“Time is an illusion, lunchtime doubly so.”
The Hitchhiker’s Guide to the Galaxy

Test 1 on Monday (Feb 26)
You cannot use your phone for a calculator, so bring one.

Asteroids and comets

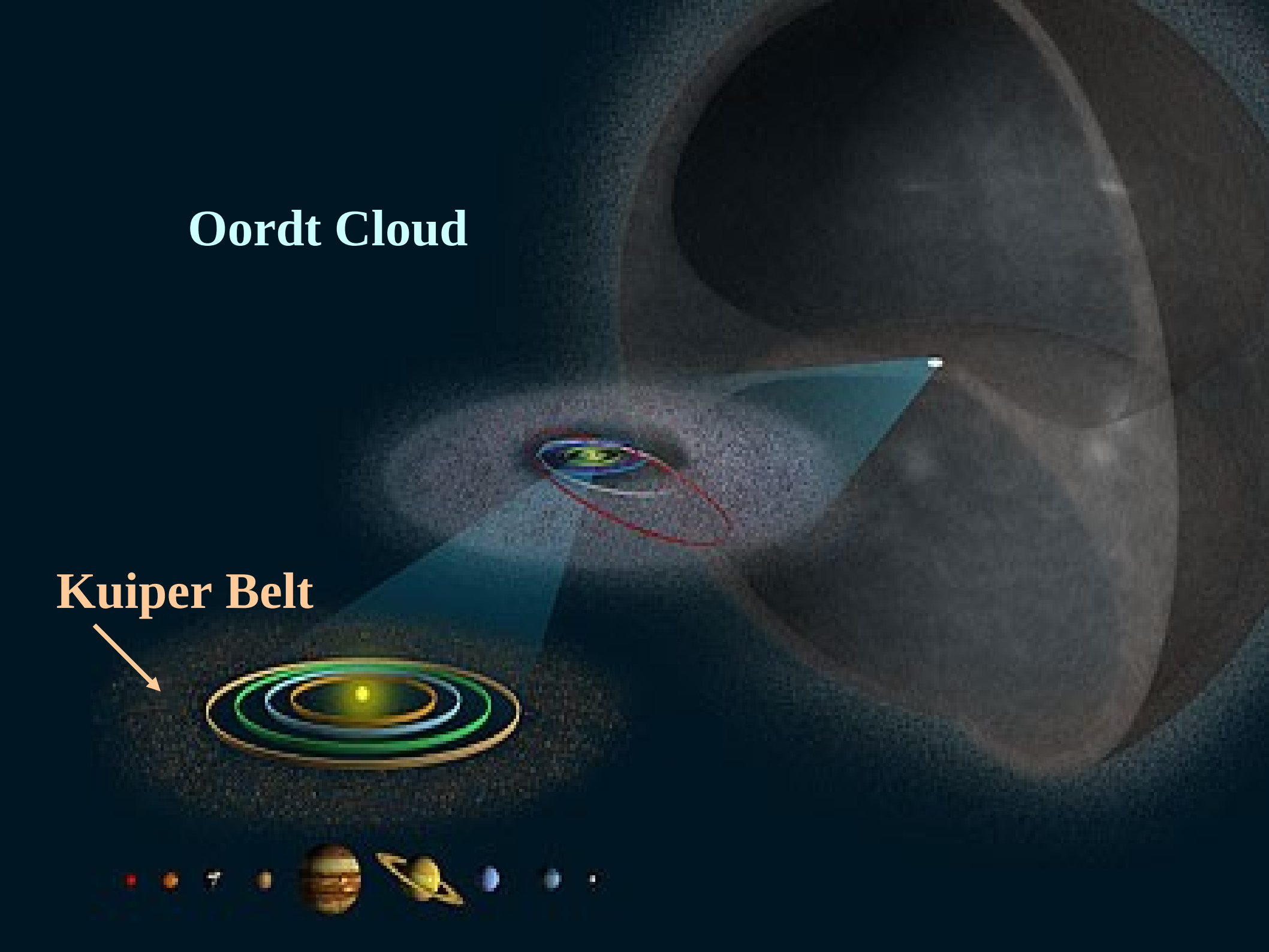
These are smaller objects in our solar system.

Important point: Asteroids indicate a transition from the inner solar system, which is rocky, to the outer solar system, which is colder, and therefore icy.

Important point:

Comets provide the structure of the outer solar system beyond the planets.

The Kuiper belt and furthest is called the Oort Cloud


Oordt Cloud
Kuiper Belt

One last item to inventory: The Sun.

It spins prograde, is made mostly of H and then He, and contains 99.87% of the mass of our entire solar system!

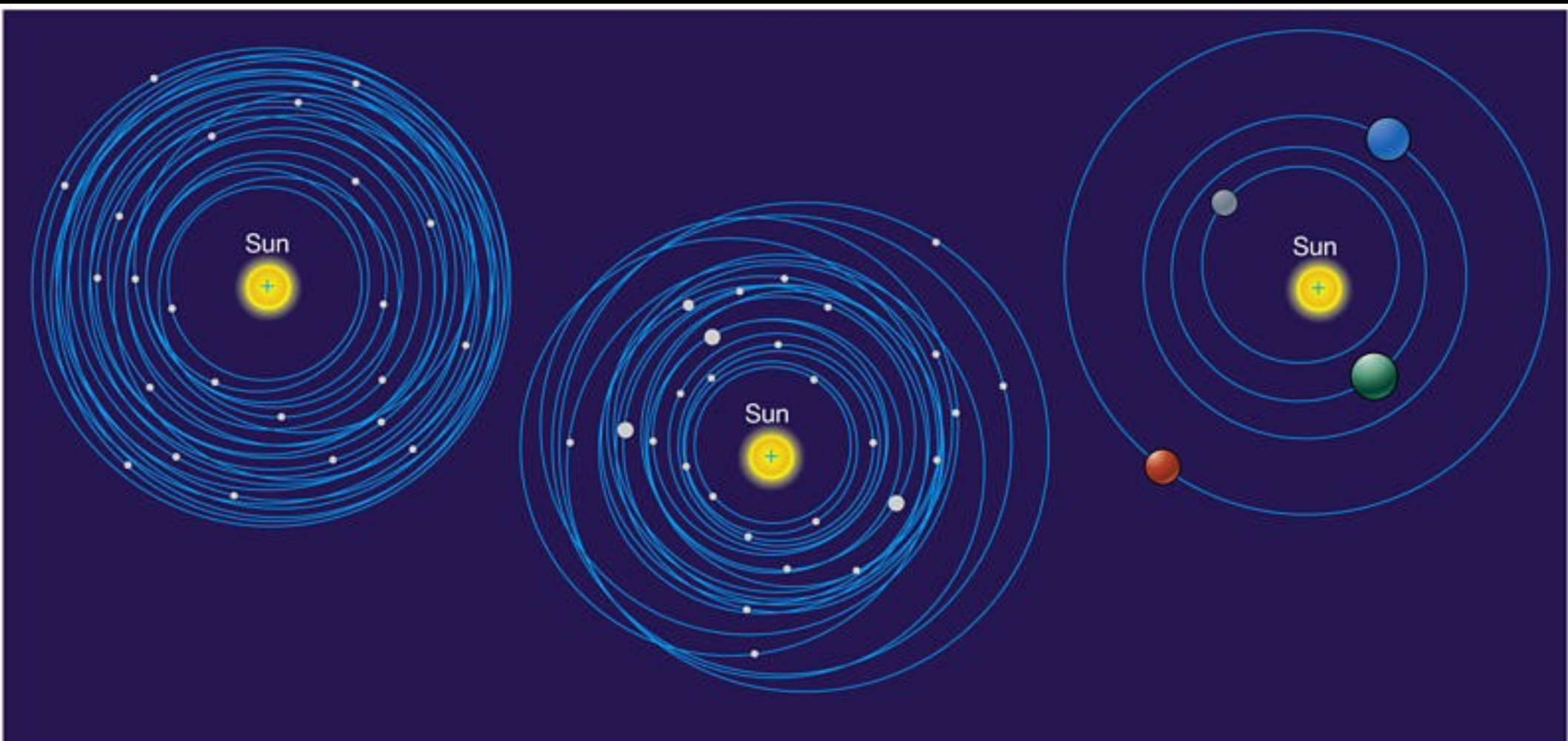
Making our solar system

Solar system observations:

- All planets orbit in the same direction and nearly on the same (ecliptic) plane.
- Nearly all planets and major moons spin (and orbit) in the same direction.
- Terrestrial planets are close to the Sun, Jovian planets are farther from the Sun.
- The asteroid belt goes from rocky to icy
- Short period comets orbit near the ecliptic plane, longer period comets orbit in any direction.
- Most massive object (Sun) at the center.
- Made mostly of H (92% by # of atoms, 70% by mass).


raw material.
Giant molecular
cloud.

Terrestrial planets: gas in disk cools → rock dust → pebbles → rocks → boulders → planetessimals → planets (NO ICE)

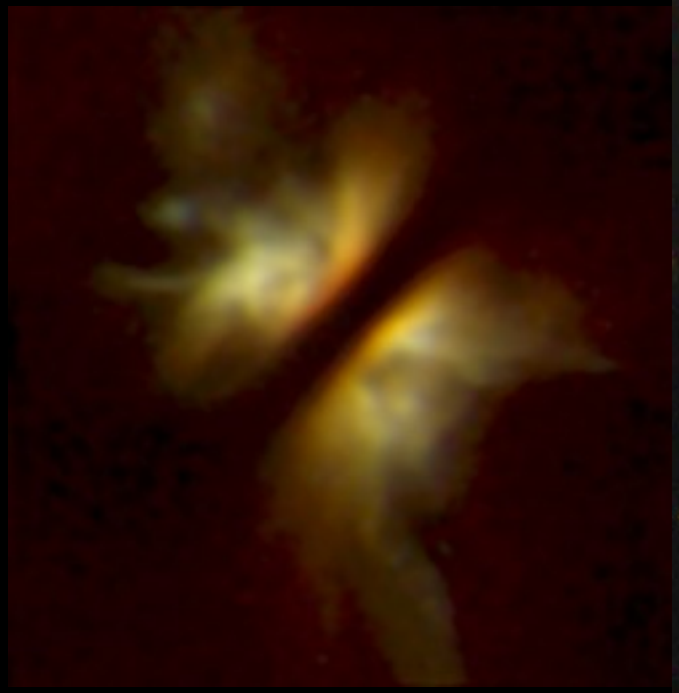


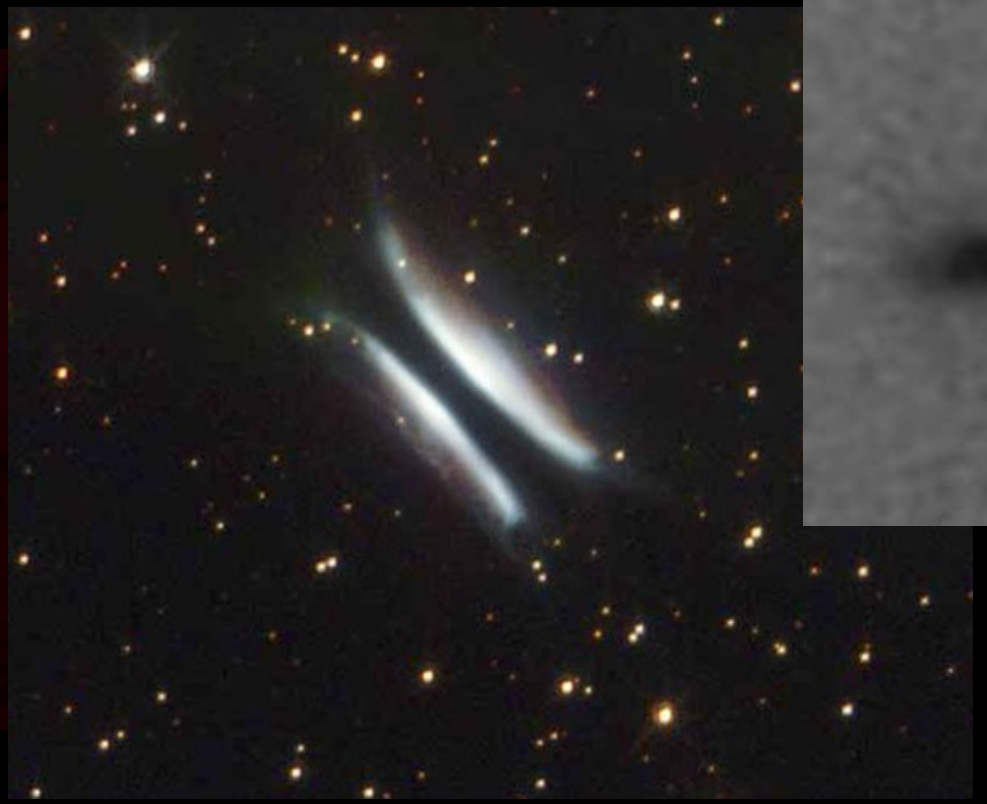
Gas giant Planets

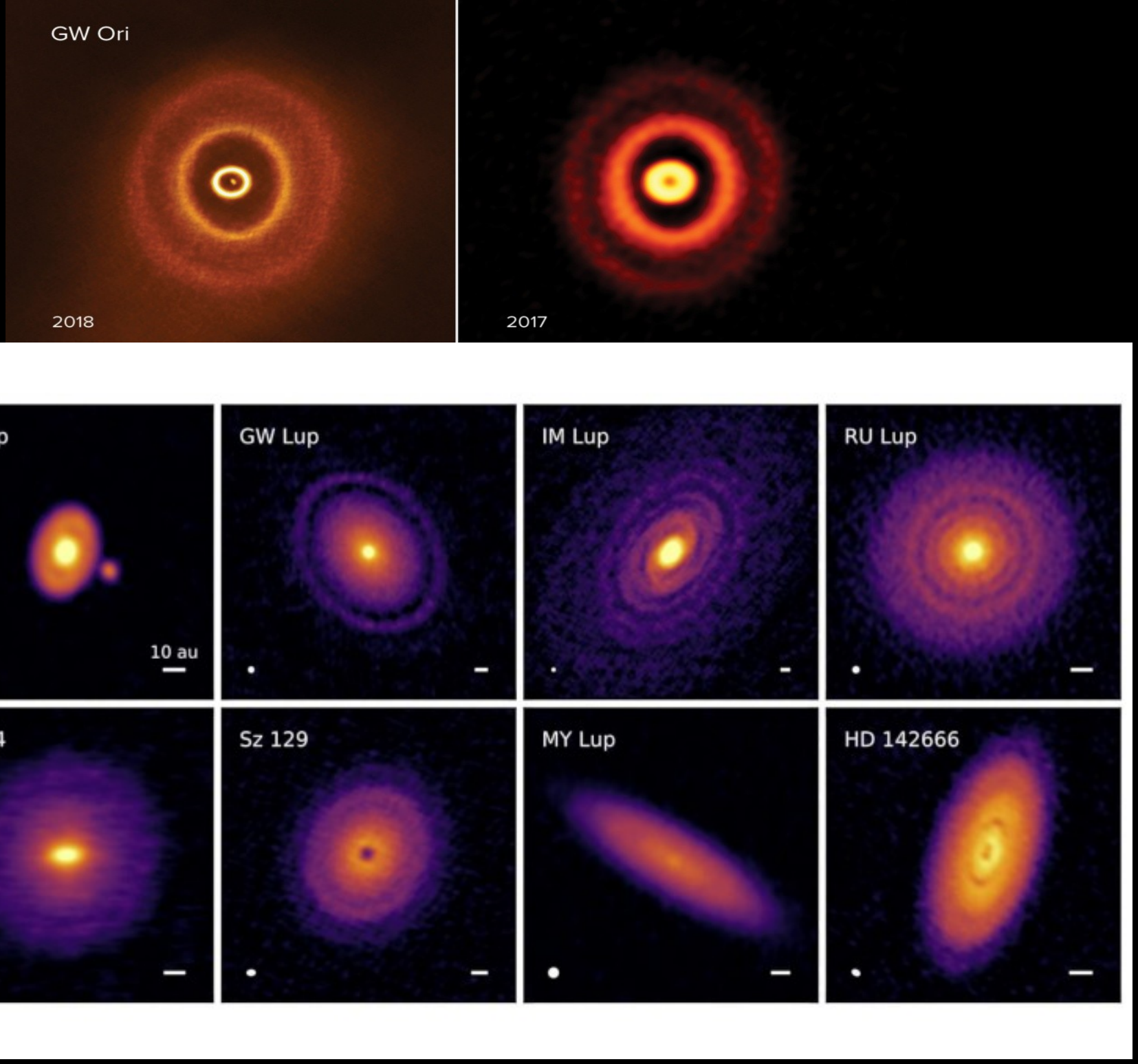
gas in disk cools → rock dust → Pebbles → boulders → +ice → massive cores → +H → massive planets.

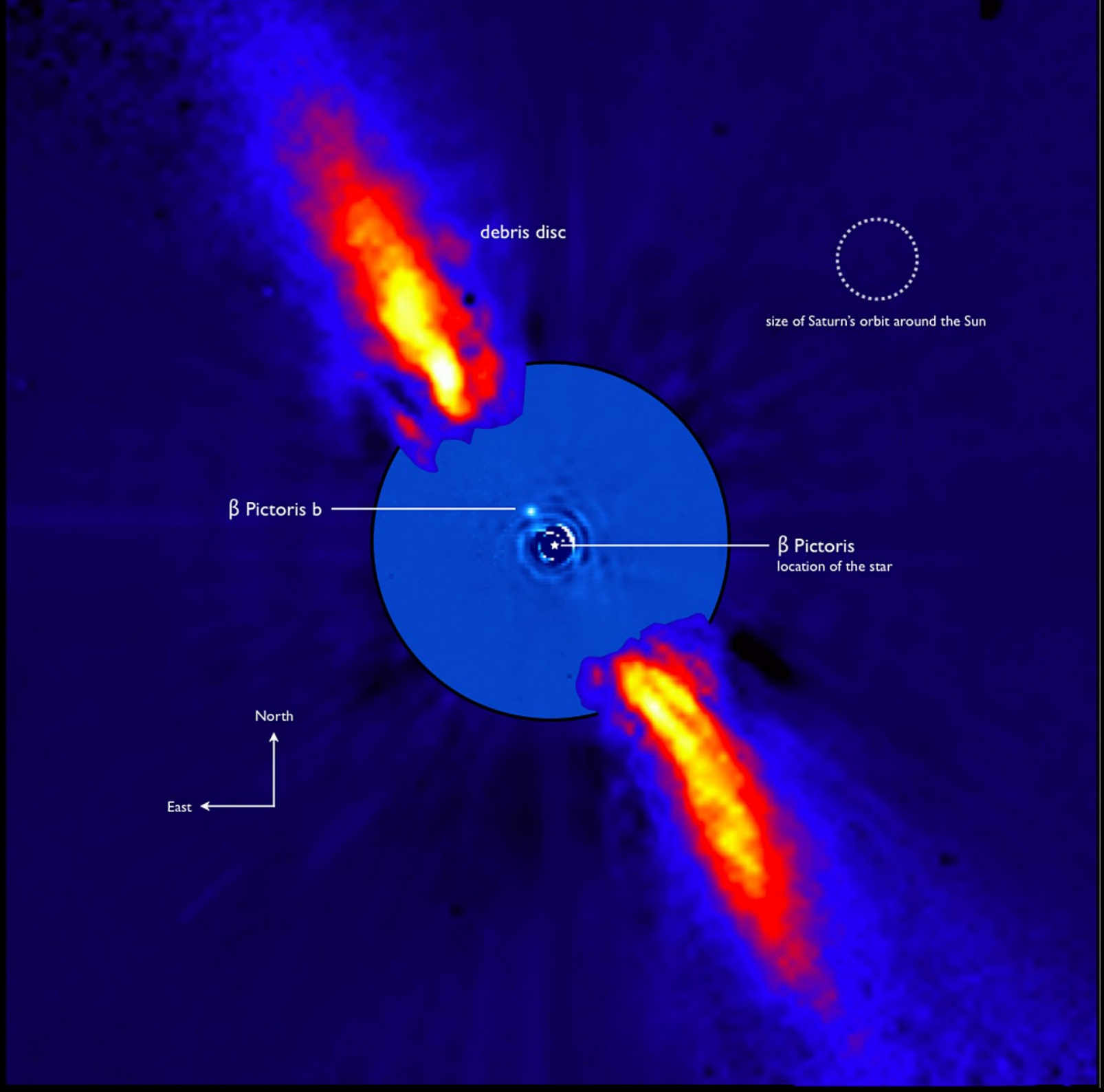
Option 2: A ‘swirl’ in the disk collapse altogether to form a gas giant planet in 1 step.

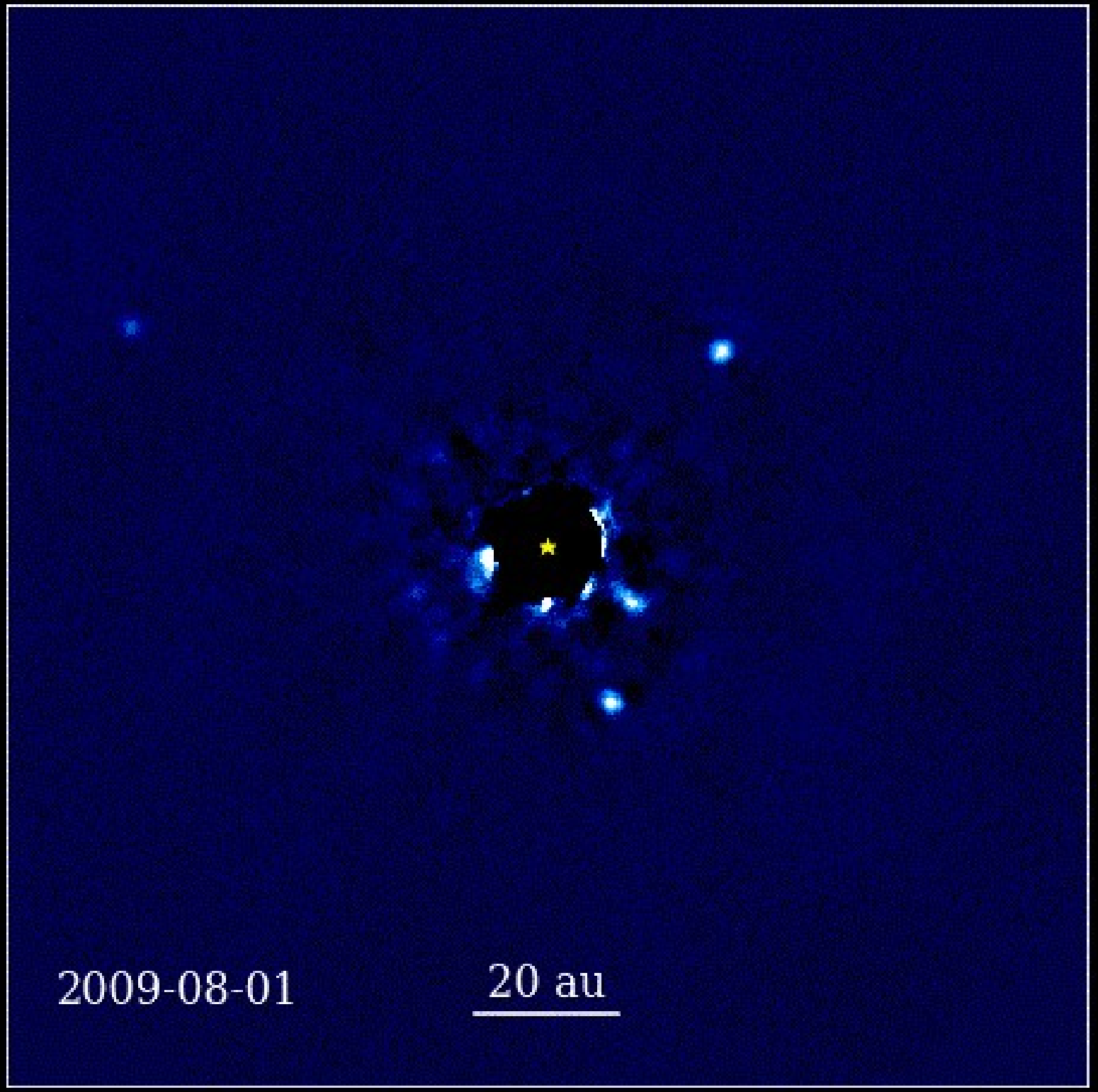
We see solar systems in the process of forming






GW Ori
2018
2017
HT Lup
10 au
GW Lup
IM Lup
RU Lup
Sz 114
Sz 129
MY Lup
HD 142666

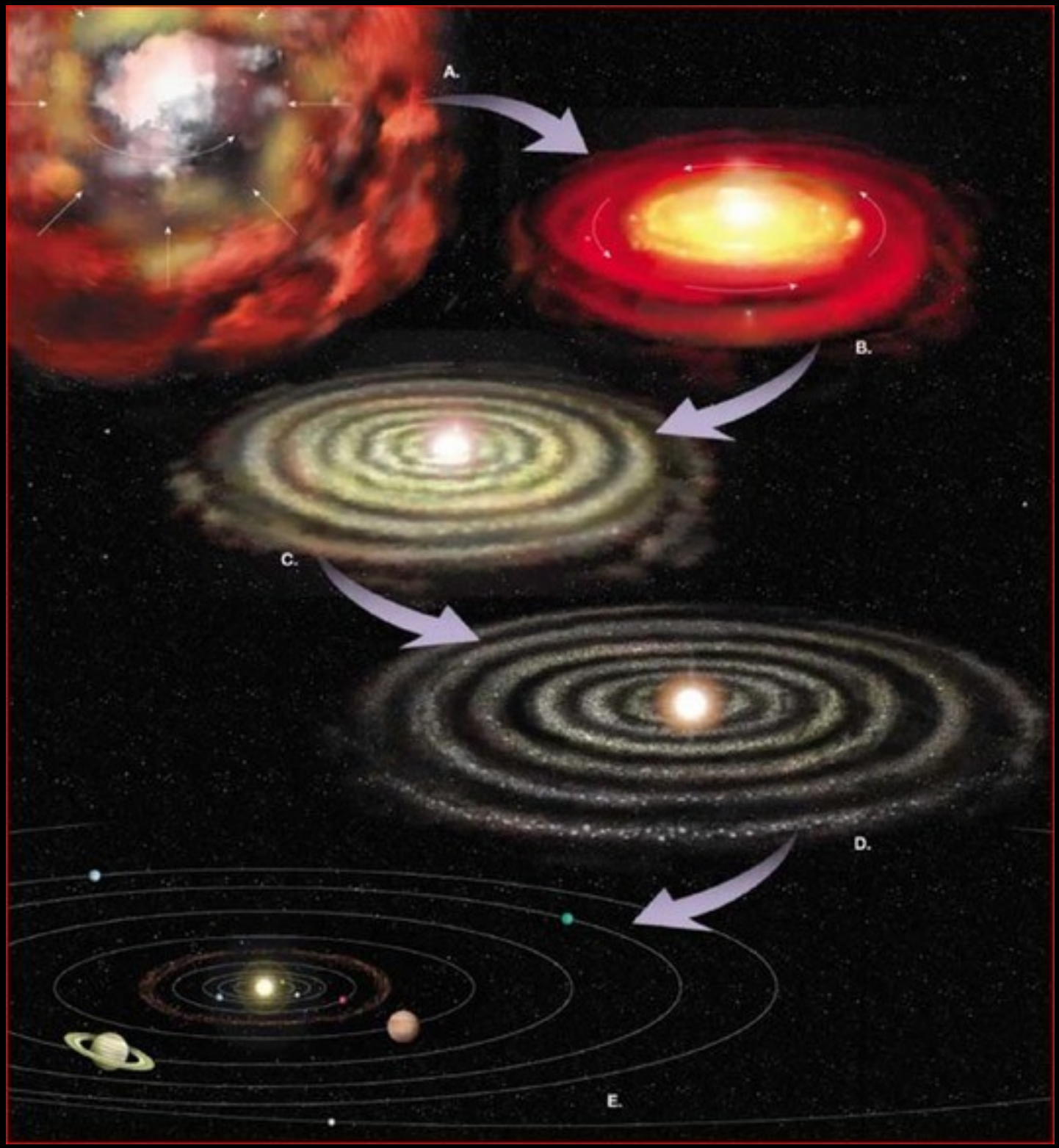

debris disc
size of Saturn's orbit around the Sun
β Pictoris b
β Pictoris
location of the star
North
East


2009-08-01
20 au

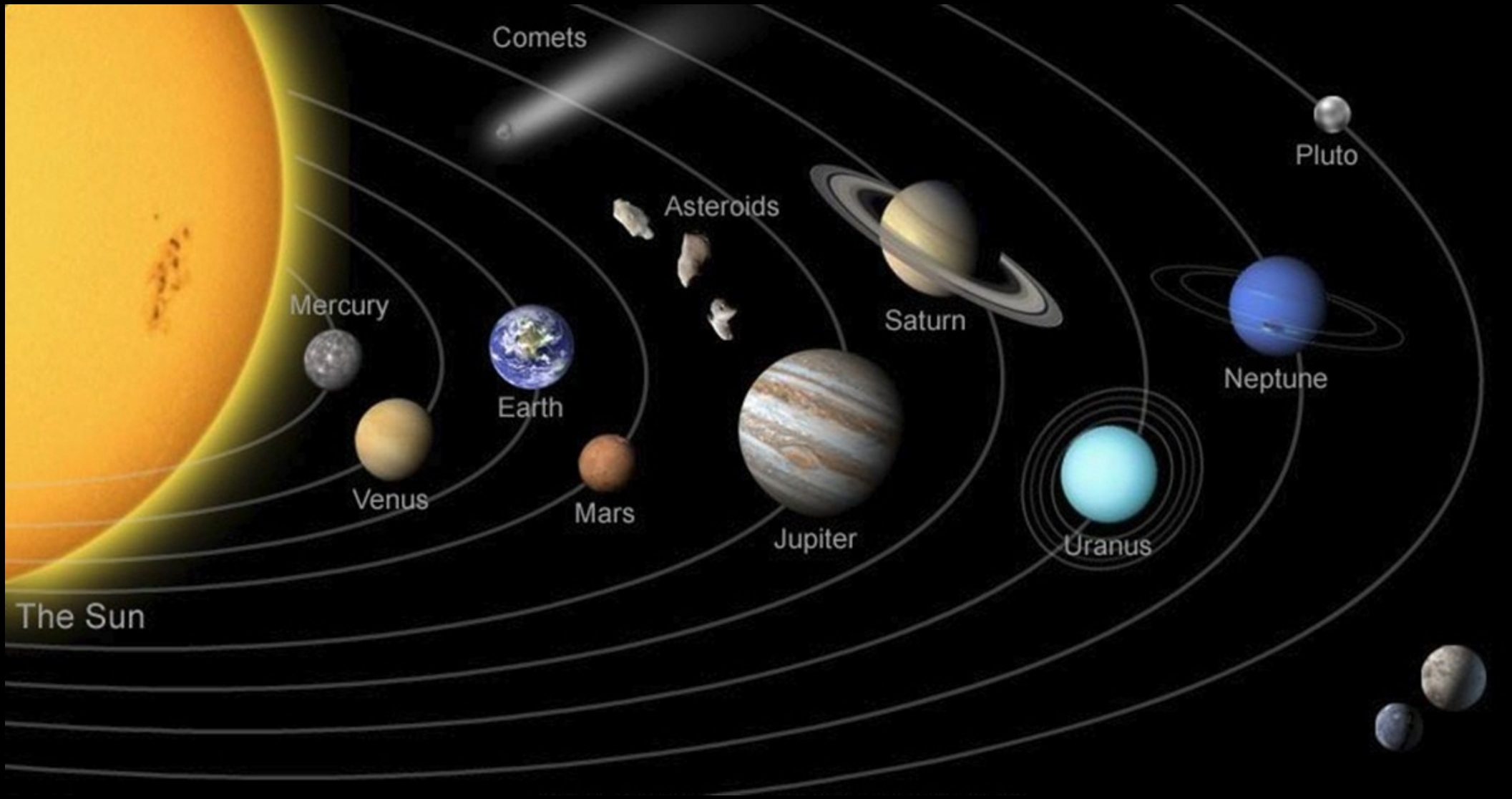
The entire solar system was forming together, at the same time.

It took roughly 50-100 million years in total.

The solar system is now 4,600 million years old.


A.
B.
C.
D.
E.

Our very ordered solar system.



Terrestrial planets form close to stars, where it is warm.
Gas giants must form past the ice line, to gain sufficient mass to hold H.

Quiz 5: what is the structure of Uranus and Neptune?

A) Thin atmosphere over rocky crust, rocky mantle, rocky core.

B) H atmosphere over liquid H over liquid metallic H over rocky core.

C) H atmosphere over liquid/ice water/ammonia/methane mantle over rocky core

D) Ice crust over liquid water ocean over rocky mantle over rocky core.

E) None of the above.

We now have 1 example of solar system formation!

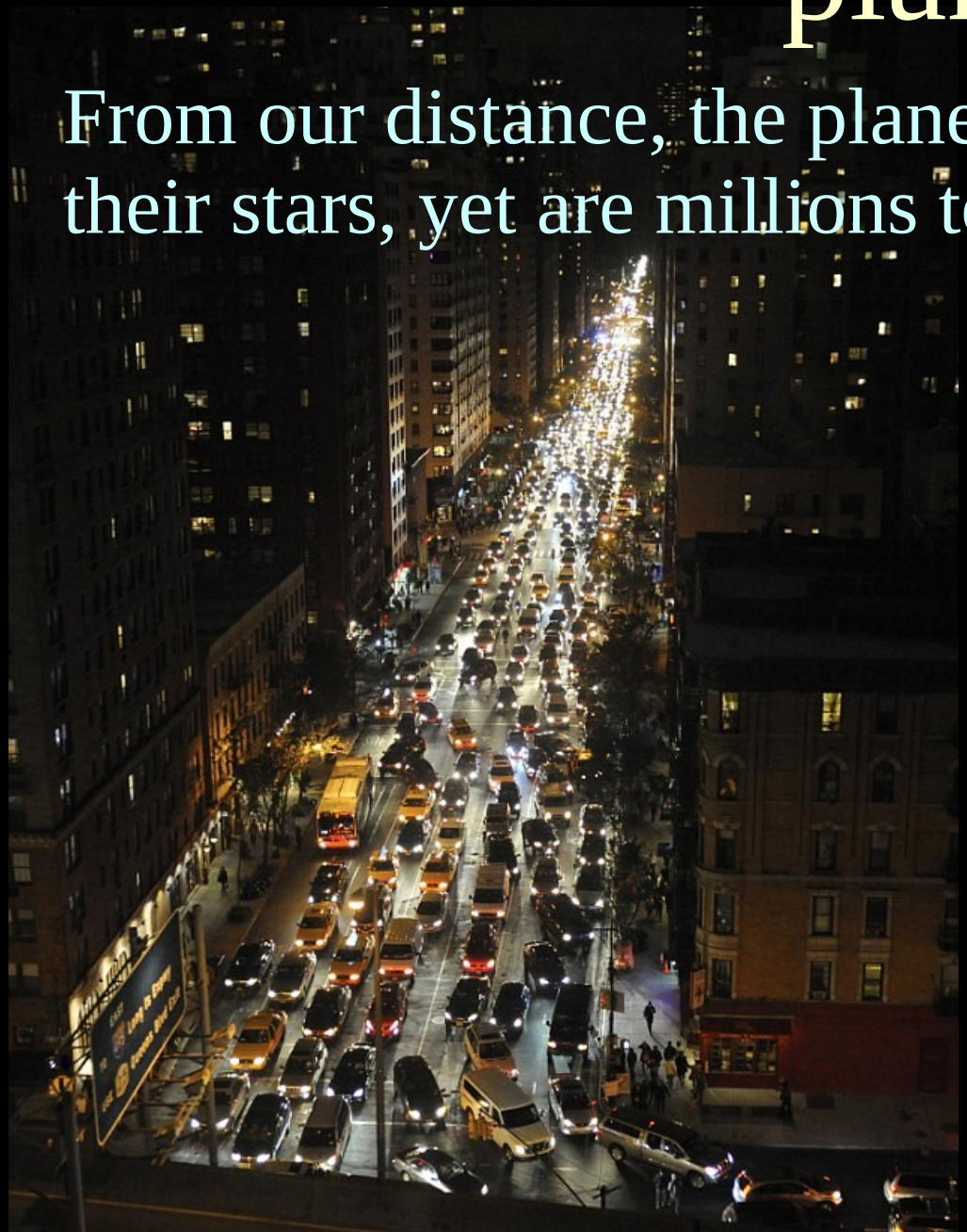
We need to apply the scientific method and observe other solar systems before we can determine if the theory is correct.

Planets around other stars- exoplanets


90% of all
stars have
planets!

How are they finding these planets?

From our distance, the planets appear right on top of their stars, yet are millions to billions of times fainter.



Finding exoplanets: 4 methods.

1) Doppler (radial velocity) wobble

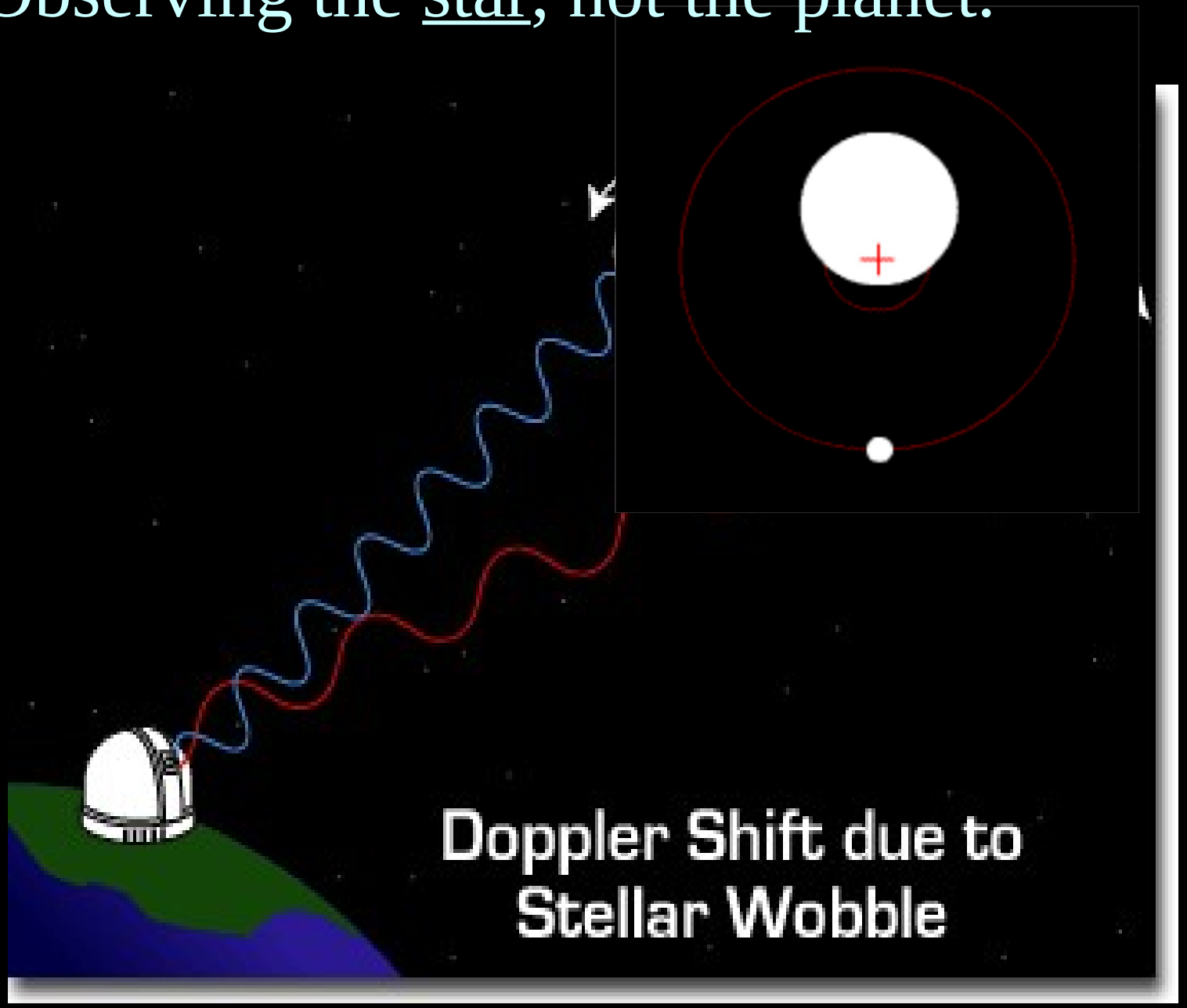
2) Transits

3) Microlensing

4) Direct imaging

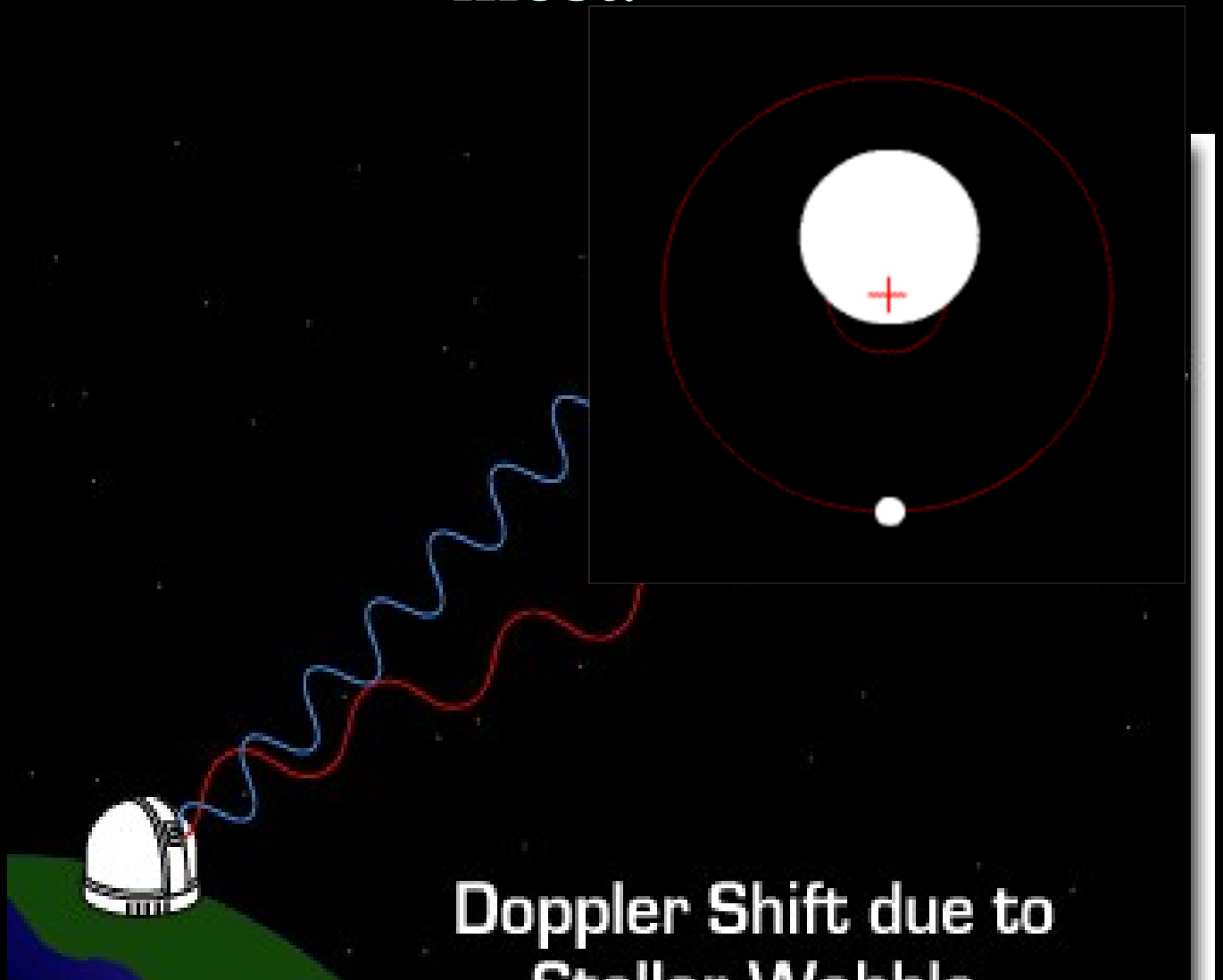
1) Doppler (radial velocity) shift

Observing the star, not the planet.



This was the first successful method of finding exoplanets.

Biased to large/close planets which move stars the most.

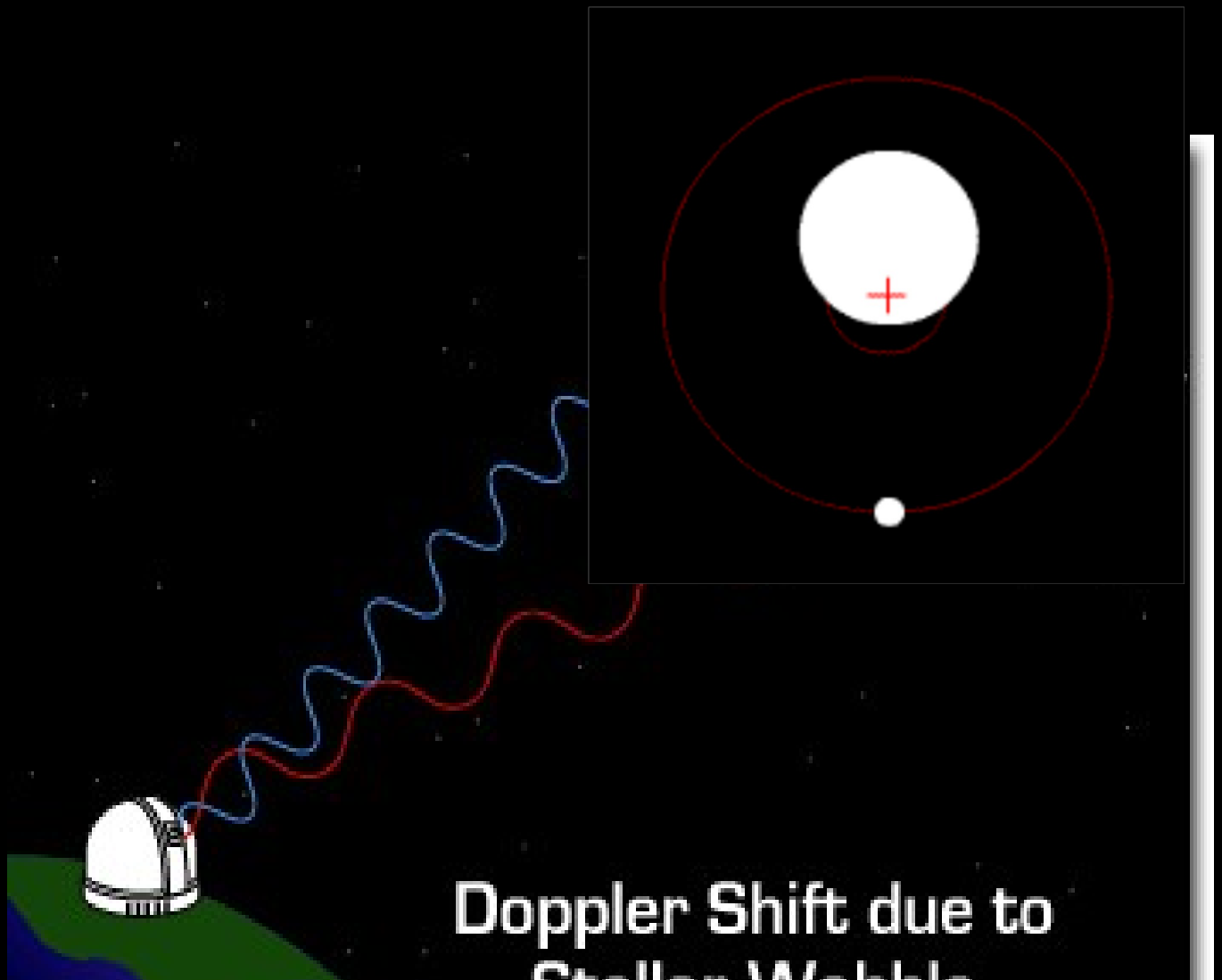


Biased to large/close planets which move stars the most.

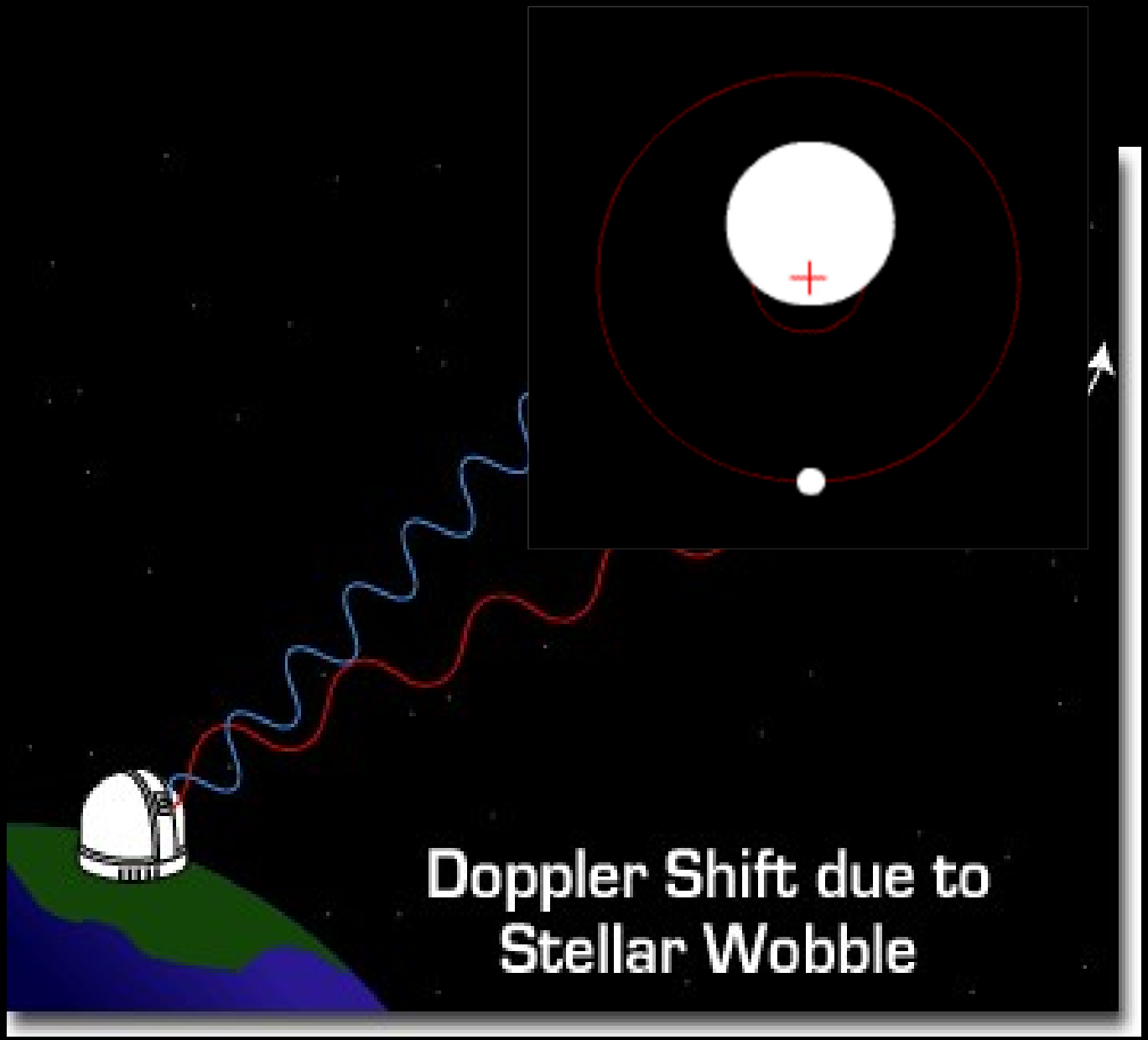
So the first planets discovered were Jupiter in size, but with orbits of a few days.

Artists conceptions- we have NO actual images of exoplanet surfaces.

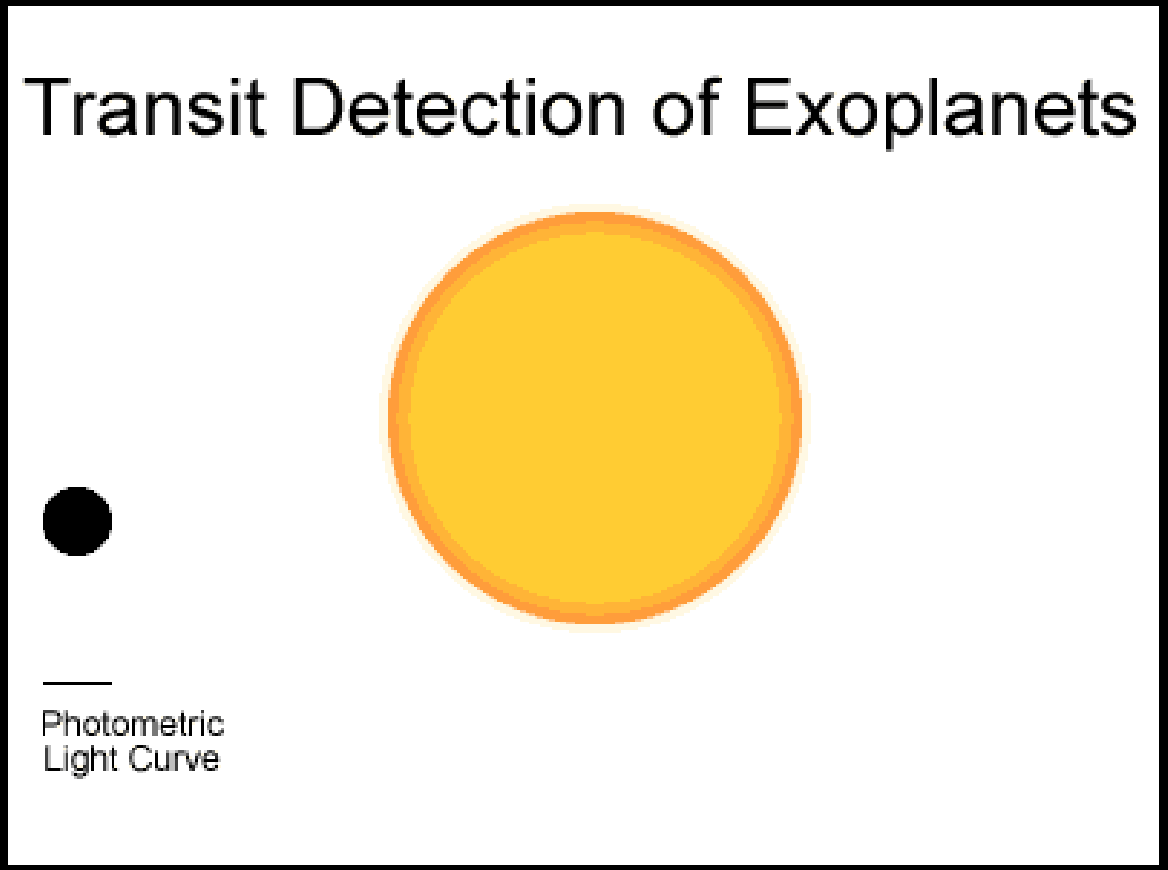
Requires at least 2 orbits for detection. Jupiter's orbital period is 12 years. Could we have found Jupiter yet?



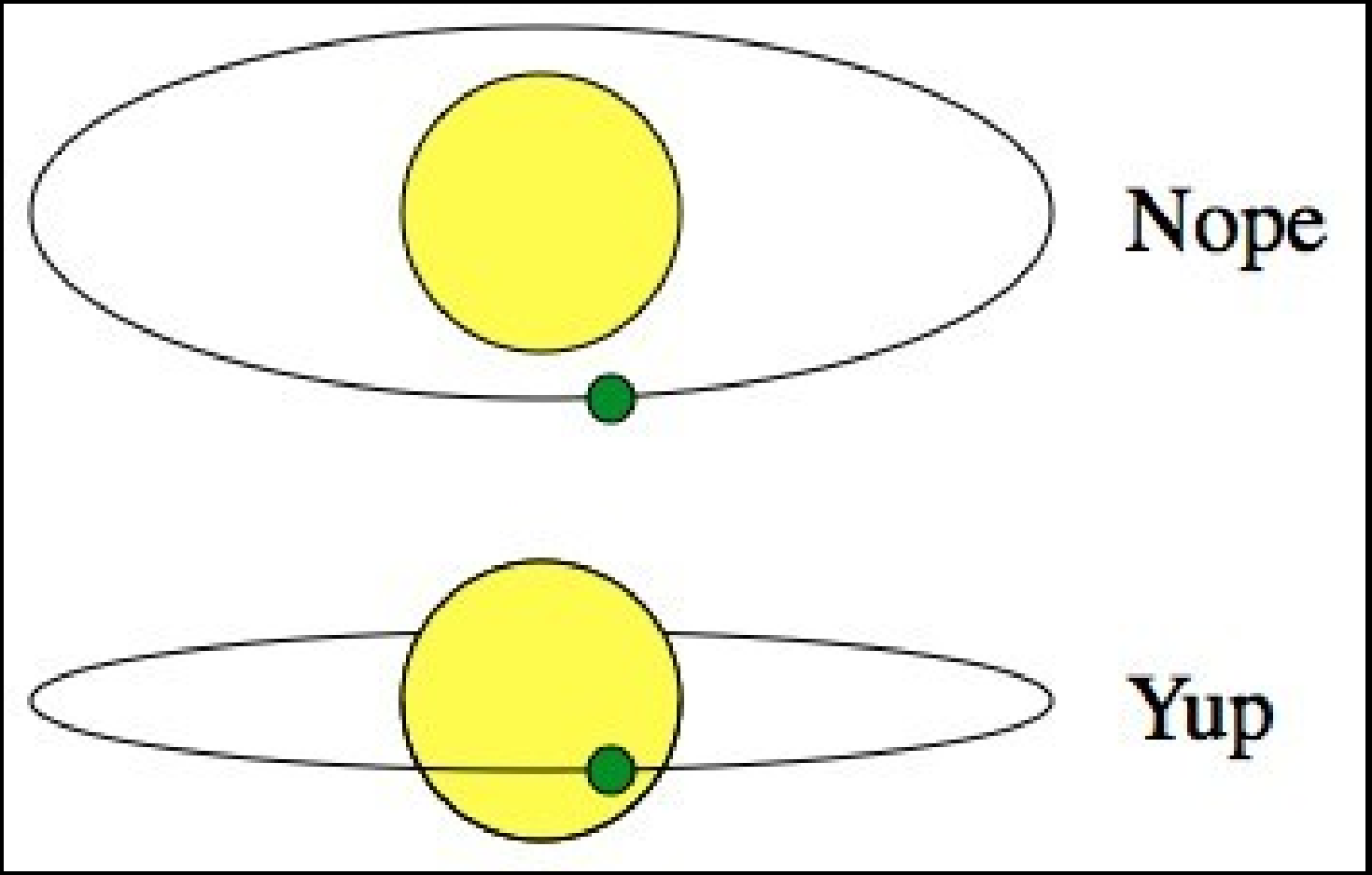
Applying to our solar system: this method could detect Jupiter and Saturn, given sufficient time.



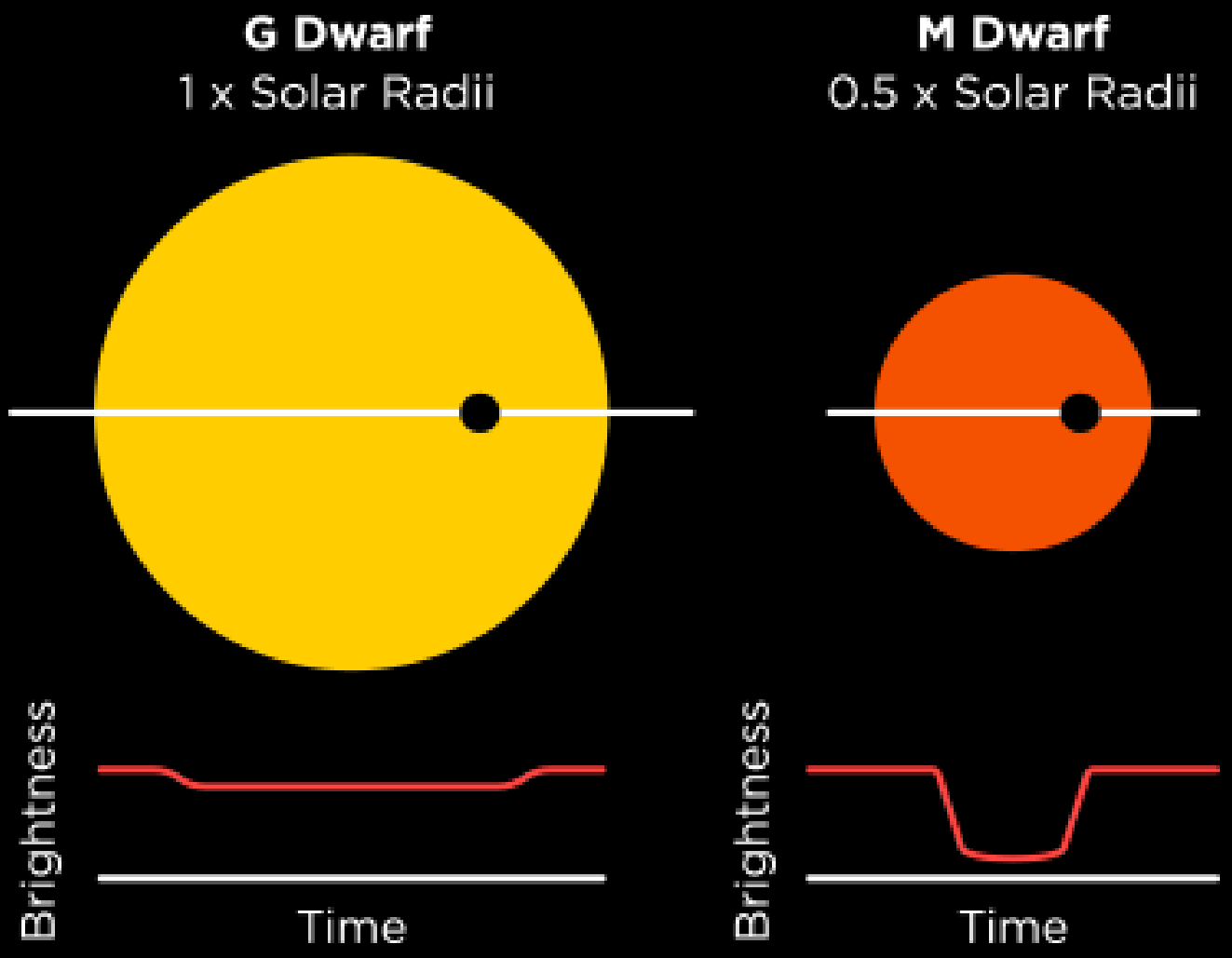
Method 2: Transit. When the planet passes in front of the star, it blocks a tiny portion of the light. Does not see the planet.



Transit: When the planet passes in front of the star, it blocks a tiny portion of the light. Only finds planets with orbits passing in front of the star

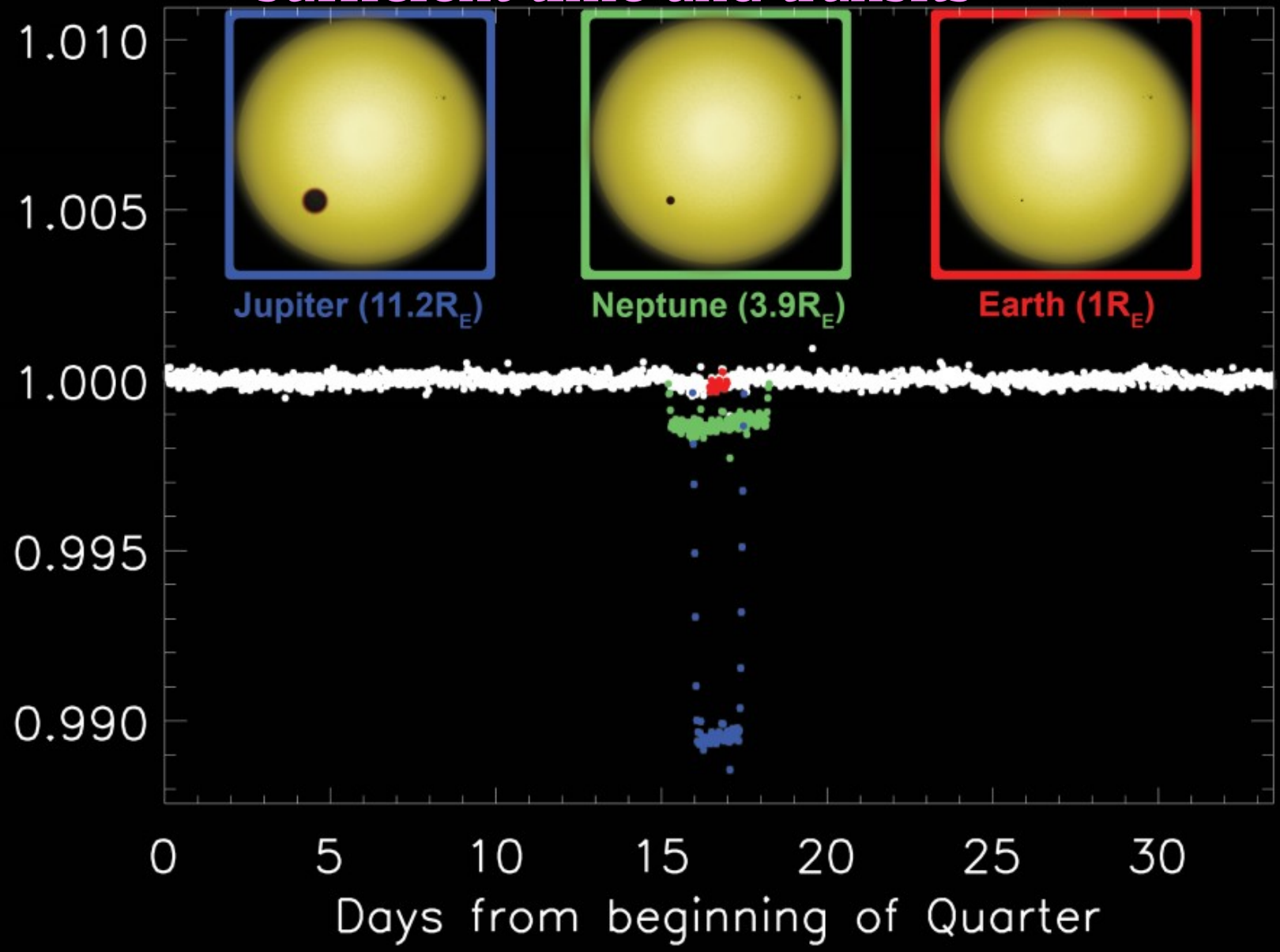


Transit: Smaller, cooler stars have deeper transits.

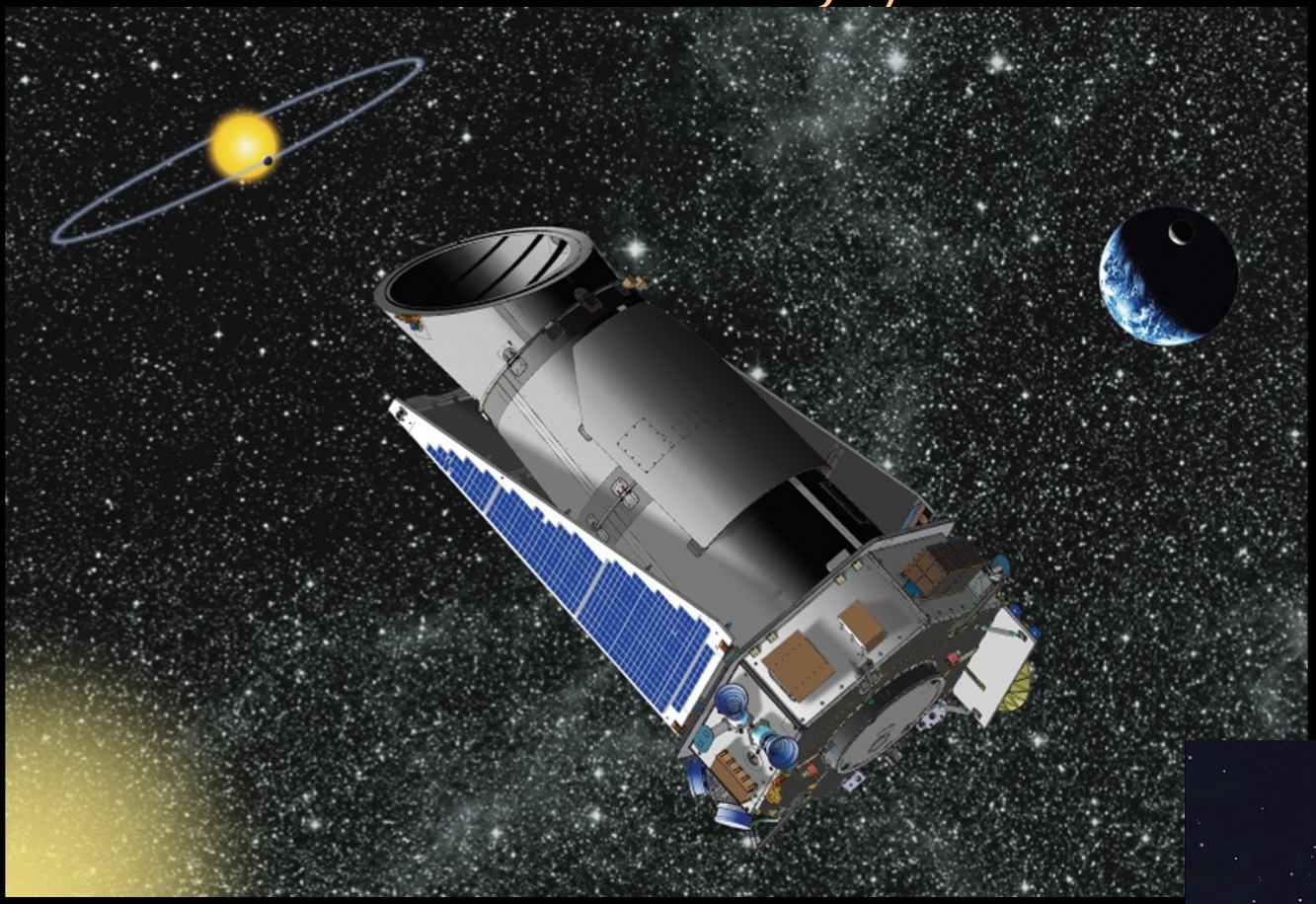


Transit: Bigger planets have deeper transits.

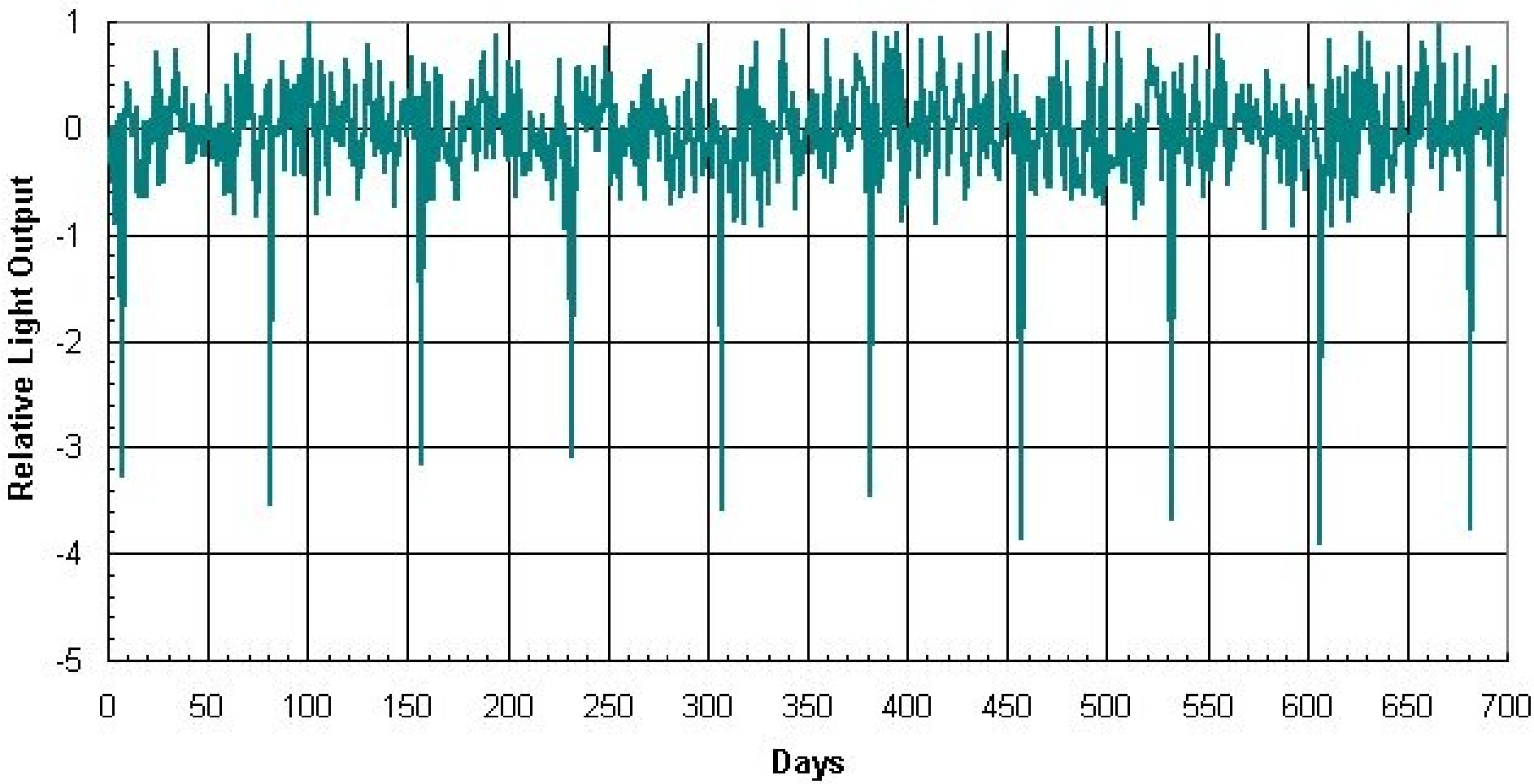
Can find all planets in our solar system given sufficient time and transits



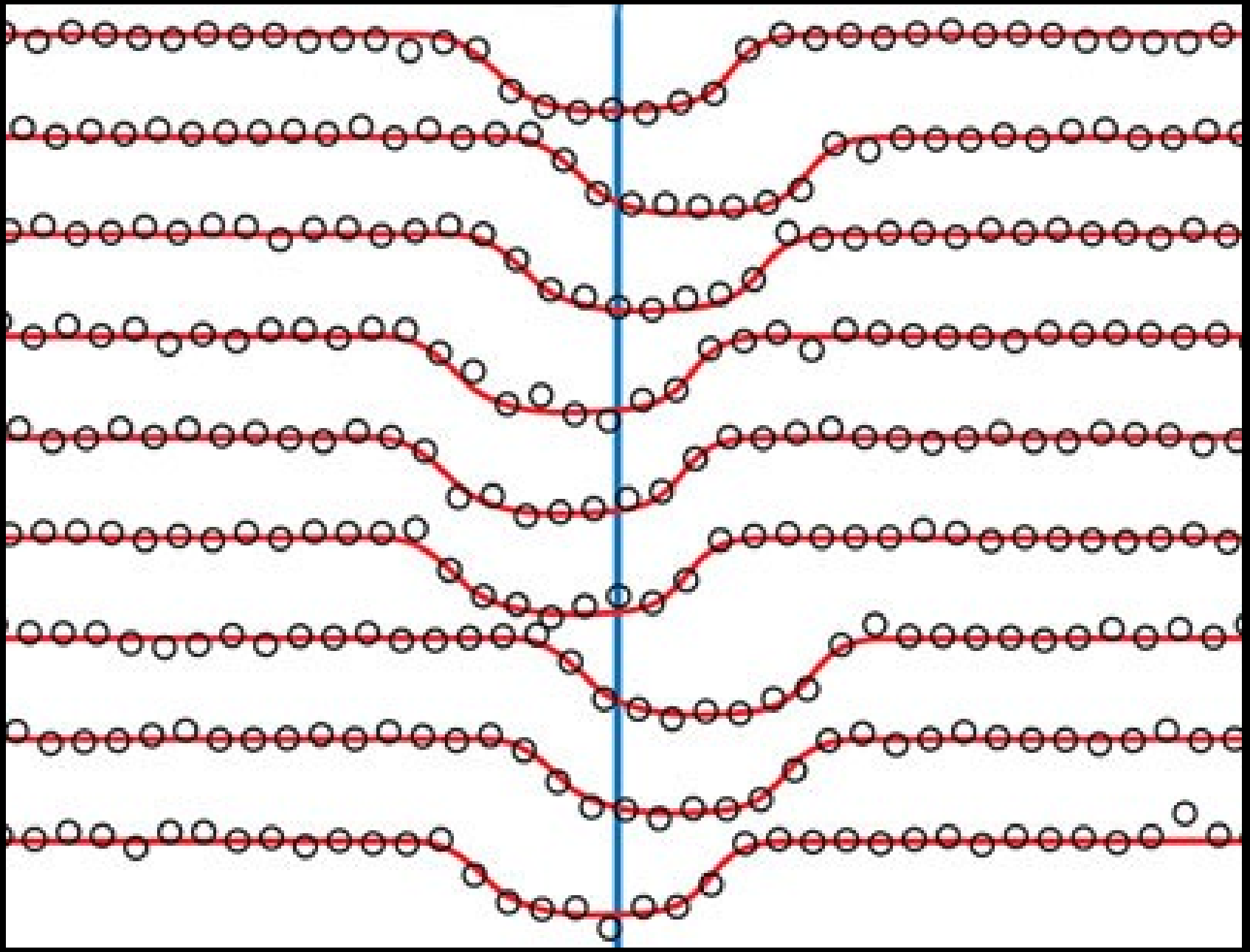
To find transits, you have to stare at stars.



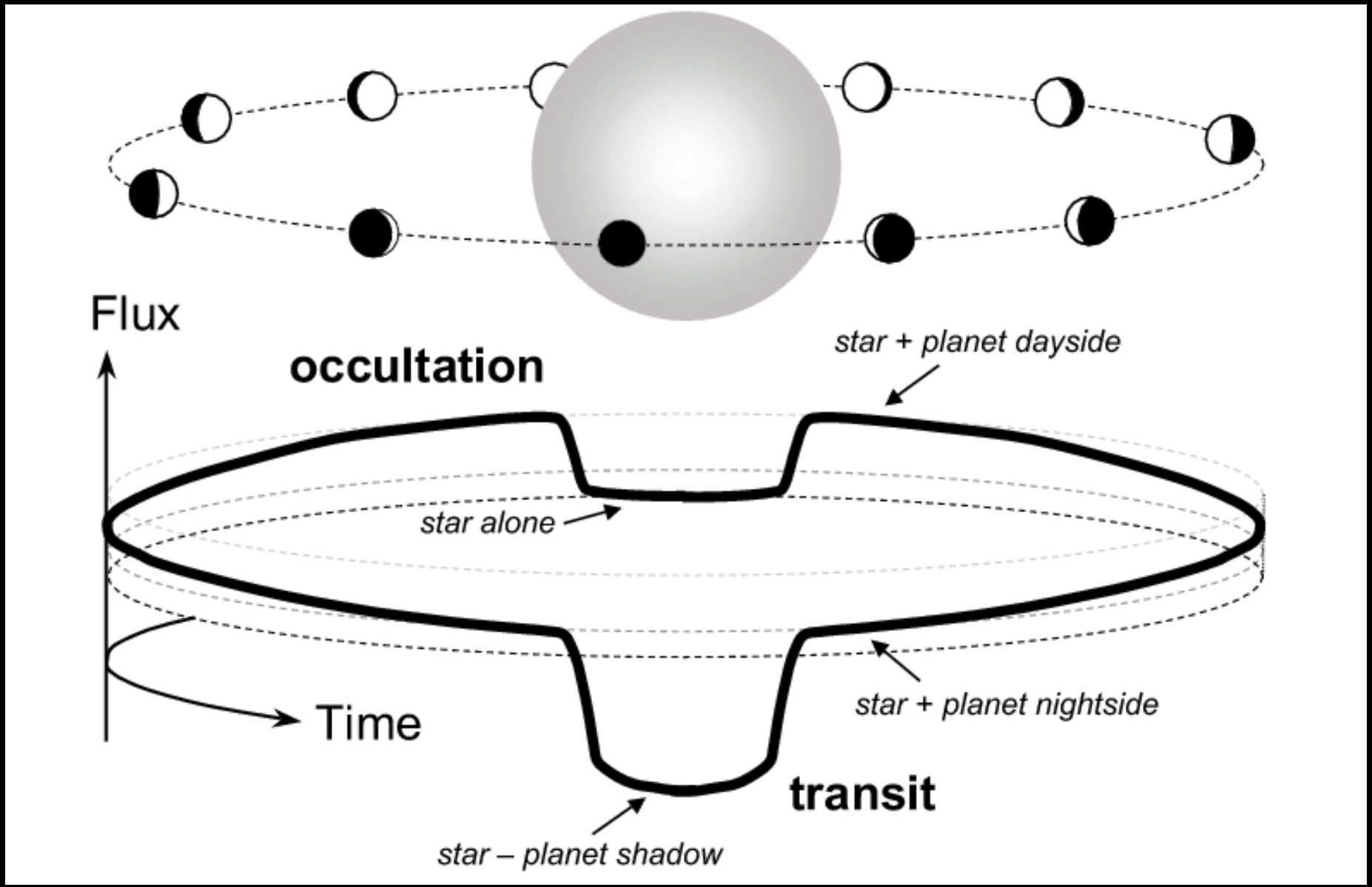
Transit data.



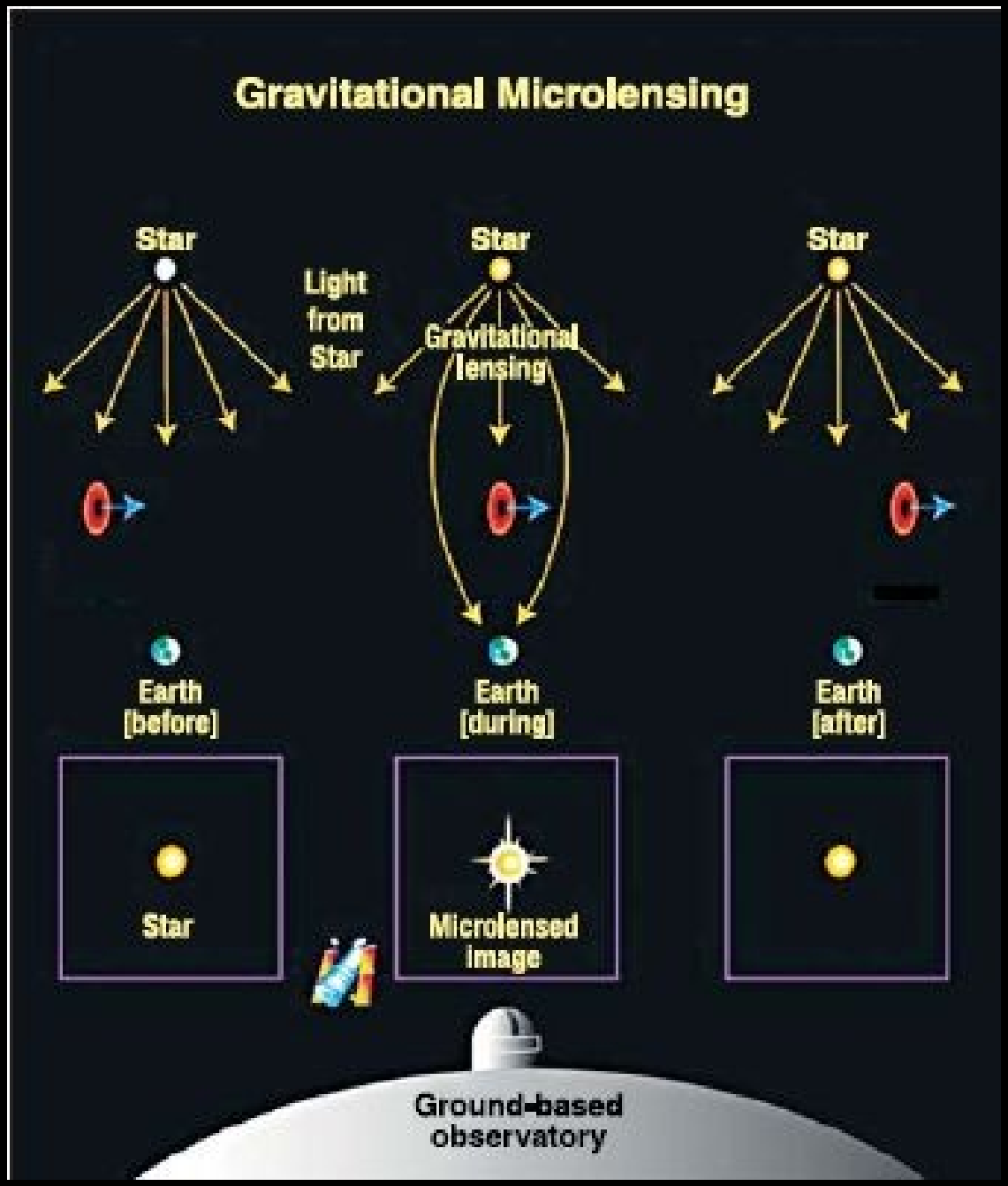
Transits can also find non-transiting planets.



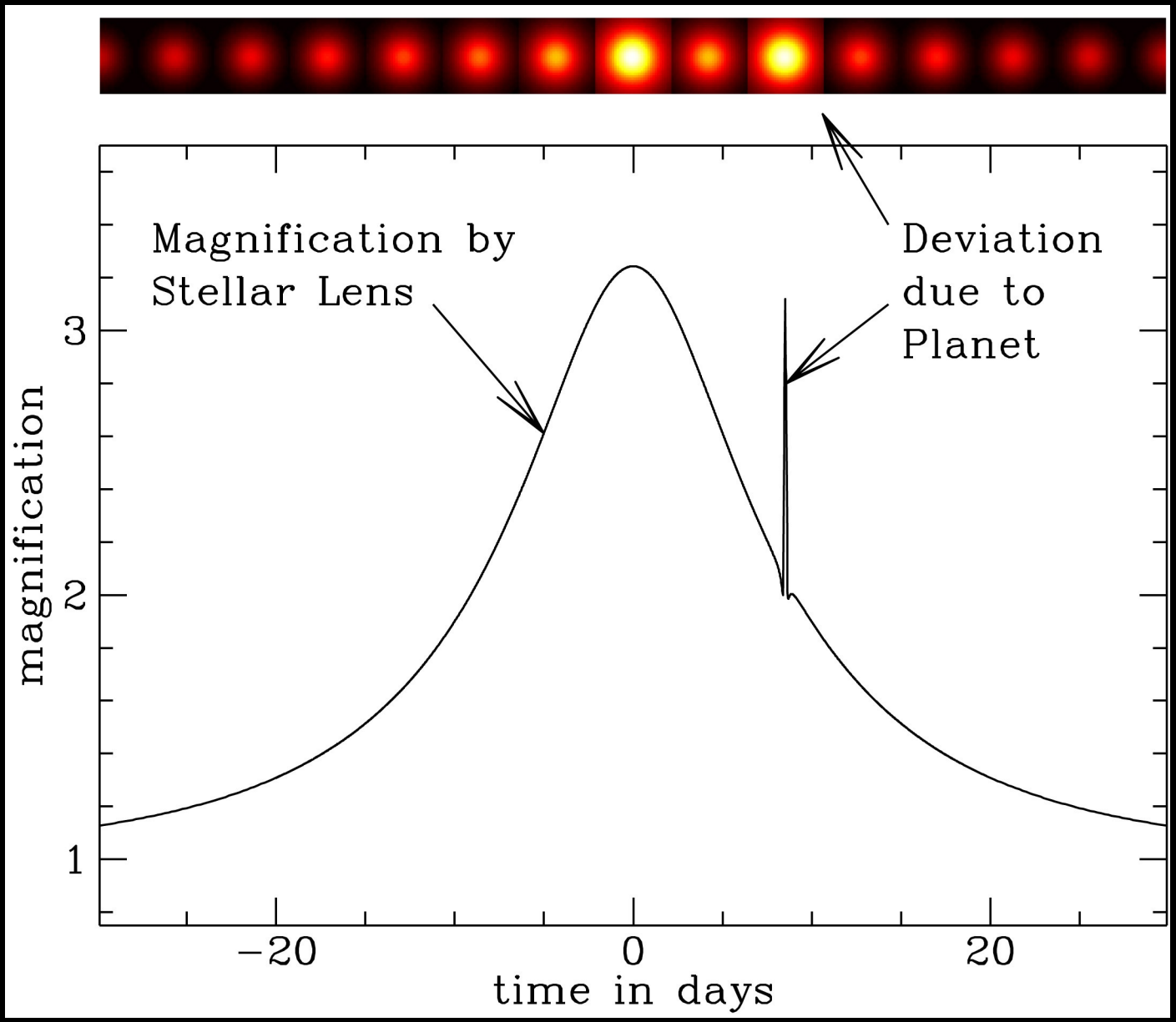
This type of observation has the possibility to see some of the planet's light.



Method 3: Microlensing

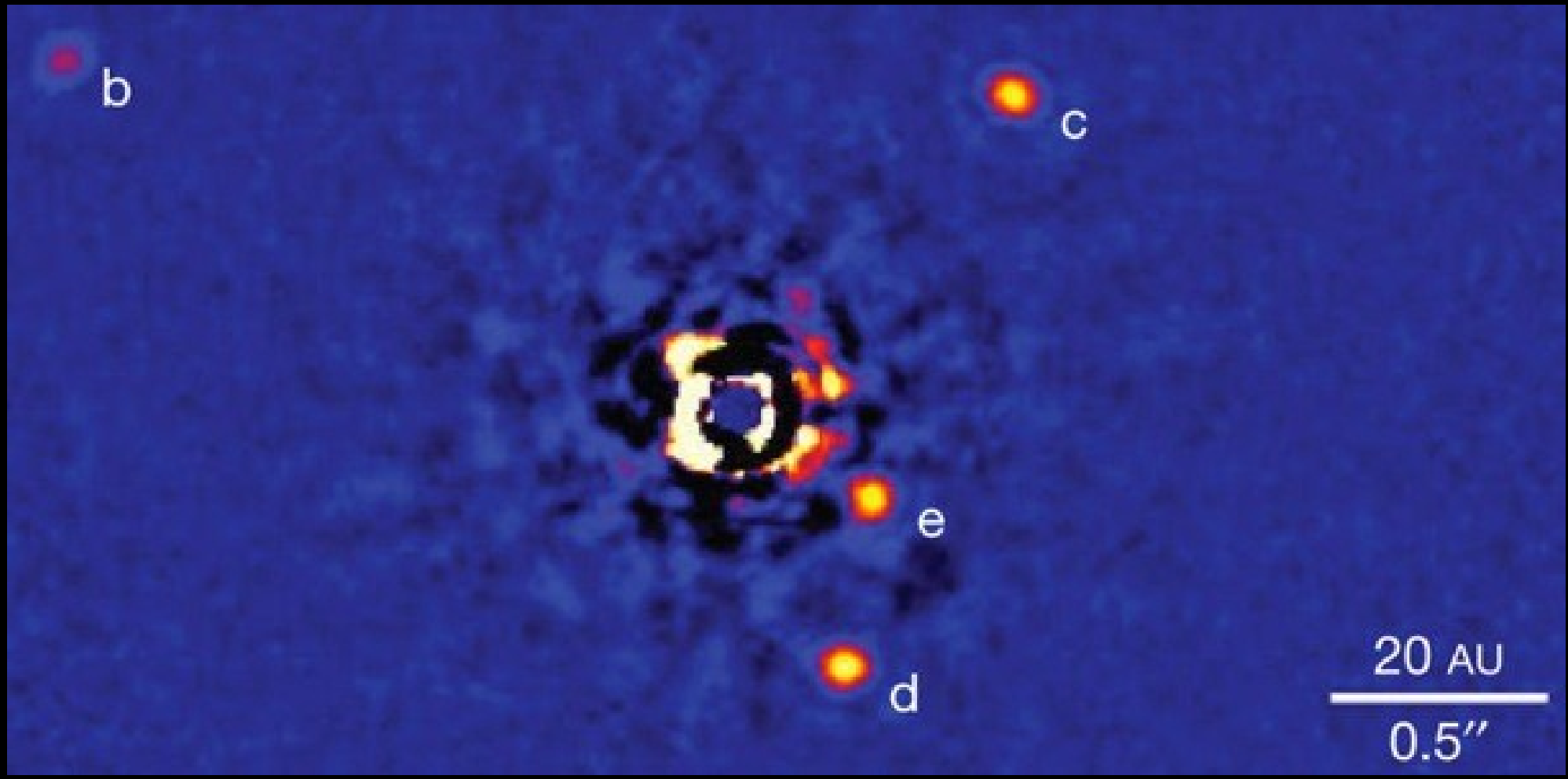


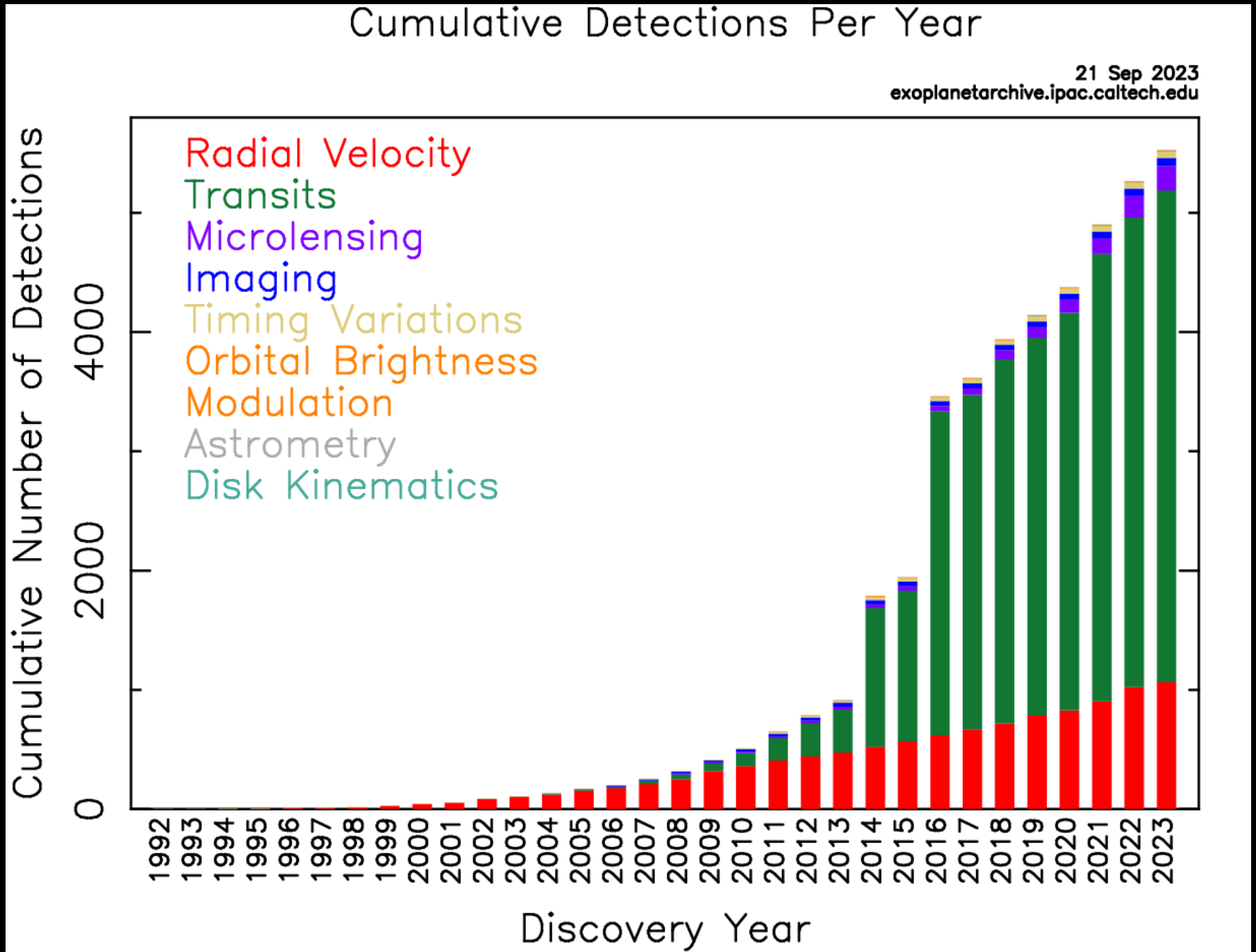
Method 3: Microlensing. Also does not ‘see’ the planet, only its gravity.

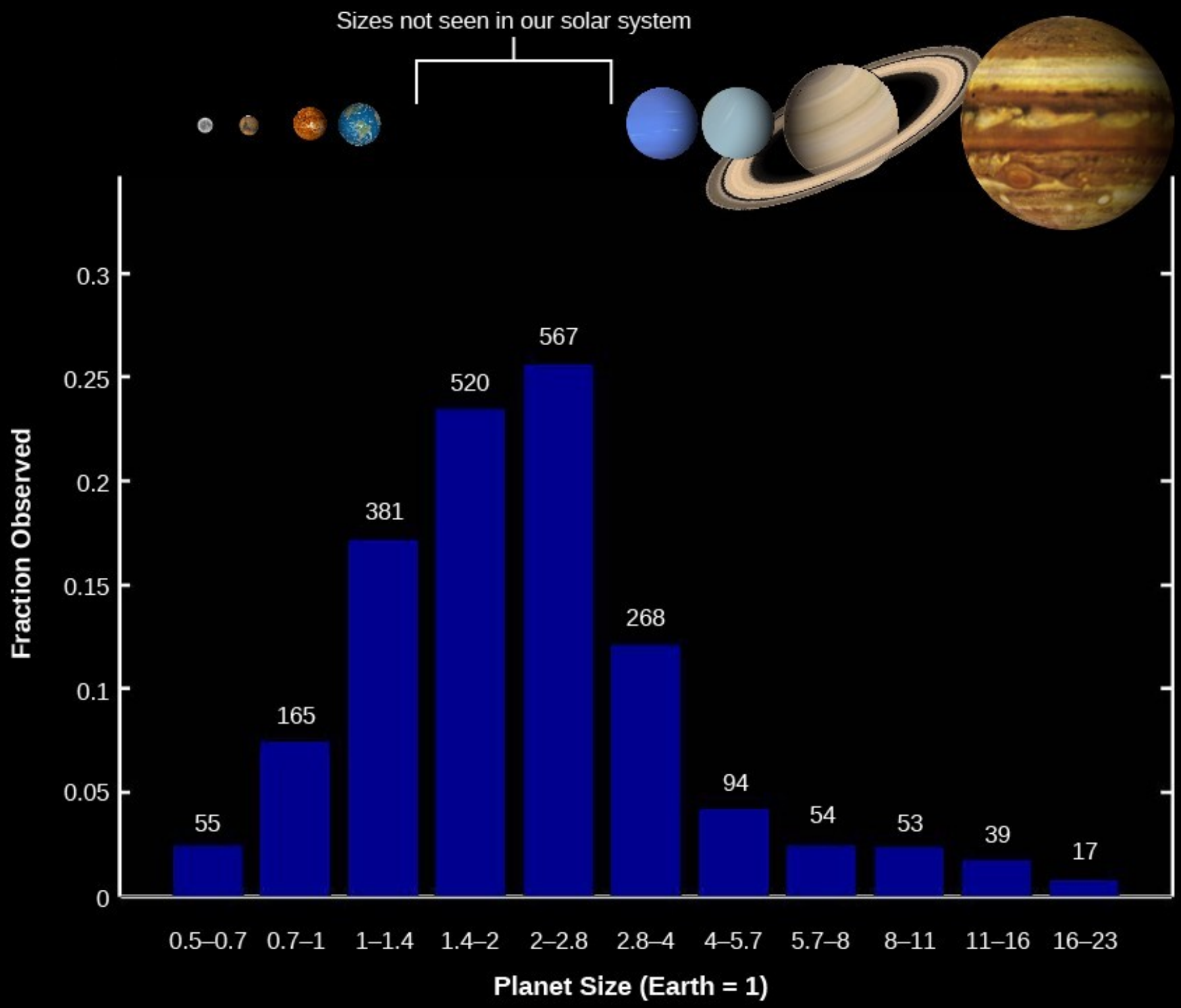


Direct Imaging: They're working on it.

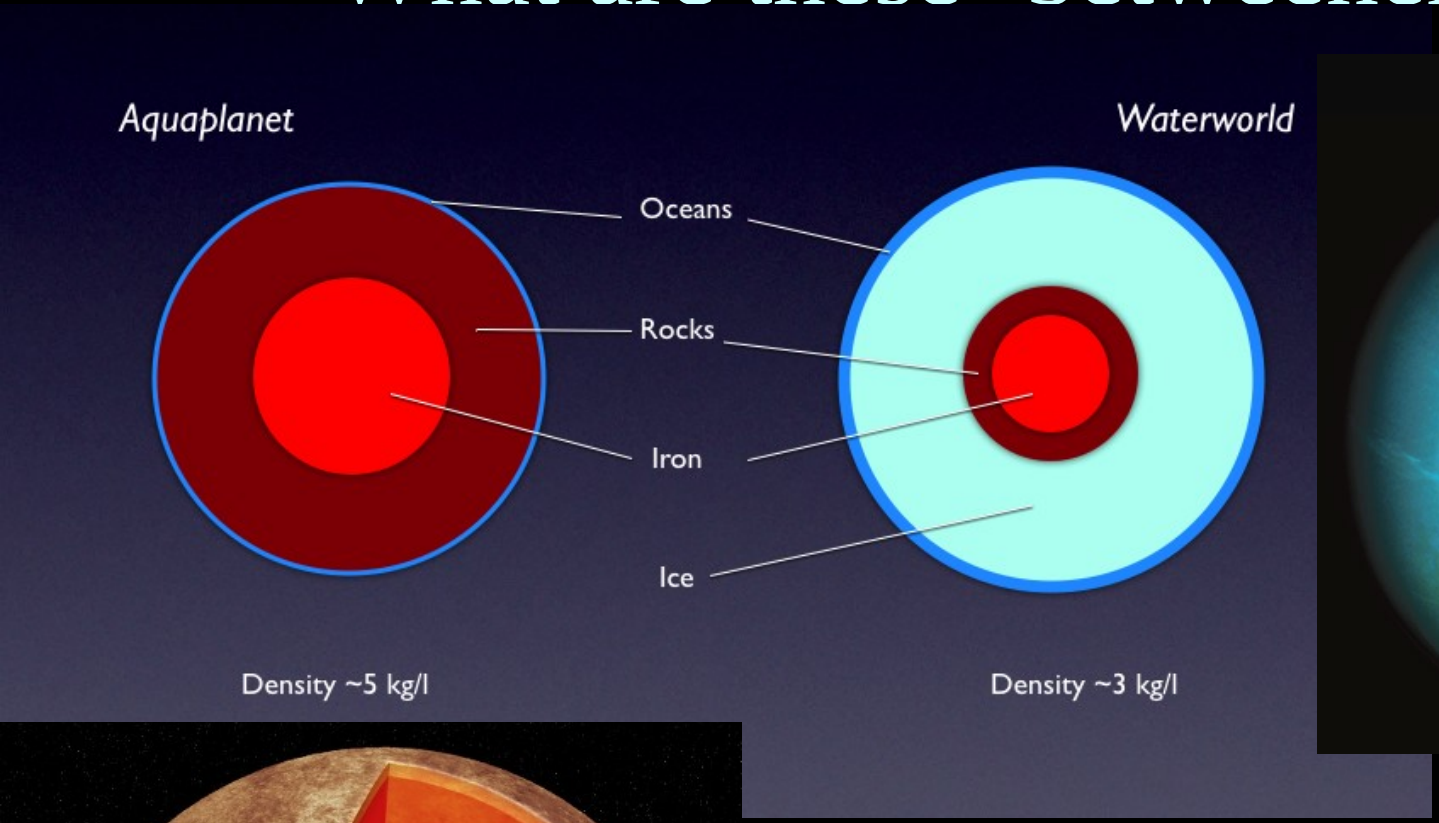
Finds large planets with large orbits

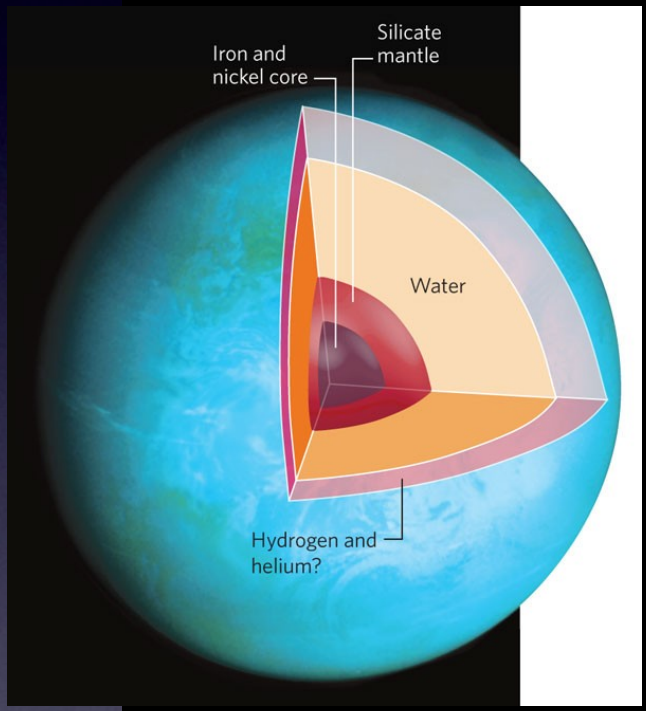


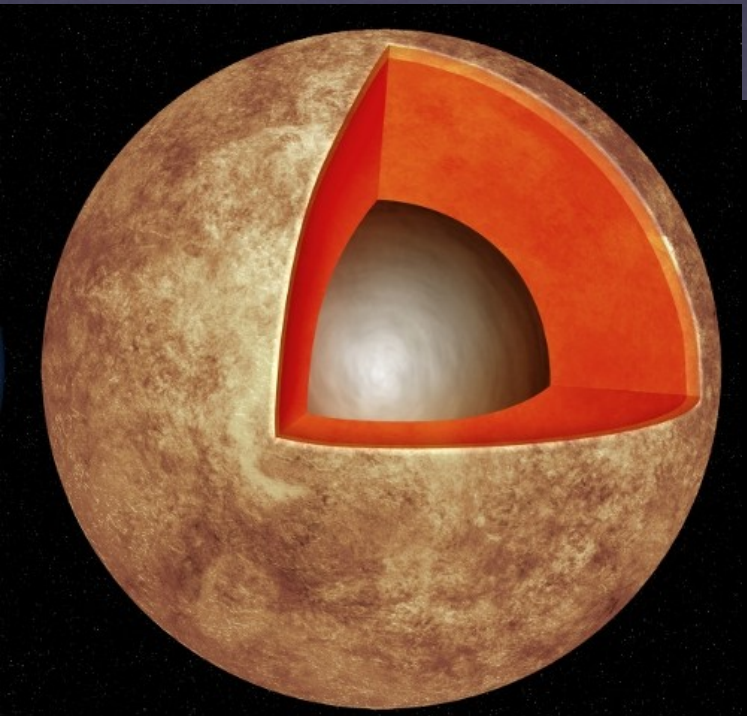

Cumulative Detections Per Year
21 Sep 2023
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
Astrometry
Disk Kinematics
Cumulative Number of Detections
0
2000
4000
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
Discovery Year

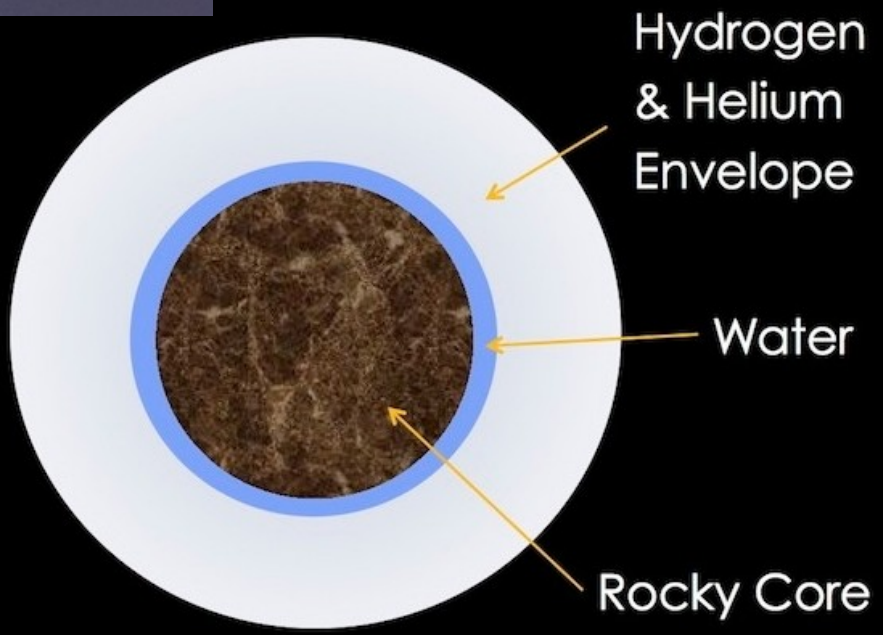

Sizes not seen in our solar system
Fraction Observed
0.3
0.25
0.2
0.15
0.1
0.05
0
55
165
381
520
567
268
94
54
53
39
17
0.5–0.7
0.7–1
1–1.4
1.4–2
2–2.8
2.8–4
4–5.7
5.7–8
8–11
11–16
16–23
Planet Size (Earth = 1)

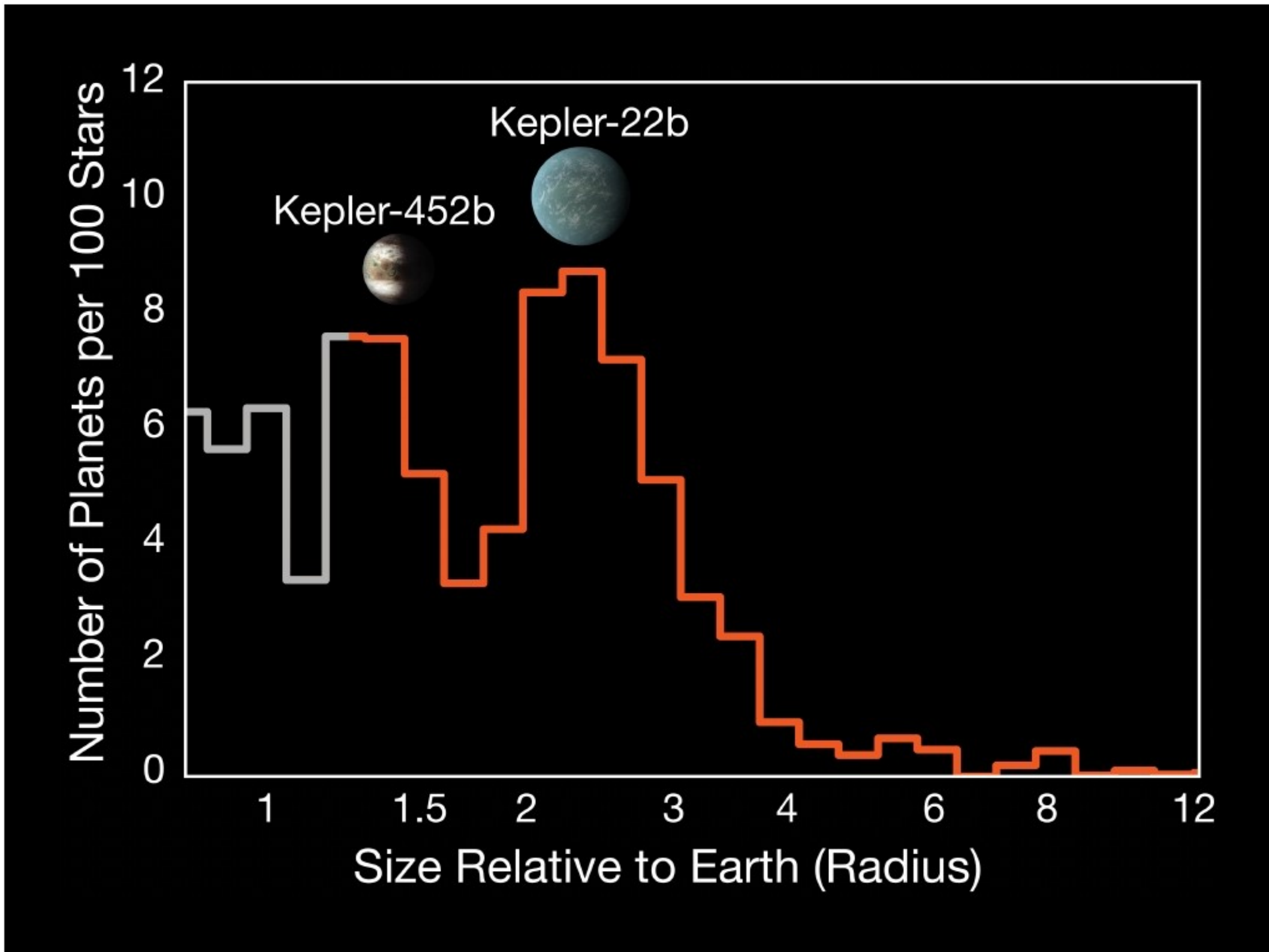
What are these ‘betweeners’ like?










Kepler-22b
Kepler-452b
Number of Planets per 100 Stars
0
2
4
6
8
10
12
1
1.5
2
3
4
6
8
12
Size Relative to Earth (Radius)

We only need 2 (or 3) for our solar system (Terrestrial and Gas Giant), but exoplanets need more

Hot/warm Jupiters
Hot/warm Neptunes
SuperEarths
Mini-Neptunes