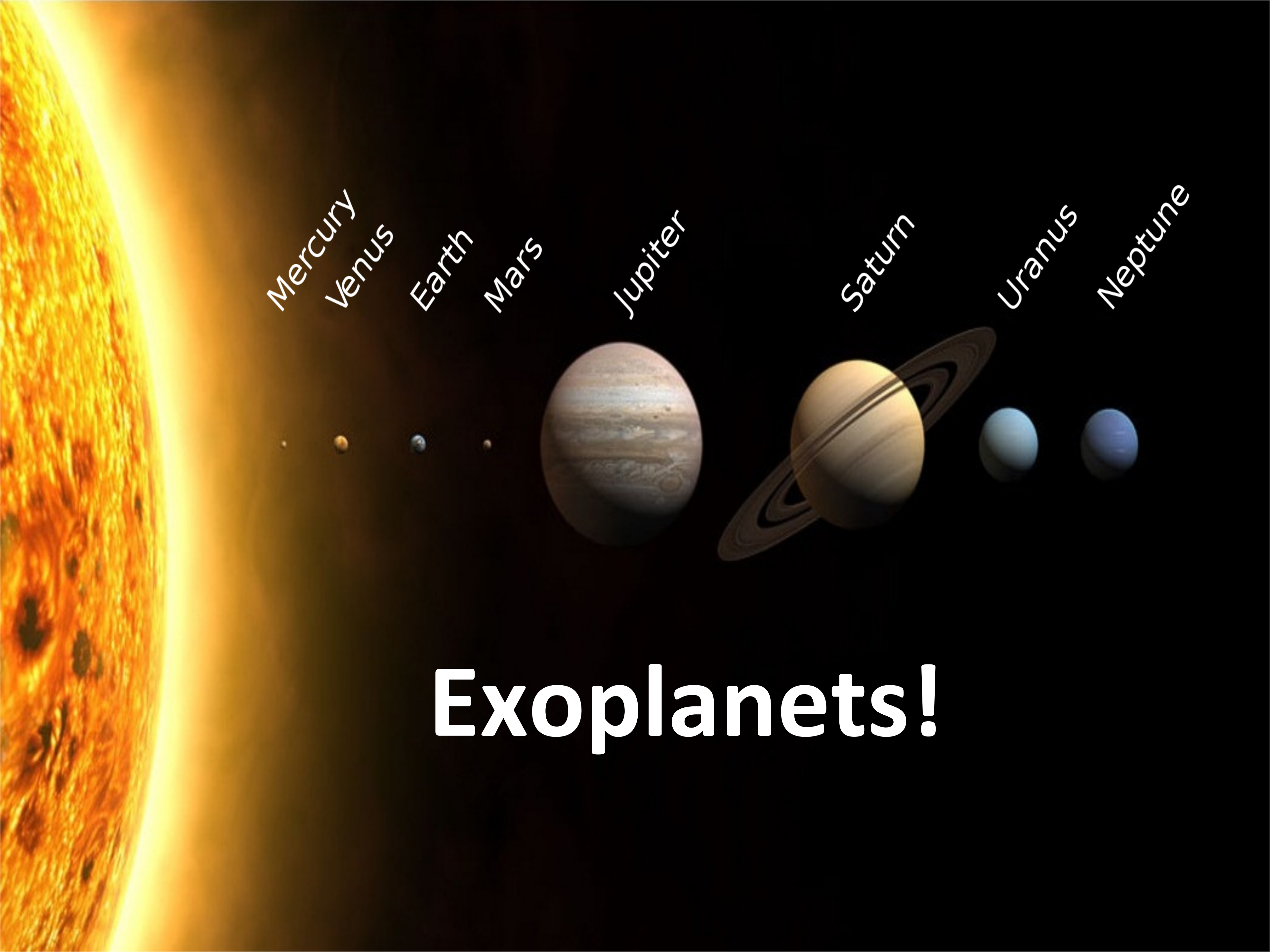
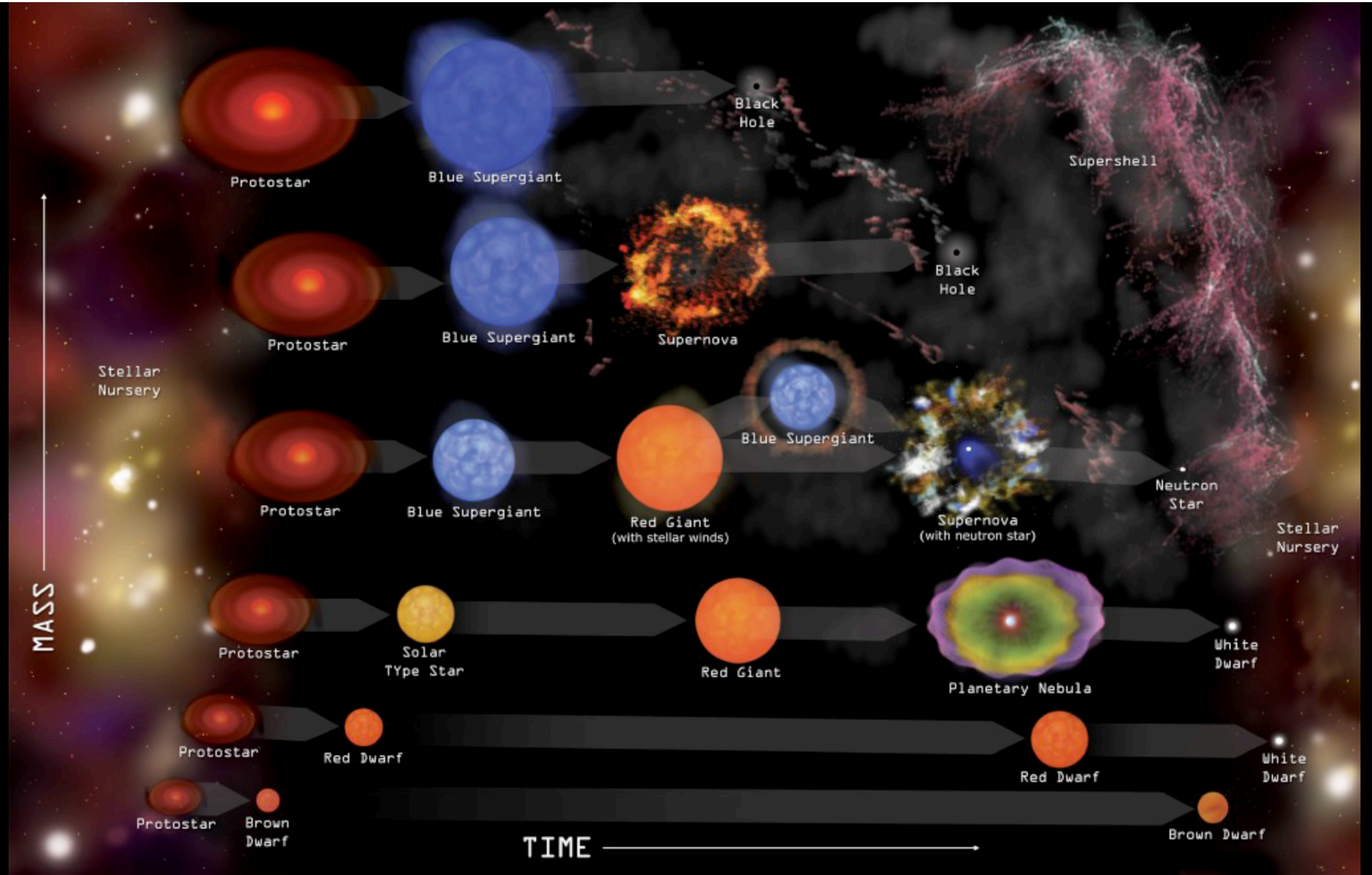


Exoplanets!

Last class: stellar evolution



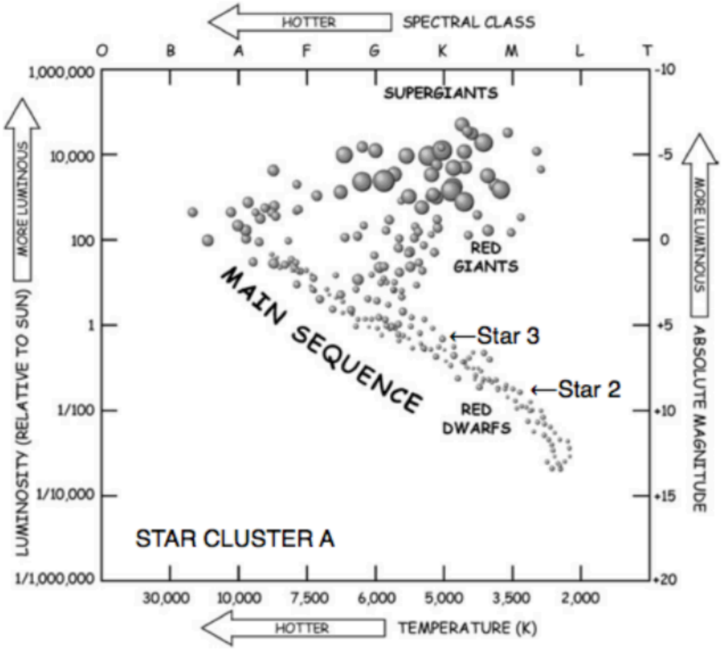
Key concepts from stars

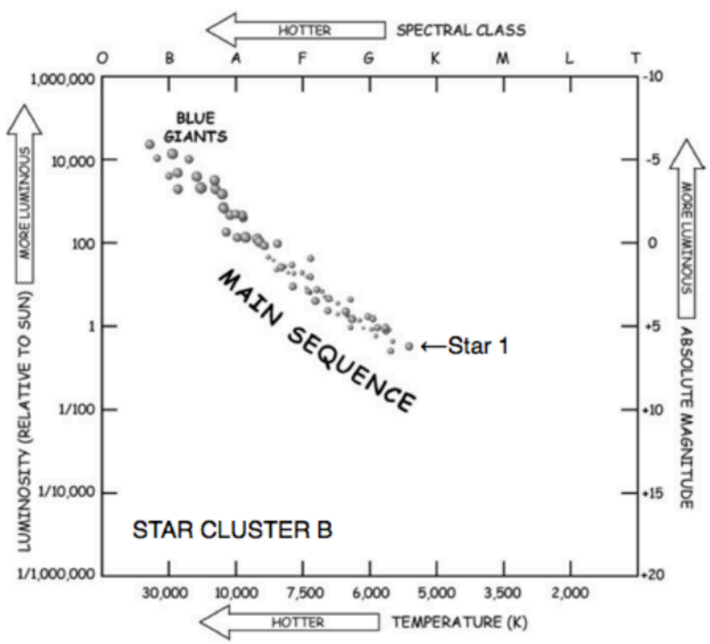
- Luminosity from fusion at core
  - 15 million degrees inside sun, 5770 K at surface
- Temperature and luminosity are determined by mass, age
  - Measurements of T, L tell us about stellar evolution
  - Higher mass stars party hard, die young
- Main sequence: H-burning
- After H-burning, stars evolve off the Main Sequence
  - Very low-mass stars: lifetime longer than age of universe
  - Low-mass stars lose mass, become white dwarfs
  - >8 Msun: supernova! Turn into neutron stars and black holes

- All that we are was made inside stars or in stellar explosions!

Homework

- Distances! If the sun is the size of a soccer ball (0.1 m radius), then:
  - Earth is 20 m away (other side of room)
  - Nearest star is 6000 km away (Europe)!
  - Nearest (large) galaxy is at location of Uranus!
- Madagascar: can see north-facing shadow sometimes (rarely)!
- Homework: some questions may not be covered in class, but can be found in the online textbook (or other online materials)
- In general, people did well. If you did not do well, please talk with me (make appt, or after class next week).





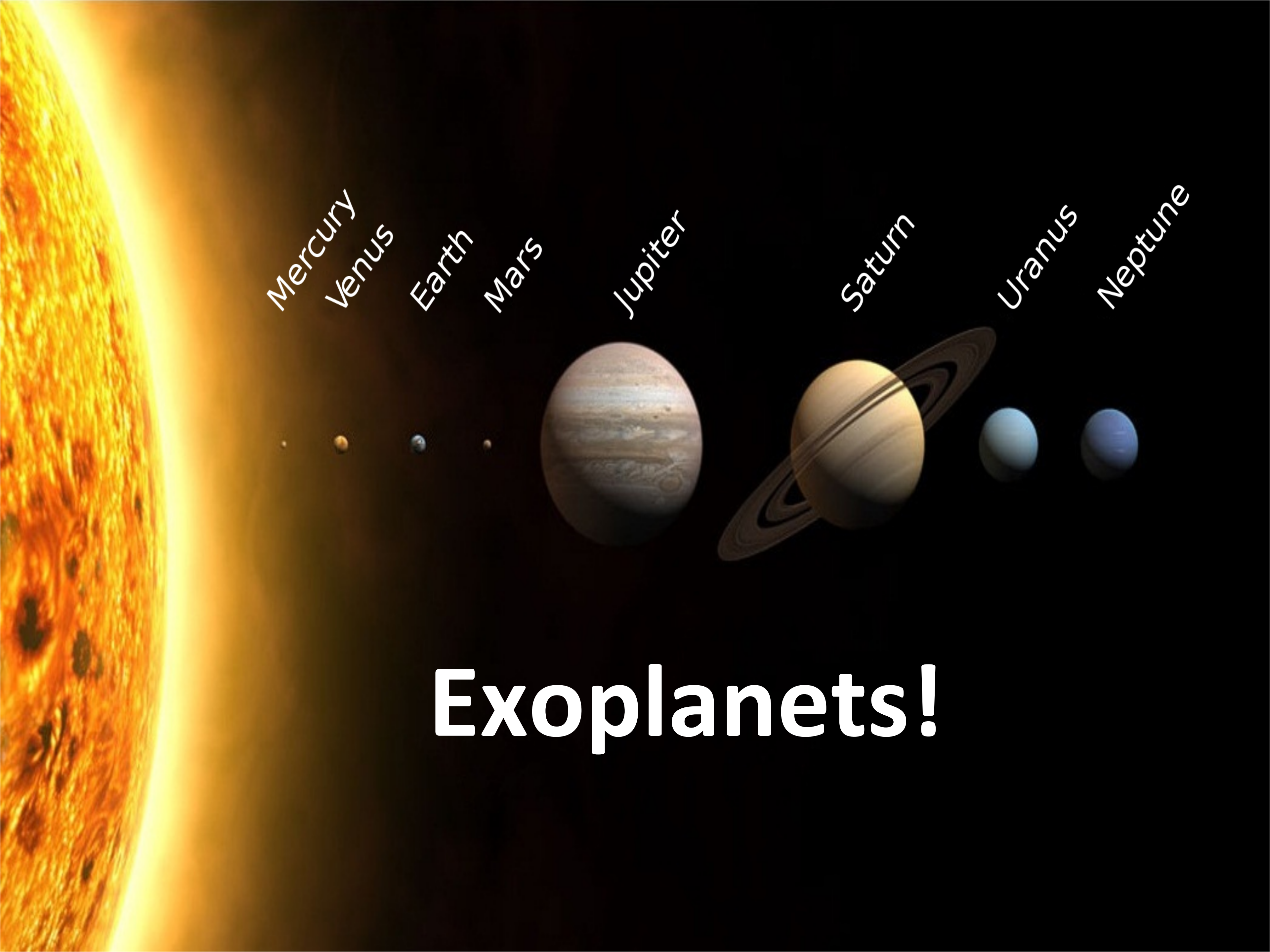
Which is more distant?

Same y-axes (absolute luminosity/magnitude).

One has fewer faint points, so likely further away

Next few months of class

- Two more homeworks
  - One due on April 4
  - One due on May 9
- Oral presentation, April 11
  - Choose topic in next weeks class (or by email, if you will not be in class)
- Written project + oral presentation
  - May 23/30 (avoids last week+final exam stress)
- Topics: Galaxies, cosmology, solar system



Exoplanets!

Exoplanets

3926 confirmed exoplanets!

first detection around normal star: 1995

3000 more likely planets

This is amazing!

Exoplanets: groups of 3-5

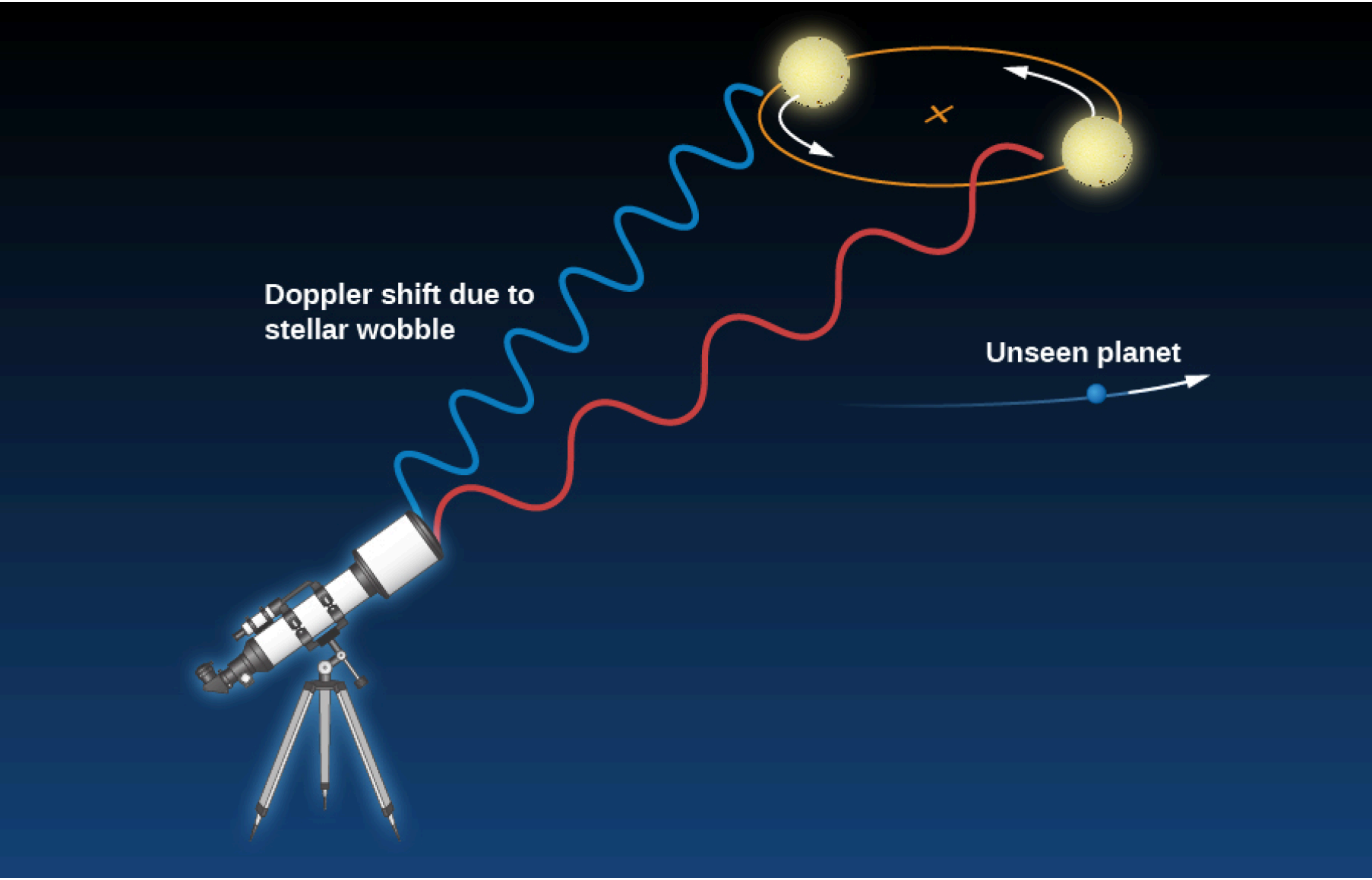
Properties & Difficulty
Radius of orbit: 2 (easy)
Atmospheric composition: 10 (very hard)
    water (extremely hard): 10
Mass of planet: 8 (hard)
Age of planet: 3 (in between)
Temperature: 6 (hard)
Moons!: 5
Doppler – combination of mass/distance
Rocky or gas giant planet: 7
Suitable for life (habitability): ~12
Planet size/radius: 1
Magnetic field: impossible
Rotation: easy

- What would you want to know
- Rate those on 1=easy to measure, 10=hard to measure

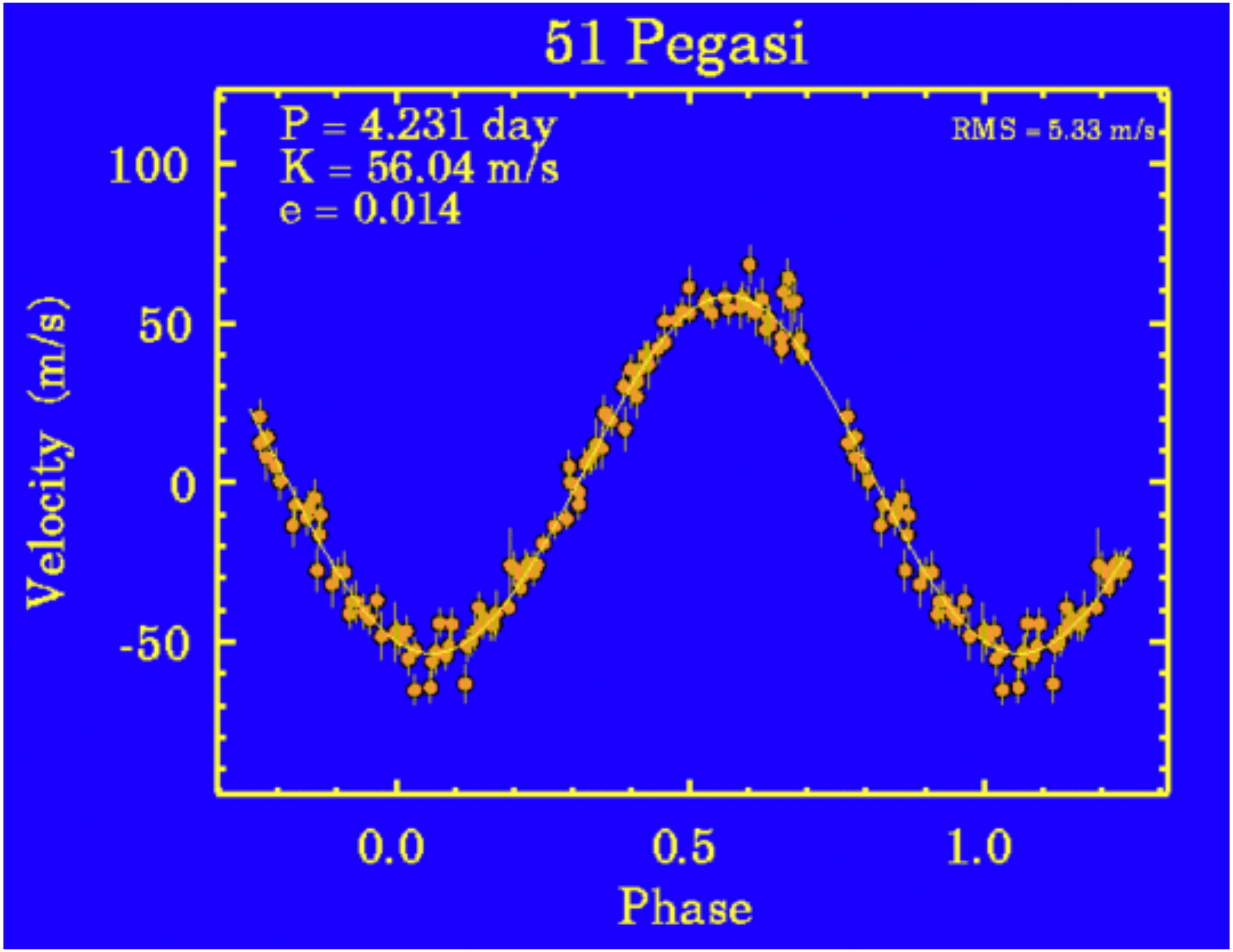
Exoplanet: a planet around any star other than our Sun

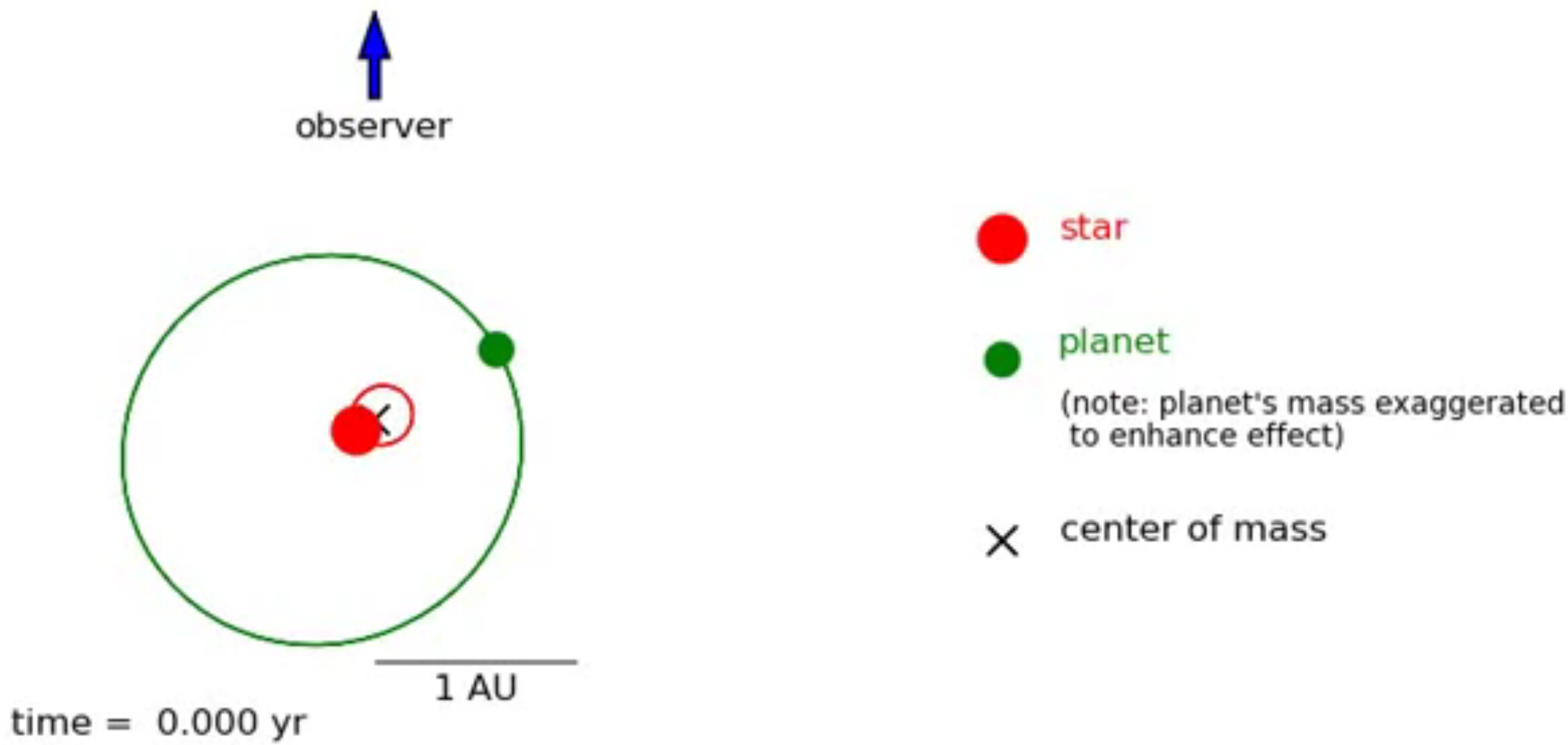
Keywords for Lecture 4

- Exoplanet: a planet around a different star
- Detection techniques: how exoplanets are detected?
  - Radial Velocity
  - Transits
  - Direct Imaging
- Atmospheres
- Protoplanetary disks
- Habitability
- Biases


Doppler shift due to
stellar wobble
Unseen planet

The first planet




observer
star
planet
(note: planet's mass exaggerated
to enhance effect)
center of mass
1 AU
time = 0.000 yr

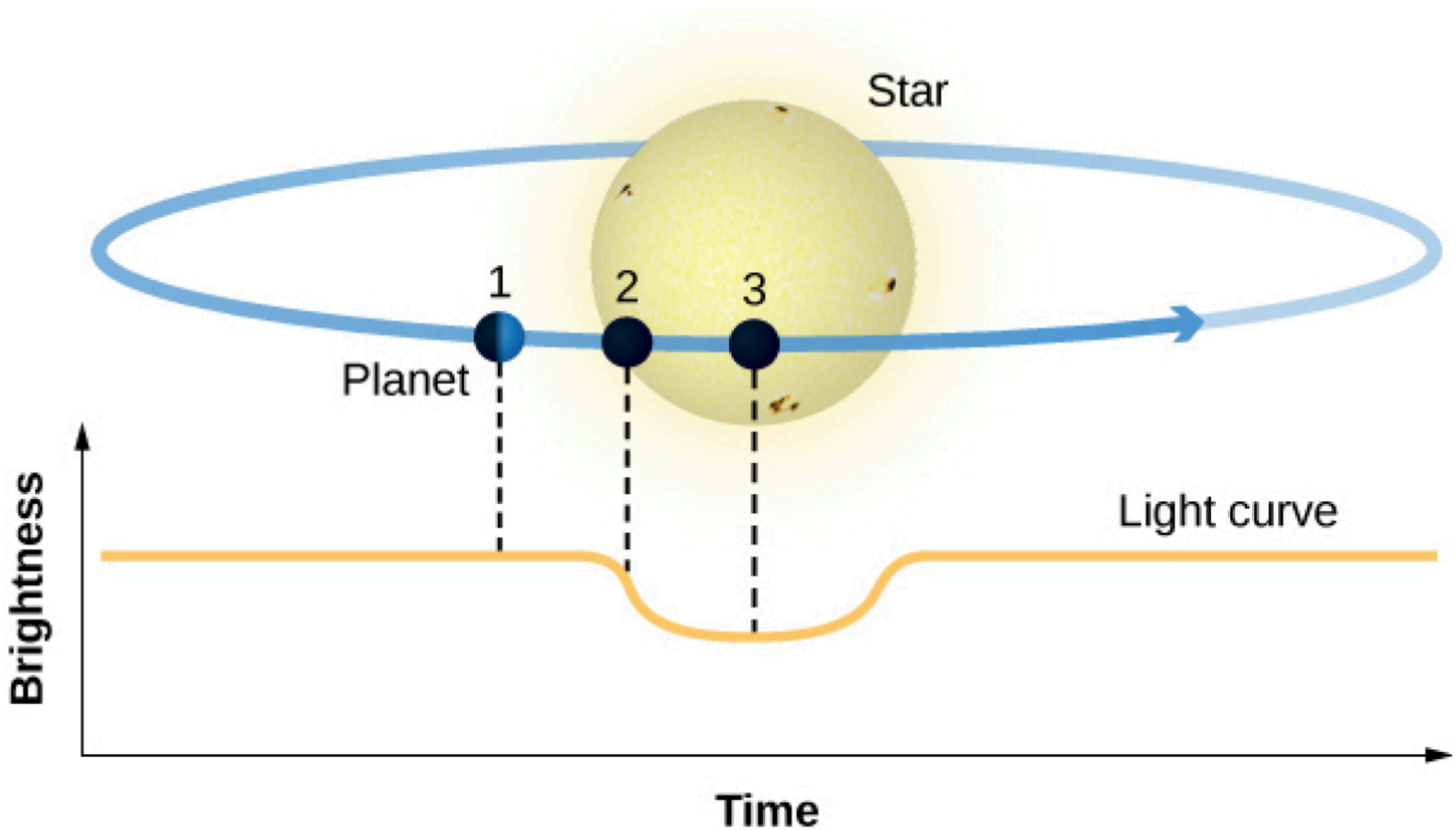
Bias of radial velocity

- What kinds of planets are easiest to detect?

- Motion of star

$$v_{\mathrm{obs}} = 28.4 \frac{M_P \sin i}{P_{\mathrm{orb}}^{1/3} M_*^{2/3}}$$

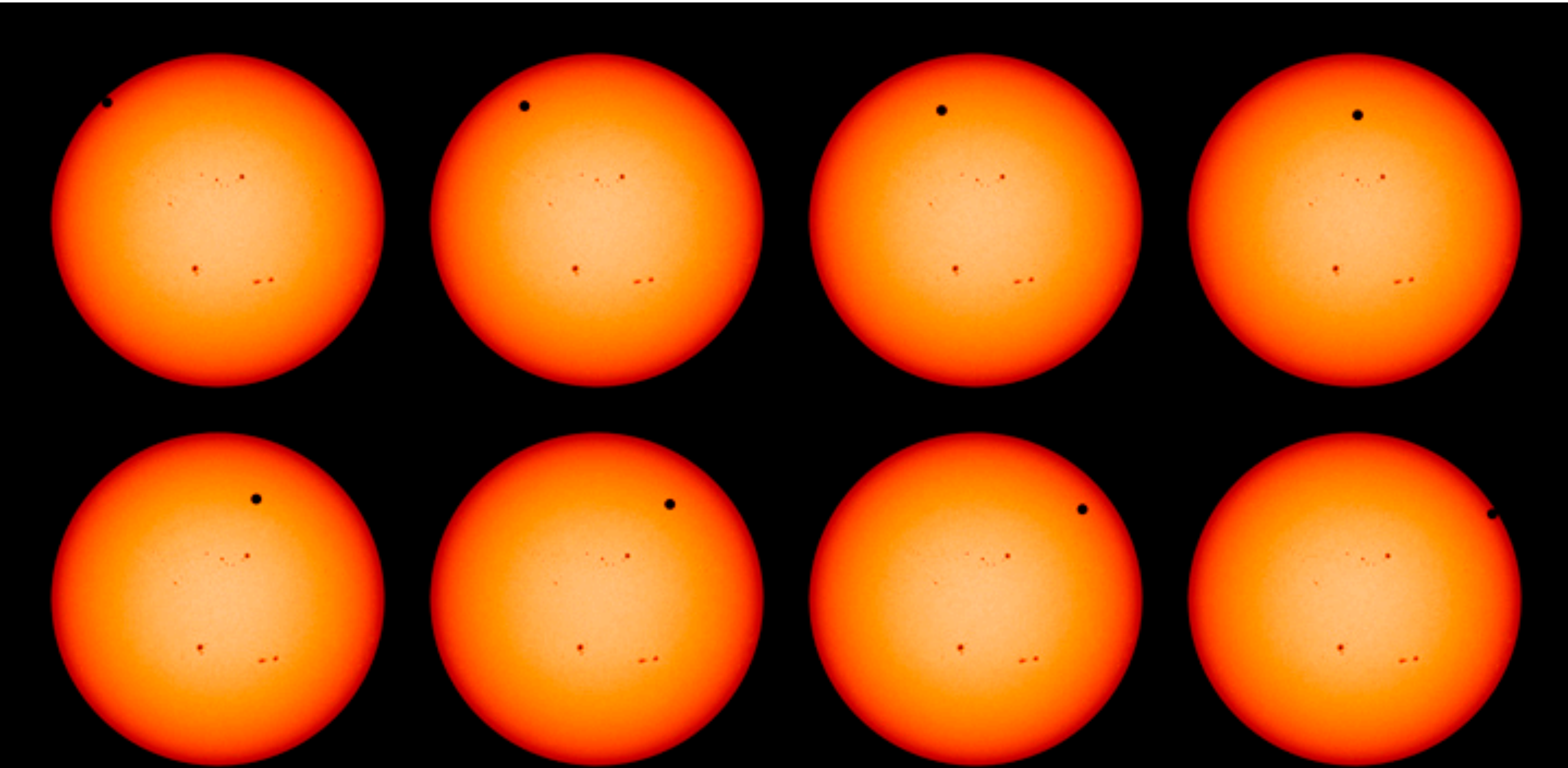
- M_p in Jupiter masses
- P_{orb} in years
- M_* in solar masses


Star
1
2
3
Planet
Light curve
Brightness
Time

Venus transit

Every 112 years: (two times, separated by 8 years)

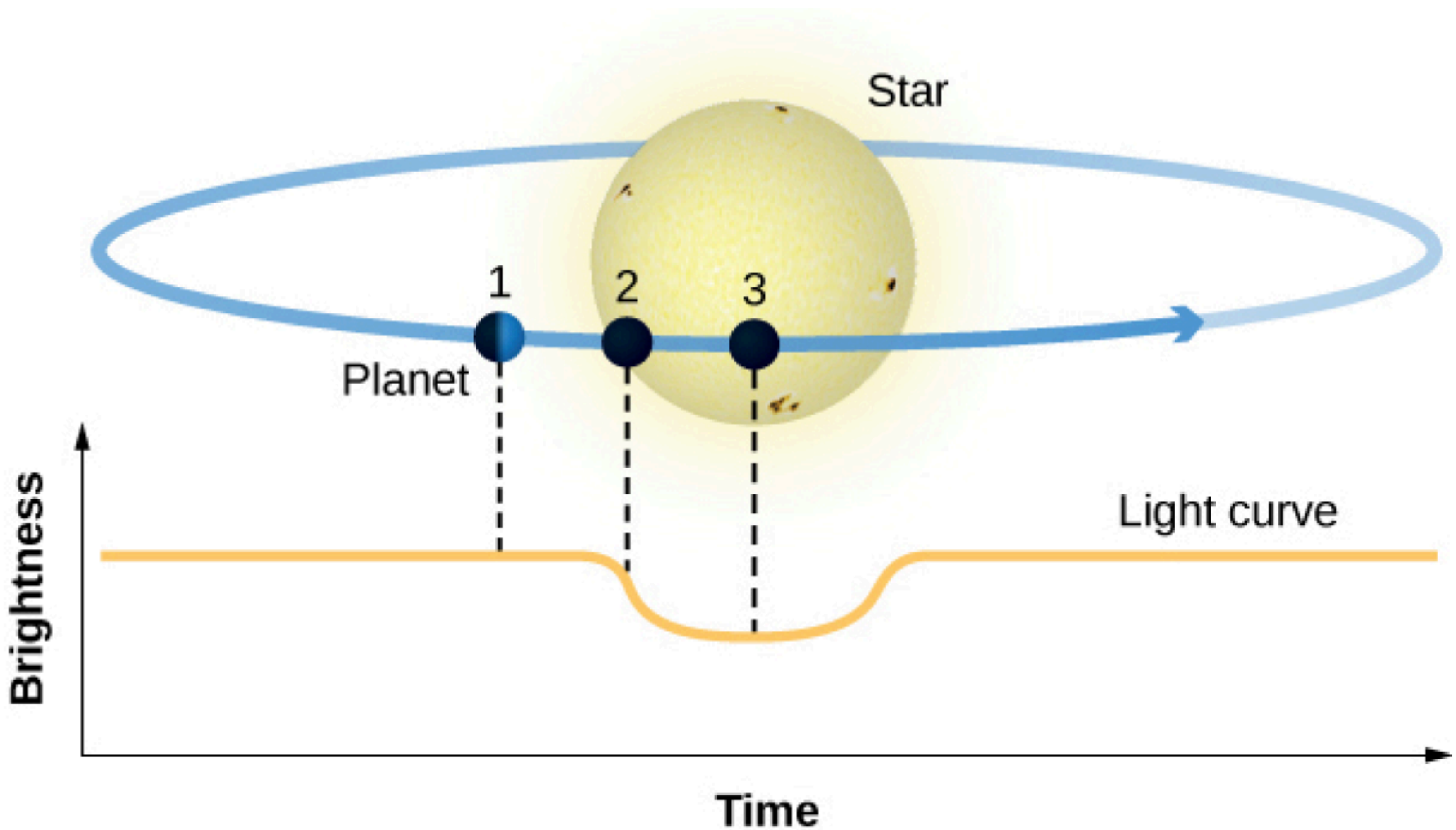
last time in 2004/2012

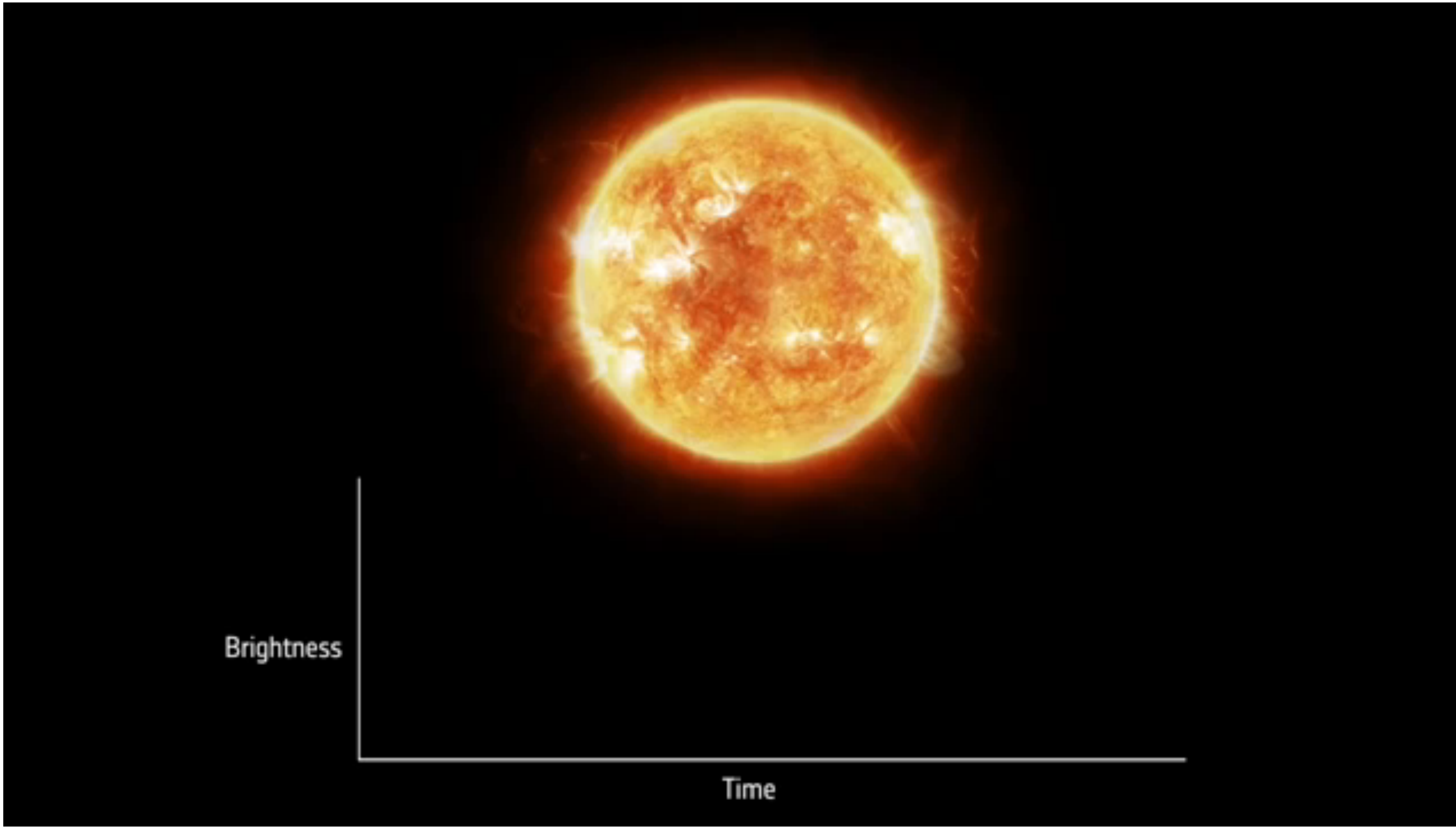


Venus transit

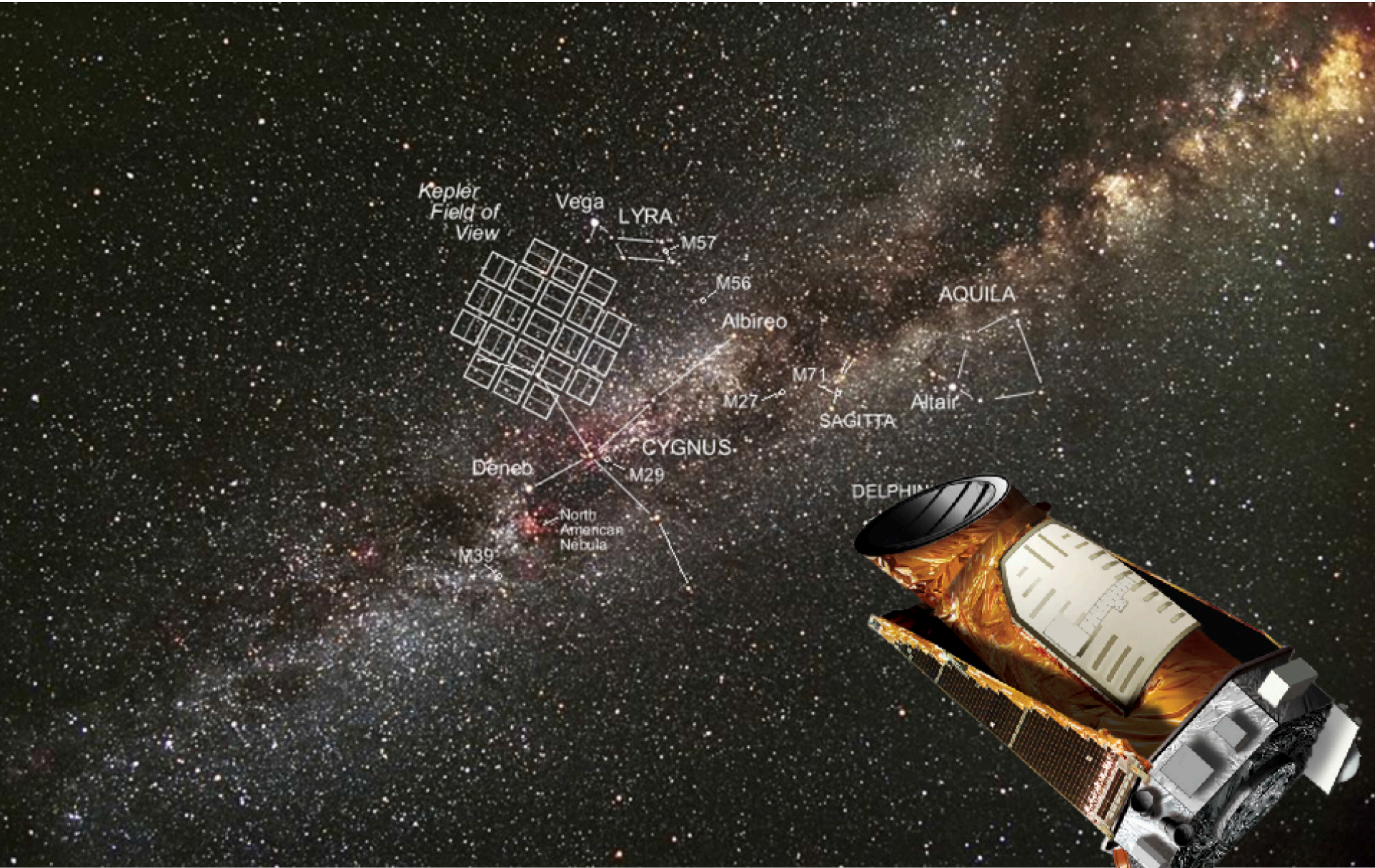
Guillaume Le Gentil: the unluckiest astronomer

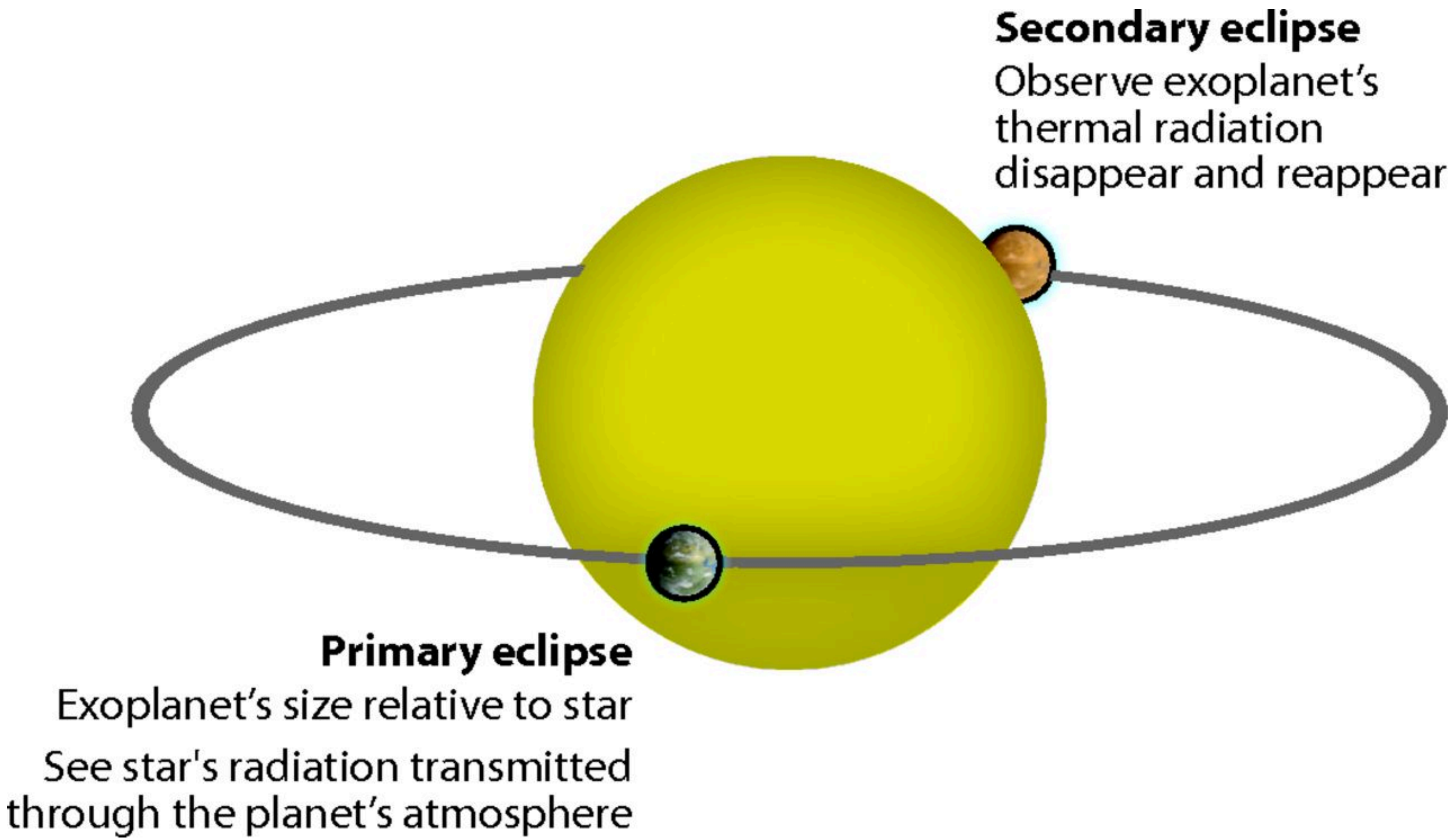
- 1761/1769 transits from India?

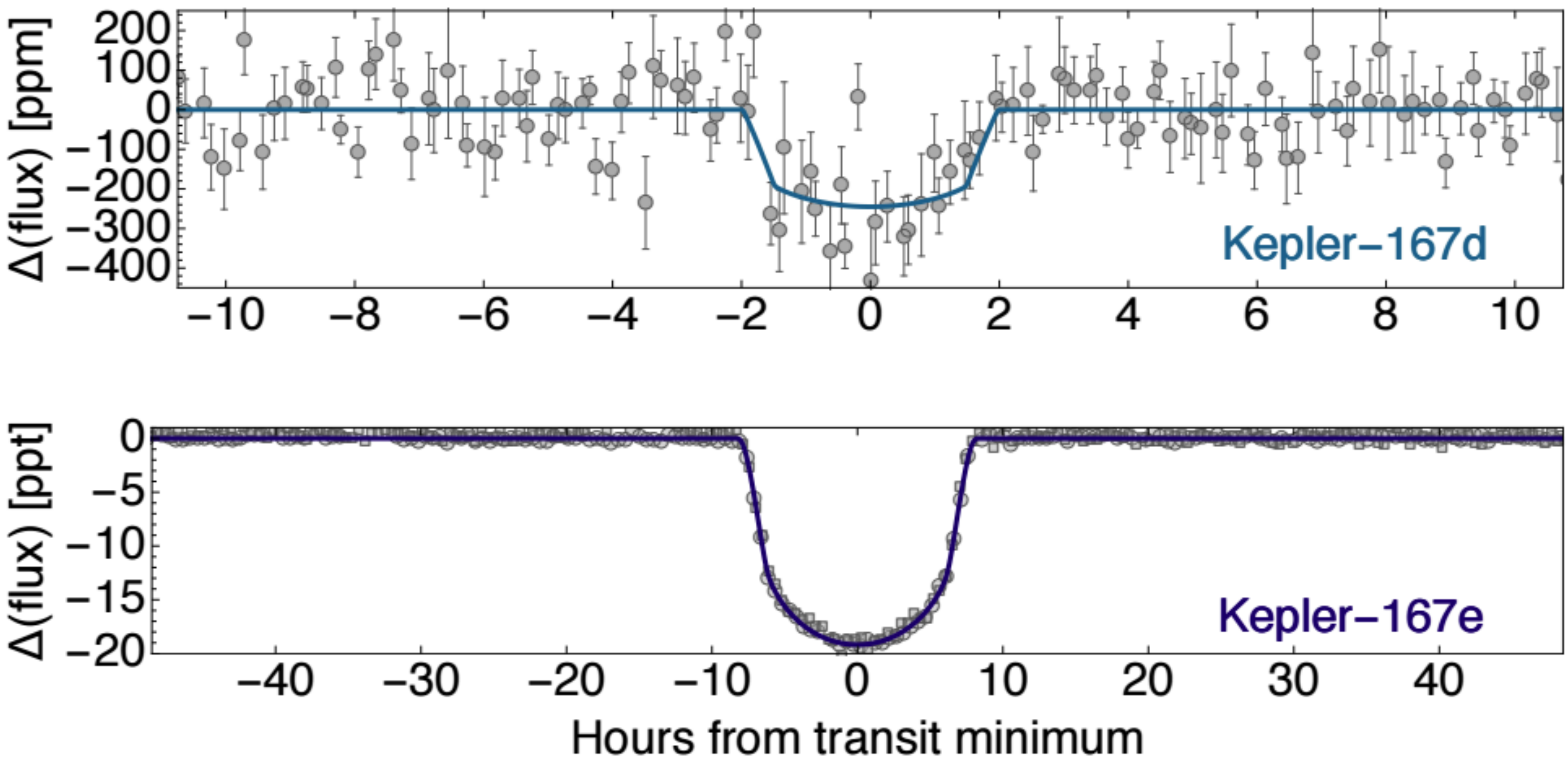

Star
1
2
3
Planet
Light curve
Brightness
Time


Brightness
Time

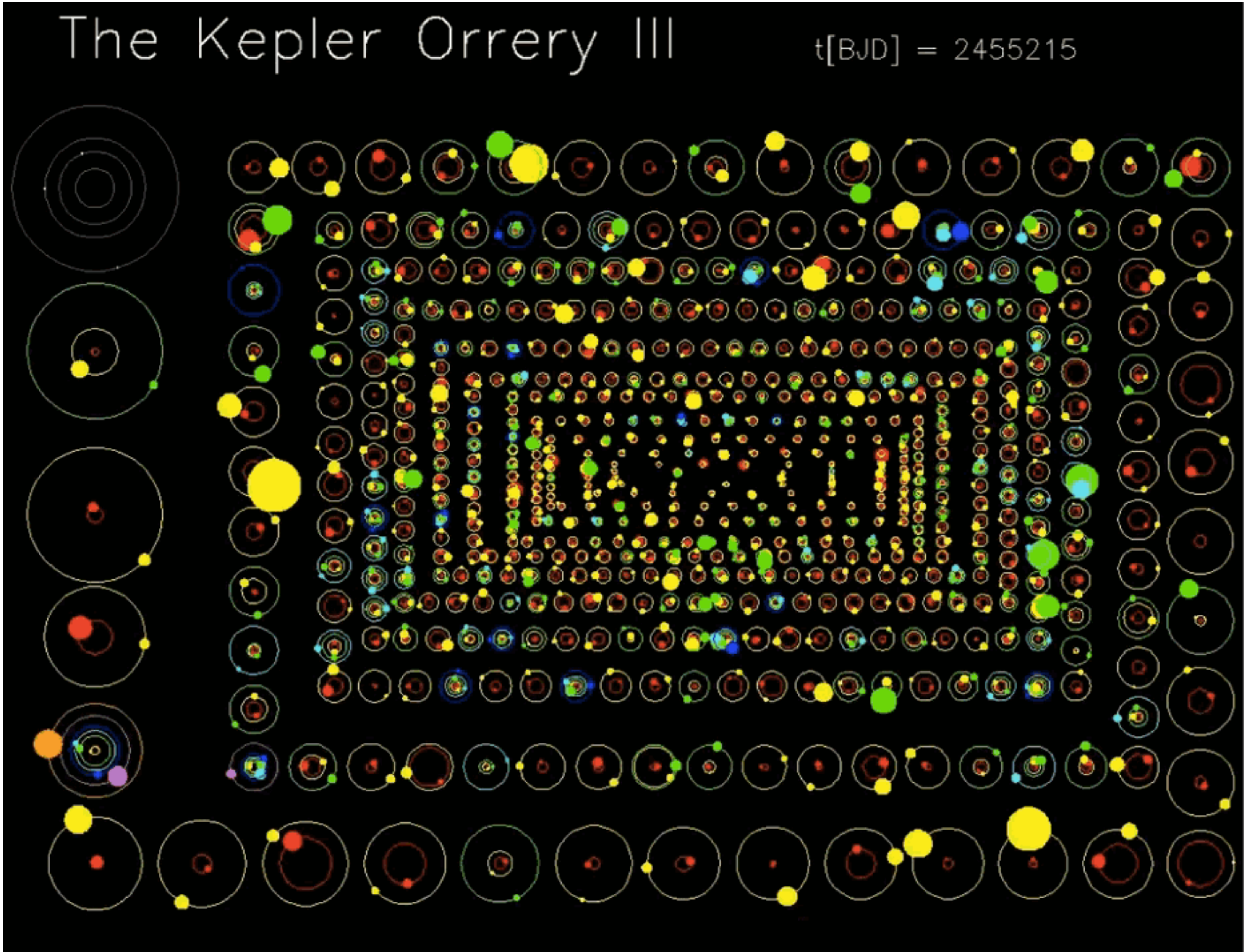
Kepler Observatory: thousands of planets




Secondary eclipse
Observe exoplanet's thermal radiation disappear and reappear
Primary eclipse
Exoplanet's size relative to star
See star's radiation transmitted through the planet's atmosphere



Δ(flux) [ppm]
200
100
0
−100
−200
−300
−400
−10
−8
−6
−4
−2
0
2
4
6
8
10
Kepler−167d
Δ(flux) [ppt]
0
−5
−10
−15
−20
−40
−30
−20
−10
0
10
20
30
40
Kepler−167e
Hours from transit minimum

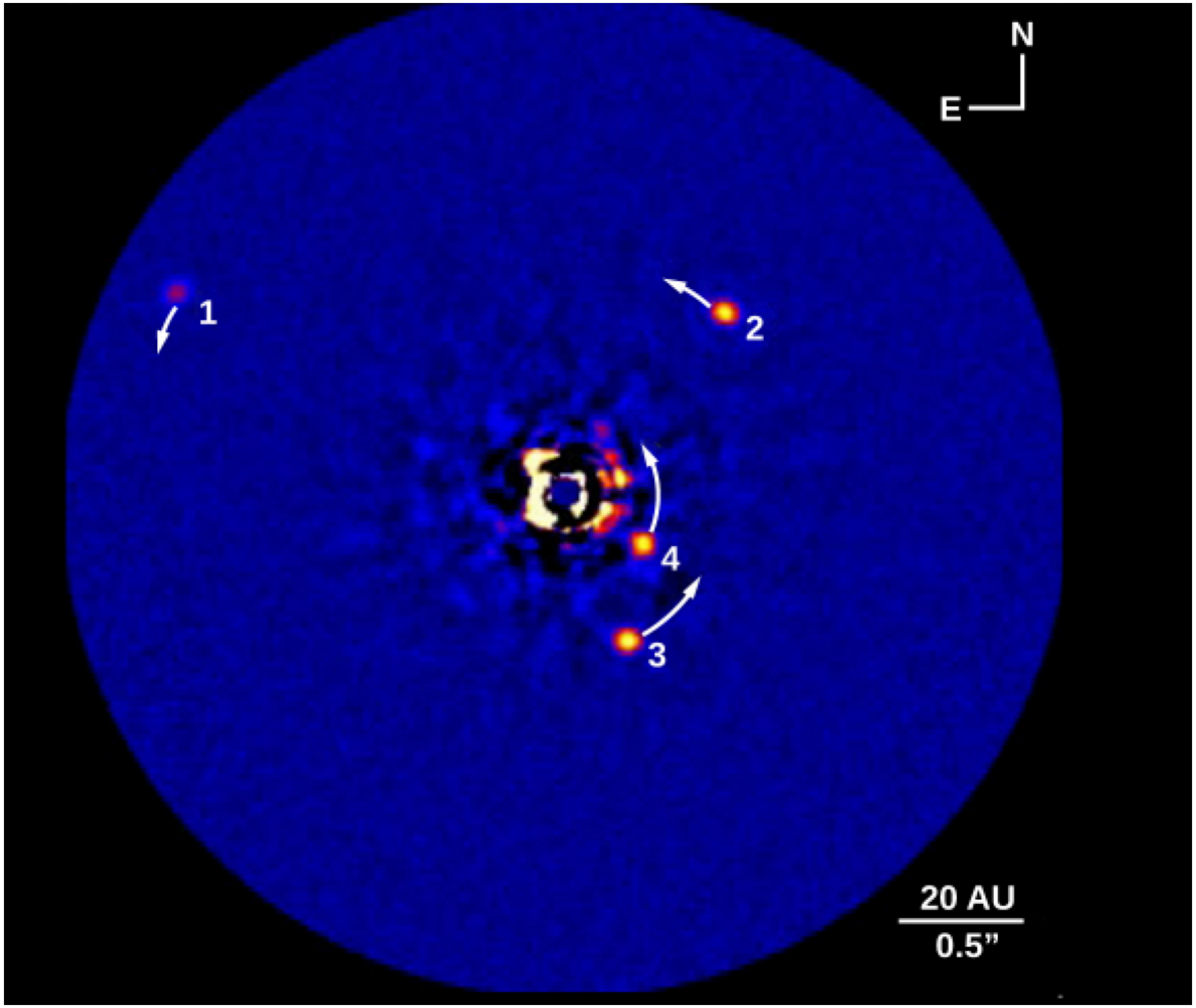

The Kepler Orrery III
t[BJD] = 2455215

Bias of transits

- What kinds of planets are easiest to detect?

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

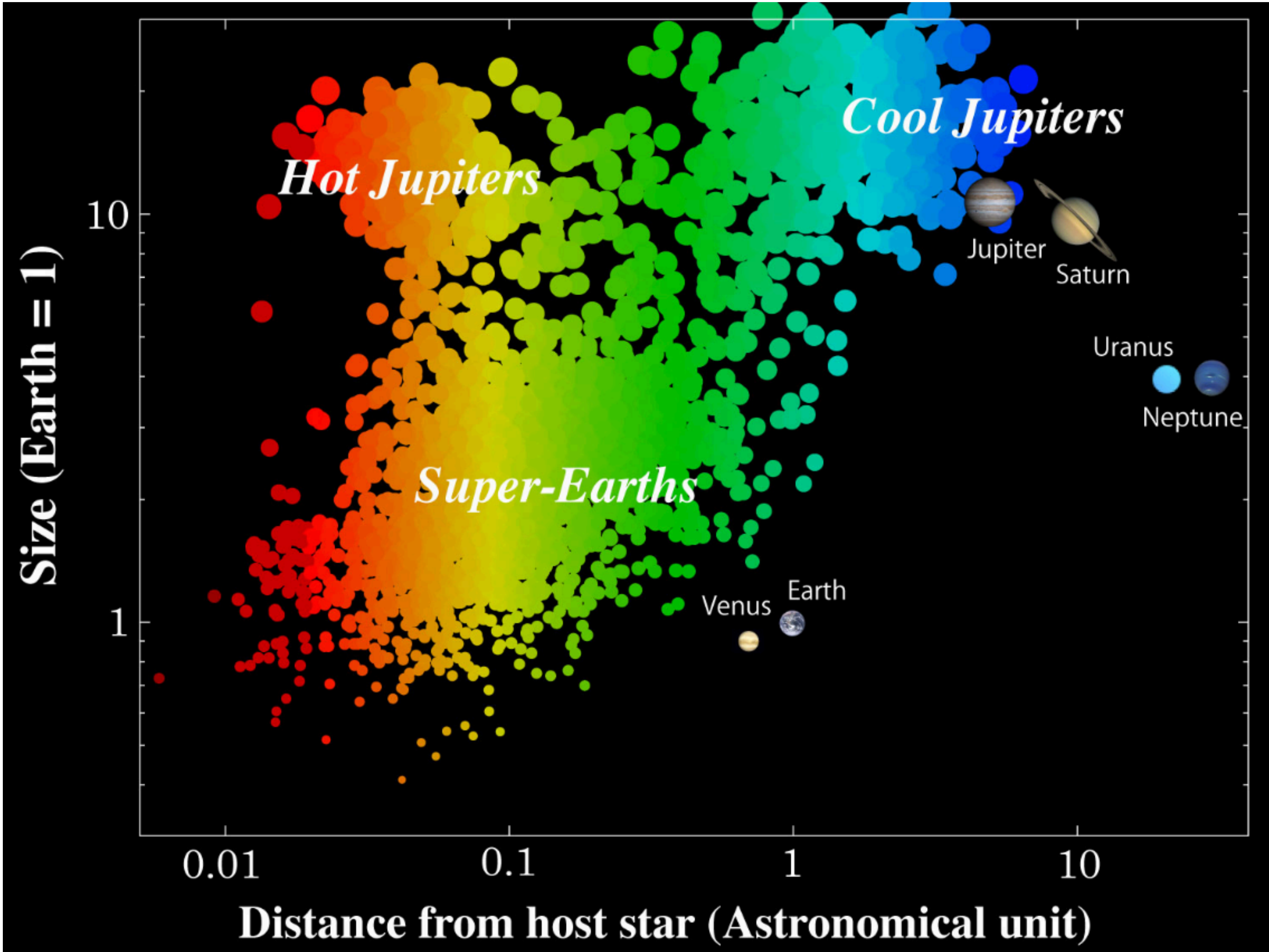
Direct Imaging: requires coronagraph to block out the star (similar to eclipse)



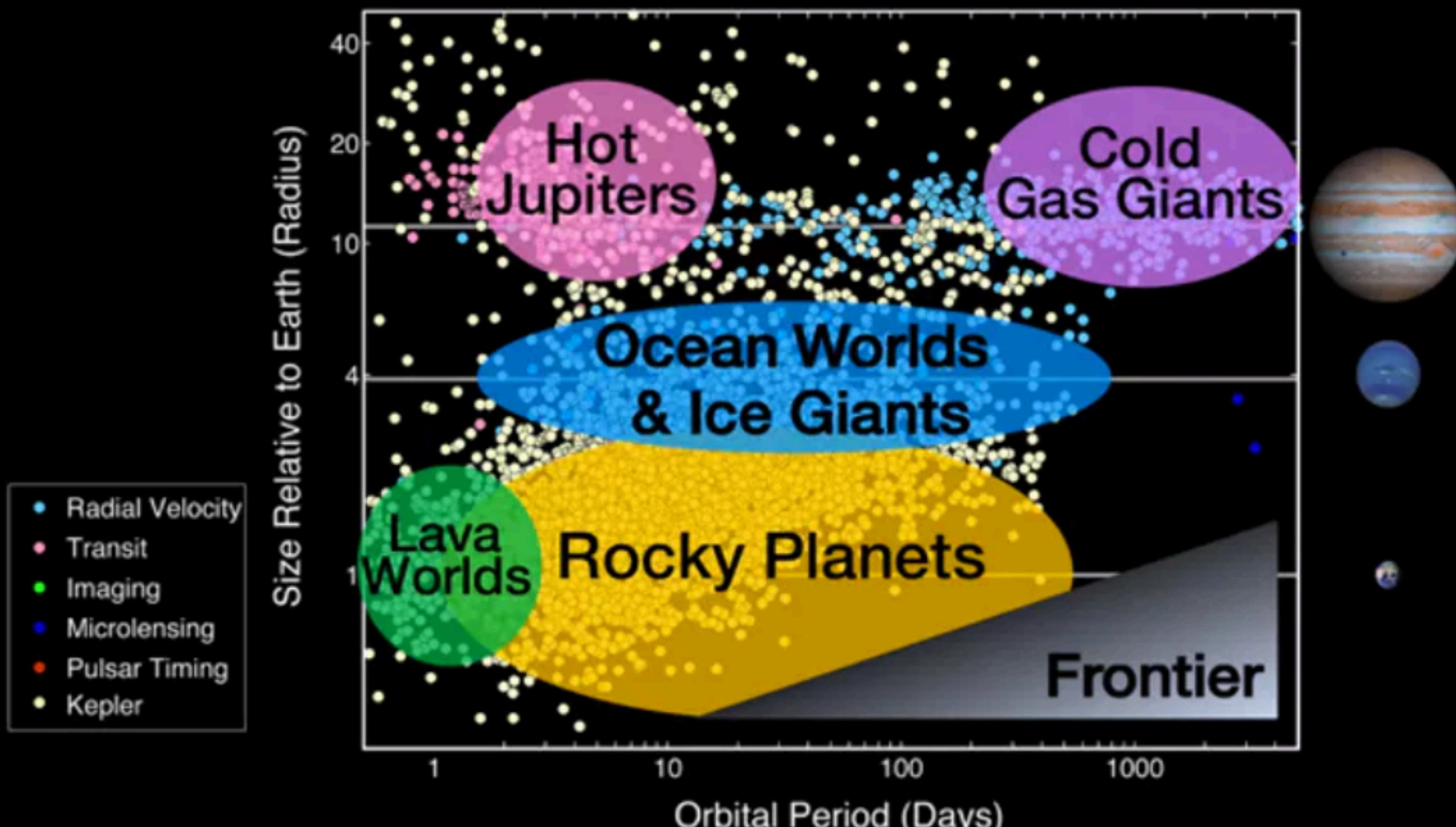
Bias of direct imaging

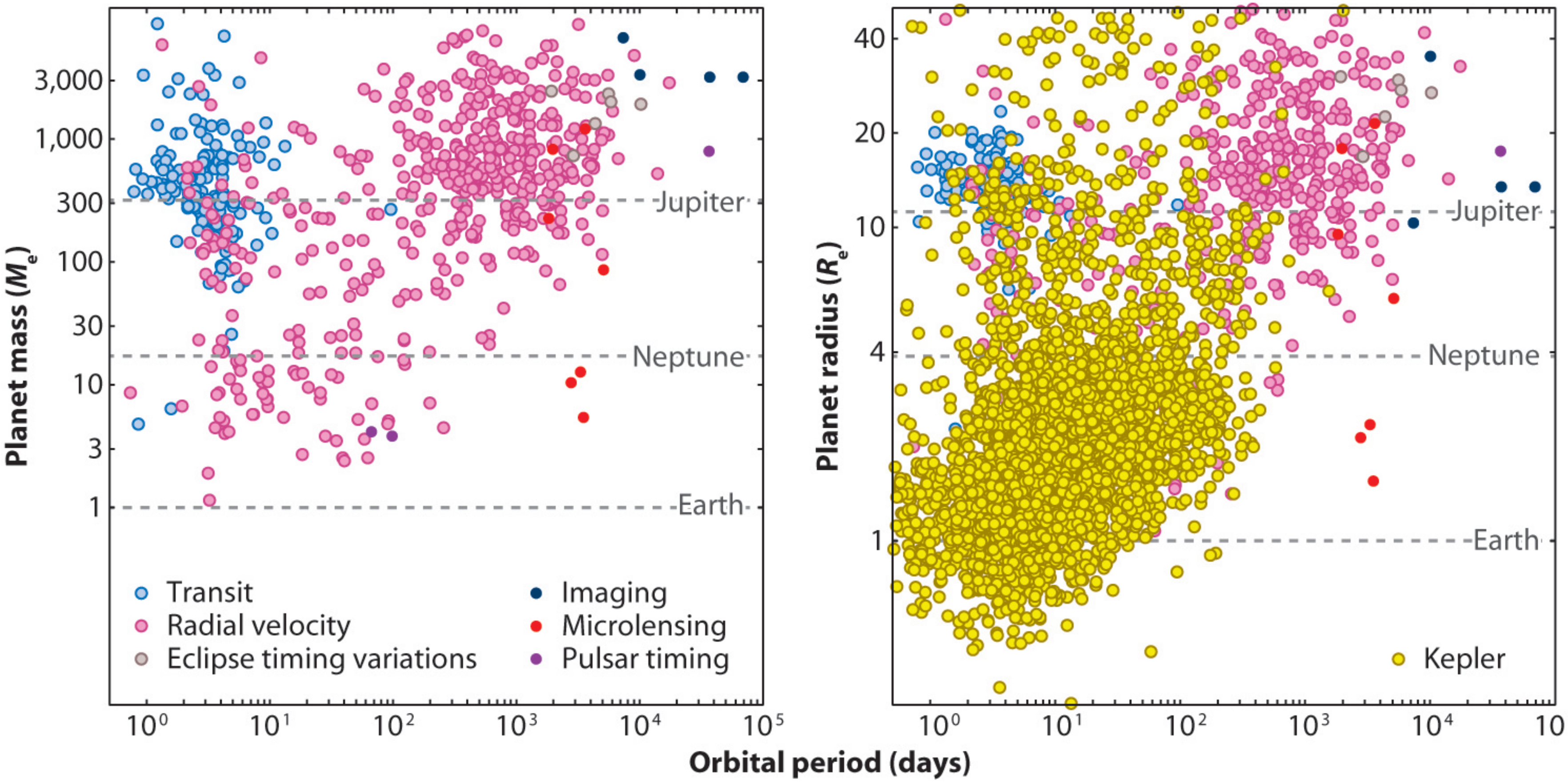
- What kinds of planets are easiest to detect?

[also this is very hard]

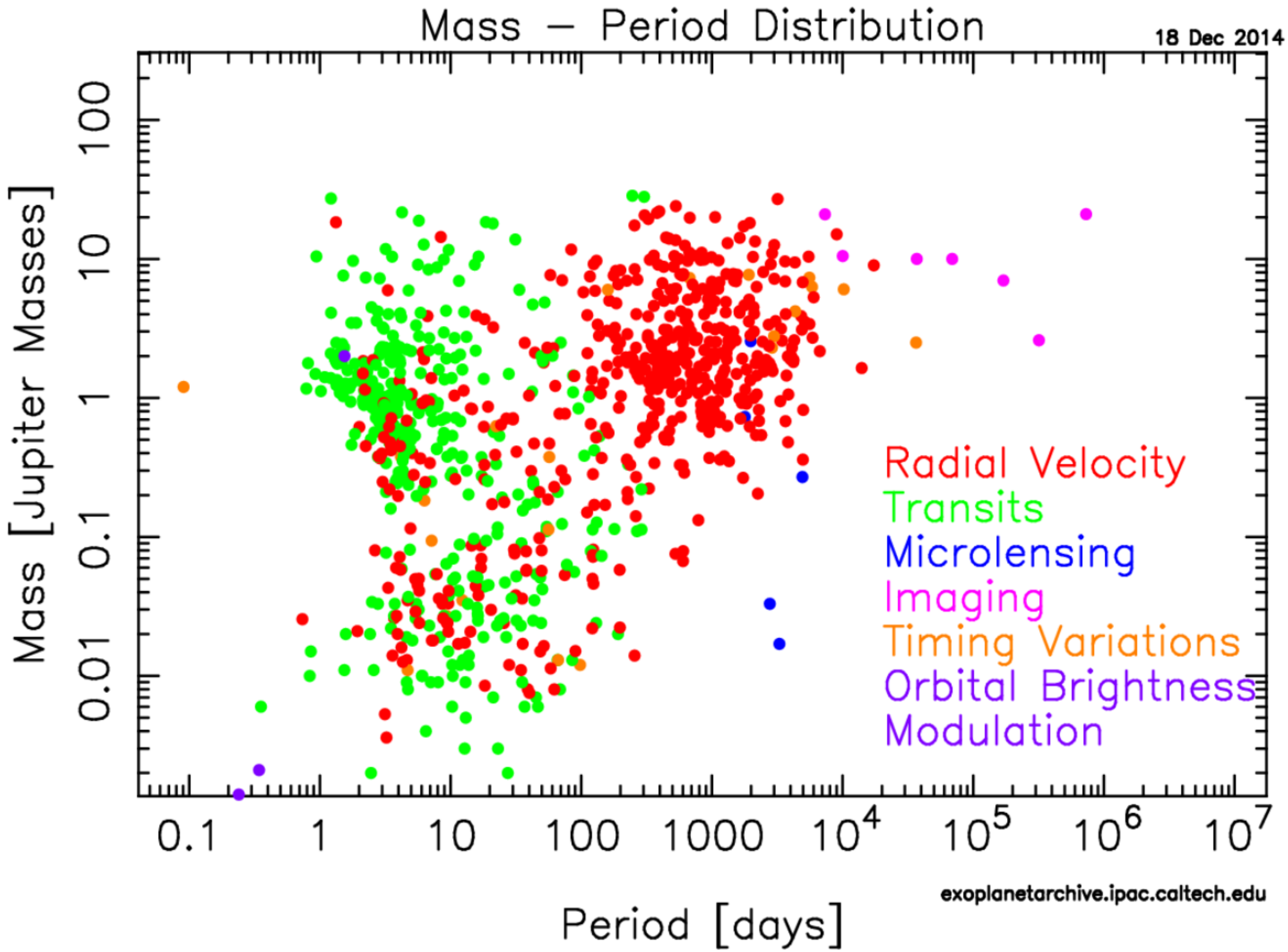

Cool Jupiters
Hot Jupiters
Super-Earths
Jupiter
Saturn
Uranus
Neptune
Venus
Earth
10
1
Size (Earth = 1)
0.01
0.1
1
10
Distance from host star (Astronomical unit)

Exoplanet Populations

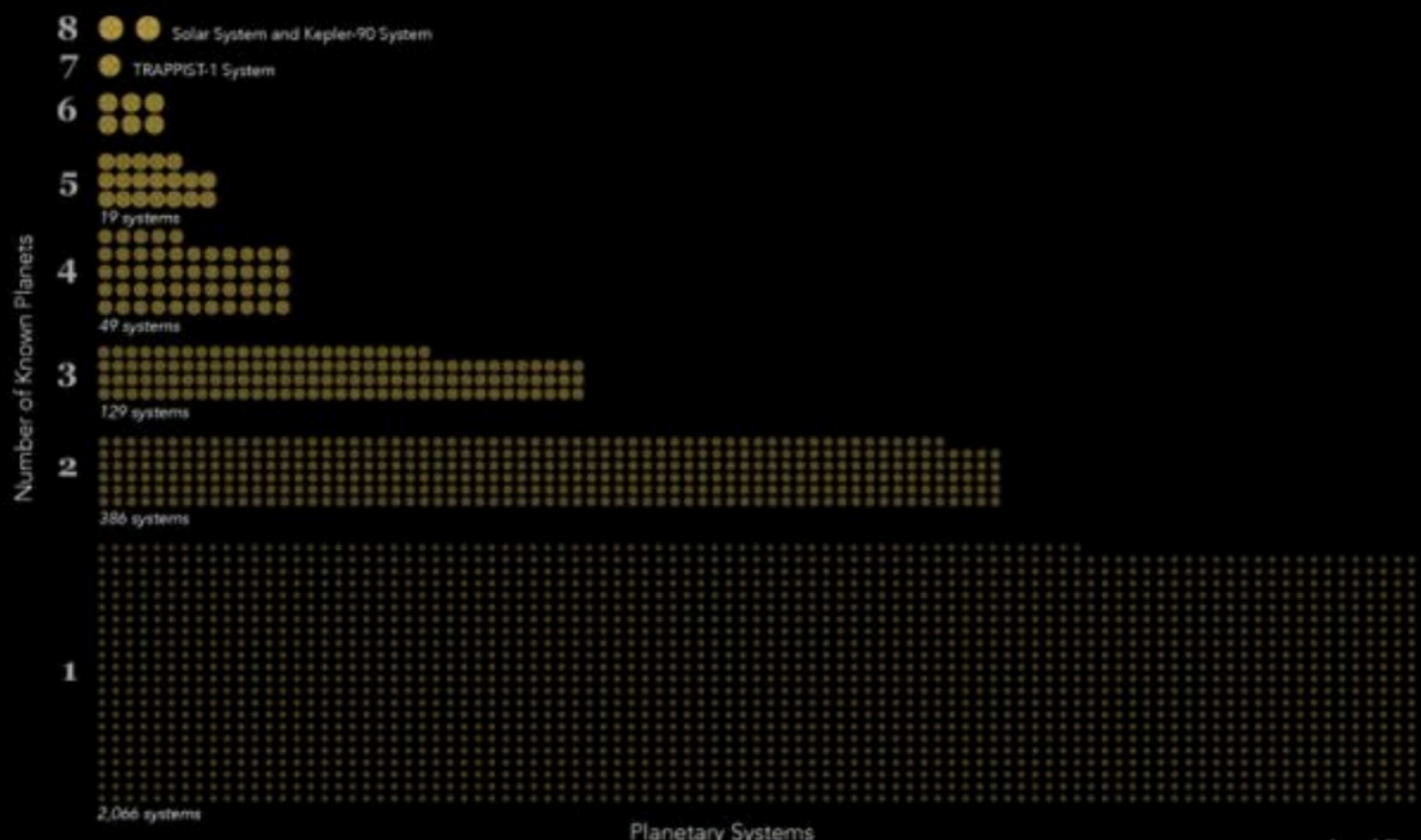



Planet mass (M_e)
3,000
1,000
300
100
30
10
3
1
Jupiter
Neptune
Earth
Transit
Radial velocity
Eclipse timing variations
Imaging
Microlensing
Pulsar timing
Planet radius (R_e)
40
20
10
4
1
Kepler
10^0
10^1
10^2
10^3
10^4
10^5
Orbital period (days)

Exoplanets are common!



Planetary Systems by Number of Known Planets



As of December 14, 2017

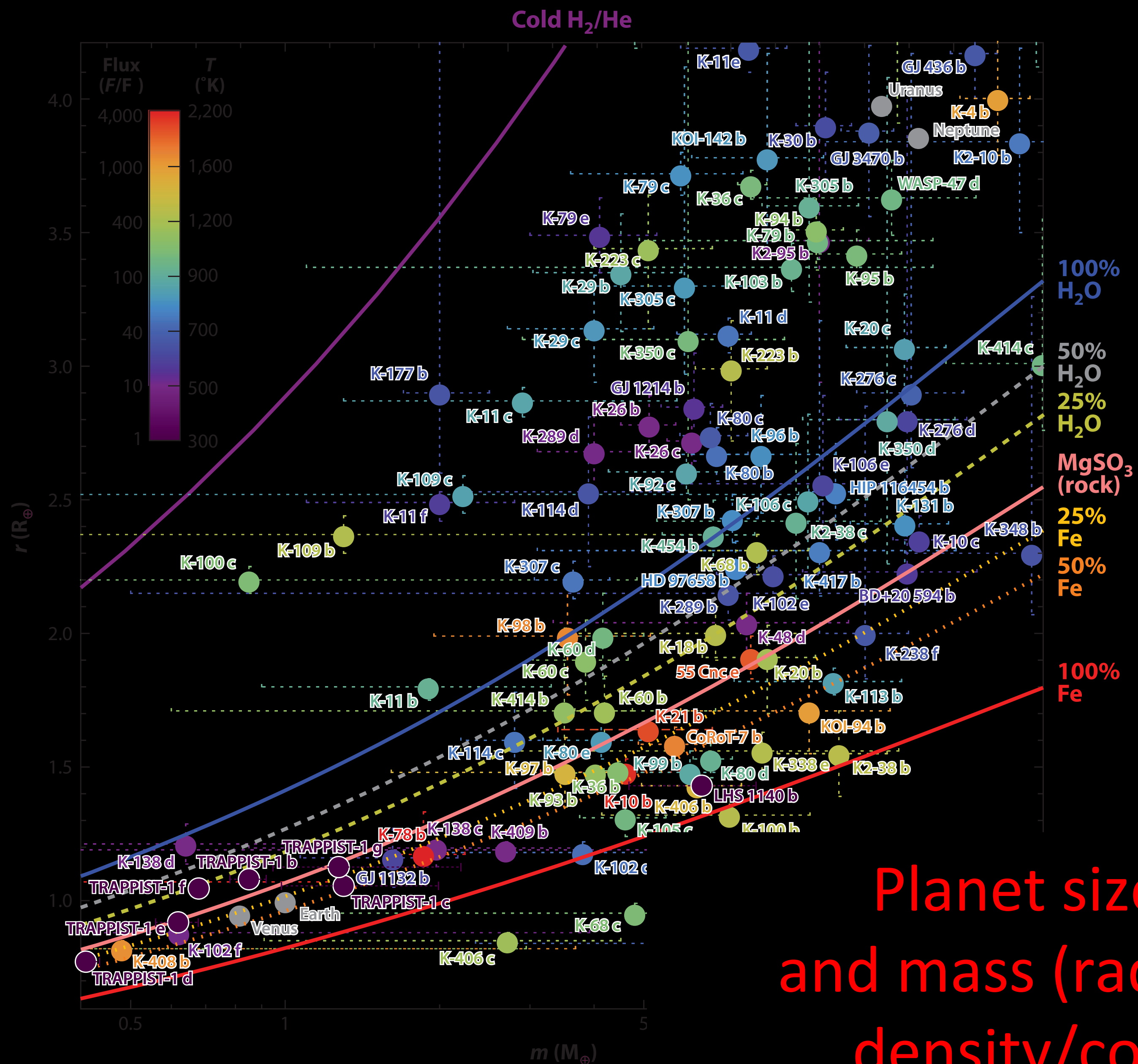
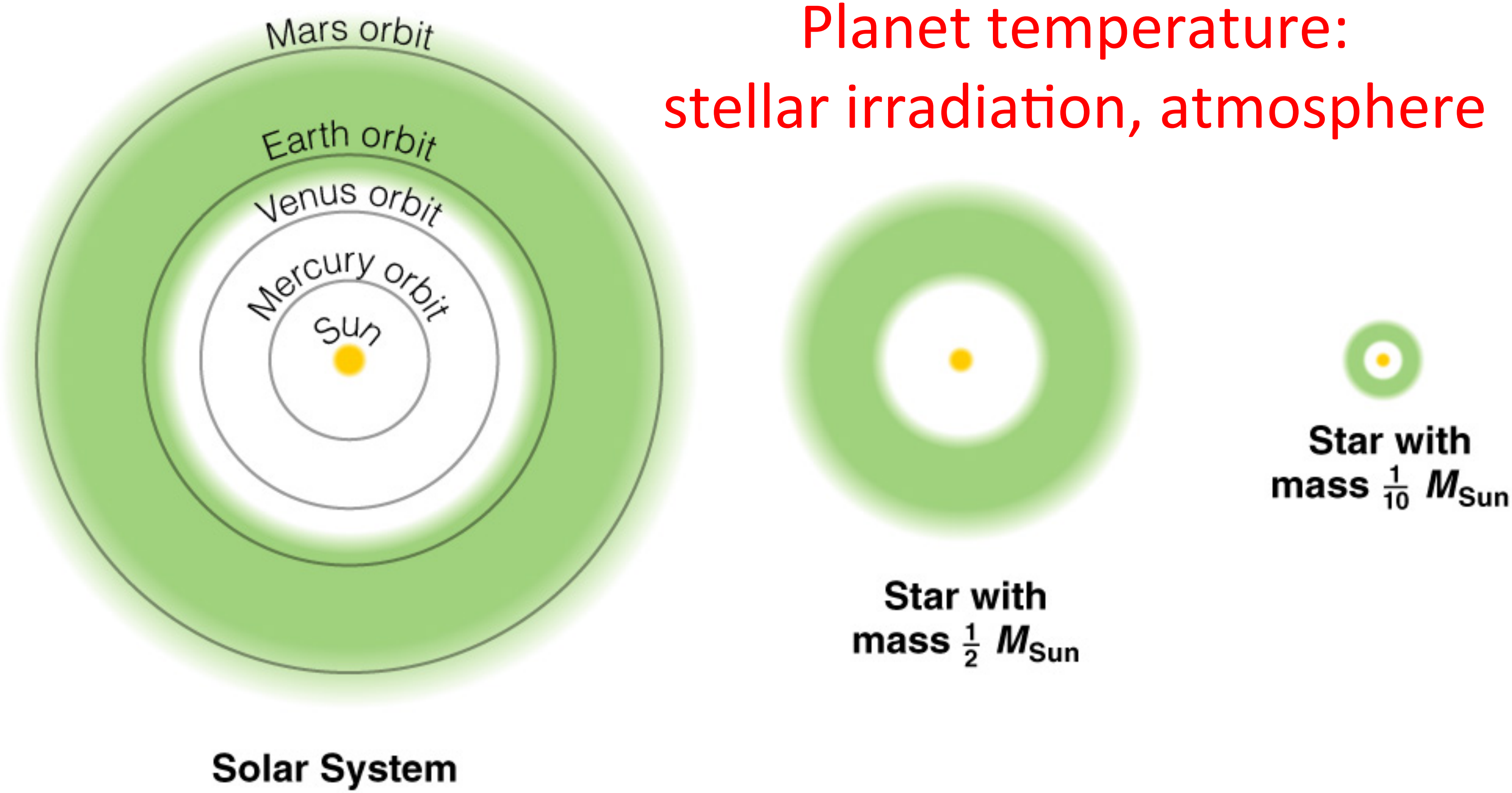


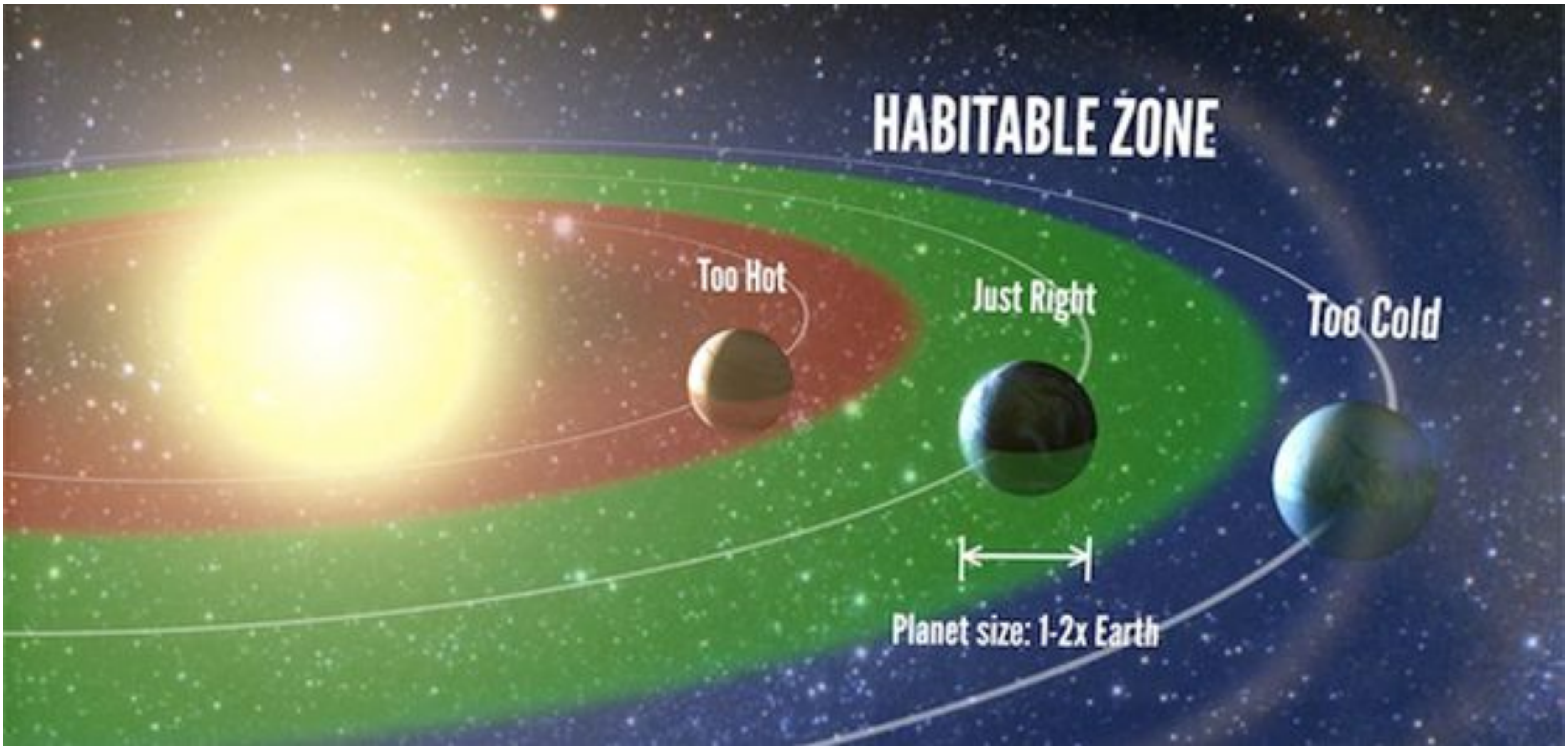
Figure 1

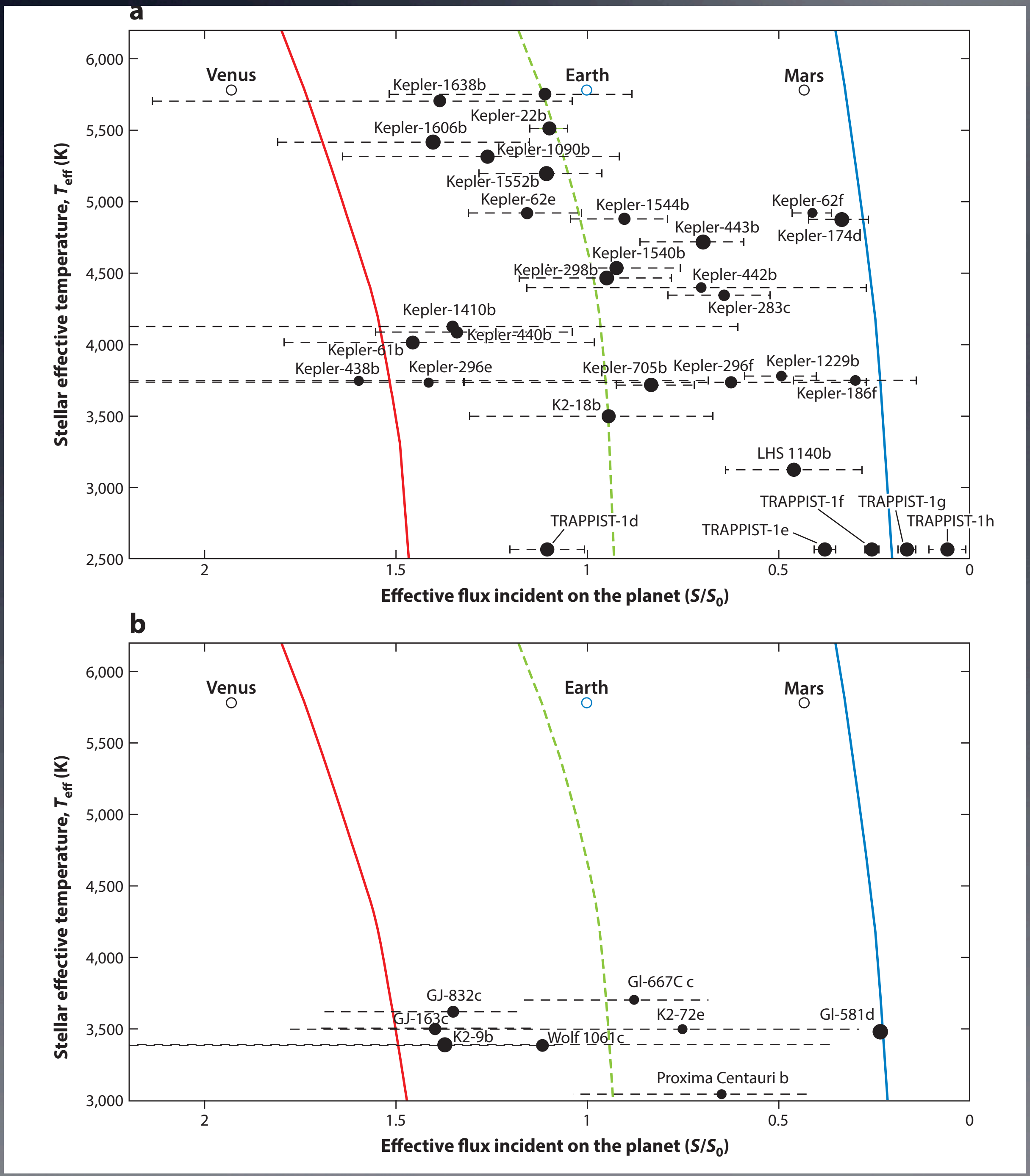
Planet size (transit) and mass (radial velocity): density/composition

Are habitable planets likely?

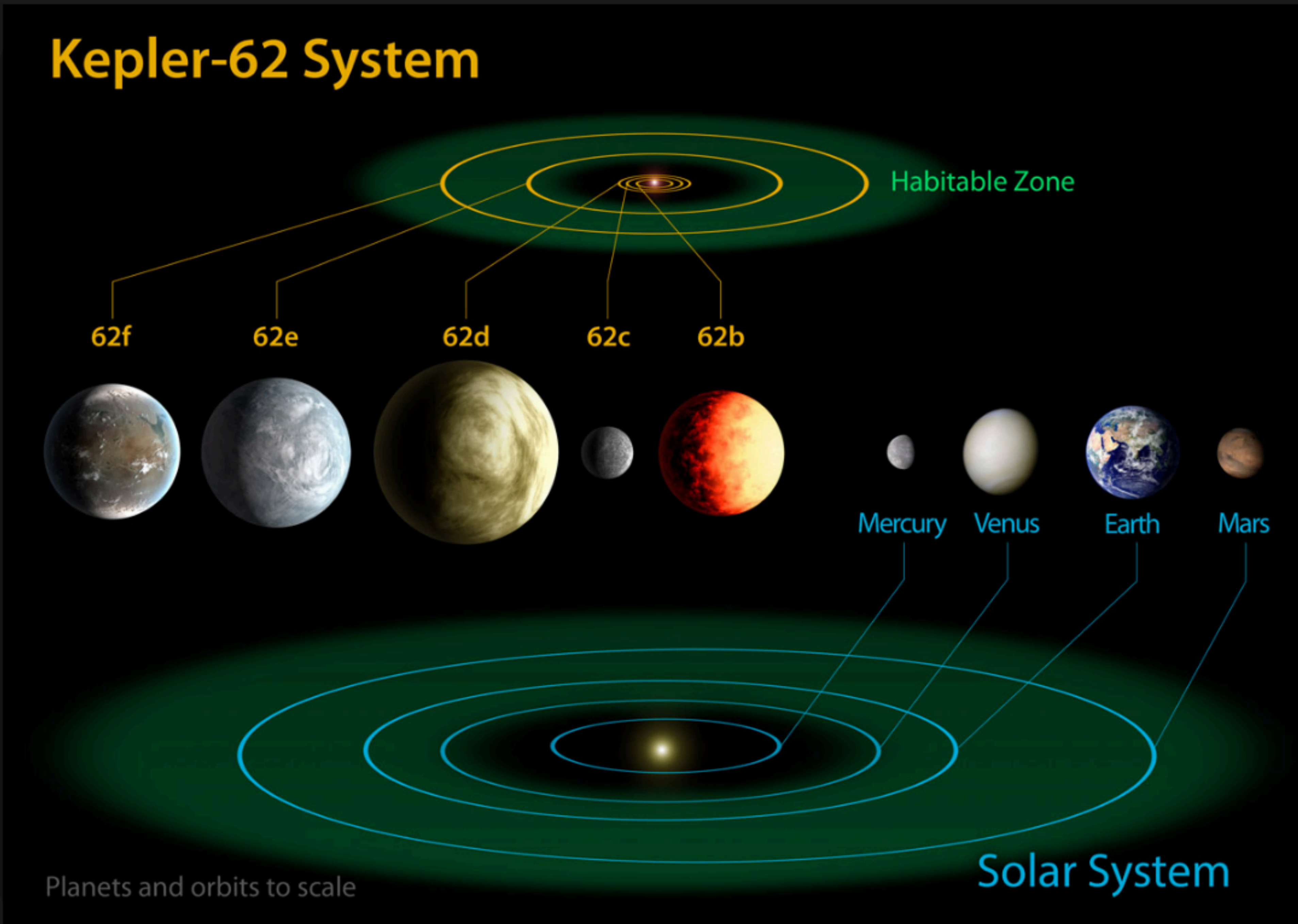
Planet temperature:
stellar irradiation, atmosphere



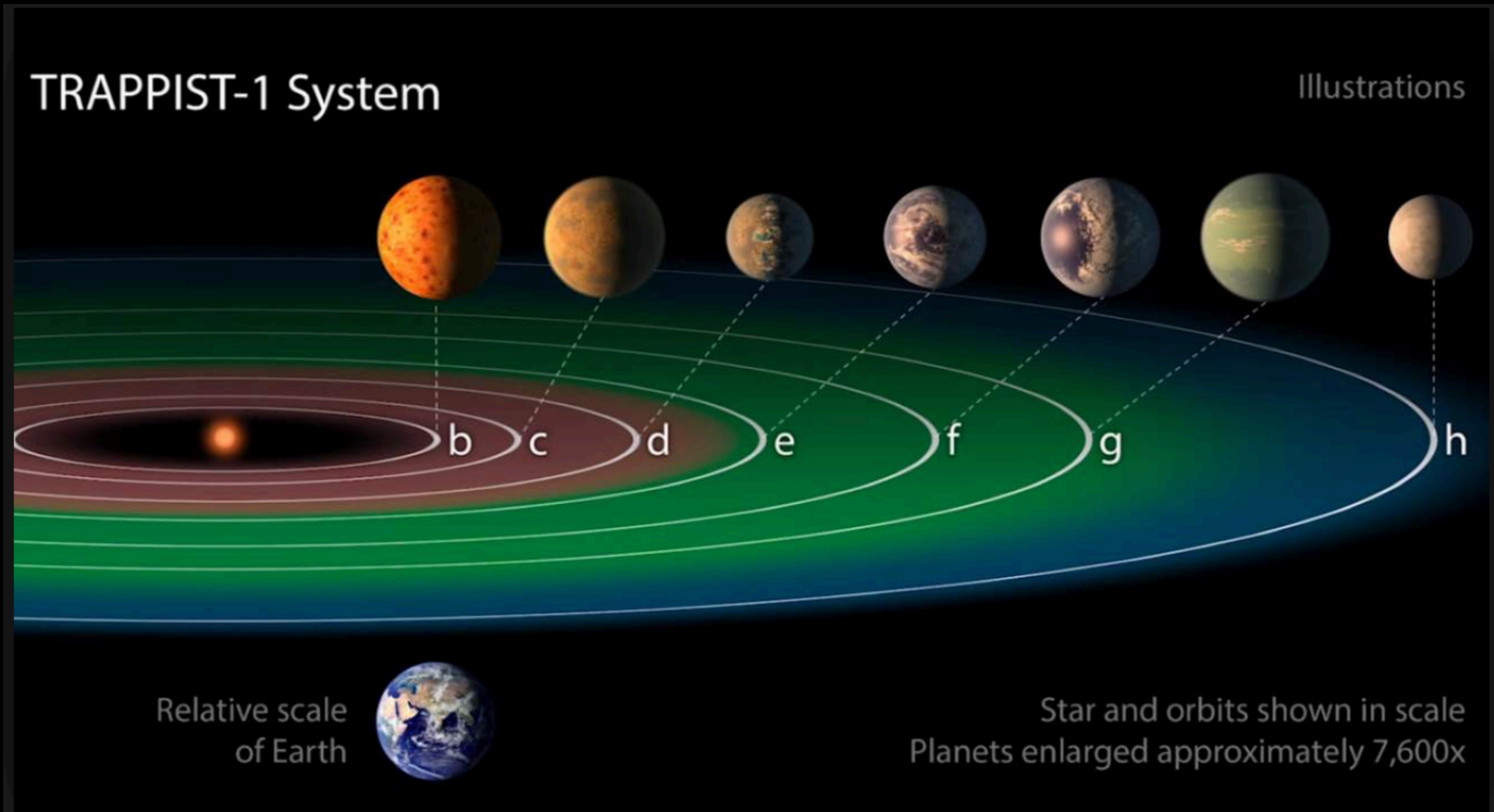

HABITABLE ZONE
Too Hot
Just Right
Too Cold
Planet size: 1-2x Earth

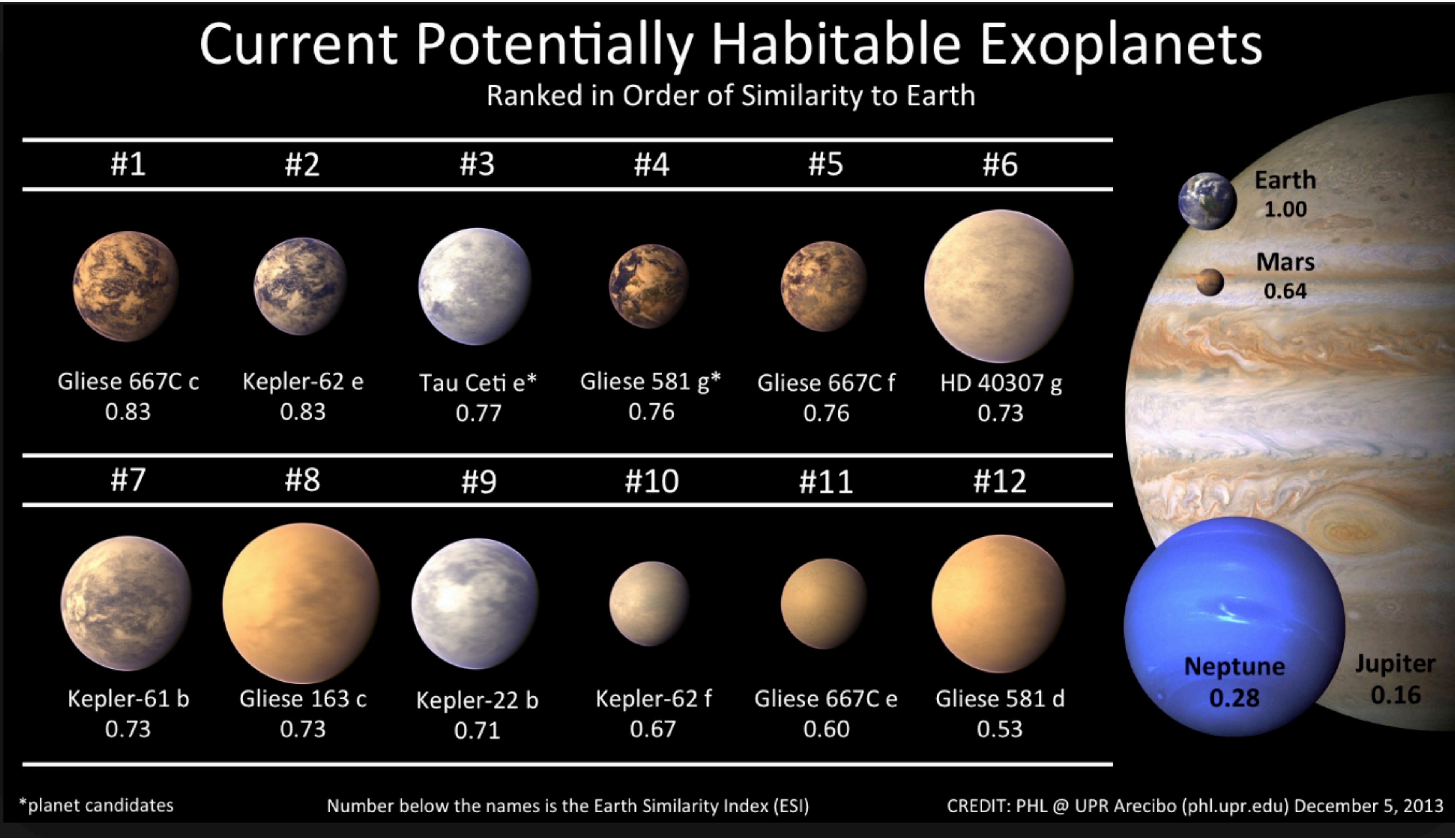


Exoplanets in habitable zone

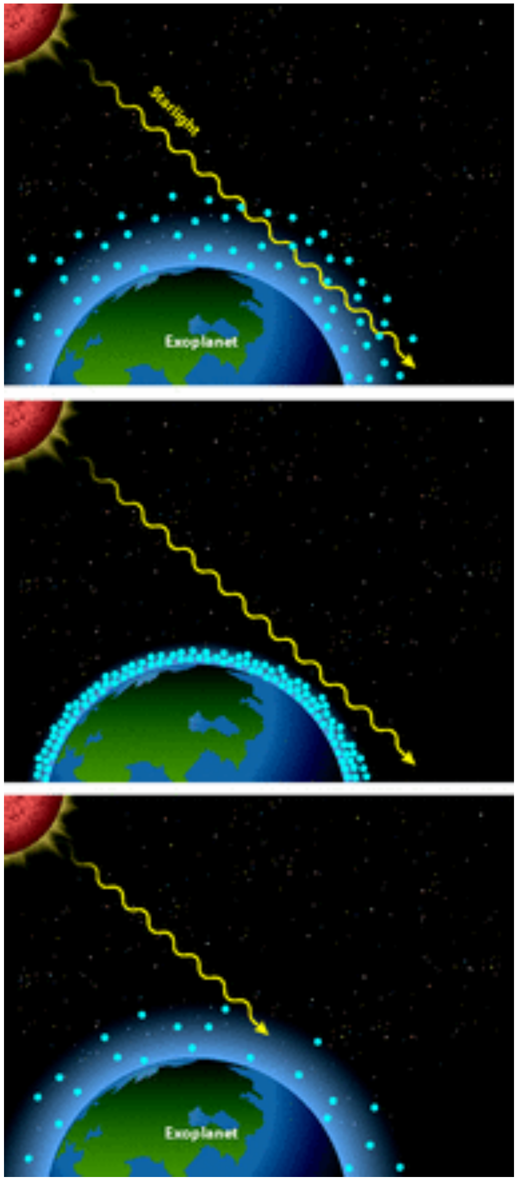


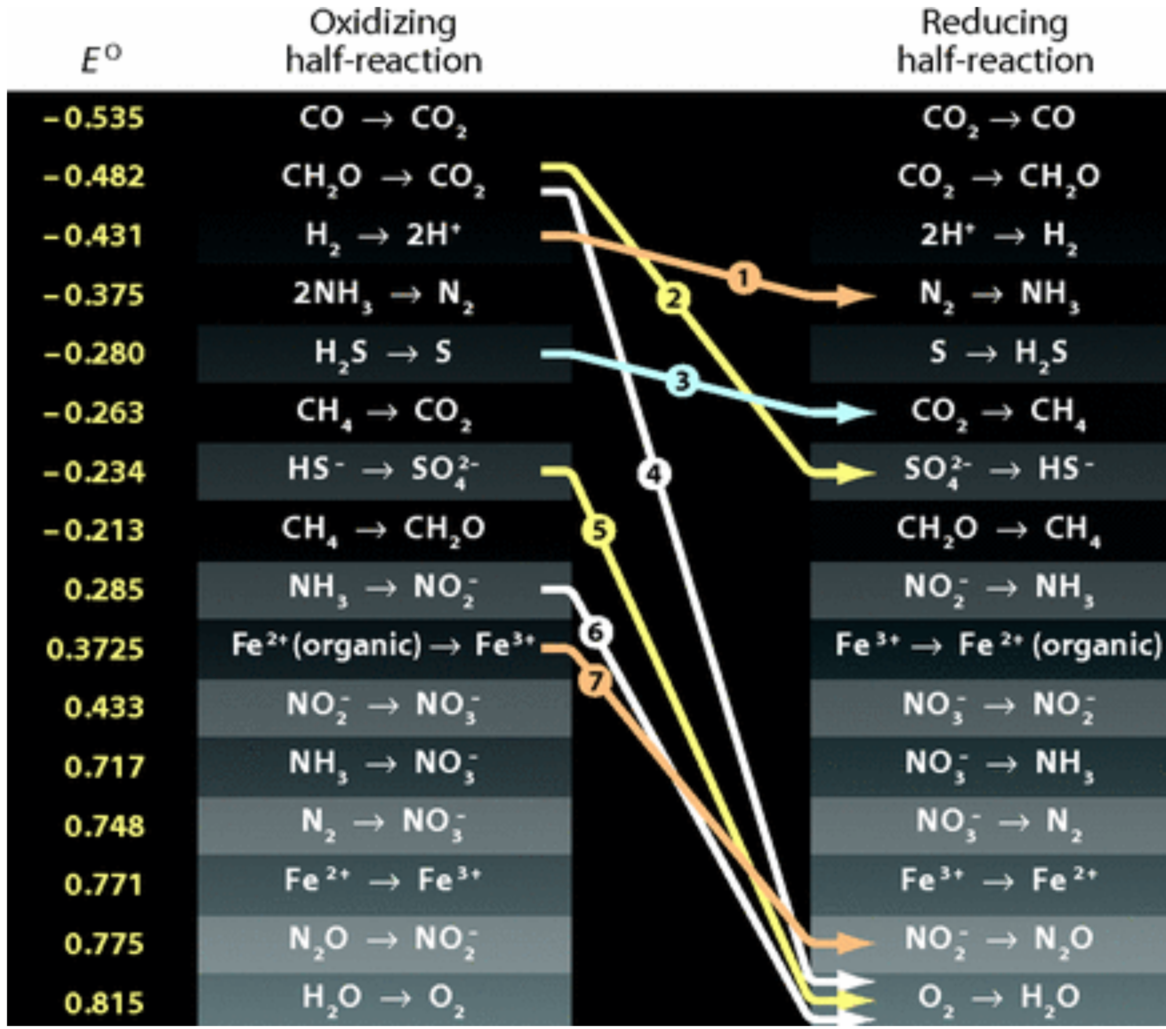
Kepler-62 System
Habitable Zone
62f
62e
62d
62c
62b
Mercury
Venus
Earth
Mars
Solar System
Planets and orbits to scale

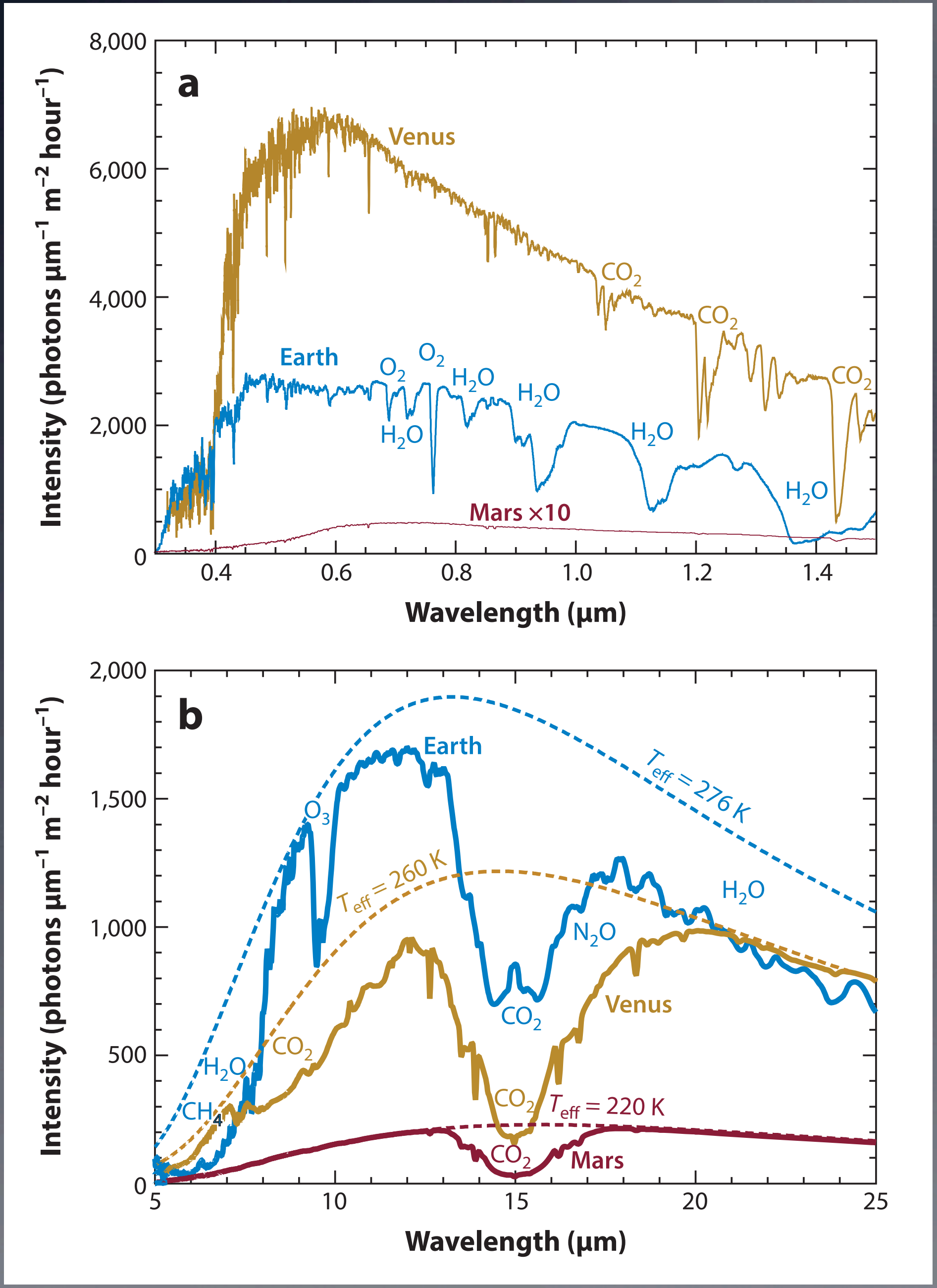

TRAPPIST-1 System
Illustrations
b
c
d
e
f
g
h
Relative scale of Earth
Star and orbits shown in scale
Planets enlarged approximately 7,600x


Current Potentially Habitable Exoplanets
Ranked in Order of Similarity to Earth
#1
#2
#3
#4
#5
#6
Gliese 667C c
0.83
Kepler-62 e
0.83
Tau Ceti e*
0.77
Gliese 581 g*
0.76
Gliese 667C f
0.76
HD 40307 g
0.73
#7
#8
#9
#10
#11
#12
Kepler-61 b
0.73
Gliese 163 c
0.73
Kepler-22 b
0.71
Kepler-62 f
0.67
Gliese 667C e
0.60
Gliese 581 d
0.53
Earth
1.00
Mars
0.64
Neptune
0.28
Jupiter
0.16
*planet candidates
Number below the names is the Earth Similarity Index (ESI)
CREDIT: PHL @ UPR Arecibo (phl.upr.edu) December 5, 2013

Exoplanet atmospheres!

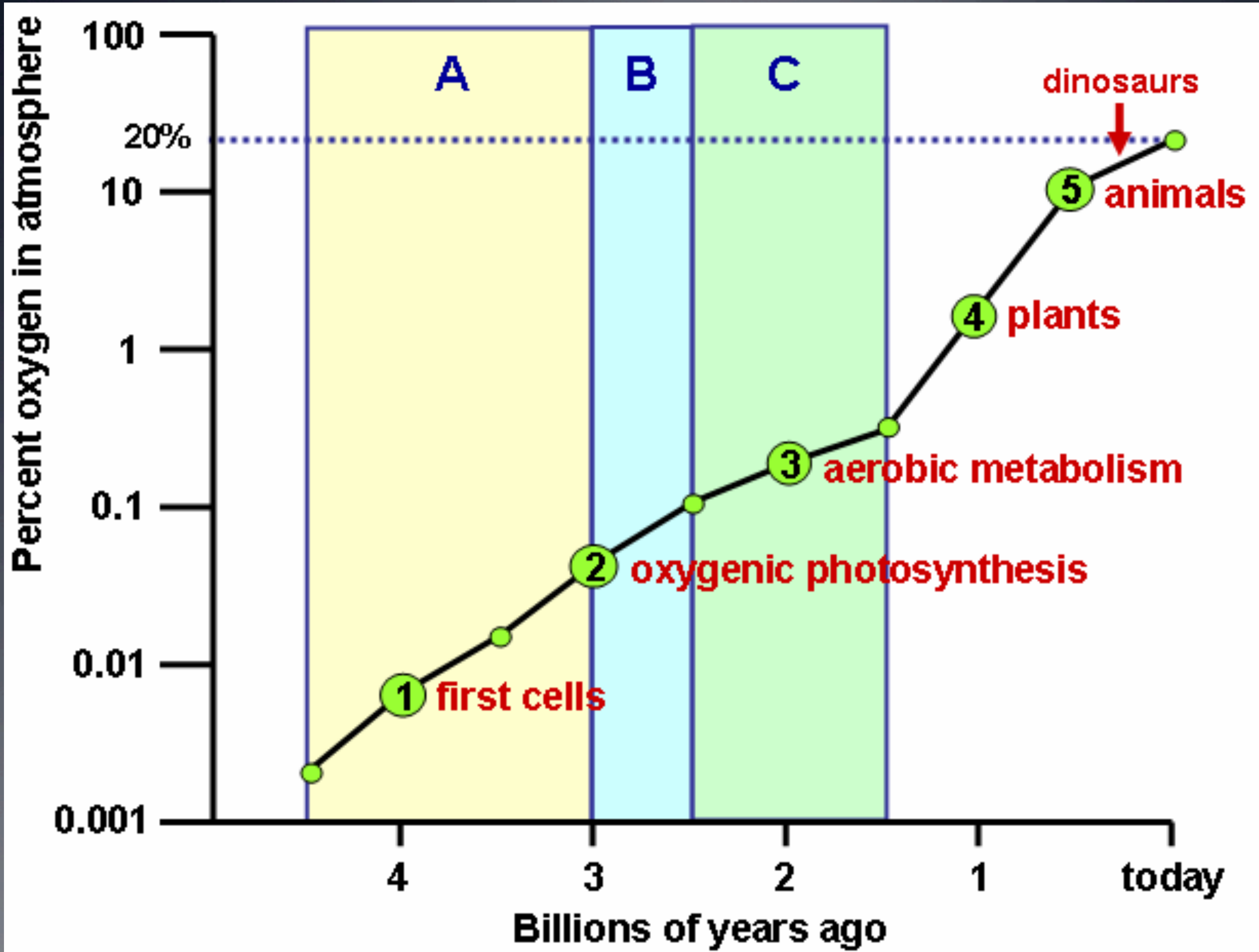






Life changes its environment

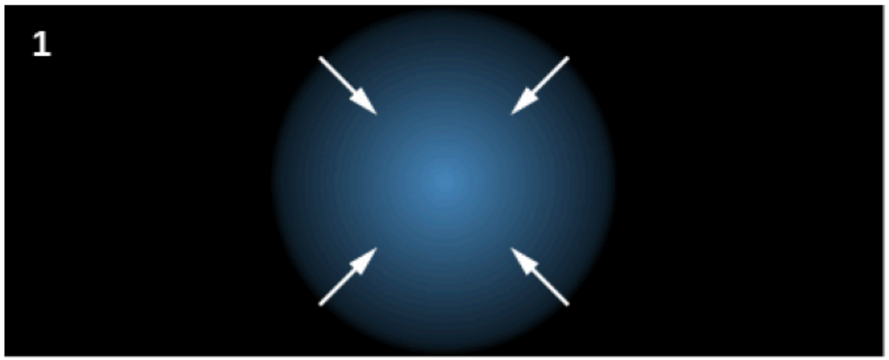
- Life needs a suitable environment to flourish.
- Feedback on environment/ atmosphere
- Changes: biosignature, a sign of the presence of life
- Oxygen in Earth's atmosphere is a biosignature of life. Looking from afar, we cannot see plants and bacteria directly, but we can infer the presence of photosynthetic life if there is atmospheric oxygen.



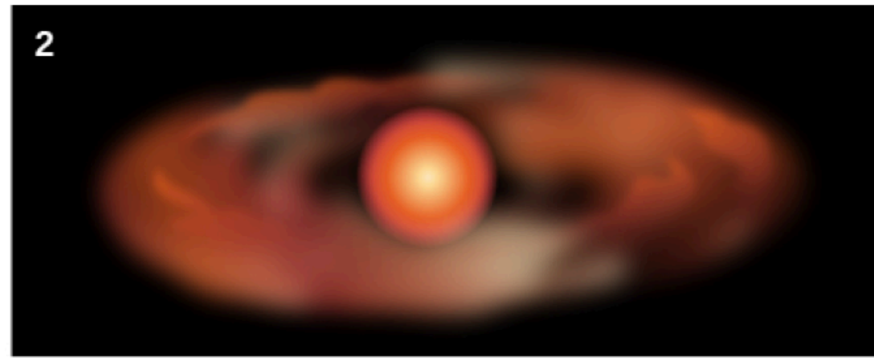
Percent oxygen in atmosphere
100
20%
10
1
0.1
0.01
0.001
A
B
C
dinosaurs
5 animals
4 plants
3 aerobic metabolism
2 oxygenic photosynthesis
1 first cells
4
3
2
1
today
Billions of years ago

Planet Formation

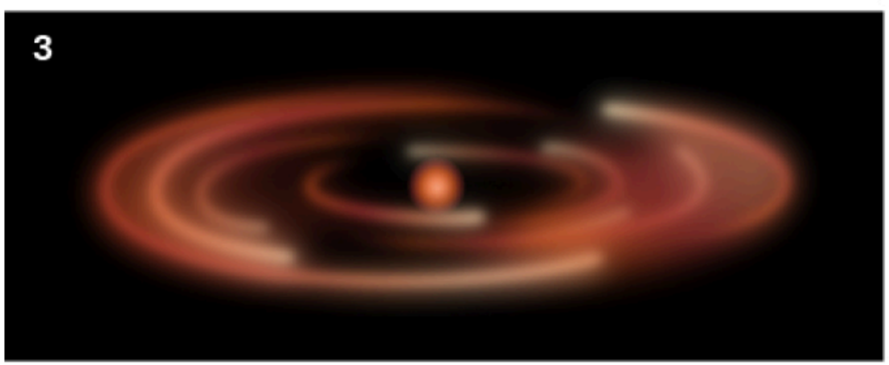
(last step in star formation, last class)



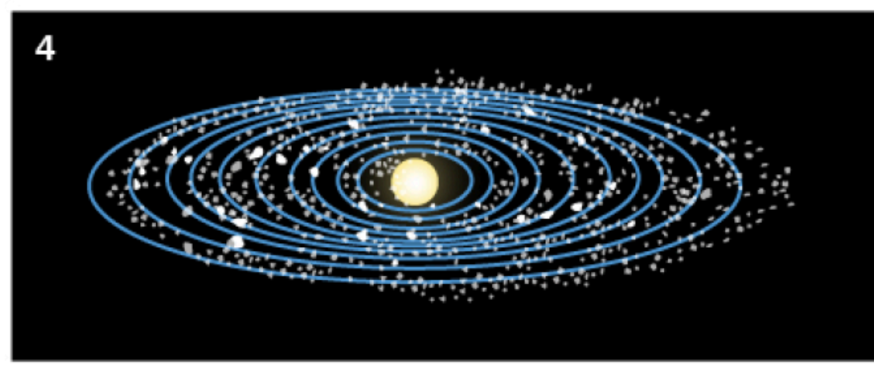
The solar nebula contracts.



As the nebula shrinks, its motion causes it to flatten.



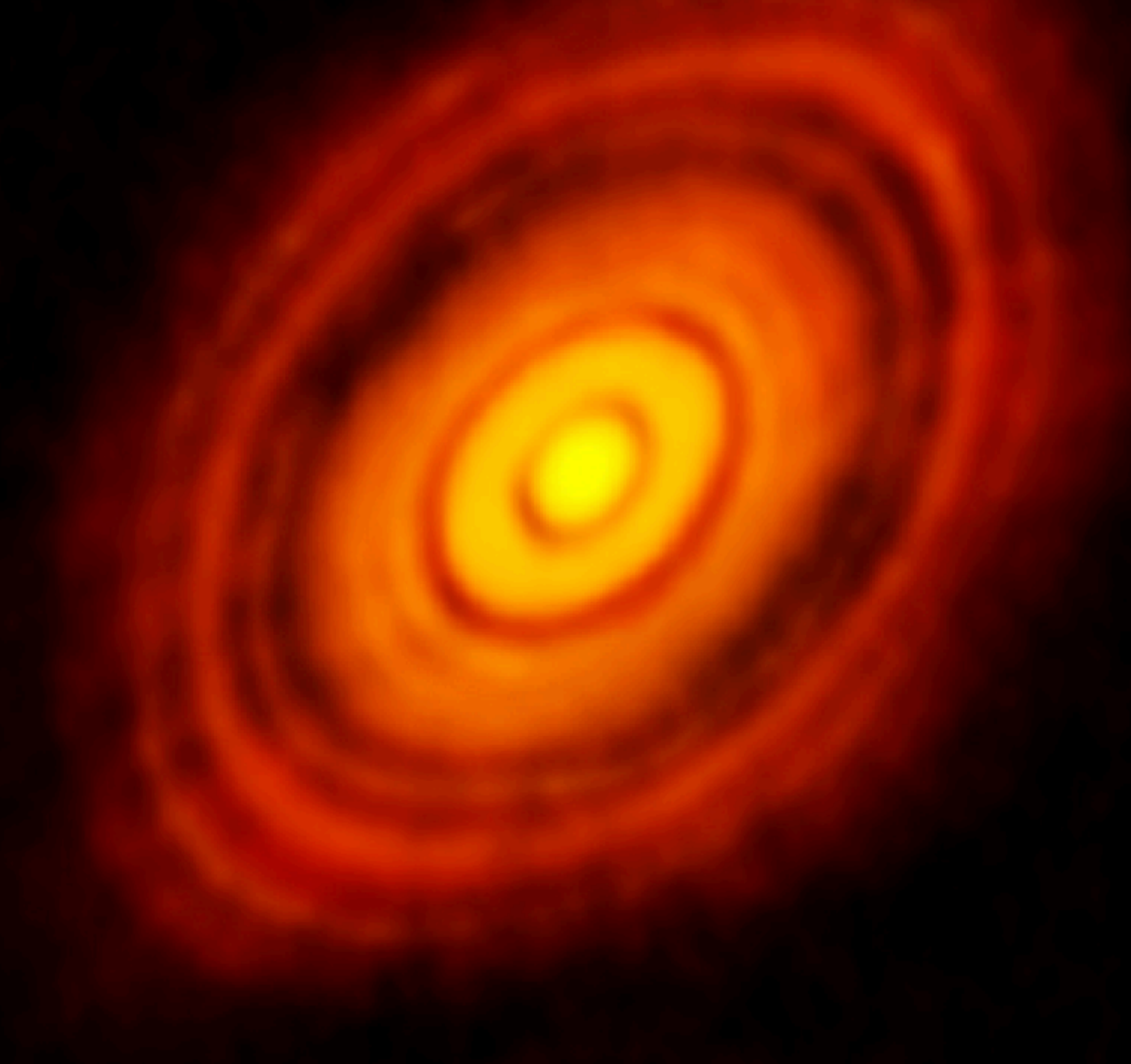
The nebula is a disk of matter with a concentration near the center.



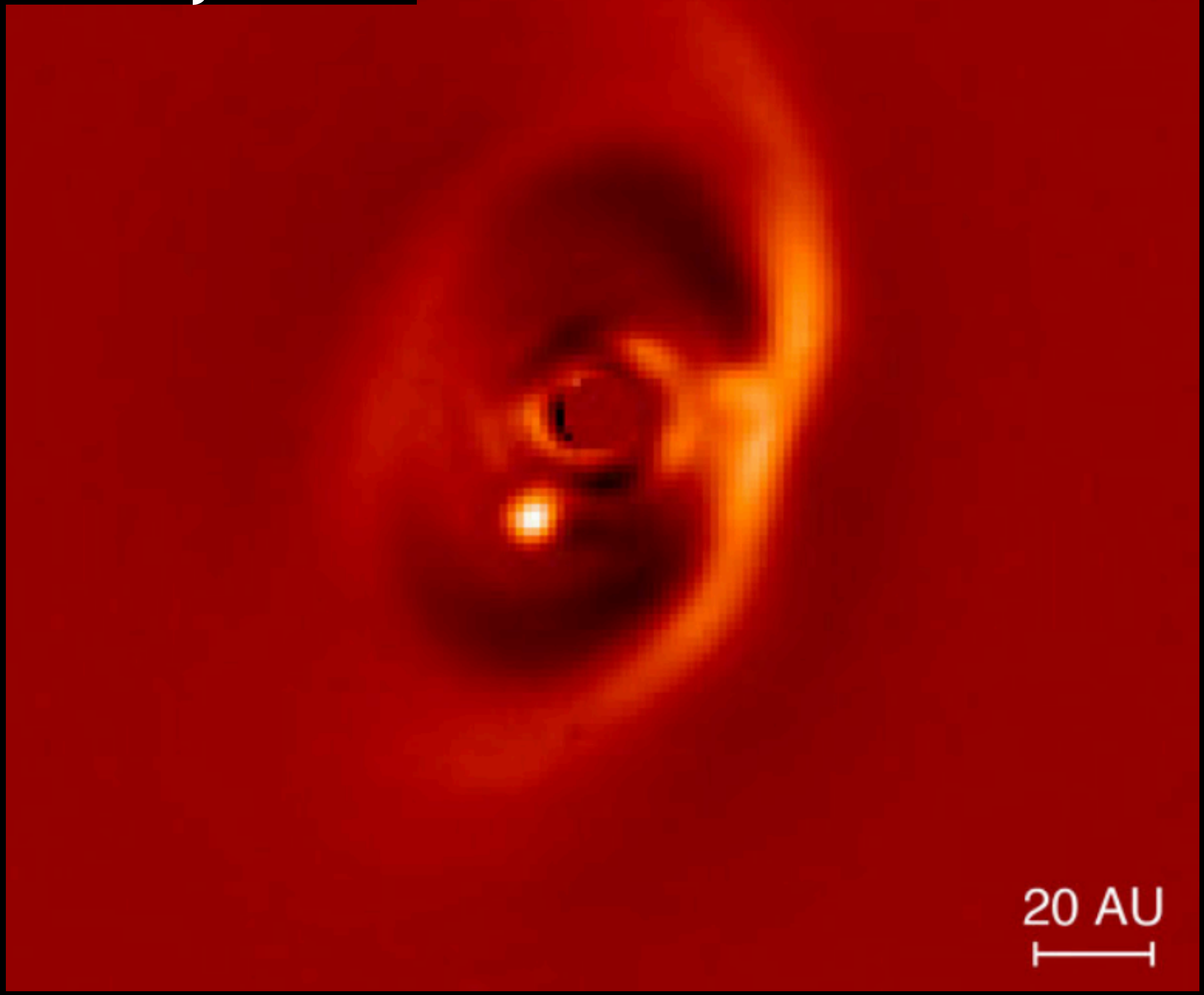
Formation of the protosun. Solid particles condense as the nebula cools, giving rise to the planetesimals, which are the building blocks of the planets.

Planets should form in disk and carve a gap

Image of a protoplanetary disk



Planet in a protoplanetary disk!



Planets are everywhere!

- Many different detection techniques
  - Earths still challenging
  - Atmospheres very challenging
  - Many biases to larger planets, closer objects

- Planet Formation
  - Observational evidence for unseen planets
  - (seen in one case)

- Understanding planet formation:
  - Microscopic interactions on tiny scales lead to planets
  - Simulations In combination with observations