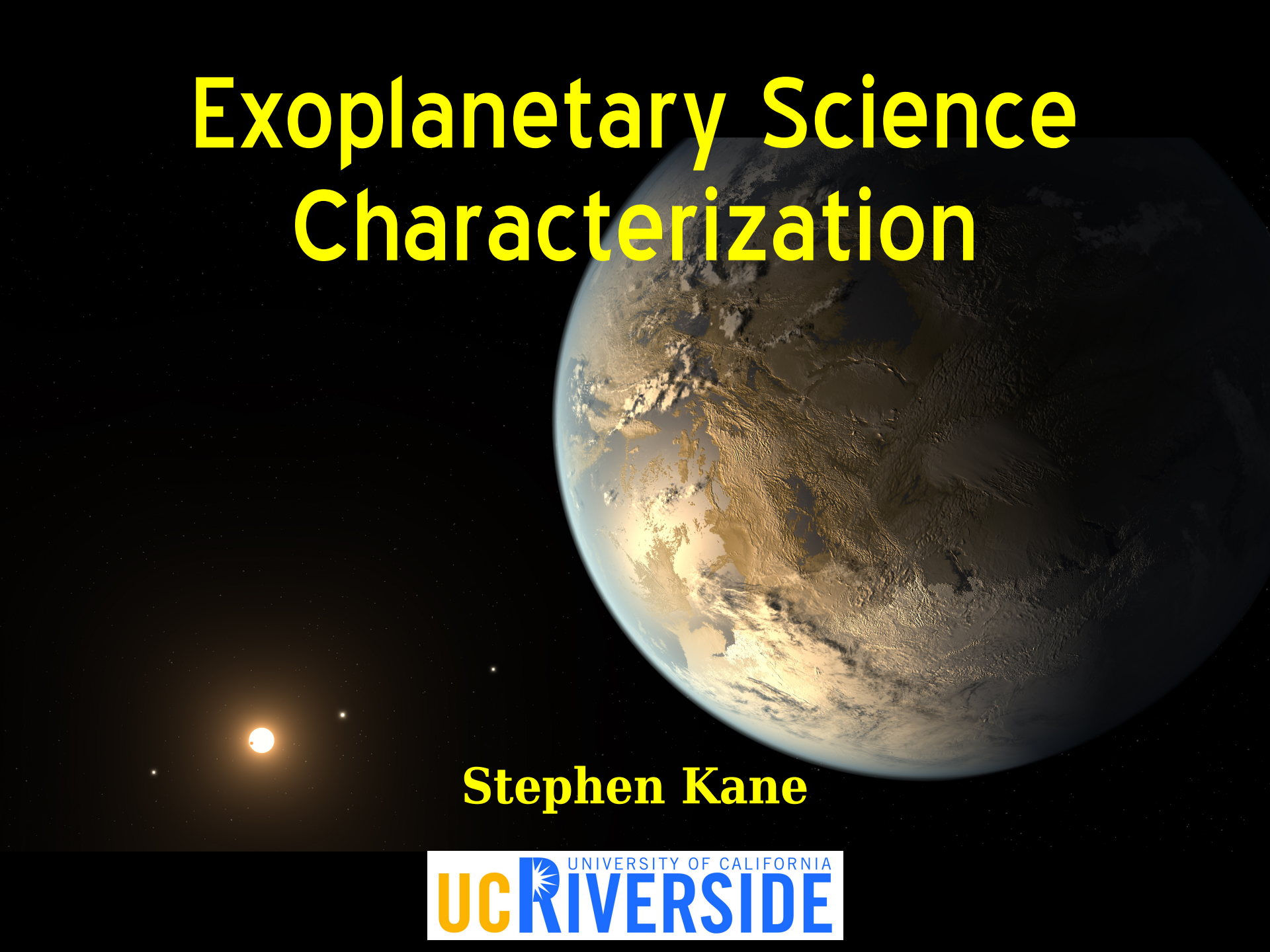
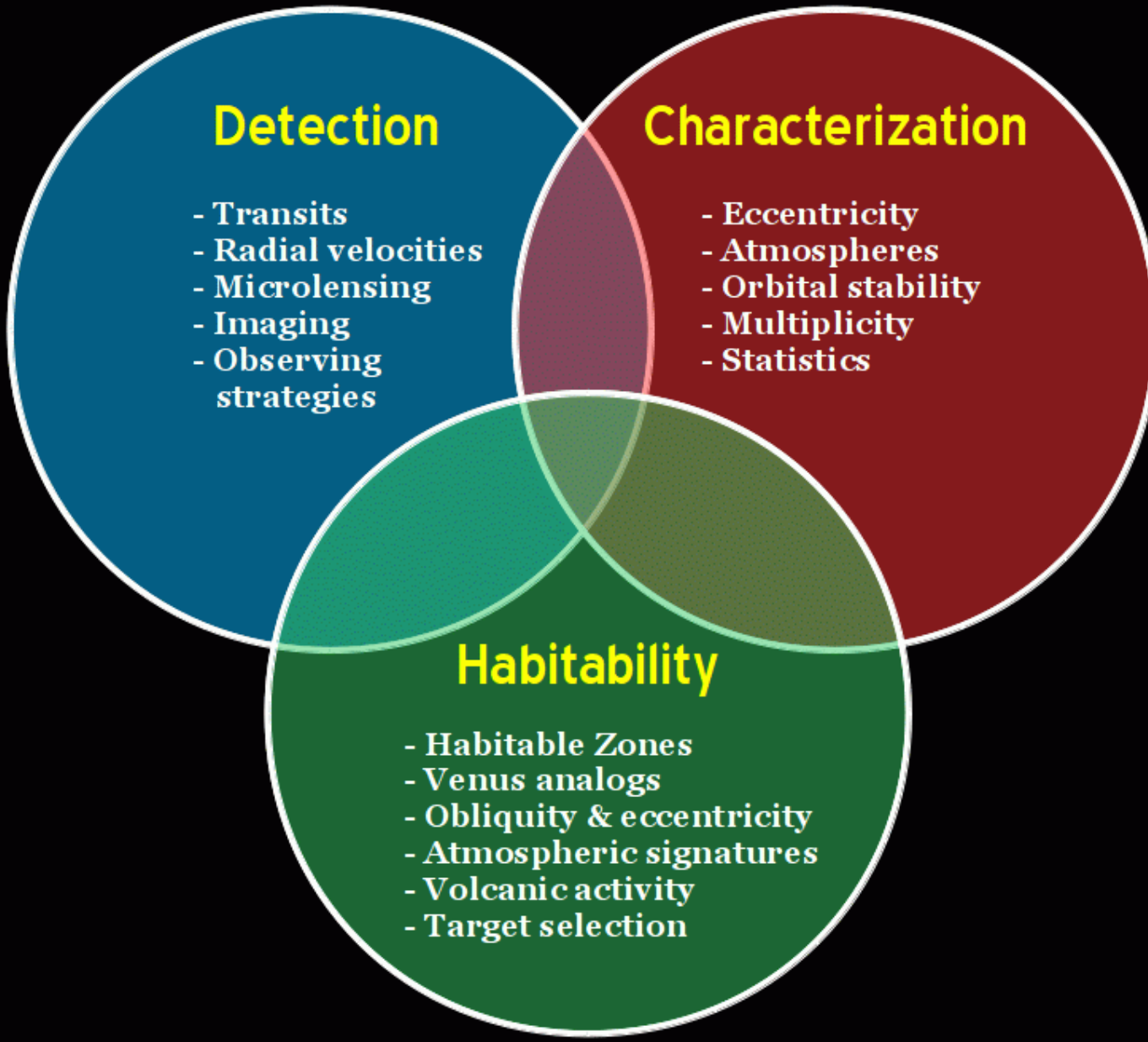
Exoplanetary Science Characterization



Stephen Kane

UNIVERSITY OF CALIFORNIA
UC RIVERSIDE


Detection
- Transits
- Radial velocities
- Microlensing
- Imaging
- Observing strategies
Characterization
- Eccentricity
- Atmospheres
- Orbital stability
- Multiplicity
- Statistics
Habitability
- Habitable Zones
- Venus analogs
- Obliquity & eccentricity
- Atmospheric signatures
- Volcanic activity
- Target selection

Natural History Museum Club

Undergraduate Research Social

Meet researchers and museum scientists of UCR!

Research opportunities & Networking

Thursday, October 3
5:30 PM
Geology 1444

nhmc.ucr@gmail.com

Light refreshments & snacks

Exoplanetary Science

- Please do not use laptops, tablets, cell phones in class.
- My office hours are every Wednesday 10am-12pm in Pierce Hall 2360.
- The class web page is live: http://stephenkane.net/teaching/g181
- The course syllabus is available from the web site.

http://stephenkane.net/teaching/g181

EXOPLANETARY SCIENCE

Welcome to the course webpage for GEO 181: Exoplanetary Science - Characterization.

Class Announcements:

2018-09-26: Juliette Becker will be visiting November 12.

2018-09-26: As mentioned in class, I will have some unavoidable travel this quarter that will result in the following classes being canceled - 11/7, 11/21. I will make up the missing classes at other times.

2018-09-26: Class announcements will appear here periodically.

Contact details:

- Instructor: Stephen Kane
- Office: Pierce Hall 2360
- Office hours: Wednesdays, 10am-12pm
- Phone: 951-827-6593
- Email: skane@ucr.edu

Download the class syllabus here.

Class times:

- Tuesday, 10:00am-11:20am Geology 1444
- Thursday, 10:00am-11:20am Geology 1444

Text:

- "The Exoplanet Handbook" by Michael Perryman
- I also recommend "Exoplanets" edited by Sara Seager

Important Dates:

- October 17: Data Project abstract due
- November 26: Data Project final report due
- December 3: Summary class
- December 5: **FINAL EXAM** 10:00am-11:20am in class

Useful Links:

- The NASA Astrophysics Data System
- astro-ph preprint server
- The Habitable Zone Gallery

Assessment:

- **Homework (40%):** There will be four homeworks during the semester. Most problems will require analytic solutions, however there will usually be one problem per assignment that will involve graphing and numerical solution with computer software such as Mathematica, MATLAB, or any programming language.
- **Data Project (30%):** Students will be required to complete a project using exoplanet data

Class Assessment

- **Assessment: Homeworks – 40%**
  Data Project – 30%
  Final Exam – 30%

Class Assessment

- Assessment: Homeworks – 40%
  Data Project – 30%
  Final Exam – 30%

- Homeworks will be due Thursdays in class. Times between issue and due dates will vary.

- Programming will be required (IDL, python, MATLAB).

- First homework will be handed out on Thursday.

Class Assessment

- Assessment: Homeworks – 40%
  Data Project – 30%
  Final Exam – 30%

- Working in groups is encouraged, but must hand in your own work.

- Late homeworks are 50% off until following Monday and 100% off after that.

- Cheat at your own risk!

Class Assessment

- Assessment: Homeworks – 40%
  Data Project – 30%
  Final Exam – 30%

- The Data Project consists of utilizing an online data resource to conduct analysis of exoplanet data.

- Final report may be up to 5 pages long, in the form of a lab report.

- Topic/abstract due Thursday, October 17 in class.

- Final report due on Tuesday, November 26 in class.

Class Assessment

- Assessment: Homeworks – 40%
  Data Project – 30%
  Final Exam – 30%

- Possible Data Project sources include:
  - The NASA Exoplanet Archive
  - The Exoplanet Data Explorer
  - The Habitable Zone Gallery
  - Exoplanet Characterization Toolkit
  - The Systemic Console

Class Assessment

- **Assessment: Homeworks – 40%**
  Data Project – 30%
  Final Exam – 30%

- **The Final Exam will be in this room Thursday, December 5, 10:00am-11:20am.**

- **Questions will cover the entire class.**

Class Assessment

- Assessment: Homeworks – 40%
  Data Project – 30%
  Final Exam – 30%

- For homeworks and literature review, hard copies are required. No email submissions!

- Do not miss homeworks/exams. There are no make-ups or extra credit!

- Extensions always require documentation!

Textbook/Lectures

- Textbook: “The Exoplanet Handbook” by Michael Perryman. Also recommend “Exoplanets” edited by Sara Seager.

- Lectures will (mostly) be available on the class website but many things covered in class won't be.

- Discussion of peer-reviewed papers.

- Guest speakers.

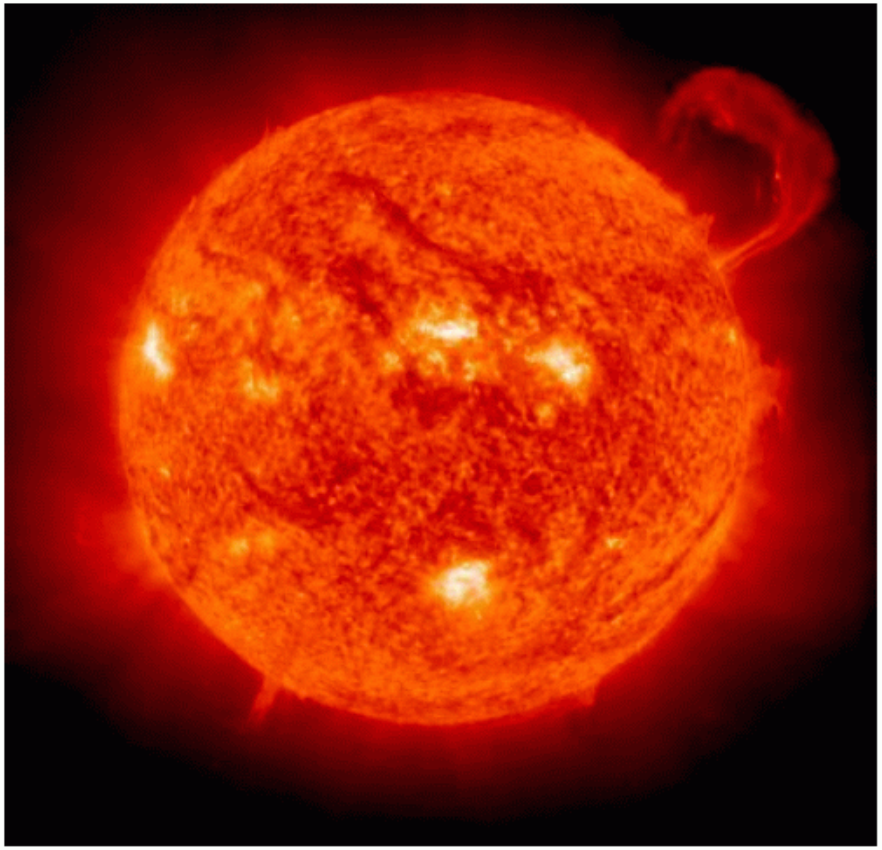
Useful Links

- The NASA Exoplanet Archive
- The Exoplanet Data Explorer
- The Habitable Zone Gallery
- Exoplanet Characterization Toolkit
- The Systemic Console
- NASA/ADS
- ArXiv preprint server (astro-ph)

Topics

- Lecture 1 – Introduction
- Lecture 2 – The Star-Planet Connection
- Lecture 3 – Keplerian Orbits
- Lecture 4 – Architectures
- Lecture 5 – Tidal Effects
- Lecture 6 – Hill radius and Roche limit
- Lecture 7 – Orbital Dynamics
- Lecture 8 – Planet Formation
- Lecture 9 – Stellar Multiplicity
- Lecture 10 – Circumbinary Planets
- Lecture 11 – Phase Variations
- Lecture 12 – Planetary Atmospheres I
- Lecture 13 – Planetary Atmospheres II
- Lecture 14 – Statistics and Diversity
- Lecture 15 – Mass-radius relationship
- Lecture 16 – Super-Earths
- Lecture 17 – Exomoons
- Lecture 18 – Space Missions
- Lecture 19 – Summary/Discussion
- Lecture 20 – Final Exam

Numbers you should know: The Sun



source: SOHO/EIT

Mass ≈ 2 x 10^{30} kg = 1 $M_\odot$

Radius ≈ 7 x 10^{8} m = 1 $R_\odot$

Distance = 1.5 x 10^{11} m = 1 AU

Luminosity = 4 x 10^{26} W = 1 $L_\odot$

Surface temperature = 5800 K

age ≈ 4.5 Gyr

spectral type = G2 V

All other stars are scaled to these parameters for convenience.

Numbers you should know: planets

- **Mass:** Sun, Jupiter, Earth are units of measurement

- **Radius:** Sun, Jupiter, Neptune, Earth are units of measurement

Planet Detection

- **Direct:** Uses either starlight reflected from or thermal radiation emitted by the planet

- **Indirect:** Uses effects of the planet on the parent star or random background star

Summary of Detection Methods

(1) Radial velocity → motion

(2) Astrometry → position

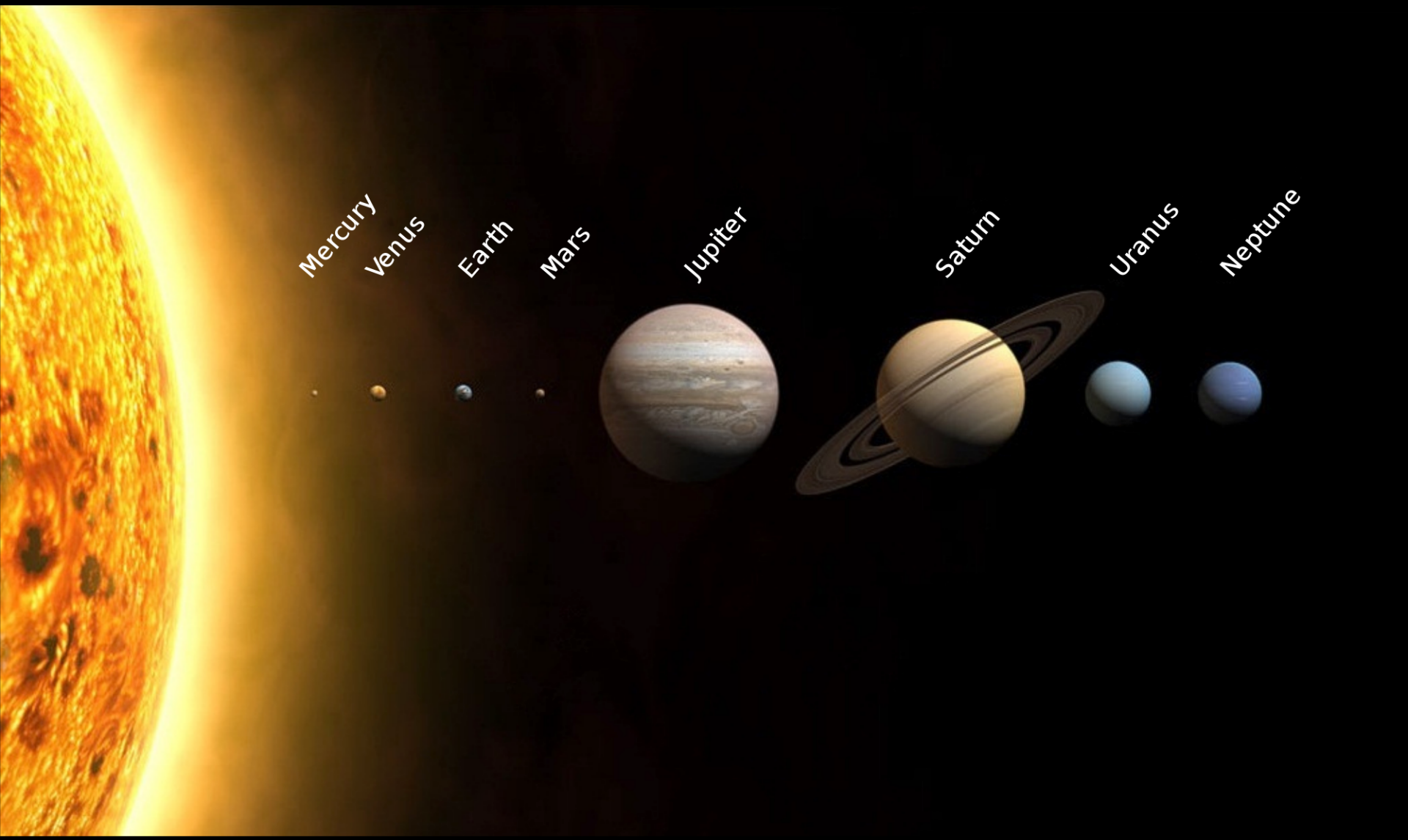
(3) Timing → motion

(4) Gravitational microlensing

Effects of a planet on a background star

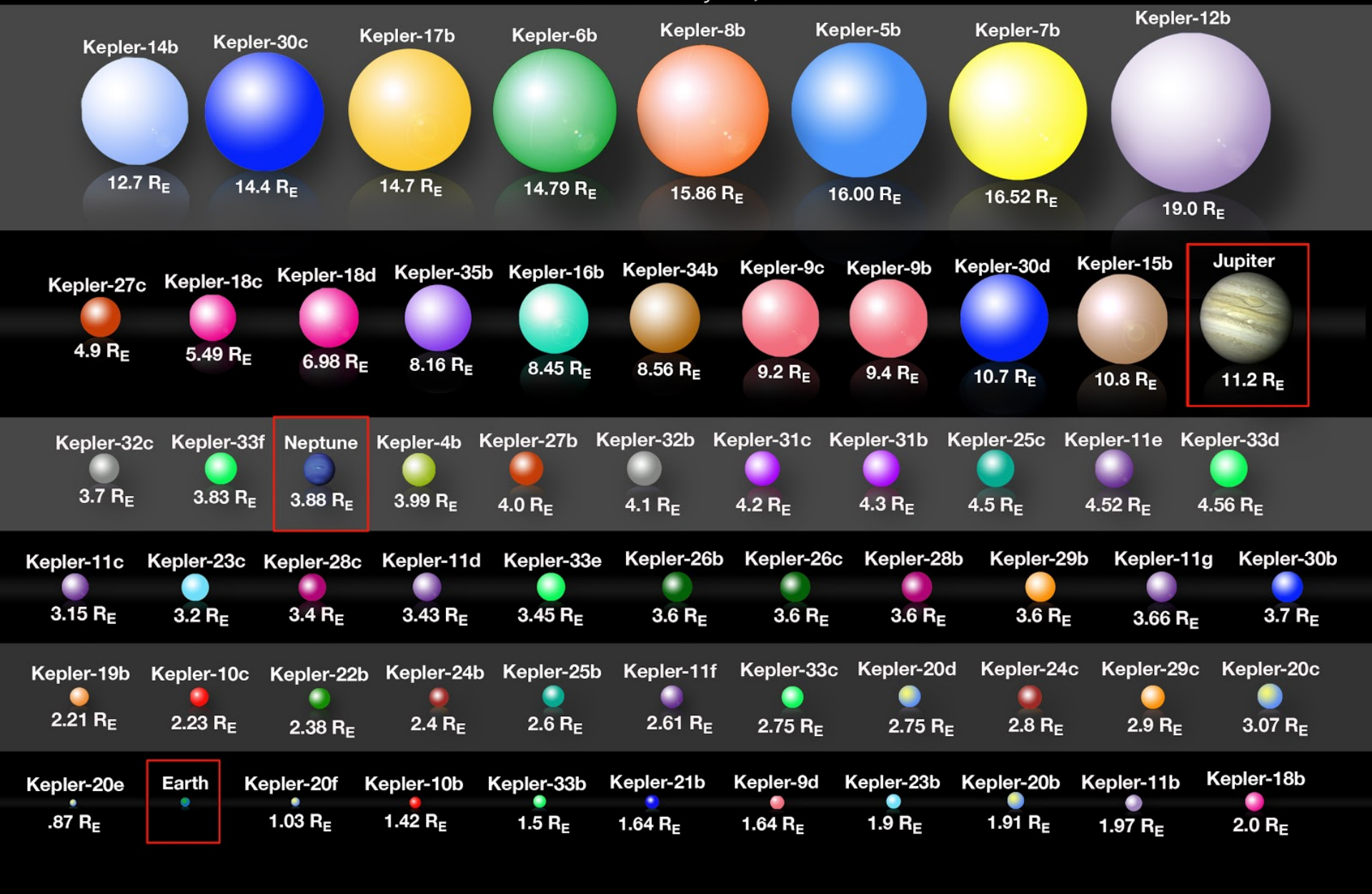
(5) Transits → brightness

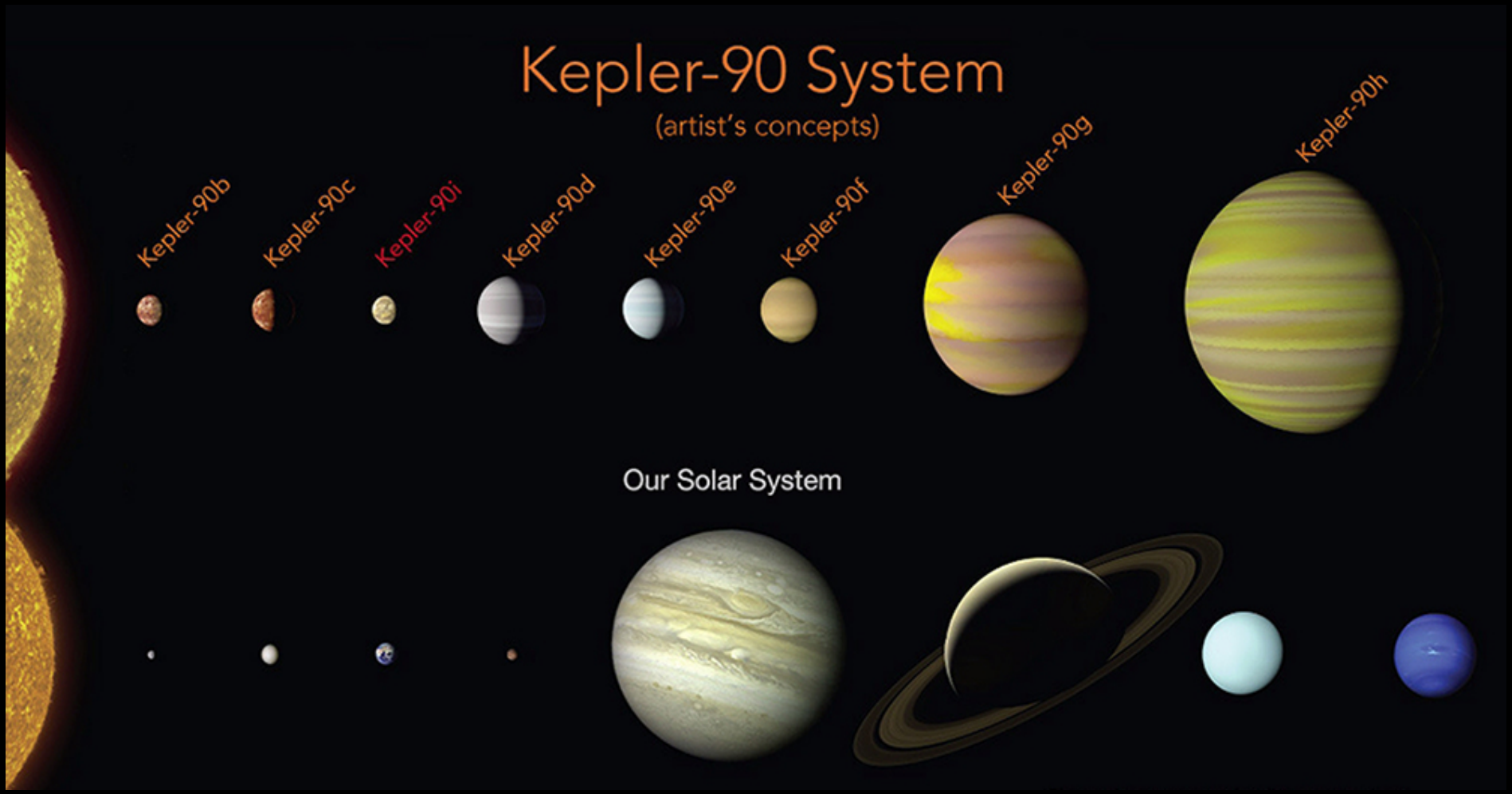
(6) Imaging

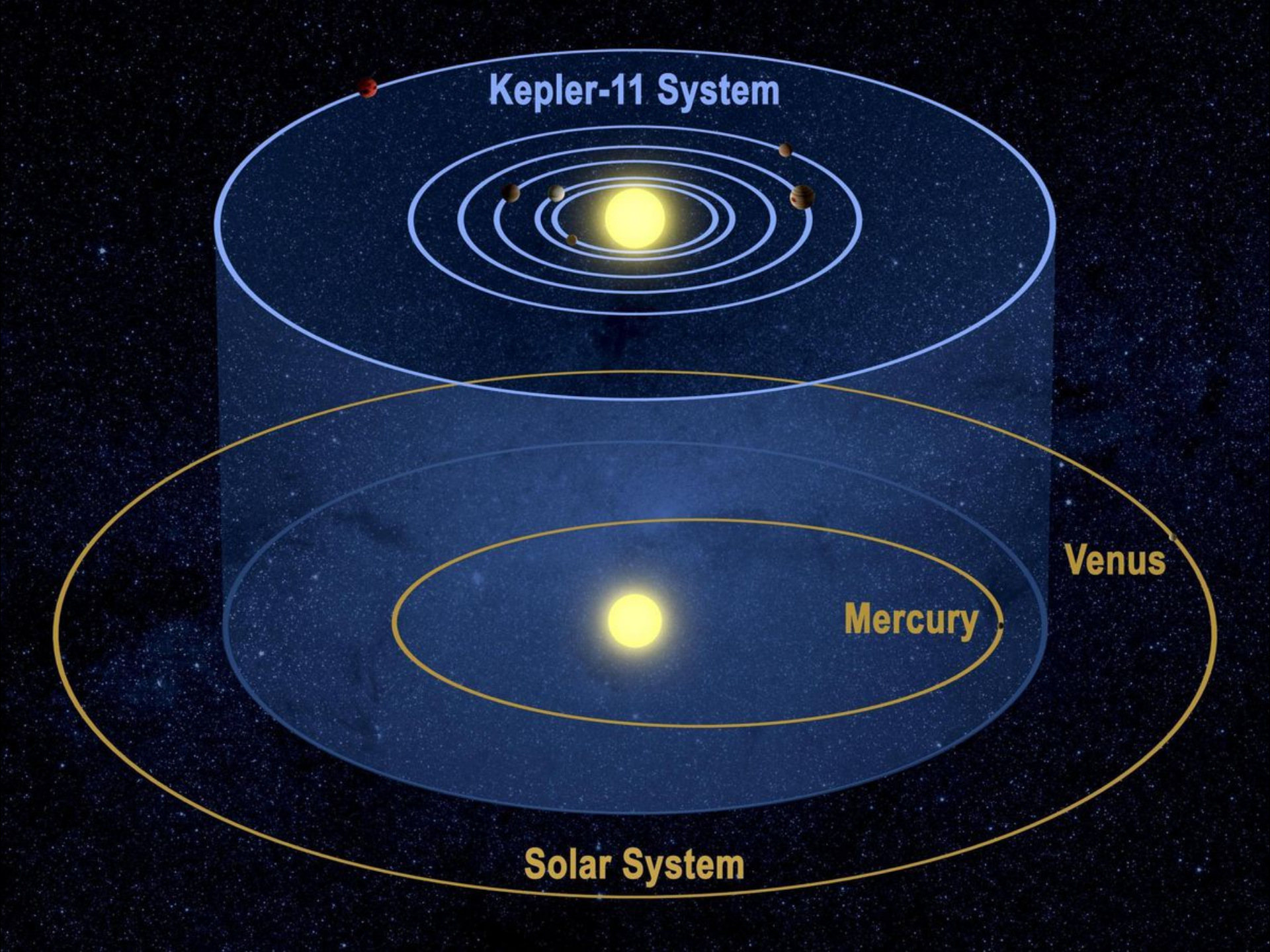

Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune

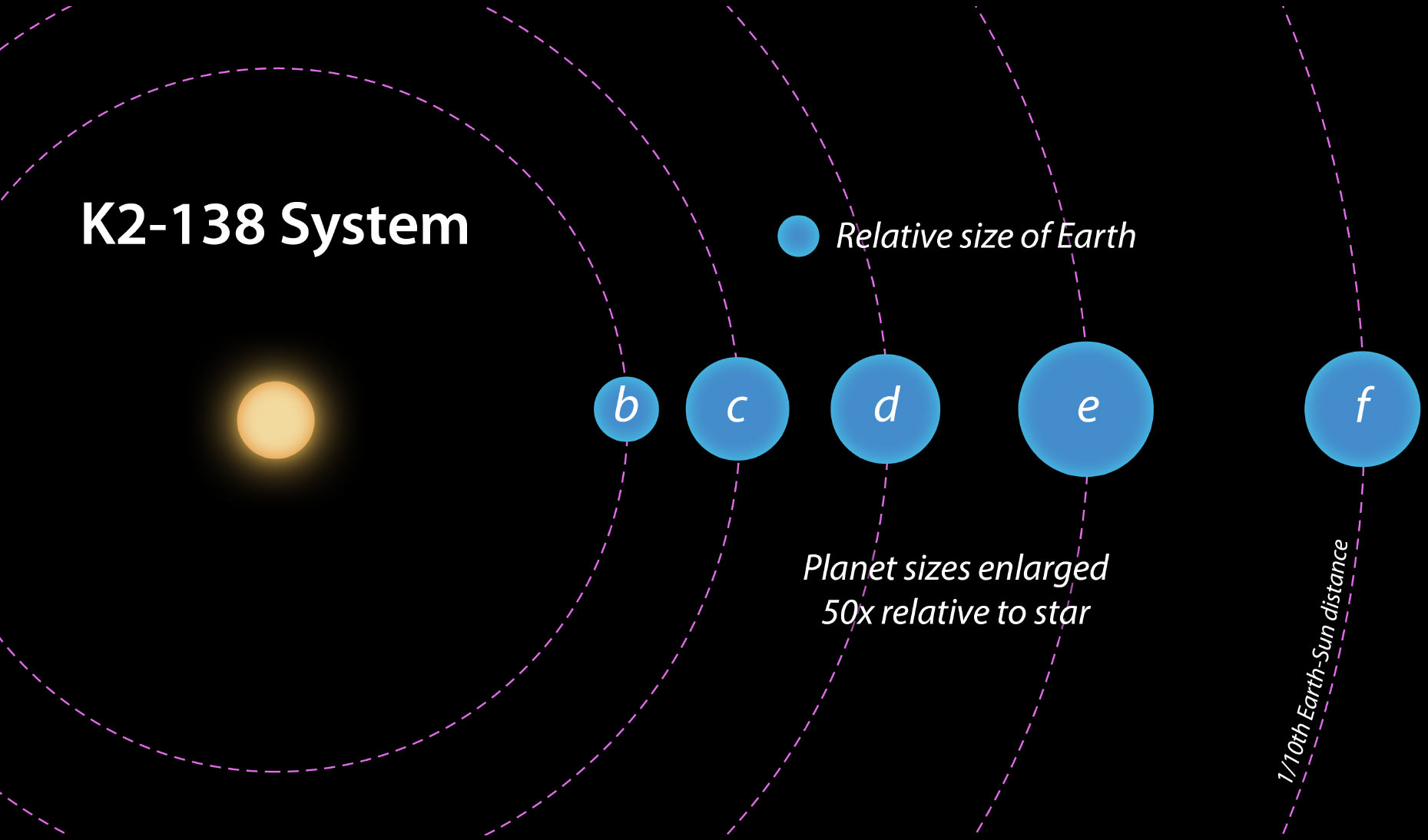
Kepler Planets

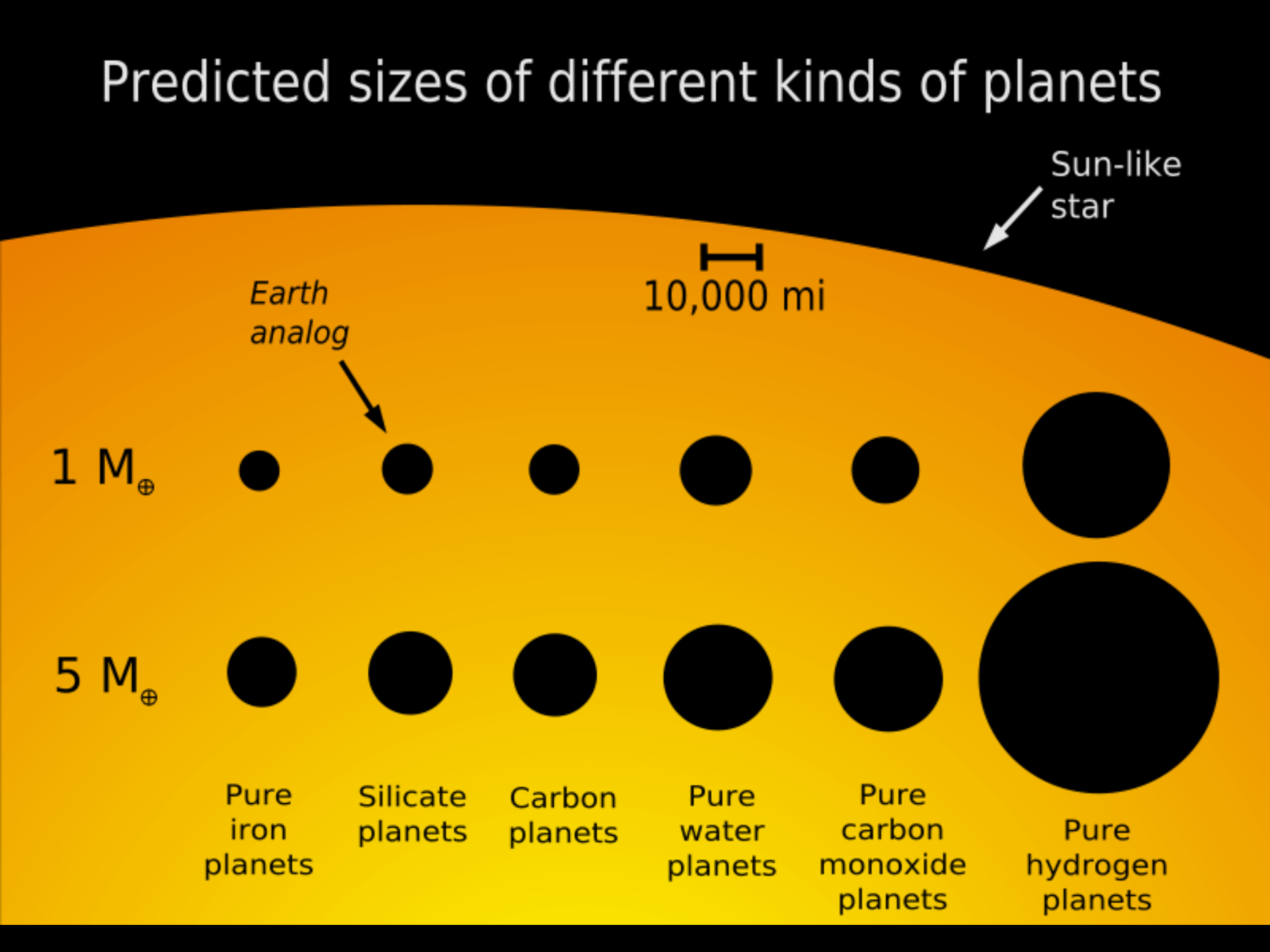
As of February 27, 2012

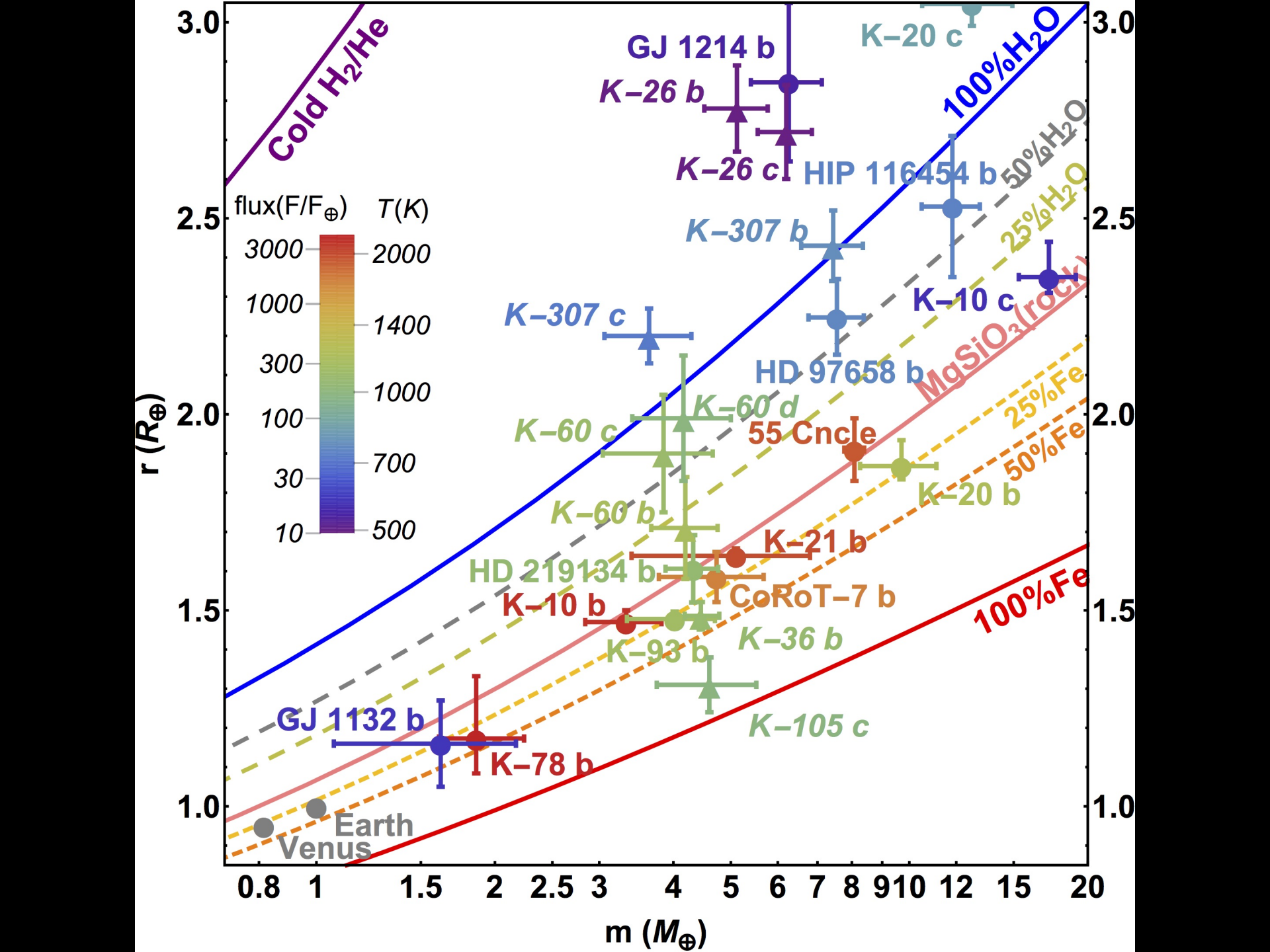


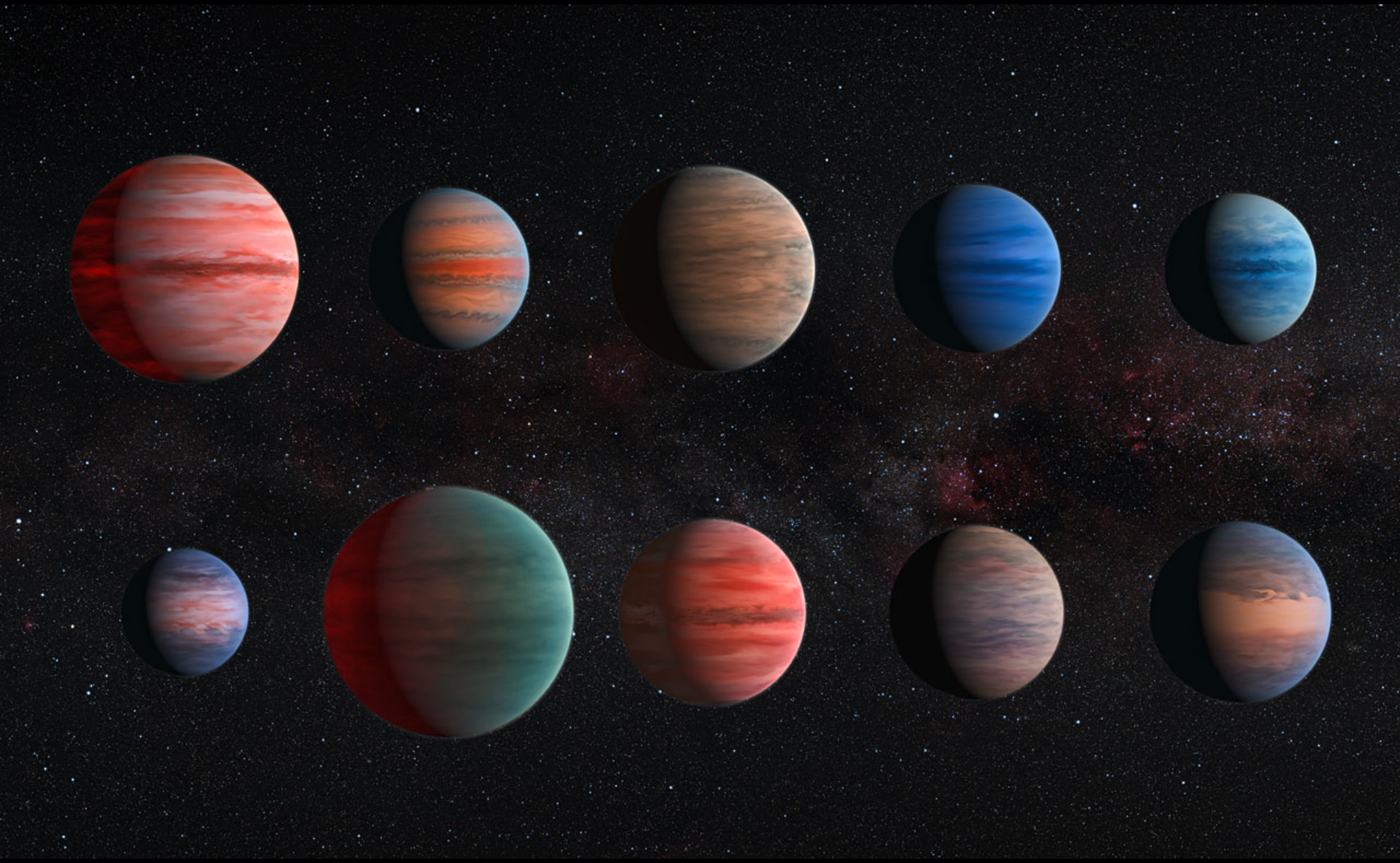

Kepler-90 System
(artist's concepts)
Kepler-90b
Kepler-90c
Kepler-90i
Kepler-90d
Kepler-90e
Kepler-90f
Kepler-90g
Kepler-90h
Our Solar System


Kepler-11 System
Venus
Mercury
Solar System


K2-138 System
Relative size of Earth
b
c
d
e
f
Planet sizes enlarged
50x relative to star
1/10th Earth-Sun distance

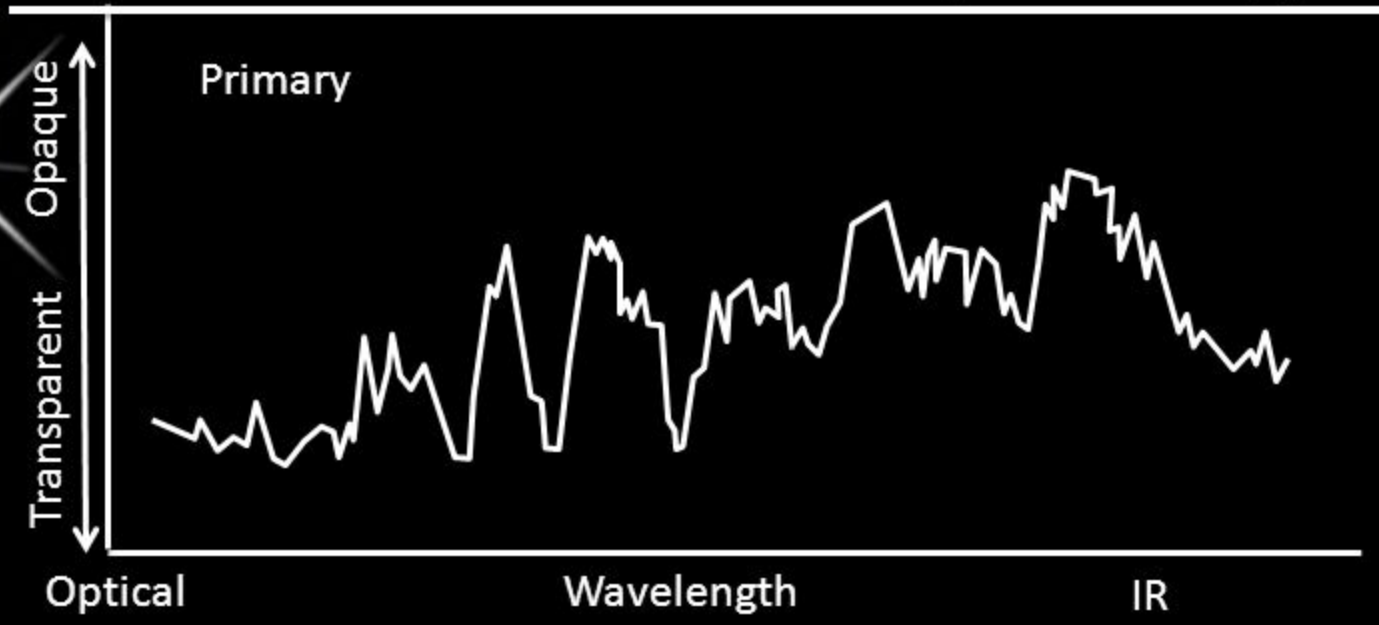

Predicted sizes of different kinds of planets
Sun-like star
10,000 mi
Earth analog
1 M⊕
5 M⊕
Pure iron planets
Silicate planets
Carbon planets
Pure water planets
Pure carbon monoxide planets
Pure hydrogen planets


Cold H_2/He
100%H_2O
50%H_2O
25%H_2O
$MgSiO_3$(rocky)
25%Fe
50%Fe
100%Fe
flux($F/F_\oplus$)
$T(K)$
3000
1000
300
100
30
10
2000
1400
1000
700
500
GJ 1214 b
K–26 b
K–26 c
K–20 c
HIP 116454 b
K–307 b
K–10 c
K–307 c
HD 97658 b
K–60 d
K–60 c
55 Cncle
K–20 b
K–60 b
K–21 b
HD 219134 b
CoRoT–7 b
K–10 b
K–36 b
K–93 b
K–105 c
GJ 1132 b
K–78 b
Earth
Venus
r ($R_\oplus$)
m ($M_\oplus$)
3.0
2.5
2.0
1.5
1.0
0.8
1
1.5
2
2.5
3
4
5
6
7
8
9
10
12
15
20

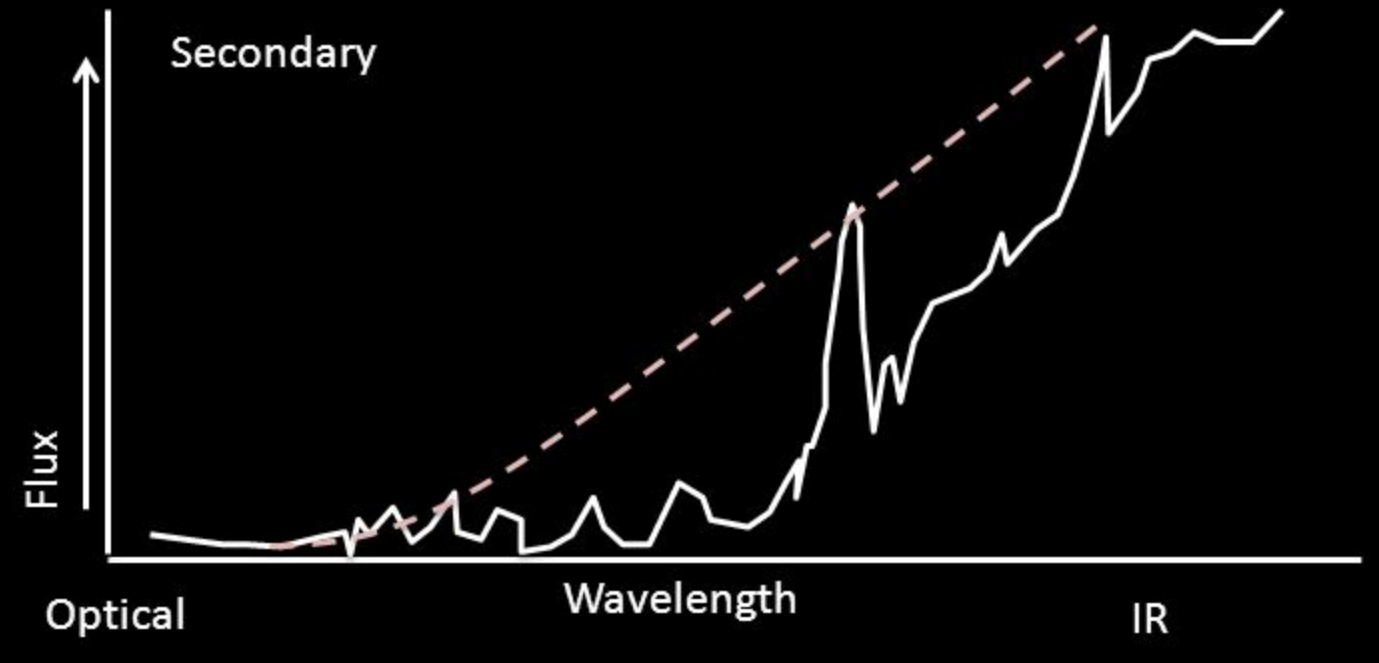


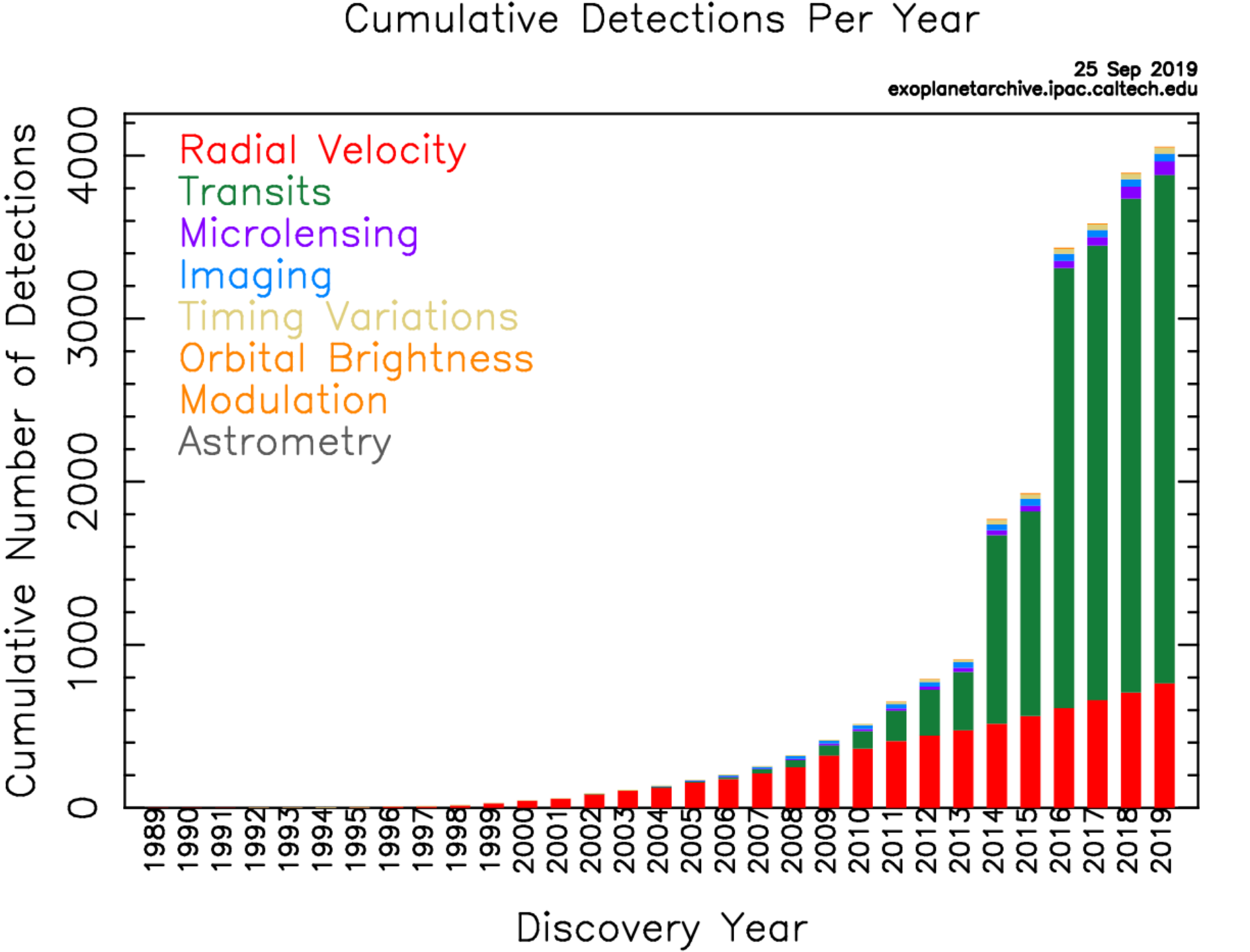
Transit Spectroscopy

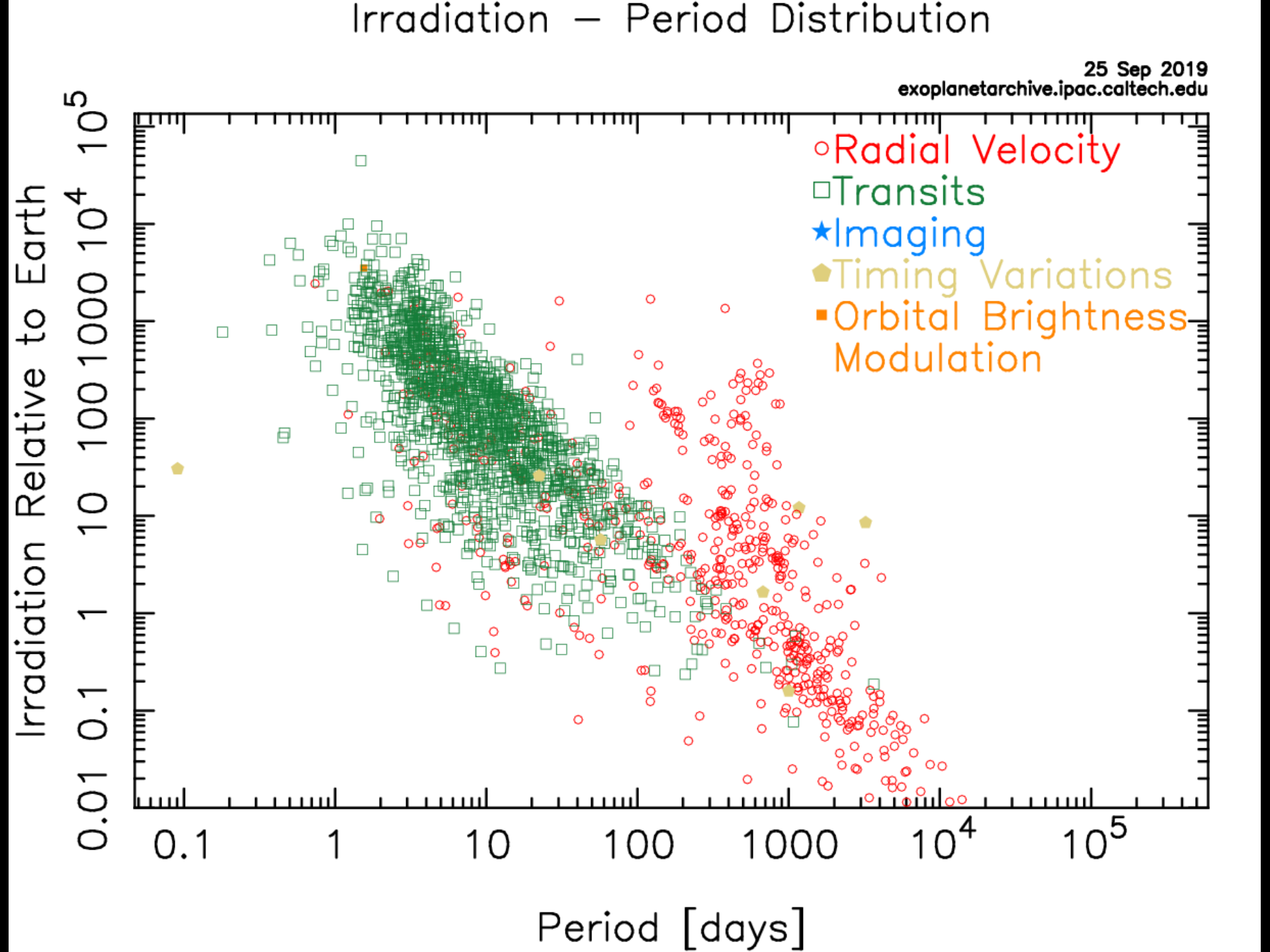
Gas abundances, cloud top pressure/particle size, mean molecular weight

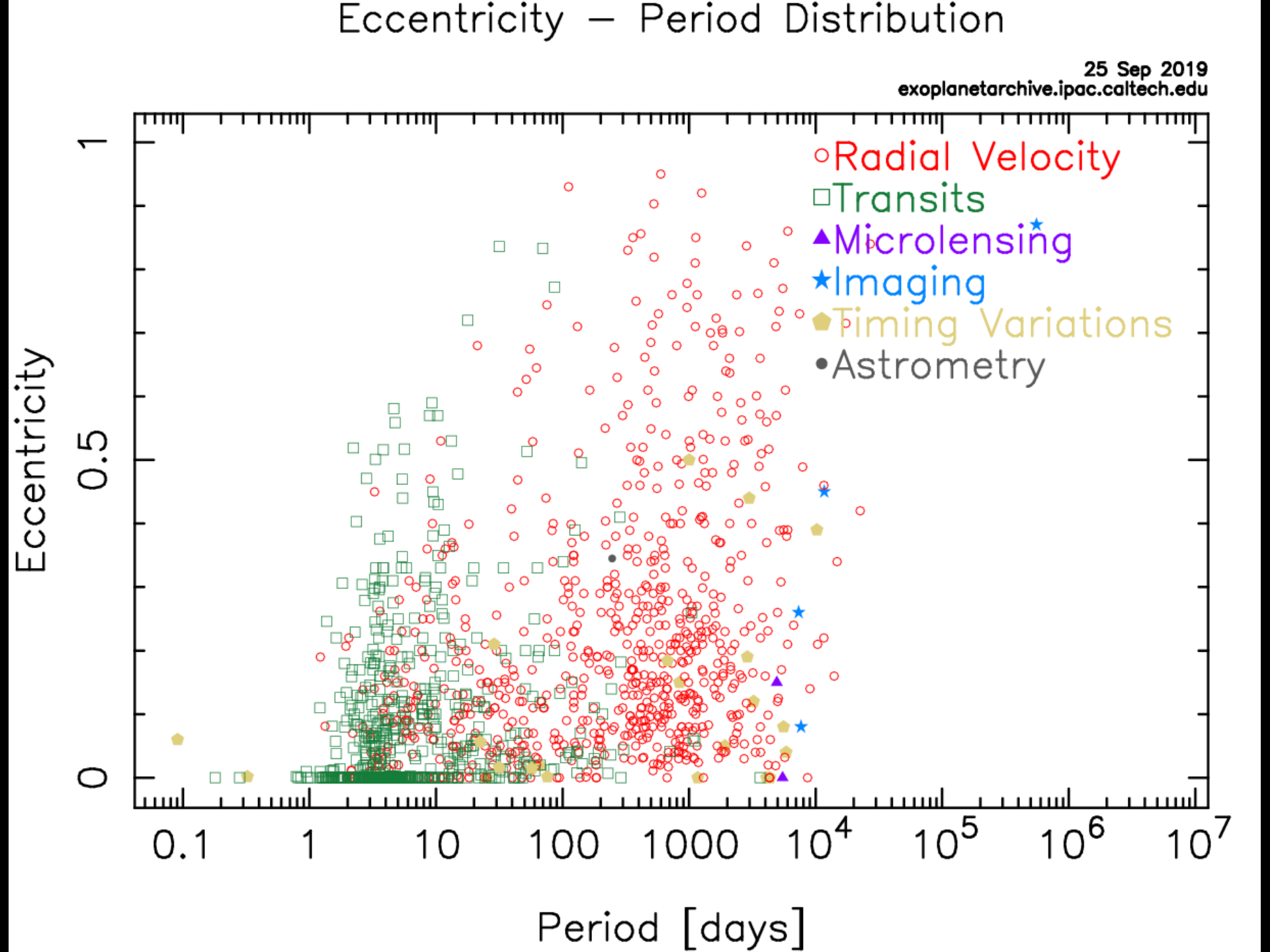


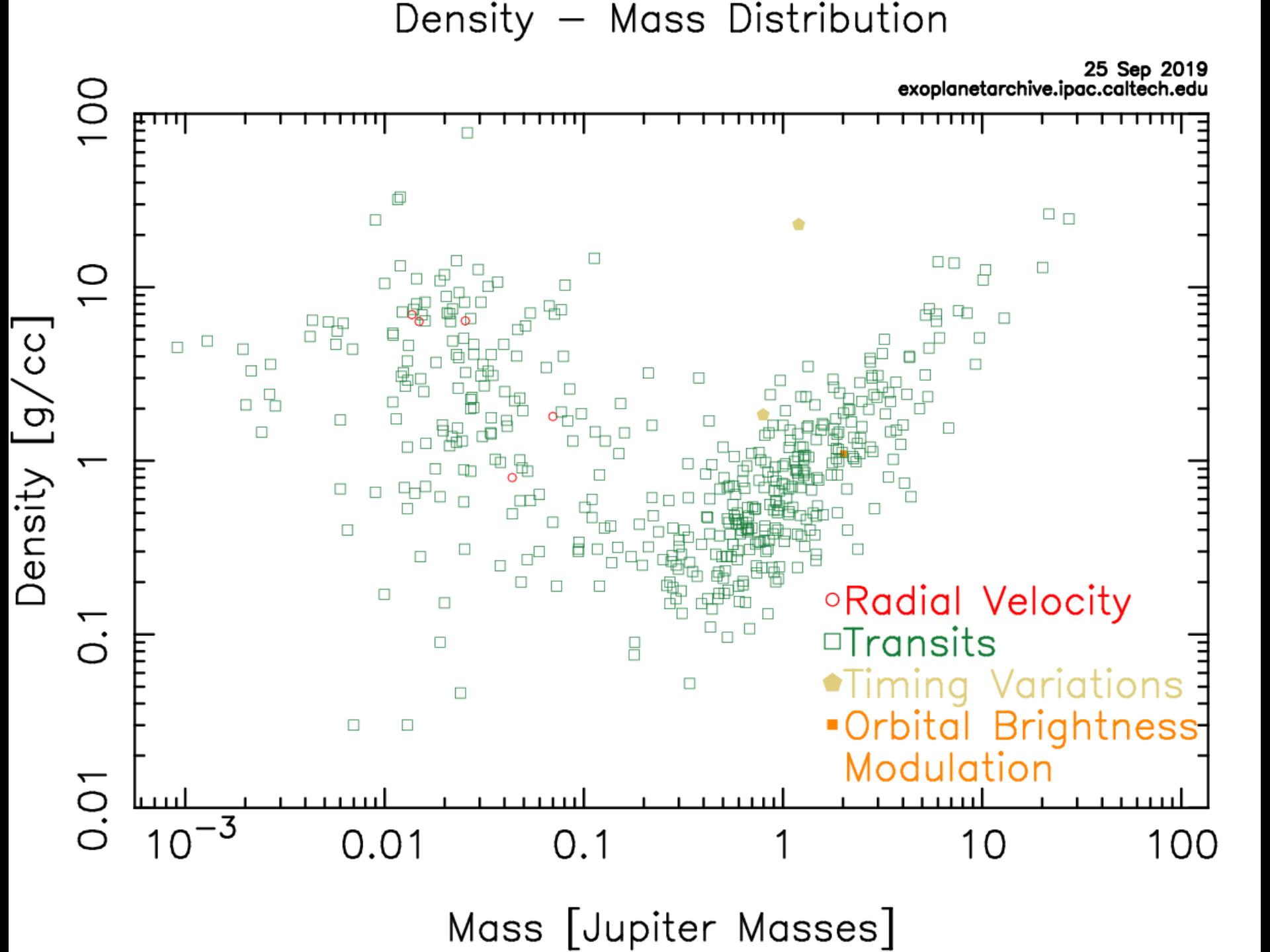
Temperature structure, gas abundances, cloud composition (maybe)

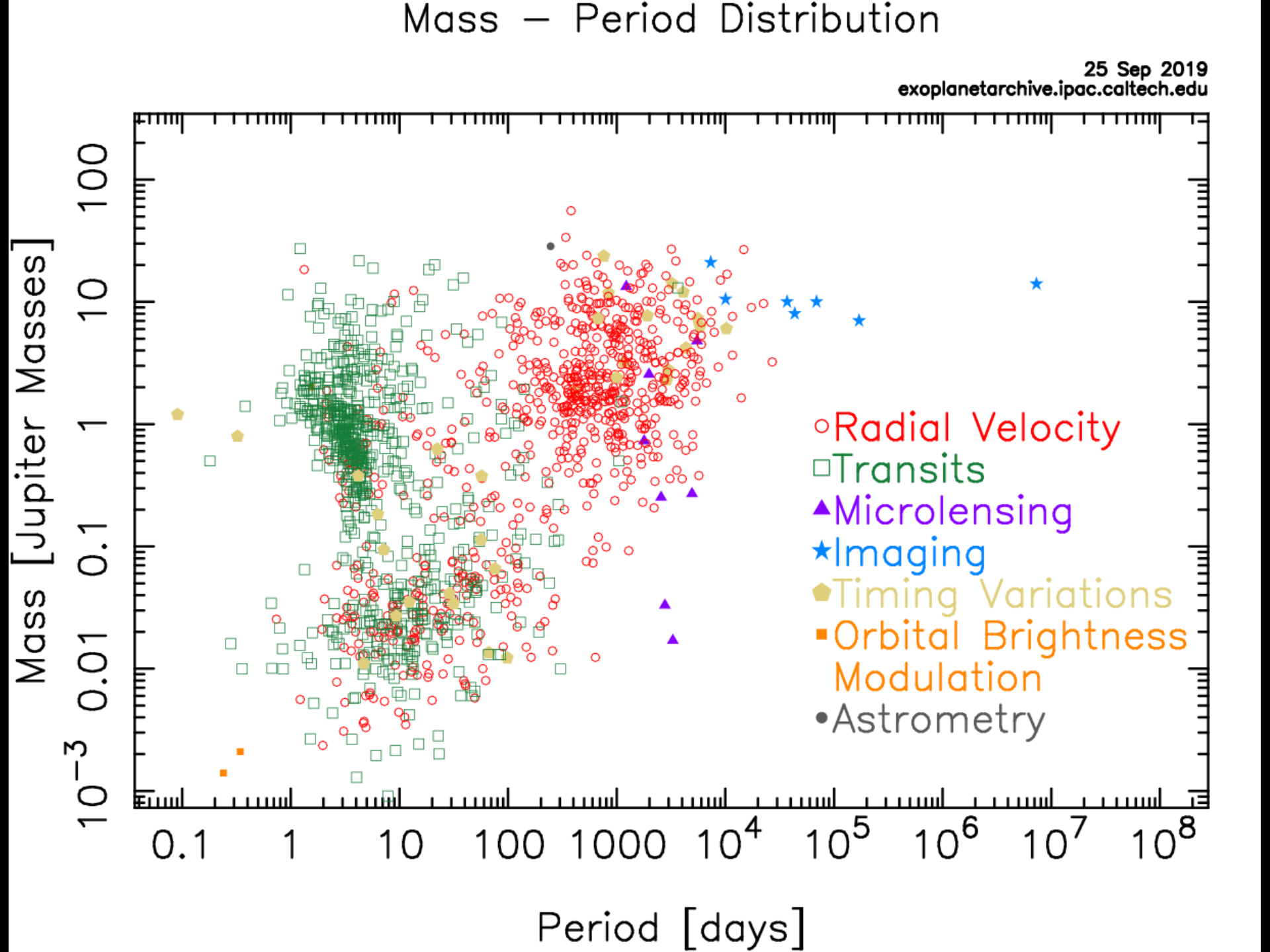


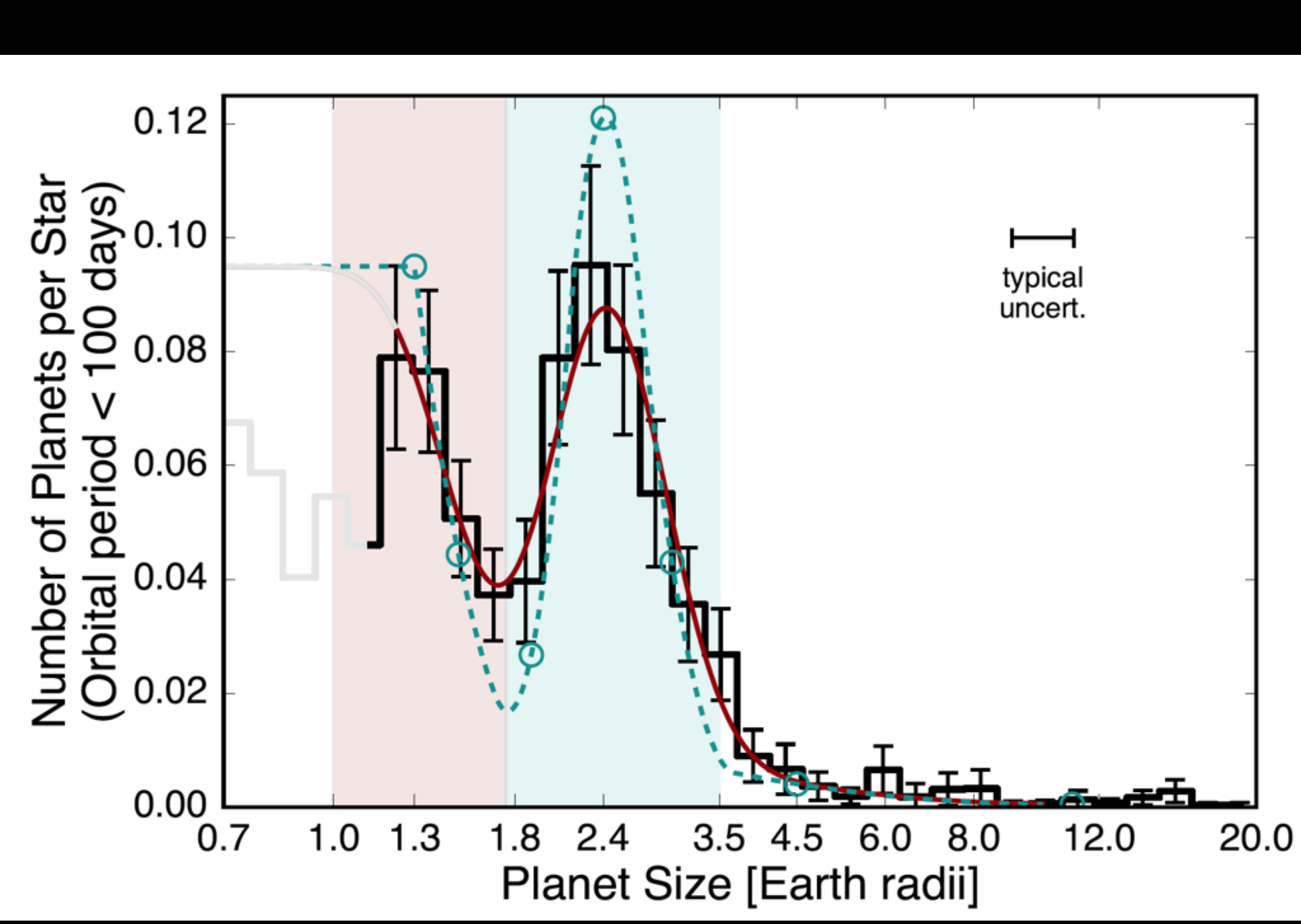

Cumulative Detections Per Year
25 Sep 2019
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
Astrometry
Cumulative Number of Detections
0
1000
2000
3000
4000
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
Discovery Year


Irradiation – Period Distribution
25 Sep 2019
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Imaging
Timing Variations
Orbital Brightness Modulation
Irradiation Relative to Earth
0.01
0.1
1
10
100
1000
10^4
10^5
0.1
1
10
100
1000
10^4
10^5
Period [days]


Eccentricity – Period Distribution
25 Sep 2019
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Astrometry
Eccentricity
0
0.5
1
0.1
1
10
100
1000
10^4
10^5
10^6
10^7
Period [days]


Density – Mass Distribution
25 Sep 2019
exoplanetarchive.ipac.caltech.edu
Density [g/cc]
100
10
1
0.1
0.01
10^{-3}
0.01
0.1
1
10
100
Mass [Jupiter Masses]
Radial Velocity
Transits
Timing Variations
Orbital Brightness Modulation


Mass – Period Distribution
25 Sep 2019
exoplanetarchive.ipac.caltech.edu
Mass [Jupiter Masses]
Period [days]
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness Modulation
Astrometry


Number of Planets per Star
(Orbital period < 100 days)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
typical
uncert.
0.7
1.0
1.3
1.8
2.4
3.5
4.5
6.0
8.0
12.0
20.0
Planet Size [Earth radii]