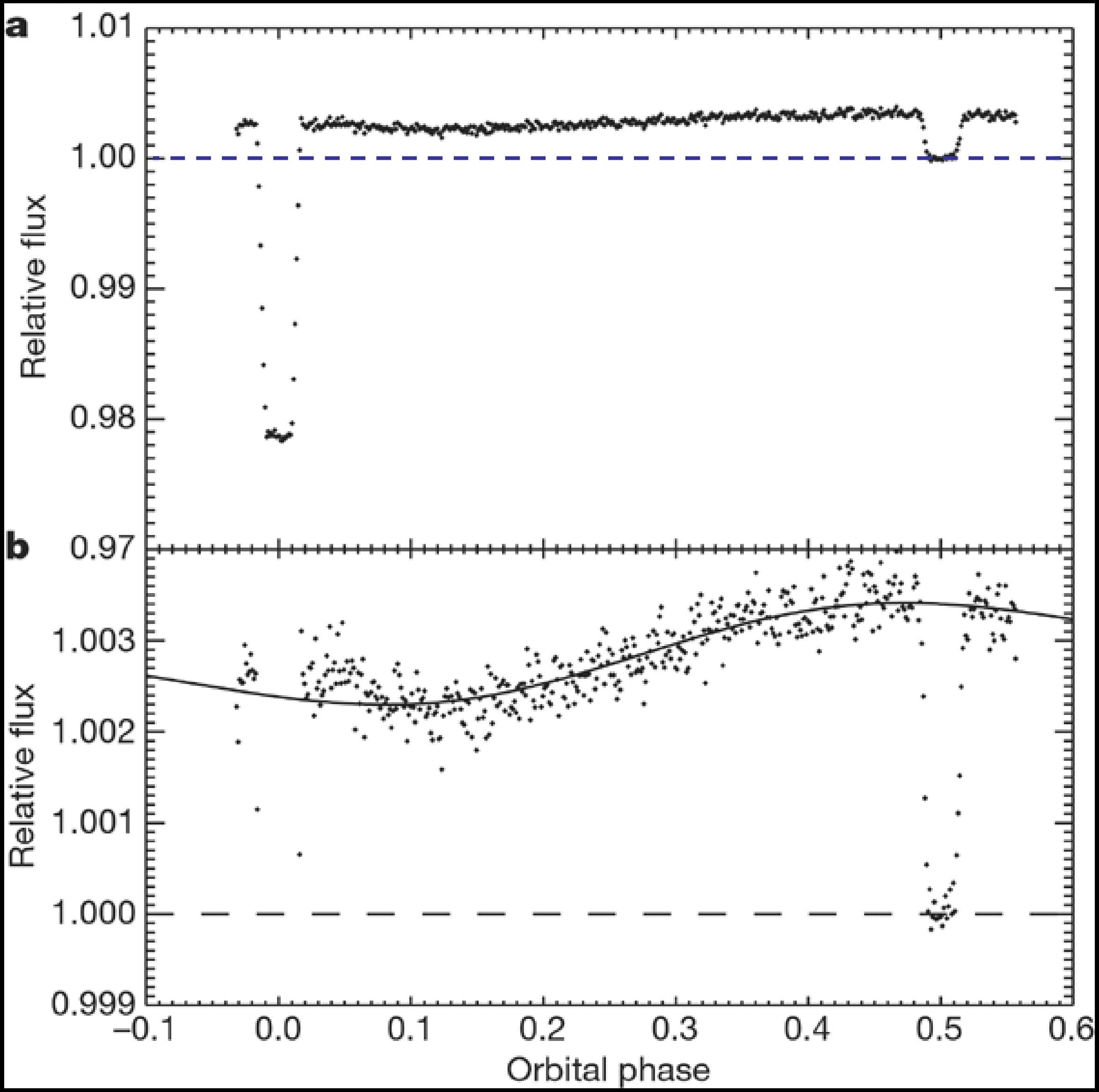
- Measure radius and mass of transiting planets
- Depth of transit → radius (ONLY WAY!)
- Radial velocities → mass (no uncertainty in inclination angle!)
- Transit Timing Variations (TTVs) also yield mass
- Determine densities → internal structures (theory) → consequences for formation and migration theories



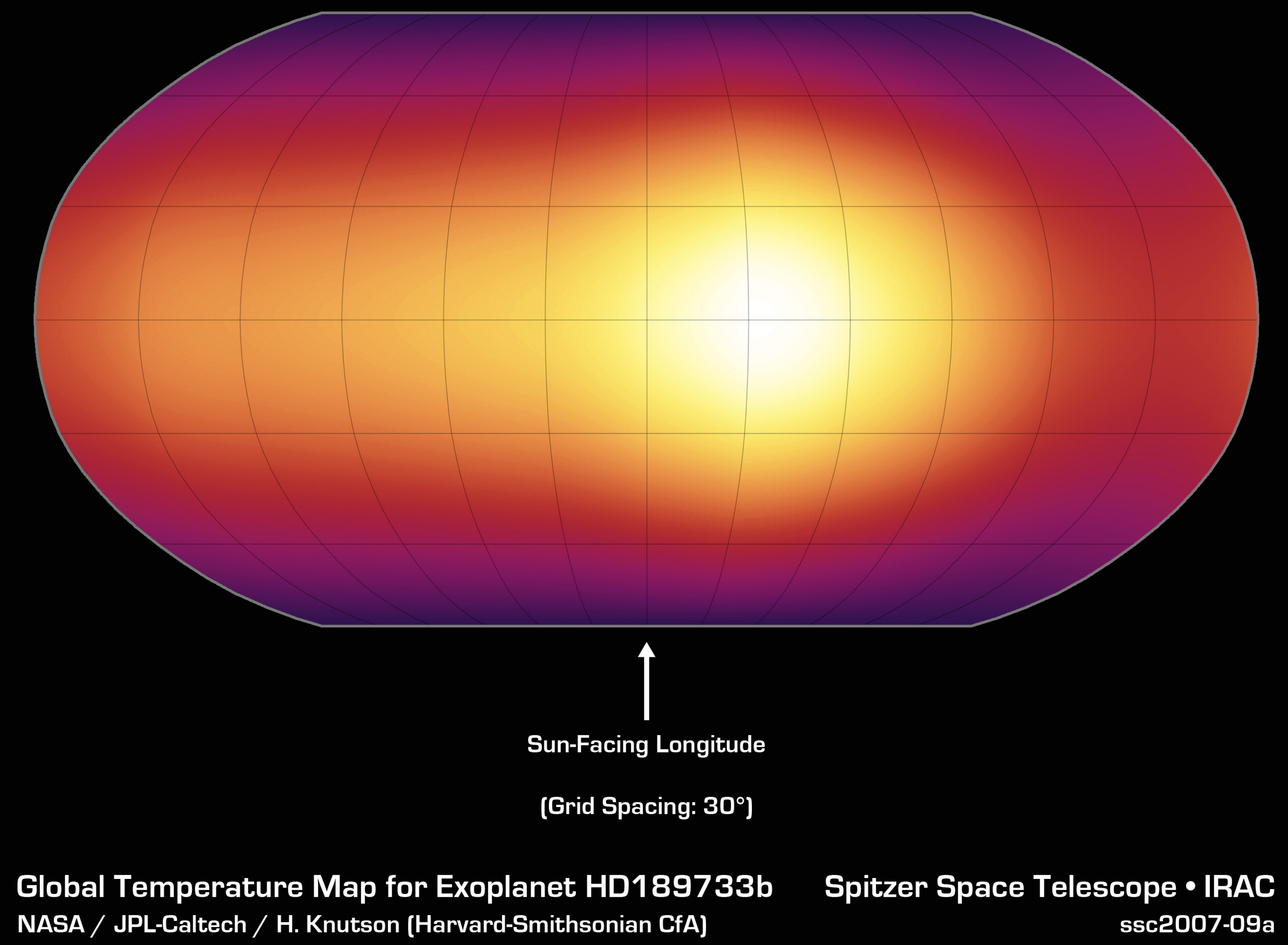


Secondary Eclipses and Phase Curves

- **Space-based and ground-based**
- **Calculation of planetary temperature as function of energy redistribution efficiency and albedo**
- **Transiting systems allow us to map the surface temperature patterns of the planet**
- **HD 189733b phase curve (Knutson et al. 2007 Spitzer/IRAC)**

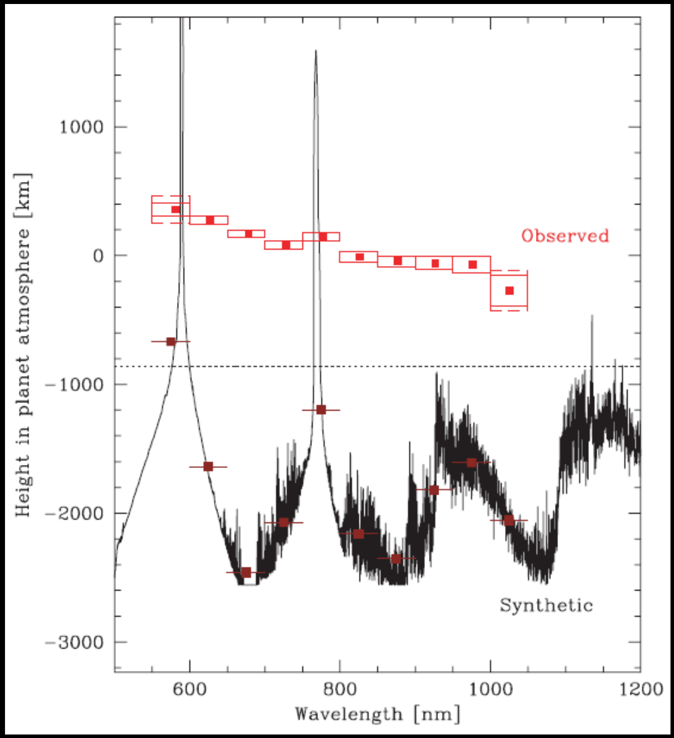


Secondary Eclipses and Phase Curves



Transmission Spectroscopy

- clouds
  - HD209458, HD189733
    - observed absorption levels are weaker than cloudless models
- haze
  - HD189733
    - HST observation found nearly flat absorption feature around 500-1000nm → haze in upper atmosphere?

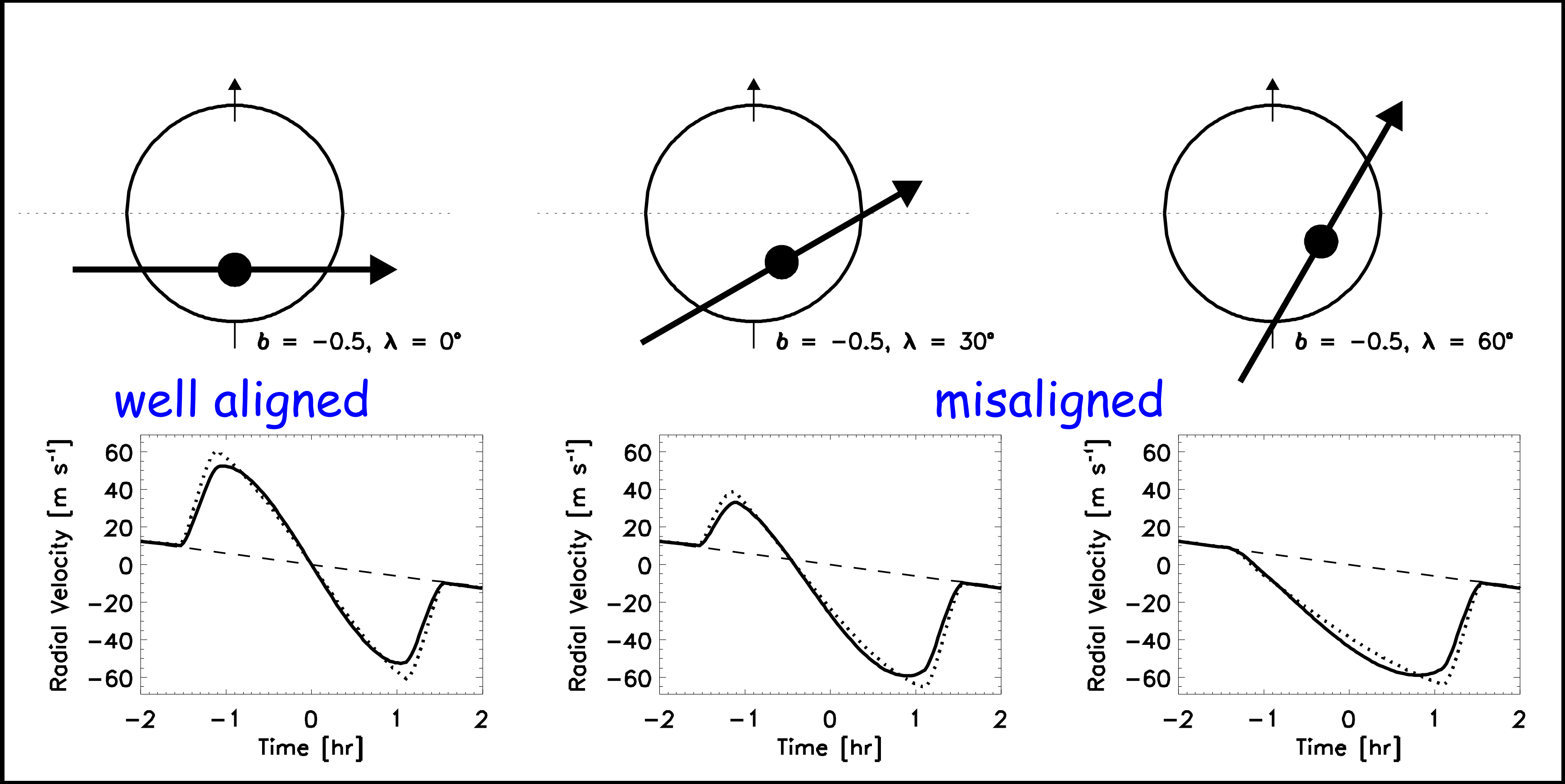


Pont et al. (2008)

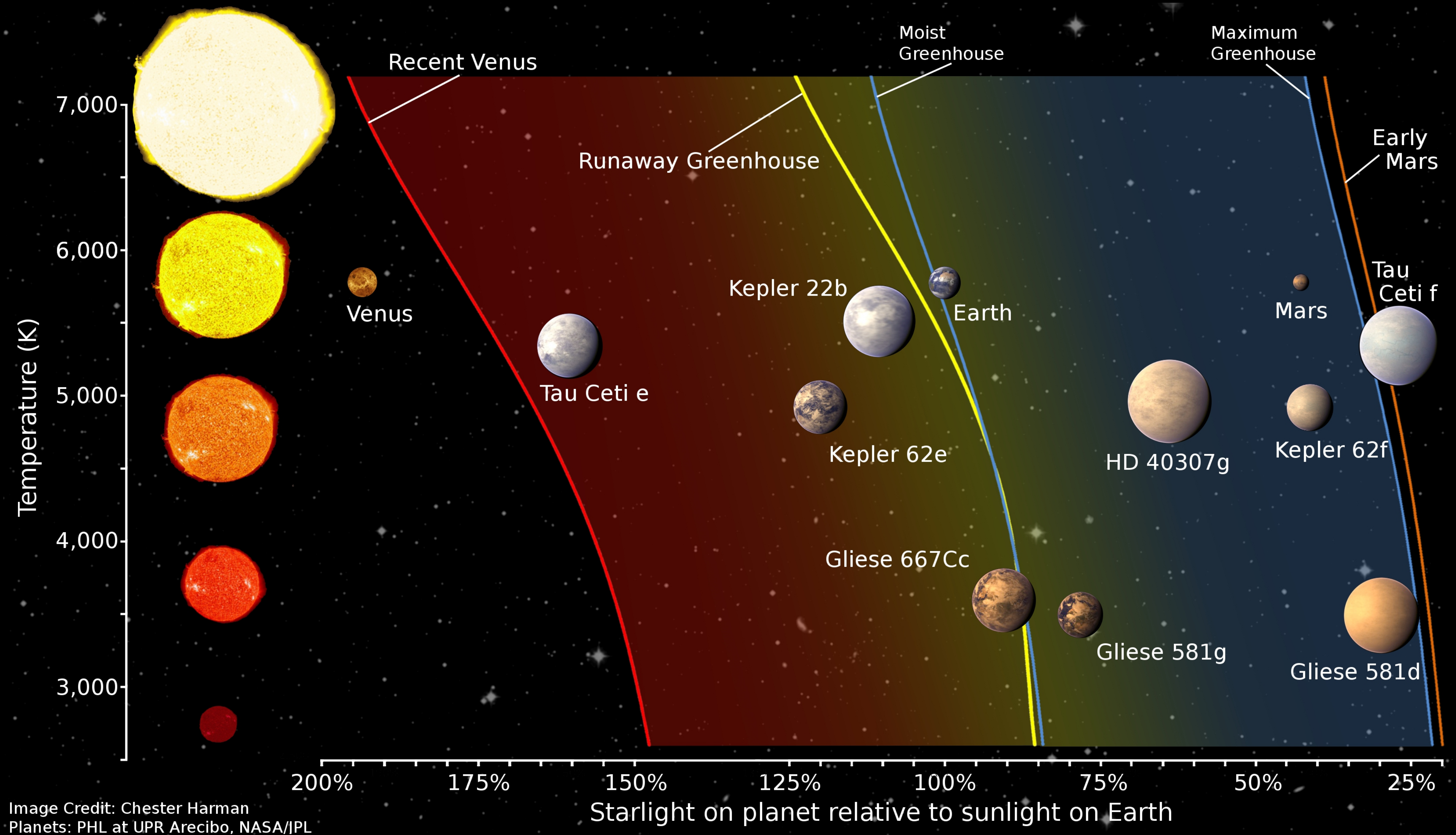
Transmission spectroscopy is useful for studying planetary atmospheres

The Rossiter-McLaughlin Effect

The shape of the R-M effect depends on the trajectory of the transiting planet



Gaudi & Winn (2007)



- **Conservative Habitable Zone: Runaway Greenhouse to Maximum Greenhouse**
- **Optimistic Habitable Zone: Recent Venus to Early Mars**

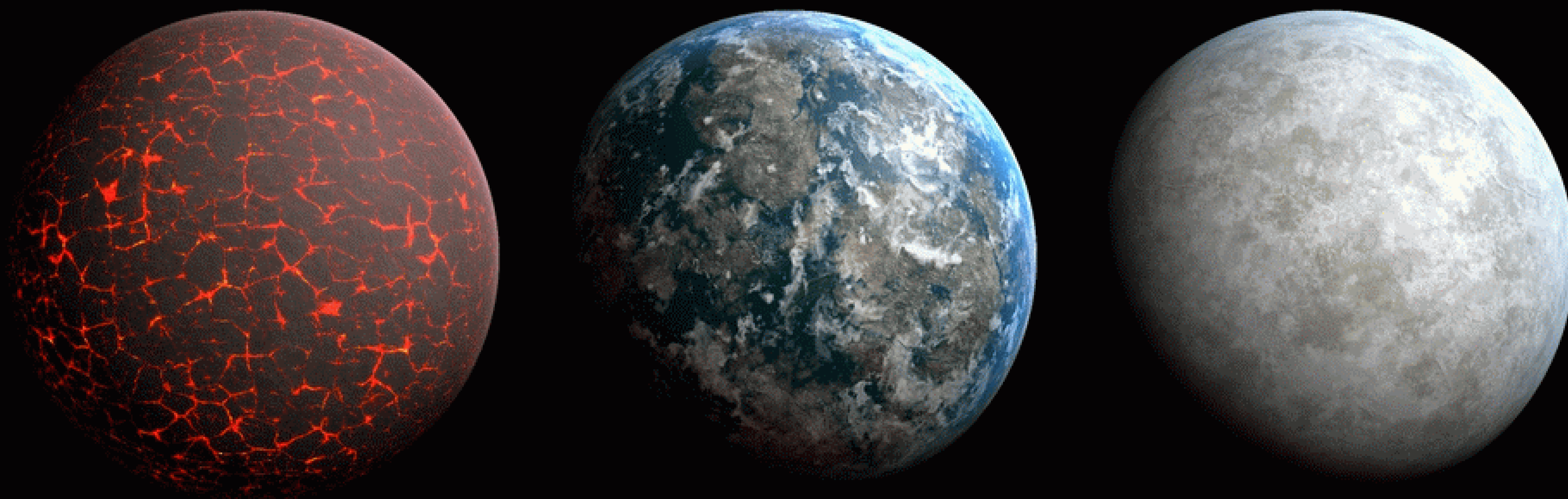
Kopparapu et al. 2013, ApJ, 765, 131

Habitable Zone Gallery

Home Gallery Table Movies About Links

This site is dedicated to tracking the orbits of exoplanets in relation to their Habitable Zones.
Summary plots for all of the exoplanets are available here.

Planets: 665 **Systems:** 532
Planets with orbits entirely within the Habitable Zone: 46 [?]
Updated: 2013 06 25 09:16:03 PDT



"The Earth is the only world known so far to harbor life. There is nowhere else, at least in the near future, to which our species could migrate. Visit, yes. Settle, not yet. Like it or not, for the moment the Earth is where we make our stand." - Carl Sagan

The Habitable Zone Gallery www.hzgallery.org

A Short-cut to Habitable Zone Planets

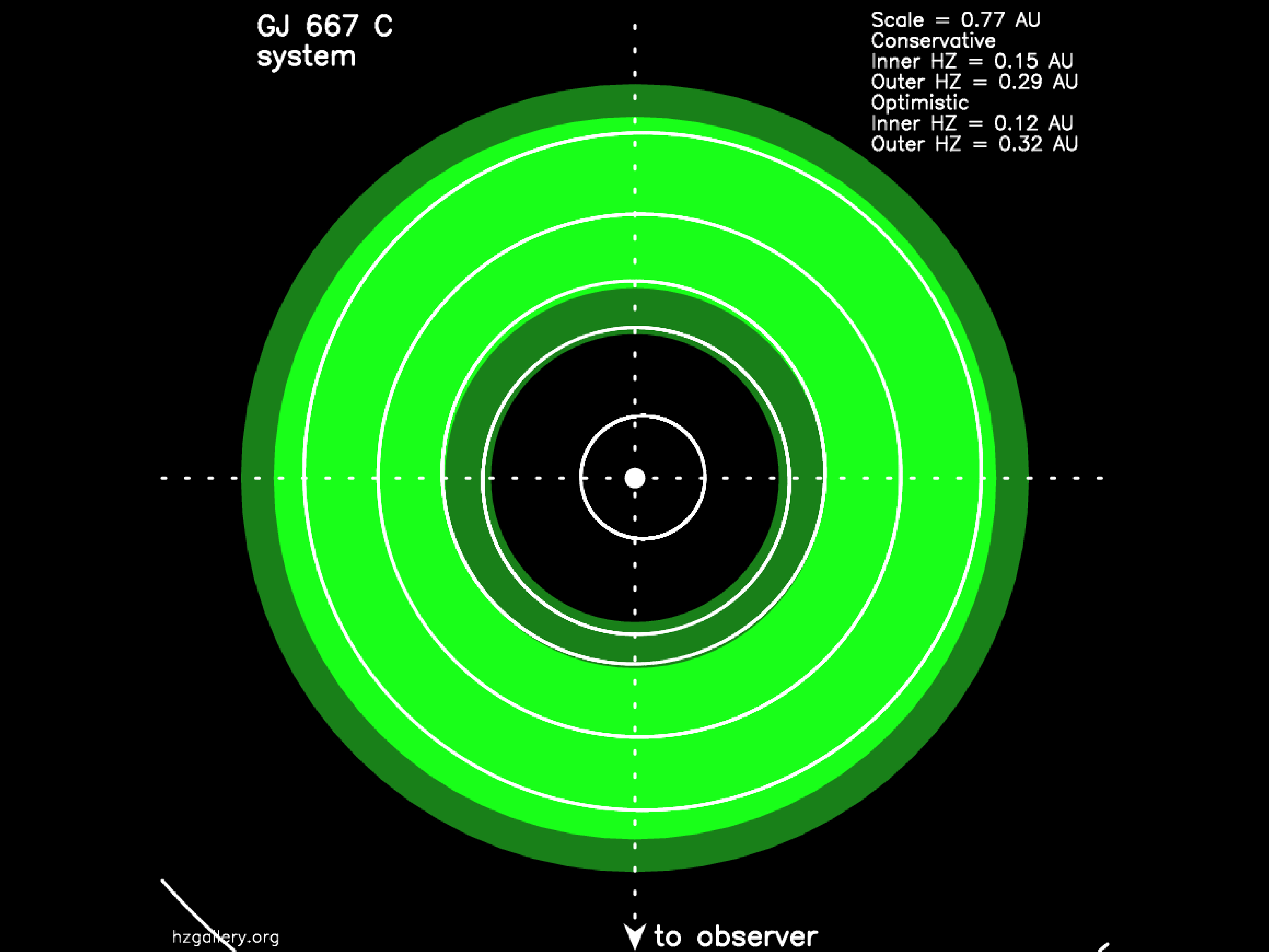
- There is an observation bias towards detecting planets around M dwarfs at shorter orbital periods

- Since the Habitable Zone is closer to the star, planets in the Habitable Zones of M dwarfs “easier” to find

HOWEVER …

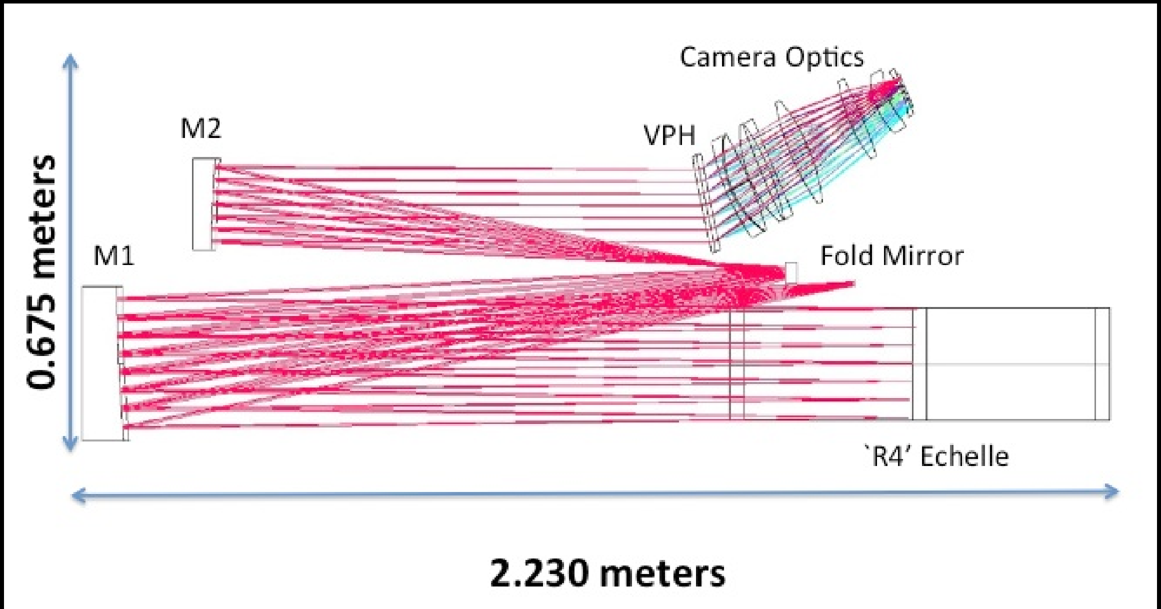
- M dwarfs tend to be more active (flares)

- Planets more likely to be tidally locked


GJ 667 C
system
Scale = 0.77 AU
Conservative
Inner HZ = 0.15 AU
Outer HZ = 0.29 AU
Optimistic
Inner HZ = 0.12 AU
Outer HZ = 0.32 AU
to observer
hzgallery.org

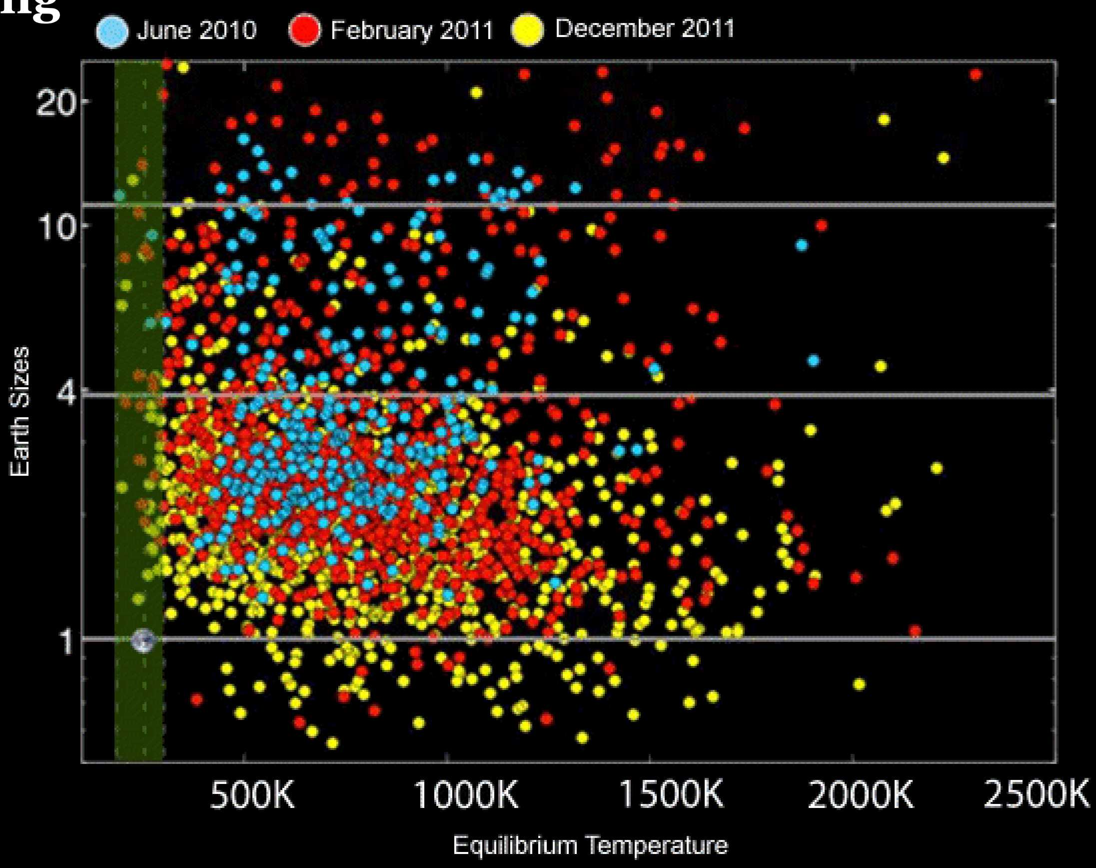
The Habitable Zone Planet Finder (HPF)

- Primary Science Goal: Detection of low mass planets around M dwarfs (PI: Suvrath Mahadevan, Penn State University)
- Resolution ~ 50,000
- f/3.65 fiber input at telescope focal plane
- 3 pixel sampling of resolution element
- Coverage 820nm-1300nm (z, Y, part of J)

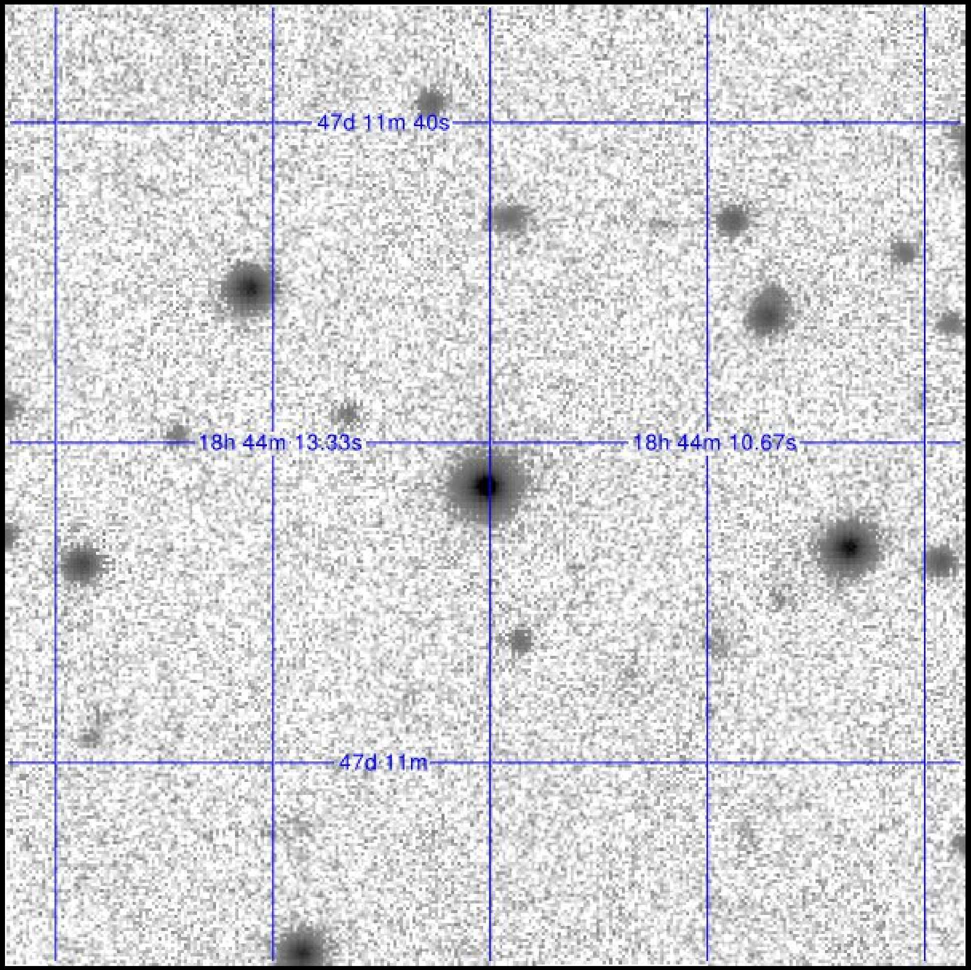


Kepler Planets in the Habitable Zone

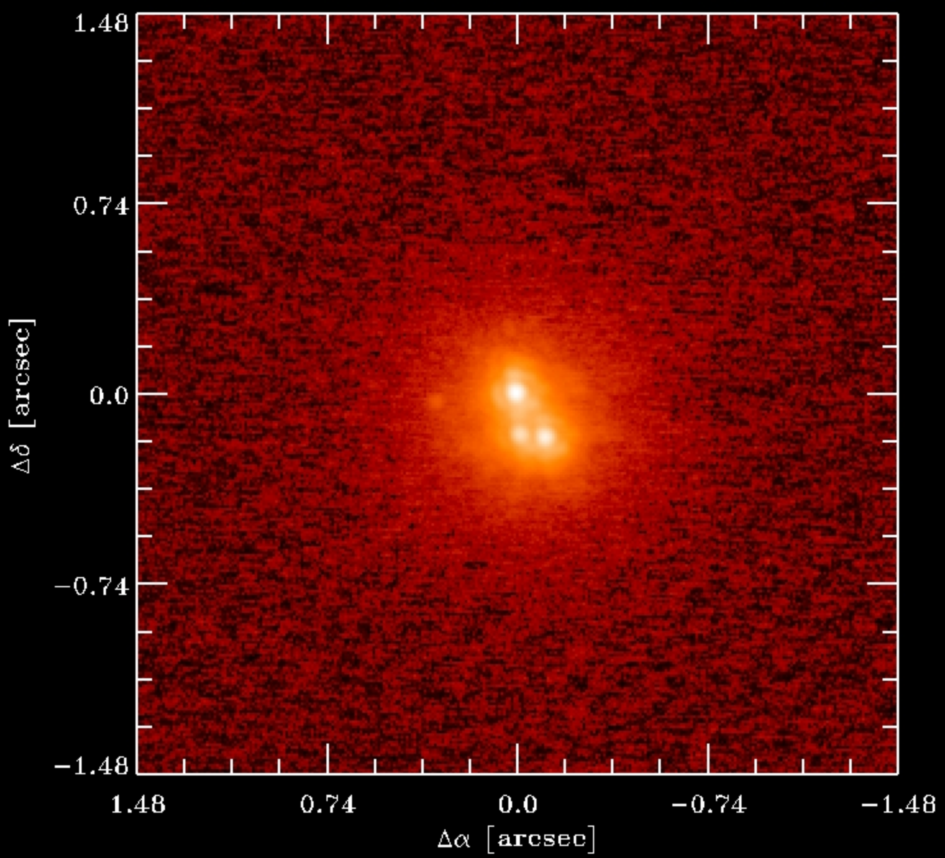
- The prime objective of the Kepler mission is to detect an Earth-like planet in the Habitable Zone of a Sun-like star
- There are currently 3,278 Kepler candidates and confirmed planets
- Kepler has a bias towards detecting transiting planets at small orbital periods
- Results show that planet frequency increases to smaller size and that multi-planet systems are common
- Several more quarters of data yet to be processed



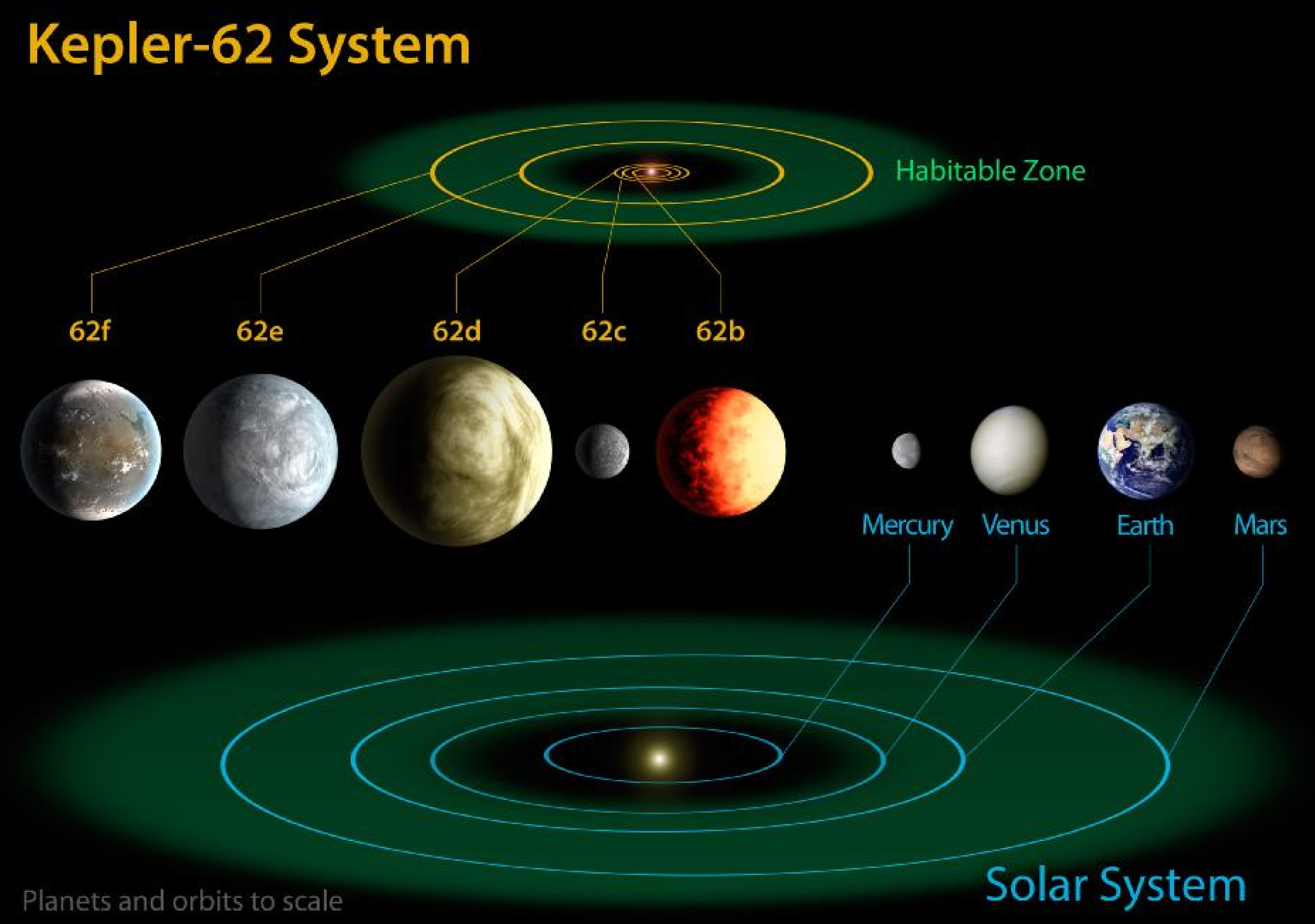
Kepler Follow-up and Multiplicity



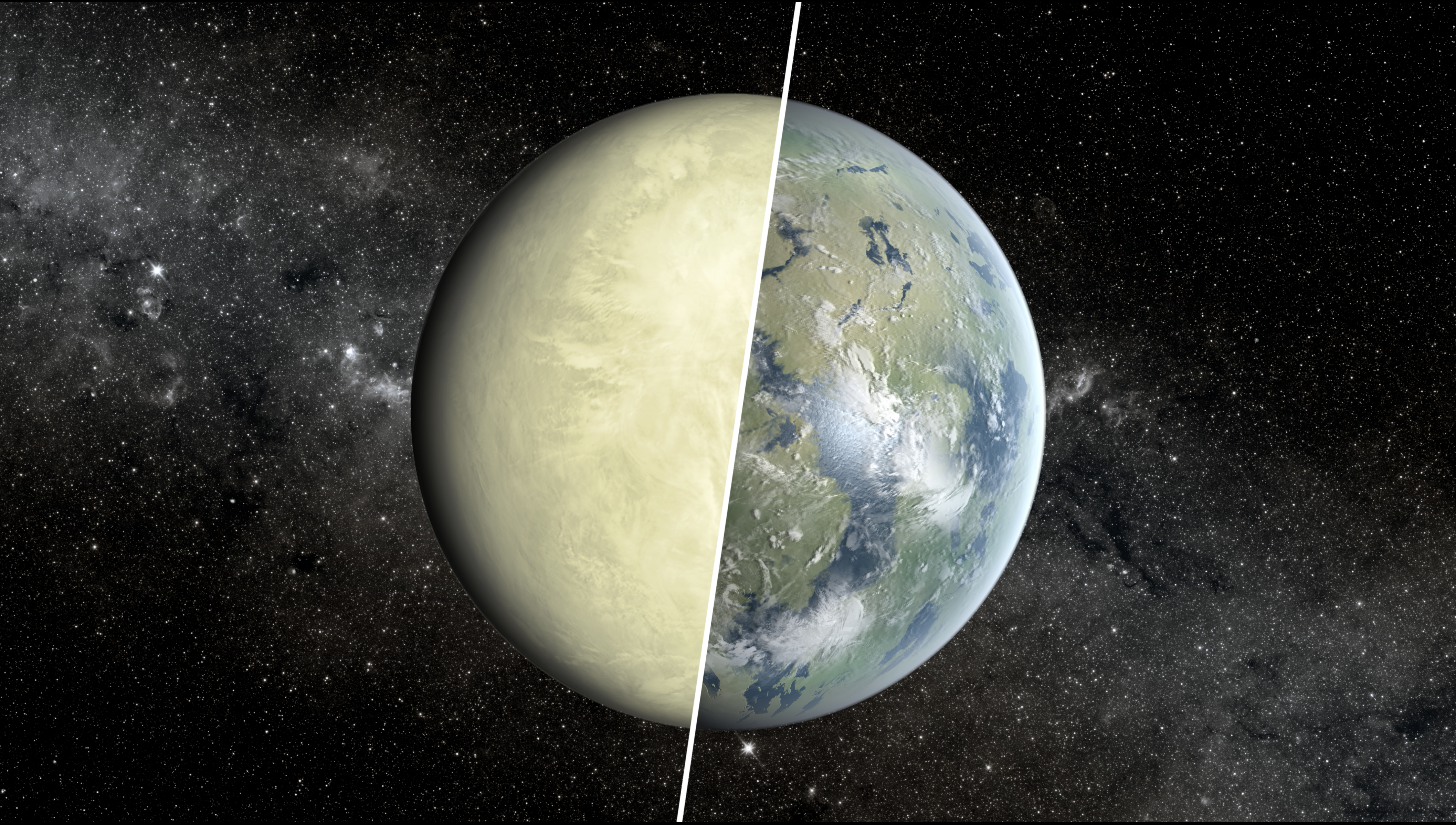
UKIRT J-band - 1 arcmin



Keck AO NIR - 3 arcsecs
Credit: David Ciardi

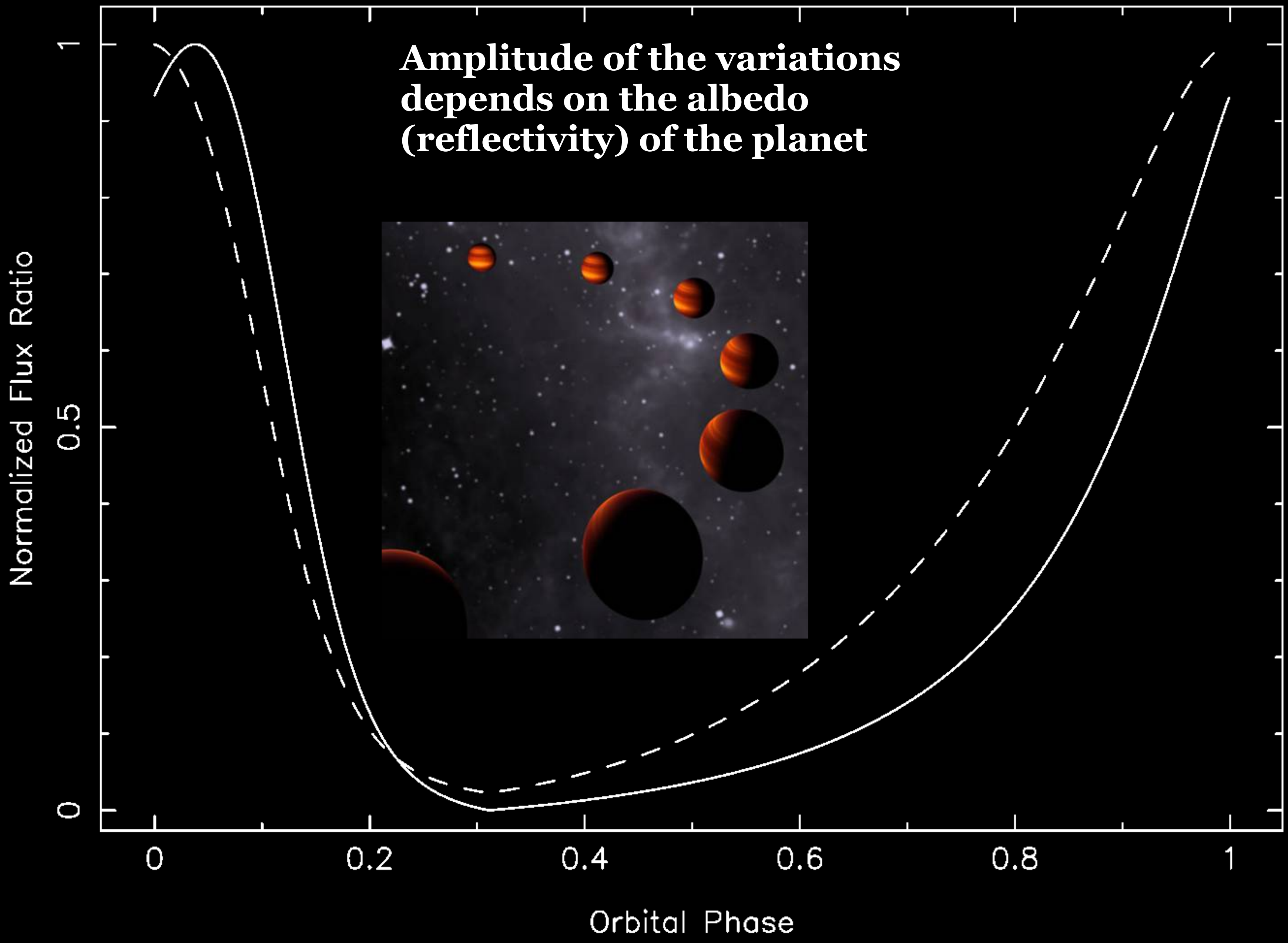


Kepler-62 System
Habitable Zone
62f
62e
62d
62c
62b
Mercury
Venus
Earth
Mars
Solar System
Planets and orbits to scale



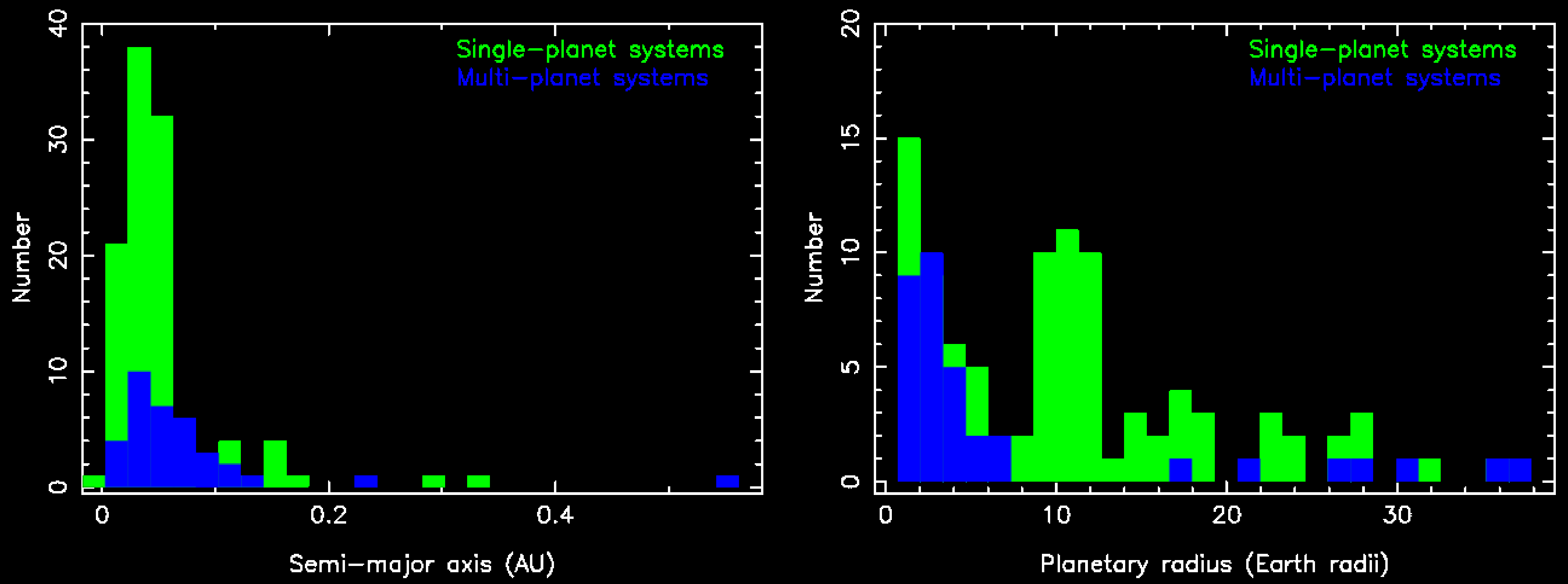
Kane, Barclay, & Gelino. 2013, ApJ, 770, L20

Phase Variations



Phase Variations

- Opportunities to measure geometric albedos for large numbers of planets
- Single short-period planets or multi-planet systems when all planets near superior conjunction
- Statistical sample of geometric albedos and dependence on planet size, semi-major axis, etc



Future Exoplanet Prospects

Future studies will delve further into characterization

- **many Jovian planets, super Earths, and smaller planets**
- **spin-orbit misalignment and orbital formation/dynamics**
- **rings, moons will be searched around transiting planets**
- **secondary eclipse observations to measure dayside temperature**
- **phase curves of exoplanets as they orbit the star**
- **transmission spectroscopy for Earth-like planets in habitable zone to search for biomarkers**

The Contribution of TMT

• Current and up-coming missions RELY on adequate follow-up resources

• The future of exoplanets lies in statistics and characterization

• So far, only the BRIGHT host stars allow characterization of their planets:
  - transiting → primary, secondary, radius, density, thermal atmosphere
  - non-transiting → inclination, mass, albedo atmosphere

• The field is evolving FAST … so concentrate on CAPABILITY … precision photometry, astrometry, imaging, and spectroscopy will always be needed!

The Contribution of TMT

- IRIS → imaging, astrometry
- HROS/NIRES → radial velocities, atmospheres
- IRMS → atmospheres
- MICHI/PFI → imaging, atmospheres