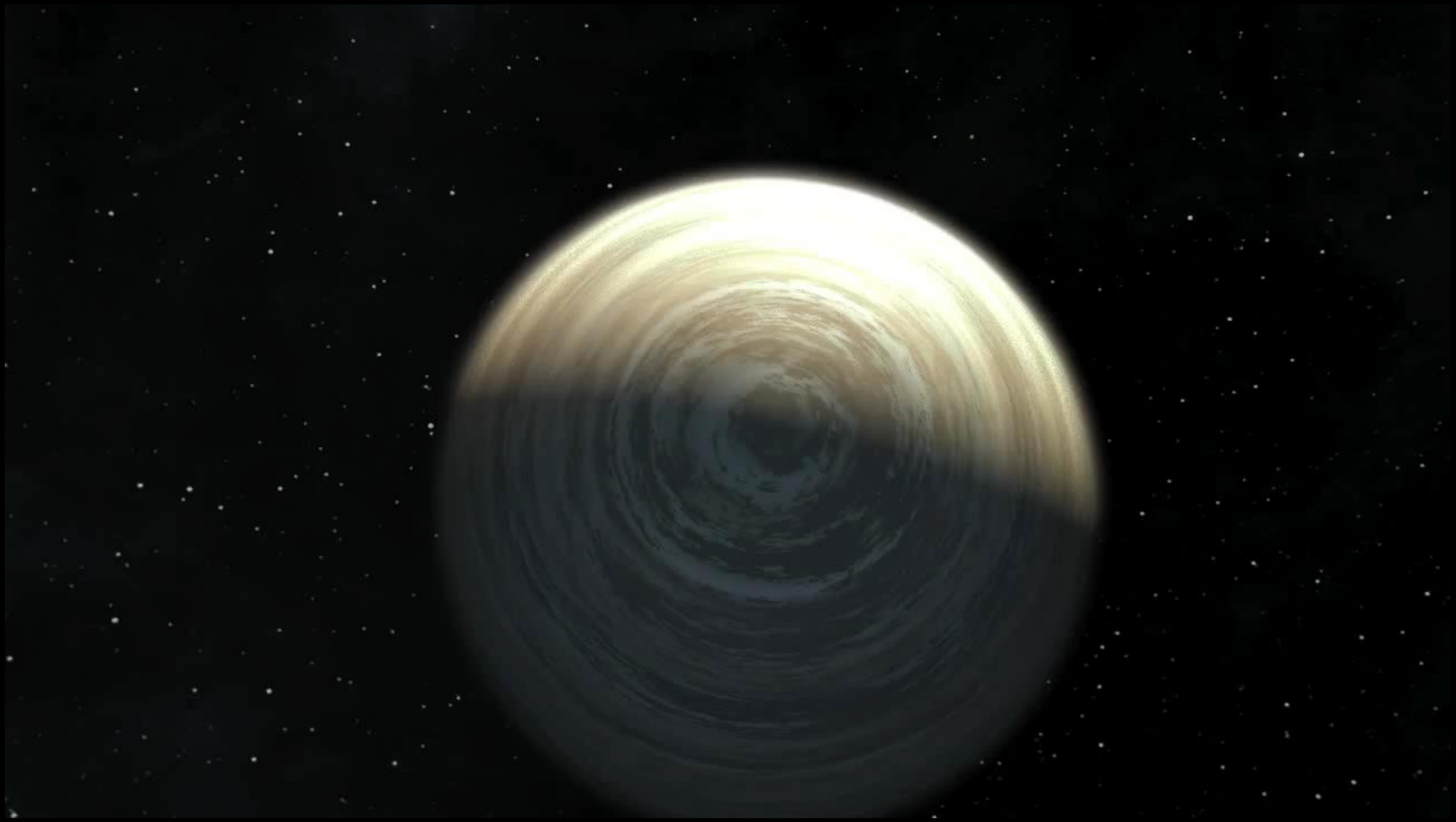
Worlds Apart - Finding Exoplanets



Illustrated Video Credit: NASA, JPL-Caltech, T. Pyle;
Acknowledgement: djxatlanta

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Osher Lifelong Learning Institute
Thursday, November 5, 2020

Outline

- A bit of info and history about planet formation theory.
- A discussion of the main exoplanet detection techniques including some of the missions and telescopes that are searching the skies.
- A few examples of “notable” results.

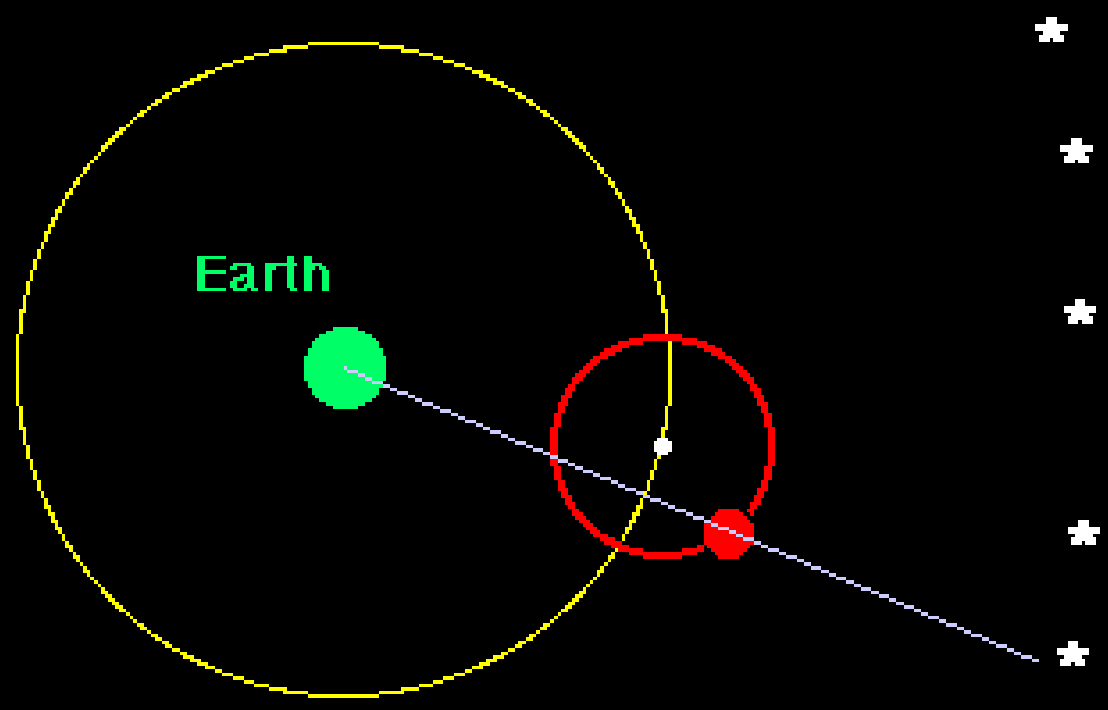
Evolution of our Thinking of the Solar System

- First “accepted models” were geocentric – Ptolemy
- Copernicus – heliocentric solar system
- By 1800s, heliocentric model widely accepted in scientific community
- 1755 – Immanuel Kant hypothesizes clouds of gas and dust
- 1796 – Kant and P.-S. LaPlace both put forward the Solar Nebula Disk Theory
- Today – if Solar System formed from an interstellar cloud, maybe other clouds formed planets elsewhere in the universe.

Retrograde Motion - Mars

Image Credits: Tunc Tezel

Retrograde Motion as Explained by Ptolemy



To explain retrograde, the concept of the epicycle was introduced. A planet would move on the epicycle (the smaller circle) as the epicycle went around the Earth on the deferent (the larger circle). The planet would appear to shift back and forth among the background stars.

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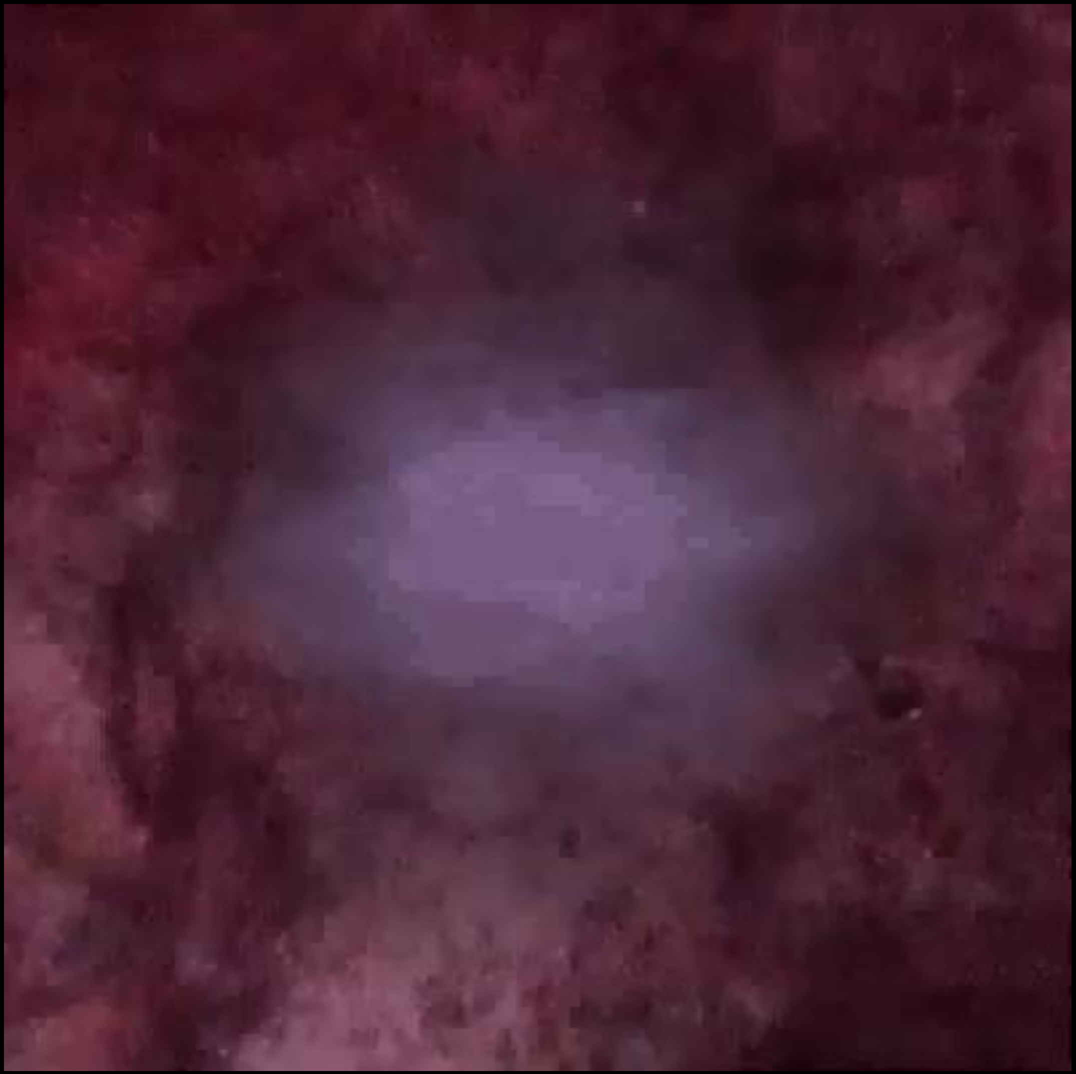
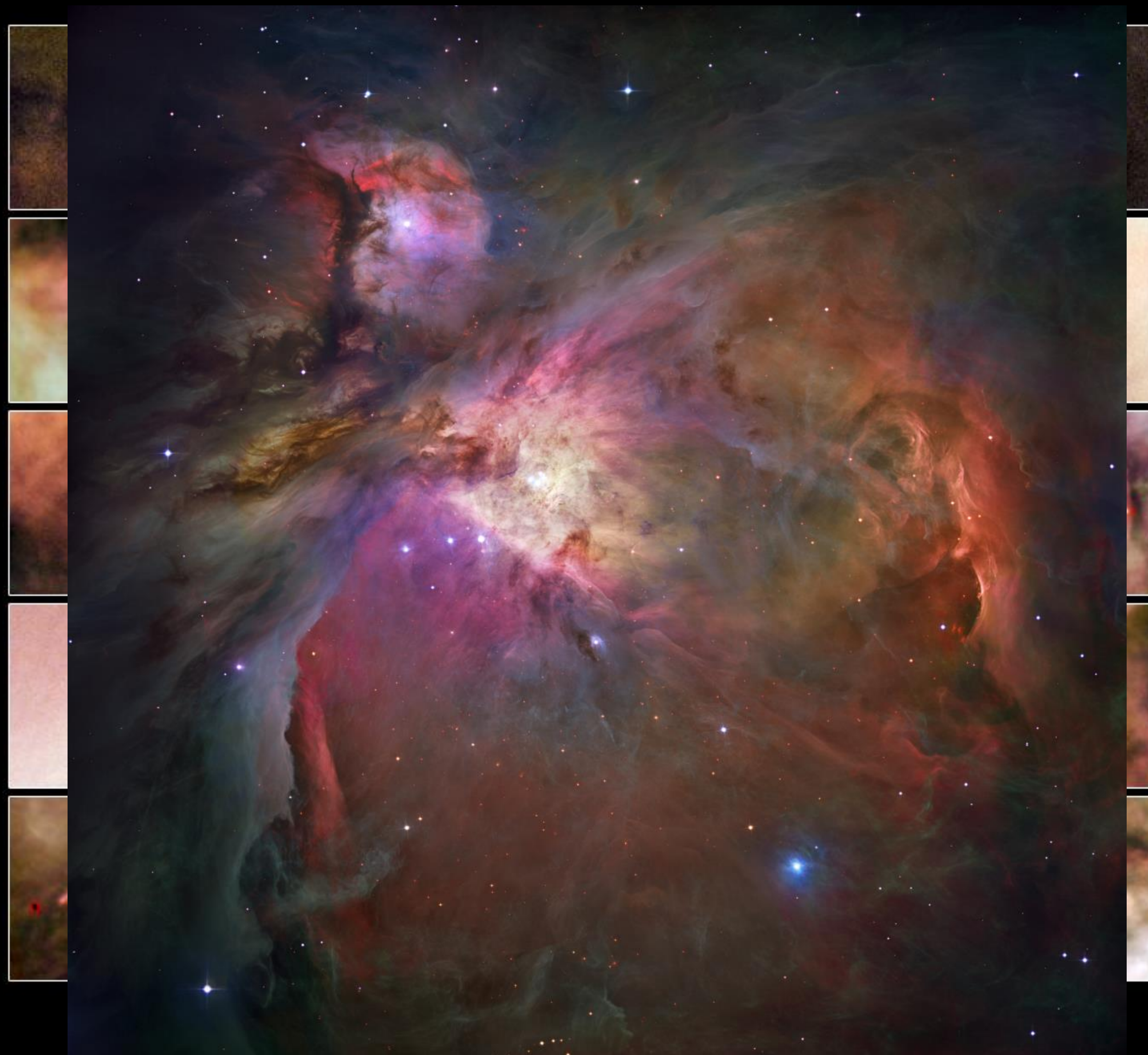
Formation of a Star



The Great Orion Nebula

Credit: Babek Tafreshi, Nat Geo Image Collection

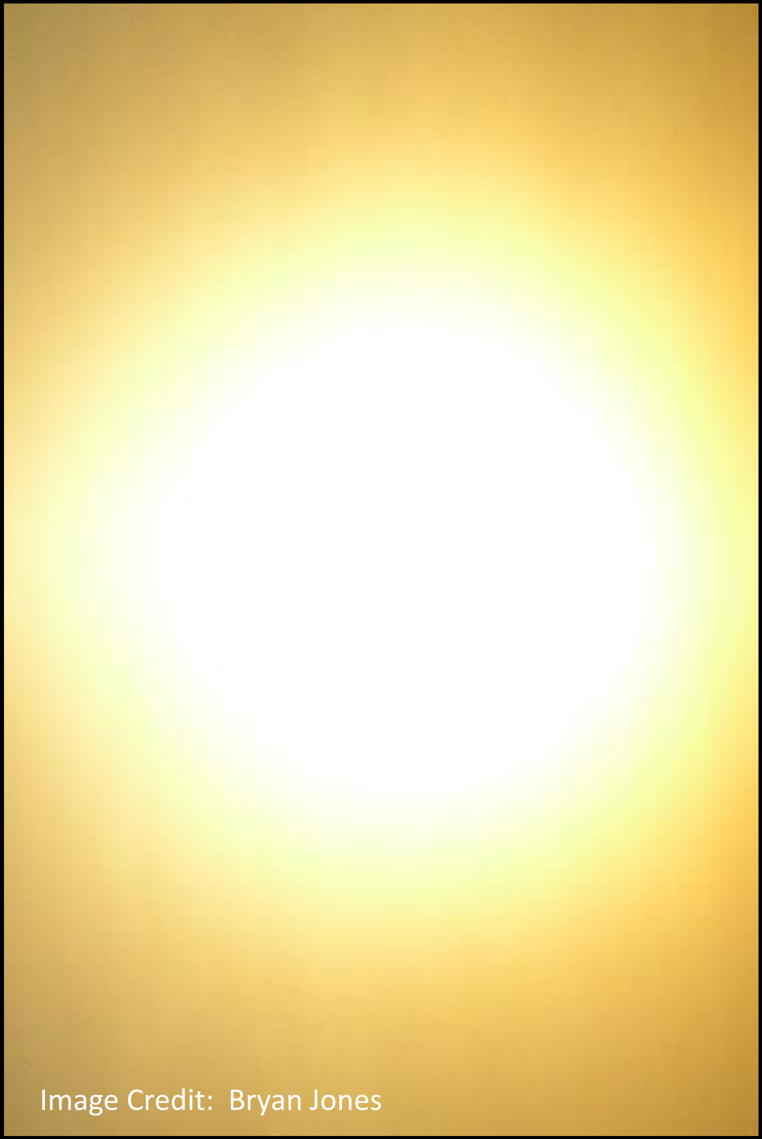
Star/Disk Formation in Action



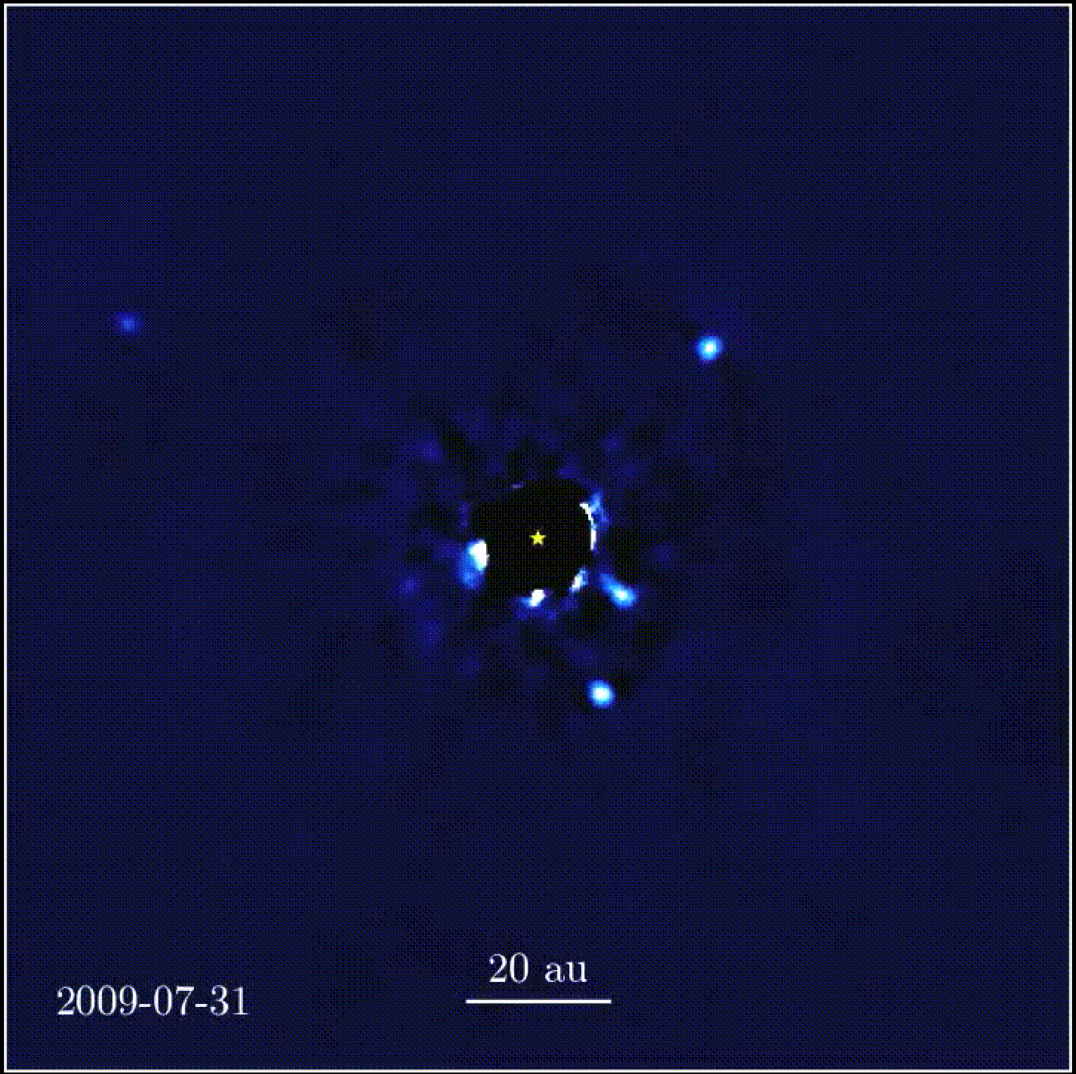
Orion

Direct Imaging

- Very difficult
  - Stars are very bright
  - Planets produce/reflect very little light by comparison
  - Planets often appear extremely close to the parent stars and are lost in the glare

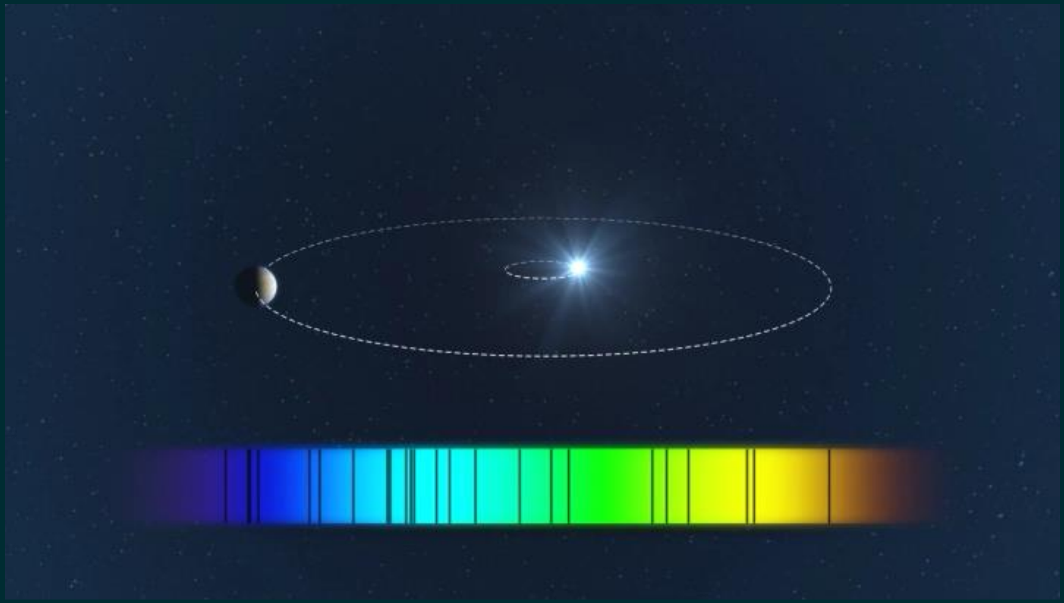


HR 8799 Directly-Imaged Planets are Now Being Probed



Credit: J. Wang et al.

Concept - Common Center of Mass



Credit: ESO/L. Calcada

- All gravitationally bound objects orbit a common center of mass.
- The more massive the object, the smaller its orbit and the slower it moves.

Astrometric Method

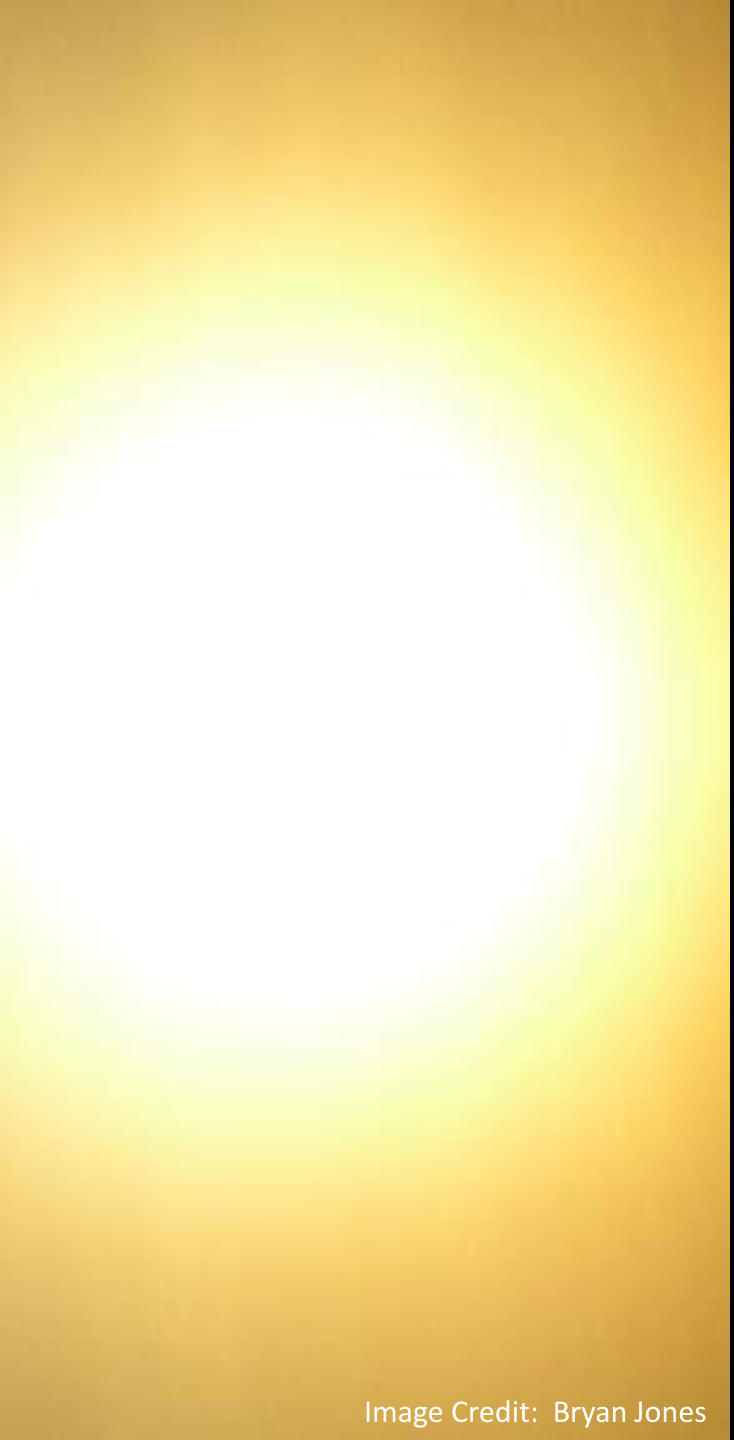
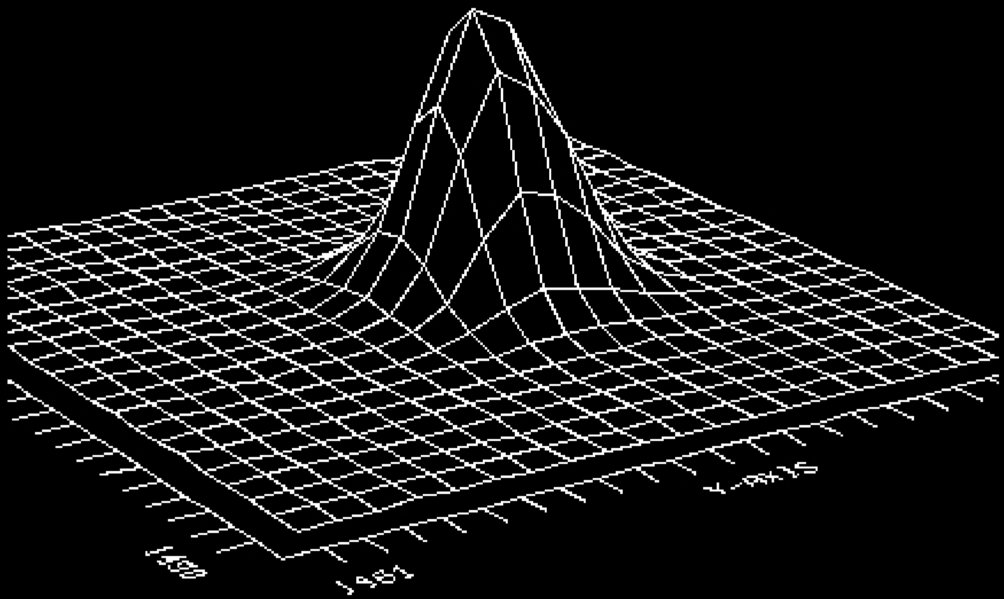


Image Credit: Bryan Jones

- As planet orbits the star, both revolve around a center of mass.
- Basic idea - watch for a star wobble.

Astrometric Method Limitations

- Wobbles are extremely small.
- Must detect movement against background stars by looking at PSF.
- Gaia mission will likely detect this.



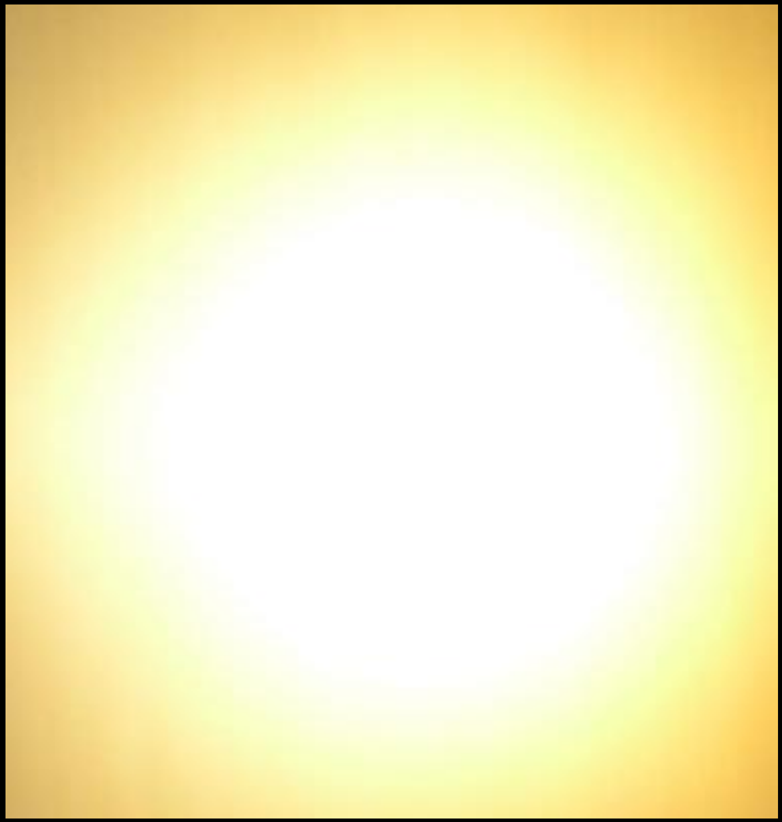
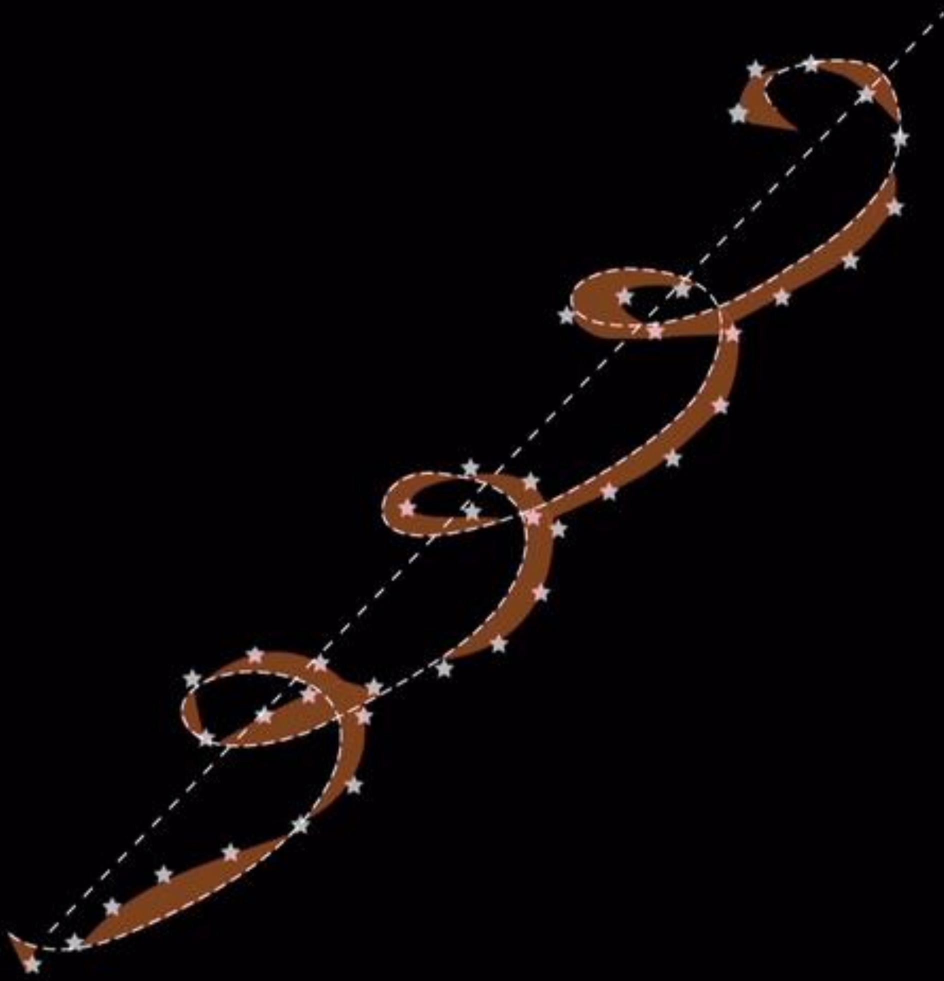
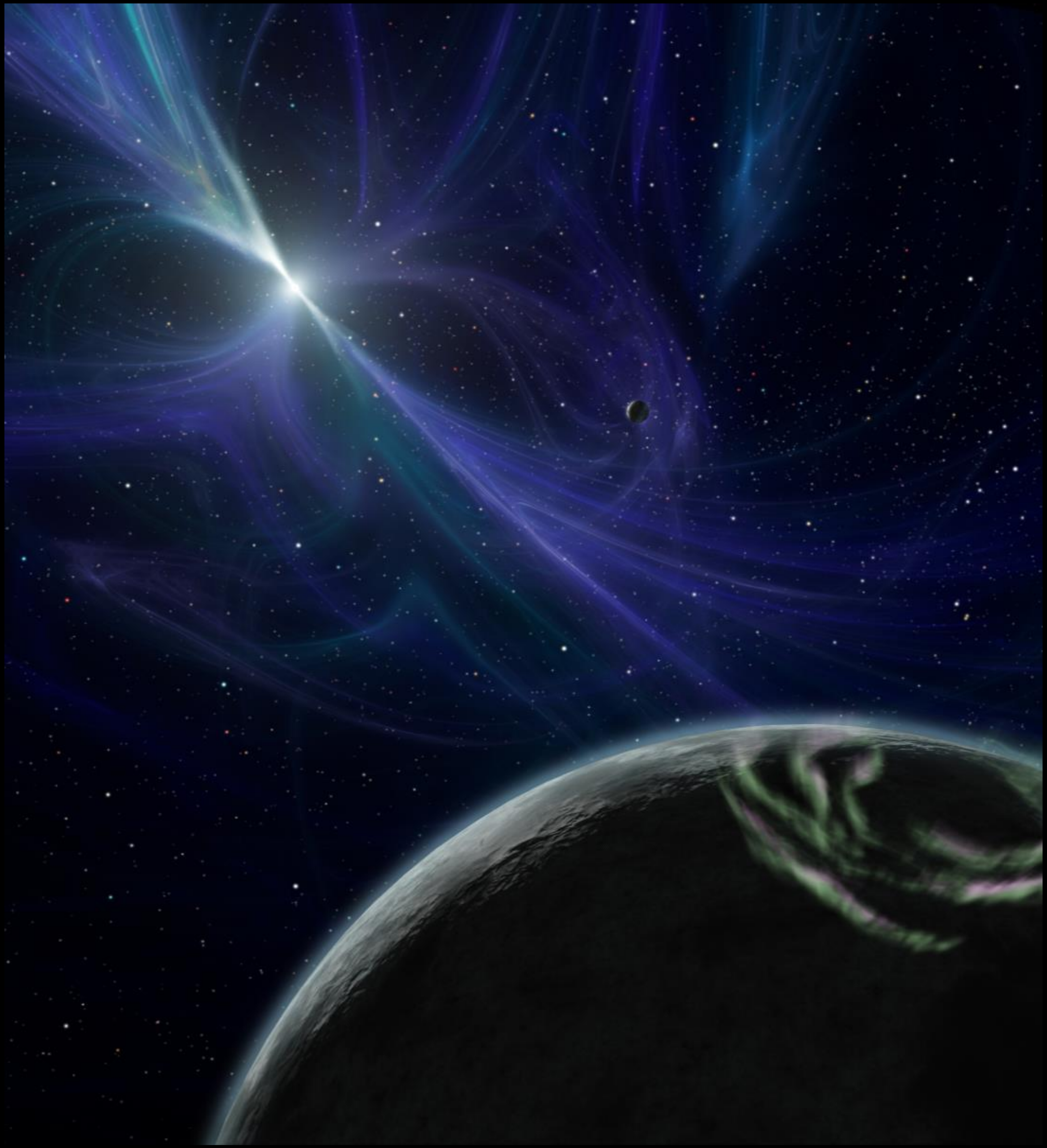


Image Credit: Bryan Jones

Gaia Finding Exoplanets



Credit: ESA



Pulsar Timing

-

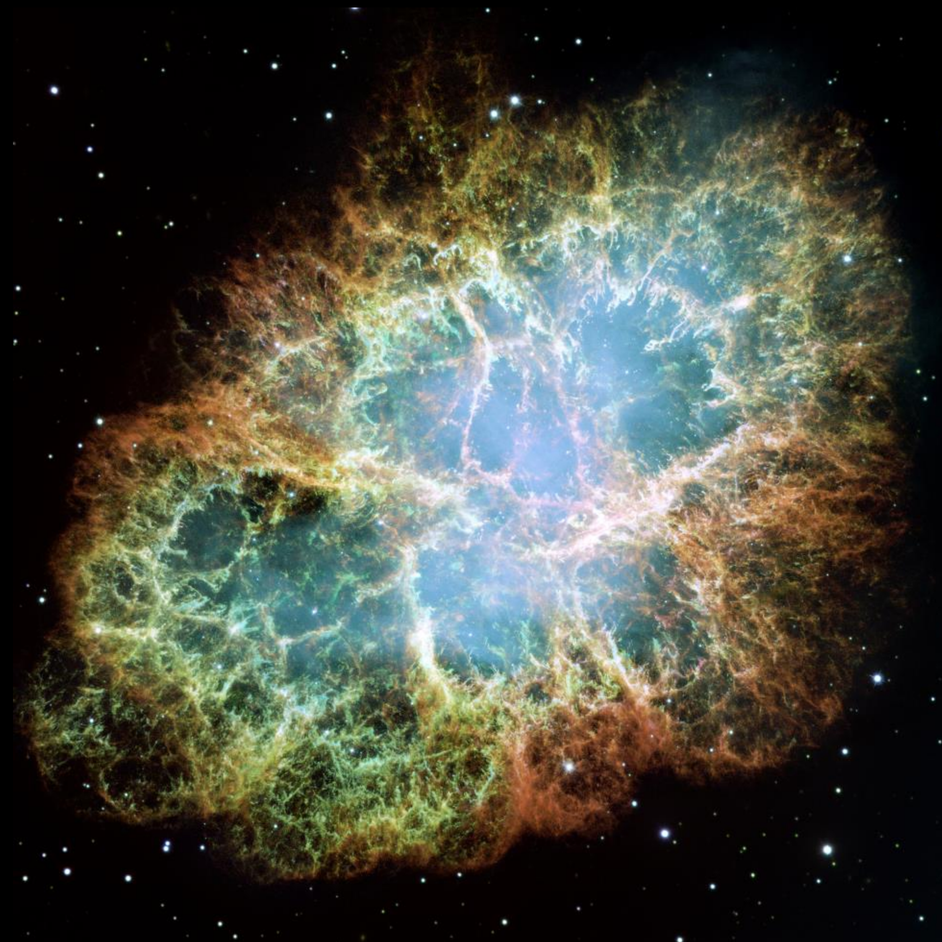
First Exoplanet Detection

Credit: NASA/JPL-Caltech/R. Hurt (SSC)

Pulsars

Credit: Institute of Astronomy, University of Cambridge

The Crab Nebula

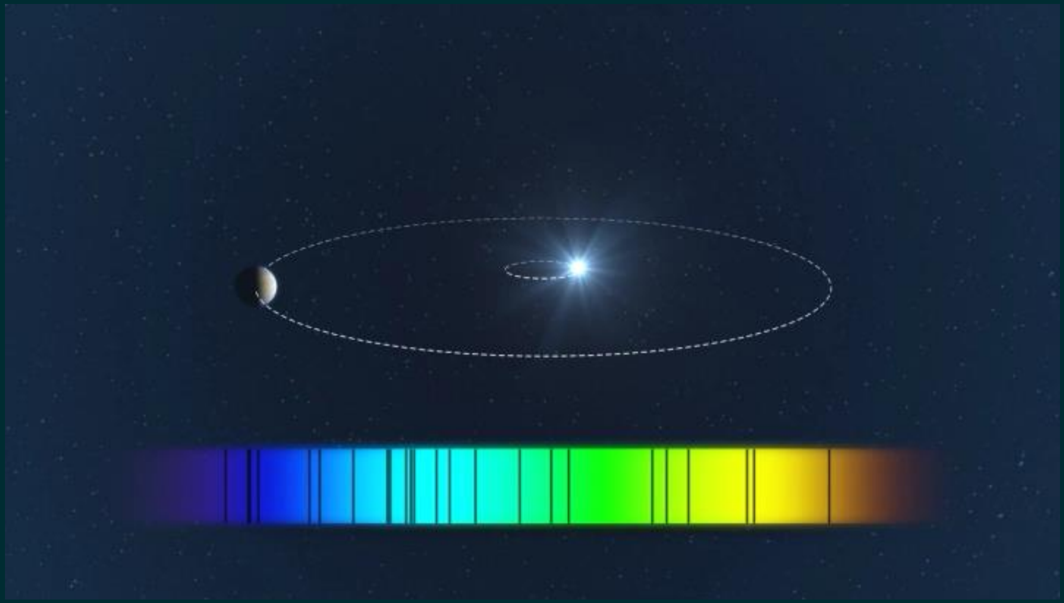


Credit: NASA, ESA, J. Hester and A. Loll (Arizona State University)

Pulsar Planet Detection

Simulation

Spectroscopic Radial Velocity Method

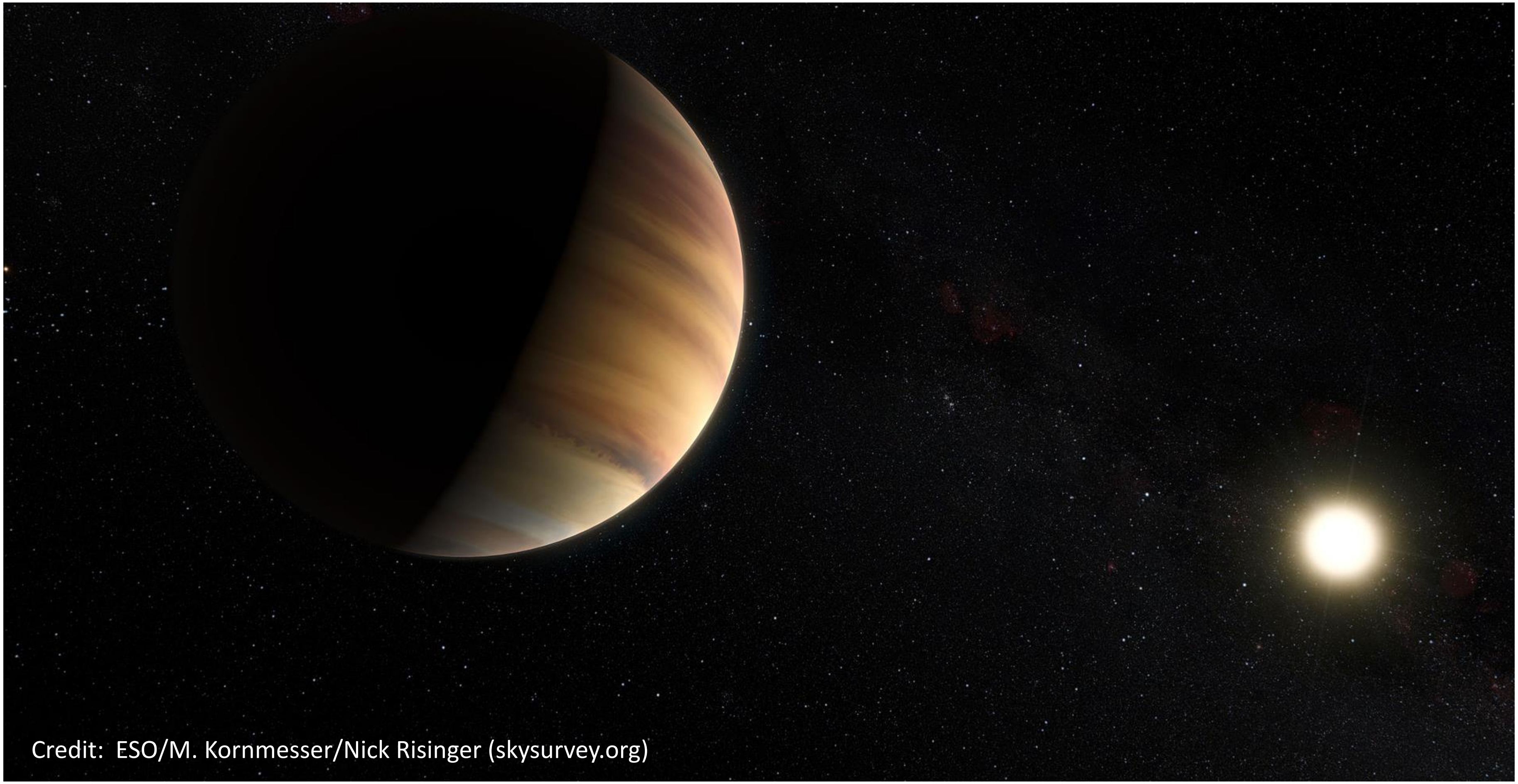


Credit: ESO/L. Calcada

- Observe a star, break up its light into a spectrum, and look for periodic line shifts

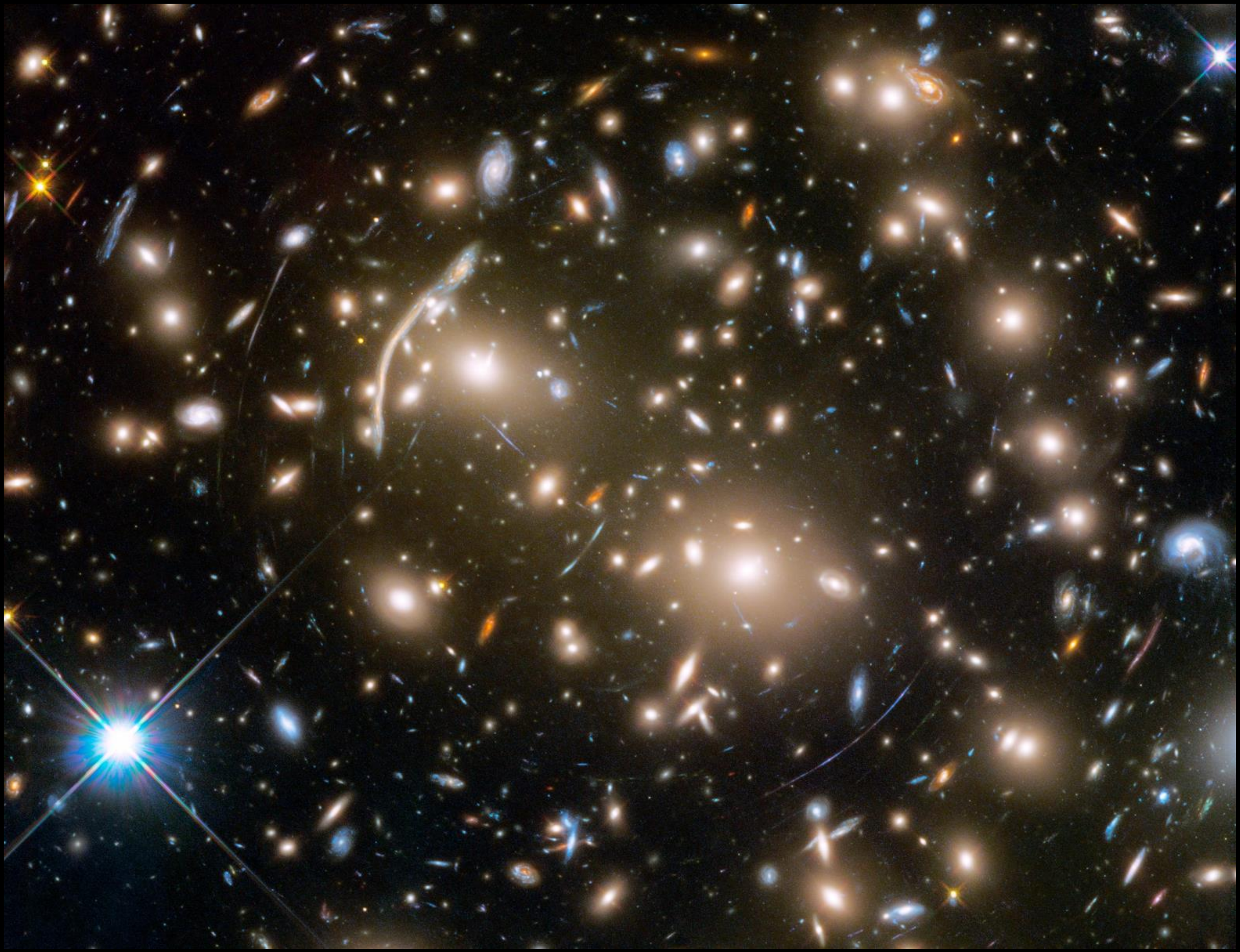
Radial Velocity Detection

Simulation



51 Pegasi b

Gravitational Lensing



Credit: NASA, ESA, and J. Lotz and the HFF Team (STScI)

Gravitational Lensing by Galaxy Clusters

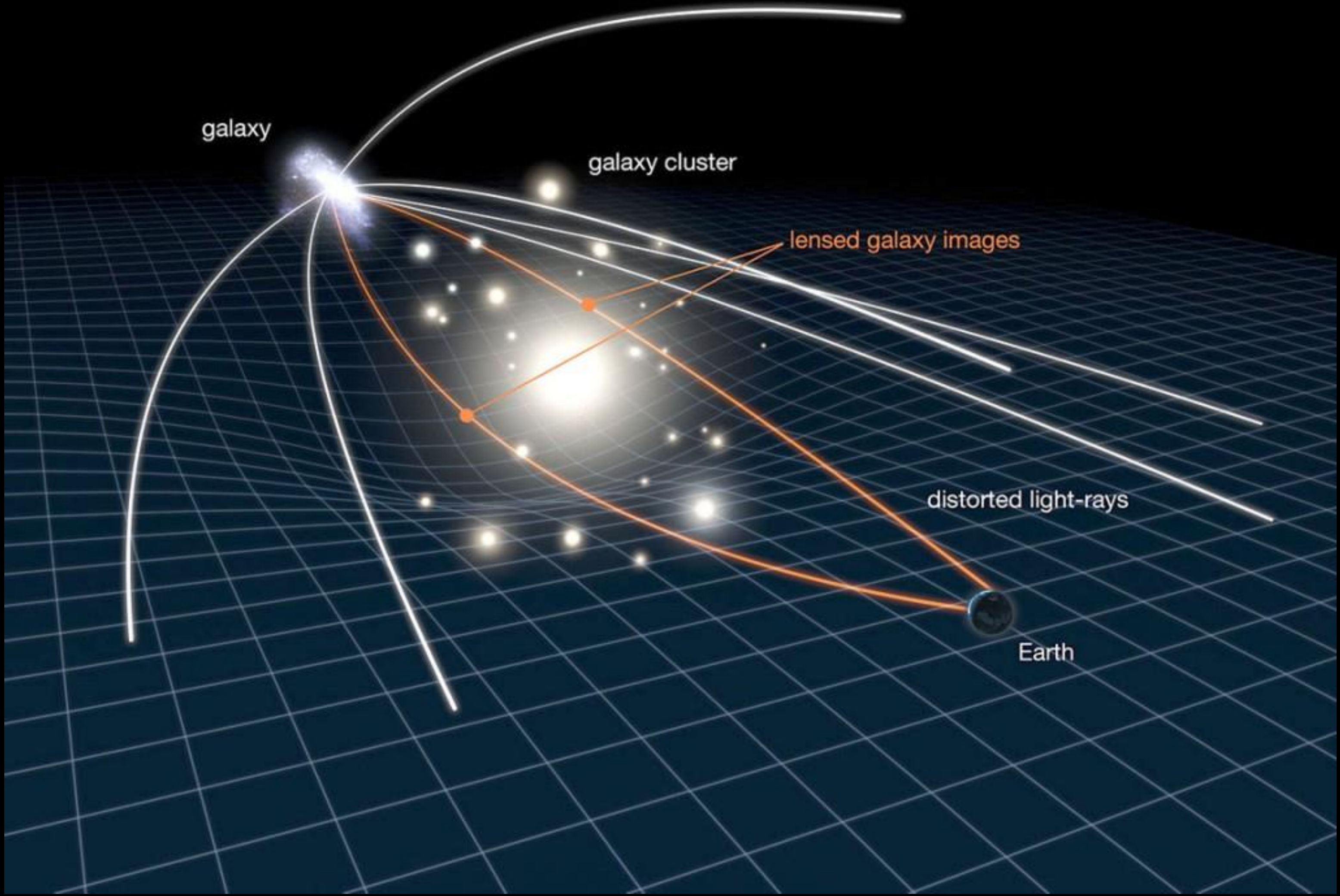
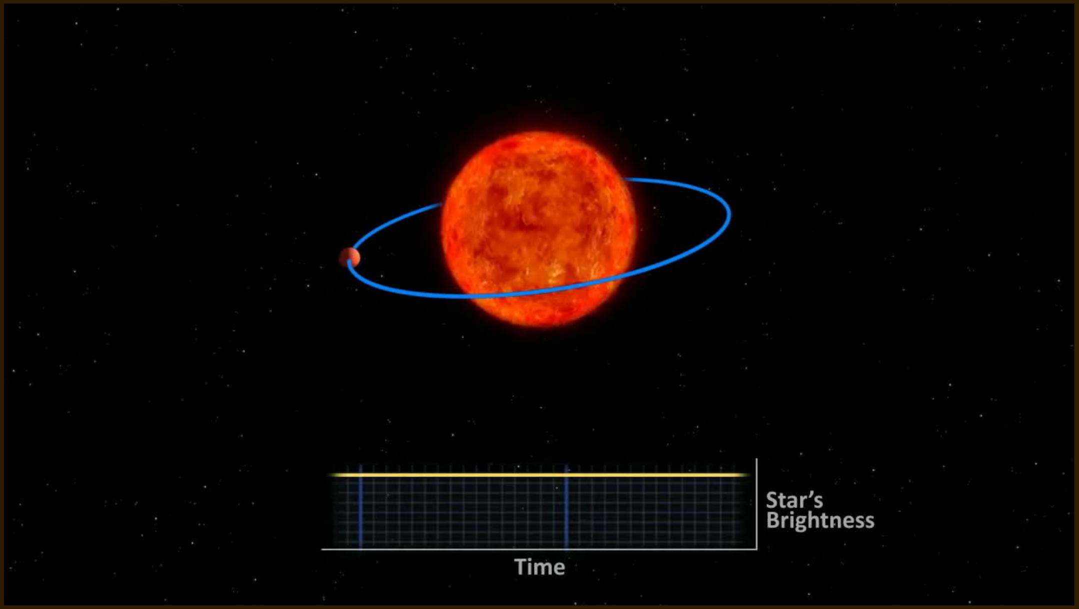


Image Credit: NASA/ESA

Gravitational Microlensing

Credit: NASA

Transit method



Credit: G. Bacon (STScI)

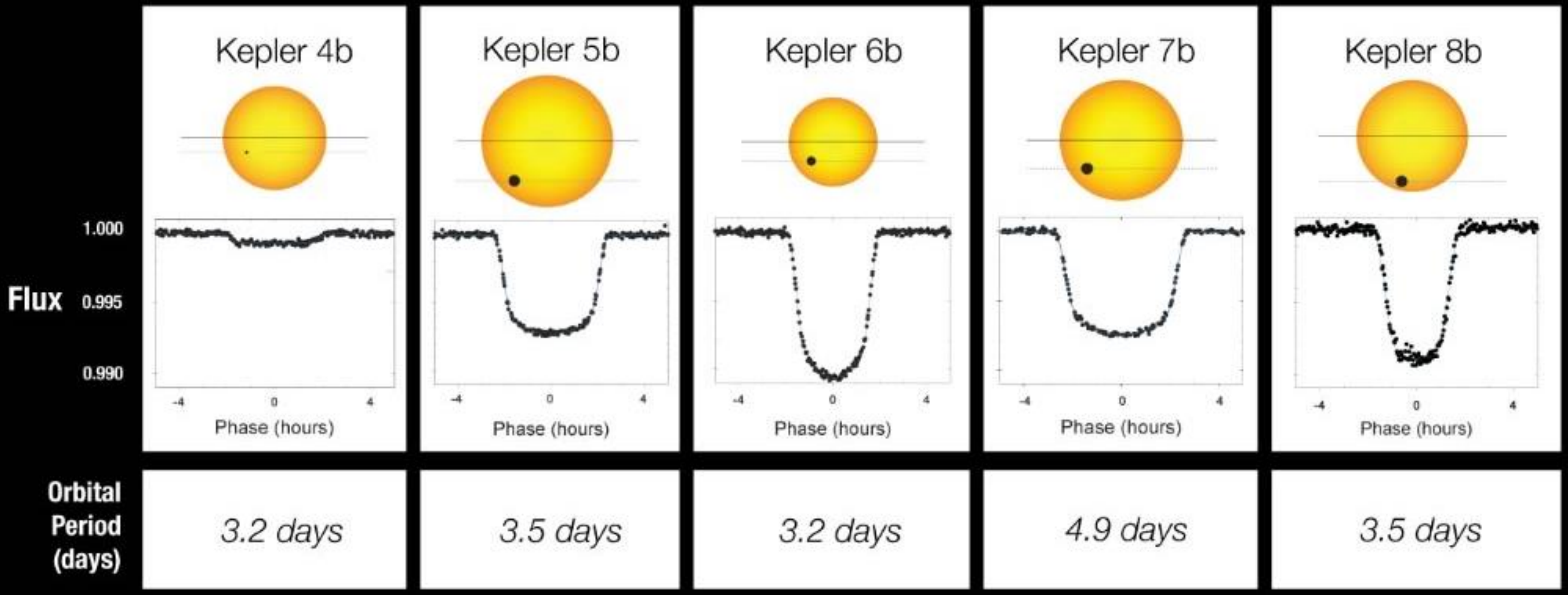
- The most lucrative detection method.
- Relies on a planet's orbital plane bring the planet between us and the parent star.
- Also dependent on the planet's distance from its star.

After Detection, What are Some Things That Can Be Learned?

- Period
  - After observing multiple transits of the star, the orbital period can be calculated.
  - After careful, repeated observations, predictions can be made for future transits.
  - Discrepancies between observed transits and predicted times can hint at the presence of other planets.

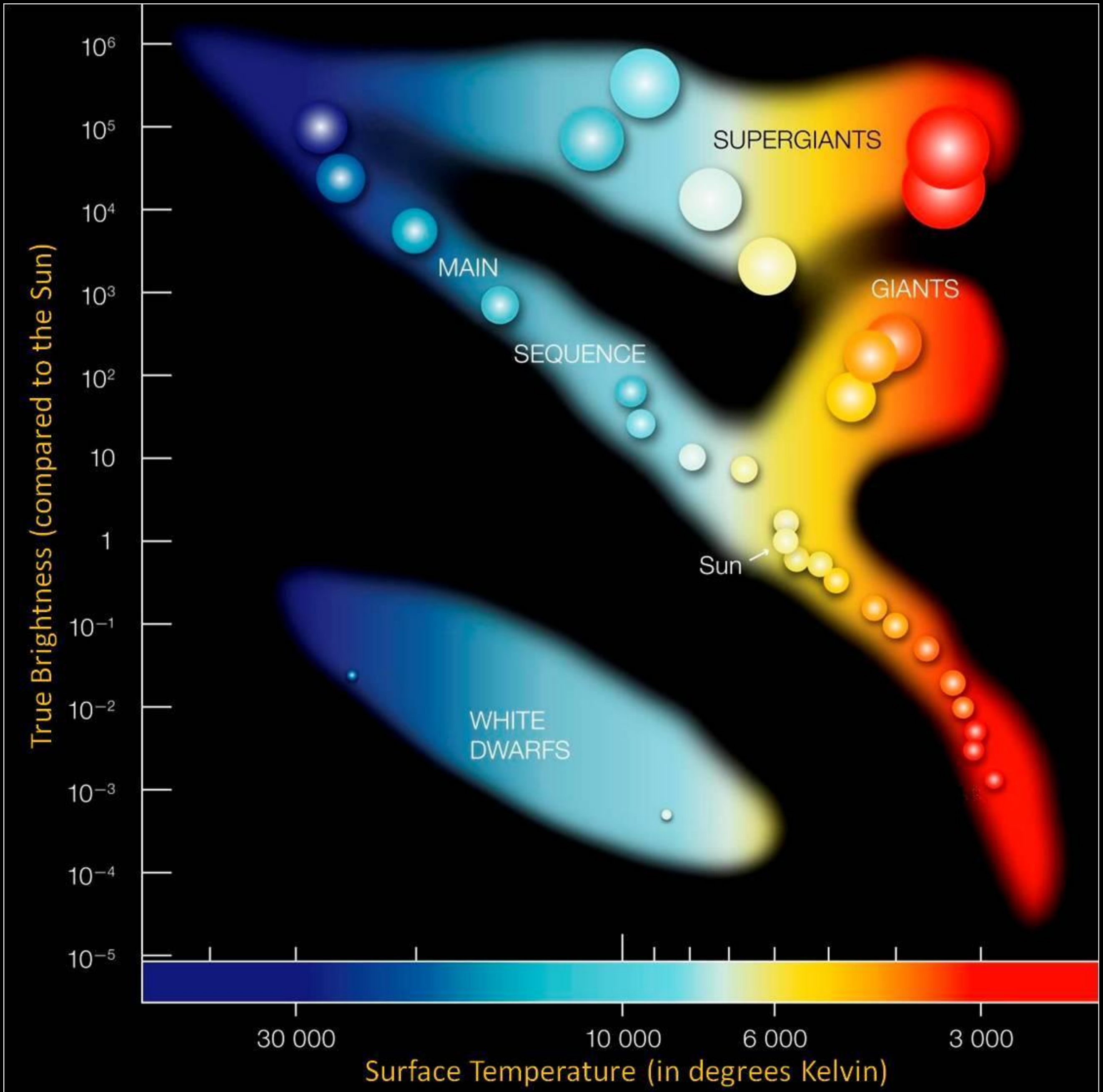
What are Some Things That Can Be Learned?

- Planet Radius
  - Change in observed flux depends on $(R_P/R_*)^2$
  - Stellar radius depends on mass and spectral classification (temperature)



Credit: NASA

Hertzsprung-Russell (HR) Diagram



Credit: ESO

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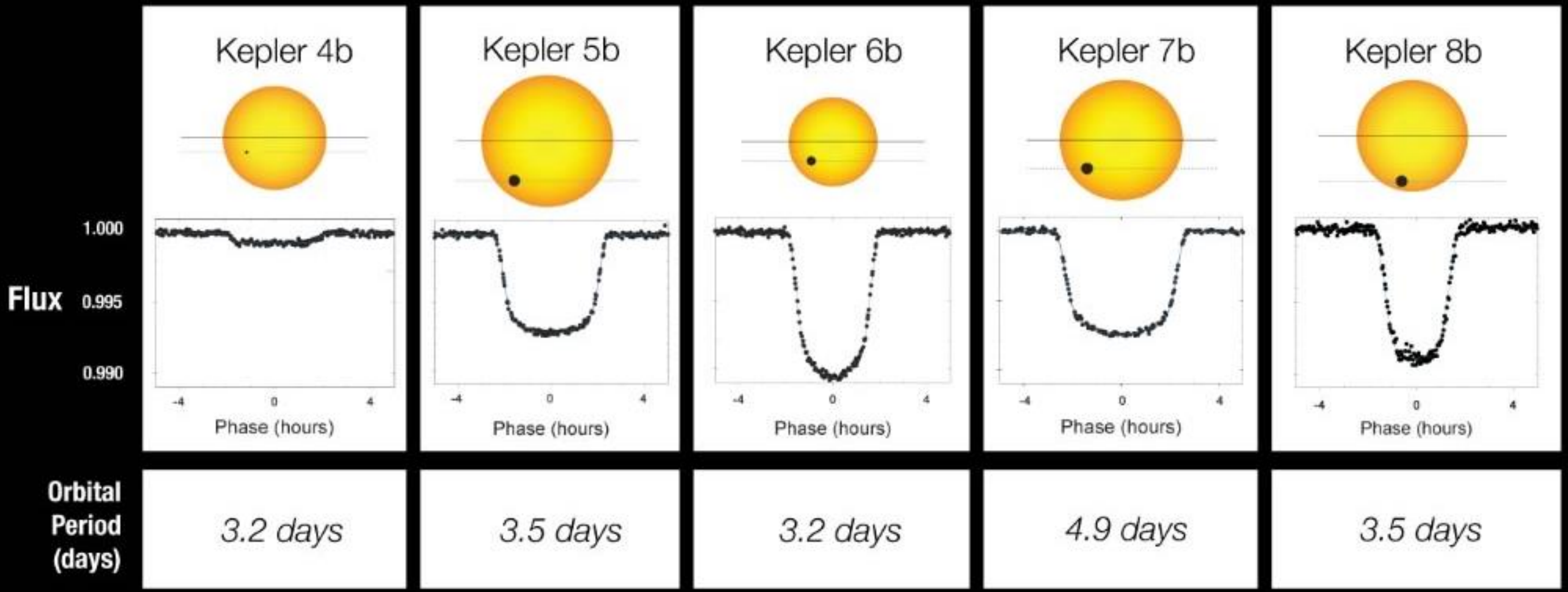
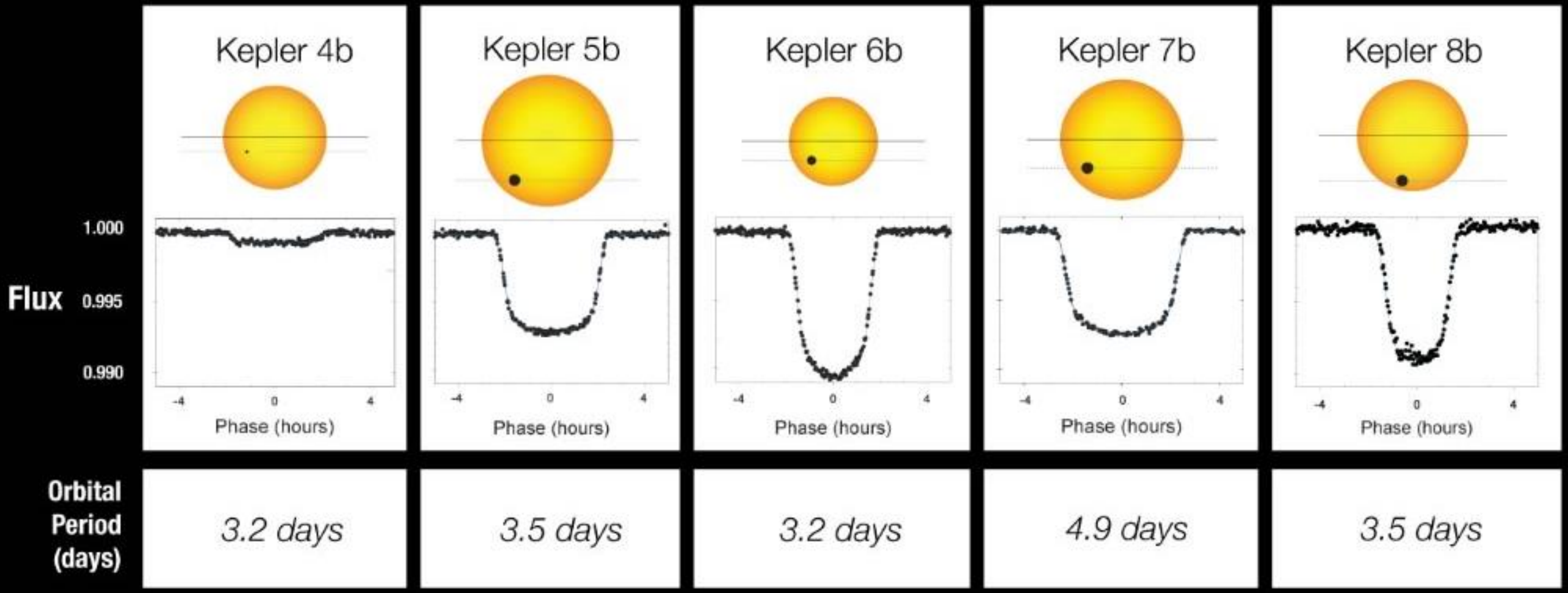


Credit: NASA

What are Some Things That Can Be Learned?

- Planet Inclination
  - Inclination determines how far from the center of the planet the transit will occur.
  - Inclination is characterized by comparing total transit time with the duration of ingress and egress.



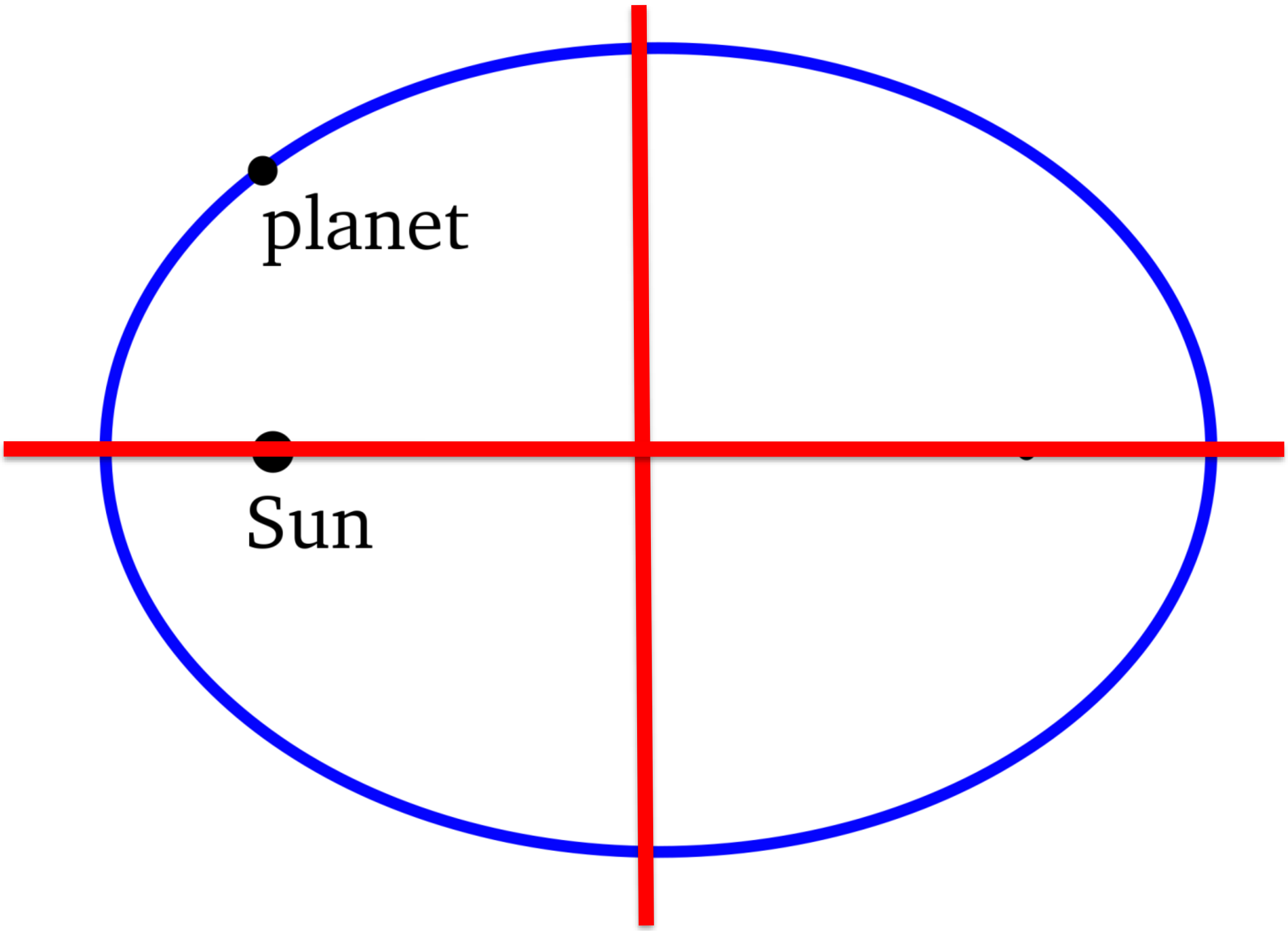
Credit: NASA

After Detection, What are Some Things That Can Be Learned?

- Semimajor axis
  - Careful observations of the star's spectrum and other parameters can yield a star's mass.
  - Using Kepler's Third Law, we can get the orbital radius of the planet:

$$p^2 = \frac{4\pi^2}{G(M_* + M_p)} a^3$$

Semimajor Axis



After Detection, What are Some Things That Can Be Learned?

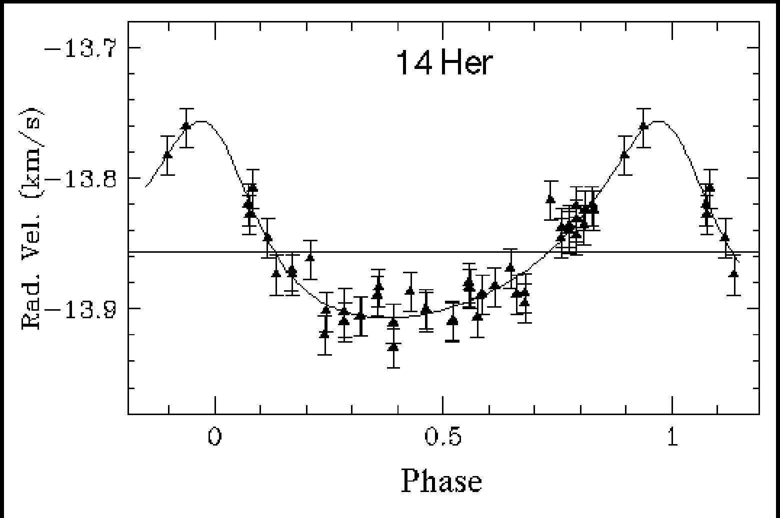
- Planet Mass
  - With a transiting planet, inclination is near 90°.
  - Observing a radial velocity plot of the star, you will get the mass of the planet as a function of mass, inclination, and semimajor axis.
  - By characterizing the inclination and radial velocity plot, a planet mass can be determined.
  - Solar System Wobble

After Detection, What are Some Things That Can Be Learned?

- Planet Density
  - Planet mass and radius have already been determined from previous results
  - Planet mass divided by a sphere with radius of the planet gives an average density.
  - Average density suggests composition (rocky, gaseous, etc.)

After Detection, What are Some Things That Can Be Learned?

- Planet Orbit Eccentricity
  - Shape of radial velocity plot reveals the eccentricity of the planet's orbit.



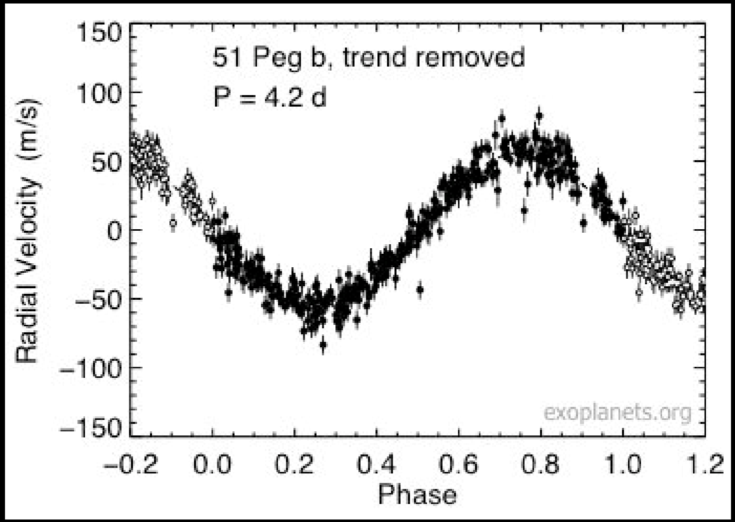


Image Source: tess.mit.edu

KELT-South

KELT-North/South

Located in South Africa

Consists of

Paramount ME

Apogee Alta U16 CCD Camera

Mamiya 80mm f/1.9 Lens with 42mm aperture

KELT-South

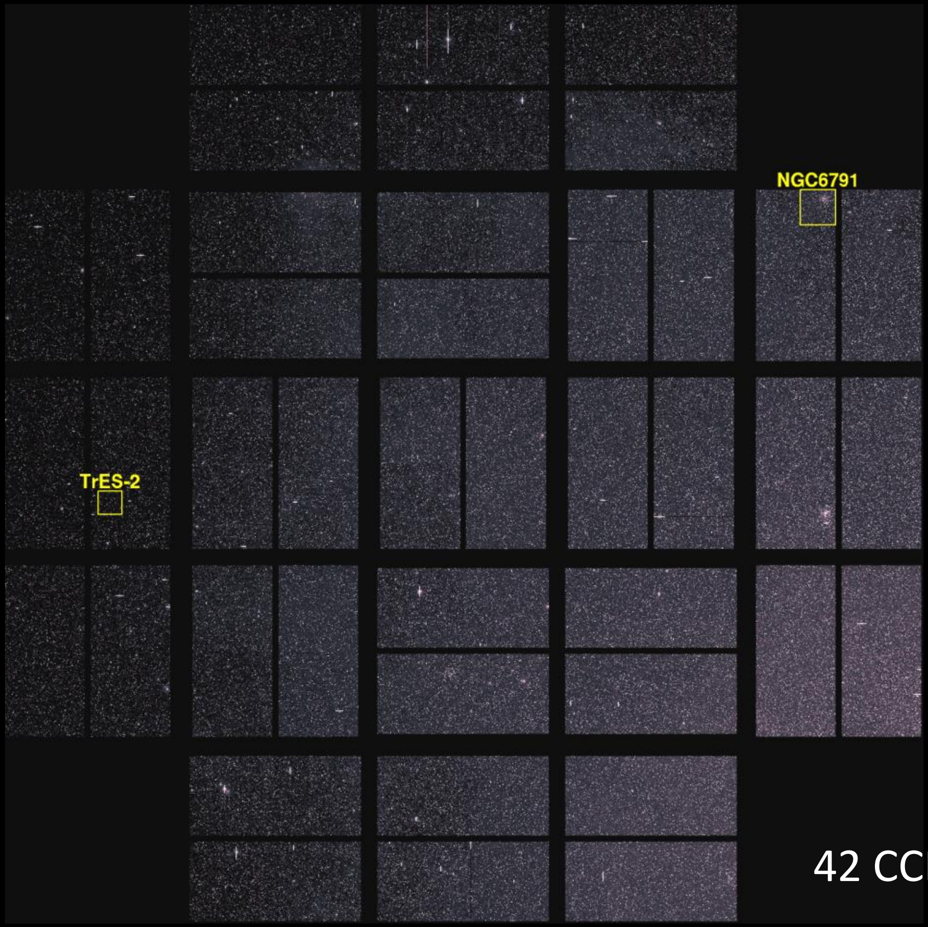
A 26° x 26° (676° square degrees) FOV gets you a lot of sky!

Kepler Mission

- 115 Square degrees FOV
- Constantly watched ~100,000 stars
- Used the transit method to detect planet candidates
- Operated for approximately four years

Credit: NASA

Kepler Mission

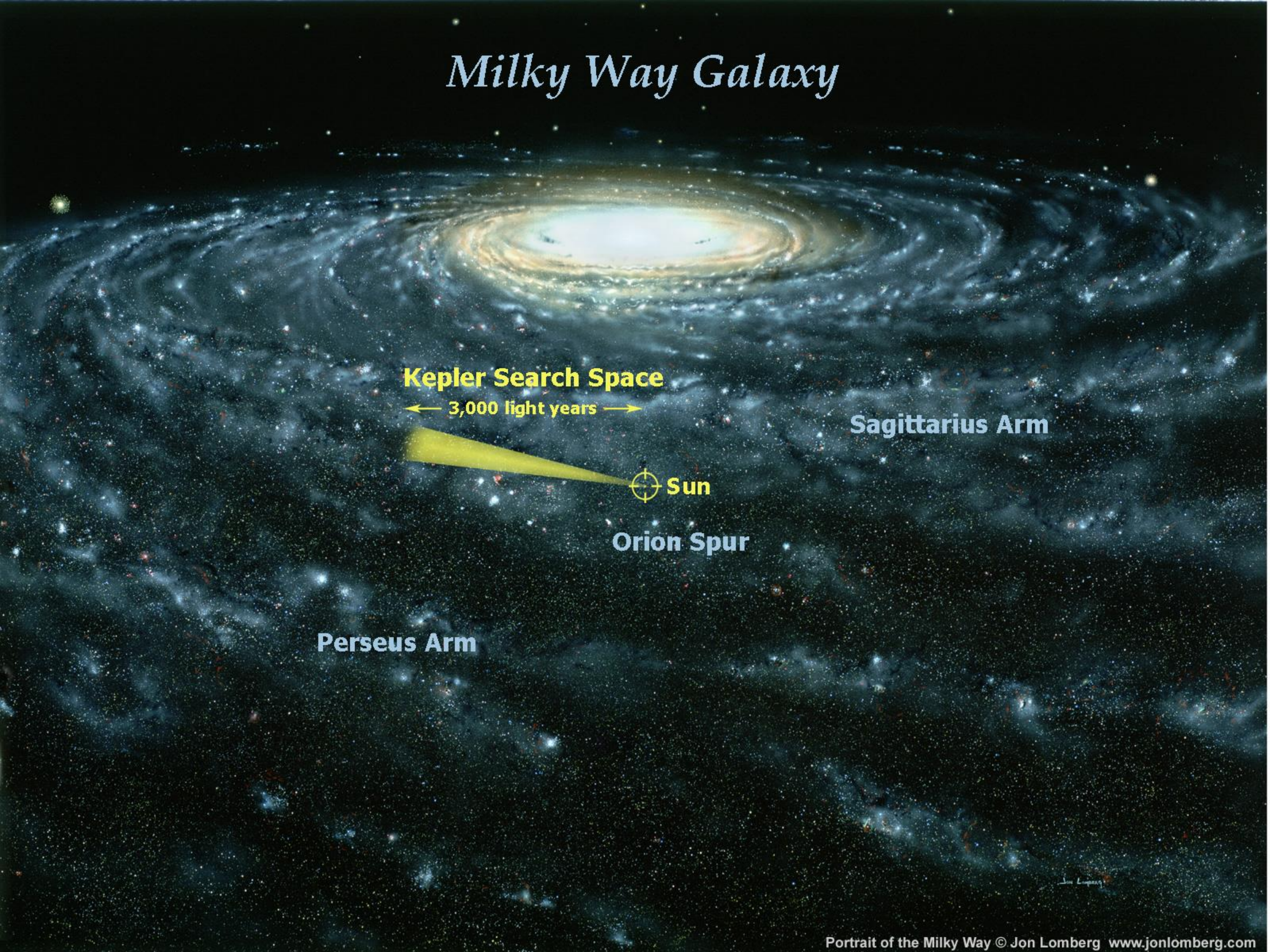


42 CCDs – 95 million pixels

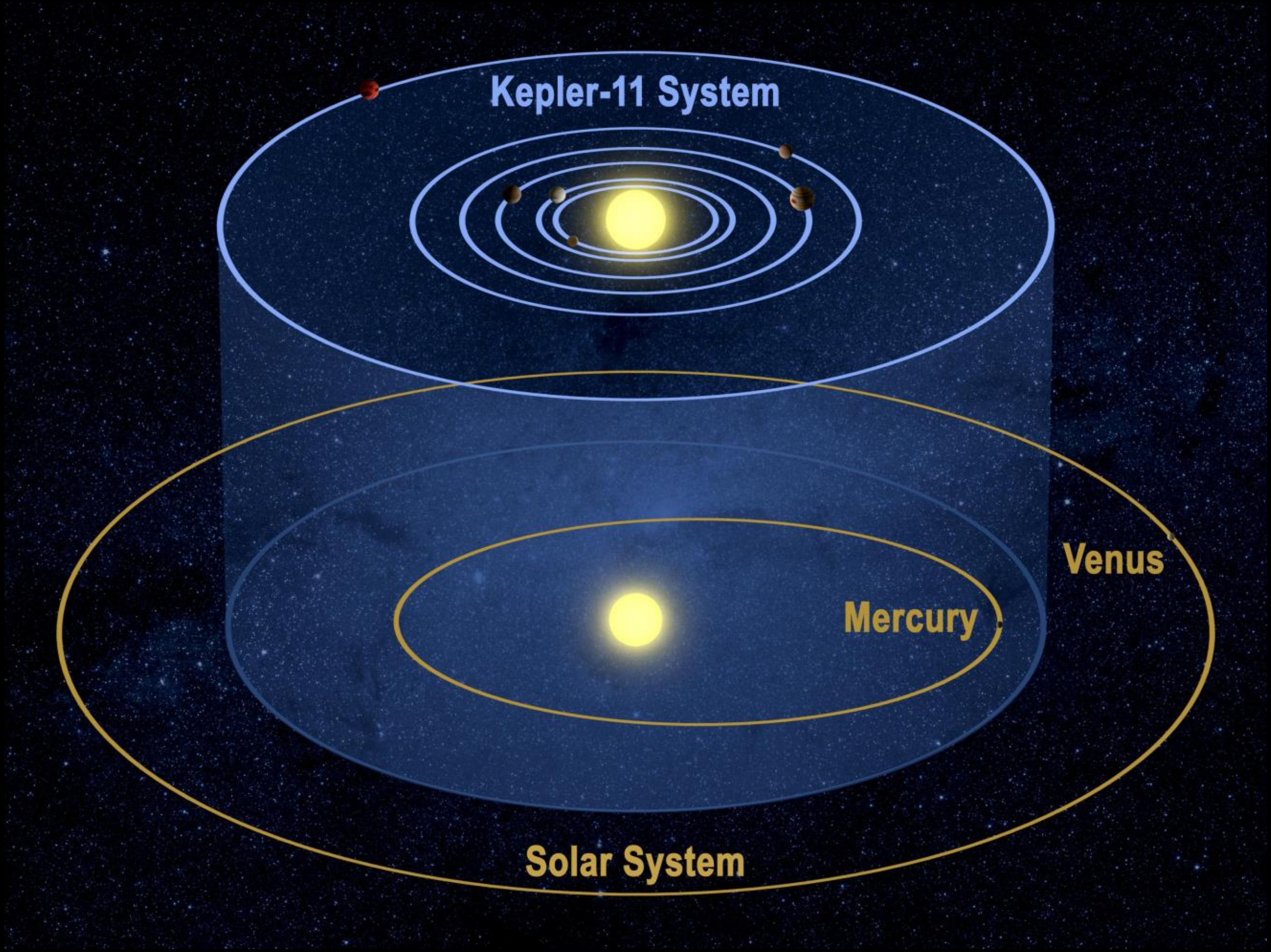
CCDs are read out every six seconds for 30 minutes

Only a certain set of pixel information is received

Credit: NASA/Kepler Mission


Milky Way Galaxy
Kepler Search Space
3,000 light years
Sagittarius Arm
Sun
Orion Spur
Perseus Arm
Portrait of the Milky Way © Jon Lomberg www.jonlomberg.com

An example of a confirmed system



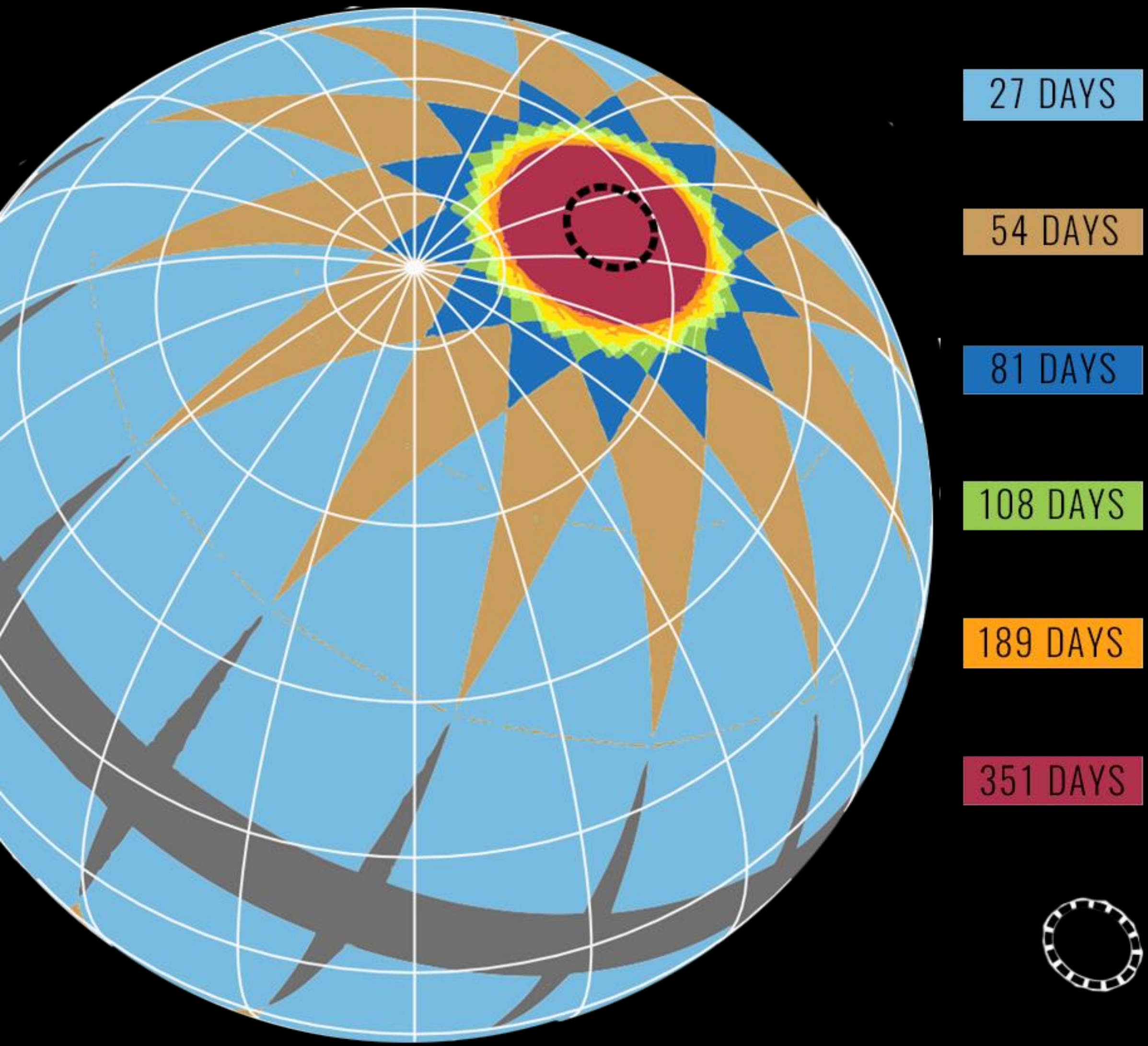
Credit: NASA/Tim Pyle

TESS

- Transiting Exoplanet Survey Satellite
- Launched in April 2018
- Two-year mission to observe 200,000 stars

Credit: NASA

TESS – Observing Pattern



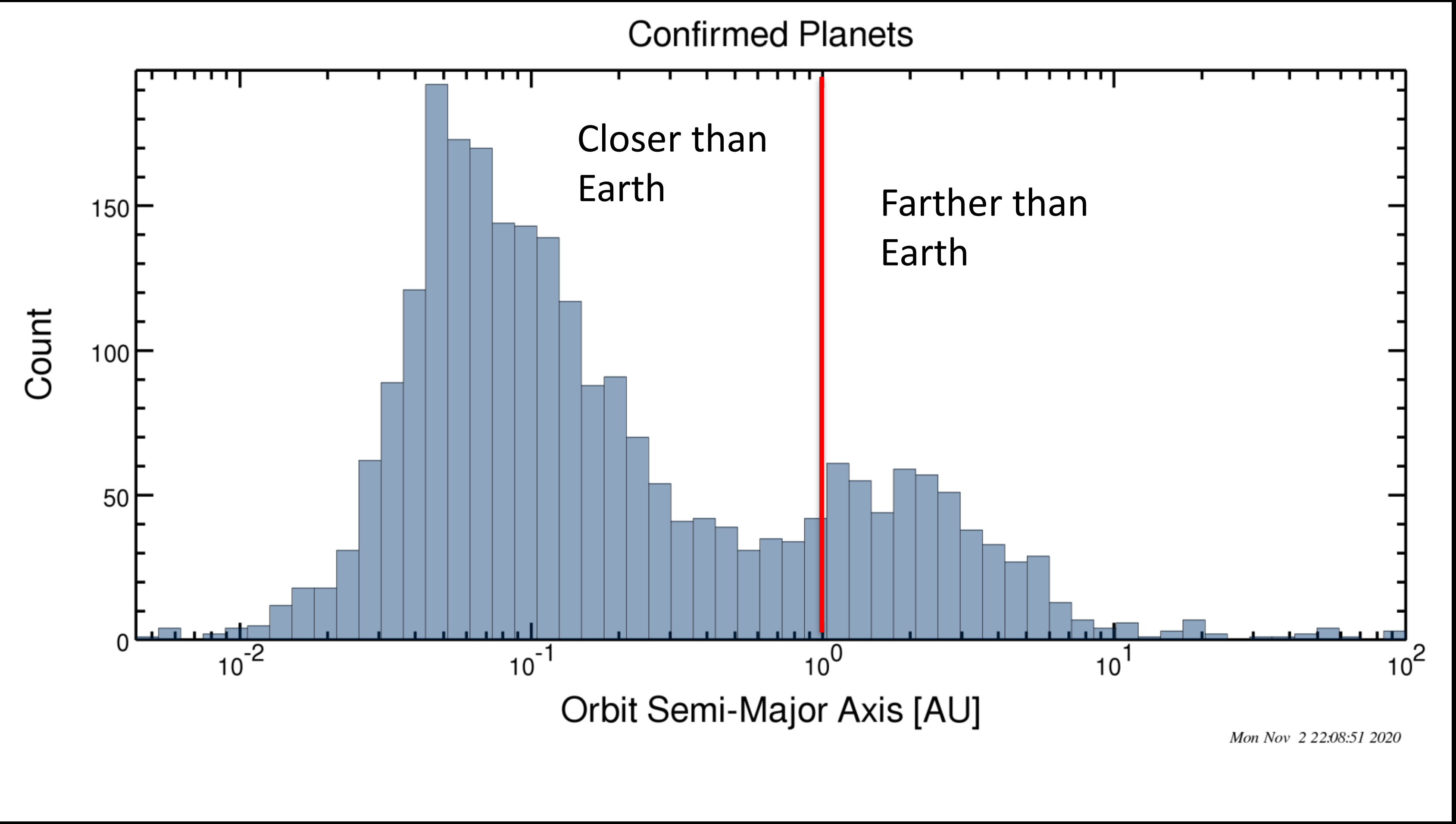
- Transiting Exoplanet Survey Satellite
- Sensitive to planets with orbital periods of less than 13 days.
- Cadence every two minutes
- Overlapping regions will be sensitive to planets with larger periods

SuperWASP - Wide Angle Search for Planets

- 8 Camera setup - 61° square FOV per camera
- Numerous confirmed detections

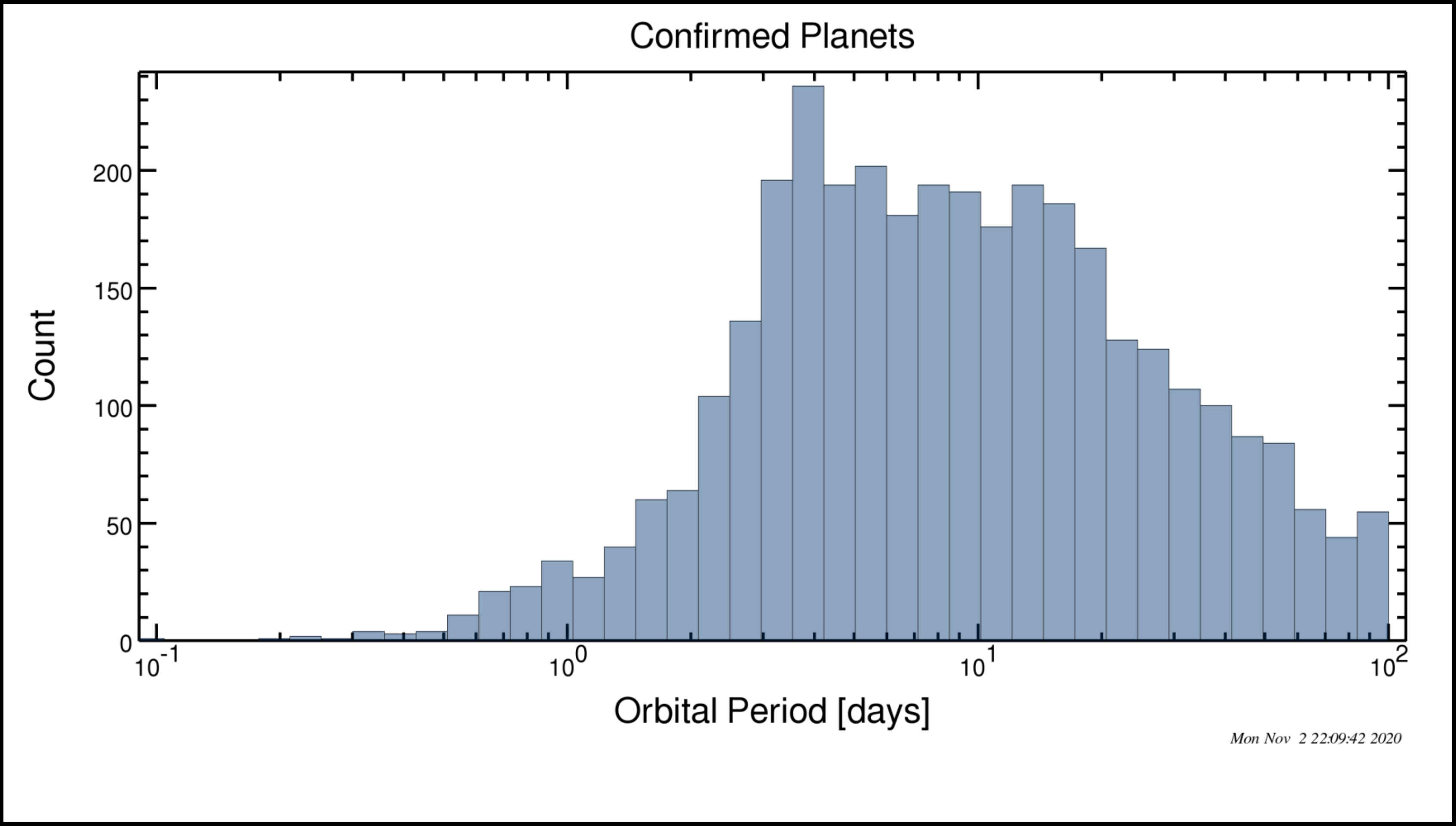
Credit: David Anderson

Results



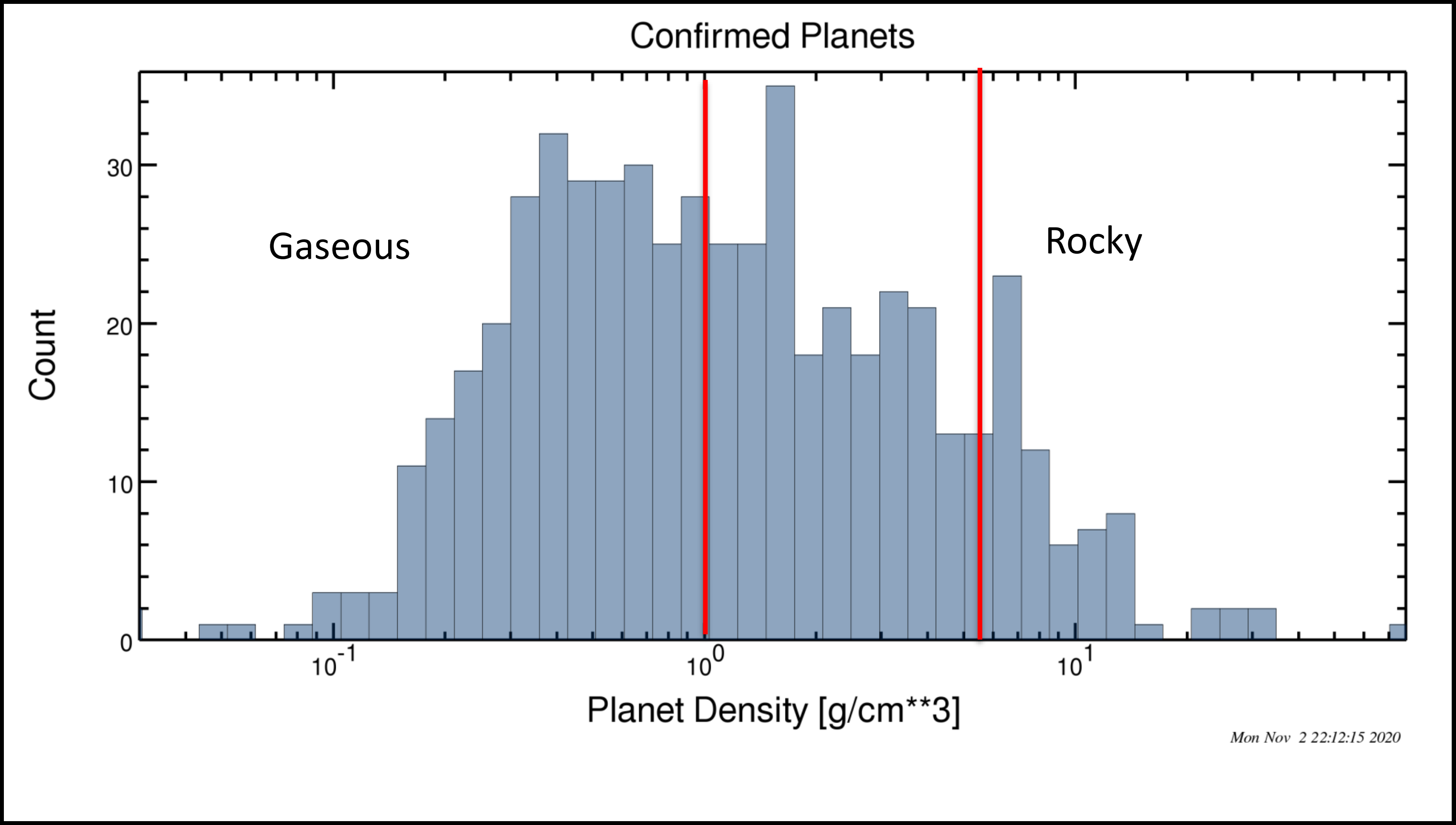
Confirmed Planets
Count
150
100
50
0
Closer than Earth
Farther than Earth
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Orbit Semi-Major Axis [AU]
Mon Nov 2 22:08:51 2020

Results

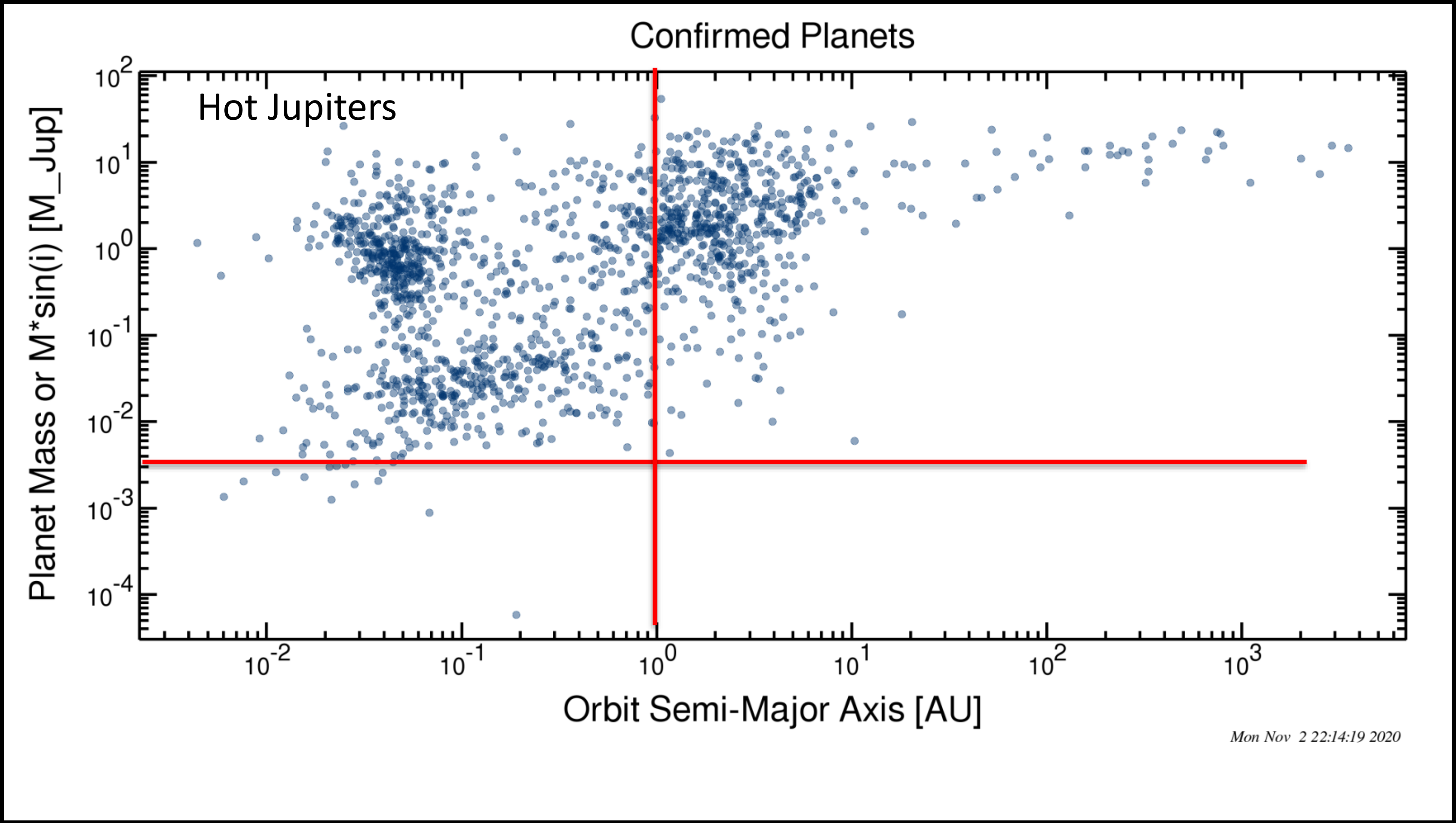


Confirmed Planets
Count
200
150
100
50
0
10^{-1}
10^{0}
10^{1}
10^{2}
Orbital Period [days]
Mon Nov 2 22:09:42 2020

Results

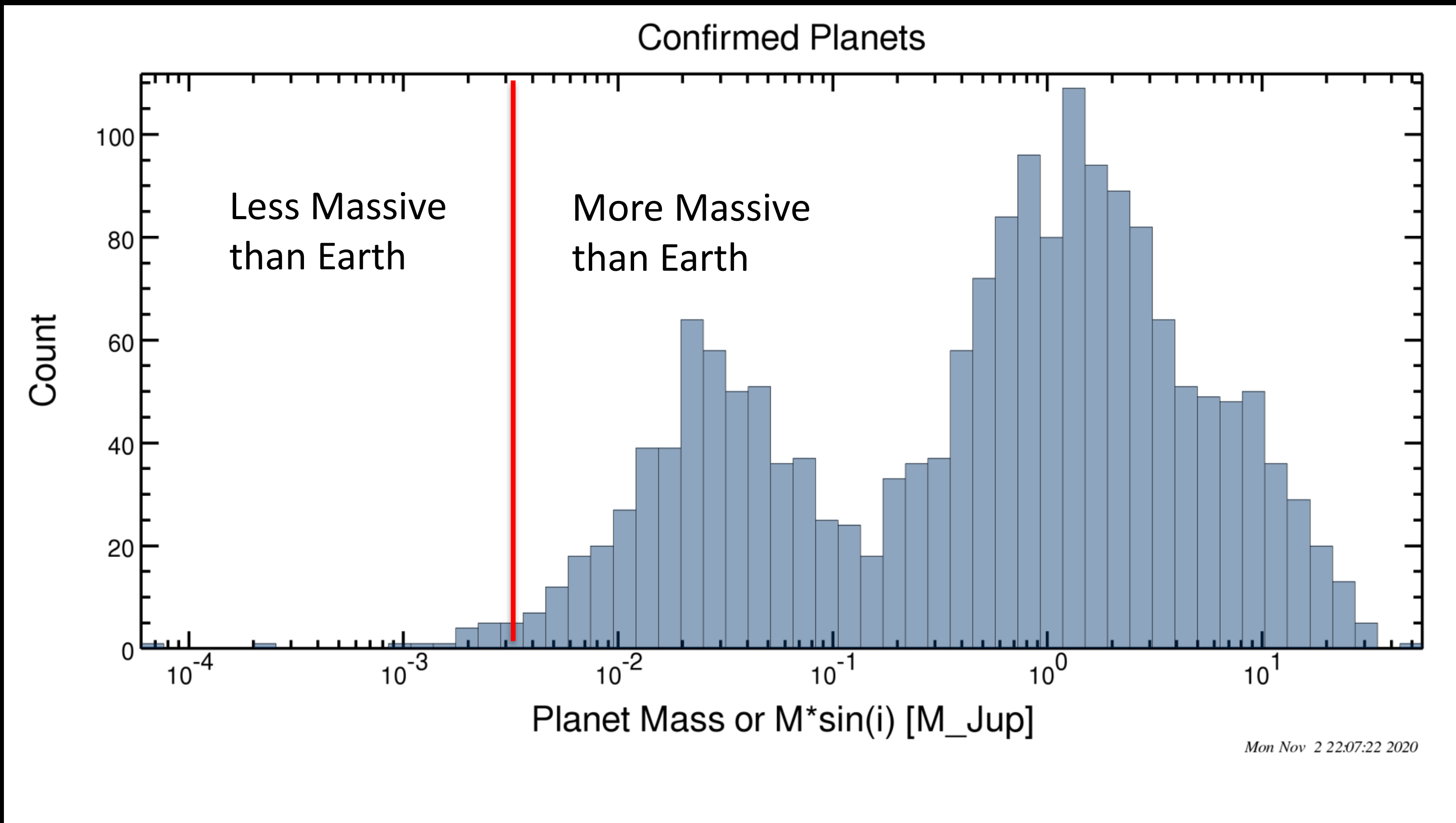

Confirmed Planets
Gaseous
Rocky
Count
30
20
10
0
10^{-1}
10^{0}
10^{1}
Planet Density [g/cm**3]
Mon Nov 2 22:12:15 2020

Results



Confirmed Planets
Hot Jupiters
Planet Mass or M*sin(i) [M_Jup]
Orbit Semi-Major Axis [AU]
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-2
10^-1
10^0
10^1
10^2
10^3
Mon Nov 2 22:14:19 2020

Results



Confirmed Planets
Less Massive than Earth
More Massive than Earth
Count
100
80
60
40
20
0
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
Planet Mass or M*sin(i) [M_Jup]
Mon Nov 2 22:07:22 2020