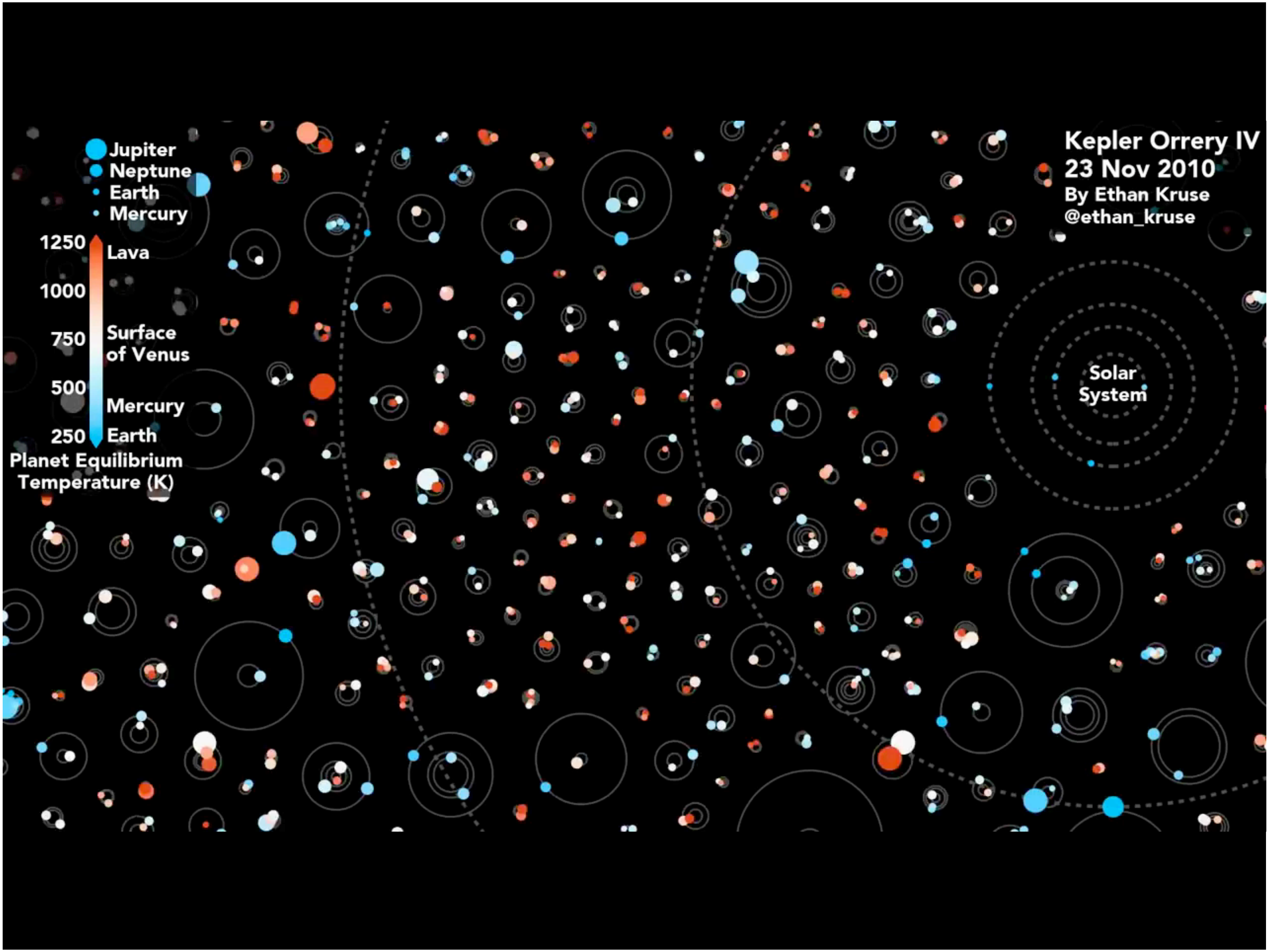

Kepler Orrery IV
23 Nov 2010
By Ethan Kruse
@ethan_kruse
Jupiter
Neptune
Earth
Mercury
1250
1000
750
500
250
Lava
Surface of Venus
Mercury
Earth
Planet Equilibrium Temperature (K)
Solar System

Midterm Exam 5 Scores — 2014, 2015, 2016, 2017

		2014	2015	2016	2017
A	85 — 100 %	18 %	13 %	12 %	12 %
B	75 — 84 %	24 %	21 %	22 %	22 %
C	60 — 74 %	36 %	42 %	47 %	47 %
D	45 — 59 %	15 %	19 %	16 %	16 %
F	0 — 44 %	7 %	4 %	3 %	3 %

Highest score on Midterm 5 = 98 % (1 person).

Lowest score on Midterm 5 = 32 % (1 person).

Part 4: Our Solar System, Life in the Universe

Tuesday, April 11 Reading: Chapter 15 (12th & 13th Edition of the textbook)

- Solar System: Introduction and Formation; Other Solar Systems

Thursday, April 13 Reading: Chapter 18 (planets)

- Solar System: Jupiter, Saturn, Uranus, Neptune

Tuesday, April 18 Reading: Chapter 18, 19

- Solar System: Outer Solar System, Pluto, Kuiper Belt, Comets, Satellites

Thursday, April 20 Reading: Chapter 16, 17, 18, 19

- Solar System: Satellites, our Moon, Mercury, Asteroids

Tuesday, April 25 Reading: Chapter 17

- Solar System: Mars and Venus

Thursday, April 27 Reading: Chapter 16

- Solar System: Earth

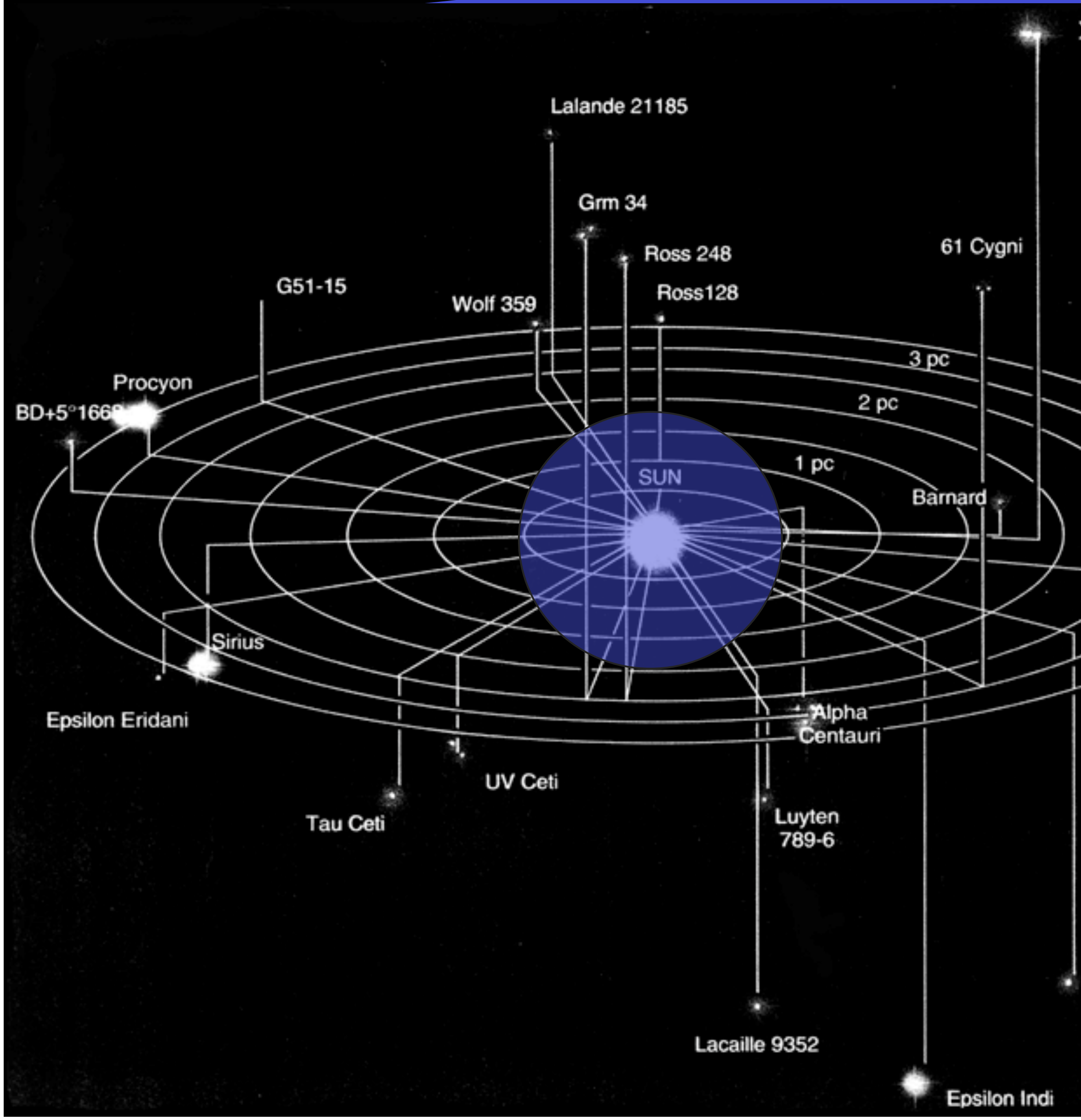
Monday, May 1 Help Session from 4 to 6 PM in RLM 4.102

Tuesday, May 2 Exam 6

Thursday, May 4 Reading: Chapter 20

- The history of life on Earth; Life in the Universe

The Solar System

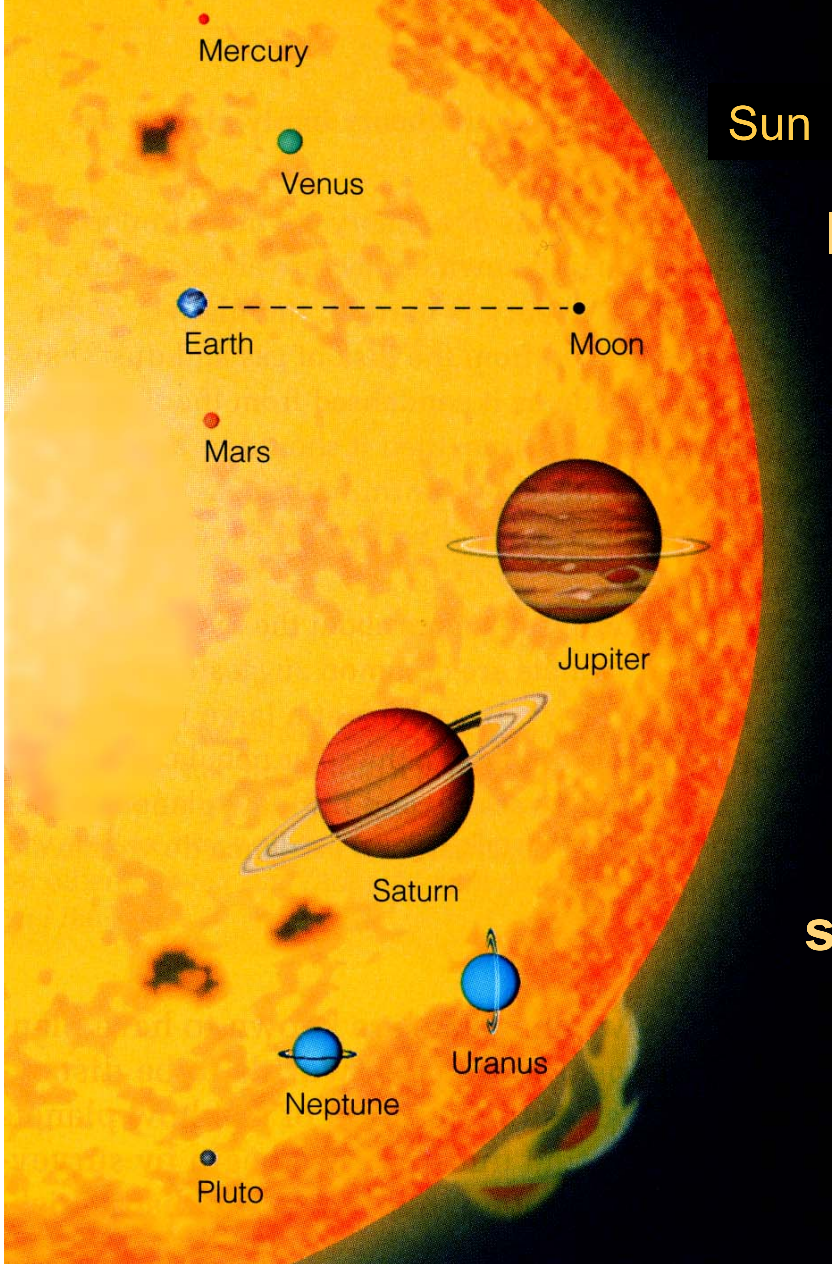


A plot of the 30 stars closest to the Sun and projected to show their three-dimensional relationships.

The typical separation of stars near the Sun is
~ 1 pc
~ 200,000 AU

Our Solar System (highlighted blue) reaches about 1/3 of the way to the nearest star.
The "Oort cloud" of comets extends out from the Sun to about 10,000 to 100,000 AU.

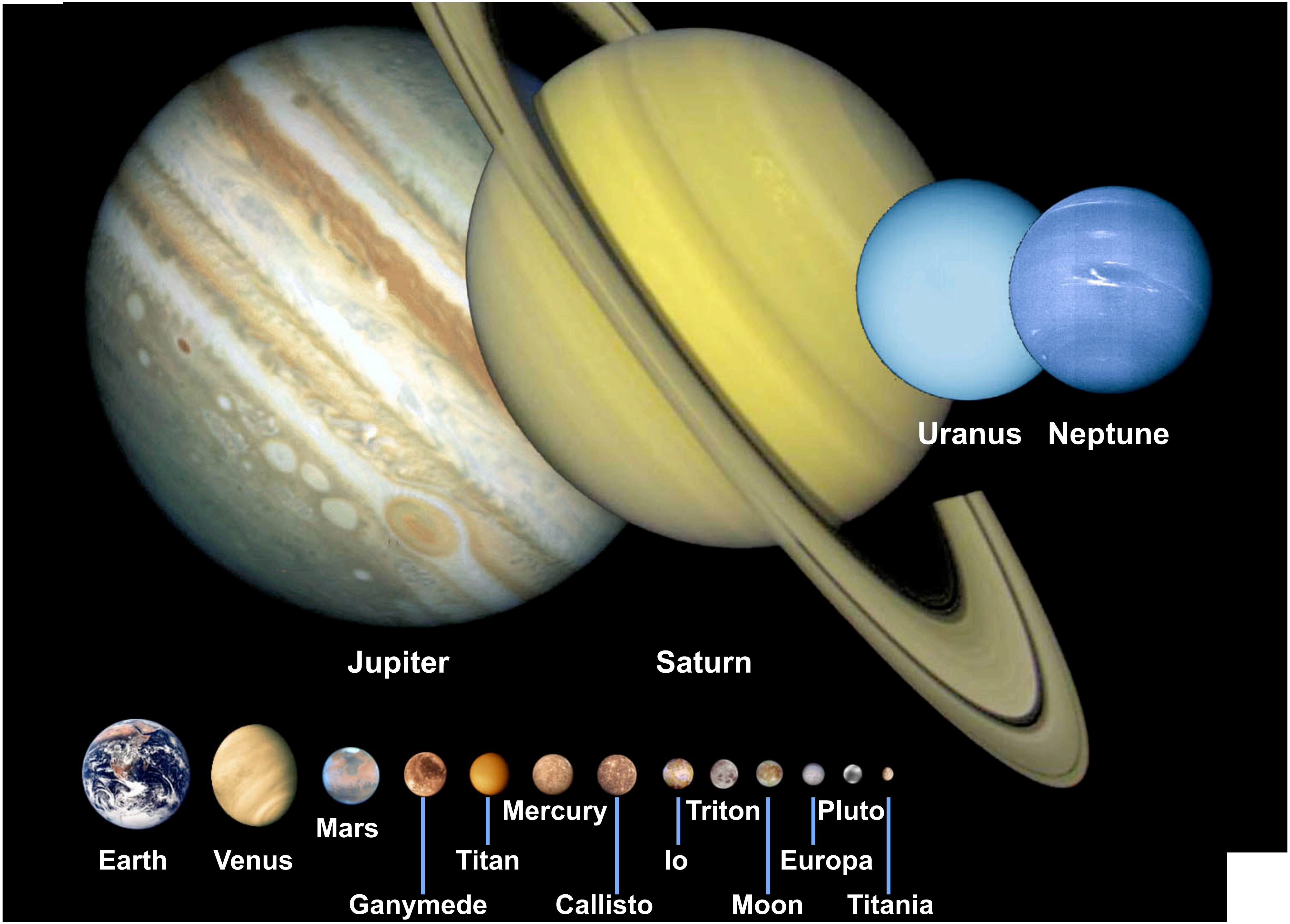
The Sun Dominates the Solar System



It is 9.7 times the diameter of Jupiter.
Its diameter is 3.6 times the distance from the Earth to the Moon.

It is 1050 times the mass of Jupiter.

But it has only 0.3 % of the angular momentum of the Solar System.
How to get rid of “excess rotation” when the Sun was grown out of a spinning debris disk is a major puzzle.



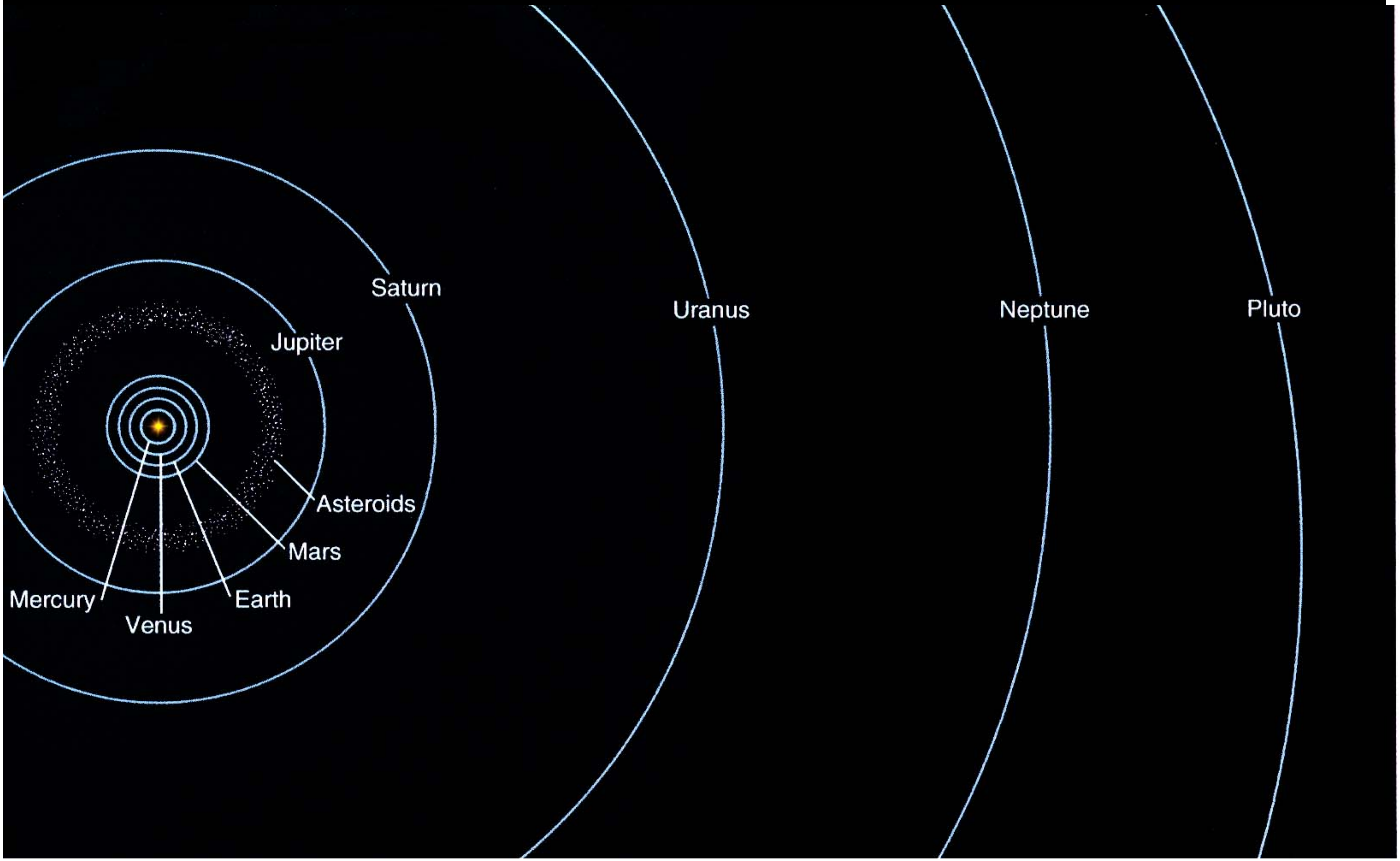
Uranus
Neptune
Jupiter
Saturn
Earth
Venus
Mars
Ganymede
Titan
Mercury
Callisto
Io
Triton
Moon
Europa
Pluto
Titania

Note: There is complete continuity between the sizes of planets and the sizes of satellites. Smaller objects are more numerous.

Orbits of the Planets

The Solar System is (mostly) a disk:

– Planets orbit in nearly the same plane and all in the same direction.

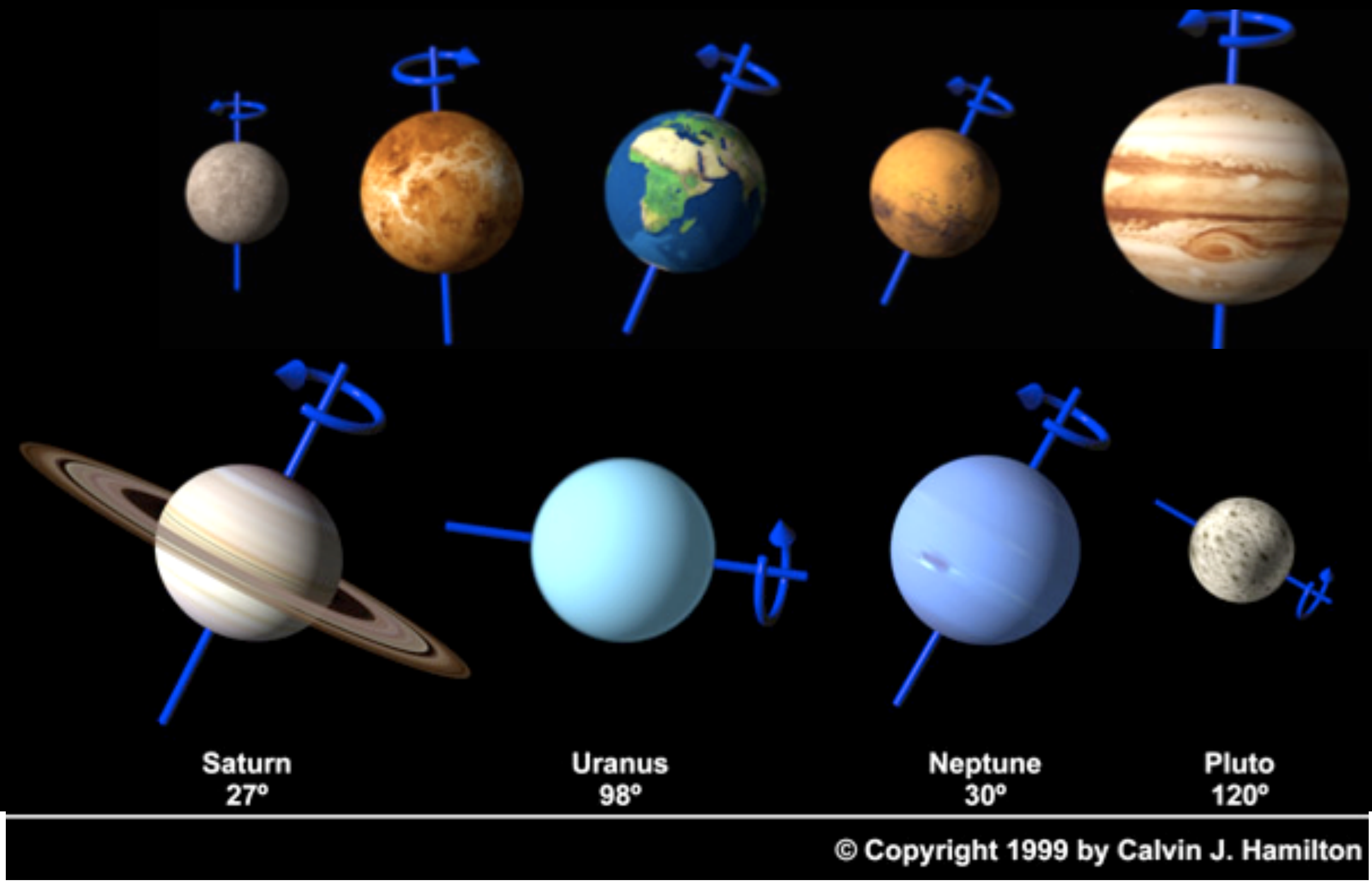


Orbits of the Planets

The Solar System is (mostly) a disk:

– Planets orbit in nearly the same plane and all in the same direction.

– Planets revolve and (mostly) rotate in the same direction (counterclockwise as seen from north).

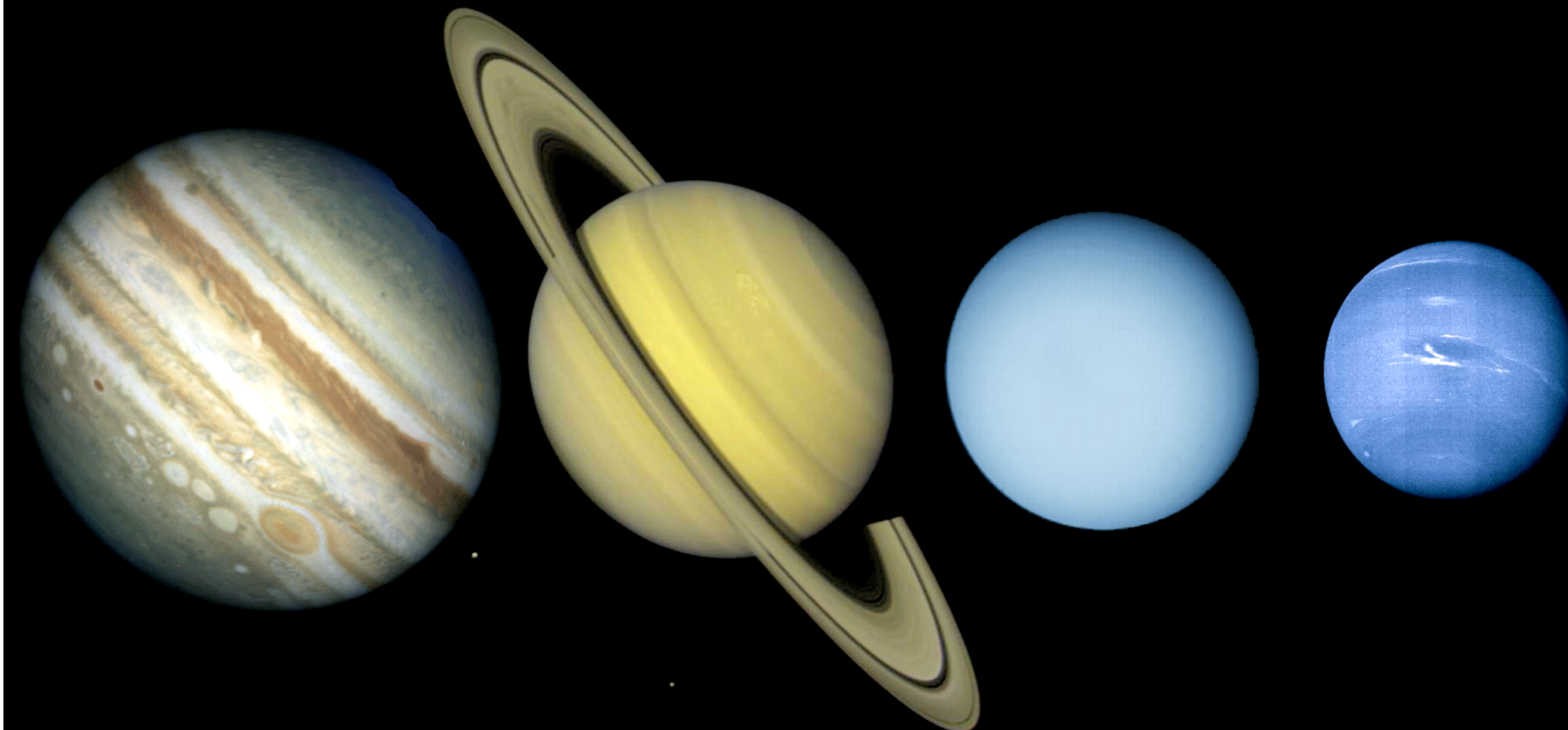


The Inner Planets

Planets come in two varieties: inner, “terrestrial” planets made of rock, iron, ...

The Outer Planets

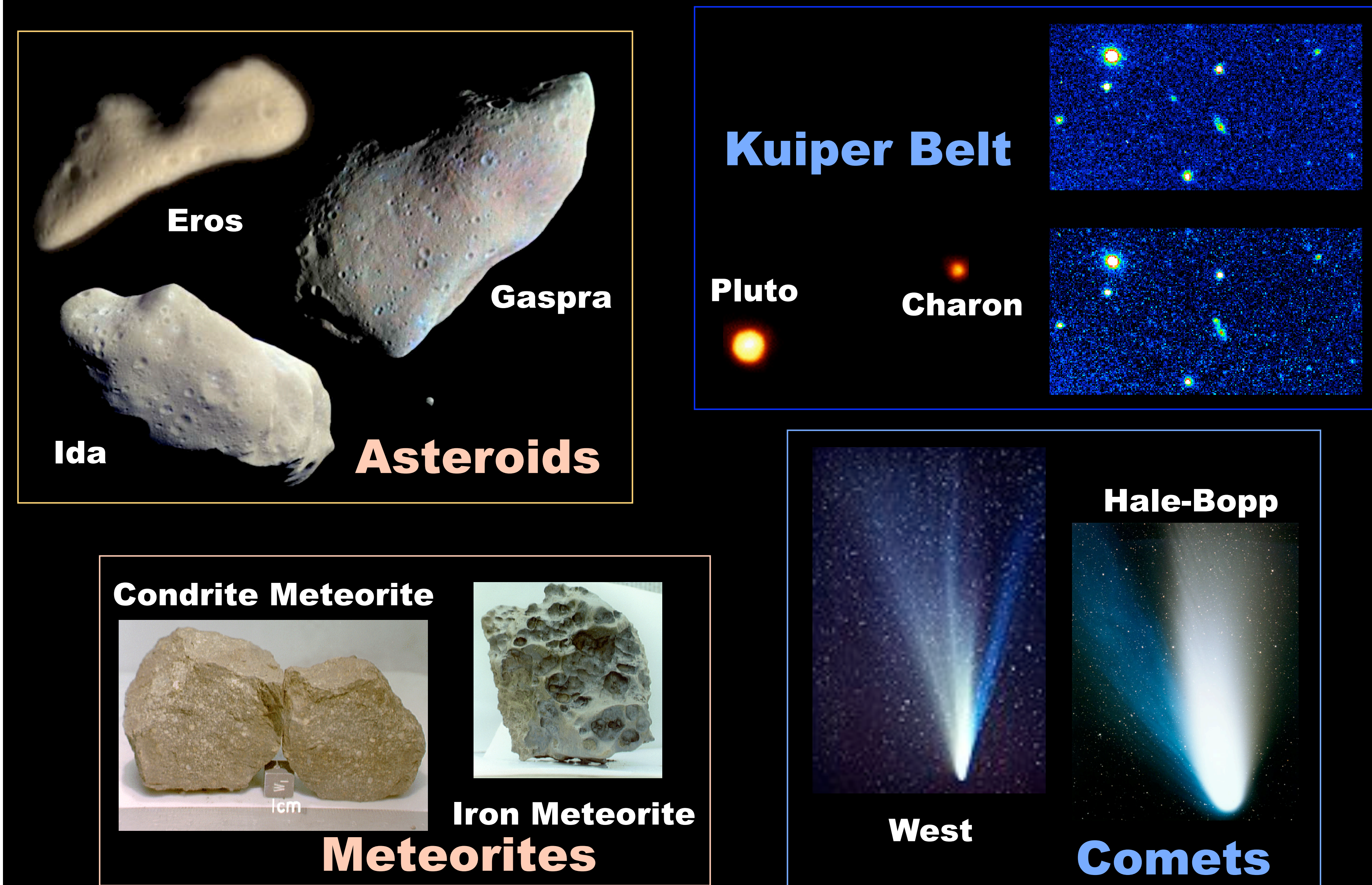
& outer “Jovian” planets made of gases with compositions like that of the Sun.



The Jovian planets are

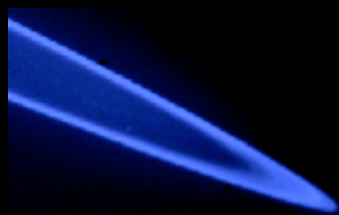
<u>much bigger</u> and <u>much more massive</u> than the terrestrial planets.

Debris: Asteroids, Comets, ...

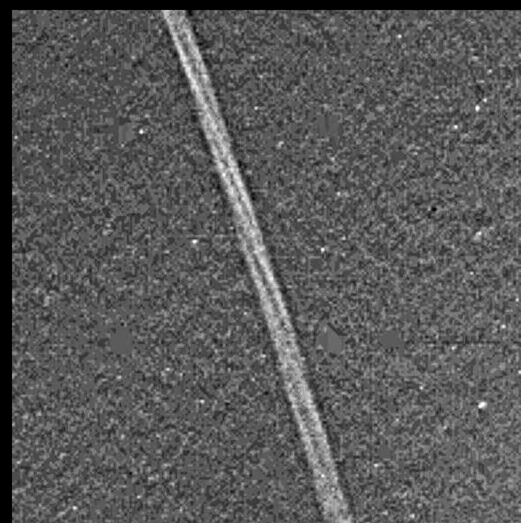


All of the Jovian planets have rings.

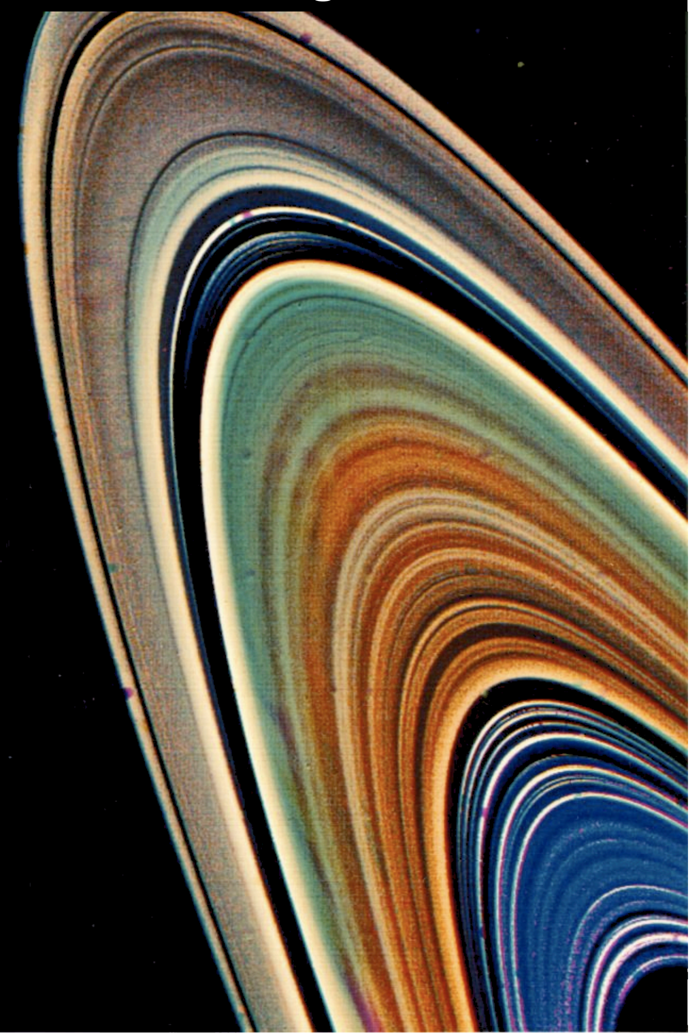
Jupiter's Rings

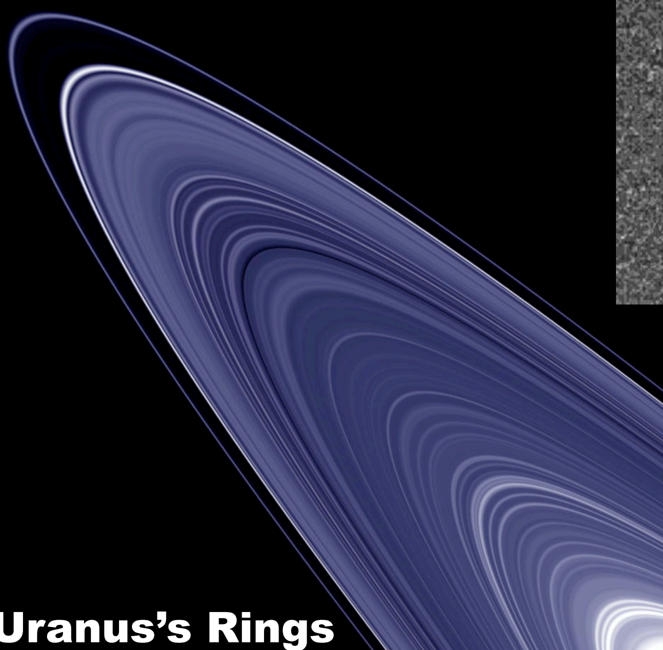


Neptune's
Twisted Rings



Saturn's Rings





Uranus's Rings

Properties of the Solar System

1 — Disk shape: orbits in nearly the same plane;
common direction of rotation and revolution

2 — Two types of planets: terrestrial = inner, small, high-density, rock+iron
Jovian = outer, giant, low-density, Solar composition

3 — Big planets have satellites; bigger planets generally have more satellites;
Jovian planets have rings

4 — Debris fills the Solar System; mostly in the asteroid and Kuiper belts;
inner debris tends to be rocky; outer debris is icy

5 — There is a continuum of sizes from Jupiter to the smallest debris;
smaller objects are more common

6 — Common age of about 4.6 billion years for Earth, Moon, meteorites, Sun

These are hints on how the Solar System formed!

The Age of the Solar System

The properties of the Solar System and our understanding of star formation tell us that: **The Solar System formed with the Sun out of its protostellar gas disk.**

Radioactivity gives us a way to measure ages of rocks and meteors = the time since they last solidified. Each kind of radioactive atom has a half-life. This is the time that it takes for 1/2 of the radioactive atoms to decay. The half-life of common uranium (^{238}U) is 4.5 billion years. If we start with 1000 atoms of ^{238}U, there will be ~ 500 atoms left after 4.5 billion years and ~ 250 atoms left after 9 billion years. The rest turned into lead (^{206}Pb).

We use this to measure the ages of rocks. By measuring the amount of uranium left and the amount of lead formed, we can tell when the rock solidified.

The oldest rocks on Earth's surface are 4.4 billion years old.

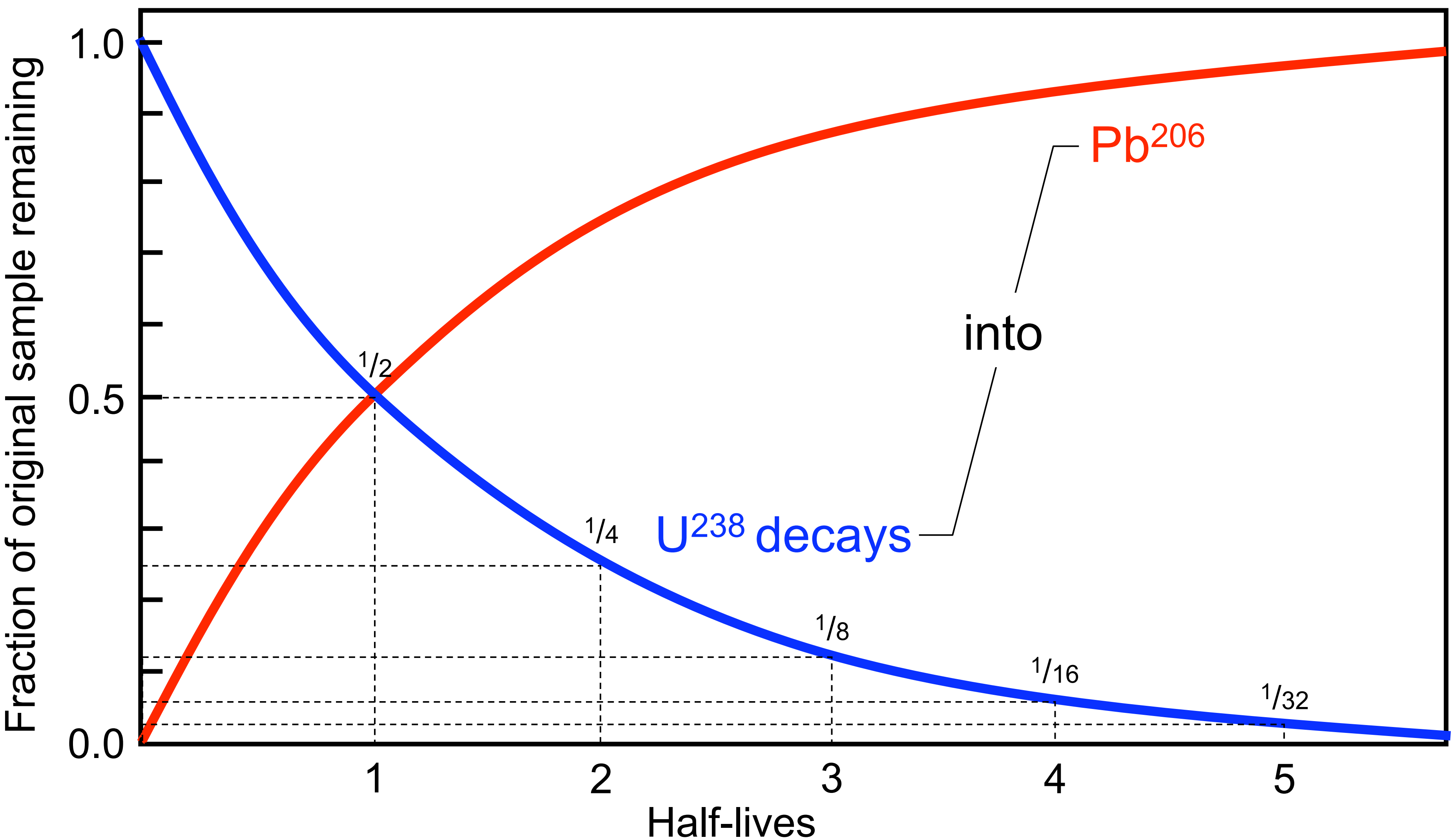
The oldest rocks from the Moon are 4.5 billion years old.

The oldest meteorites are 4.6 billion years old.

Small rocks cool quickly in space, so this should be the age of the Solar System. It agrees with theoretical calculations for the age of the Sun.

We conclude that the Solar System is about 4.6 billion years old.

Uranium Decays Into Lead



Comets and Stardust

Comets have almost the same composition as the Sun. Only hydrogen and helium are deficient in comets. Why? Because small objects don't have enough gravity to hold onto light gases.

Comets and carbon-rich meteorites contain <u>tiny dust grains</u>. They are older than the Solar System. Some grains are rich in carbon, others in metals. Different types of dust formed in different environments. <u>Carbon grains formed in the atmospheres of giant stars.</u> <u>Metal-rich grains formed in supernova explosions.</u> After solidifying, these dust grains were mixed with hydrogen and helium.

Some grains contain simple organic molecules. Such molecules cannot form in stars, because the temperature is too high. They form in cold clouds of gas drifting between stars.

The Solar System formed from such a cloud of dust and gas.

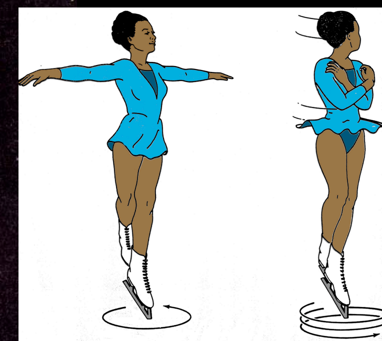
Planet Formation

The proto-solar cloud was cold, so gas pressure inside it was too small to resist gravity.

Every atom in the cloud was gravitationally attracted to every other atom.

As a result, the cloud collapsed.

At first, the cloud was irregular and slowly rotating.



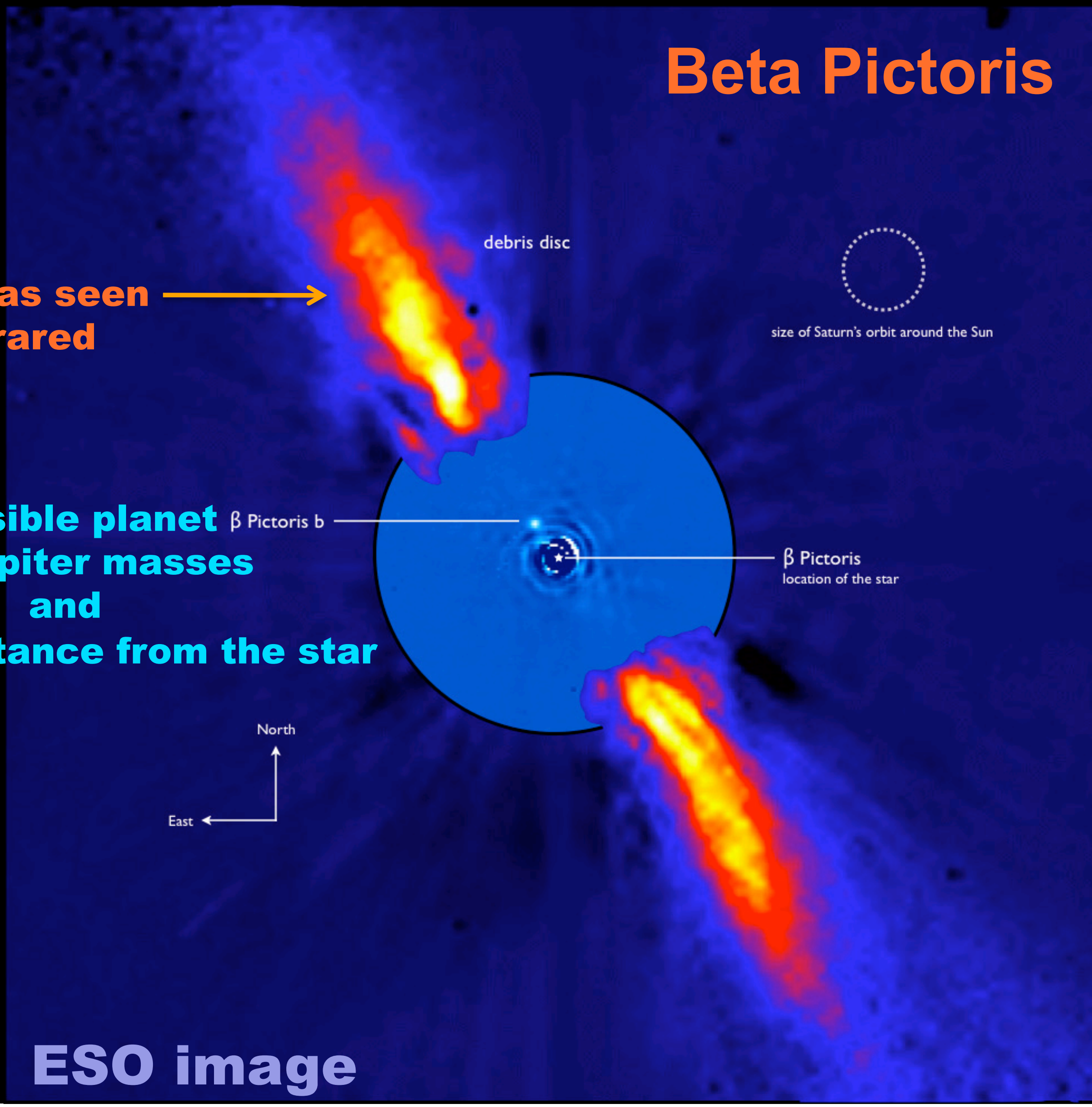
But as the cloud got smaller, conservation of angular momentum increased the rate of rotation in proportion to the amount of collapse.

Eventually the outer parts formed a disk in circular rotation around the center.

Dust particles in the disk collided, stuck together and grew into proto-planets.

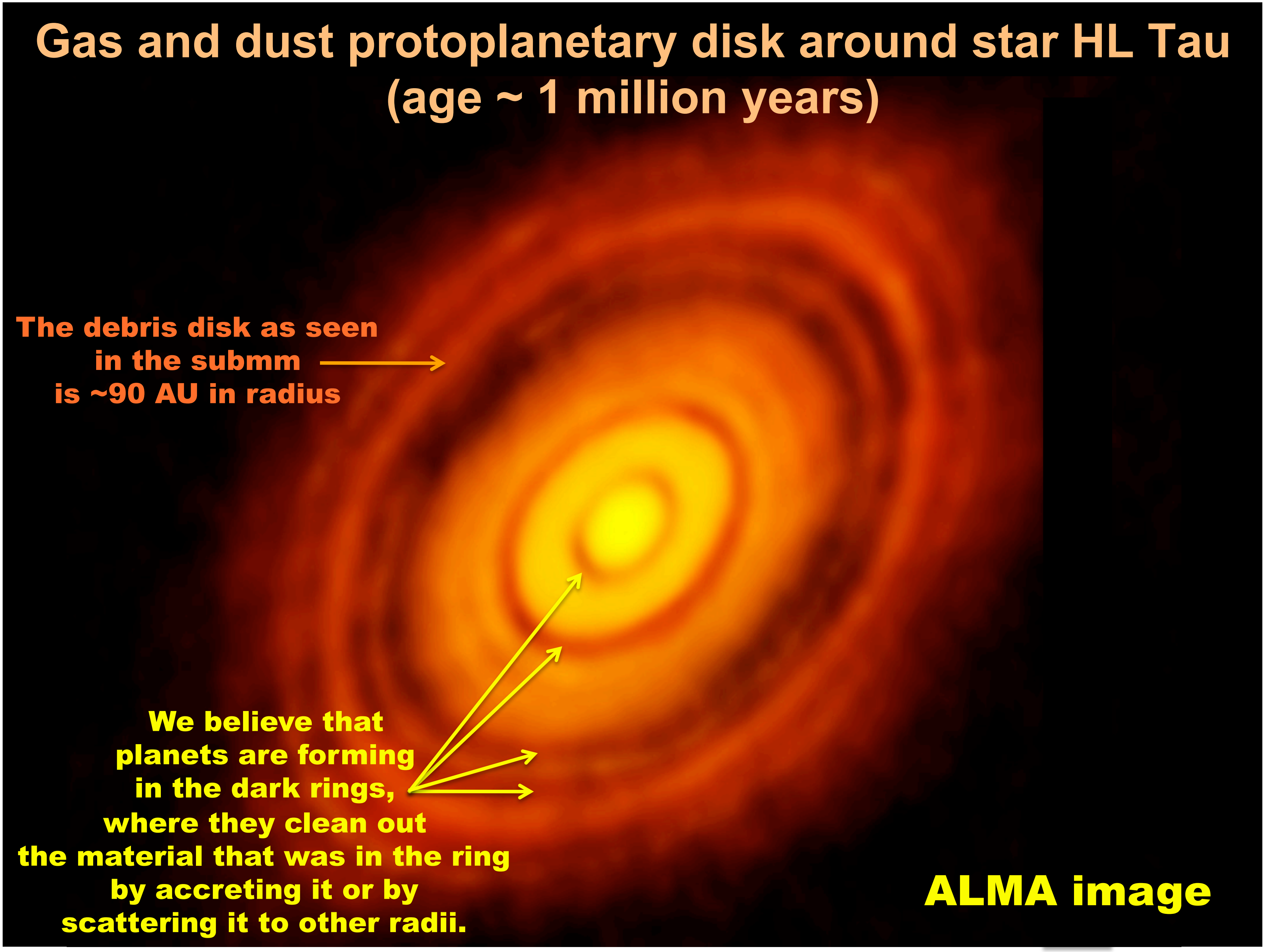
Protoplanets swept up much of the remaining disk, first by sticking together in collisions and later by gravitational accretion.

Dust disks are seen around many young stars.



Debris disk as seen in the infrared

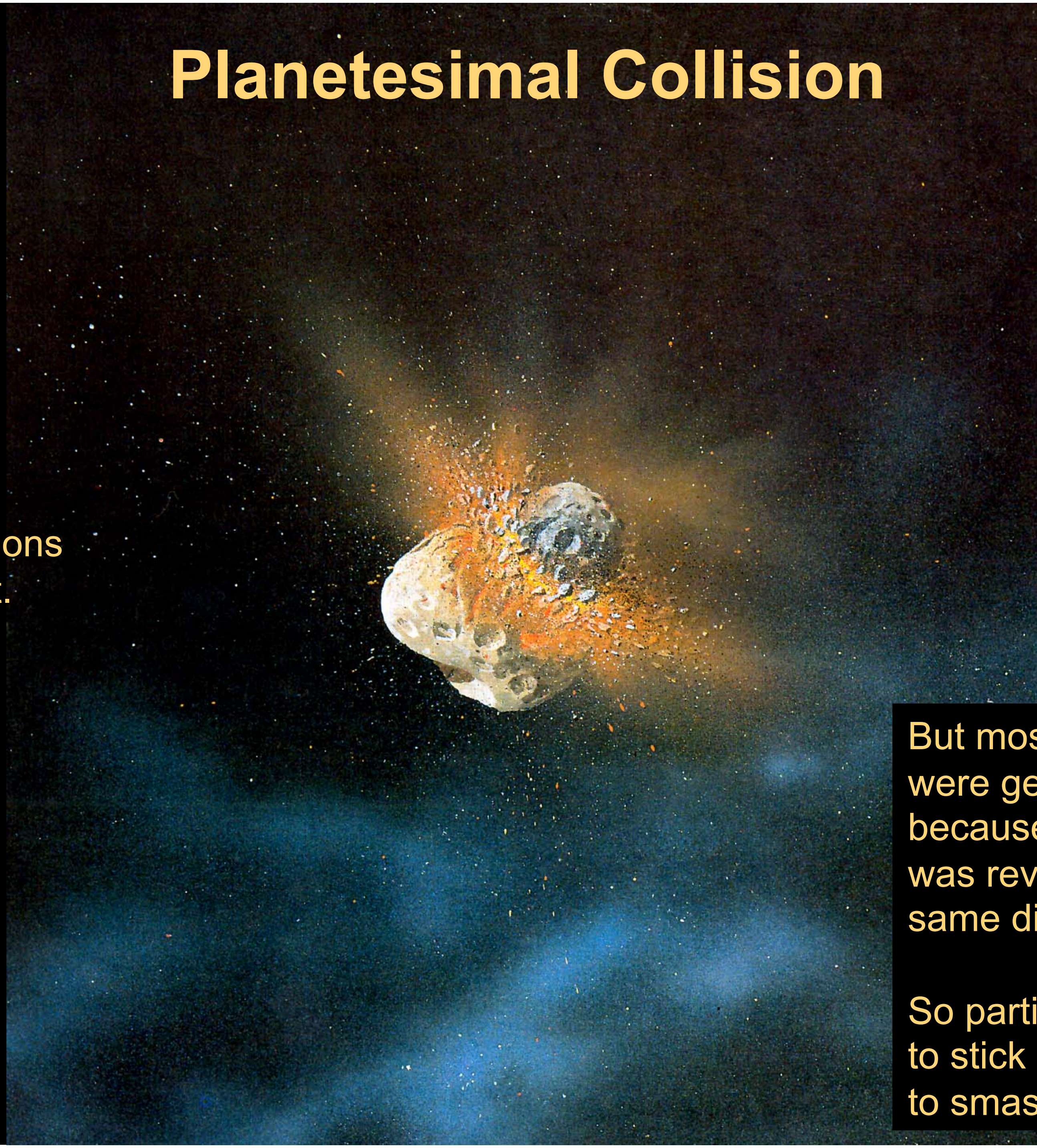
Possible planet
~ 8 Jupiter masses
and
~ Saturn distance from the star


Gas and dust protoplanetary disk around star HL Tau
(age ~ 1 million years)
The debris disk as seen
in the submm
is ~90 AU in radius
We believe that
planets are forming
in the dark rings,
where they clean out
the material that was in the ring
by accreting it or by
scattering it to other radii.
ALMA image

Particle Accretion in the Disk Around the Proto-Sun

Planetesimal Collision

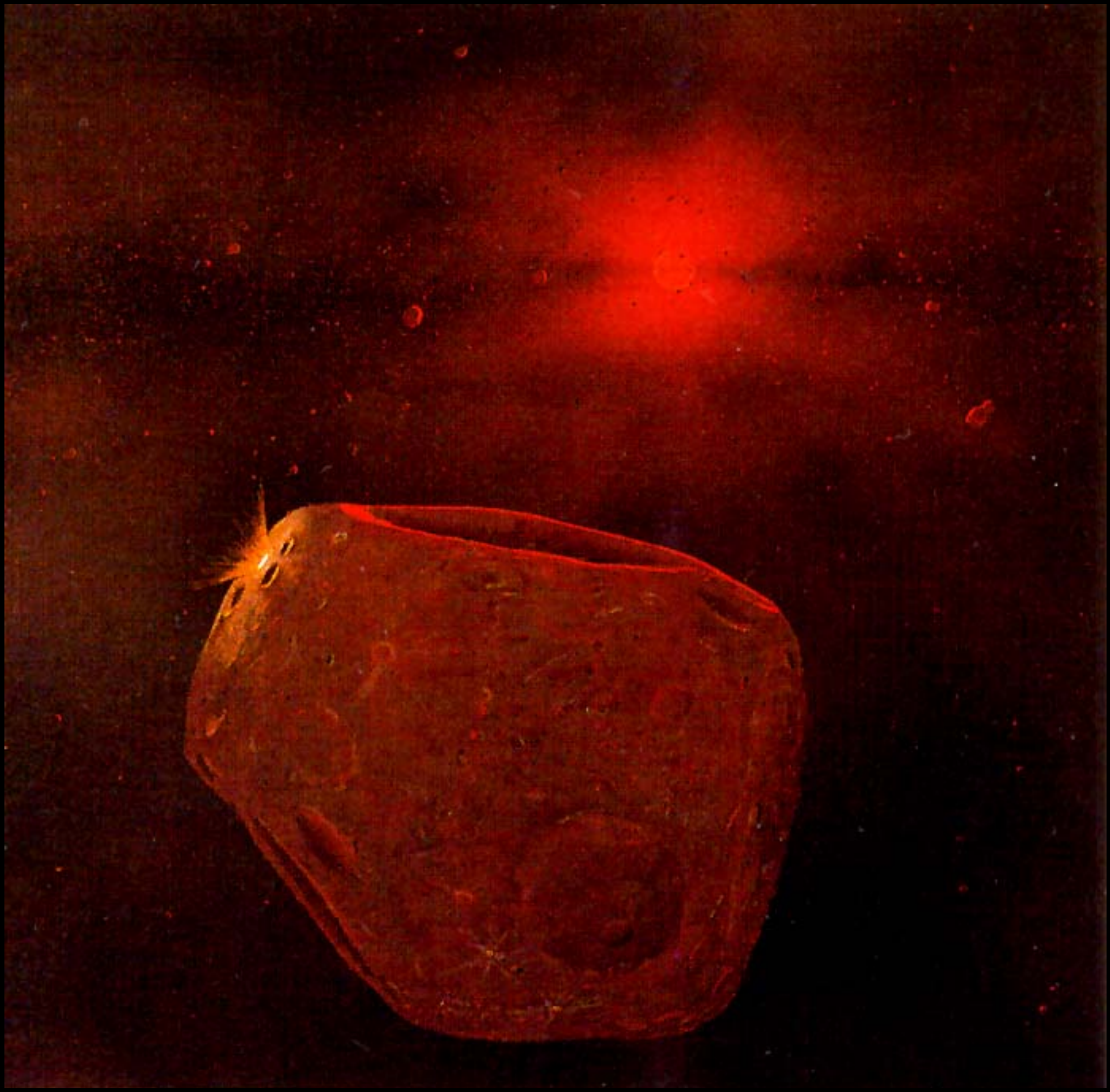
Some collisions were violent.



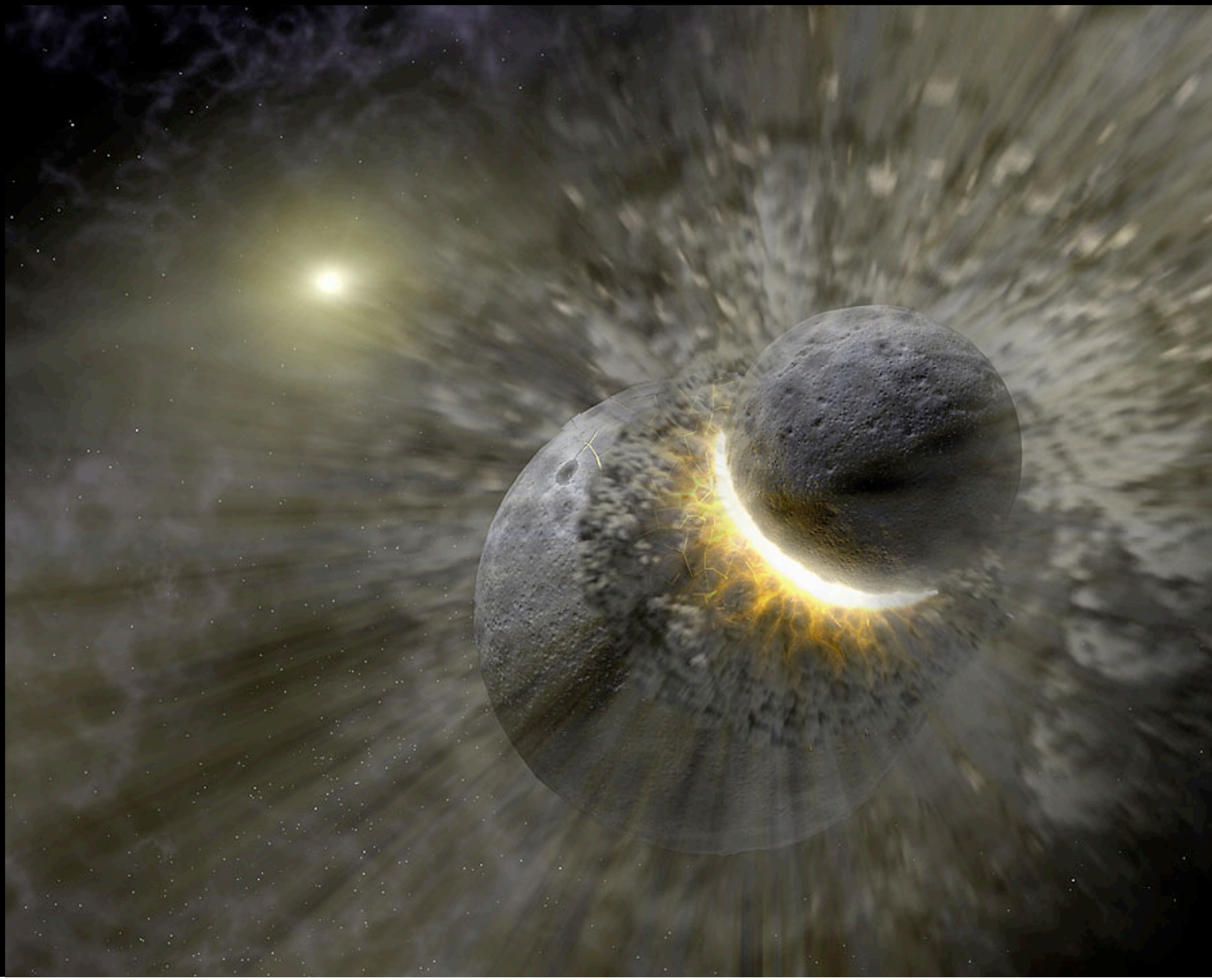
But most collisions were gentle, because all material was revolving in the same direction.

So particles tended to stick together, not to smash each other.

Gradually the embryo Earth grew ...



A violent collision with a Mars-sized protoplanet is believed to have knocked loose the material that then collected together to form our Moon.



When the Moon assembled,
it was much closer
to the Earth
than it is now.

Condensation

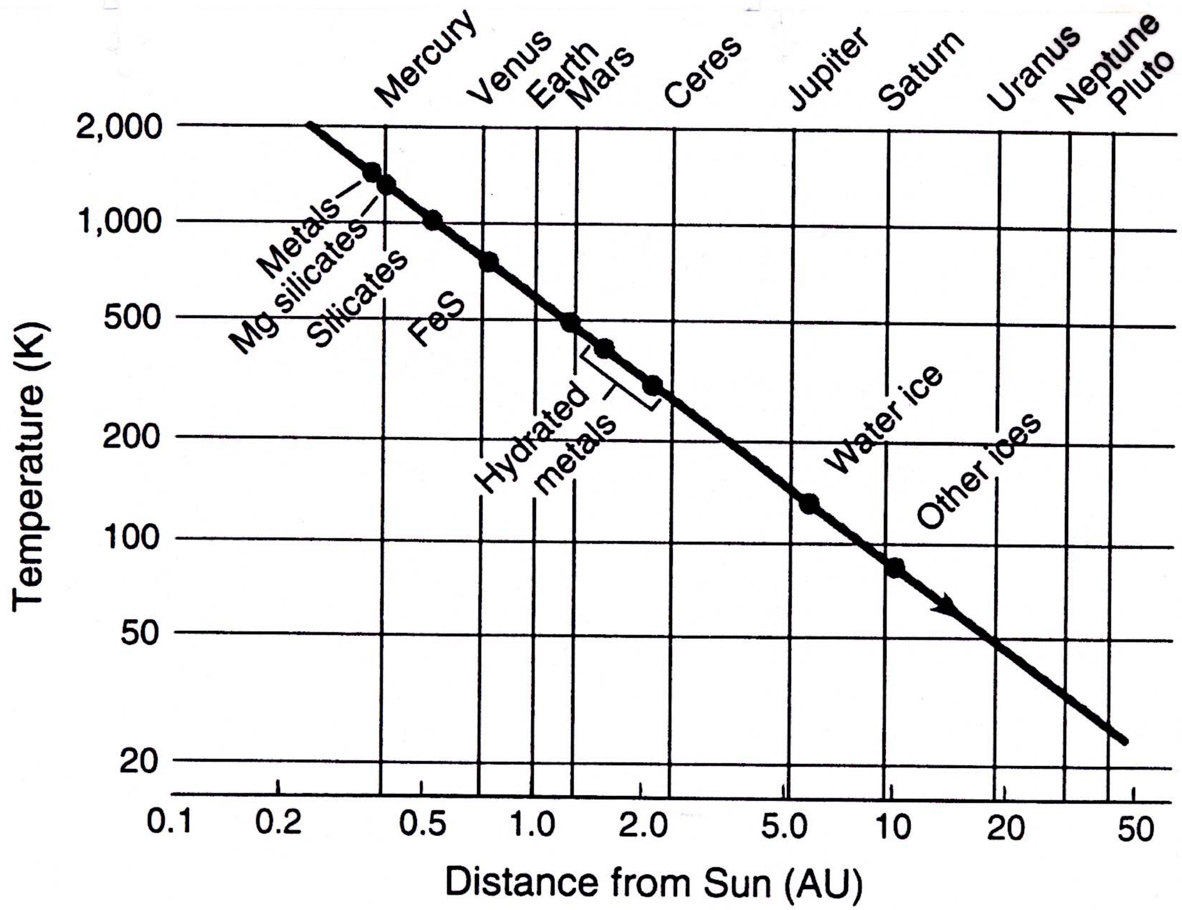


Figure 17.35 *Temperature in the early solar nebula is plotted against distance from the Sun. Different substances condense at different distances (indicated by dots) as the temperature drops.*

The temperature of the protoplanetary disk decreased outward from the Sun. So metals and silicates condensed near the Sun, forming the rock-and-iron terrestrial planets. Note how their uncompressed densities decrease outward from the Sun.

16-2 Observed and Uncompressed Densities

Planet	Observed Density (g/cm³)	Uncompressed Density (g/cm³)
Mercury	5.44	5.4
Venus	5.24	4.2
Earth	5.50	4.2
Mars	3.94	3.3
(Moon)	3.36	3.35

Farther out, it was cold enough for ices to condense. The Jovian planets grew huge because of this. Then they could gravitationally capture hydrogen and helium and get even bigger. This is also why debris in the outer Solar System is mostly icy.

Planet Formation: Summary of Important Processes

Condensation: A particle adds atoms, one at a time (like the growth of snowflakes).

- Small grains grow rapidly.

Accretion: A particle grows because other particles hit it and stick to it.

Gravitational Attraction helps accretion when a protoplanet gets big enough.

- big planetesimals grow fastest.

Differentiation: As planetesimals grow, they heat up (accretion, pressure, radioactivity).

- heavy stuff (like iron) melts and sinks to the center.
- light stuff (like the lightest rock) floats to the surface.

$\Rightarrow$ iron core + light rocky crust

Outgassing : Trapped gases escape from the interior to form the atmosphere.

Summary of Important Processes:

Two Types of Planets

Heat from the Sun boils off volatile gases like hydrogen and helium. So:

There are 2 kinds of planets:
(i) rocky-iron "terrestrial" planets near the Sun that lost their volatiles;
(ii) "Jovian" gas giant planets far from the Sun that kept their volatiles.

Radiation pressure
Solar wind
Sweeping up of small particles

} clears away most of the rest of the Solar nebula.

Planet Formation:
Summary of Important Processes

Many orbits in the Solar System are unstable – sometimes a little, sometimes a lot.

Gravitational perturbations by (especially) Jupiter, … , Neptune change orbits:
eventually a close encounter ejects a planetesimal from the Solar System unless

(i) it gets swallowed, or

(ii) it gets moved into a stable orbit.

This has cleared out some of the outer Solar System.

The Solar System is still evolving:

Orbits are getting rearranged.

Small objects are getting ejected.

Debris fragments hit each other and hit planets.

This can cause planetary catastrophes like mass extinctions of life on Earth.

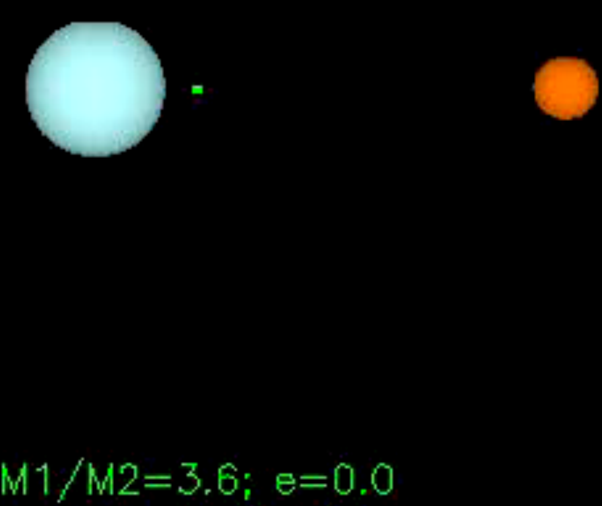
The Search For Planets Around Other Stars

Artist's View of a Planet around the Star 79 Ceti

NASA

We discover planets around other stars by measuring the reflex speed of the star and looking for periodic variations.

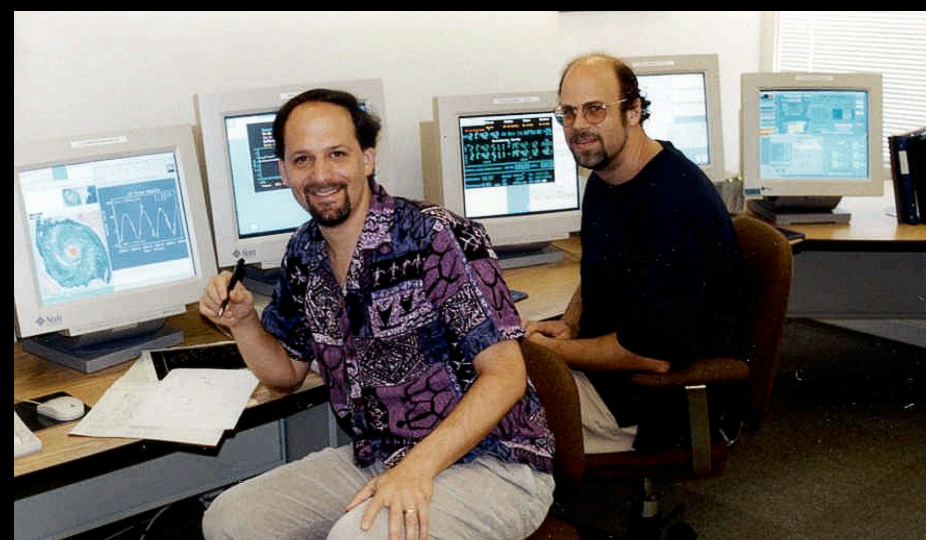
Example: Detecting Jupiter (mass ≈ 1/1000 $M_{\odot}$)



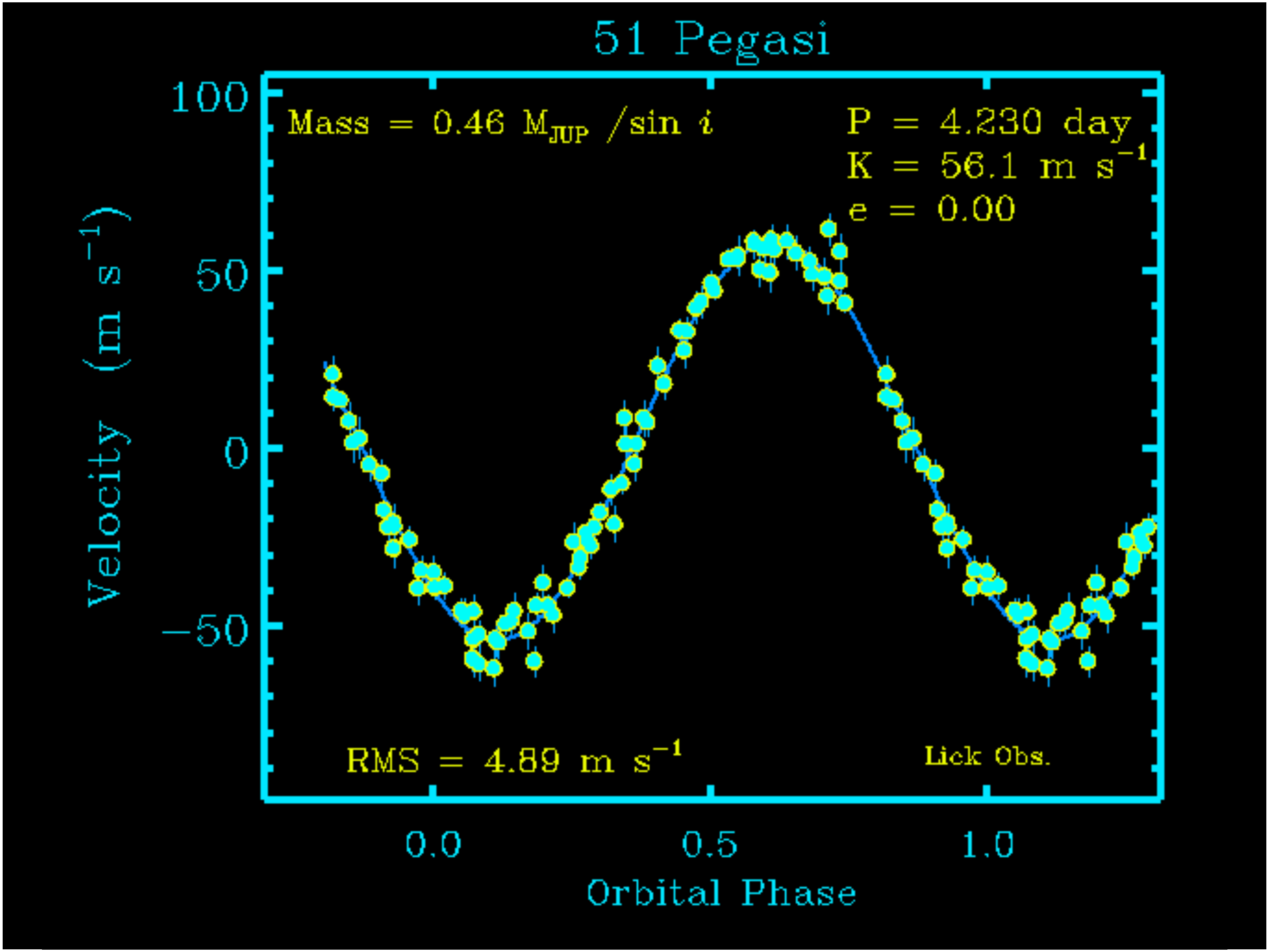
The reflex orbital speed of our Sun because of Jupiter is 0.014 km/s = 31 miles/hour over a period of 11.2 years!

The first extrasolar planet around a main sequence star (51 Pegasi) was discovered by Michel Mayor & Didier Queloz (Geneva) and by Geoff Marcy (then at Berkeley) and Paul Butler (Carnegie Inst).

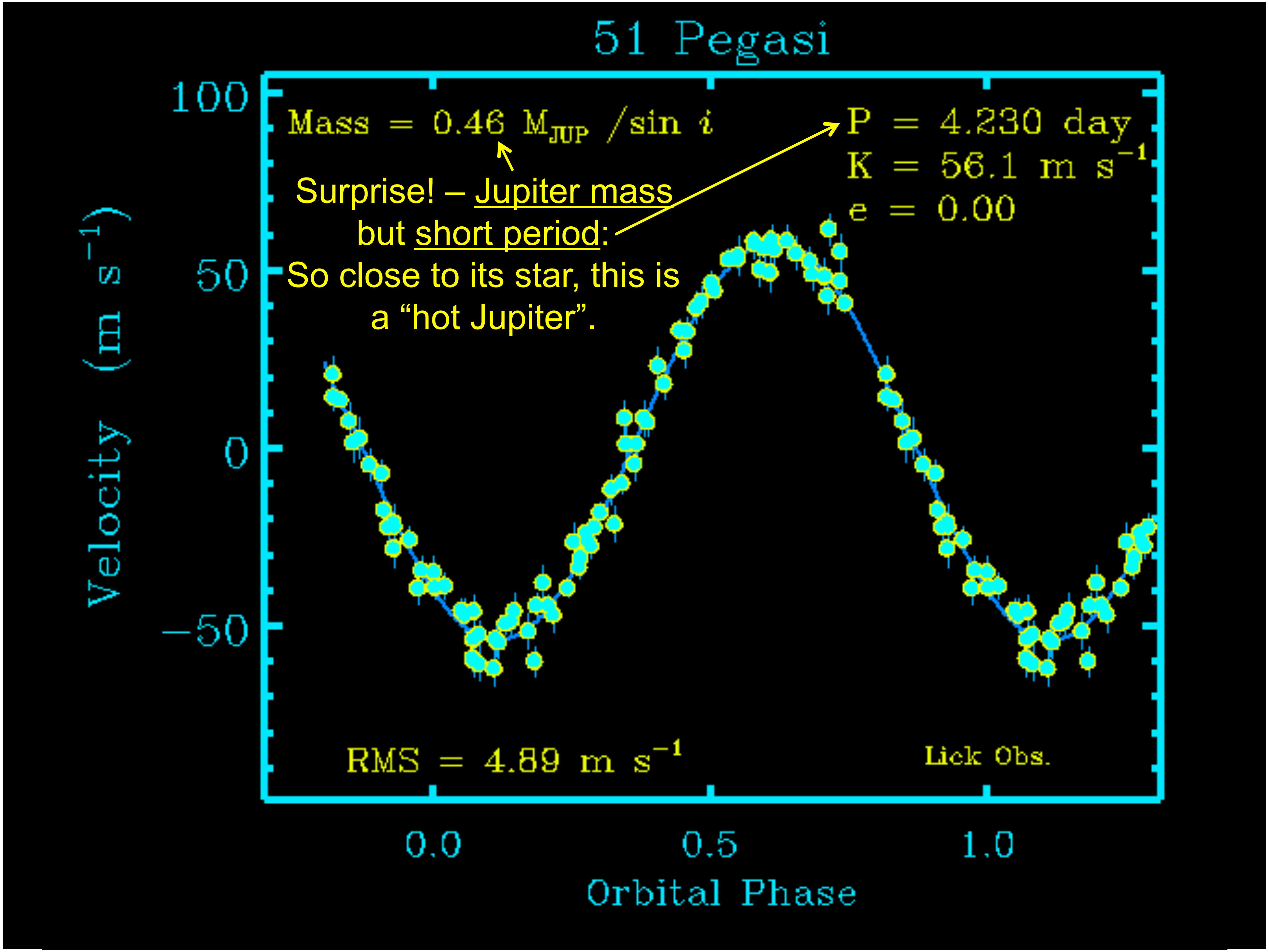
Michel Mayor & Didier Queloz:
discovery announced 1995 Oct. 6



Geoff Marcy & Paul Butler:
confirmation 1995 Oct. 12

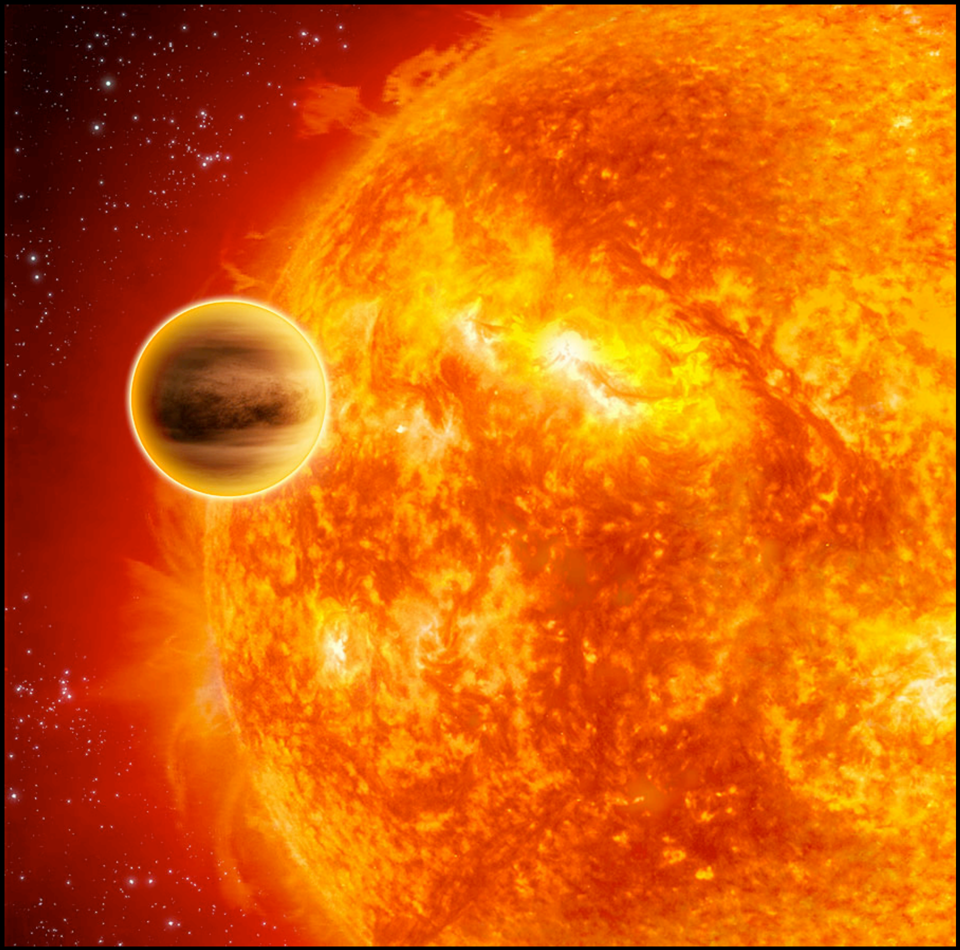


51 Pegasi
Mass = 0.46 M_JUP /sin i
P = 4.230 day
K = 56.1 m s^-1
e = 0.00
RMS = 4.89 m s^-1
Lick Obs.
Velocity (m s^-1)
100
50
0
−50
0.0
0.5
1.0
Orbital Phase



51 Pegasi
Mass = 0.46 M_{JUP} /sin i
Surprise! – Jupiter mass but short period: So close to its star, this is a “hot Jupiter”.
P = 4.230 day
K = 56.1 m s^{-1}
e = 0.00
RMS = 4.89 m s^{-1}
Lick Obs.
100
50
0
−50
0.0
0.5
1.0
Velocity (m s^{-1})
Orbital Phase

Surprise: Orbits much smaller than Earth's are common even for high-mass planets ("hot Jupiters")



How can hot Jupiters form?
Their stars should have evaporated volatile gases.

Probably hot Jupiters form far from their stars where it is cold –
where protoplanets can accrete ices and hydrogen + helium gas.
Then they “sink” toward their star by flinging smaller planets outward.
Result = hot Jupiter + colder Neptune.
Luckily, this happened only a little in our Solar System!

Formation of Hot Jupiters is Dangerous for Earth-Like Planets

It seems clear that planet formation was chaotic and violent.

Inward-sinking Jupiters would swallow Earths or eject them from the Solar System.

It is possible that there were more Earth-sized planets even in our Solar System that got ejected by protoplanetary interactions.

It is likely that there are at least as many free-floating, interstellar planets as there are planets that revolve around stars.

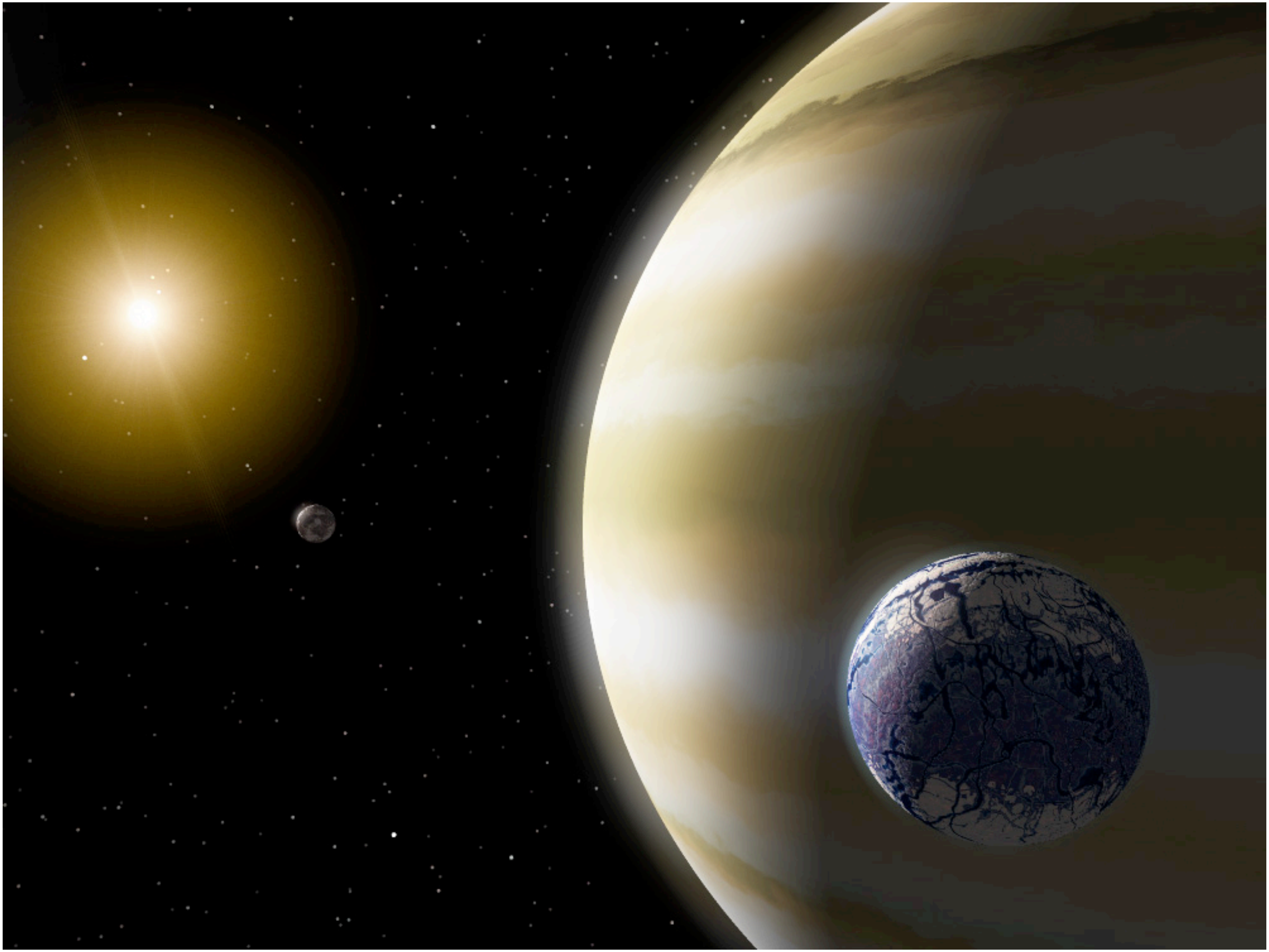
What do we learn about Earth-like planets?

The discovery of extrasolar planets confirms that Solar Systems are common.

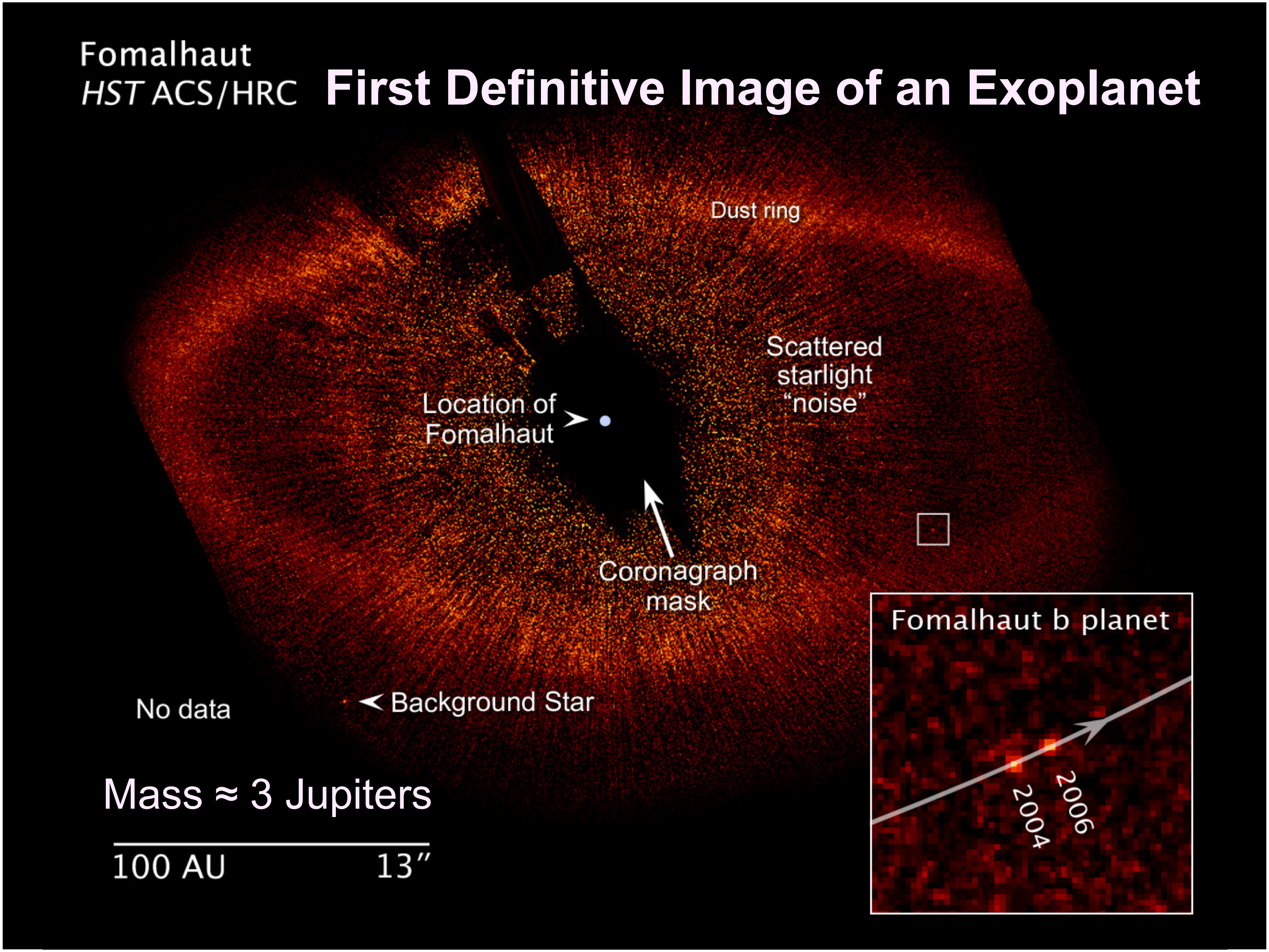
Most planets that have been found so far live very close to their stars and are very hot. Many are hot Jupiters, but even more are hot “super-Earths”.

At first, there was little direct evidence for Earth-like planets, but the Kepler mission is now finding lots of them.

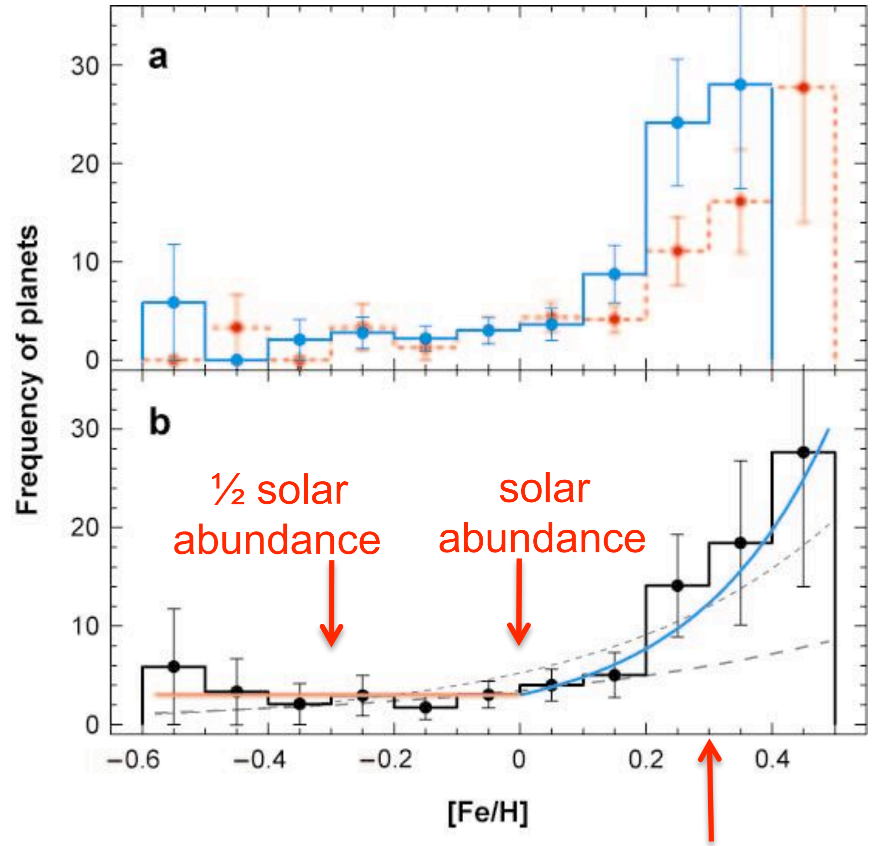
Also, melted, formerly icy moons of hot Jupiters − water worlds − could be very suitable for life.




JAMES CAMERON'S
AVATAR


Fomalhaut
HST ACS/HRC
First Definitive Image of an Exoplanet
Dust ring
Scattered
starlight
"noise"
Location of
Fomalhaut
Coronagraph
mask
No data
Background Star
Fomalhaut b planet
2004
2006
Mass ≈ 3 Jupiters
100 AU
13″

The probability that a star has planets is large if it contains lots of iron.



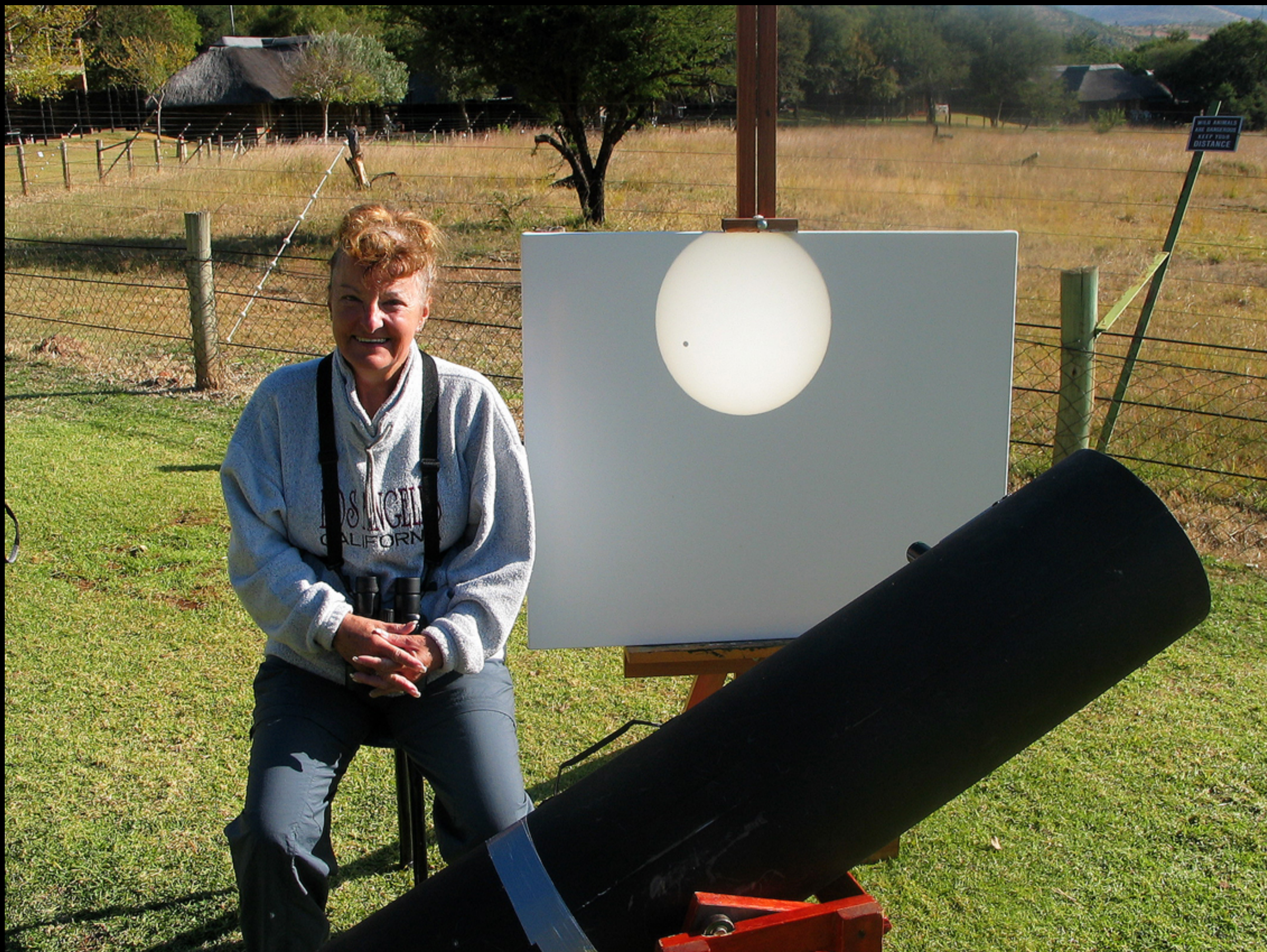
Udry S, Santos NC. 2007.
Annu. Rev. Astron. Astrophys. 45:397–439

More planets are being found almost daily.

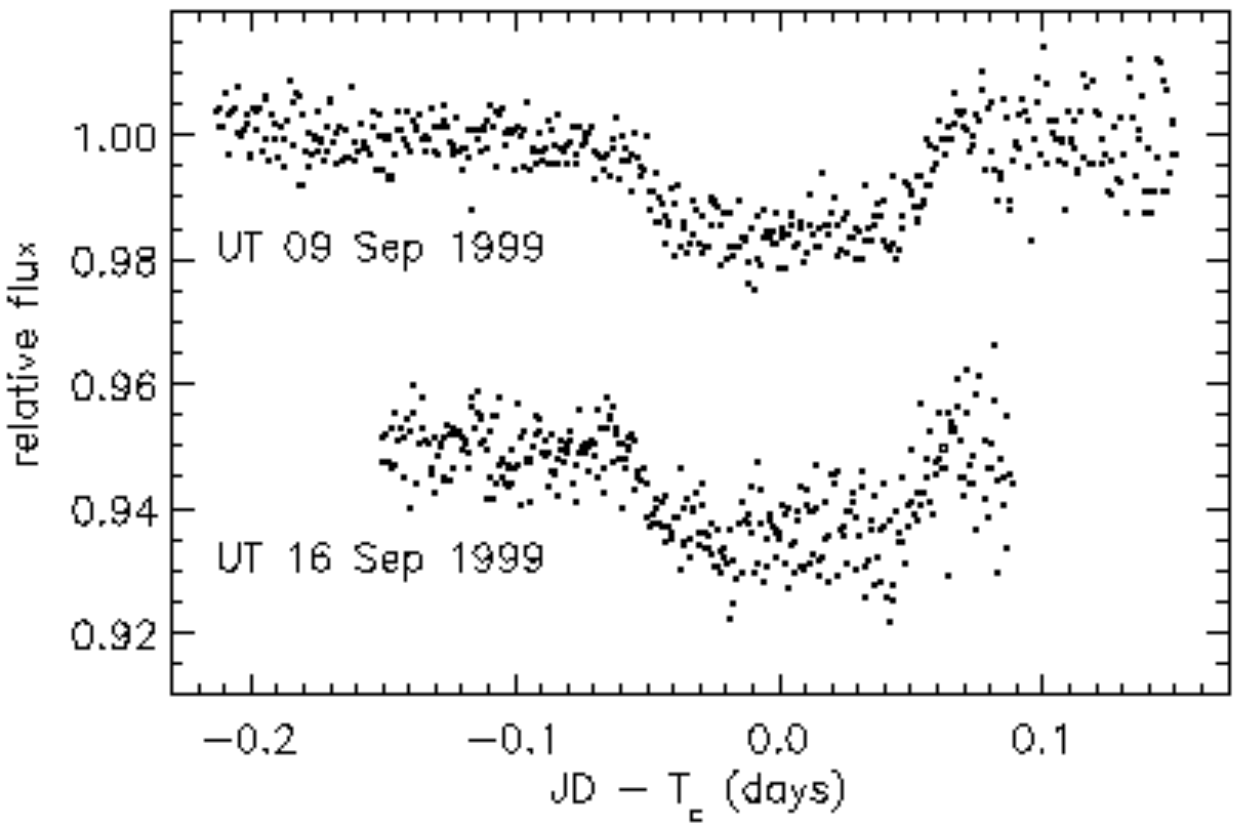
At first, most were found by radial velocity searches. Now, the Kepler mission is finding lots of (more or less) Earth-like planets.

Kepler detects Earth-like planets by “seeing” them transit in front of their stars (http://kepler.nasa.gov).

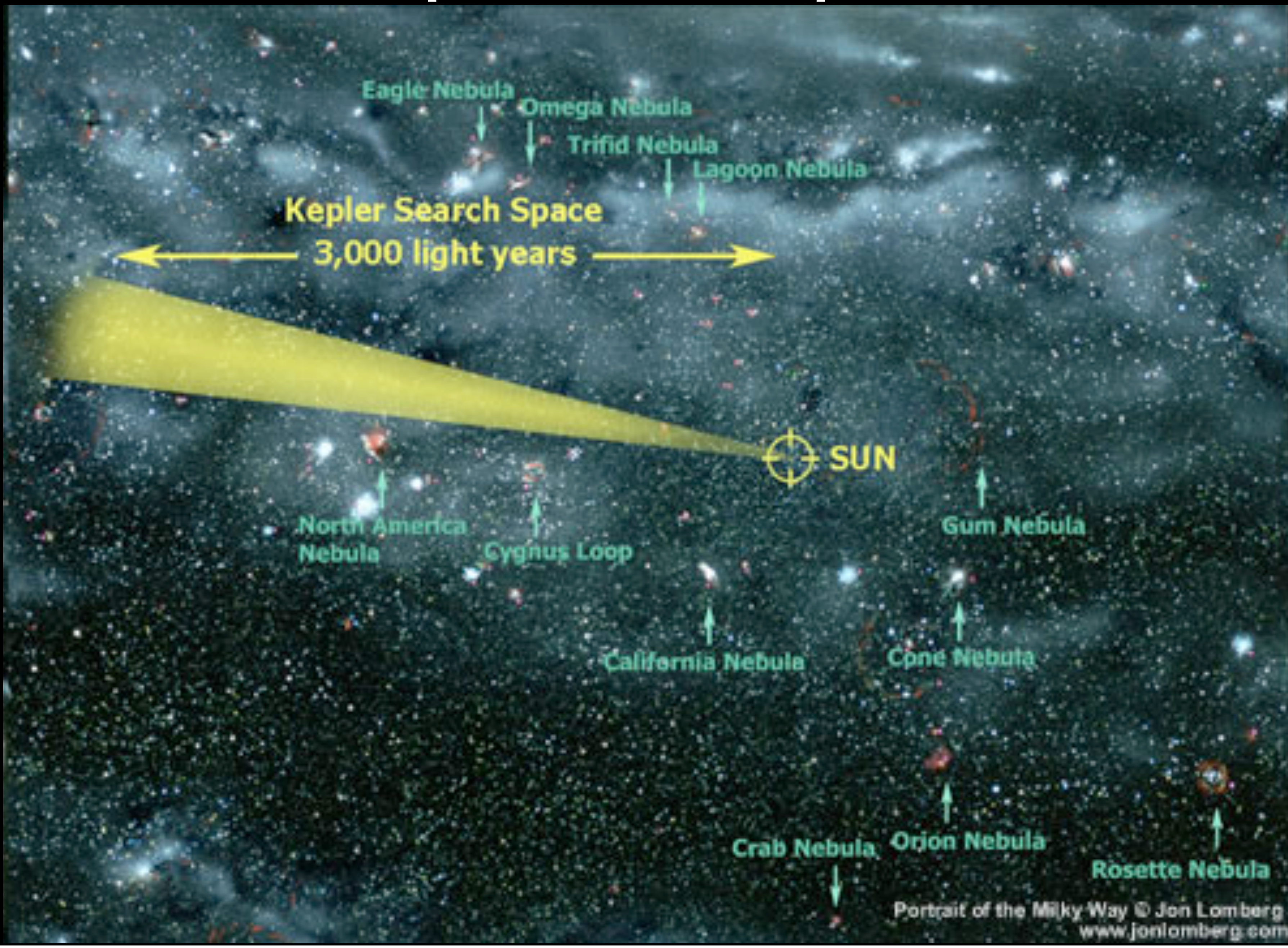
Annular Solar Eclipse by Venus (“Venus Transit”)
South Africa, June 8, 2004



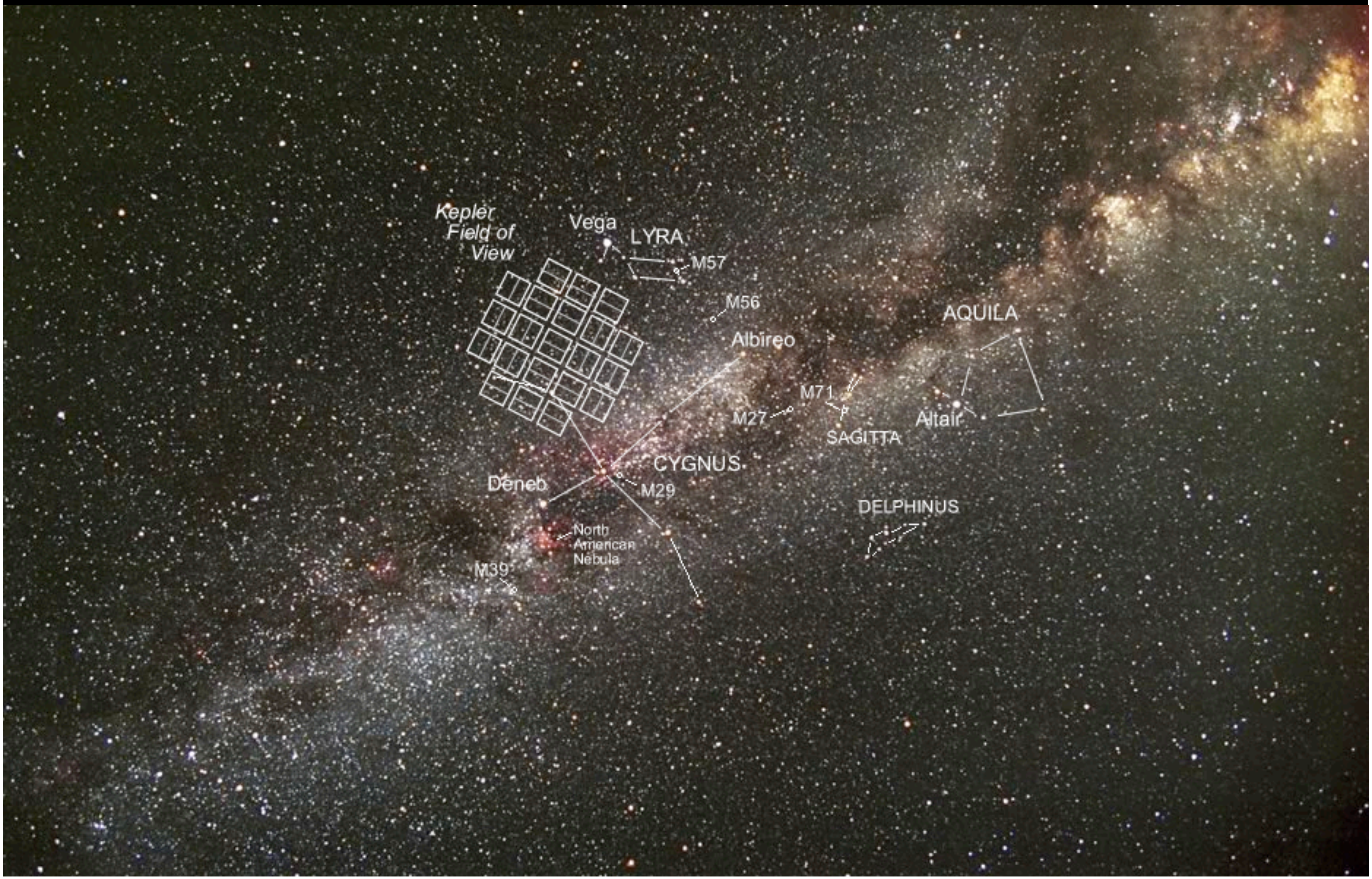
The HD 209458 solar system is edge-on, so the planet passes in front of the star. We can measure the eclipses.



Kepler Search Space



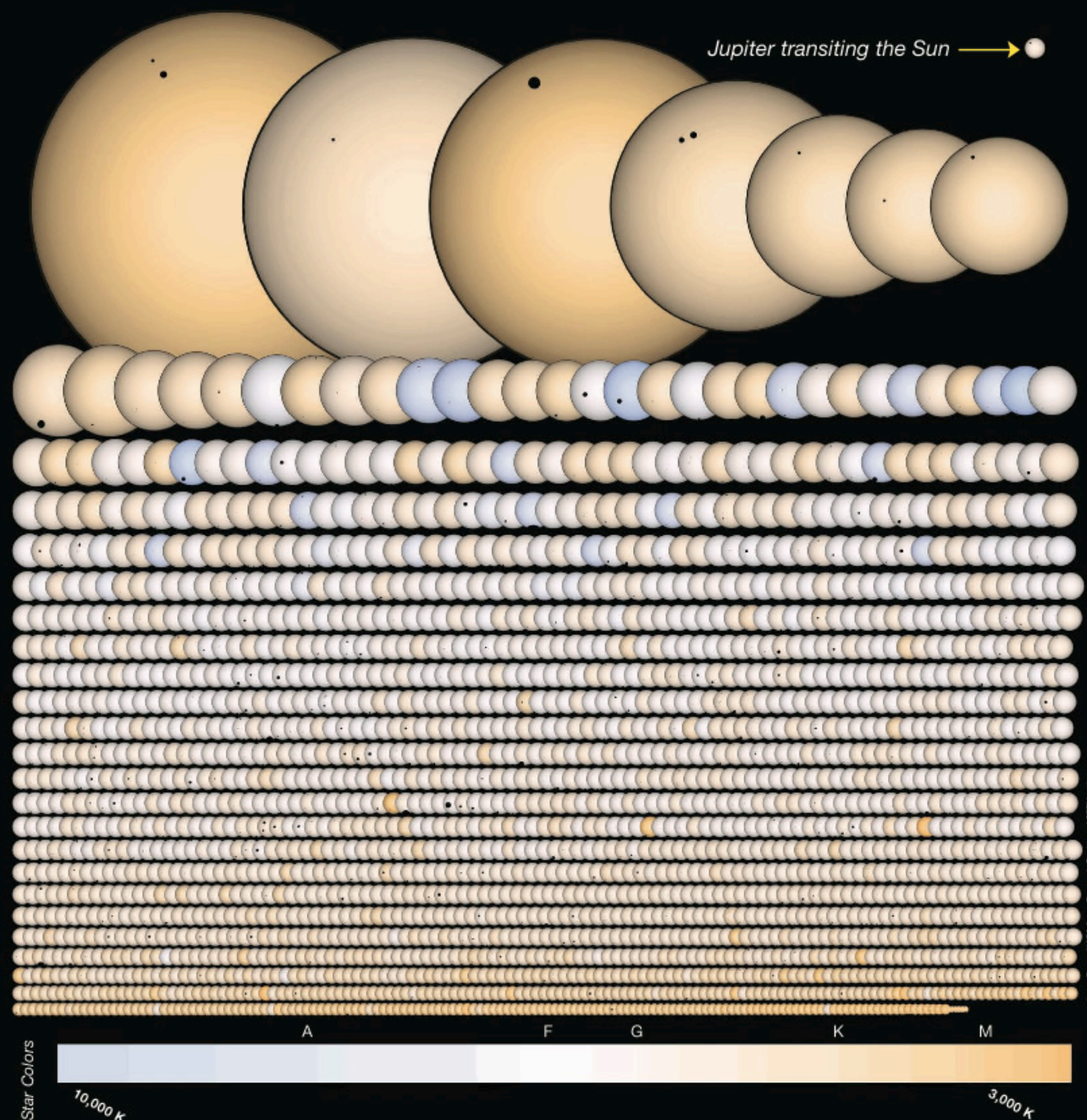
Kepler measured more than 145,000 stars in this field of view:



National Aeronautics and Space Administration

KEPLER'S PLANET CANDIDATES

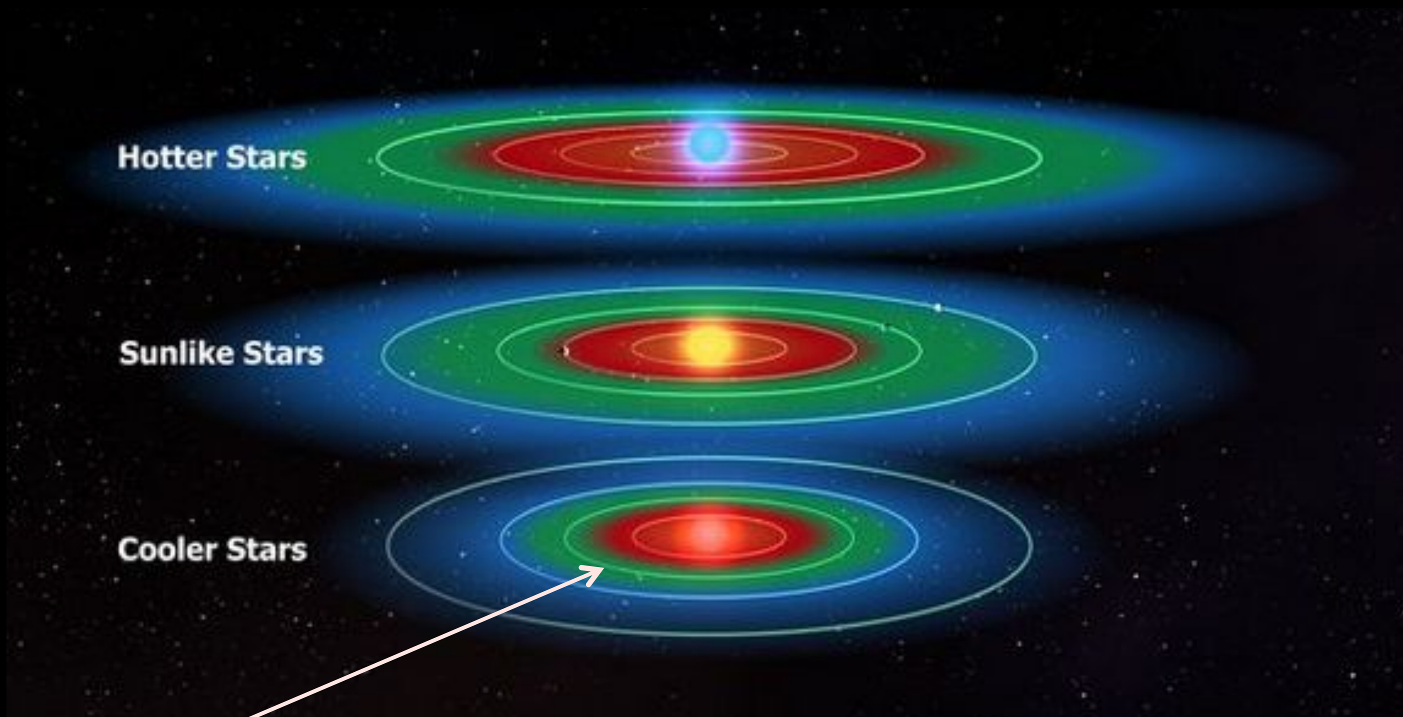
2,740 AS OF JANUARY, 2013



Using NASA's planet-hunting Kepler spacecraft, astronomers have discovered 2,740 planet candidates orbiting 2,036 other suns in a search for Earth-size worlds. The search began in 2009. Kepler monitors a rich star field for planetary transits, which cause a slight dimming of starlight when a planet crosses the face of its star. In "Kepler's Planet Candidates," the systems are ordered by star diameter. The star's color represents its temperature as shown in the lower scale, and the letters (A, F, G, K, M) designate star types. The simulated stellar disks and the planet silhouettes are shown at the same scale, with saturated star colors. Look carefully: some systems have multiple planets. For reference, Jupiter is shown transiting

Life Zones Around Stars

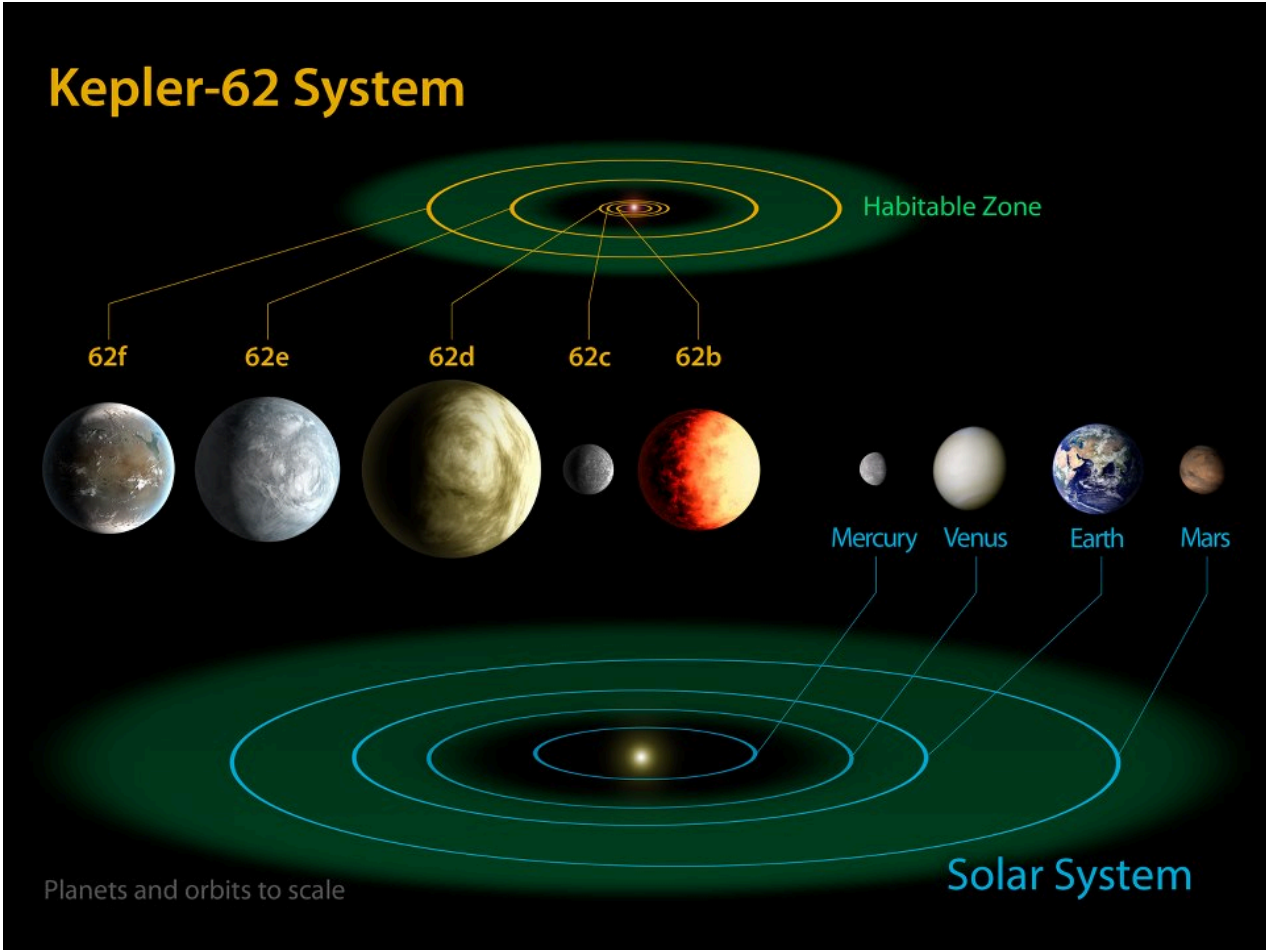
The life zone around a star (green) is the region where a planet would have a moderate temperature that allows water to be liquid.



Red dwarf stars were thought to be disfavored – their life zones are small.

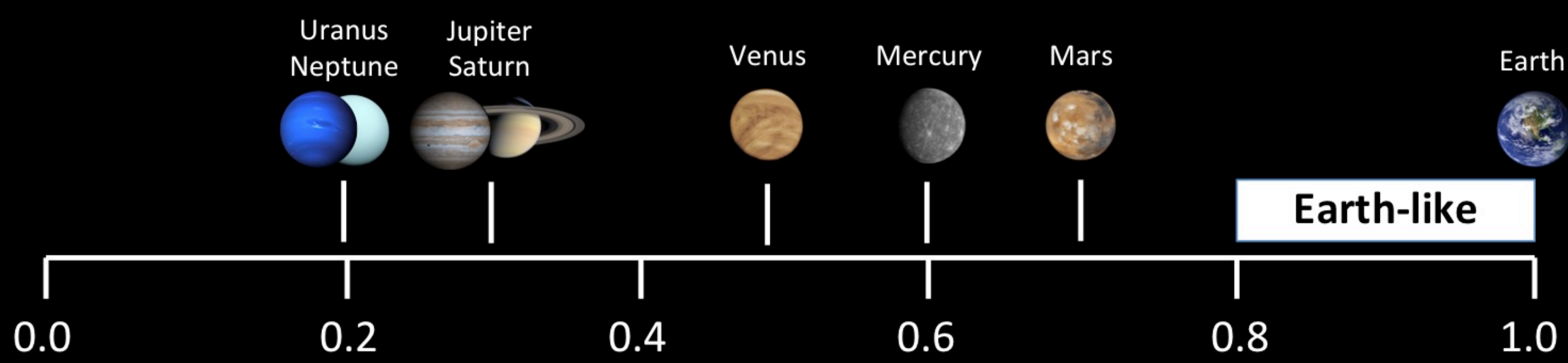
<u>This anthropocentric view is too pessimistic.</u>

We find lots of planets in the life zones around such stars!



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

Earth Similarity Index (ESI)



The Earth Similarity Index (ESI) is a measure of Earth-likeness for exoplanets as a number between zero (no similarity) and one (identical to Earth).

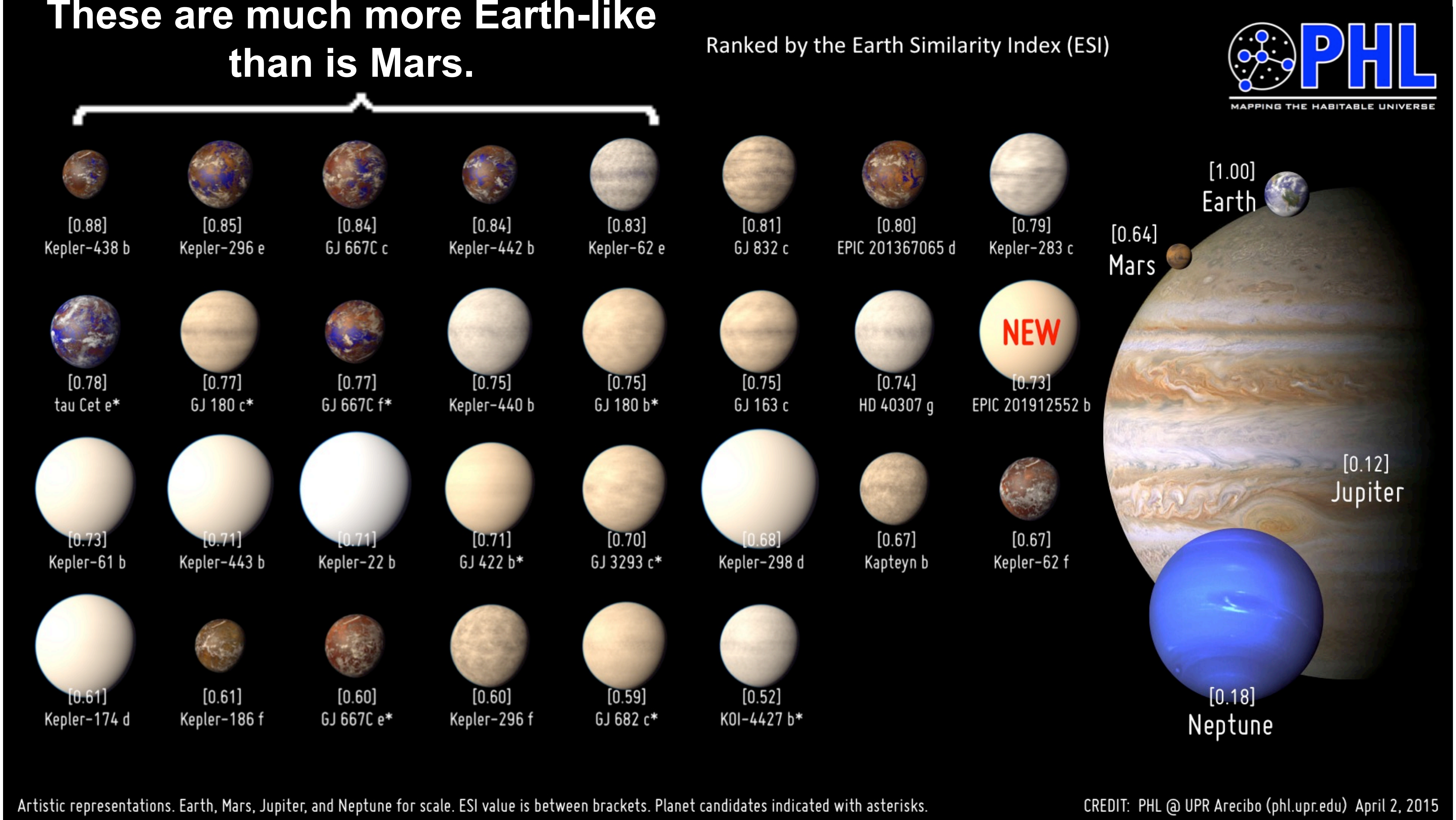
Any exoplanet with an ESI value above 0.8 can be considered Earth-like, which means that it has a similar size and composition to Earth with a temperate atmosphere that might potentially support terrestrial life forms.

The ESI scale is a function of the radius, bulk density, escape velocity, and surface temperature of an exoplanet, but it is much more sensitive to surface temperature.

The Habitable Exoplanets Catalog, Planetary Habitability Laboratory, phl.upr.edu, 2011.

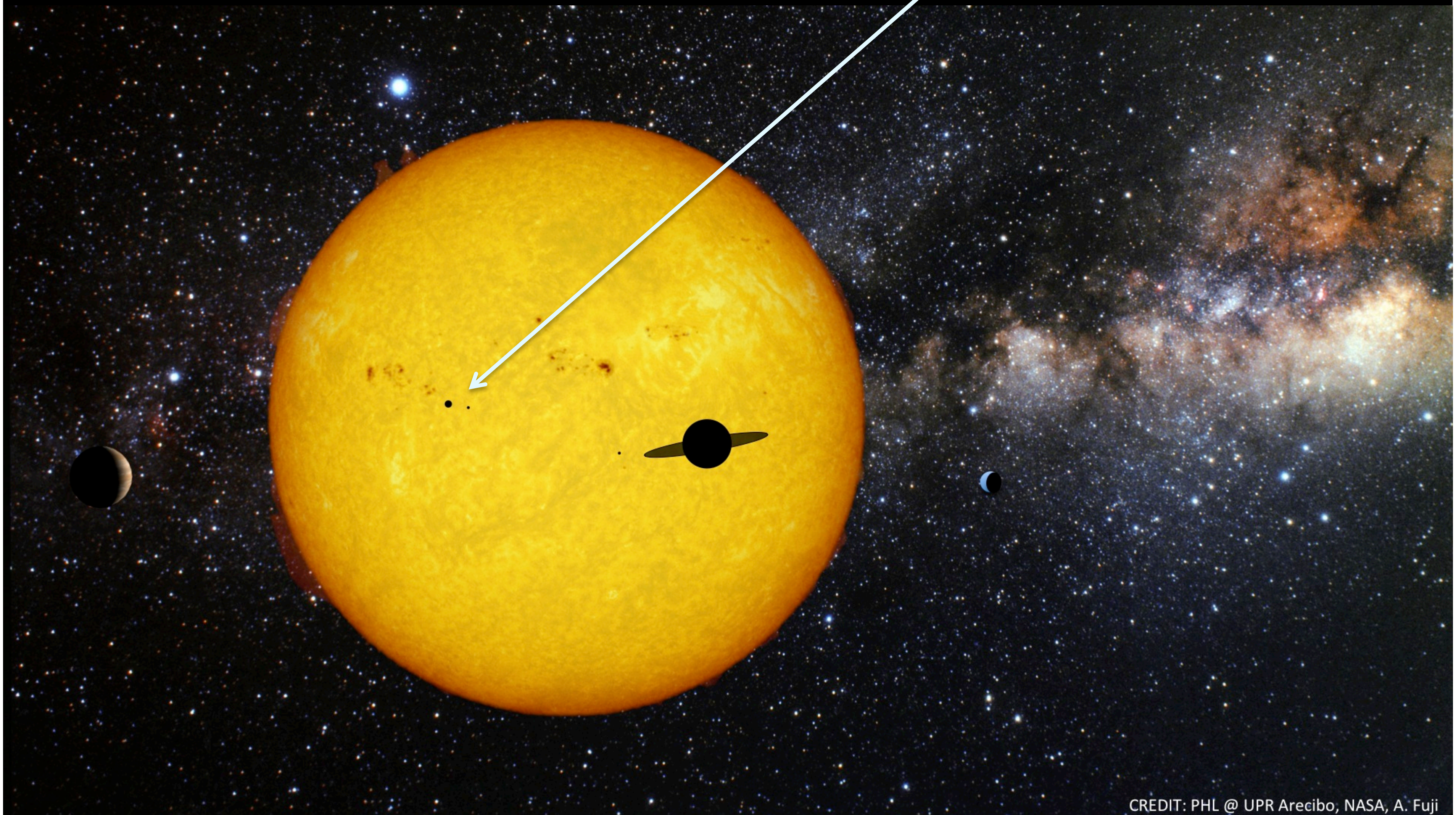
We are discovering many Earth-like planets:

These are much more Earth-like than is Mars.



This is already out of date! More planets are discovered almost daily.

It is difficult to find Earth-like planets
in part because it is hard to distinguish them from starspots.



A terrestrial planet candidate in a temperate orbit around Proxima Centauri

Nature, 536, 438 (August 25, 2016)

Guillem Anglada-Escudé , Pedro J. Amado , John Barnes , Zaira M. Berdiñas , R. Paul Butler , Gavin A. L. Coleman , Ignacio de la Cueva , Stefan Dreizler , Michael Endl , Benjamin Giesers , Sandra V. Jeffers , James S. Jenkins , Hugh R. A. Jones , Marcin Kiraga , Martin Kürster , María J. López-González , Christopher J. Marvin , Nicolás Morales , Julien Morin , Richard P. Nelson , José L. Ortiz , Aviv Ofir , Sijme-Jan Paardekooper , Ansgar Reiners , Eloy Rodríguez , Cristina Rodríguez-López , Luis F. Sarmiento , John P. Strachan , Yiannis Tsapras , Mikko Tuomi & Mathias Zechmeister

3.25 light years

At a distance of 1.295 parsecs, the red dwarf Proxima Centauri (α Centauri C) is the Sun's closest stellar neighbour.

It has an effective temperature of only around 3,050 kelvin, a luminosity of 0.15 per cent of that of the Sun, a measured radius of 14 per cent of the radius of the Sun and a mass of about 12 per cent of the mass of the Sun. Although Proxima is considered a moderately active star, its rotation period is about 83 days.

Here we report observations that reveal the presence of a small planet with a minimum mass of about 1.3 Earth masses orbiting Proxima with a period of approximately 11.2 days at a semi-major-axis distance of around 0.05 astronomical units. Its equilibrium temperature is within the range where water could be liquid on its surface.

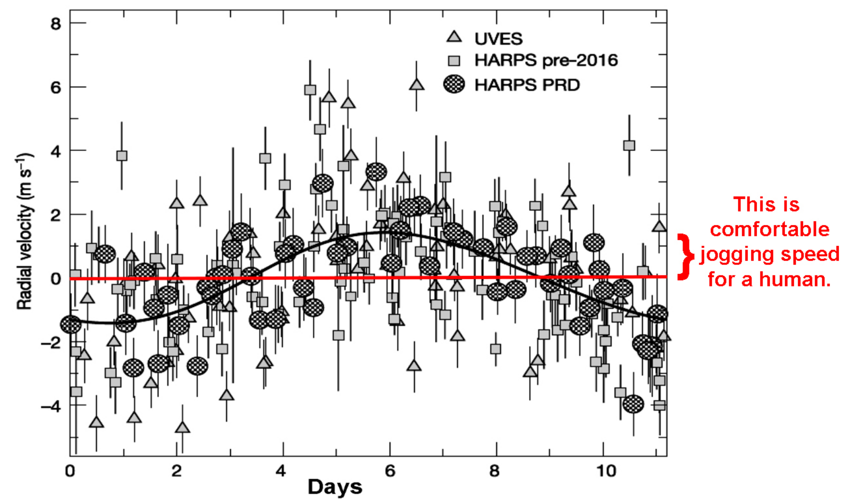


Figure 2 | All of the data sets phase-folded at the 11.2 d signal. Radial velocity measurements phase folded at the 11.2 d period of the planet candidate for 16 years of observations.

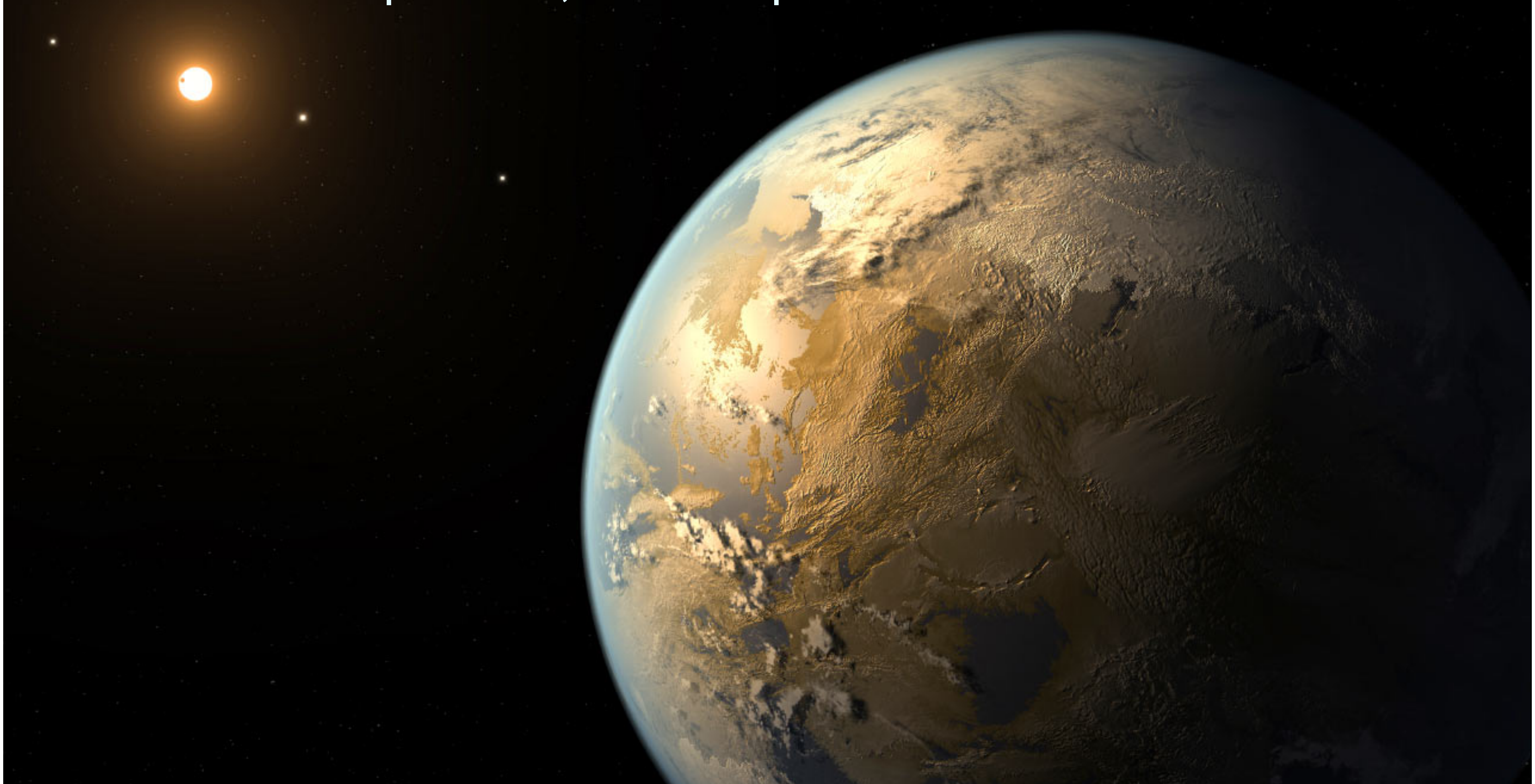
This planet could be a mini-Neptune, warmed up – possibly a water world.

It could be a rocky desert or have a runaway greenhouse effect like Venus.

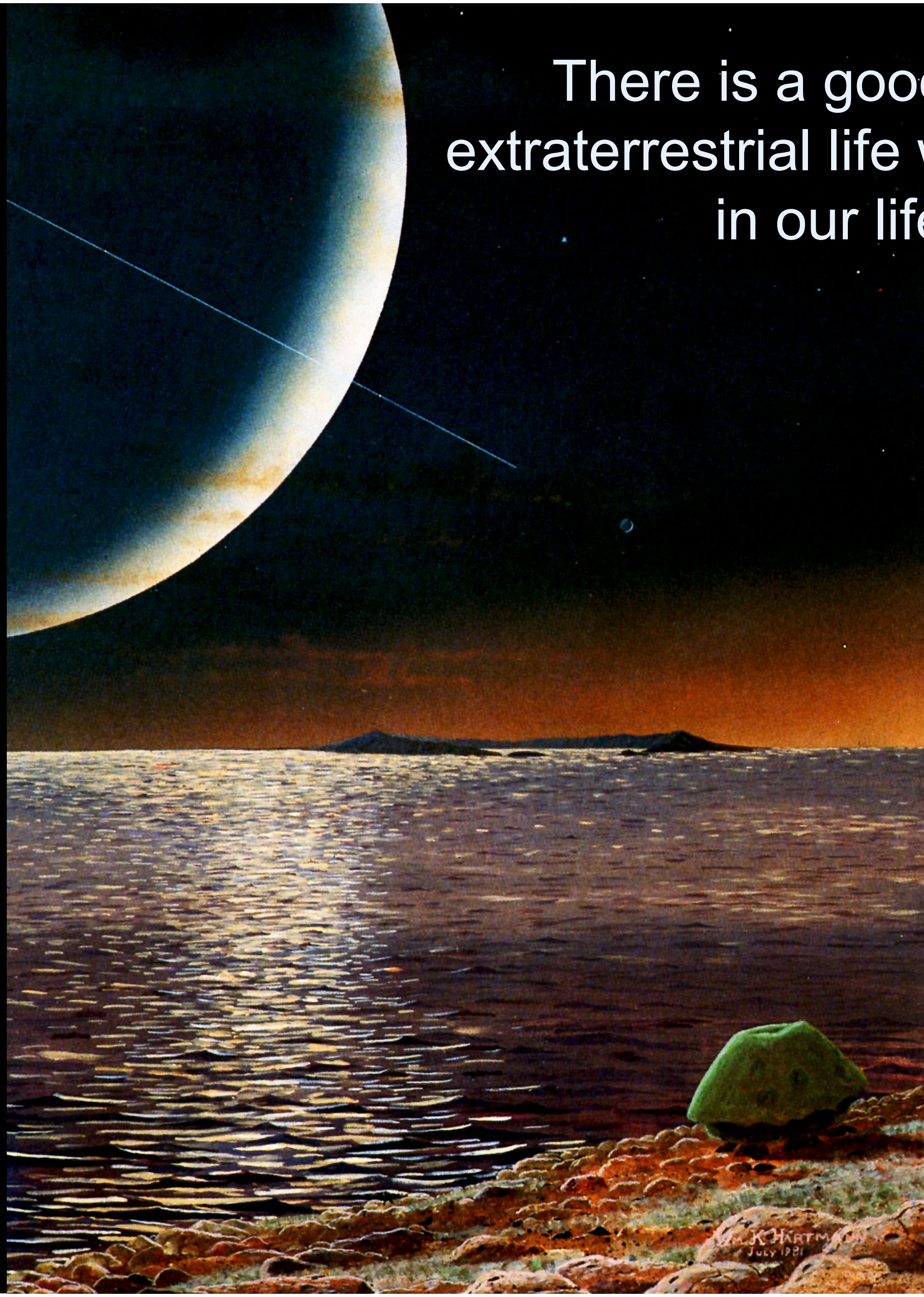
Or it could be Earth-like enough to support life.

The Breakthrough Starshot initiative plans to send many postage-stamp-sized spacecraft to Proxima Centauri, accelerated via lasers to ~ 20 % of the speed of light. The trip there would take about 20 years.

It is essentially certain that “Earth duplicates” in mass, composition, and temperature will be found.



Spacecraft are planned (but not funded) to take spectra of exolanets that could find water or even oxygen. Finding O_2 would be a signature of life.



There is a good chance that
extraterrestrial life will be discovered
in our lifetimes.