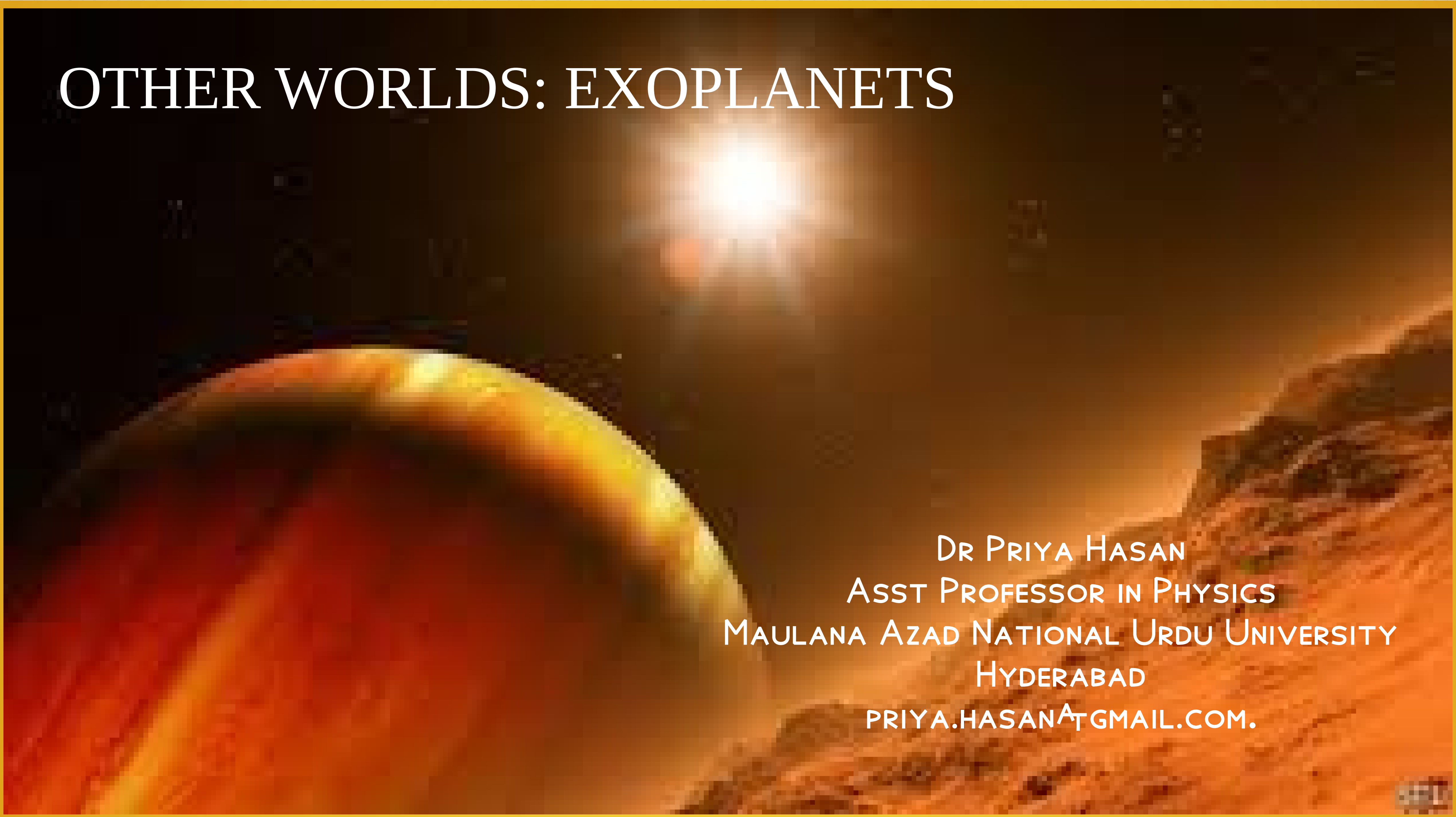

OTHER WORLDS: EXOPLANETS

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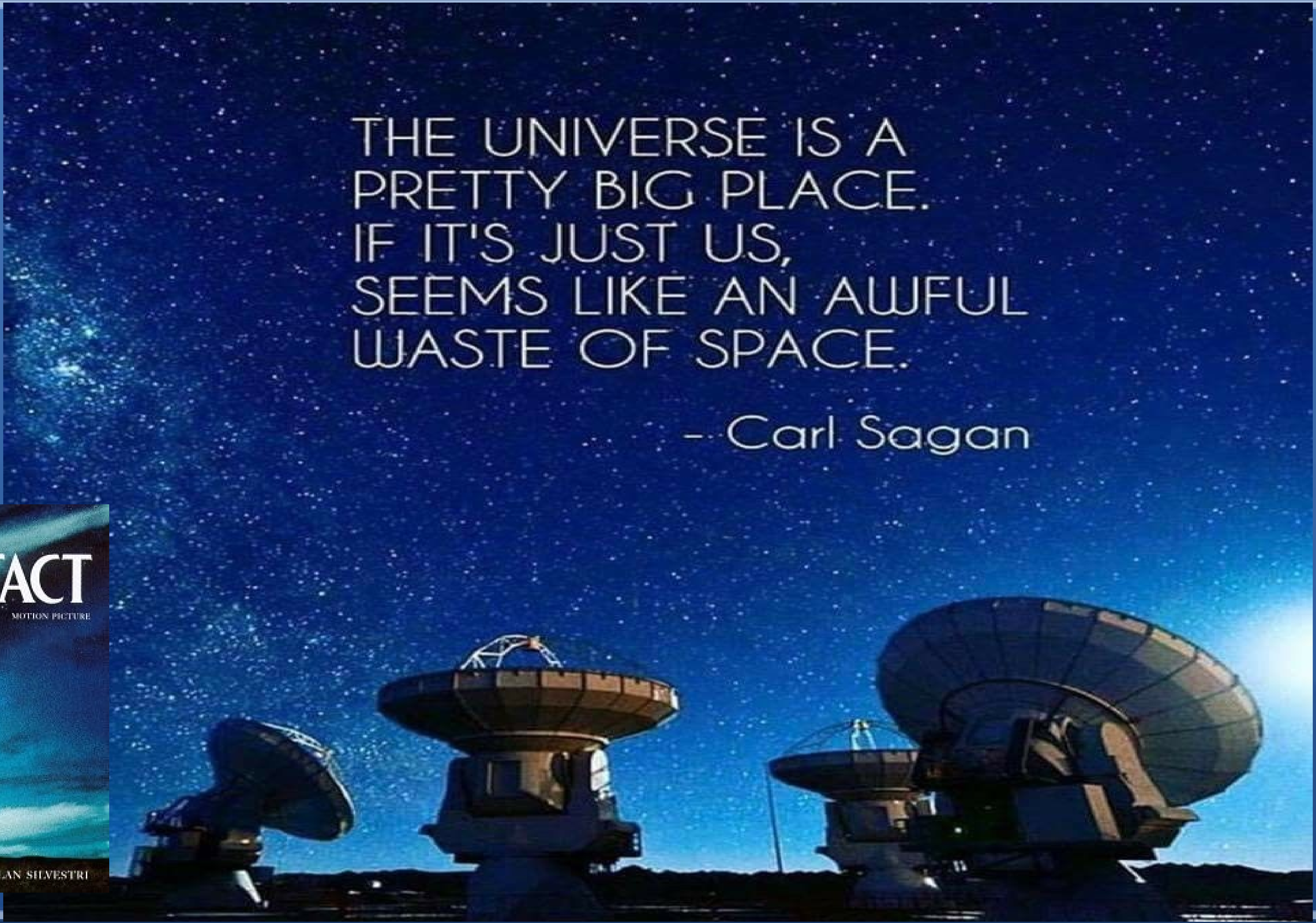
Asst Professor in Physics
Maulana Azad National Urdu University
Hyderabad
priya.hasanAtgmail.com.

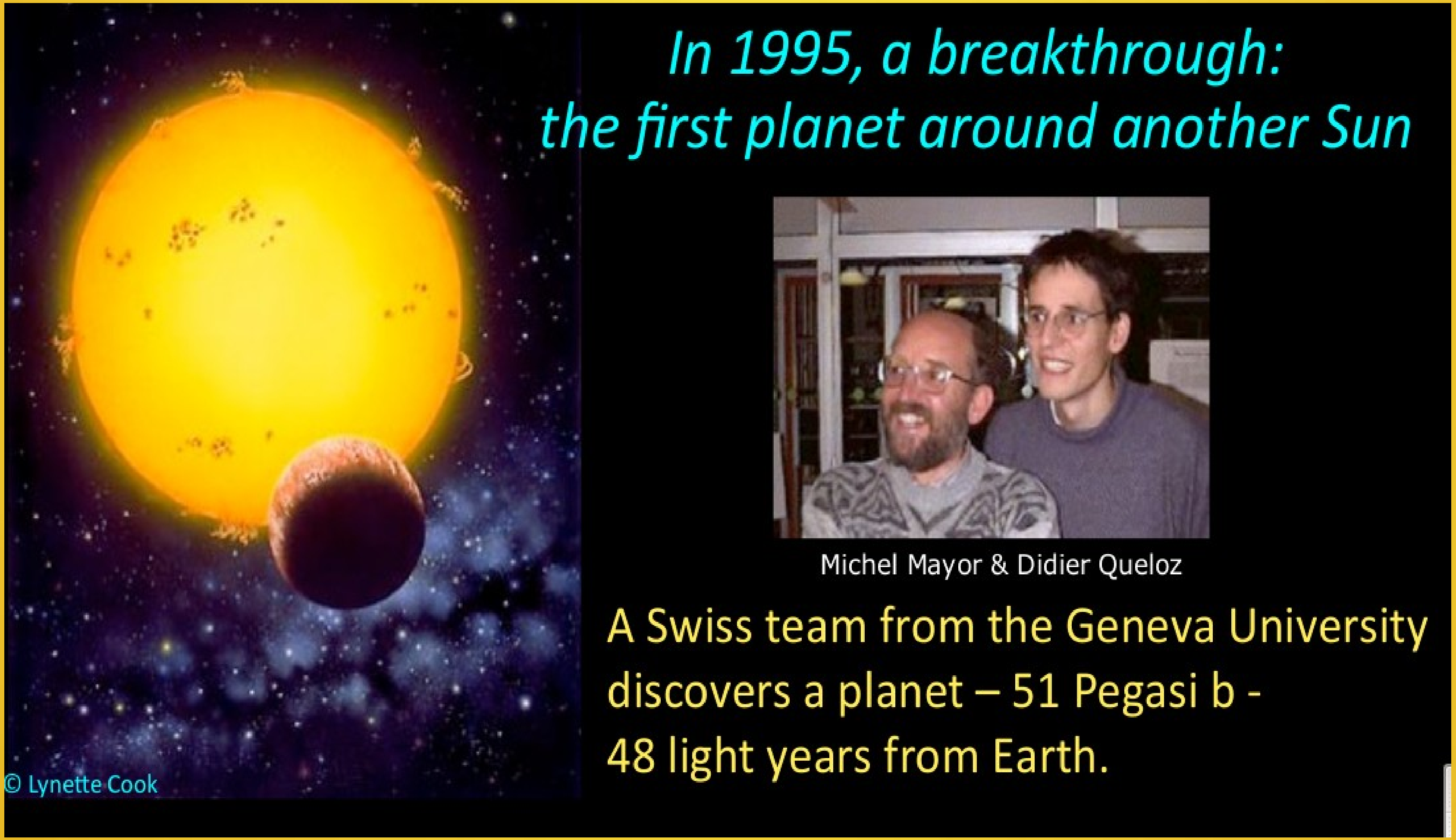
What is an exoplanet?

An exoplanet or an extrasolar planet is a planet outside the Solar System.


THE UNIVERSE IS A
PRETTY BIG PLACE.
IF IT'S JUST US,
SEEMS LIKE AN AWFUL
WASTE OF SPACE.
- Carl Sagan


MUSIC FROM THE
CONTACT
MOTION PICTURE
MUSIC BY ALAN SILVESTRI

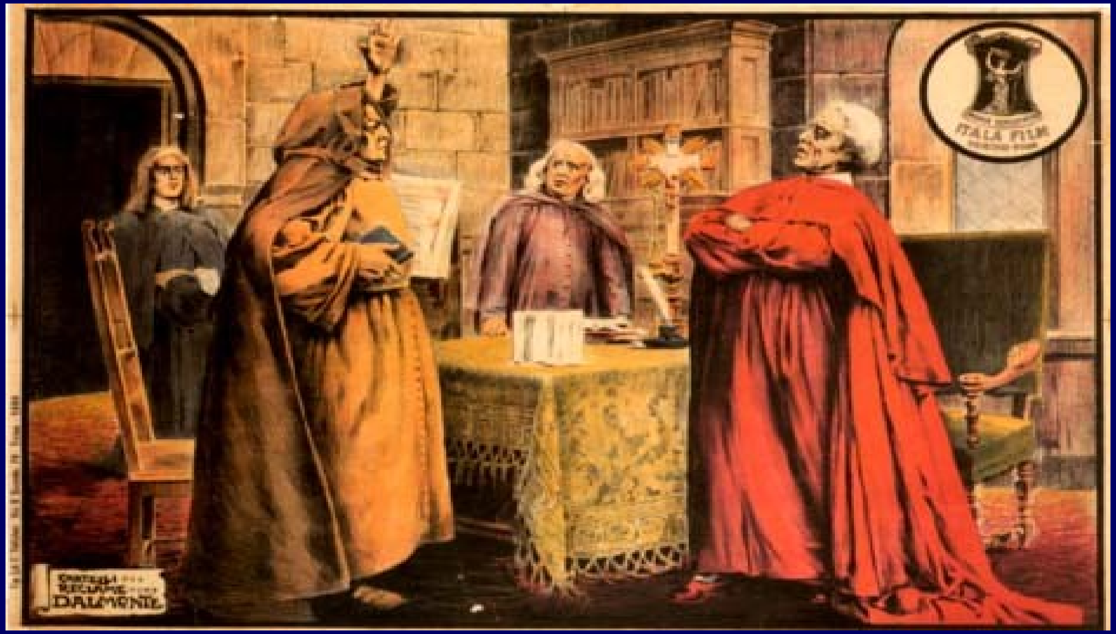
*One half of the Nobel Prize for physics for the year 2019 was awarded to Michel Mayor and Didier Queloz for their discovery of the first exoplanet orbiting a **sun-like star**.*



Why do we look for exoplanets?

Giordano Bruno
1548-1600

“On the Infinite Universe and the Worlds"



This was one of the most eagerly awaited discoveries - Searches ongoing for decades:

- many teams
- many stars
- different techniques

Without success!

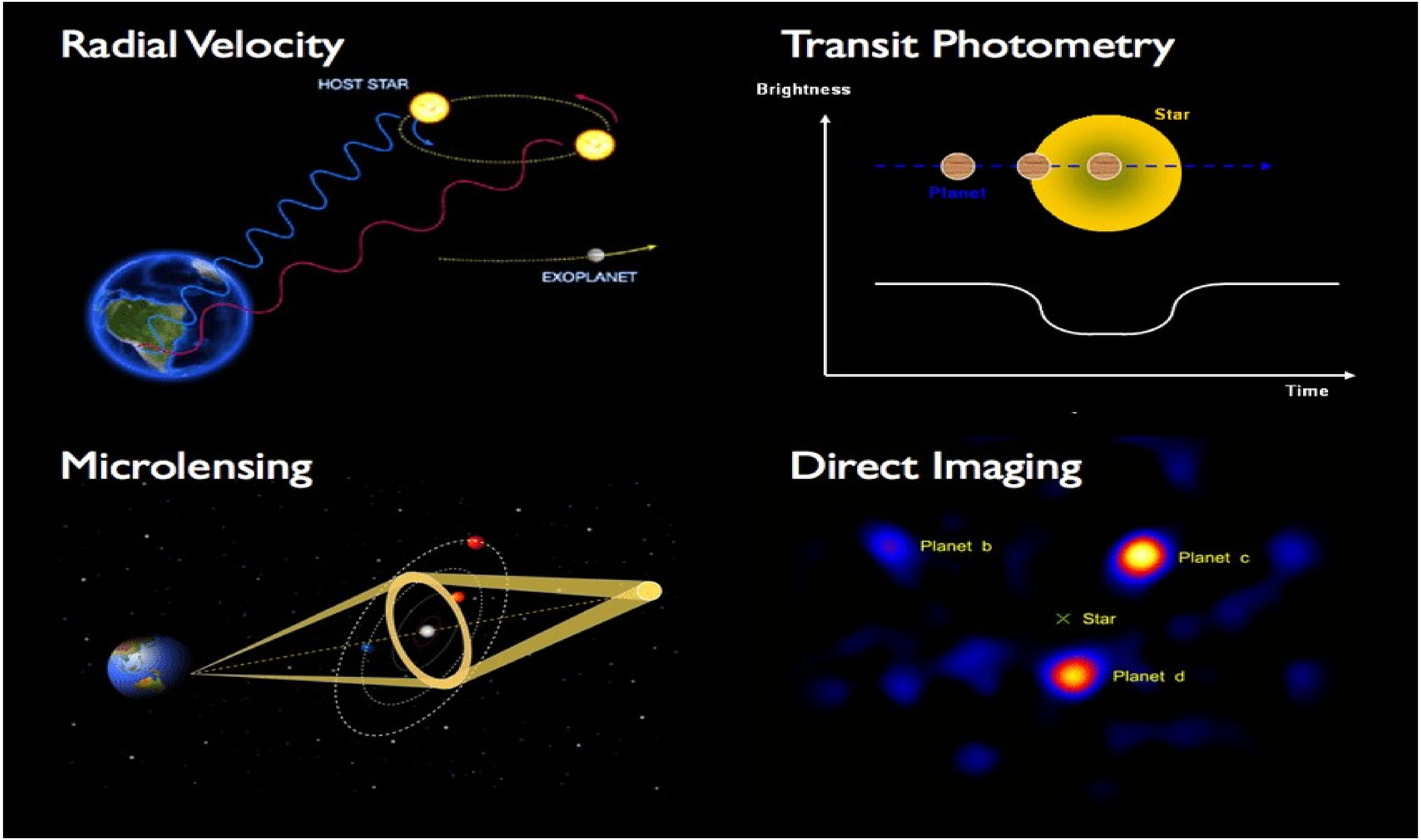
Why?

- Were the techniques not sensitive enough?
- Perhaps there were no planets after all?

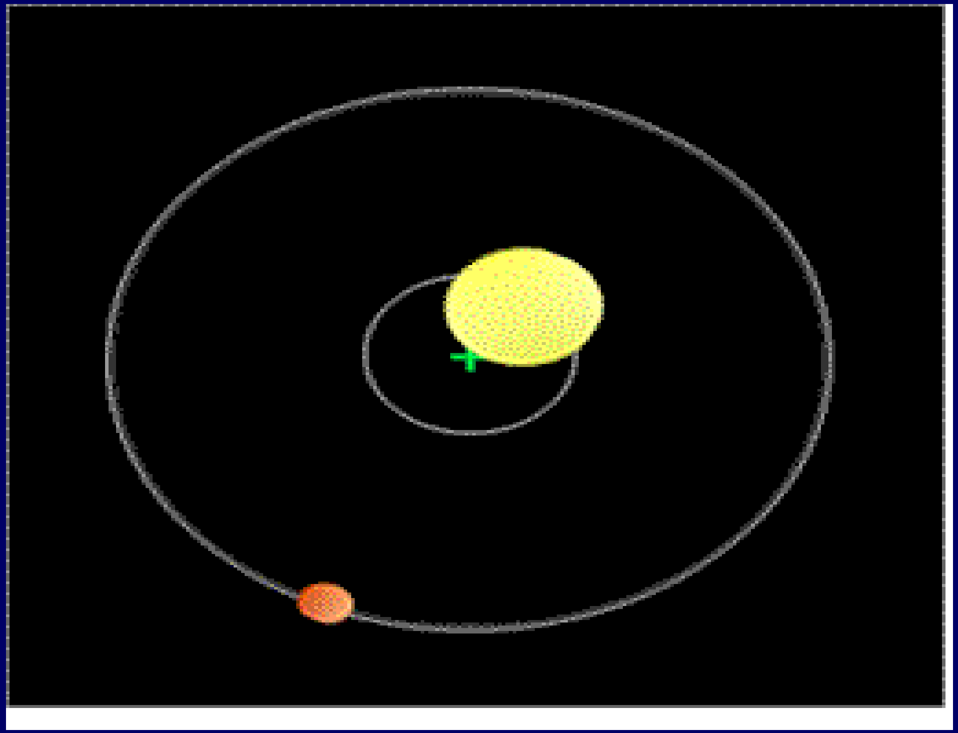
The first possible evidence of an exoplanet was noted in 1917,

but was not recognized as such.

The first confirmation of detection occurred in 1992.(pulsar)


Radial Velocity
HOST STAR
EXOPLANET
Transit Photometry
Brightness
Star
Planet
Time
Microlensing
Direct Imaging
Planet b
Planet c
Star
Planet d

Radial Velocity: Using the effects of gravity

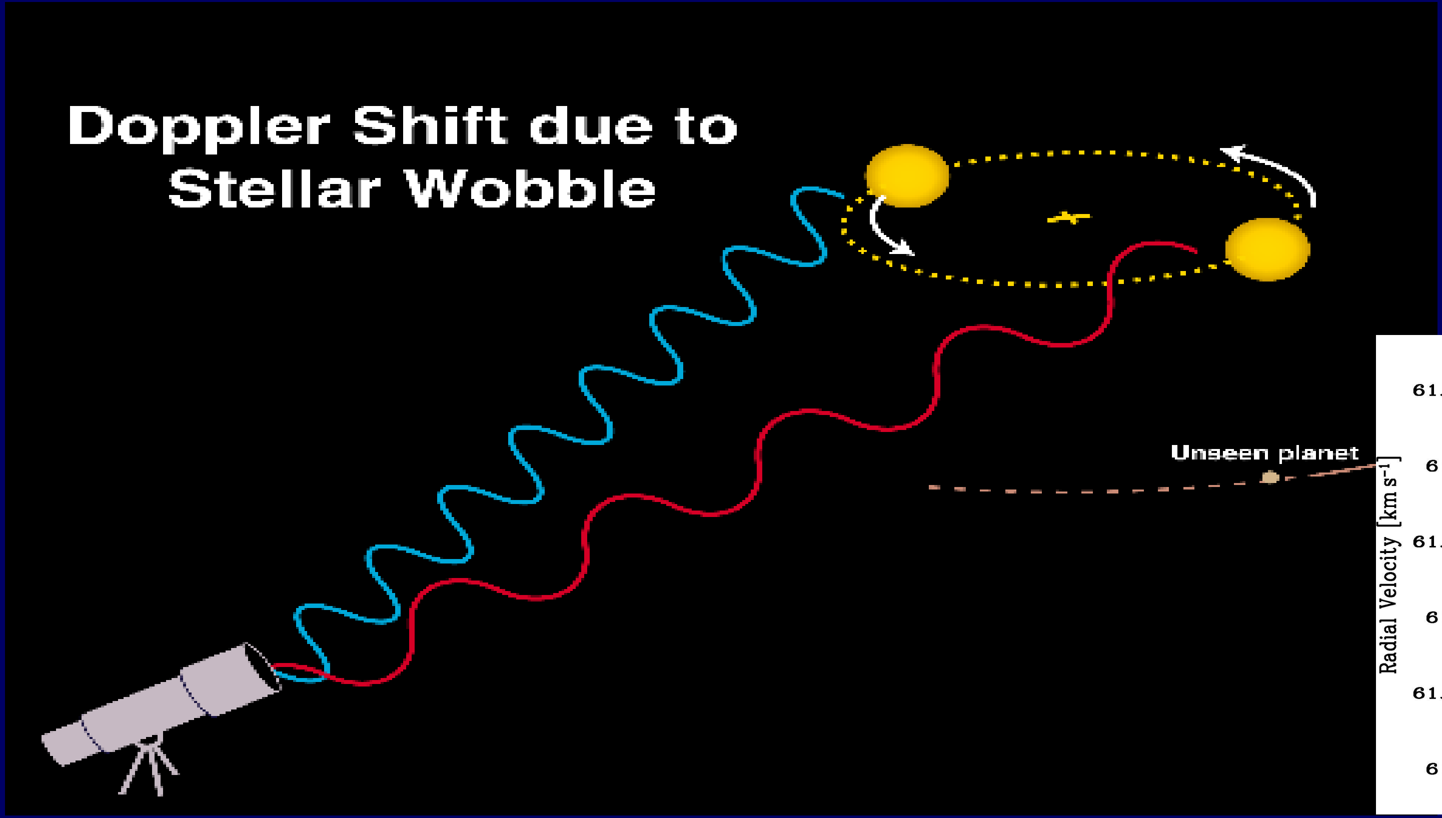


Depending on our relative position we see either

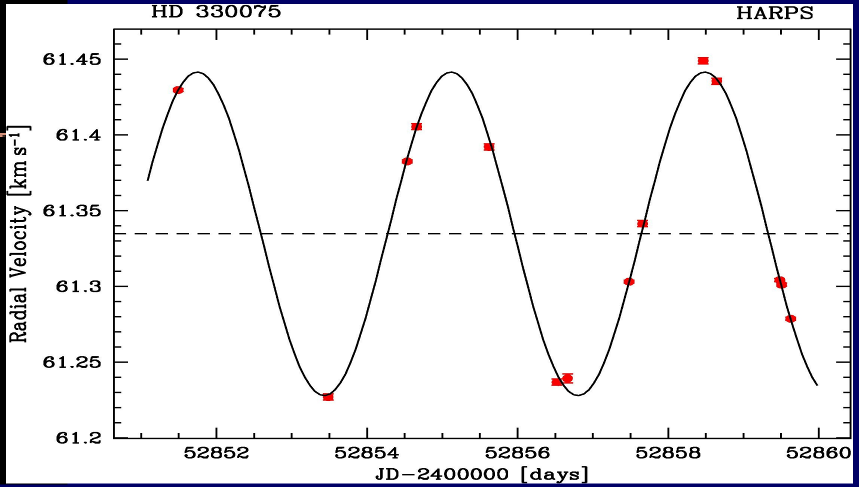
- a “wobble” in the star’s position or
- a “wobble” in the star’s velocity

Period = orbital period of the companion

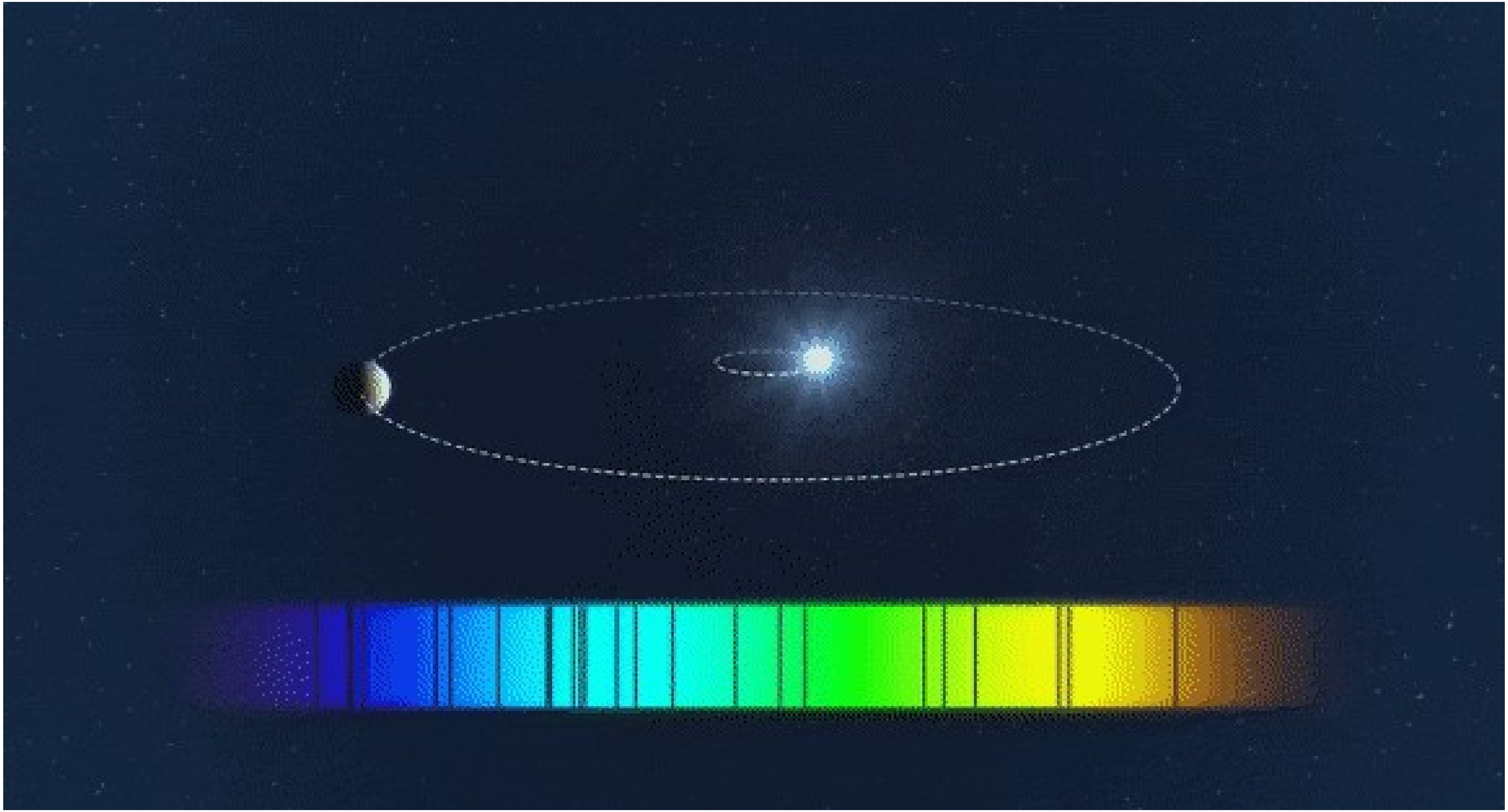
Radial Velocity



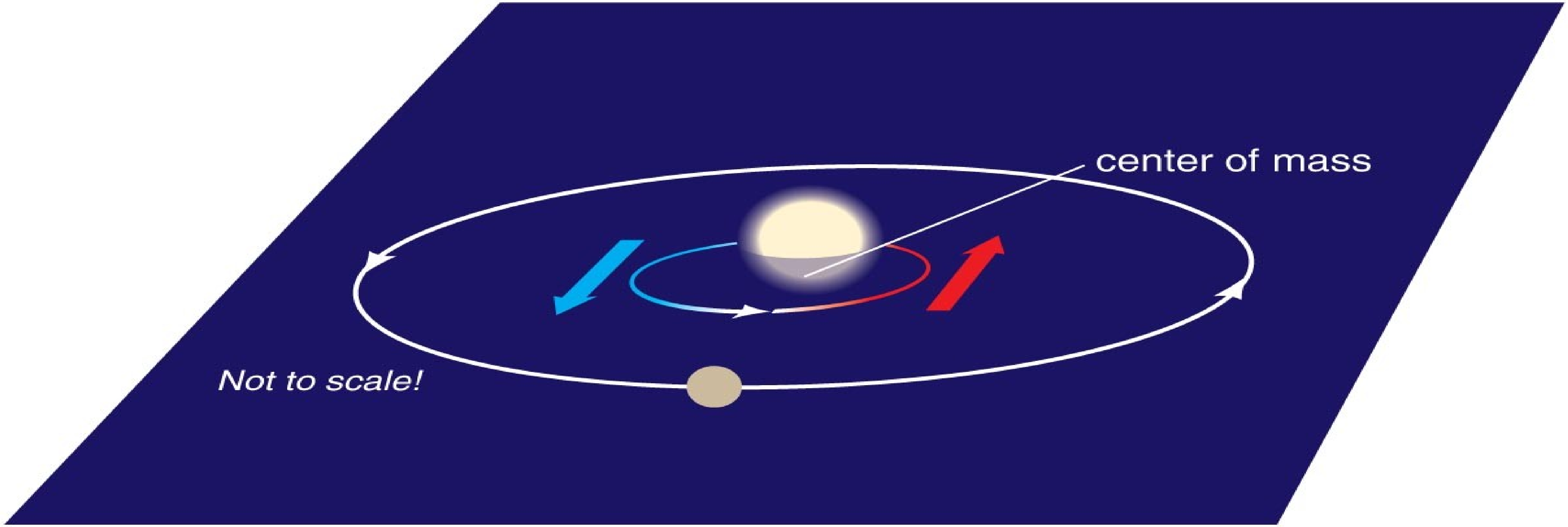
Geneva team



- Dependent on the mass ratio star/planet
- Independent of the distance from the observer
- Jupiter causes 13m/s variation, Earth only 0.1m/s
- Measurement limit 1m/s (HARPS at ESO 3.6m)



Planet Mass and Orbit Tilt



We cannot measure an exact mass for a planet without knowing the tilt of its orbit, because Doppler shift tells us only the velocity toward or away from us.

Doppler data give us lower limits on masses.

YEARS OF EFFORT:

Jupiter causes the Sun to wobble by a velocity of ~10 m/s. Issue in achieving Doppler velocity measurement precision better than 1,000 m/s, 300 m/s was impossible.

Roger F. Griffin (1967-)

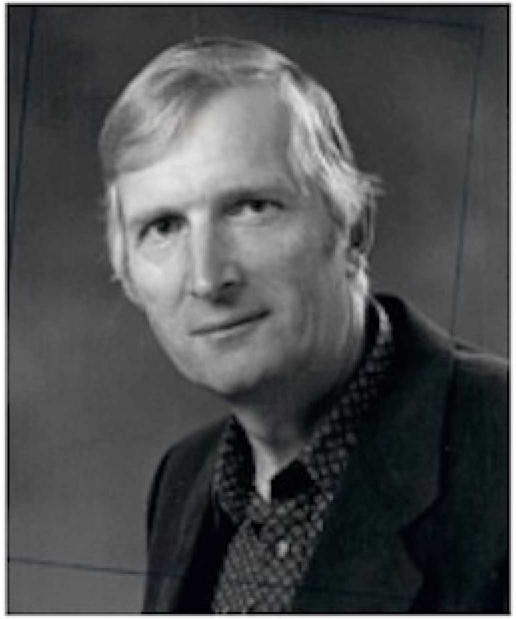
Campbell & Walker (1981-1988)

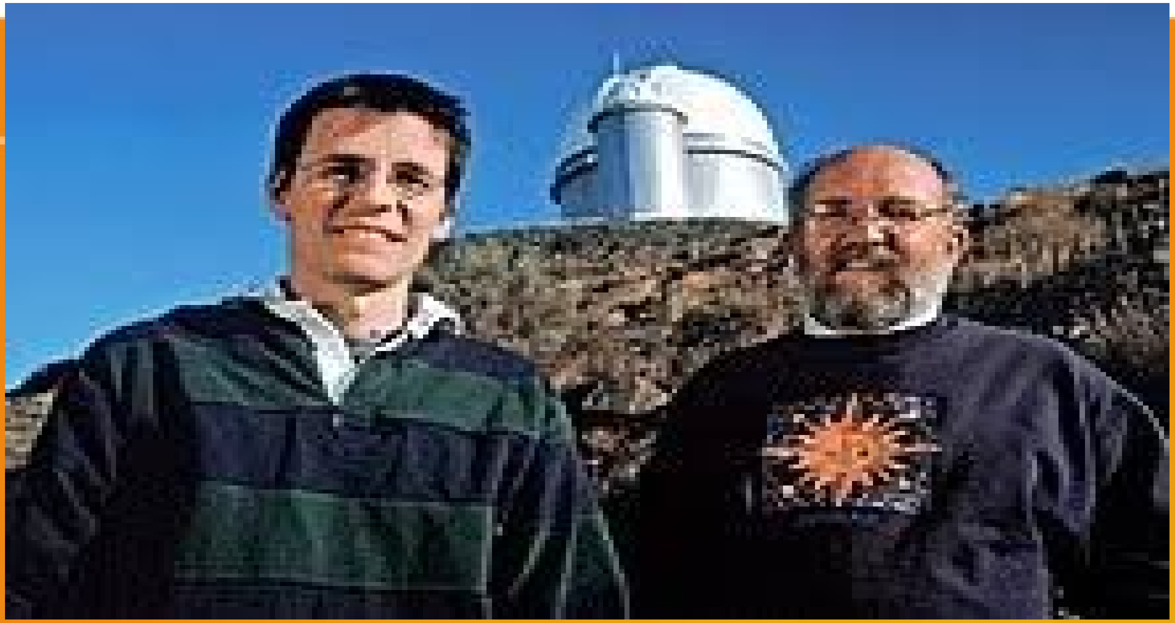
Latham et al. (1984-1990)

Marcy & Butler (1992 -)

Hatzes & Cochran (1993 -)

Mayor & Queloz (1994 -)



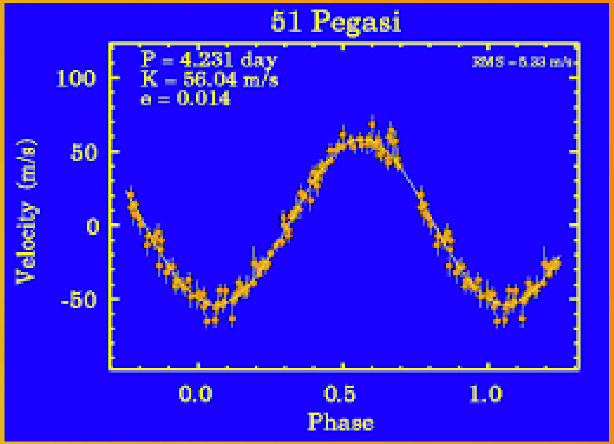


Michel Mayor& Didier Queloz

$$\frac{\Delta\lambda}{\lambda} = \frac{\lambda_{obs} - \lambda_{res}}{\lambda_{res}} = \frac{V_{RV}}{c}$$

The first confirmation of an exoplanet orbiting a main-sequence star was made in 1995, when a giant planet was found in a four-day orbit around the nearby star 51 Pegasi.

For example, in our solar system, the gravitational tug of Jupiter orbiting at 5AU distance causes the Sun to move at a speed of 12 m/s. This is a wavelength shift of 10^{-14} m (10^{-5} nm) in the visible light



HOT JUPITER?

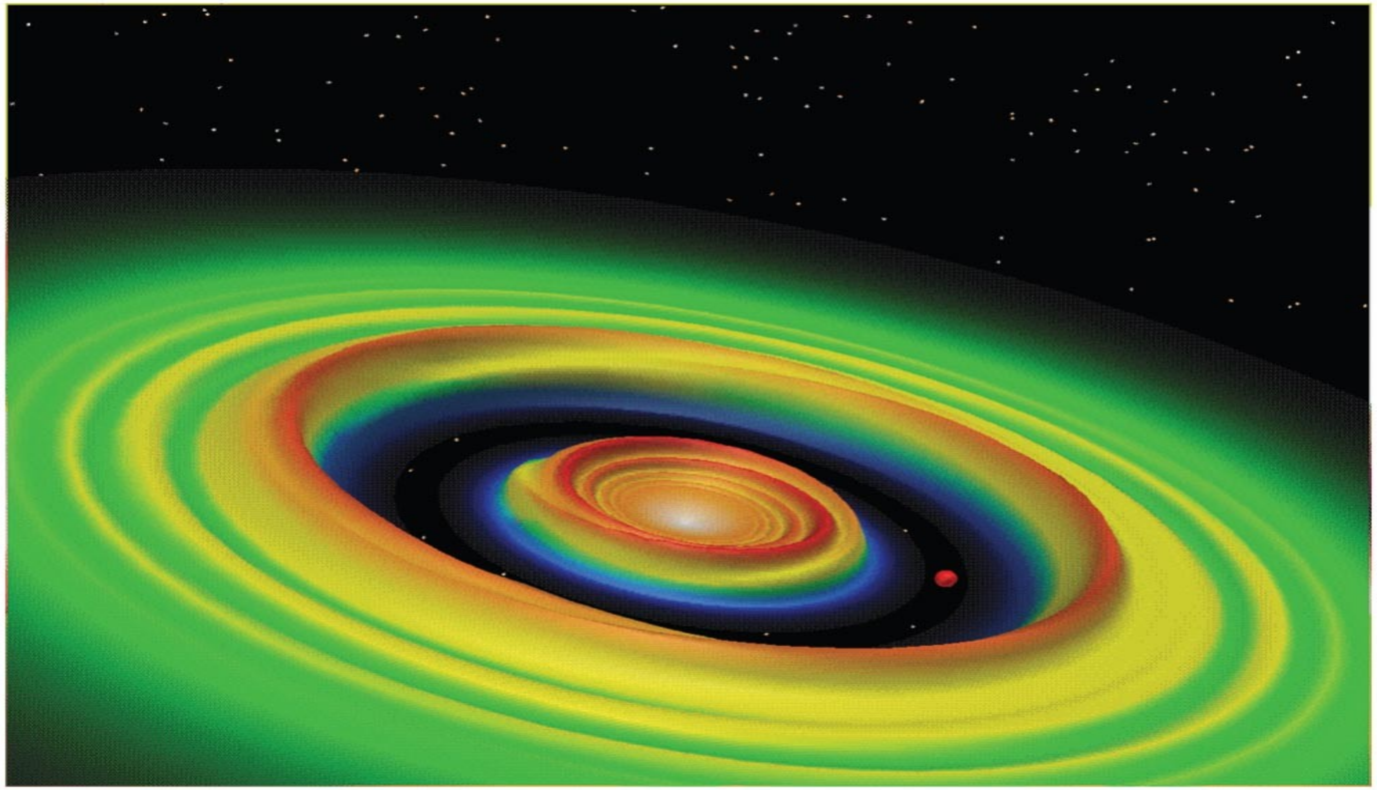
A strange object orbiting the star 51 Pegasi, twice the size of Jupiter, but about 7 times closer to its star than Mercury is to our sun. 51 Peg b. puzzling that a big gas giant could form so very close to its star, since those gases need cooler temperatures (beyond the "snow line") to coalesce and form a planet. This new object made no sense with old models of planet formation — how could a Jupiter-like planet get so close to its star?

MIGRATION?

brown dwarf? that lost some of its atmosphere due to the high temperatures from 51 Pegasi, the star it orbits.

Since then, we've figured out it's likely a Jupiter that formed farther away from 51 Pegasi and migrated inwards towards the star, for one reason or another.

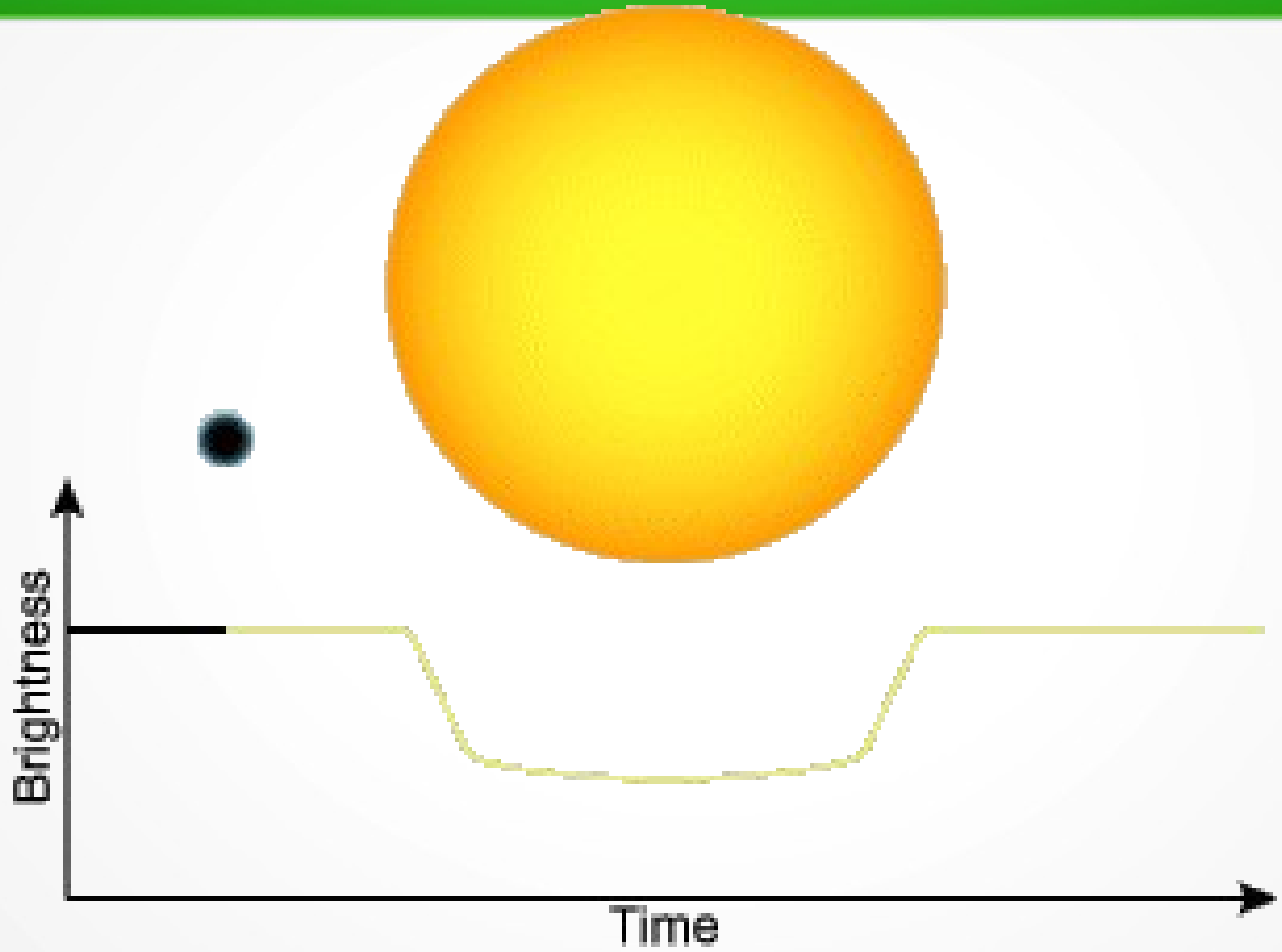
Planetary Migration

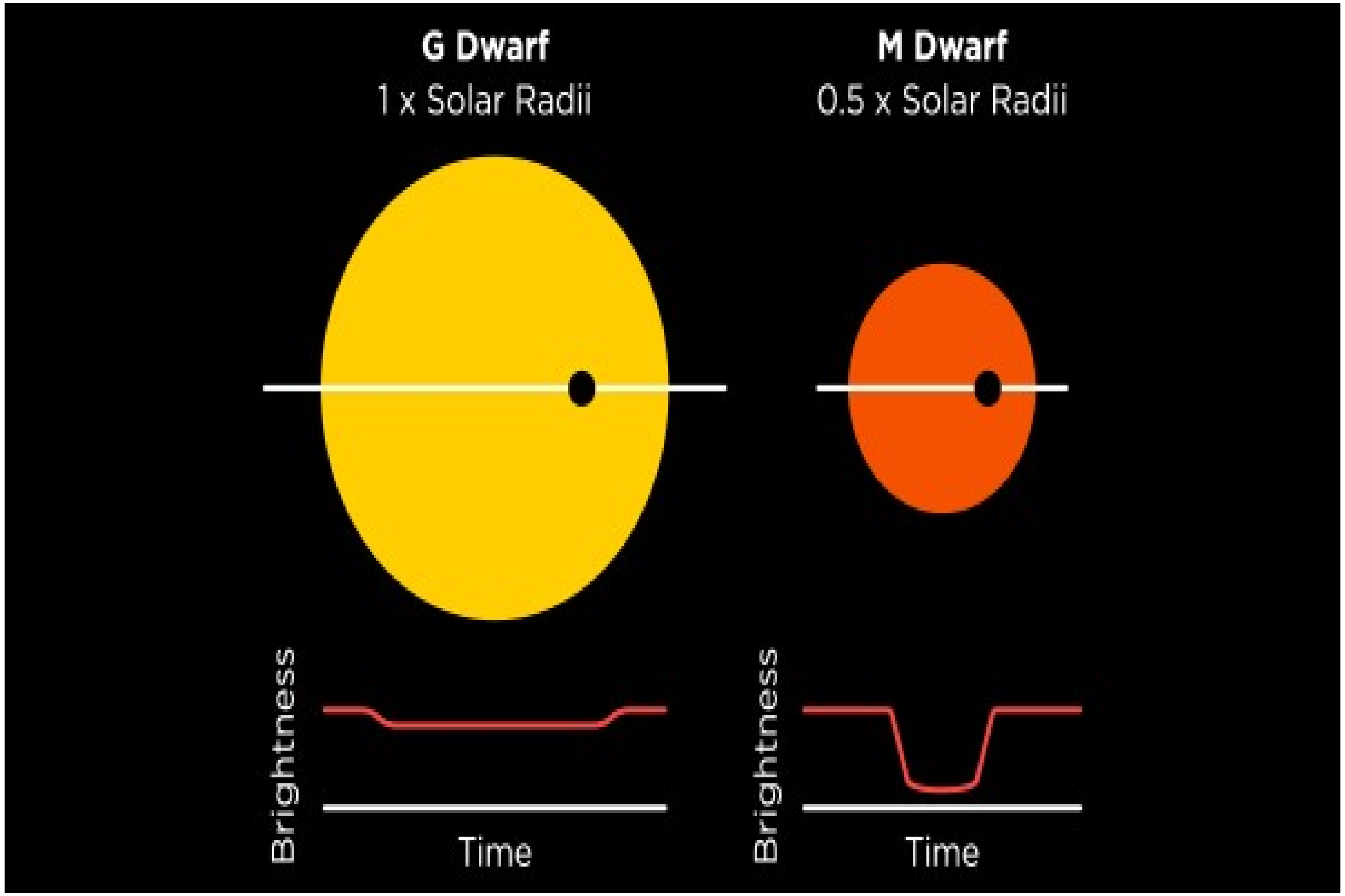


A young planet's motion can create waves in a planet-forming disk.

Models show that matter in these waves can tug on a planet, causing its orbit to migrate inward.

Light Curve of a Star During Planetary Transit





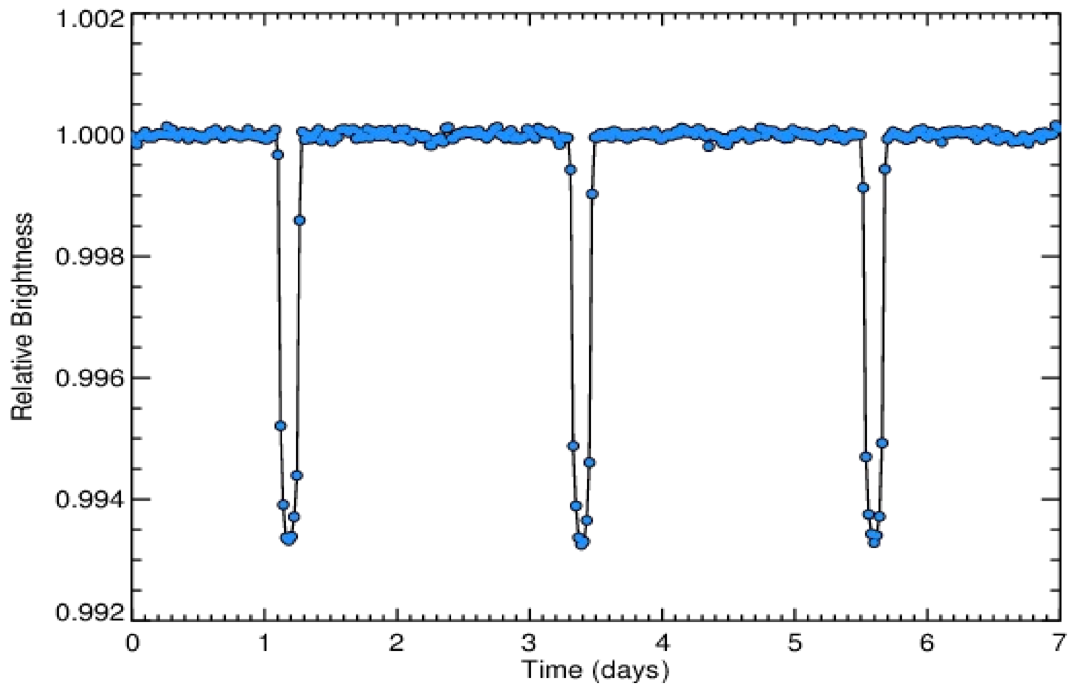
$$\text{Depth} = \left(\frac{R_p}{R_\star}\right)^2$$

$$R_p = R_\star \sqrt{\text{Depth}}$$

For Sun & Earth:
R ^2/R_planet^2
=(7. 10^5)^2 / (6.4 *10^3)^2
=10^4

Kepler light curve of an exoplanet called HAT-P-7 b

This planet is a hot Jupiter - one of the easiest types of planets to detect.



Notice:

1% dip

3 transits to confirm

Size of planet

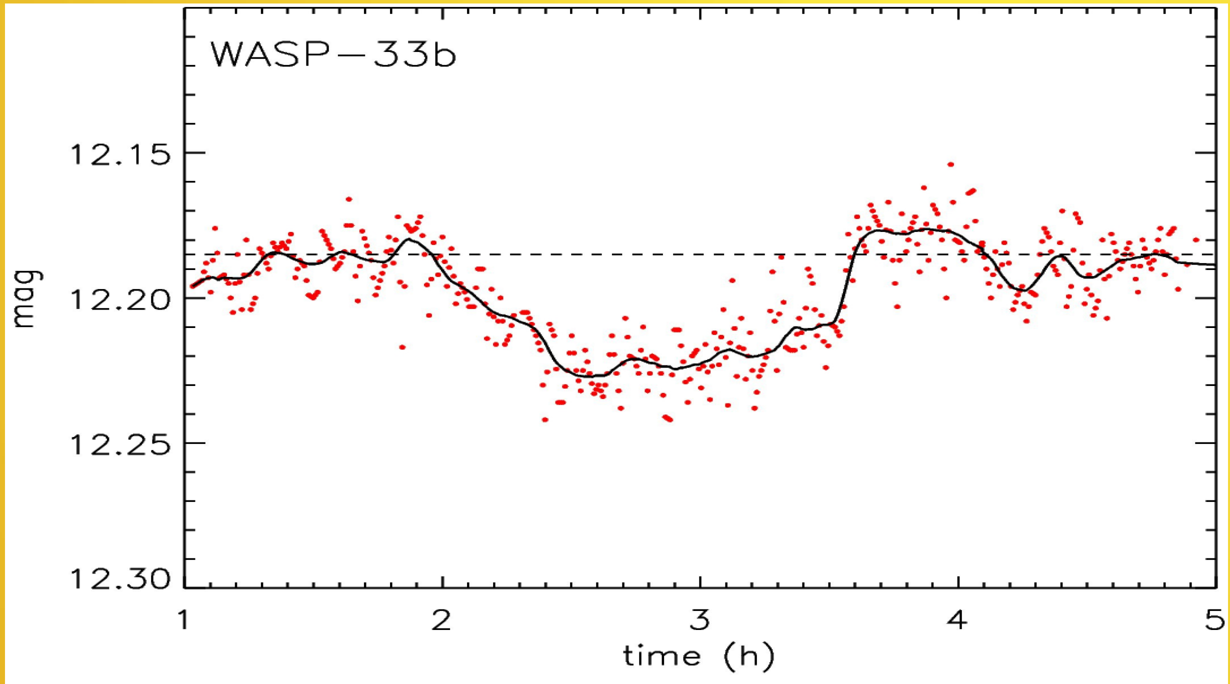
Number of planets

Orbital period

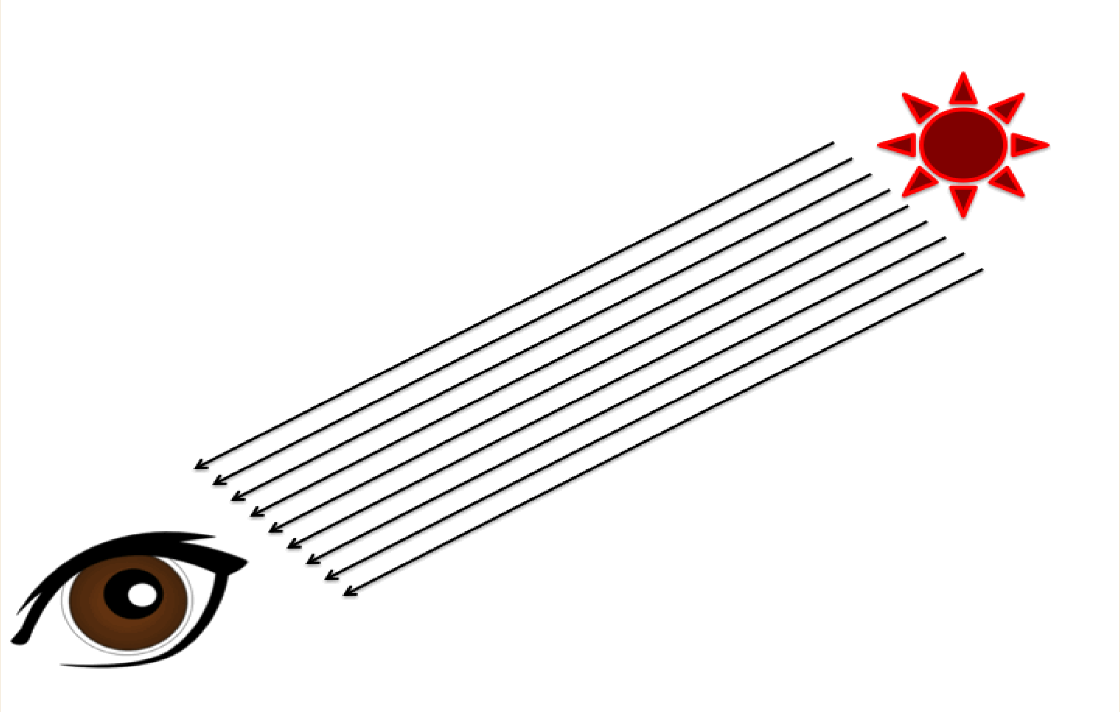
Inclination effect

WASP-33b

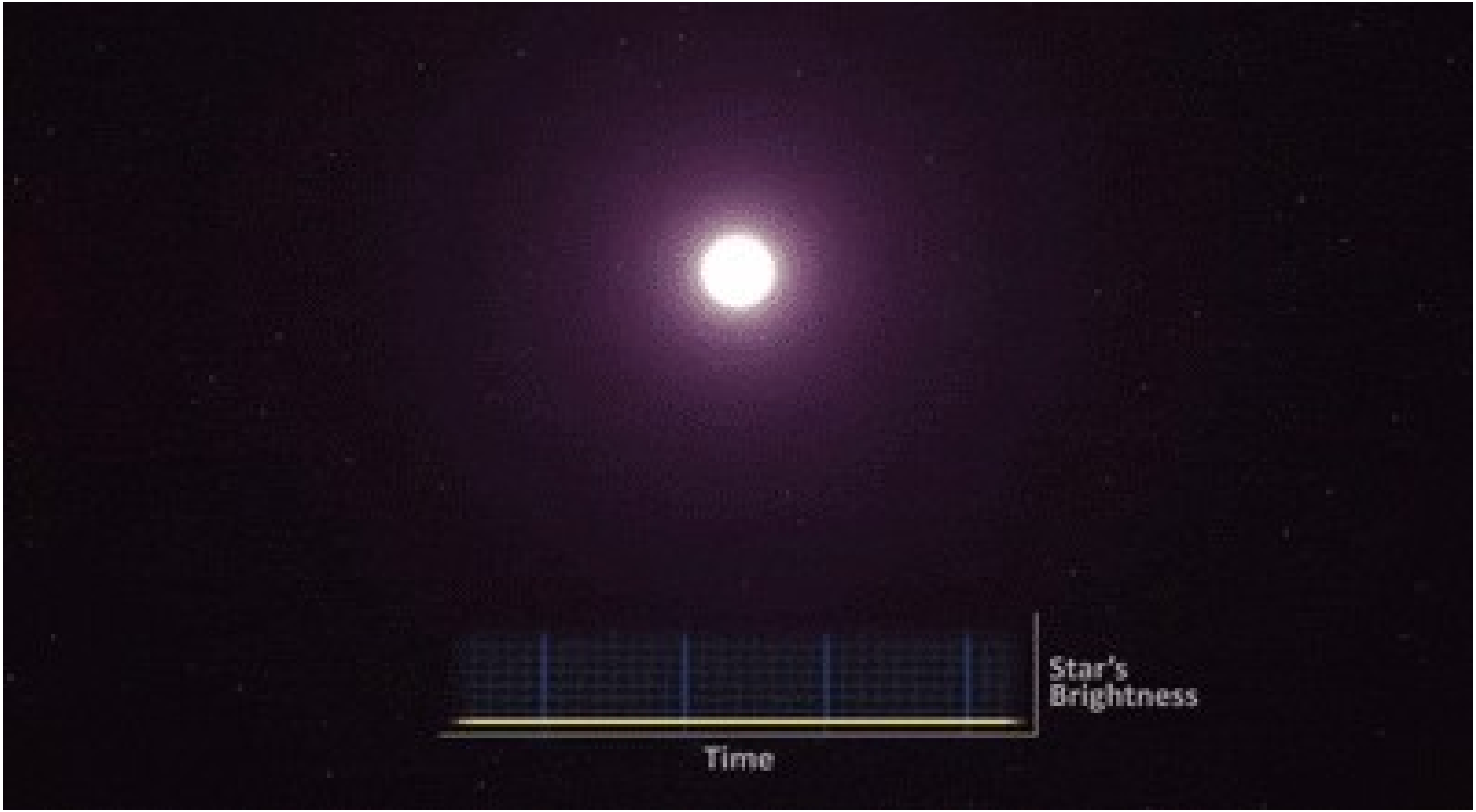
The exoplanet around star WASP-33b has a transit period of 1.6 hours and a depth of 0.03 magnitudes.Light curve for WASP-33b Durham 16-inch Far-East Telescope in December 2016.

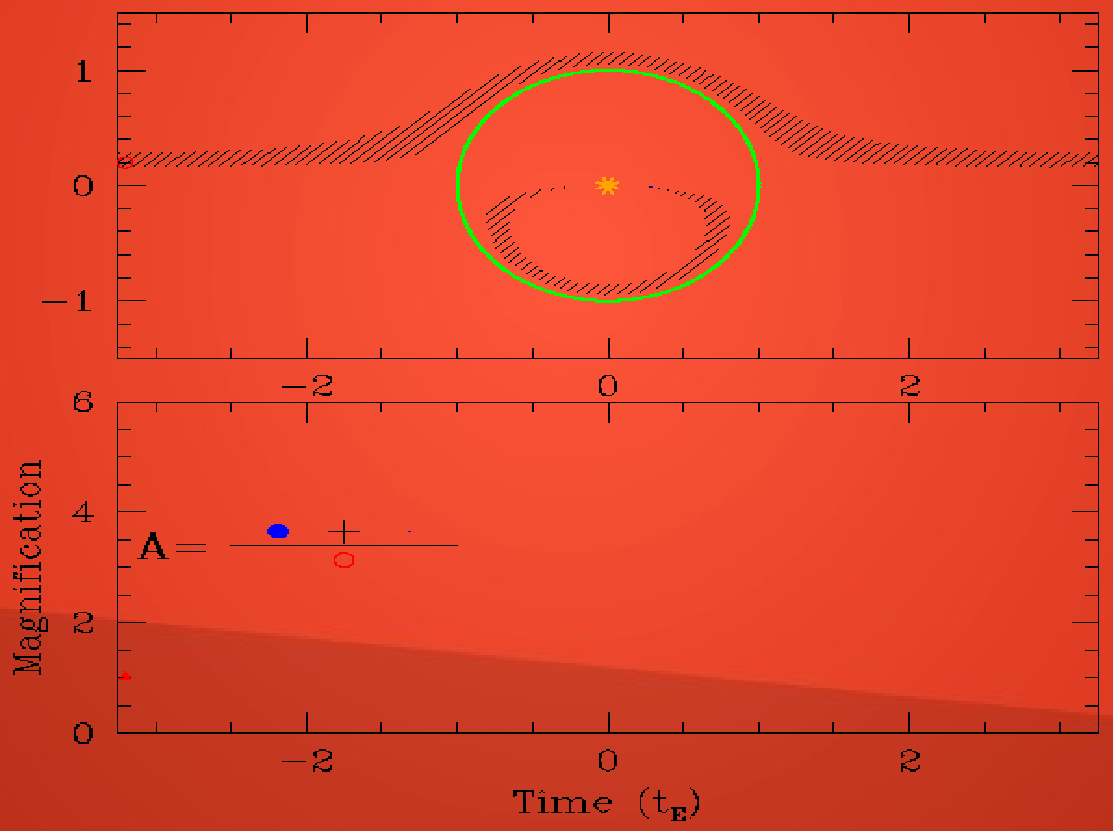


Microlensing



If the lens star is orbited by a planet, the planet will further deflect the light from the source star. We can detect the planet by measuring the magnification curve and observing the small bump it produces. If the deflection is strong enough, the distant star appears to be two stars. These are called "images" of the distant star.


Star's
Brightness
Time



1
0
−1
−2
0
2
6
4
2
0
Magnification
A=
Time (t_E)

Direct imaging of the planet

VERY difficult due to

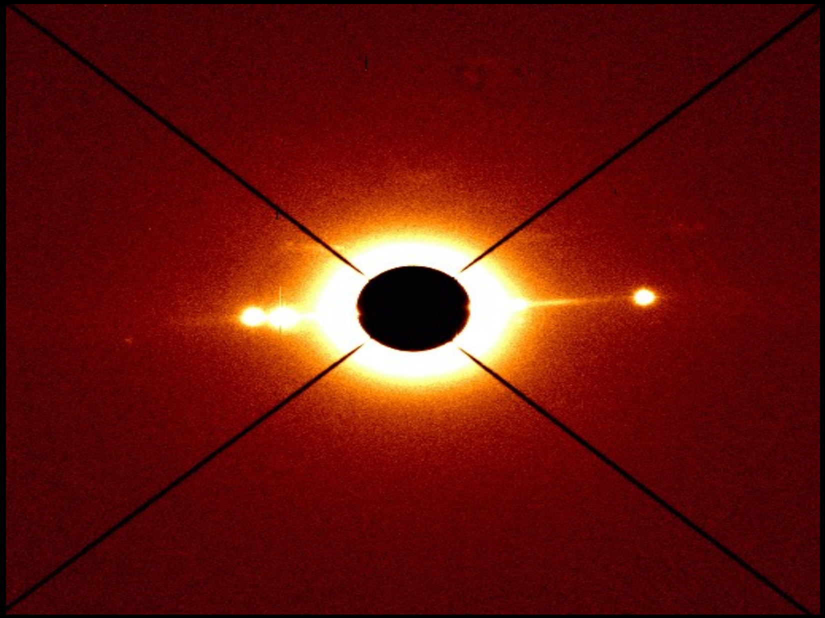
- extreme contrast: about 1:10^9
  in the case of Jupiter/Sun at 5pc distance
- very small angular separation: <1"

51 Pegasi

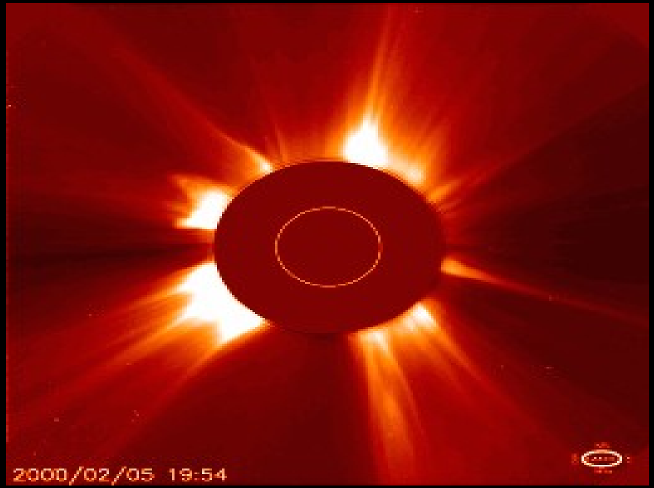
- only from space:
  "nulling interferometry"
- GENIE (ESA/ESO VLTI 2008)
- DARWIN (ESA)
- TPF (NASA)

Can you think of a way around the problem?

Can you think of a way around the problem?



Telescope image of Saturn, rings and moons with a coronagraph

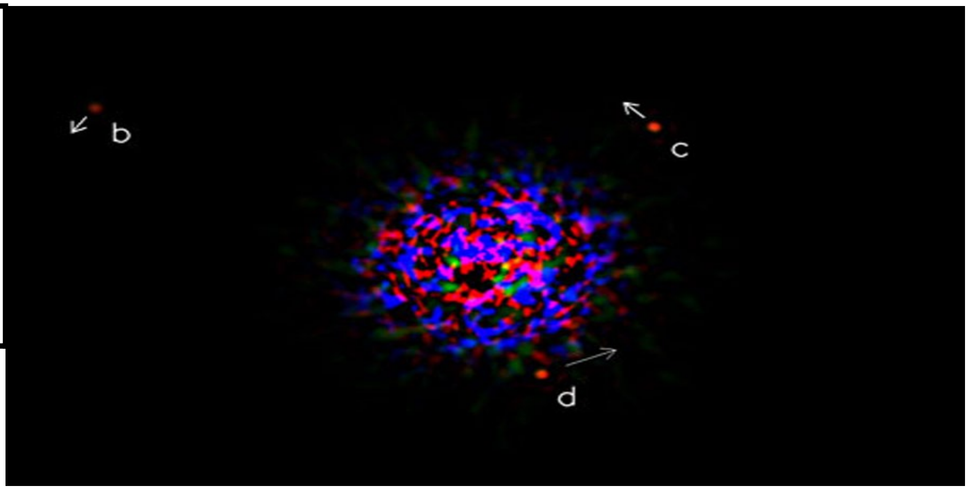


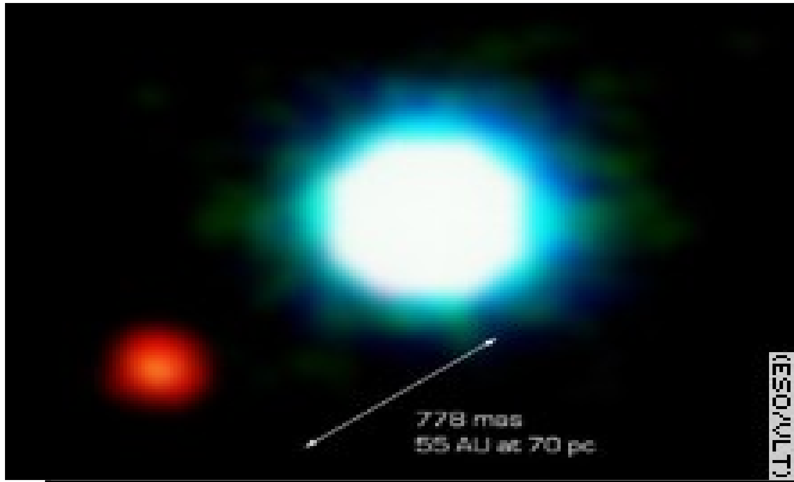
SOHO spacecraft image of the sun with a coronagraph

?

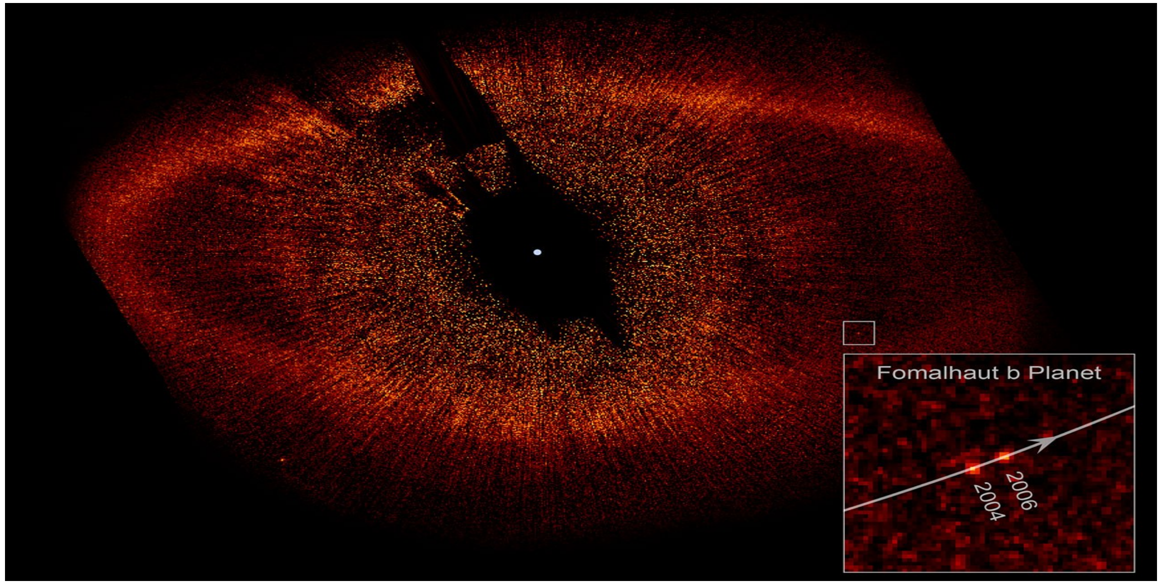
Direct Imaging

Keck adaptive optic image showing planets orbiting HR 8799. http://apod.nasa.gov/apod/ap081117.html





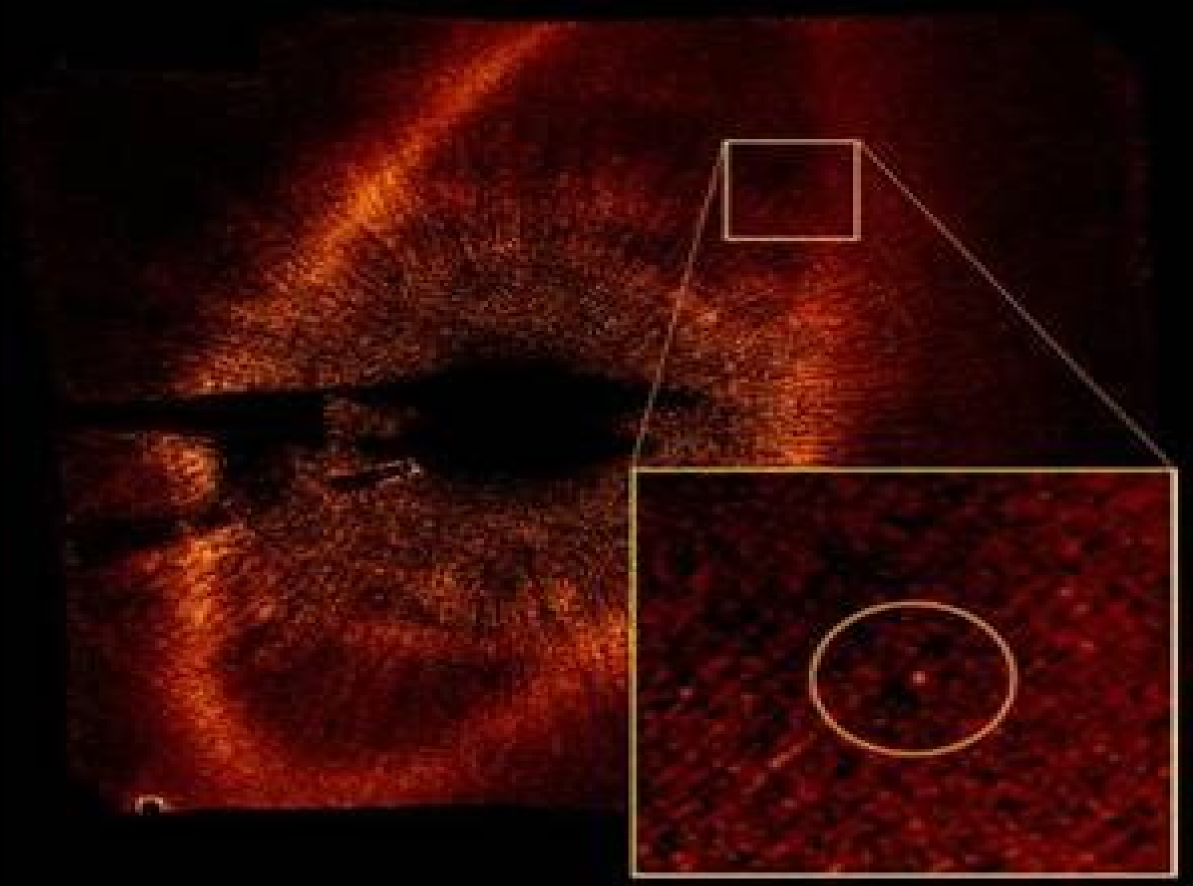
A VLT infrared image of a hot young planet around a brown dwarf star.

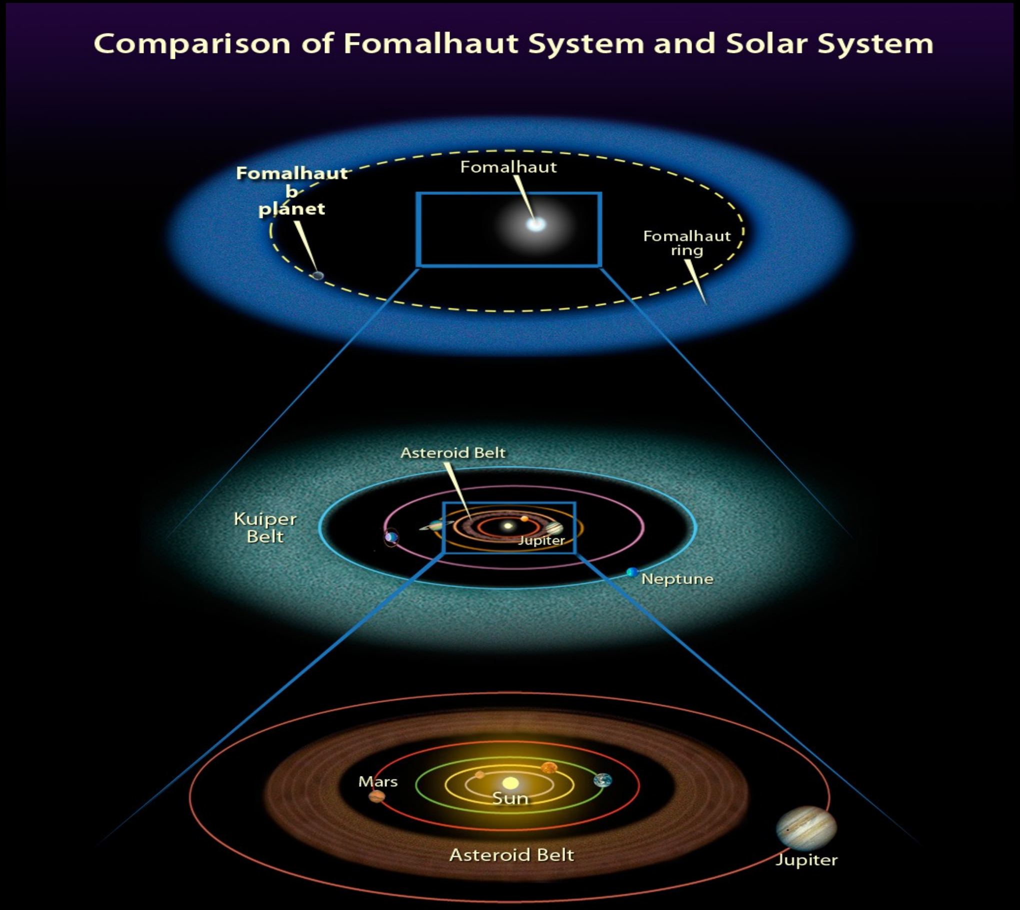


An HST coronograph image of a planet around Fomalhaut.

http://apod.nasa.gov/apod/ap081114.html

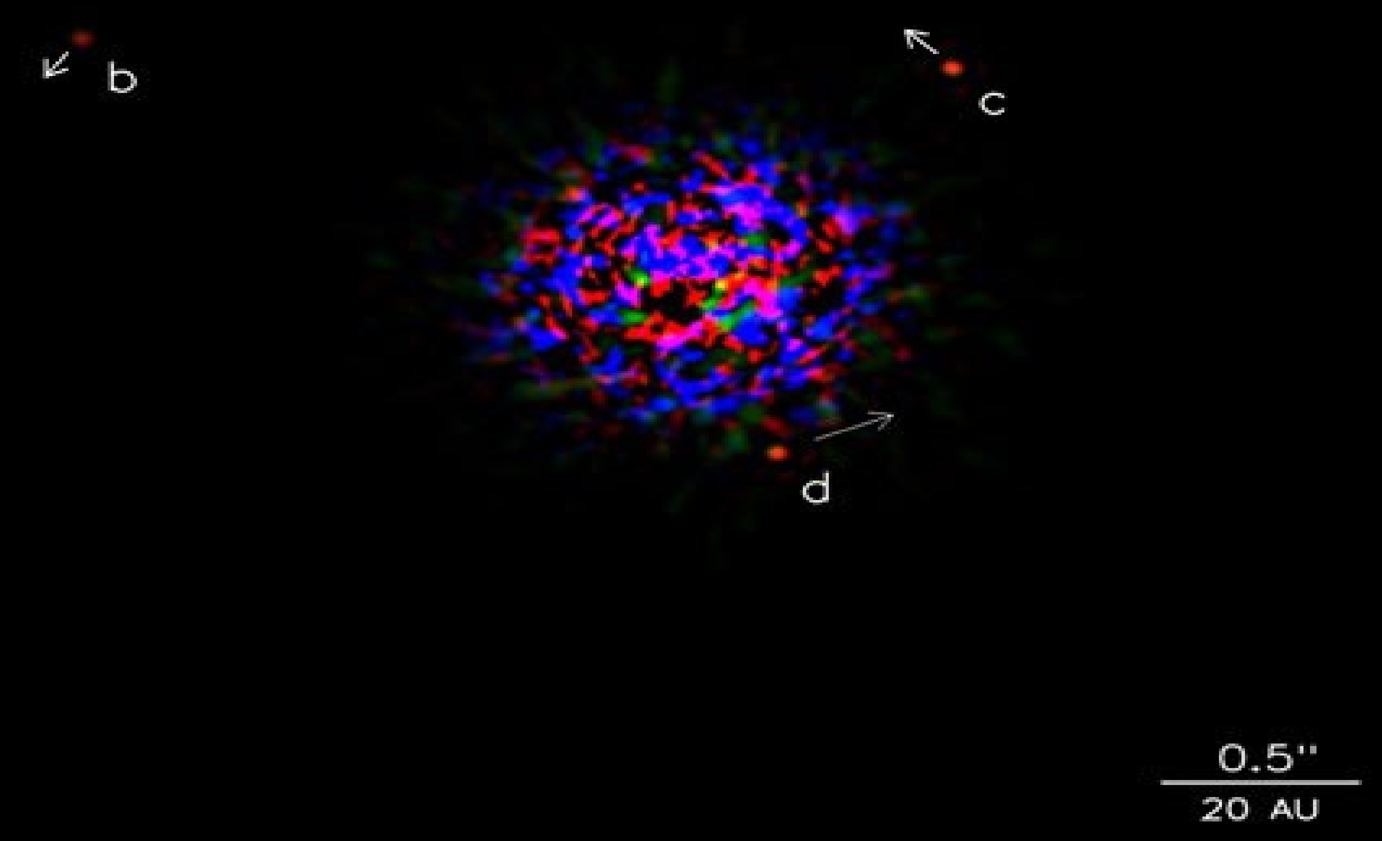
Fomalhaut



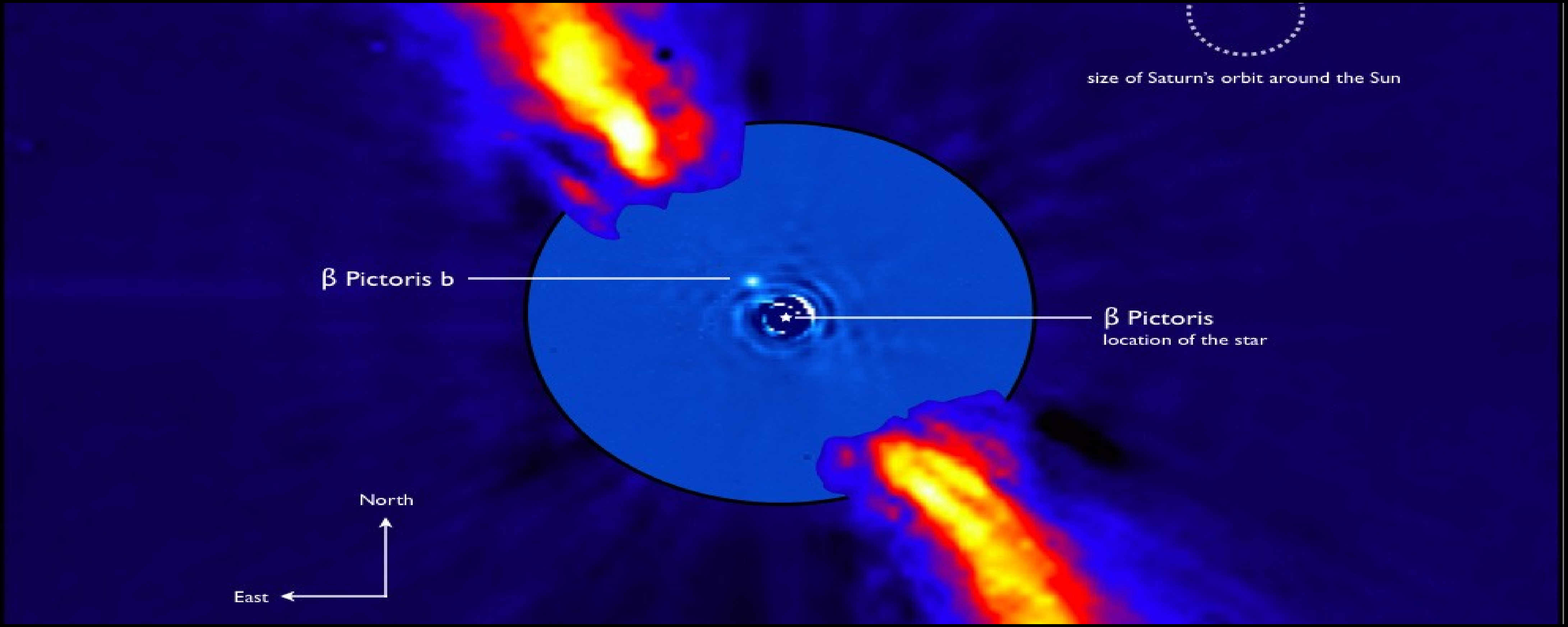


Comparison of Fomalhaut System and Solar System
Fomalhaut b planet
Fomalhaut
Fomalhaut ring
Asteroid Belt
Kuiper Belt
Jupiter
Neptune
Mars
Sun
Asteroid Belt
Jupiter

HR 8799

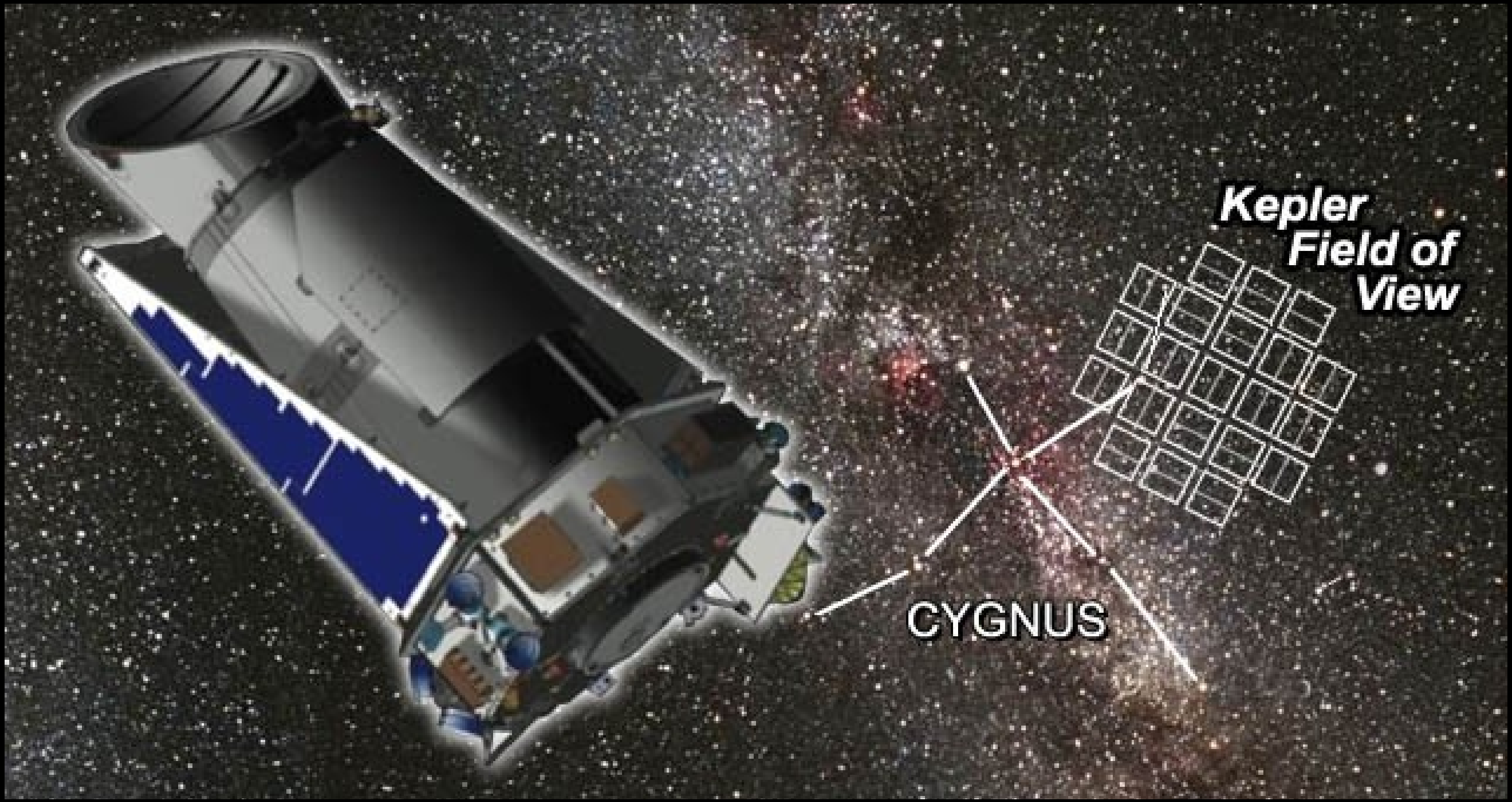


Beta Pictoris



Combination of two near-infrared images obtained with the Very Large Telescope

The Kepler Mission



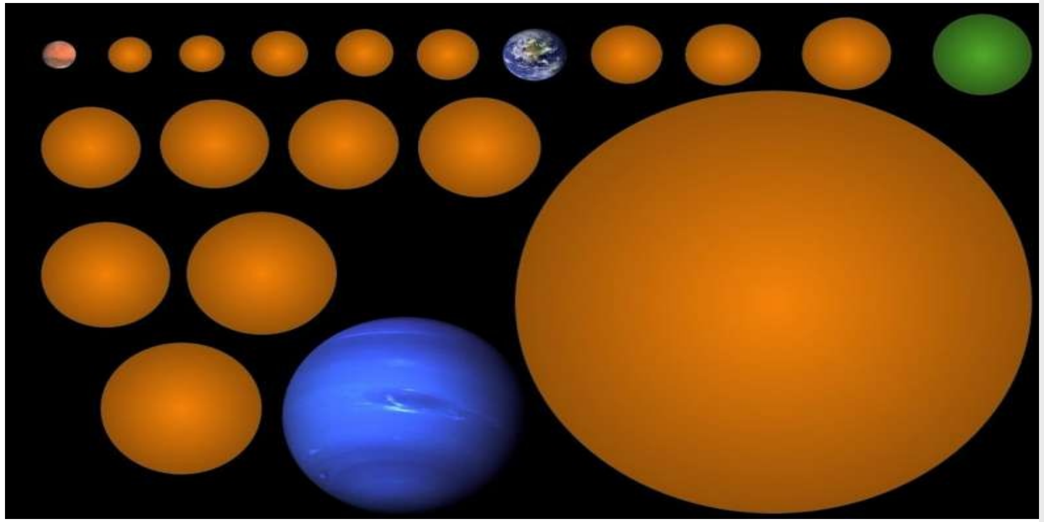
Kepler primary mirror 1.4 m
Launch date:March 7, 2009
FOV 115 square degrees, around 0.25 percent of the sky
(Fist at arms length!!)

To avoid the Sun the FOV must be out of the ecliptic plane. Also, the FOV should have the largest possible number of stars. This leads to the selection of a region in the Cygnus and Lyra constellations of our Galaxy

The loss of a second of the four reaction wheels on board the Kepler spacecraft in May 2013 brought an end to Kepler's four-year science mission to continuously monitor more than 150,000 stars to search for transiting exoplanets. Developed over the months following this failure, the K2 mission represents a new concept for spacecraft operations that enables continued scientific observations with the Kepler space telescope. K2 became fully operational in May 2014 and retired on 31 October 2018.

NASA's Transiting Exoplanet Survey Satellite (TESS)

Designed to search for exoplanets using the transit method in an area 400 times larger than that covered by the Kepler mission.
Launch date: 18 April 2018



SPACE

Astronomy Student in Canada Discovers 17 Exoplanets New to Science

VICTOR TANGERMANN, FUTURISM
2 MAR 2020

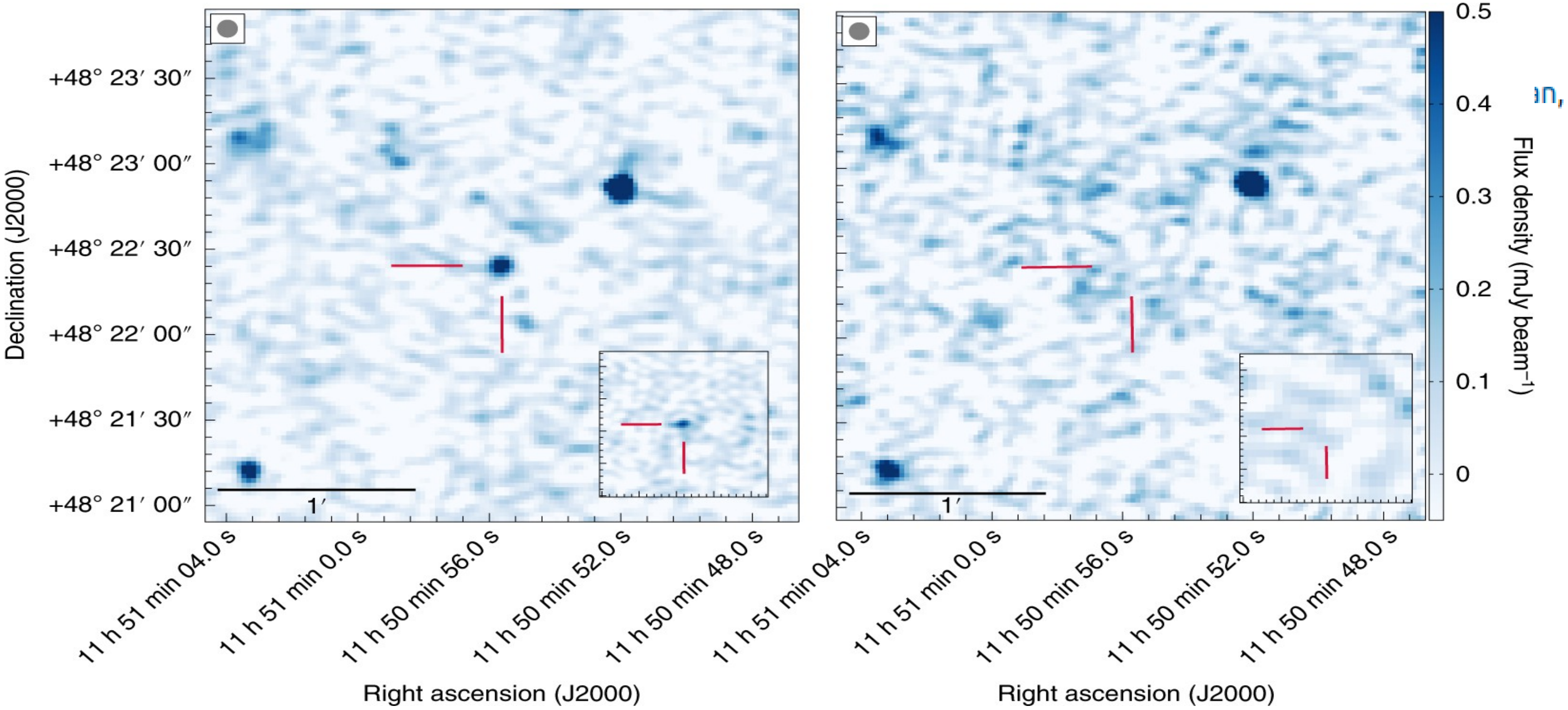
By combing through data collected by NASA's planet-hunting Kepler space telescope, University of British Columbia astronomy PhD candidate Michelle

By combing through data collected by NASA's planet-hunting Kepler space telescope, University of British Columbia astronomy PhD candidate Michelle Kunimoto discovered evidence of an impressive 17 new exoplanets - including a roughly Earth-sized world found in the "habitable zone", the region around a star where liquid water could exist. 2 MAR 2020

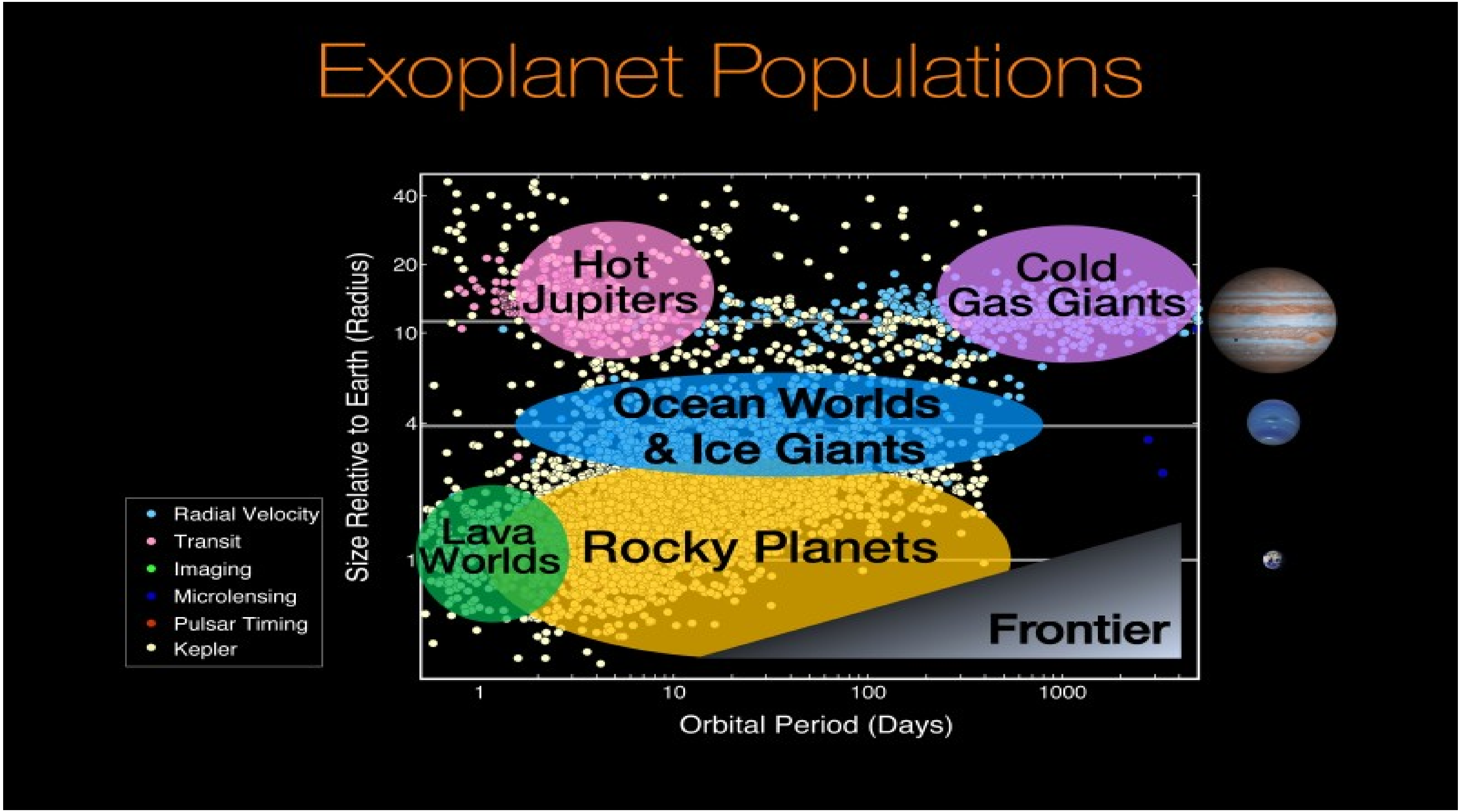
MENU
nature astronomy

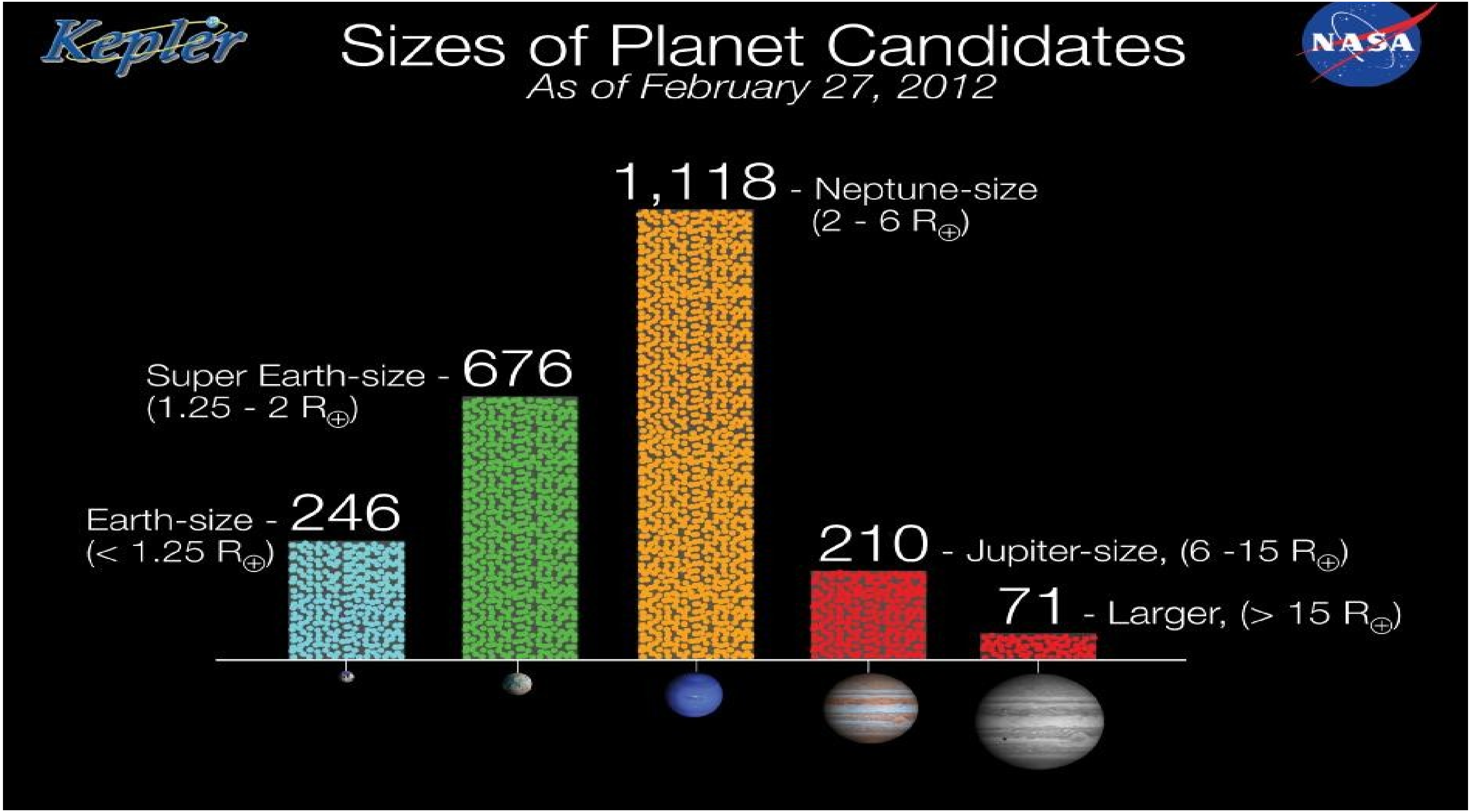
Letter | Published: 17 February 2020

Coherent radio emission from a quiescent red dwarf indicative of star–planet interaction



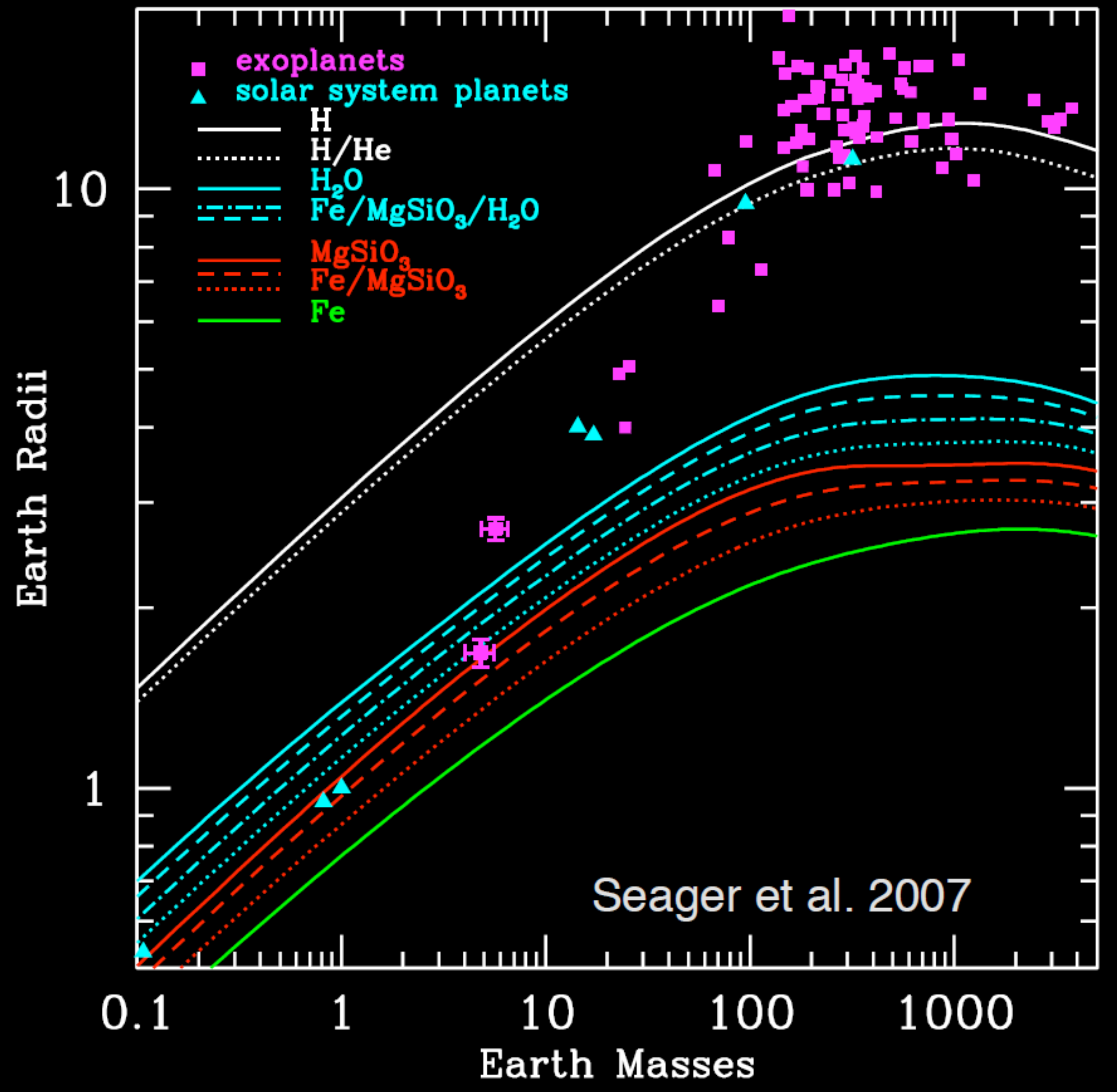
Exoplanet
Missions
NASA
JWST
WFIRST-AFTA
TESS
Kepler
New Worlds Telescope
Spitzer
Hubble
Astronomy and Astrophysics in the New Millennium
2001 Decadal Survey
New Worlds, New Horizons in Astronomy and Astrophysics
2010 Decadal Survey
Ground-based Observatories


Exoplanet Populations
Hot Jupiters
Cold Gas Giants
Ocean Worlds & Ice Giants
Lava Worlds
Rocky Planets
Frontier
Size Relative to Earth (Radius)
40
20
10
4
1
1
10
100
1000
Orbital Period (Days)
Radial Velocity
Transit
Imaging
Microlensing
Pulsar Timing
Kepler

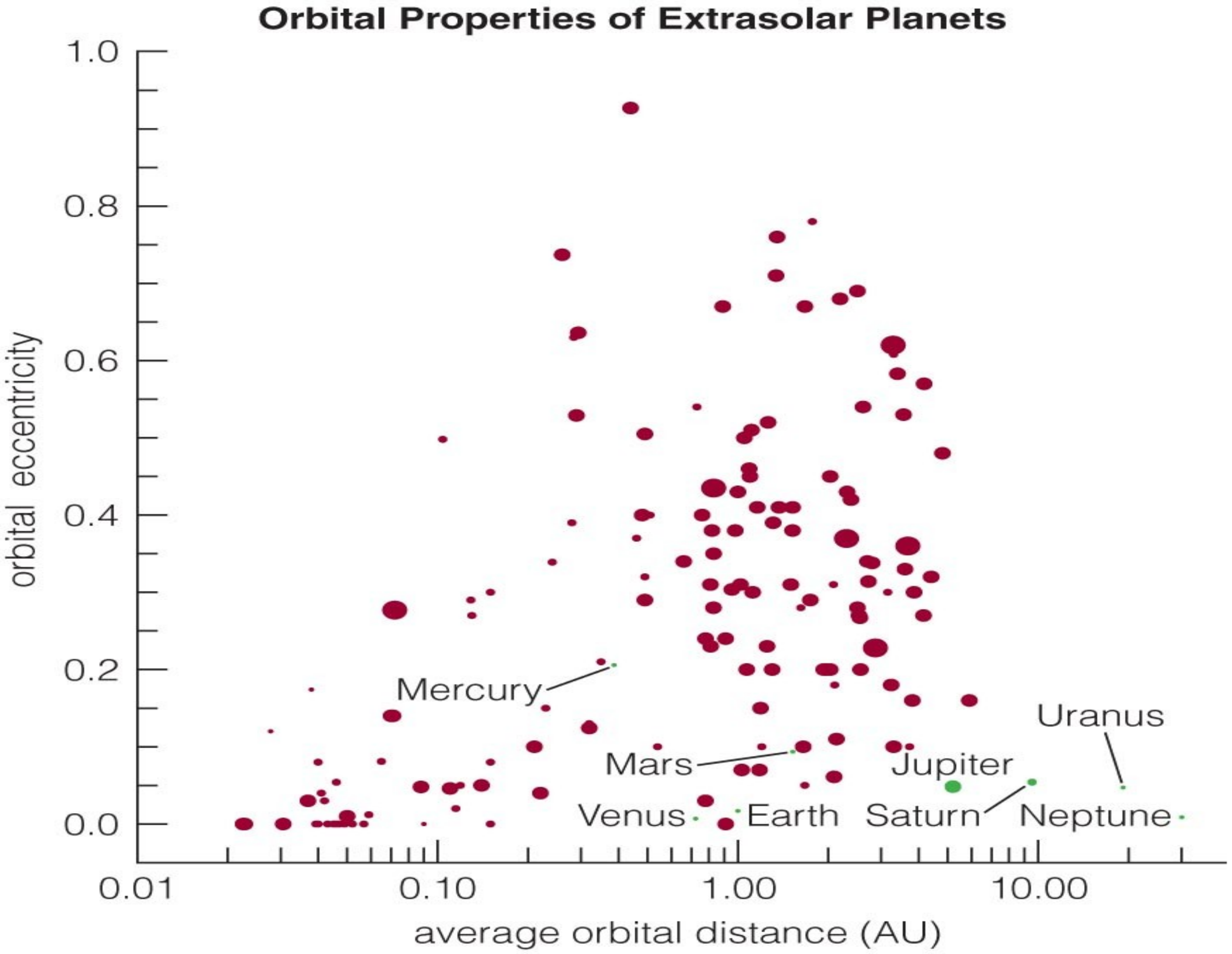

Kepler
Sizes of Planet Candidates
As of February 27, 2012
NASA
1,118 - Neptune-size
(2 - 6 R⊕)
Super Earth-size - 676
(1.25 - 2 R⊕)
Earth-size - 246
(< 1.25 R⊕)
210 - Jupiter-size, (6 -15 R⊕)
71 - Larger, (> 15 R⊕)

Exoplanet Mass-Radius Diagram

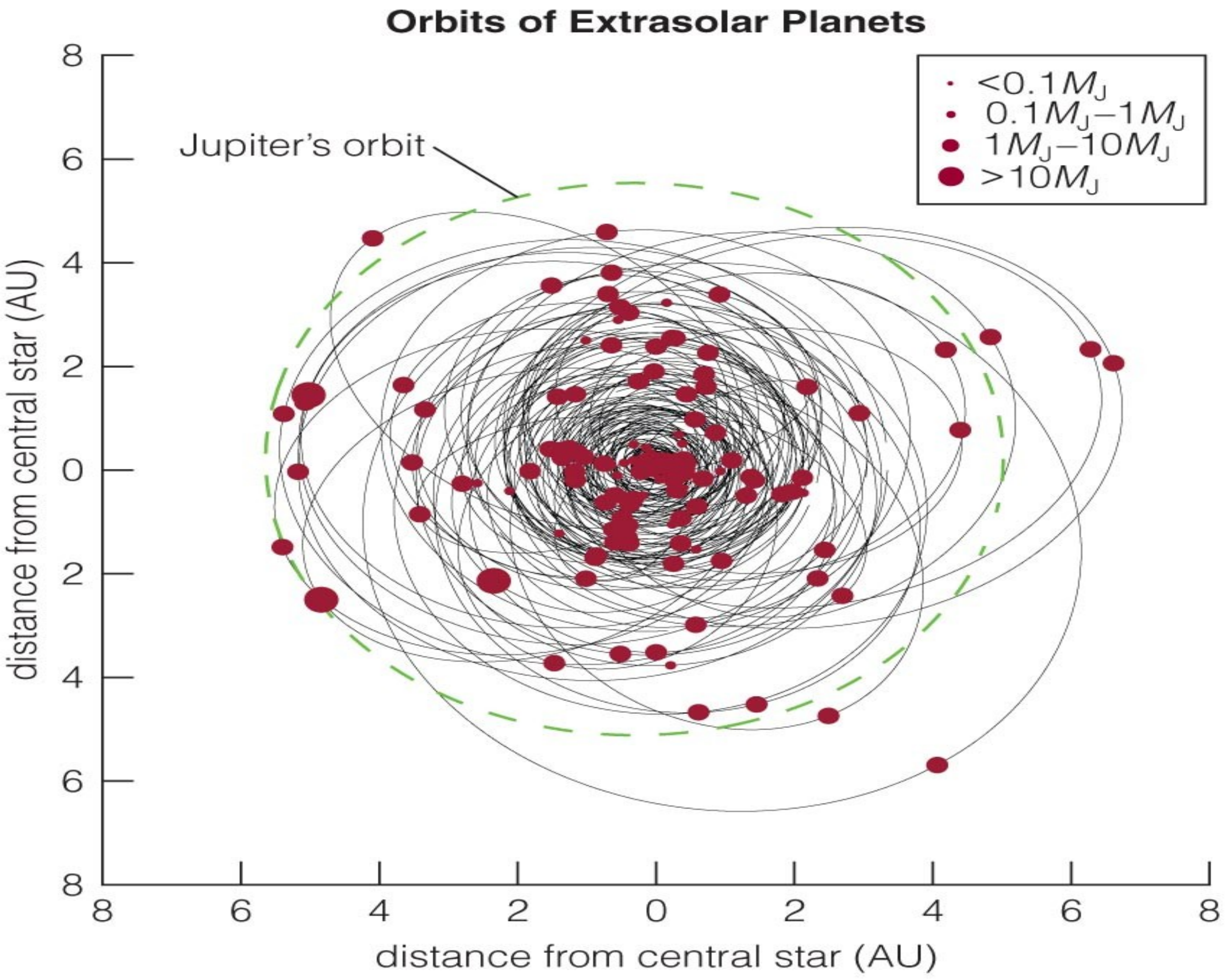
Aim to infer an exoplanet's bulk composition from its M and R



What have we learned about extrasolar planets?



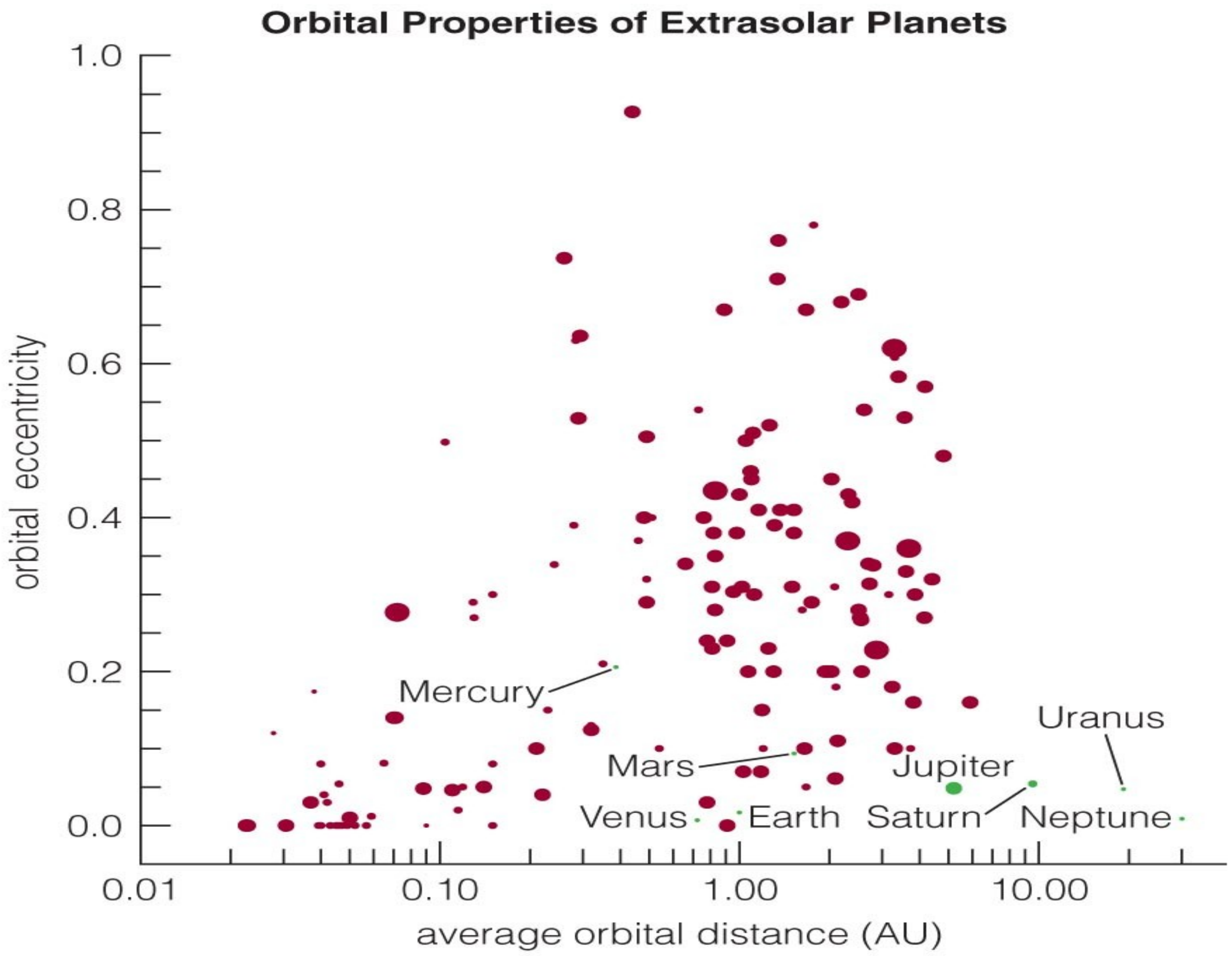
Orbits of Extrasolar Planets



Most of the detected planets have orbits smaller than Jupiter's.

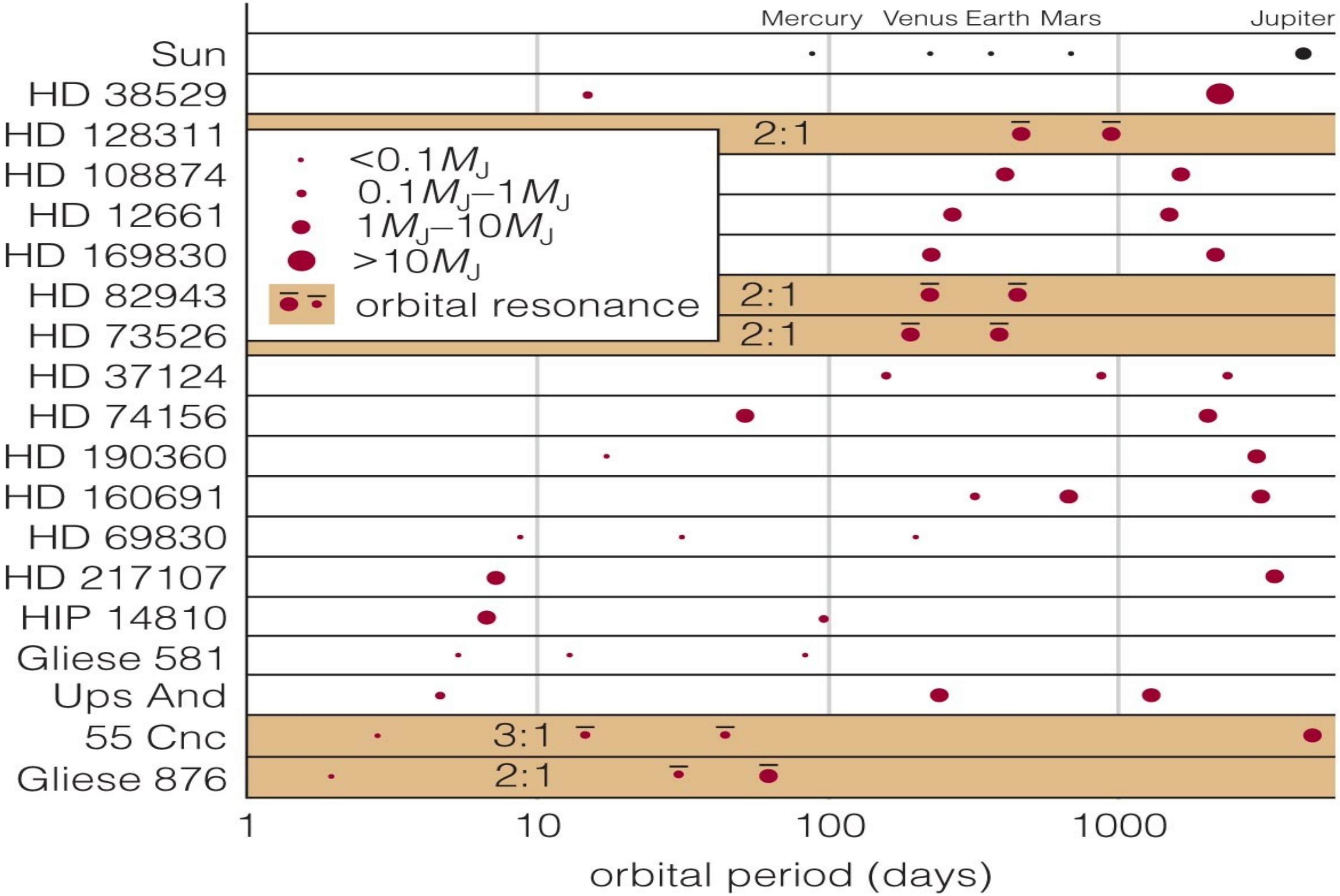
Planets at greater distances are harder to detect with the Doppler technique.

Orbits of Extrasolar Planets



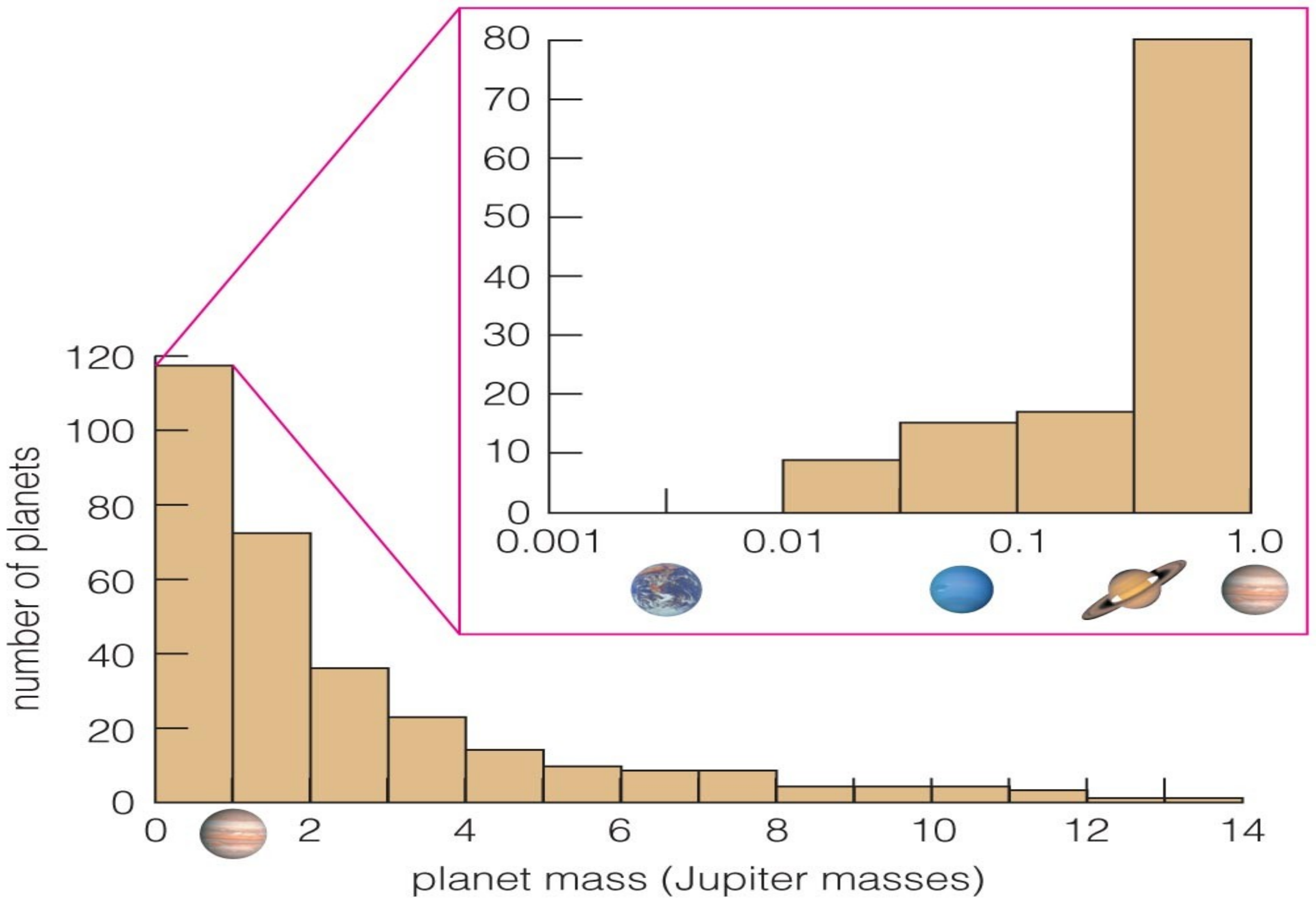
Orbits of some extrasolar planets are much more elongated (have a greater eccentricity) than those in our solar system.

Multiple-Planet Systems



Some stars have more than one detected planet.

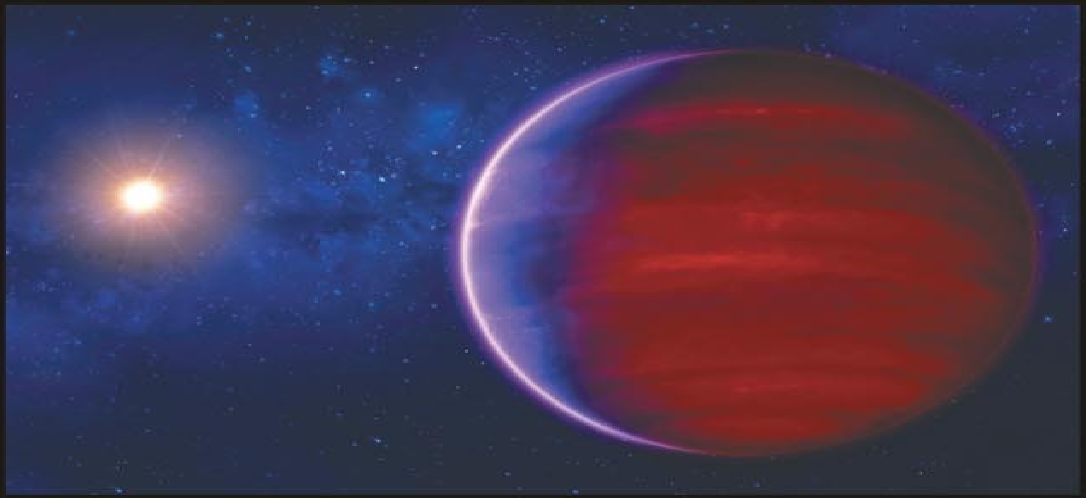
Orbits of Extrasolar Planets



Most of the detected planets have greater mass than Jupiter.

Planets with smaller masses are harder to detect with Doppler technique.

Hot Jupiters

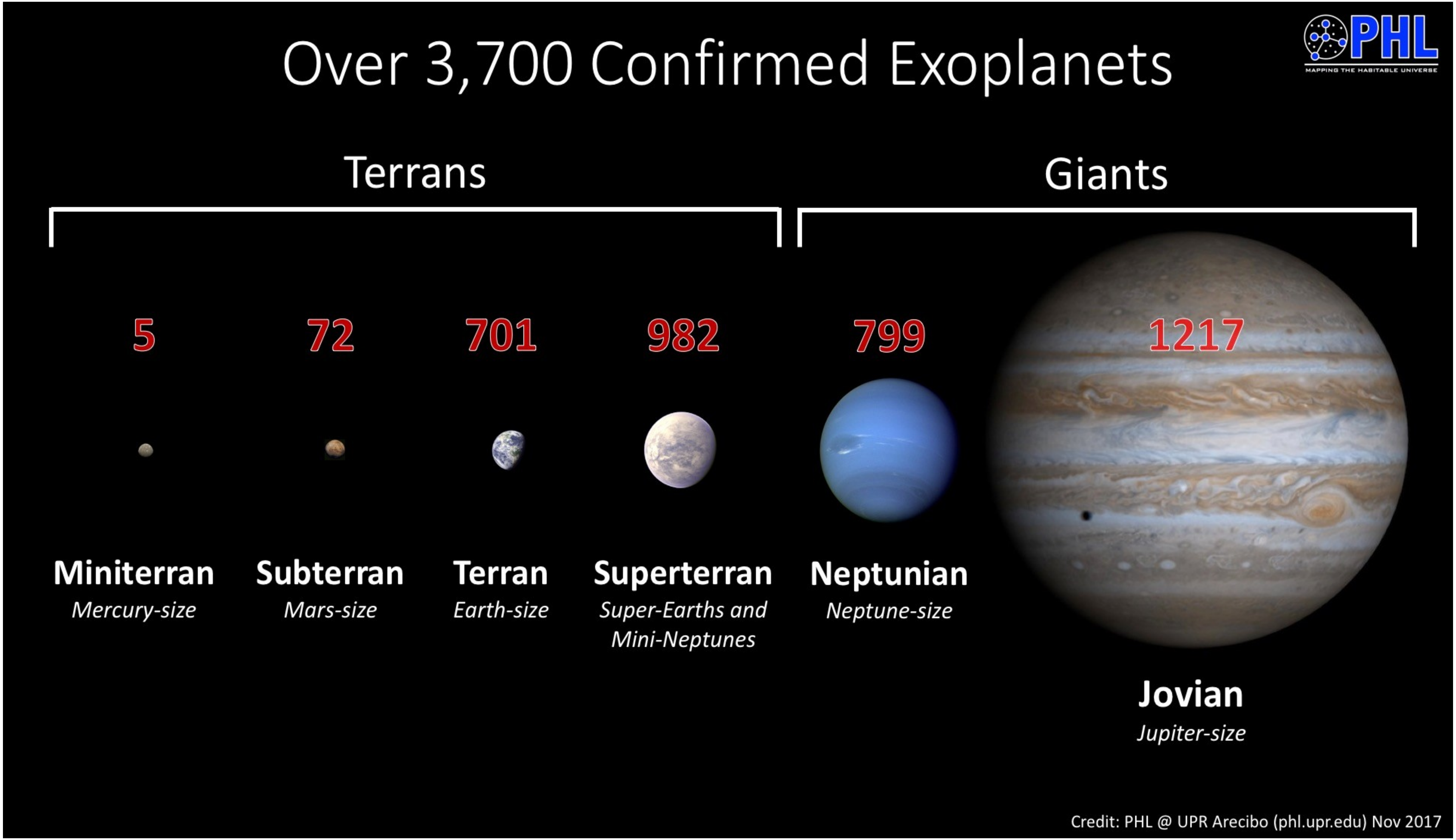


Jupiter

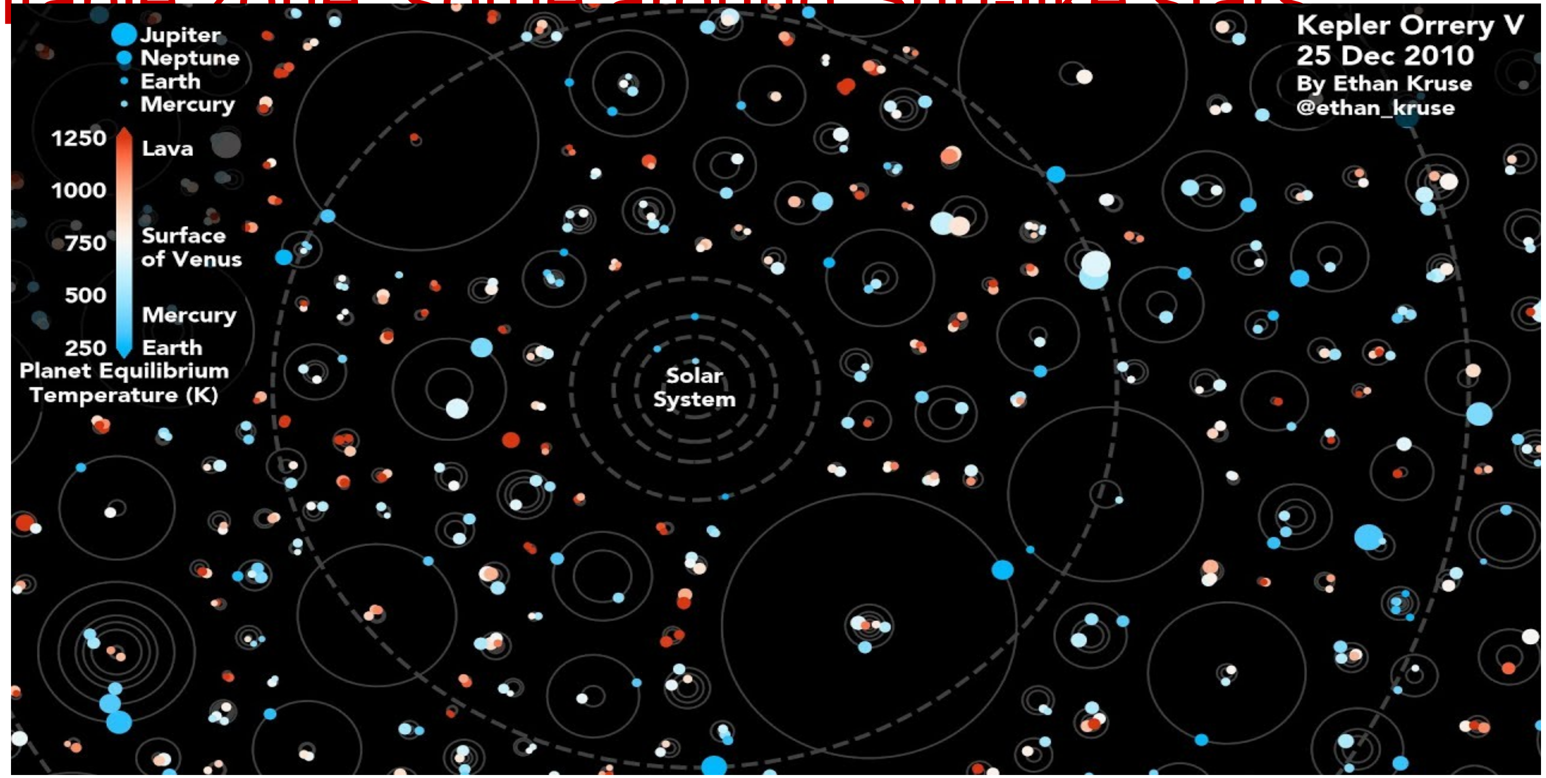
Composed primarily of hydrogen and helium
5 AU from the Sun
Orbit takes 12 Earth years
Cloudtop temperatures ≈130 K
Clouds of various hydrogen compounds
Radius = 1 Jupiter radius
Mass = 1 Jupiter mass
Average density = 1.33 g/cm^3
Moons, rings, magnetosphere

Hot Jupiters orbiting other stars

Composed primarily of hydrogen and helium
As close as 0.03 AU to their stars
Orbit as short as 1.2 Earth days
Cloudtop temperatures up to 1300 K
Clouds of “rock dust”
Radius up to 1.3 Jupiter radii
Mass from 0.2 to 2 Jupiter masses
Average density as low as 0.2 g/cm^3
Moons, rings, magnetospheres: unknown


Over 3,700 Confirmed Exoplanets
PHL
MAPPING THE HABITABLE UNIVERSE
Terrans
Giants
5
72
701
982
799
1217
Miniterran
Mercury-size
Subterran
Mars-size
Terran
Earth-size
Superterran
Super-Earths and Mini-Neptunes
Neptunian
Neptune-size
Jovian
Jupiter-size
Credit: PHL @ UPR Arecibo (phl.upr.edu) Nov 2017

As of January 2020, NASA's Kepler and TESS missions had identified 4374 planetary candidates yet to be confirmed, several of them being nearly Earth-sized and located in the habitable zone, some around Sun-like stars.

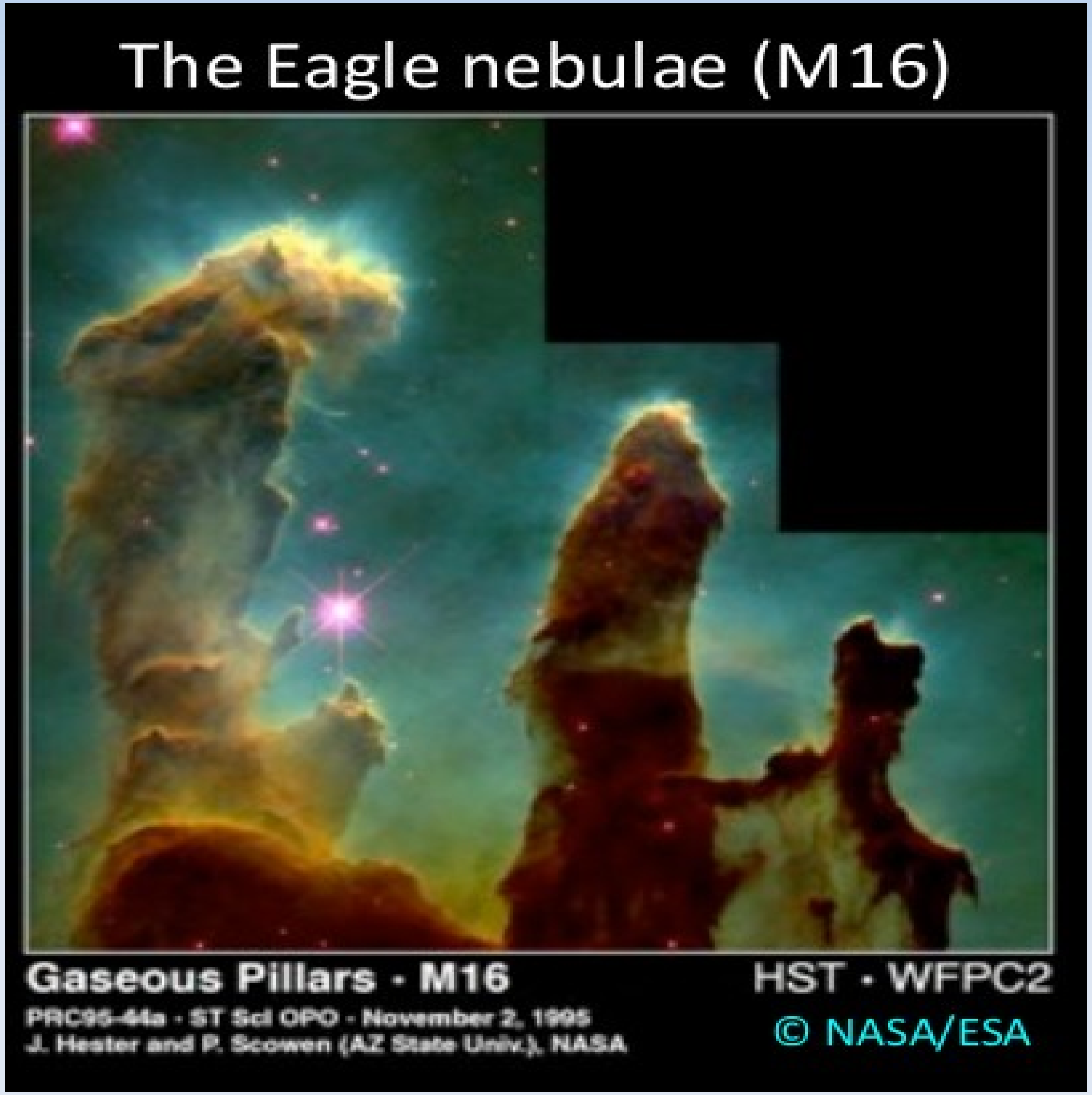


Now that we know how to detect them, how many exoplanets do we expect to find?

Solar nebula hypothesis

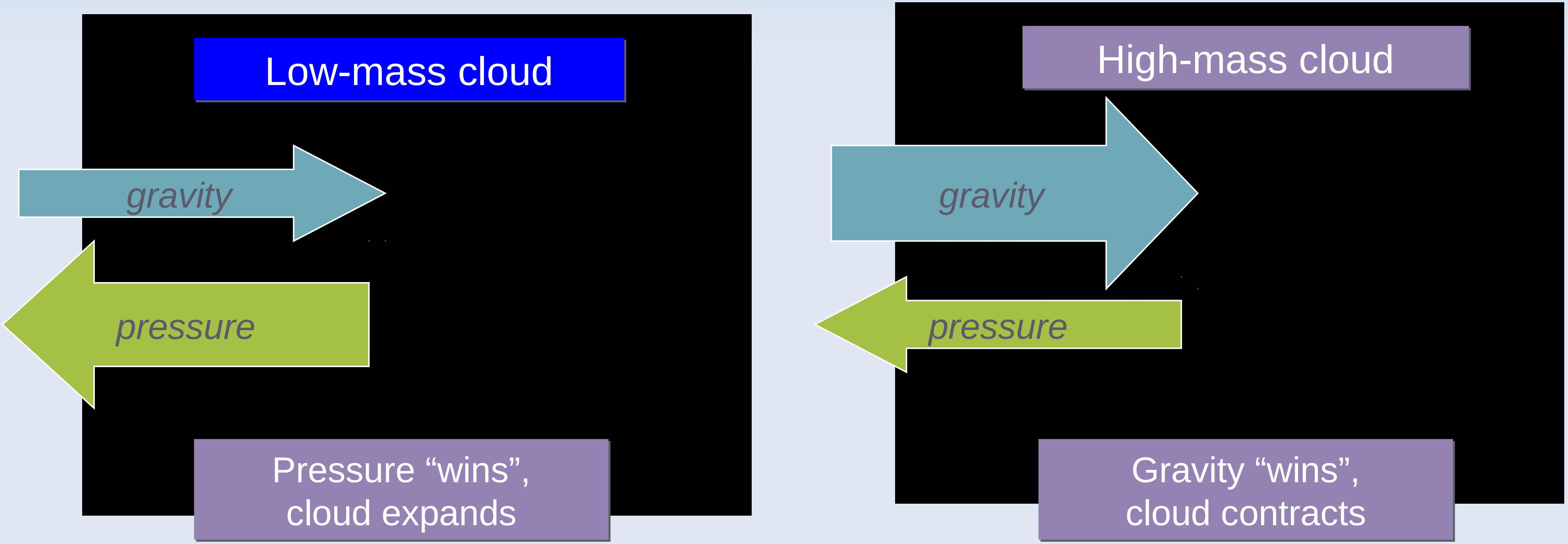
Planets formed within the disk of gas (mainly hydrogen) and fine ‘dust’ particles of heavier elements and molecules left over from earlier cycles of stellar evolution. As the relevant gas cloud collapses, initiated by complex processes of interstellar shock waves, the gas and dust falls into a giant flattened, circulating, pancake-like ‘protoplanetary’ disk.

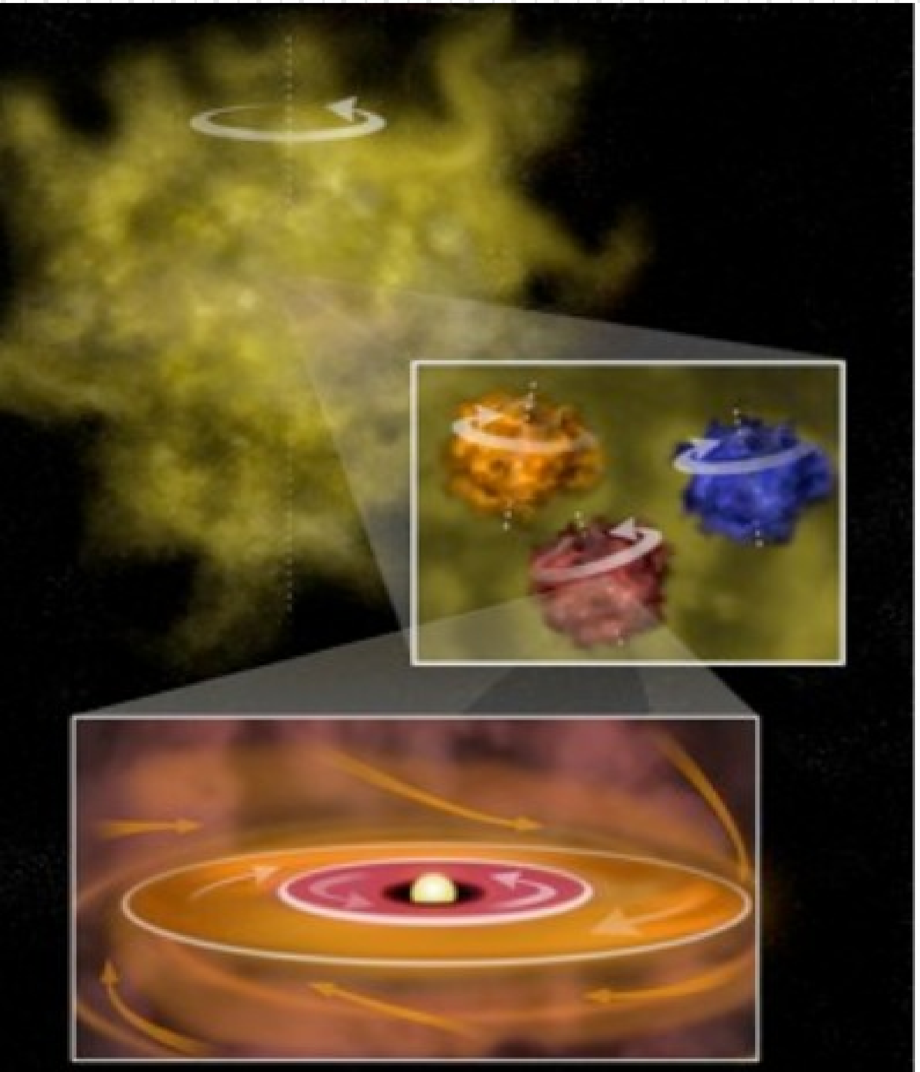
Star Formation



- Giant Molecular clouds
- Very thin, low-density cloud (10,000 atoms per cm^3)
- Very cold, T~10-20 K, so molecules can form --> molecular cloud
- Made mostly of H (75%) and He (23-25%) gas and a bit of heavier atoms (<2%).

If a nebula contains enough mass, it may begin to collapse because of gravity. Whether it succeeds in collapsing depends on the mass: pressure within the gas and dust opposes the collapse.

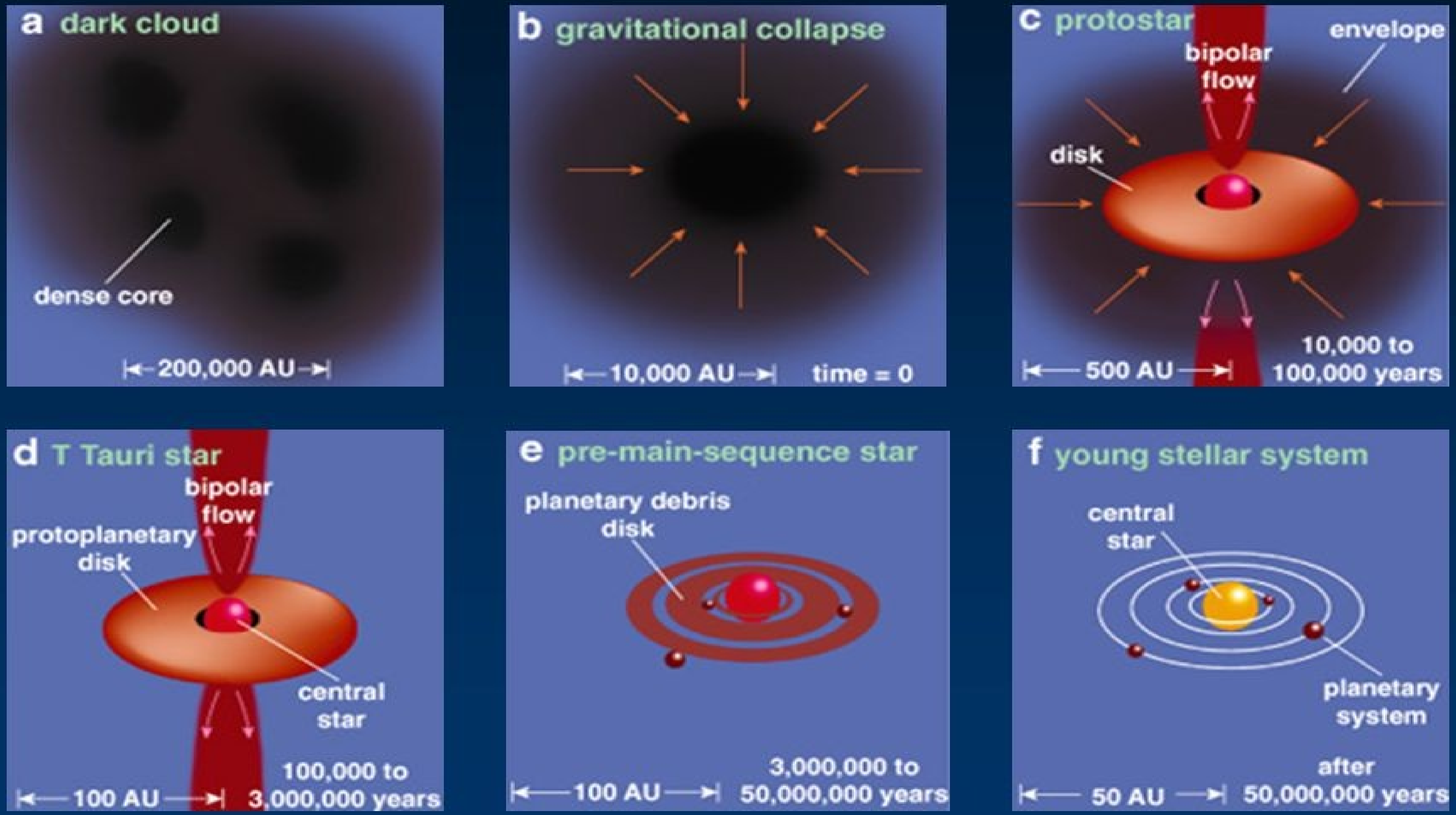




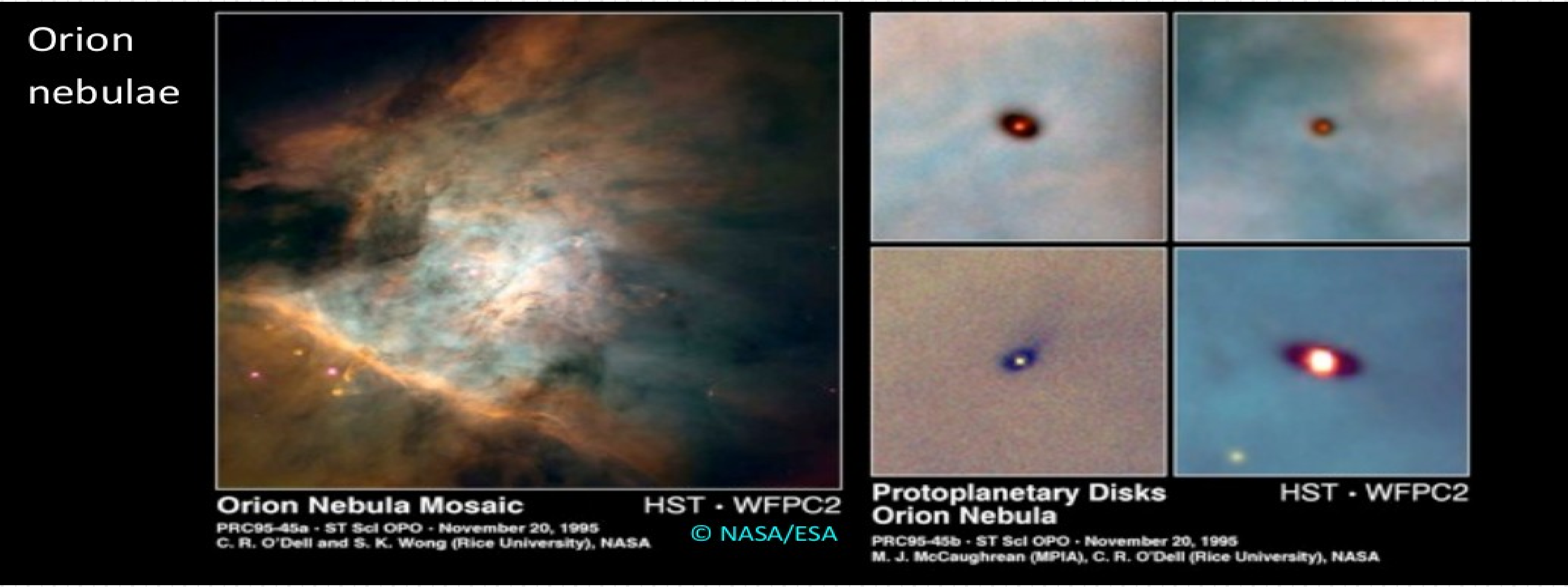
Star and planet formation (sketch)

- Collapse of a molecular cloud
  - under its own gravitation
  - fragmentation
- Conservation of angular momentum
  => increase of rotation
- Formation of a disk
- Planet formation in the disk
  - from the dust and gas in the disk

Obligatory star & planet formation slide



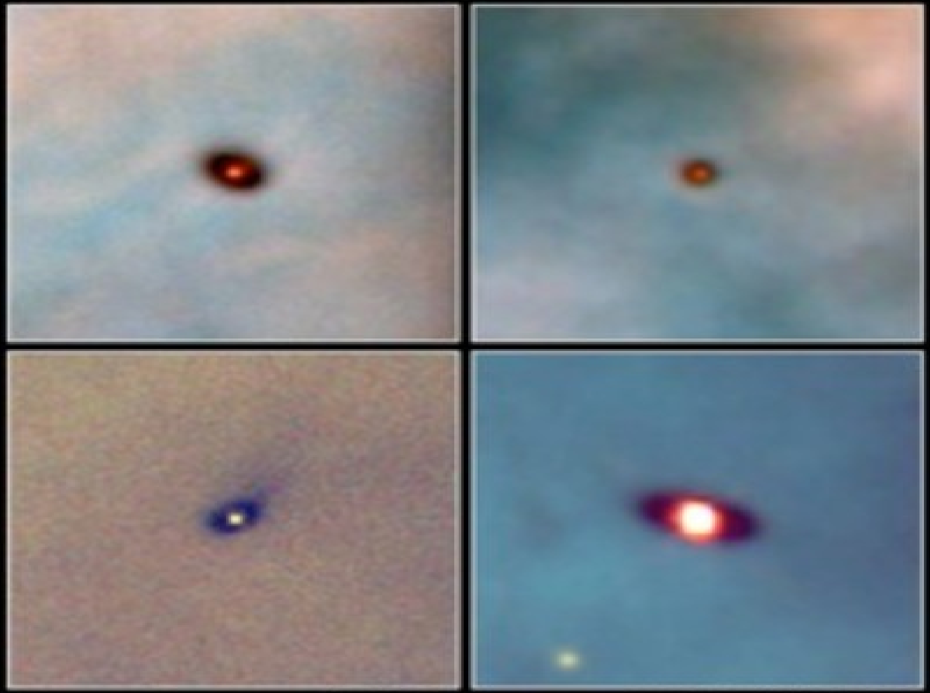
Star forming regions



Star forming regions – image of protoplanetary disks

Orion nebulae

Edge-On Protoplanetary Disk HST · WFPC2
Orion Nebula
PRC95-45c · ST ScI OPO · November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA



Protoplanetary Disks HST · WFPC2
Orion Nebula
PRC95-45b · ST ScI OPO · November 20, 1995
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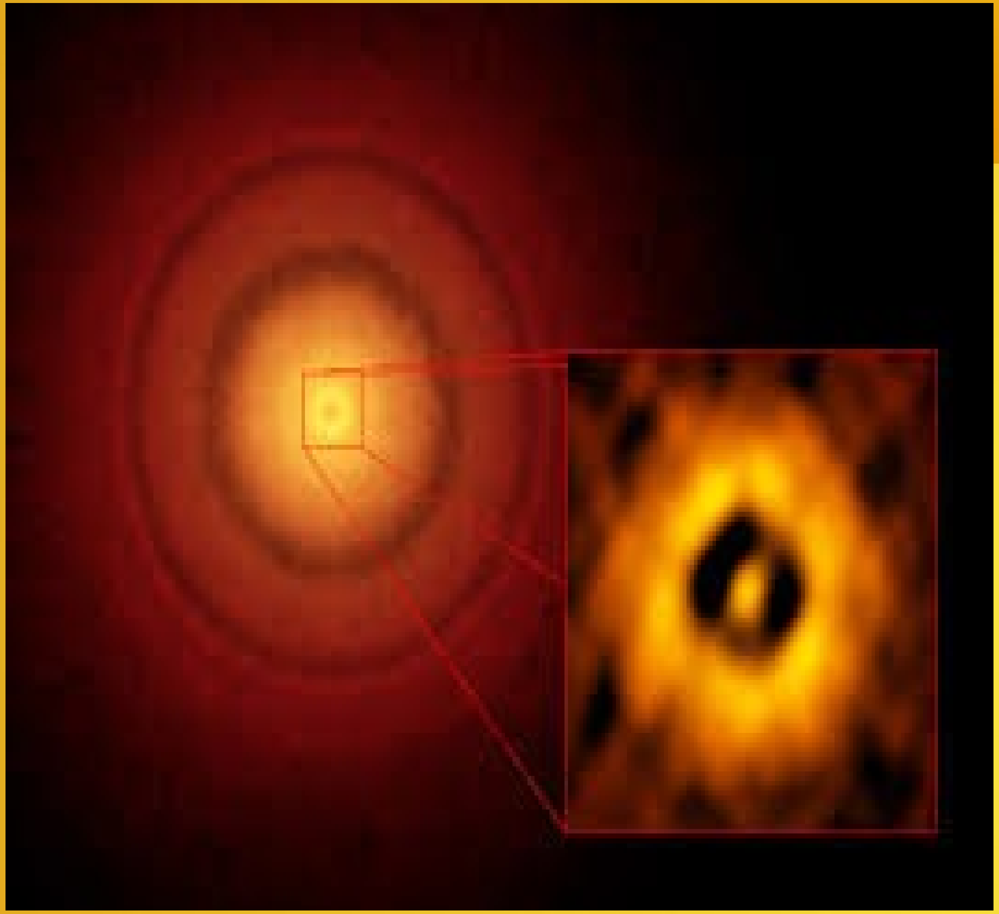
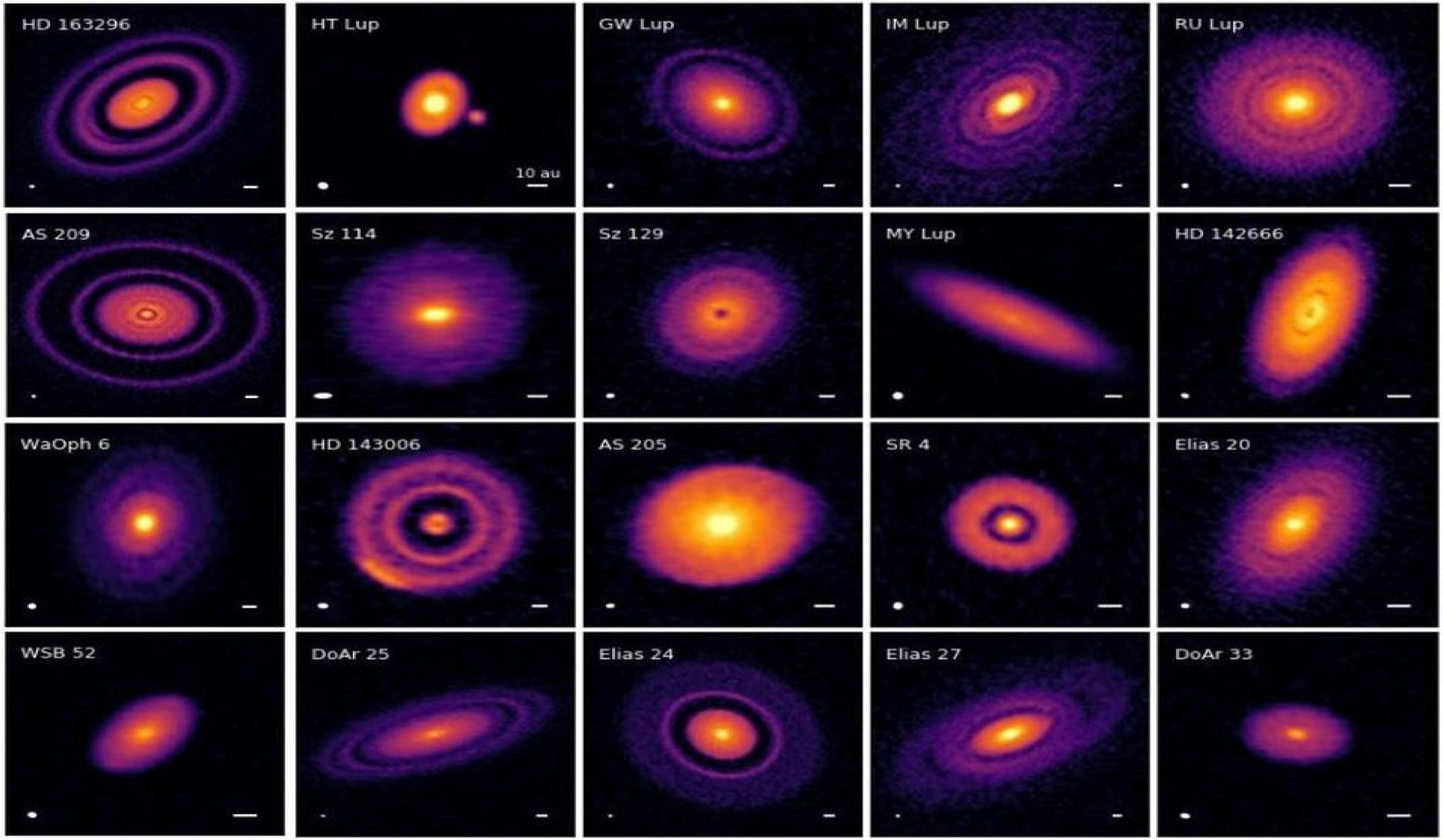


ALMA image of TW Hydrae

Zooms in on the gap nearest to the star, which is at the same distance as the Earth is from the Sun, suggesting an infant version of our home planet could be emerging from the dust and gas.
The additional concentric light and dark features represent other planet-forming regions farther out in the disk.
Credit: S. Andrews (Harvard-Smithsonian CfA), ALMA (ESO/NAOJ/NRAO)


HD 163296
HT Lup
10 au
GW Lup
IM Lup
RU Lup
AS 209
Sz 114
Sz 129
MY Lup
HD 142666
WaOph 6
HD 143006
AS 205
SR 4
Elias 20
WSB 52
DoAr 25
Elias 24
Elias 27
DoAr 33

Planetary Formation is a by product of Star Formation

Planets are Common!!

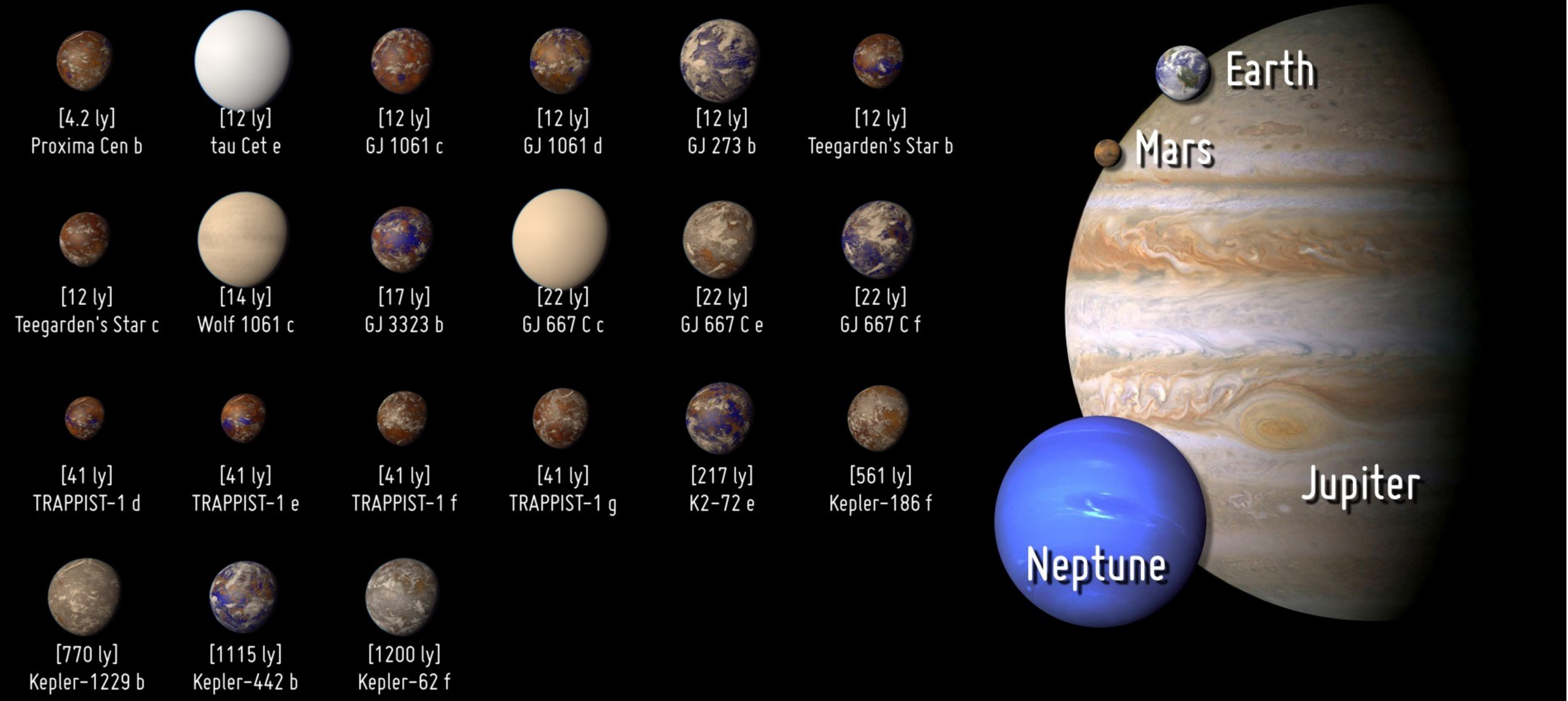
Almost every star has planet(s)

What is our goal?

Habitable Planets: Goldilocks Zone

Potentially Habitable Exoplanets

Ranked by Distance from Earth (light years)



Artistic representations. Earth, Mars, Jupiter, and Neptune for scale. Distance from Earth is between brackets.

CREDIT: PHL @ UPR Arecibo (phl.upr.edu) Sep 4, 2019

Nobel Winner Michel Mayor Says

We'll Never Colonise Exoplanets.


Look again at that dot.
That's here.
That's home.
That's us.

Take Aways

- Very likely all stars, or nearly all stars, have planets based on our current detection rates, keeping in mind our limitations.

- At least a few percent of systems with planets, and likely more, have Earth-like planets. Worst case scenario: tens of millions in the Milky Way.
 Previous space-based exoplanet missions like Kepler and CoRoT along with ground-based facilities such as HARPS, WASP, HIRES and KELT have shown us that exoplanets are ubiquitous.

 Hot Jupiters

- Big planets farther out, Cthonian worlds, water worlds, super Earths, rogues
- Some highly eccentric orbits
- "Tatooine" – planets in binary star systems (which are common)

- **FIELD IS CHANGING FAST –CHECK THE WEB/APPS!**

And the most imp…….


Today's science fiction is tomorrow's science fact.
Isaac Asimov