XVIII IAG/USP Advanced School on Astrophysics (AWSA-II): Exoplanet Science in a Solar System Context

Andrew Szentgyorgyi
Harvard-Smithsonian Center for Astrophysics

Universidad de Sao Paulo, 26 Feb 2018

Talk Outline

- Exoplanet science in a historical context
- Exoplanet science today
- Solar System context
- Exoplanet science today, in a little more detail
- Orbital resonance
- Intro to planet formation

Exoplanet: A planet orbiting a star other than the Sun

Planet: Less massive than a star, more massive than a planetesimal.

- No internal nuclear burning, ever (but may be self-luminous from gravitational contraction).
- Shaped by gravity (spherical) rather than agglutination.
- Formed in protoplanetary disk.

Exoplanet Science- A Historical Context

Paleohistory of Exoplanet Science:

- Giordano Bruno (1584) speculates on the inevitability that Earth-like exoplanets must exist.

- Newton (1713) asserts that exo-solar systems will not only harbor exo-Earths, but will be identical to the Solar System.

- Struve (1952) argues that there is no reason exoplanets should not be much closer to a host star than Mercury is to the Sun.

- Further proposes that super-Jupiters in close orbits should be detectable by Doppler spectroscopy of host star and forground extinction during transits.

"This space we declare to be infinite... In it are an infinity of worlds of the same kind as our own."

- *De l'infinito universo et mondi* (1584)

"And if the fixed stars are the centres of similar systems, they will all be constructed according to a similar design and subject to the dominion of *One*."."

- *Principia, 2nd Edition* (1713)

"But there seems to be no compelling reason why hypothetical stellar planets should not, in some instances, be closer to their parent stars than is the case in the solar system [sic]."

The Observatory, **72,** 1952

PROPOSAL FOR A PROJECT OF HIGH-PRECISION STELLAR RADIAL VELOCITY WORK

By Otto Struve

The Observatory, **72,** 1952

Lost in the Wilderness

- W.S. Jacob ”discovers” a spurious planet orbiting 70 Oph by visually astrometry from the Madras Observatory. Rejected on stability grounds and later observationally.
- In the *Observatory* article, Struve asserts exoplanets have been discovered. 61 Cyg planet was 16 $M_{2\text{Ɨ}}$ “discovered” by photographic astrometry.
- In the 1950’s & 60’s Peter van de Kamp make the claims Barnard’s star hosts 1.1 $M_{2\text{Ɨ}}$ &0.8 $M_{2\text{Ɨ}}$ exoplanets. Subsequently disproved.
- Campbell *et al.* (1988 - γ Ceph) & Latham *et al.* (1989 - HD114762) finally discover exoplanets, but data is not definitive and confirmation not made for 2 decades.

There is, then, some positive evidence in favour of the existence of a planetary body in connexion with this system, enough for us to pronounce it highly probable ⋯

MNRAS, 1855

“K. A. Strand’s discovery of a planet-like companion in the system 61 Cygni ⋯”

-*The Observatory,* **72,** 1952

Alternate Dynamical Analysis of Barnard's Star

PETER VAN DE KAMP

Sproul Observatory, Swarthmore College, Swarthmore, Pennsylvania

(Received 12 May 1969)

Astronomical Journal, **74,** 1969

letters to nature

Nature **339**, 38 - 40 (04 May 1989); doi:10.1038/339038a0

The unseen companion of HD114762: a probable brown dwarf

DAVID W. LATHAM*, TSEVI MAZEH†, ROBERT P. STEFANIK*, MICHEL MAYOR‡ & GILBERT BURKI

The Watershed

- 1992 - Wolszczan & Frail discover several Earth-mass planets orbiting pulsar PSR B1257+12 by pulsar timing.
- article

Nature **378**, 355 - 359 (23 November 1995); doi:10.1038/378355a0

A Jupiter-mass companion to a solar-type star

MICHEL MAYOR & DIDIER QUELOZ

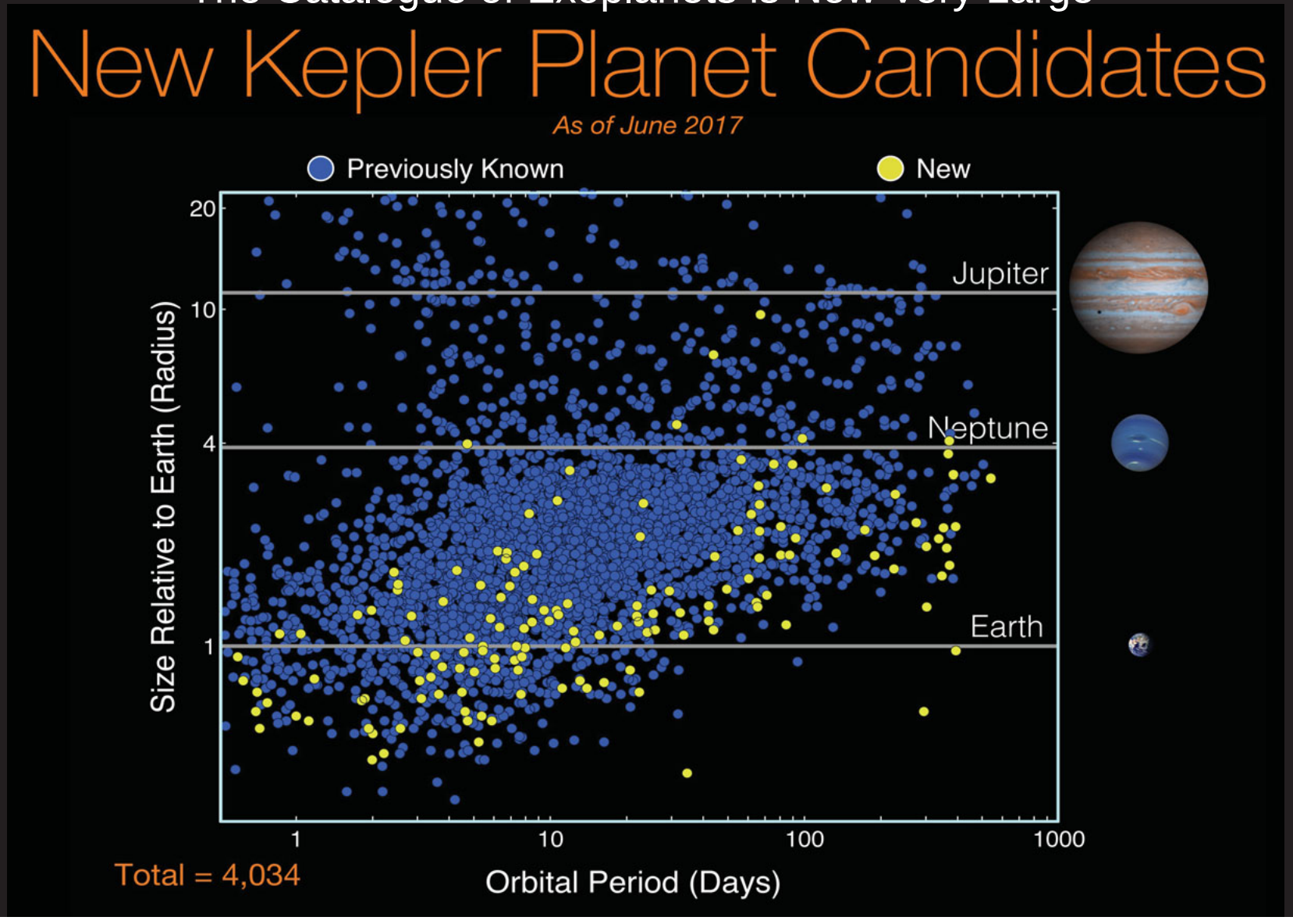
Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.

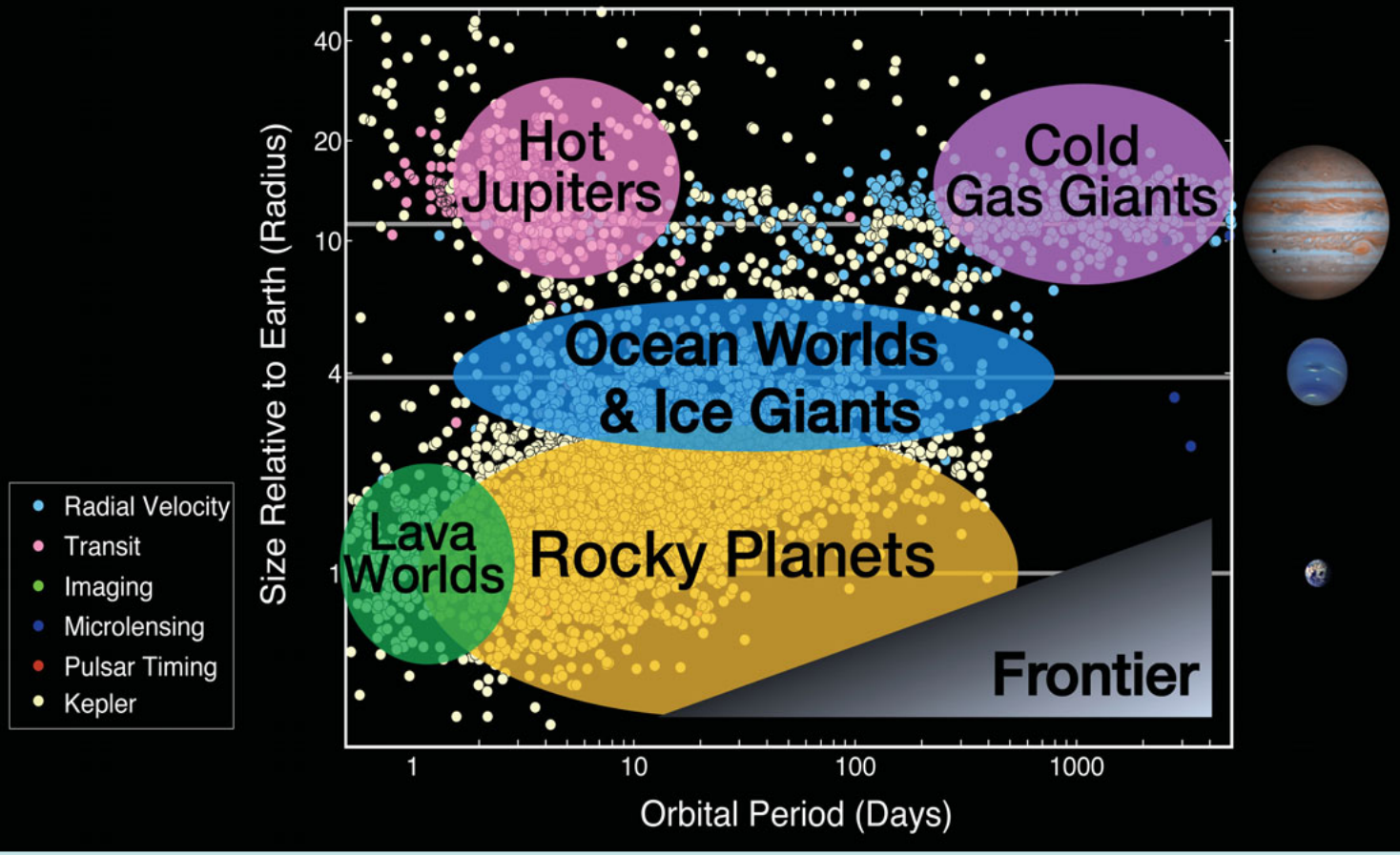
- 1999 - υ And is found to be a multiple star system (Lissauer).
- 1999 − Charbonneau *et al.* & Henry *et al.* detect transit of HD408458b. The radius of an exoplanet is measured. Mass (not *m Sin(i)*) is measured by PRV.
- 1999 − β Pic b, Fomalhaut b & HR8977 b,c,d & e are imaged.
- 2003 − Exoplanets are discovered by : 2003-BLG-235) ams.
- on launches and begin ~year later. 0 Kepler exoplanet candidates measured.
- 2014 − Kepler Discovers first Earth-sized, habitable-zone (HZ) planet Kepler-186f.
- 2016 − Trappist 1 system has multiple HZ planets (3).

Exoplanet Science Today

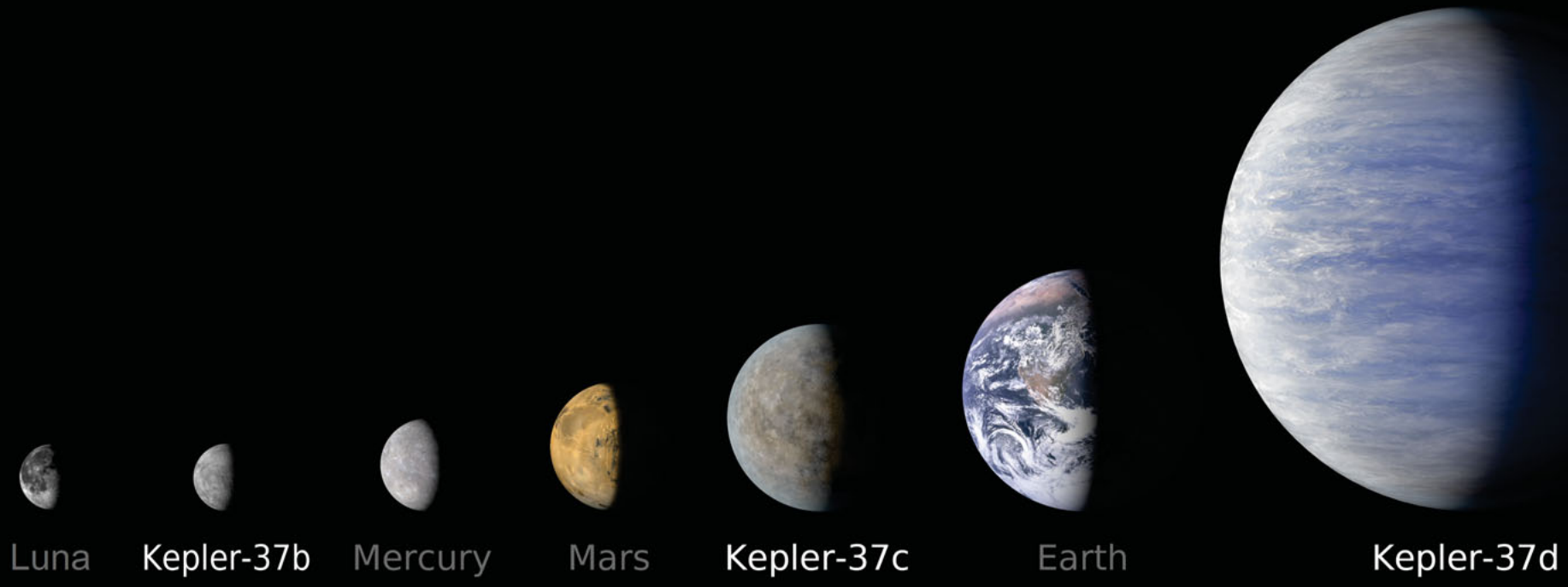
The Catalogue of Exoplanets is Now Very Large



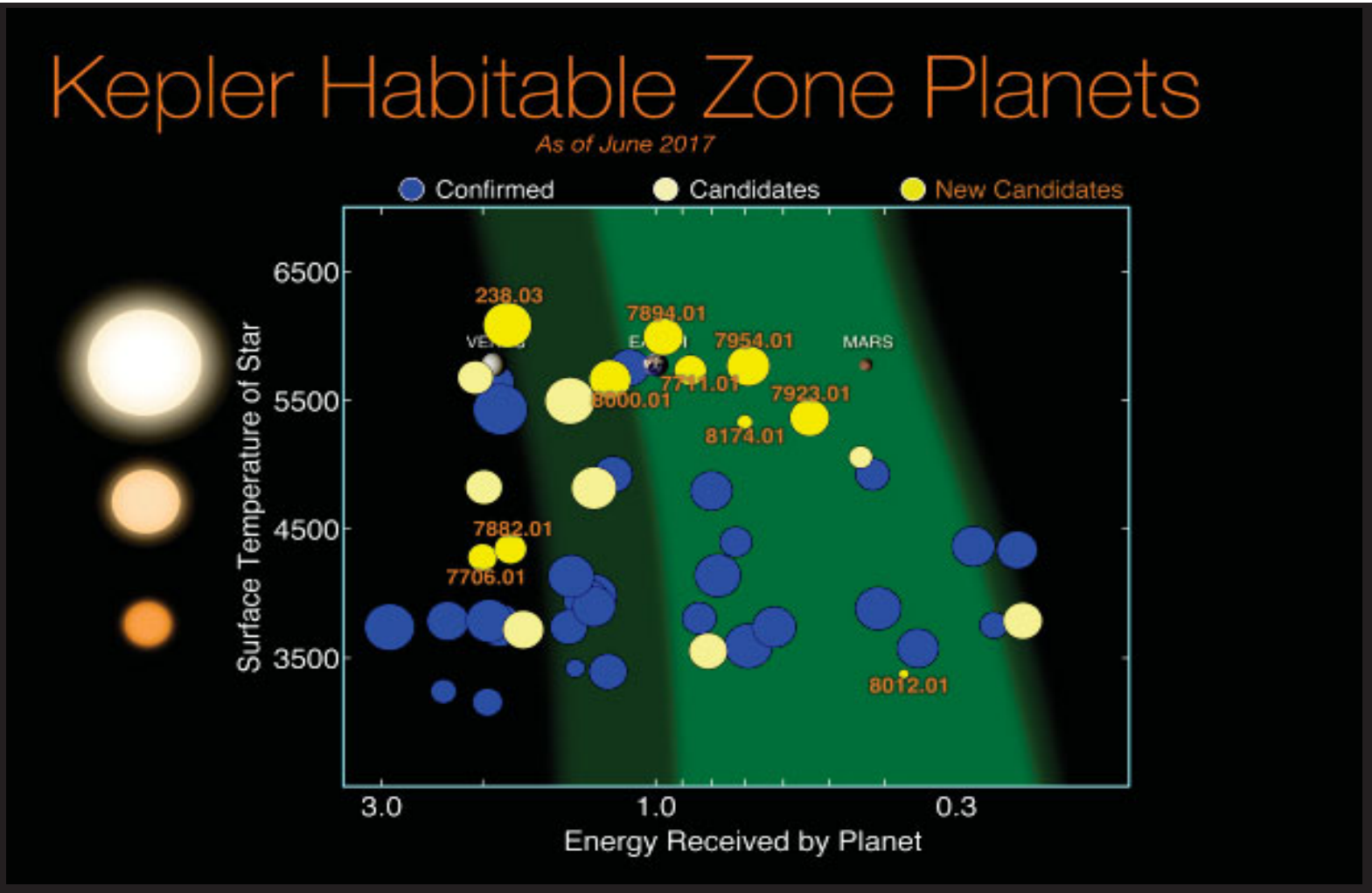
Exoplanet Populations



Many exoplanets are extremely small

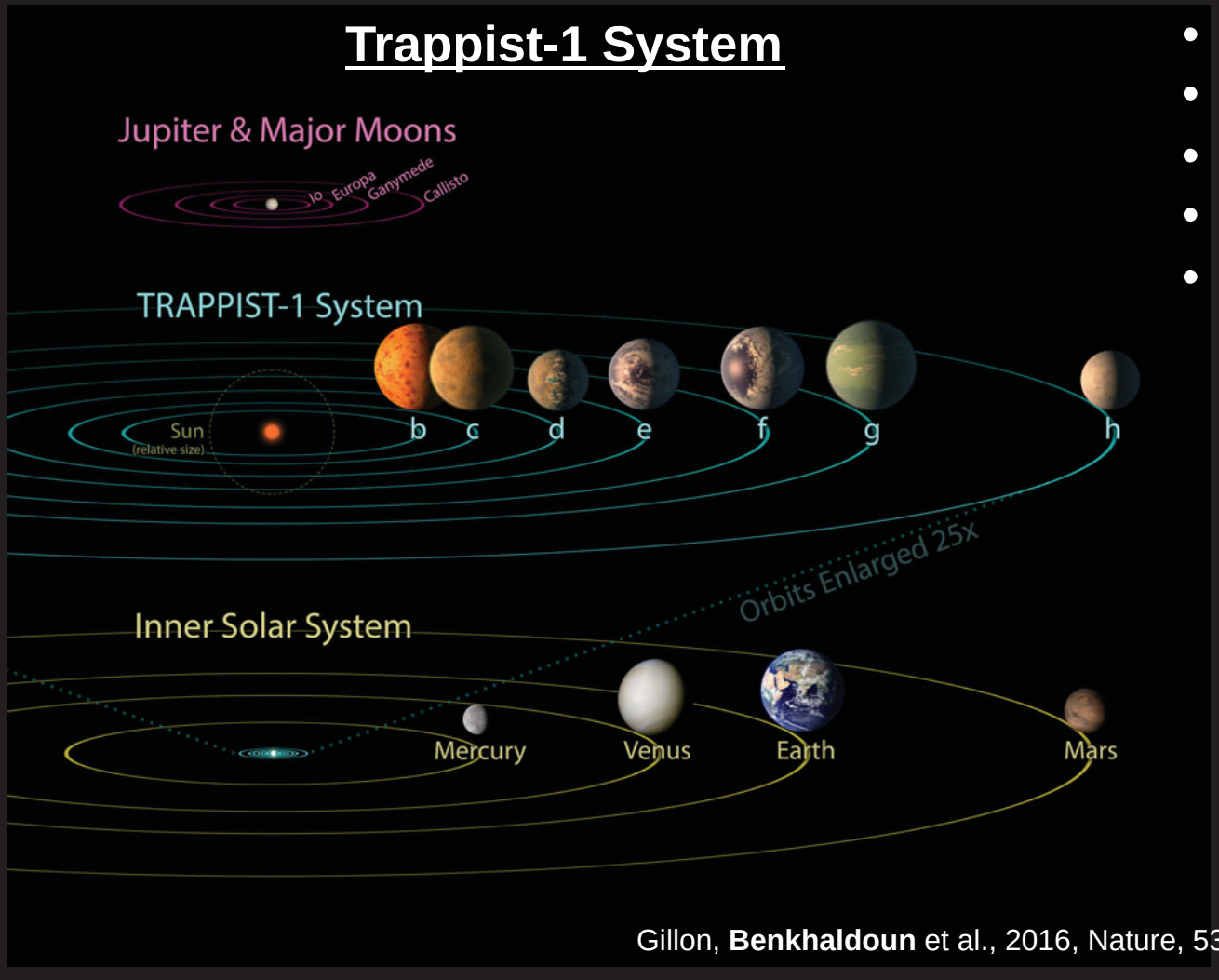


Many exoplanets with radii smaller than the Earth have been discovered, however their masses cannot be measured with currently available telescopes.



Many exoplanets have been discovered within the exoplanetary Habitable Zones (HZ's) where the surface temperature is "right" for water to be liquid (not vapor or solid).

Not All Interesting Exoplanets are Discovered by Space Missions

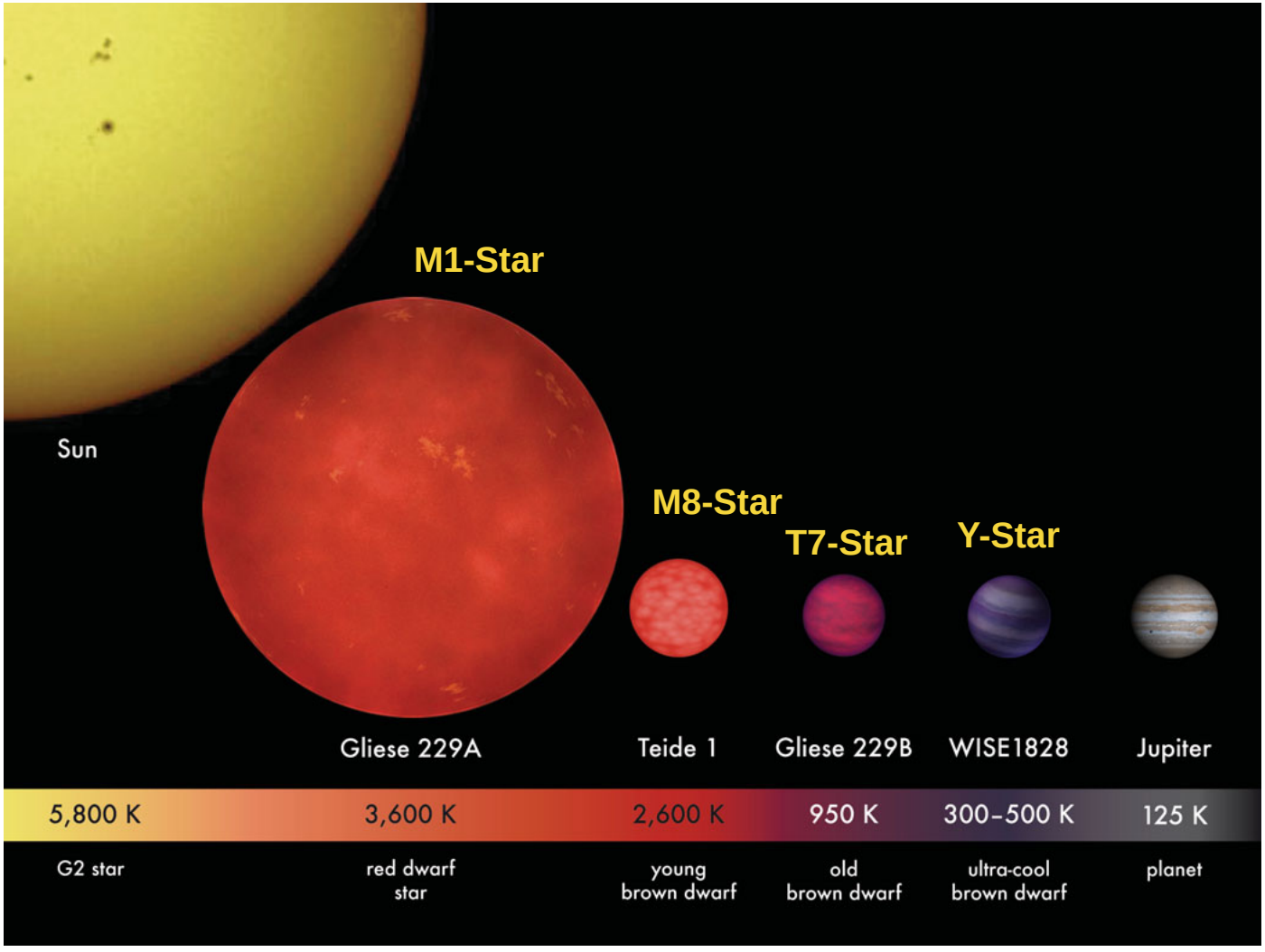


- Spectral Type: M8V
- M_V ~ 18.8
- 7 terrestrial, temperate planets
- 3 (e,f,g) in habitable zone
- Nearest neighbor resonances: 8/5, 5/, 3/2, 3/2, 4/3, and 3/2

Gillon, **Benkhaldoun** et al., 2016, Nature, 533, 221

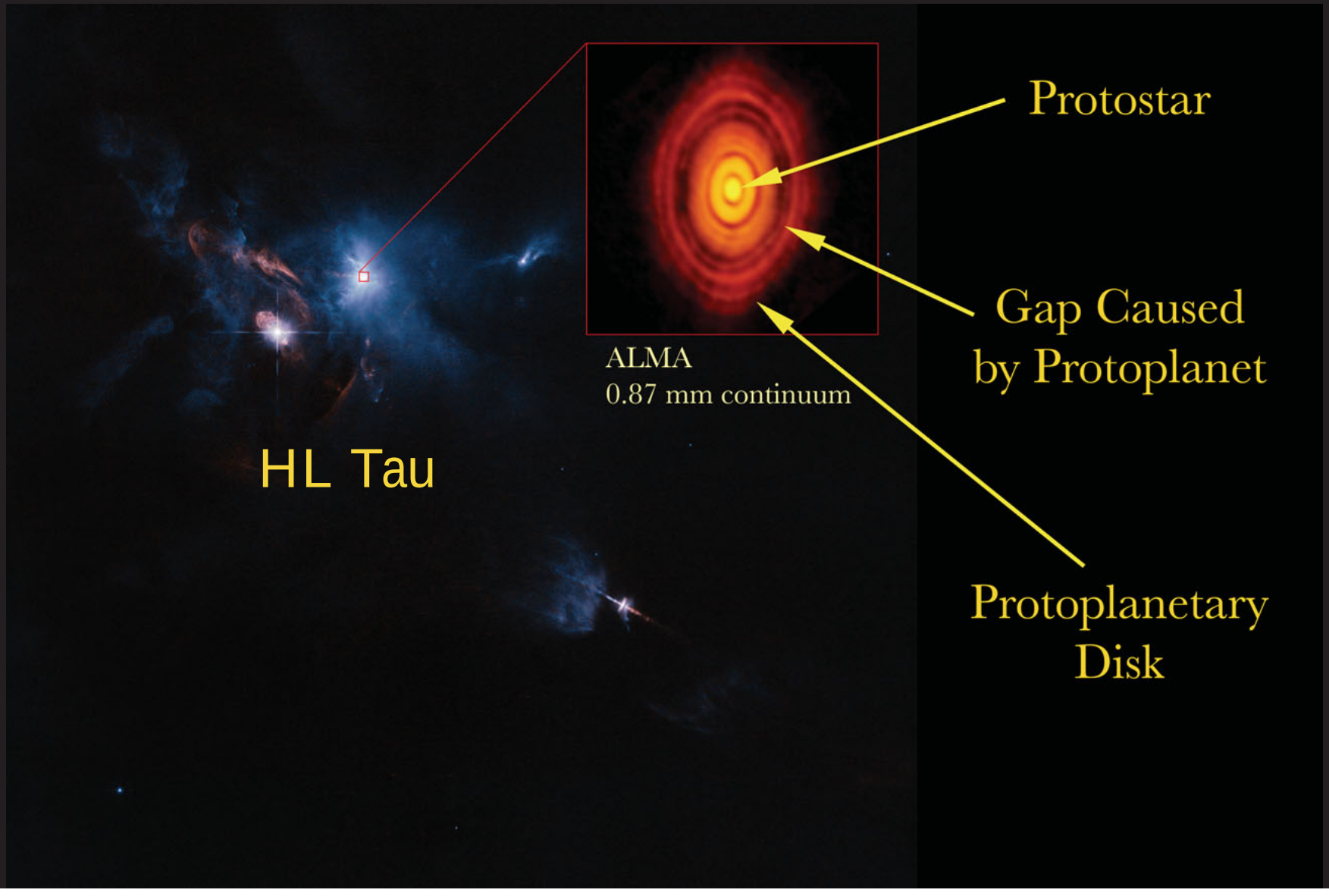
Trappist North, Oukaïmden Observatory, Morocco

Planets vs. Stars: Stars Don't Burn Nuclear Fuel



Star	Mass
GL 229A	607 $M_{♃}$ (0.58 $M_{\odot}$)
Teide 1	57 $M_{♃}$
GL 229B	21 – 52 $M_{♃}$
Wise 1828	5-20 $M_{♃}$

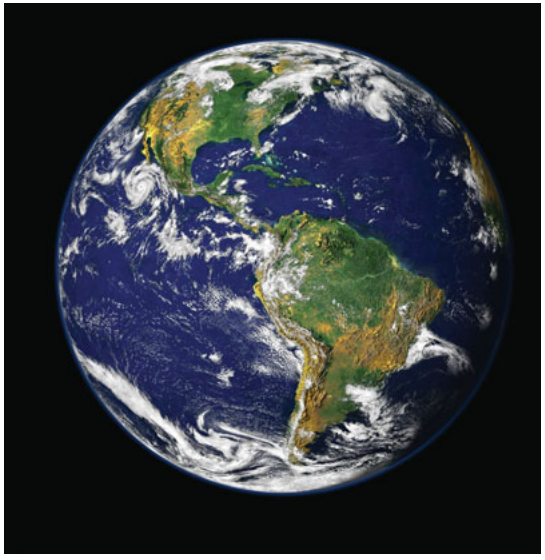
Planets vs. Stars: Stars Have Disks, Planets Form in Them



Planets vs. Planetesimals: Planets are Spherical, Planetesimal May Not Be

Ida

Pluto



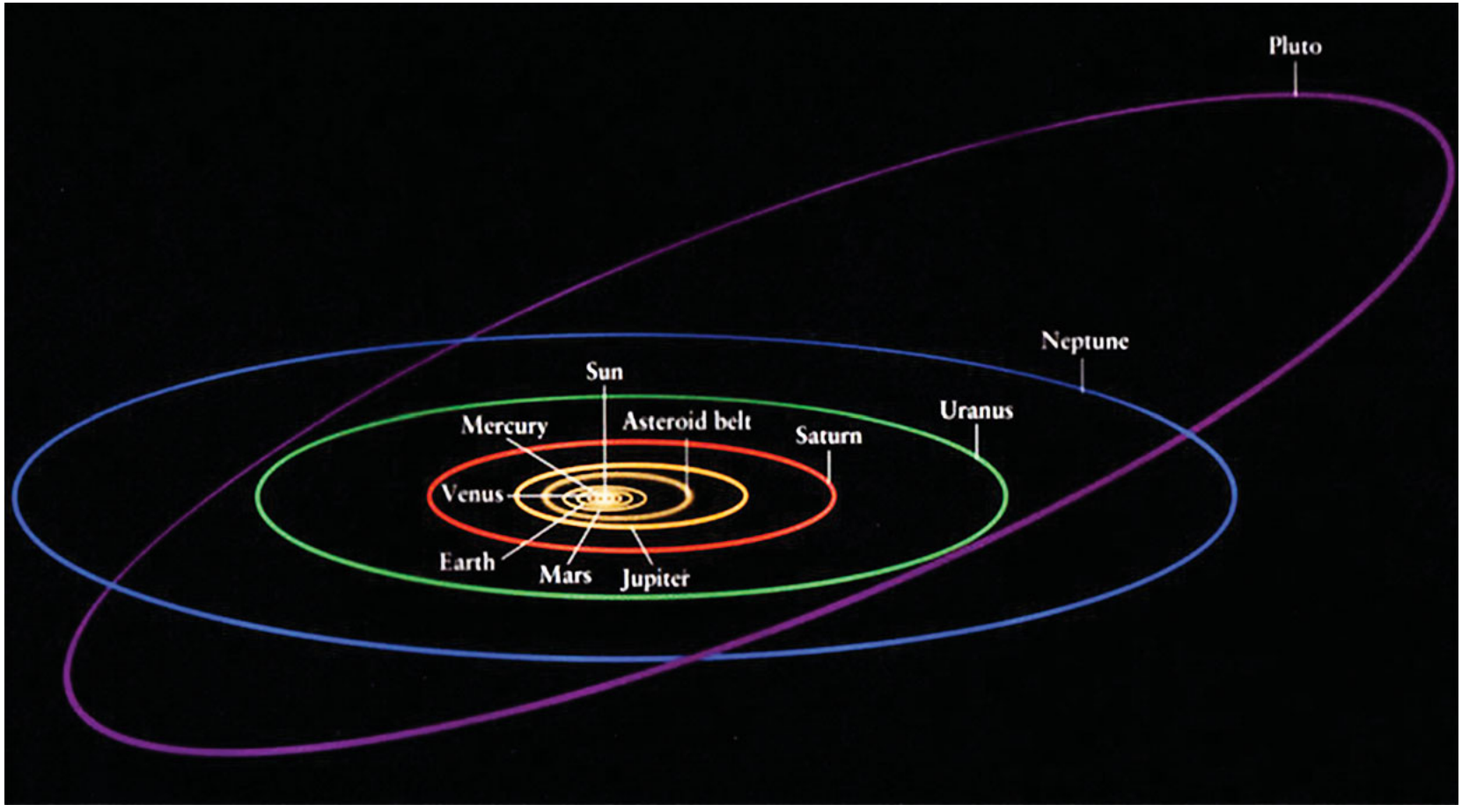
Earth

Gravity dominates the morphology of planets.

If Pluto is Spherical, Why is it a Planetesmial?

A Solar System Context for Exoplanet Science

The “old” Solar system, i.e. the 9 planets we knew on October 5, 1995



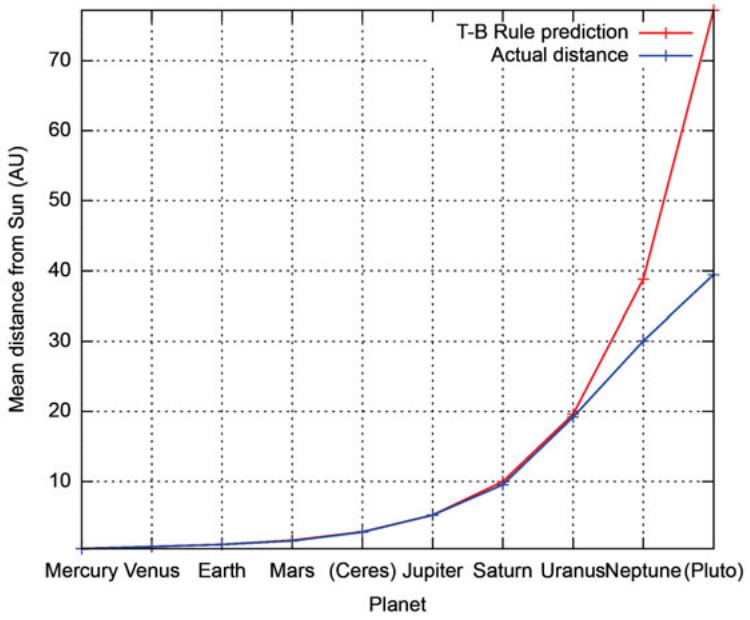
Bode's "Mysterious" Law

- With such a small sample, planetary science was (mostly) reduced to numerology for 2 ½ centuries …
- Bode's (really Titius') "law":
  - a = 4 + x (a = orbital semimajor axis)
  - Scaled to a_{Earth}= 10
  - x = 0, 3, 6, 12, 24, 48 for other planets
- "Mysterious" doubling of values.

Johann Daniel Titius
1729 - 1796

Johann Elert Bode
1749 – 1826)

See Murray & Dermont ***Solar System Dynamics*** for extended discussion of likelihood of Bode's law

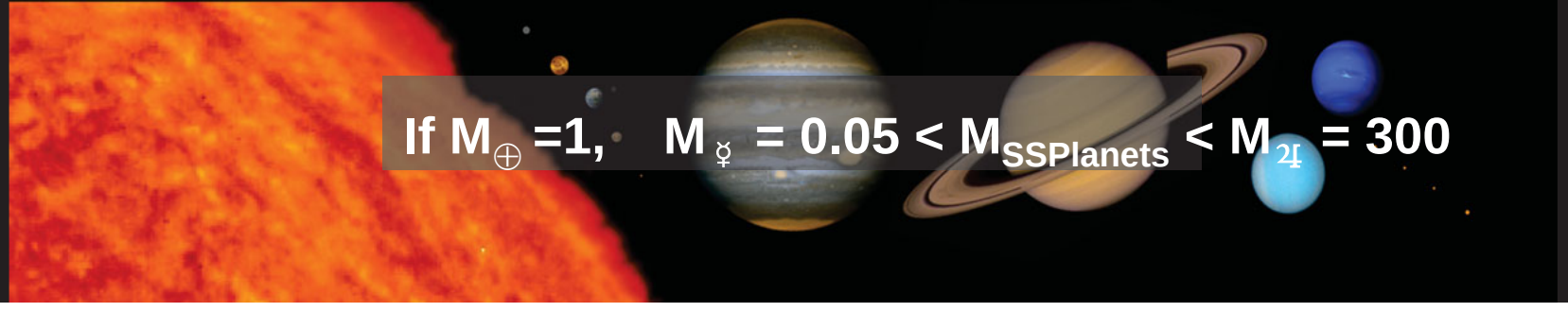


Solar system fact-sheet

	Sun	Mercury	Venus	Earth	Moon	Mars	Ceres	Jupiter	Saturn	Uranus	Neptune	Pluto	Makemake	Haumea	Eris
	star (G2V)	planet	planet	planet	satellite	planet	dwarf planet	planet	planet	planet	planet	dwarf planet	dwarf planet	dwarf planet	dwarf planet
Diameter (km)	1,392,000	4,879.4	12,103.6	12,742	3,476.3	6,792.4	974.6	14,2984	120,536	51,118	49,528	2,390	1,500	1,500	2,600
Mass (10^{24} kg)	1,989,100	0.33	4.87	5.97	0.073	0.64	0.000943	1898.6	568.46	86.81	102.43	0.013	0.0004	0.0042	0.0167
Temperature, min (°C)	5,505	–173	462	–89	–173	–87	–106	–161	–189	–224	–218	–240	–243	–241	–243
Temperature, max (°C)	17,000,000	427	462	58	117	–5	–106	–161	–189	–216	–218	–218	–238	–241	–218
Rotation period (days)	25.1	58.6	–243.0	1.0	27.3	1.0	0.4	0.4	0.4	–0.7	0.7	–6.4	?	0.163	0.3
Axial tilt (°)	——	0.04	177.3	23.4	6.7	25.2	3	3.1	26.7	97.8	28.3	119.6	?	?	?
Surface gravity ($m.s^{2}$)	274.0	3.7	8.9	9.8	1.6	3.7	0.3	24.8	9.0	8.7	11.2	0.6	~0.5	0.4	~0.8
Escape velocity ($km.s^{-1}$)	617.7	4.3	10.5	11.2	2.38	5.0	0.5	59.5	35.5	21.3	23.5	1.2	~0.8	0.84	?
Surface area (10^{6} km^{2})	6,087,700	75	460	510	37.9	145	3	62,180	42,700	8,116	7,641	18	~7		21
Volume (10^{12} km^{3})	1,412,200	0.06	0.9	1.1	0.02	0.16	0.0005	1431	827	68	63	0.007	~0.002		0.009
Density ($kg.m^{3}$)	1.41	5.41	5.19	5.51	3.35	3.93	1.89	1.33	0.69	1.27	1.64	1.86	~2	~3	~2
Albedo	——	0.11	0.65	0.37	0.12	0.15	0.09	0.52	0.47	0.51	0.41	0.58	?	0.6	0.86
Apparent magnitude (V)	–26.7	–1.9	–4.6	——	–12.9	–2.9	6.9	–2.9	–0.2	5.3	7.8	13.7	16.7	17.5	18.7
Angular diameter, max. (")	1,962.0	13.0	66.0	——	2,046	25.1	0.8	50.1	20.1	4.1	2.4	0.1	0.02	0.02	0.04
Rings	——	no	no	no	no	no	no	yes	yes	yes	yes	no	no	no	no
Satellites	billions!	0	0	1	no	2	0	63	60	27	13	3	0	2	1
Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun
Perihelion (10^{6} km)	——	46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650
Aphelion (10^{6} km)	——	69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600
Semimajor axis (AU)	——	0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7
Eccentricity	——	0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44
Inclination (°)	——	7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2
Orbital period (days)	——	88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600
Orbital period (years)	——	0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4
Orbital velocity ($km.s^{-1}$)	——	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)	——	——	——	——	——	1801	——	——	——	1781	1846	1930	2005	2004	2003

Solar system fact-sheet

	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792.4	14,2984	120,536	51,118	49,528	2,390
Mass (10^{24} kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013
Axial tilt (°)	——	0.04	177.3	23.4	6.7	25.2	3	3.1	26.7	97.8	28.3	119.6	?	?	?
Surface gravity ($m.s^2$)	274.0	3.7	8.9	9.8	1.6	3.7	0.3	24.8	9.0	8.7	11.2	0.6	~0.5	0.4	~0.8
Escape velocity ($km.s^{-1}$)	617.7	4.3	10.5	11.2	2.38	5.0	0.5	59.5	35.5	21.3	23.5	1.2	~0.8	0.84	?
Surface area (10^6 km^2)	6,087,700	75	460	510	37.9	145	3	62,180	42,700	8,116	7,641	18	~7		21
Volume (10^{12}	1,412,200	0.06	0.9	1.1	0.02	0.16	0.0005	1431	827	68	63	0.007	~0.002		0.009
Density ($kg.m^3$)	1.41	5.41	5.19	5.51	3.35	3.93	1.89	1.33	0.69	1.27	1.64	1.86	~2	~3	~2
Albedo	——	0.11	0.65	0.37	0.12	0.15	0.09	0.52	0.47	0.51	0.41	0.58	?	0.6	0.86
Apparent magnitude (V)	–26.7	–1.9	–4.6	——	–12.9	–2.9	6.9	–2.9	–0.2	5.3	7.8	13.7	16.7	17.5	18.7
Angular diameter, max. (")	1,962.0	13.0	66.0	——	2,046	25.1	0.8	50.1	20.1	4.1	2.4	0.1	0.02	0.02	0.04
Rings	——	no	no	no	no	no	no	yes	yes	yes	yes	no	no	no	no
Satellites	billions!	0	0	1	no	2	0	63	60	27	13	3	0	2	1
Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun
Perihelion (10^6 km)	——	46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650
Aphelion (10^6 km)	——	69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600
Semimajor axis (AU)	——	0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7
Eccentricity	——	0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44
Inclination (°)	——	7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2
Orbital period (days)	——	88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600
Orbital period (years)	——	0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4
Orbital velocity ($km.s^{-1}$)	——	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)	——	——	——	——	——	1801	——	——	——	1781	1846	1930	2005	2004	2003



$$\text{If } M_{\oplus} = 1, \quad M_{☿} = 0.05 < M_{SSPlanets} < M_{♃} = 300$$

Solar system fact-sheet

	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792.4	14,2984	120,536	51,118	49,528	2,390
Mass (10^{24} kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013
Density (kg.m^3)	5.41	5.19	5.51	3.35	3.93	1.33	0.69	1.27	1.64	1.86

Axial tilt (°)	——	0.04	177.3	23.4	6.7	25.2	3	3.1	26.7	97.8	28.3	119.6	?	?	?
Surface gravity (m.s^2)	274.0	3.7	8.9	9.8	1.6	3.7	0.3	24.8	9.0	8.7	11.2	0.6	~0.5	0.4	~0.8
Escape velocity (km.s^{-1})	617.7	4.3	10.5	11.2	2.38	5.0	0.5	59.5	35.5	21.3	23.5	1.2	~0.8	0.84	?
Surface area (10^6 km^2)	6,087,700	75	460	510	37.9	145	3	62,180	42,700	8,116	7,641	18	~7		21
Volume (10^{12}	1,412,200	0.06	0.9	1.1	0.02	0.16	0.0005	1431	827	68	63	0.007	~0.002		0.009
Density (kg.m^3)	1.41	5.41	5.19	5.51	3.35	3.93	1.89	1.33	0.69	1.27	1.64	1.86	~2	~3	~2
Albedo	——	0.11	0.65	0.37	0.12	0.15	0.09	0.52	0.47	0.51	0.41	0.58	?	0.6	0.86
Apparent magnitude (V)	–26.7	–1.9	–4.6	——	–12.9	–2.9	6.9	–2.9	–0.2	5.3	7.8	13.7	16.7	17.5	18.7
Angular diameter, max. (")	1,962.0	13.0	66.0	——	2,046	25.1	0.8	50.1	20.1	4.1	2.4	0.1	0.02	0.02	0.04
Rings	——	no	no	no	no	no	no	yes	yes	yes	yes	no	no	no	no
Satellites	billions!	0	0	1	no	2	0	63	60	27	13	3	0	2	1
Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun
Perihelion (10^6 km)	——	46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650
Aphelion (10^6 km)	——	69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600
Semimajor axis (AU)	——	0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7
Eccentricity	——	0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44
Inclination (°)	——	7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2
Orbital period (days)	——	88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600
Orbital period (years)	——	0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4
Orbital velocity (km.s^{-1})	——	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)	——	——	——	——	——	1801	——	——	——	1781	1846	1930	2005	2004	2003

Solar system fact-sheet

	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792.4	14,2984	120,536	51,118	49,528	2,390
Mass (10^{24} kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013
Density (kg.m^3)	5.41	5.19	5.51	3.35	3.93	1.33	0.69	1.27	1.64	1.86

Axial tilt (°)	——	0.04	177.3	23.4	6.7	25.2	3	3.1	26.7	97.8	28.3	119.6	?	?	?
Surface gravity (m.s^2)	274.0	3.7	8.9	9.8	1.6	3.7	0.3	24.8	9.0	8.7	11.2	0.6	~0.5	0.4	~0.8
Escape velocity (km.s^{-1})	617.7	4.3	10.5	11.2	2.38	5.0	0.5	59.5	35.5	21.3	23.5	1.2	~0.8	0.84	?
Surface area (10^6 km^2)	6,087,700	75	460	510	37.9	145	3	62,180	42,700	8,116	7,641	18	~7		21
Volume (10^{12}	1,412,200	0.06	0.9	1.1	0.02	0.16	0.0005	1431	827	68	63	0.007	~0.002		0.009
Density (kg.m^3)	1.41	5.41	5.19	5.51	3.35	3.93	1.89	1.33	0.69	1.27	1.64	1.86	~2	~3	~2
Albedo	——	0.11	0.65	0.37	0.12	0.15	0.09	0.52	0.47	0.51	0.41	0.58	?	0.6	0.86
Apparent magnitude (V)	–26.7	–1.9	–4.6	——	–12.9	–2.9	6.9	–2.9	–0.2	5.3	7.8	13.7	16.7	17.5	18.7
Angular diameter, max. (°)	1,962.0	13.0	66.0	——	2,046	25.1	0.8	50.1	20.1	4.1	2.4	0.1	0.02	0.02	0.04
Rings	——	no	no	no	no	no	no	yes	yes	yes	yes	no	no	no	no
Satellites	billions!	0	0	1	no	2	0	63	60	27	13	3	0	2	1
Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun
Perihelion (10^6 km)	——	46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650
Aphelion (10^6 km)	——	69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600
Semimajor axis (AU)	——	0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7
Eccentricity	——	0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44
Inclination (°)	——	7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2
Orbital period (days)	——	88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600
Orbital period (years)	——	0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4
Orbital velocity (km.s^{-1})	——	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)	——	——	——	——	——	1801	——	——	——	1781	1846	1930	2005	2004	2003

Solar system fact-sheet

	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792.4	14,2984	120,536	51,118	49,528	2,390
Mass (10^{24} kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013
Density (kg.m^3)	5.41	5.19	5.51	3.35	3.93	1.33	0.69	1.27	1.64	1.86

Rocky Planets

Axial tilt (°)	——								26.7	97.8	28.3	119.6	?	?	?
Surface gravity (m.s^2)	274.0								9.0	8.7	11.2	0.6	~0.5	0.4	~0.8
Escape velocity (km.s^{-1})	617.7								35.5	21.3	23.5	1.2	~0.8	0.84	?
Surface area (10^6 km^2)	6,087								42,700	8,116	7,641	18	~7		21
Volume (10^{12}	1,412,200	0.06	0.9	1.1	0.02	0.16	0.0005	1431	827	68	63	0.007	~0.002		0.009
Density (kg.m^3)	1.41	5.41	5.19	5.51	3.35	3.93	1.89	1.33	0.69	1.27	1.64	1.86	~2	~3	~2
Albedo	——	0.11	0.65	0.37	0.12	0.15	0.09	0.52	0.47	0.51	0.41	0.58	?	0.6	0.86
Apparent magnitude (V)	–26.7	–1.9	–4.6	——	–12.9	–2.9	6.9	–2.9	–0.2	5.3	7.8	13.7	16.7	17.5	18.7
Angular diameter, max. (")	1,962.0	13.0	66.0	——	2,046	25.1	0.8	50.1	20.1	4.1	2.4	0.1	0.02	0.02	0.04
Rings	——	no	no	no	no	no	no	yes	yes	yes	yes	no	no	no	no
Satellites	billions!	0	0	1	no	2	0	63	60	27	13	3	0	2	1
Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun
Perihelion (10^6 km)	——	46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650
Aphelion (10^6 km)	——	69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600
Semimajor axis (AU)	——	0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7
Eccentricity	——	0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44
Inclination (°)	——	7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2
Orbital period (days)	——	88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600
Orbital period (years)	——	0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4
Orbital velocity (km.s^{-1})	——	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)	——	——	——	——	——	1801	——	——	——	1781	1846	1930	2005	2004	2003

Rocky Planets

Solar system fact-sheet

	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792.4	14,2984	120,536	51,118	49,528	2,390
Mass (10^{24} kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013
Density (kg.m^3)	5.41	5.19	5.51	3.35	3.93	1.33	0.69	1.27	1.64	1.86

Rocky Planets

Gas Giants

Axial tilt (°)	——												?	?	?
Surface gravity (m.s^2)	274.0												~0.5	0.4	~0.8
Escape velocity (km.s^{-1})	617.7												~0.8	0.84	?
Surface area (10^6 km^2)	6,087												~7		21
Volume (10^{12}	1,412,200	0.06	0.9	1.1	0.02	0.16	0.0005	1431	827	68	63	0.007	~0.002		0.009
Density (kg.m^3)	1.41	5.41	5.19	5.51	3.35	3.93	1.89	1.33	0.69	1.27	1.64	1.86	~2	~3	~2
Albedo	——	0.11	0.65	0.37	0.12	0.15	0.09	0.52	0.47	0.51	0.41	0.58	?	0.6	0.86
Apparent magnitude (V)	–26.7	–1.9	–4.6	——	–12.9	–2.9	6.9	–2.9	–0.2	5.3	7.8	13.7	16.7	17.5	18.7
Angular diameter, max. (°)	1,962.0	13.0	66.0	——	2,046	25.1	0.8	50.1	20.1	4.1	2.4	0.1	0.02	0.02	0.04
Rings	——	no	no	no	no	no	no	yes	yes	yes	yes	no	no	no	no
Satellites	billions!	0	0	1	no	2	0	63	60	27	13	3	0	2	1
Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun
Perihelion (10^6 km)	——	46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650
Aphelion (10^6 km)	——	69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600
Semimajor axis (AU)	——	0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7
Eccentricity	——	0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44
Inclination (°)	——	7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2
Orbital period (days)	——	88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600
Orbital period (years)	——	0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4
Orbital velocity (km.s^{-1})	——	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)	——	——	——	——	——	1801	——	——	——	1781	1846	1930	2005	2004	2003

Rocky Planets

Solar system fact-sheet

	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792.4	14,2984	120,536	51,118	49,528	2,390
Mass (10^{24} kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013
Density (kg.m^3)	5.41	5.19	5.51	3.35	3.93	1.33	0.69	1.27	1.64	1.86

Rocky Planets

Gas Giants

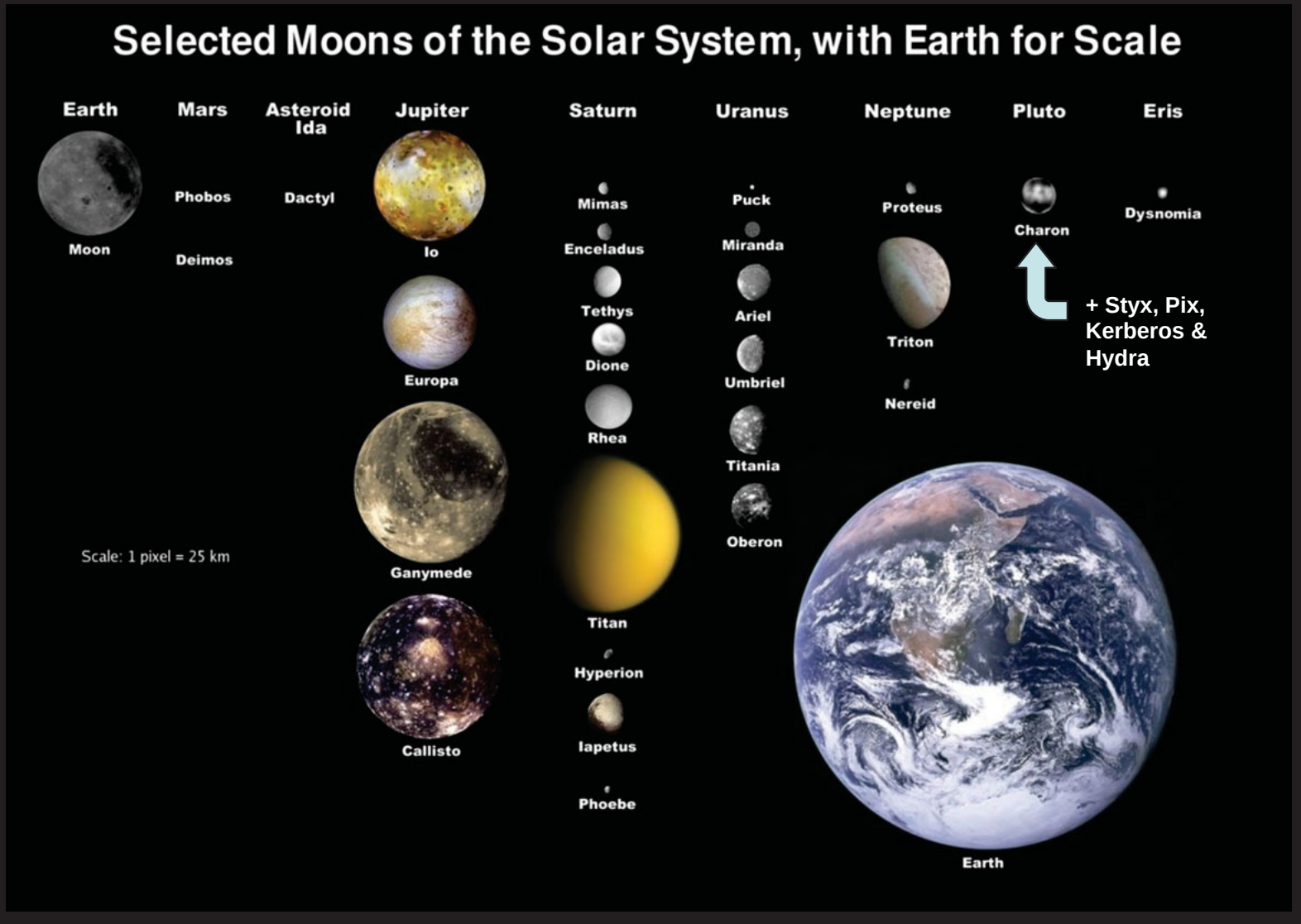
Ice Giants

Axial tilt (°)	——														
Surface gravity (m.s^2)	274.0														
Escape velocity (km.s^{-1})	617.7														
Surface area (10^6 km^2)	6,087														
Volume (10^{12}	1,412,200	0.06	0.9	1.1	0.02	0.16	0.0005	1431	827	68	63	0.007	~0.002		0.009
Density (kg.m^3)	1.41	5.41	5.19	5.51	3.35	3.93	1.89	1.33	0.69	1.27	1.64	1.86	~2	~3	~2
Albedo	——	0.11	0.65	0.37	0.12	0.15	0.09	0.52	0.47	0.51	0.41	0.58	?	0.6	0.86
Apparent magnitude (V)	–26.7	–1.9	–4.6	——	–12.9	–2.9	6.9	–2.9	–0.2	5.3	7.8	13.7	16.7	17.5	18.7
Angular diameter, max. (")	1,962.0	13.0	66.0	——	2,046	25.1	0.8	50.1	20.1	4.1	2.4	0.1	0.02	0.02	0.04
Rings	——	no	no	no	no	no	no	yes	yes	yes	yes	no	no	no	no
Satellites	billions!	0	0	1	no	2	0	63	60	27	13	3	0	2	1
Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun
Perihelion (10^6 km)	——	46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650
Aphelion (10^6 km)	——	69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600
Semimajor axis (AU)	——	0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7
Eccentricity	——	0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44
Inclination (°)	——	7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2
Orbital period (days)	——	88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600
Orbital period (years)	——	0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4
Orbital velocity (km.s^{-1})	——	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)	——	——	——	——	——	1801	——	——	——	1781	1846	1930	2005	2004	2003

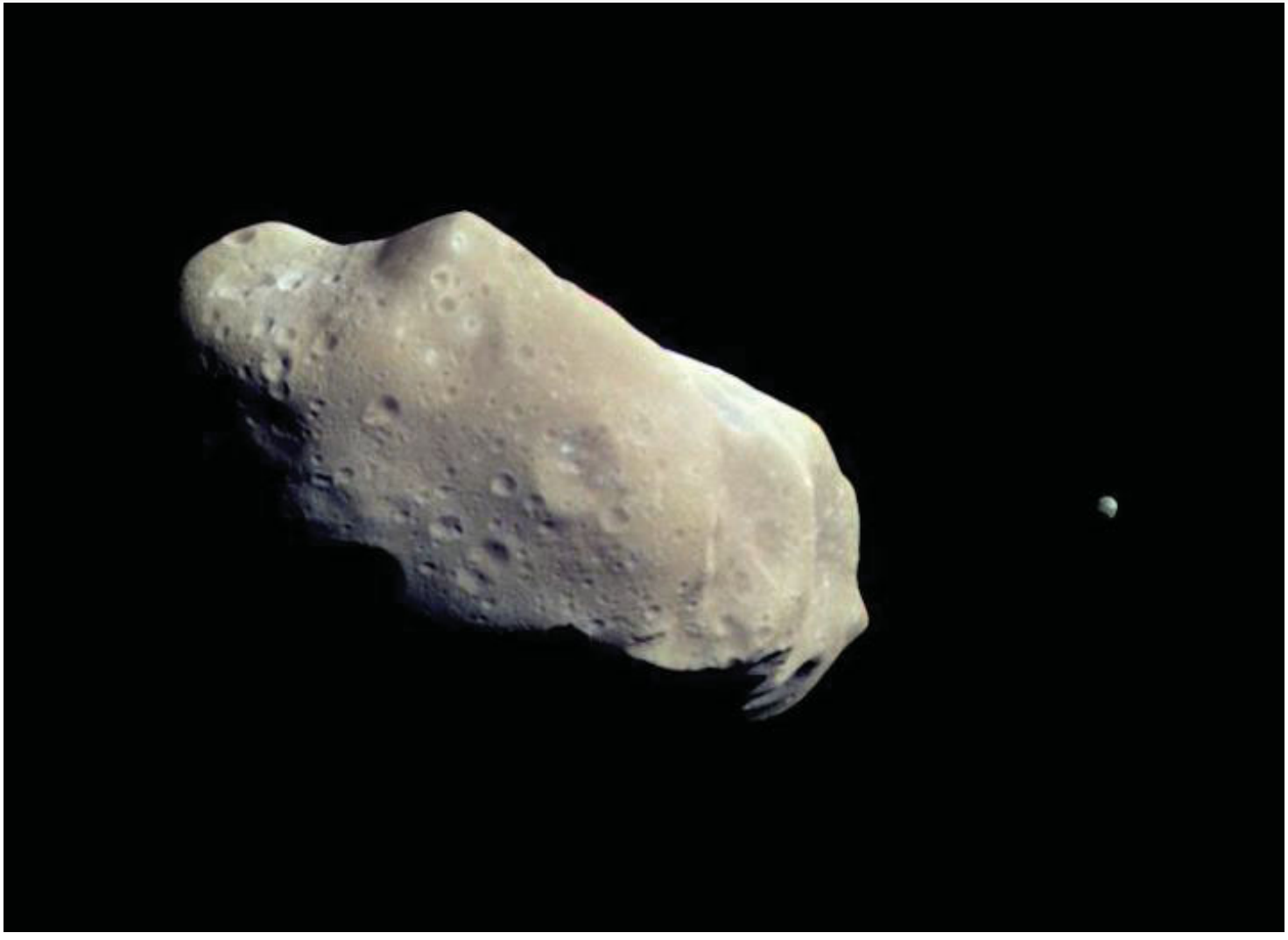
Rocky Planets

Solar system fact-sheet

	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792.4	14,2984	120,536	51,118	49,528	2,390
Mass (10^{24} kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013
Density (kg.m^3)	5.41	5.19	5.51	3.35	3.93	1.33	0.69	1.27	1.64	1.86
Satellites	0	0	1	no	2	63	60	27	13	X
Axial tilt (°)	——	0.04	177.3	23.4	6.7	25.2	3	3.1	26.7	97.8	28.3	119.6	?	?	?	5
Surface gravity (m.s^2)	274.0	3.7	8.9	9.8	1.6	3.7	0.3	24.8	9.0	8.7	11.2	0.6	~0.5	0.4	~0.8	
Escape velocity (km.s^{-1})	617.7	4.3	10.5	11.2	2.38	5.0	0.5	59.5	35.5	21.3	23.5	1.2	~0.8	0.84	?	
Surface area (10^6 km^2)	6,087,700	75	460	510	37.9	145	3	62,180	42,700	8,116	7,641	18	~7		21	
Volume (10^{12}	1,412,200	0.06	0.9	1.1	0.02	0.16	0.0005	1431	827	68	63	0.007	~0.002		0.009	
Density (kg.m^3)	1.41	5.41	5.19	5.51	3.35	3.93	1.89	1.33	0.69	1.27	1.64	1.86	~2	~3	~2	
Albedo	——	0.11	0.65	0.37	0.12	0.15	0.09	0.52	0.47	0.51	0.41	0.58	?	0.6	0.86	
Apparent magnitude (V)	–26.7	–1.9	–4.6	——	–12.9	–2.9	6.9	–2.9	–0.2	5.3	7.8	13.7	16.7	17.5	18.7	
Angular diameter, max. (")	1,962.0	13.0	66.0	——	2,046	25.1	0.8	50.1	20.1	4.1	2.4	0.1	0.02	0.02	0.04	
Rings	——	no	no	no	no	no	no	yes	yes	yes	yes	no	no	no	no	
Satellites	billions!	0	0	1	no	2	0	63	60	27	13	3	0	2	1	
Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	
Perihelion (10^6 km)	——	46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650	
Aphelion (10^6 km)	——	69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600	
Semimajor axis (AU)	——	0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7	
Eccentricity	——	0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44	
Inclination (°)	——	7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2	
Orbital period (days)	——	88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600	
Orbital period (years)	——	0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4	
Orbital velocity (km.s^{-1})	——	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4	
Discovery (year)	——	——	——	——	——	1801	——	——	——	1781	1846	1930	2005	2004	2003	


Selected Moons of the Solar System, with Earth for Scale
Earth
Mars
Asteroid Ida
Jupiter
Saturn
Uranus
Neptune
Pluto
Eris
Moon
Phobos
Deimos
Dactyl
Io
Europa
Ganymede
Callisto
Mimas
Enceladus
Tethys
Dione
Rhea
Titan
Hyperion
Iapetus
Phoebe
Puck
Miranda
Ariel
Umbriel
Titania
Oberon
Proteus
Triton
Nereid
Charon
Dysnomia
+ Styx, Pix, Kerberos & Hydra
Scale: 1 pixel = 25 km
Earth

Even Planeteismals Have Moons - 243 Ida and Moon Dactyl



Solar system fact-sheet

	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792.4	14,2984	120,536	51,118	49,528	2,390
Mass (10^{24} kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013
Density (kg.m^3)	5.41	5.19	5.51	3.35	3.93	1.33	0.69	1.27	1.64	1.86
Satellites	0	0	1	no	2	63	60	27	13	~~X~~ 5
Axial tilt (°)	——	0.04	177.3	23.4	6.7	25.2	3	3.1	26.7	97.8	28.3	119.6	?	?	?
Surface gravity (m.s^2)	274.0											0.6	~0.5	0.4	~0.8
Escape velocity (km.s^{-1})	617.7											1.2	~0.8	0.84	?
Surface area (10^6 km^2)	6,087,700										1	18	~7		21
Volume (10^{12}	1,412,200											0.007	~0.002		0.009
Density (kg.m^3)	1.41											1.86	~2	~3	~2
Albedo	——											0.58	?	0.6	0.86
Apparent magnitude (V)	–26.7											13.7	16.7	17.5	18.7
Angular diameter, max. (°)	1,962.0											0.1	0.02	0.02	0.04
Rings	——											no	no	no	no
Satellites	billions!	0	0	1	no	2	0	63	60	27	13	3	0	2	1
Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun
Perihelion (10^6 km)	——	46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650
Aphelion (10^6 km)	——	69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600
Semimajor axis (AU)	——	0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7
Eccentricity	——	0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44
Inclination (°)	——	7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2
Orbital period (days)	——	88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600
Orbital period (years)	——	0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4
Orbital velocity (km.s^{-1})	——	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)	——	——	——	——	——	1801	——	——	——	1781	1846	1930	2005	2004	2003

Big planets have lots of satellites.
Small planets do not.

Solar system fact-sheet

	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792.4	14,2984	120,536	51,118	49,528	2,390
Mass (10^{24} kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013
Density (kg.m^3)	5.41	5.19	5.51	3.35	3.93	1.33	0.69	1.27	1.64	1.86
Satellites	0	0	1	no	2	63	60	27	13	3
Rotation period (days)	58.6	–243.0	1.0	27.3	1.0	0.4	0.4	–0.7	0.7	–6.4
Axial tilt (°)	0.04	177.3	23.4	6.7	25.2	3.1	26.7	97.8	28.3	119.6

Density (kg.m^3)	1.41	5.41	5.19	5.51	3.35	3.93	1.89	1.33	0.69	1.27	1.64	1.86	~2	~3	~2
Albedo	——	0.11	0.65	0.37	0.12	0.15	0.09	0.52	0.47	0.51	0.41	0.58	?	0.6	0.86
Apparent magnitude (V)	–26.7	–1.9	–4.6	——	–12.9	–2.9	6.9	–2.9	–0.2	5.3	7.8	13.7	16.7	17.5	18.7
Angular diameter, max. (")	1,962.0	13.0	66.0	——	2,046	25.1	0.8	50.1	20.1	4.1	2.4	0.1	0.02	0.02	0.04
Rings	——	no	no	no	no	no	no	yes	yes	yes	yes	no	no	no	no
Satellites	billions!	0	0	1	no	2	0	63	60	27	13	3	0	2	1
Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun
Perihelion (10^6 km)	——	46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650
Aphelion (10^6 km)	——	69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600
Semimajor axis (AU)	——	0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7
Eccentricity	——	0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44
Inclination (°)	——	7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2
Orbital period (days)	——	88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600
Orbital period (years)	——	0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4
Orbital velocity (km.s^{-1})	——	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)	——	——	——	——	——	1801	——	——	——	1781	1846	1930	2005	2004	2003

Solar system fact-sheet

	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792.4	14,2984	120,536	51,118	49,528	2,390
Mass (10^{24} kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013
Density (kg.m^3)	5.41	5.19	5.51	3.35	3.93	1.33	0.69	1.27	1.64	1.86
Satellites	0	0	1	no	2	63	60	27	13	3
Rotation period (days)	58.6	–243.0	1.0	27.3	1.0	0.4	0.4	–0.7	0.7	–6.4
Axial tilt (°)	0.04	177.3	23.4	6.7	25.2	3.1	26.7	97.8	28.3	119.6

Virtually every spin configuration is present – prograde, retorgrade, angular momentum parallel and perpendicular to orbital plane …..

Semimajor axis (AU)	—	0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7
Eccentricity	—	0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44
Inclination (°)	—	7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2
Orbital period (days)	—	88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600
Orbital period (years)	—	0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4
Orbital velocity (km.s^{-1})	—	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)	—	—	—	—	—	1801	—	—	—	1781	1846	1930	2005	2004	2003

Solar system fact-sheet

	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792.4	14,2984	120,536	51,118	49,528	2,390
Mass (10^{24} kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013
Density (kg.m^3)	5.41	5.19	5.51	3.35	3.93	1.33	0.69	1.27	1.64	1.86
Satellites	0	0	1	no	2	63	60	27	13	3
Rotation period (days)	58.6	–243.0	1.0	27.3	1.0	0.4	0.4	–0.7	0.7	–6.4
Axial tilt (°)	0.04	177.3	23.4	6.7	25.2	3.1	26.7	97.8	28.3	119.6
Semimajor axis (AU)	0.4	0.7	1.0	0.003	1.5	5.2	9.6	19.2	30.1	39.5

Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun
Perihelion (10^6 km)	—	46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650
Aphelion (10^6 km)	—	69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600
Semimajor axis (AU)	—	0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7
Eccentricity	—	0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44
Inclination (°)	—	7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2
Orbital period (days)	—	88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600
Orbital period (years)	—	0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4
Orbital velocity (km.s^{-1})	—	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)	—	—	—	—	—	1801	—	—	—	1781	1846	1930	2005	2004	2003

Solar system fact-sheet

	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792.4	14,2984	120,536	51,118	49,528	2,390
Mass (10^{24} kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013
Density (kg.m^3)	5.41	5.19	5.51	3.35	3.93	1.33	0.69	1.27	1.64	1.86
Satellites	0	0	1	no	2	63	60	27	13	3
Rotation period (days)	58.6	–243.0	1.0	27.3	1.0	0.4	0.4	–0.7	0.7	–6.4
Axial tilt (°)	0.04	177.3	23.4	6.7	25.2	3.1	26.7	97.8	28.3	119.6
Semimajor axis (AU)	0.4	0.7	1.0	0.003	1.5	5.2	9.6	19.2	30.1	39.5

- Rocky planets are all inside ~1.5 AU.
- Gas giants @ ~5 AU or greater?
- Gas giants must form beyond the “Ice/ Snow Line” where water, ammonia, methane, CO2, &c. freeze out

Orbits the:														Sun	Sun
Perihelion (10^6 km														5,260	5,650
Aphelion (10^6 km)														7,708	14,600
Semimajor axis (A														43.3	67.7
Eccentricity														0.19	0.44
Inclination (°)														28.2	44.2
Orbital period (day														104,234	203,600
Orbital period (yea														285.4	557.4
Orbital velocity (kn														4.5	3.4
Discovery (year)	—	—	—	—	—	1801	—	—	—	1781	1846	1930	2005	2004	2003

Solar system fact-sheet

	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792.4	14,2984	120,536	51,118	49,528	2,390
Mass (10^{24} kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013
Density (kg.m^3)	5.41	5.19	5.51	3.35	3.93	1.33	0.69	1.27	1.64	1.86
Satellites	0	0	1	no	2	63	60	27	13	3
Rotation period (days)	58.6	–243.0	1.0	27.3	1.0	0.4	0.4	–0.7	0.7	–6.4
Axial tilt (°)	0.04	177.3	23.4	6.7	25.2	3.1	26.7	97.8	28.3	119.6
Semimajor axis (AU)	0.4	0.7	1.0	0.003	1.5	5.2	9.6	19.2	30.1	39.5
Orbital period (days)	88.0	224.7	365.3	27.3	687.0	4,331.6	10,832.3	30,799	60,190	90,613

Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun
Perihelion (10^6 km)	——	46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650
Aphelion (10^6 km)	——	69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600
Semimajor axis (AU)	——	0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7
Eccentricity	——	0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44
Inclination (°)	——	7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2
Orbital period (days)	——	88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600
Orbital period (years)	——	0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4
Orbital velocity (km.s^{-1})	——	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)	——	——	——	——	——	1801	——	——	——	1781	1846	1930	2005	2004	2003

Solar system fact-sheet

	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792.4	14,2984	120,536	51,118	49,528	2,390
Mass (10^{24} kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013
Density (kg.m^3)	5.41	5.19	5.51	3.35	3.93	1.33	0.69	1.27	1.64	1.86
Satellites	0	0	1	no	2	63	60	27	13	3
Rotation period (days)	58.6	–243.0	1.0	27.3	1.0	0.4	0.4	–0.7	0.7	–6.4
Axial tilt (°)	0.04	177.3	23.4	6.7	25.2	3.1	26.7	97.8	28.3	119.6
Semimajor axis (AU)	0.4	0.7	1.0	0.003	1.5	5.2	9.6	19.2	30.1	39.5
Orbital period (days)	88.0	224.7	365.3	27.3	687.0	4,331.6	10,832.3	30,799	60,190	90,613

$$\frac{P^2}{a^3} = \frac{4\pi^2}{G(M+m)} \approx \frac{4\pi^2}{GM} = \text{constant}$$

Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun
Perihelion (10^6 km)	—	46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650
Aphelion (10^6 km)	—	69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600
Semimajor axis (AU)	—	0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7
Eccentricity	—	0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44
Inclination (°)	—	7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2
Orbital period (days)	—	88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600
Orbital period (years)	—	0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4
Orbital velocity (km.s^{-1})	—	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)	—	—	—	—	—	1801	—	—	—	1781	1846	1930	2005	2004	2003

Solar system fact-sheet

	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792.4	14,2984	120,536	51,118	49,528	2,390
Mass (10^{24} kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013
Density (kg.m^3)	5.41	5.19	5.51	3.35	3.93	1.33	0.69	1.27	1.64	1.86
Satellites	0	0	1	no	2	63	60	27	13	3
Rotation period (days)	58.6	–243.0	1.0	27.3	1.0	0.4	0.4	–0.7	0.7	–6.4
Axial tilt (°)	0.04	177.3	23.4	6.7	25.2	3.1	26.7	97.8	28.3	119.6
Semimajor axis (AU)	0.4	0.7	1.0	0.003	1.5	5.2	9.6	19.2	30.1	39.5
Orbital period (days)	88.0	224.7	365.3	27.3	687.0	4,331.6	10,832.3	30,799	60,190	90,613
Eccentricity	0.21	0.01	0.02	0.06	0.09	0.05	0.06	0.05	0.01	0.25

Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun
Perihelion (10^6 km)	—	46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650
Aphelion (10^6 km)	—	69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600
Semimajor axis (AU)	—	0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7
Eccentricity	—	0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44
Inclination (°)	—	7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2
Orbital period (days)	—	88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600
Orbital period (years)	—	0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4
Orbital velocity (km.s^{-1})	—	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)	—	—	—	—	—	1801	—	—	—	1781	1846	1930	2005	2004	2003

Solar system fact-sheet

	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792.4	14,2984	120,536	51,118	49,528	2,390
Mass (10^{24} kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013
Density (kg.m^3)	5.41	5.19	5.51	3.35	3.93	1.33	0.69	1.27	1.64	1.86
Satellites	0	0	1	no	2	63	60	27	13	3
Rotation period (days)	58.6	–243.0	1.0	27.3	1.0	0.4	0.4	–0.7	0.7	–6.4
Axial tilt (°)	0.04	177.3	23.4	6.7	25.2	3.1	26.7	97.8	28.3	119.6
Semimajor axis (AU)	0.4	0.7	1.0	0.003	1.5	5.2	9.6	19.2	30.1	39.5
Orbital period (days)	88.0	224.7	365.3	27.3	687.0	4,331.6	10,832.3	30,799	60,190	90,613
Eccentricity	0.21	0.01	0.02	0.06	0.09	0.05	0.06	0.05	0.01	0.25

Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun
Perihelion (10^6 km)	—	46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650
Aphelion (10^6 km)	—	69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600
Semimajor axis (AU)	—	0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7
Eccentricity	—	0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44
Inclination (°)	—	7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2
Orbital period (days)	—	88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600
Orbital period (years)	—	0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4
Orbital velocity (km.s^{-1})	—	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)	—	—	—	—	—	1801	—	—	—	1781	1846	1930	2005	2004	2003

Solar system fact-sheet

	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792.4	14,2984	120,536	51,118	49,528	2,390
Mass (10^{24} kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013
Density (kg.m^3)	5.41	5.19	5.51	3.35	3.93	1.33	0.69	1.27	1.64	1.86
Satellites	0	0	1	no	2	63	60	27	13	3
Rotation period (days)	58.6	–243.0	1.0	27.3	1.0	0.4	0.4	–0.7	0.7	–6.4
Axial tilt (°)	0.04	177.3	23.4	6.7	25.2	3.1	26.7	97.8	28.3	119.6
Semimajor axis (AU)	0.4	0.7	1.0	0.003	1.5	5.2	9.6	19.2	30.1	39.5
Orbital period (days)	88.0	224.7	365.3	27.3	687.0	4,331.6	10,832.3	30,799	60,190	90,613
Eccentricity	0.21	0.01	0.02	0.06	0.09	0.05	0.06	0.05	0.01	0.25
Inclination (°)	7.0	3.4	0	5.1	1.9	1.3	2.5	0.8	1.8	17.1

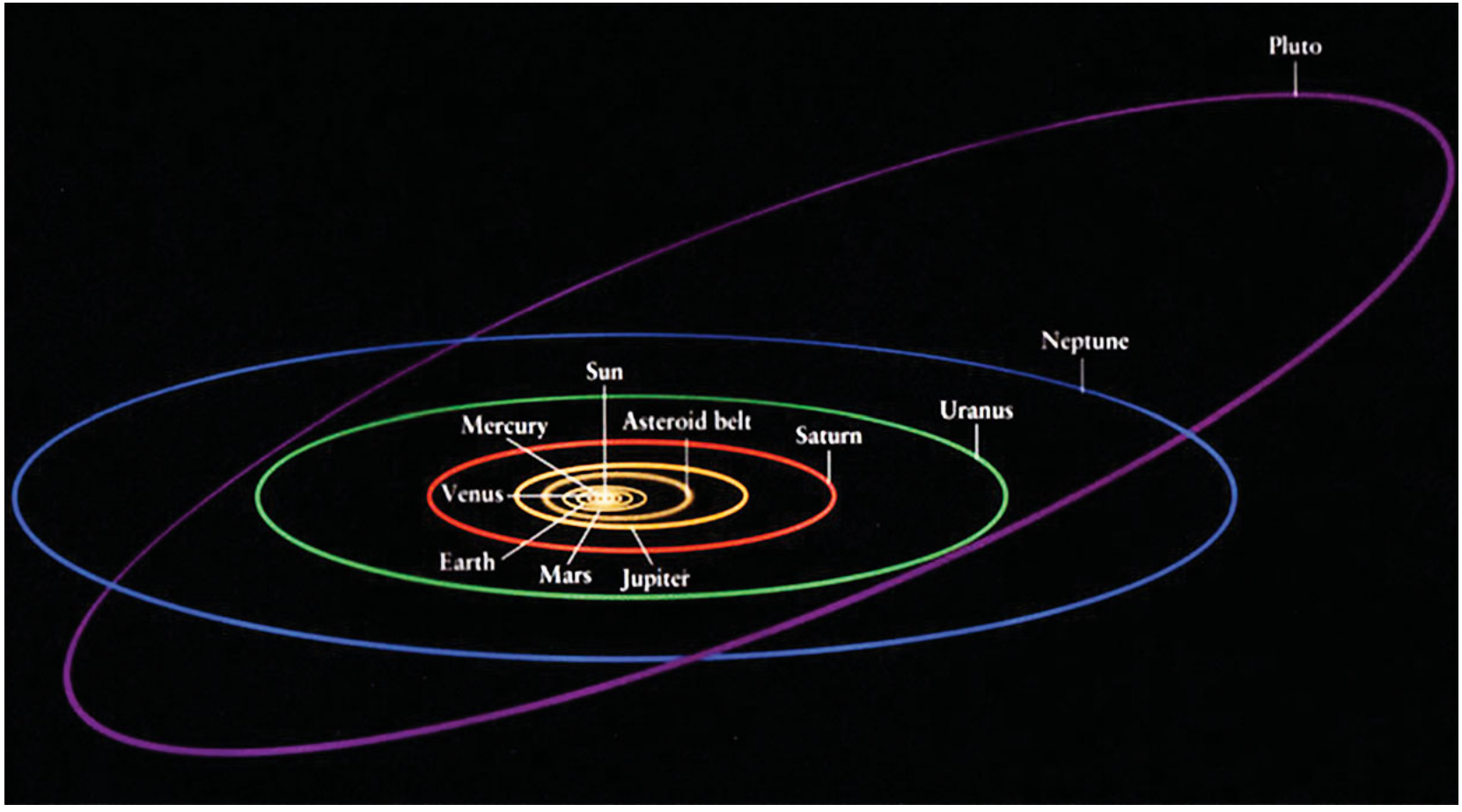
Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun
Perihelion (10^6 km)	—	46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650
Aphelion (10^6 km)	—	69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600
Semimajor axis (AU)	—	0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7
Eccentricity	—	0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44
Inclination (°)	—	7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2
Orbital period (days)	—	88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600
Orbital period (years)	—	0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4
Orbital velocity (km.s^{-1})	—	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)	—	—	—	—	—	1801	—	—	—	1781	1846	1930	2005	2004	2003

Solar system fact-sheet

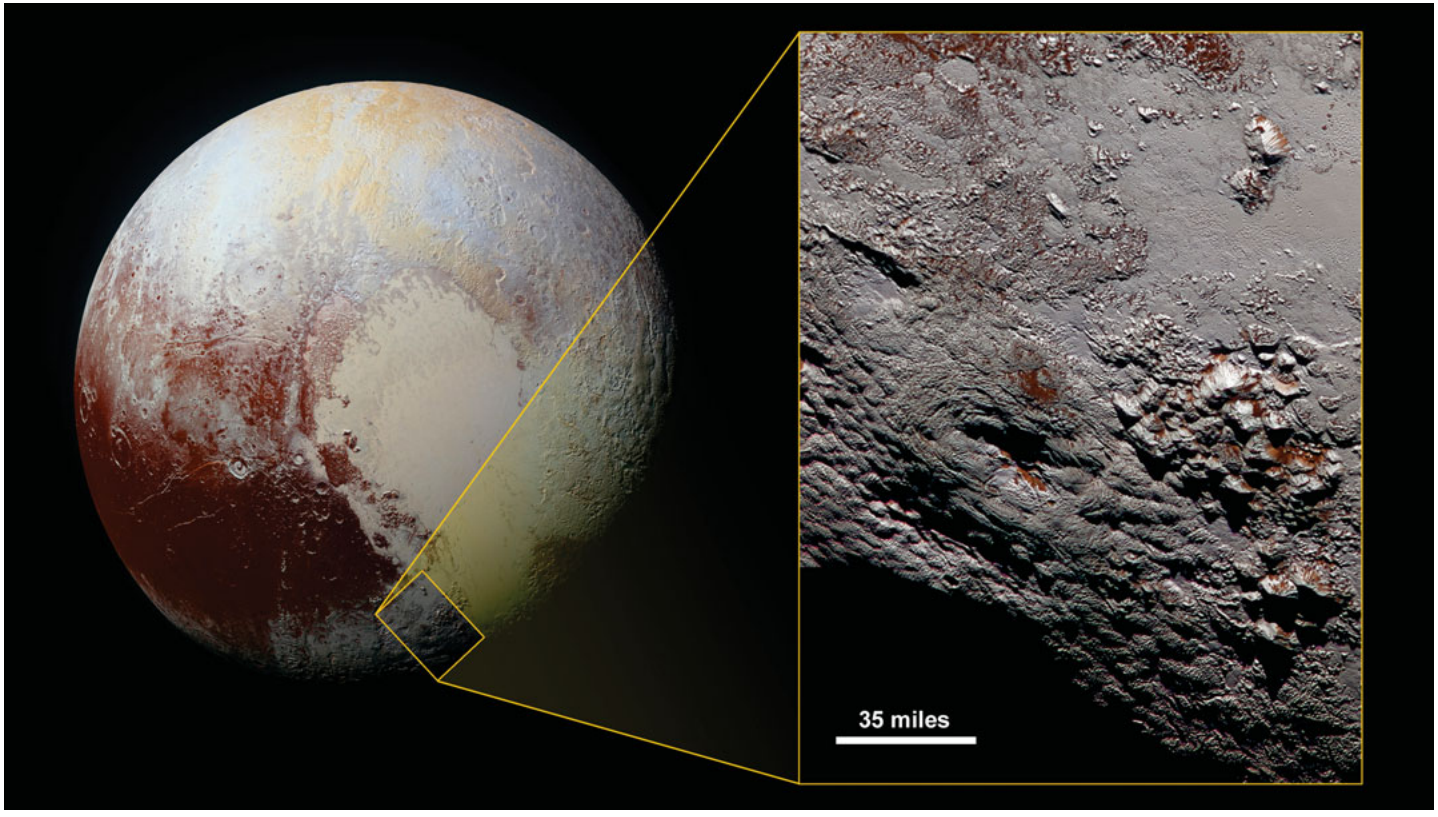
	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792.4	14,2984	120,536	51,118	49,528	2,390
Mass (10^{24} kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013
Density (kg.m^3)	5.41	5.19	5.51	3.35	3.93	1.33	0.69	1.27	1.64	1.86
Satellites	0	0	1	no	2	63	60	27	13	3
Rotation period (days)	58.6	–243.0	1.0	27.3	1.0	0.4	0.4	–0.7	0.7	–6.4
Axial tilt (°)	0.04	177.3	23.4	6.7	25.2	3.1	26.7	97.8	28.3	119.6
Semimajor axis (AU)	0.4	0.7	1.0	0.003	1.5	5.2	9.6	19.2	30.1	39.5
Orbital period (days)	88.0	224.7	365.3	27.3	687.0	4,331.6	10,832.3	30,799	60,190	90,613
Eccentricity	0.21	0.01	0.02	0.06	0.09	0.05	0.06	0.05	0.01	0.25
Inclination (°)	7.0	3.4	0	5.1	1.9	1.3	2.5	0.8	1.8	17.1

Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun
Perihelion (10^6 km)	—	46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650
Aphelion (10^6 km)	—	69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600
Semimajor axis (AU)	—	0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7
Eccentricity	—	0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44
Inclination (°)	—	7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2
Orbital period (days)	—	88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600
Orbital period (years)	—	0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4
Orbital velocity (km.s^{-1})	—	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)	—	—	—	—	—	1801	—	—	—	1781	1846	1930	2005	2004	2003

Pluto is “different”

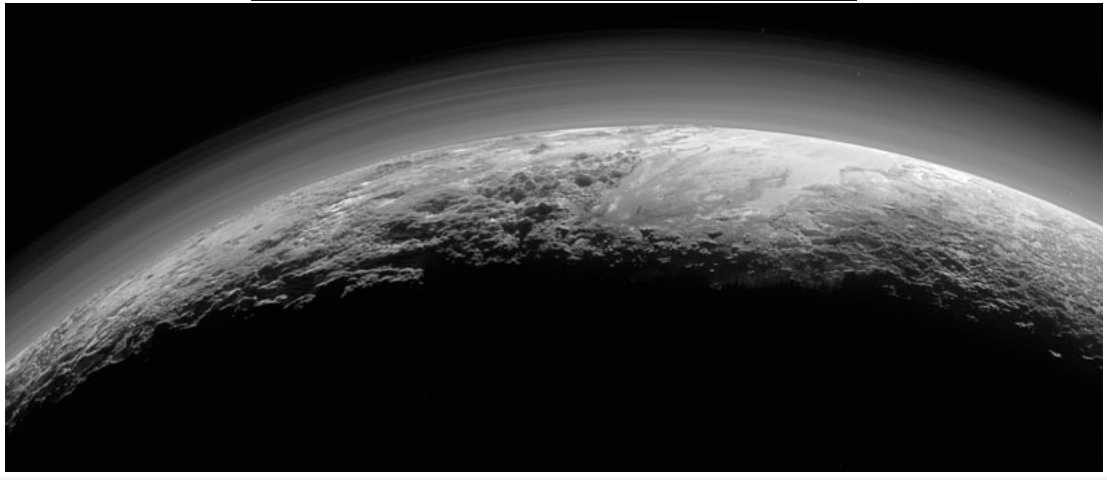


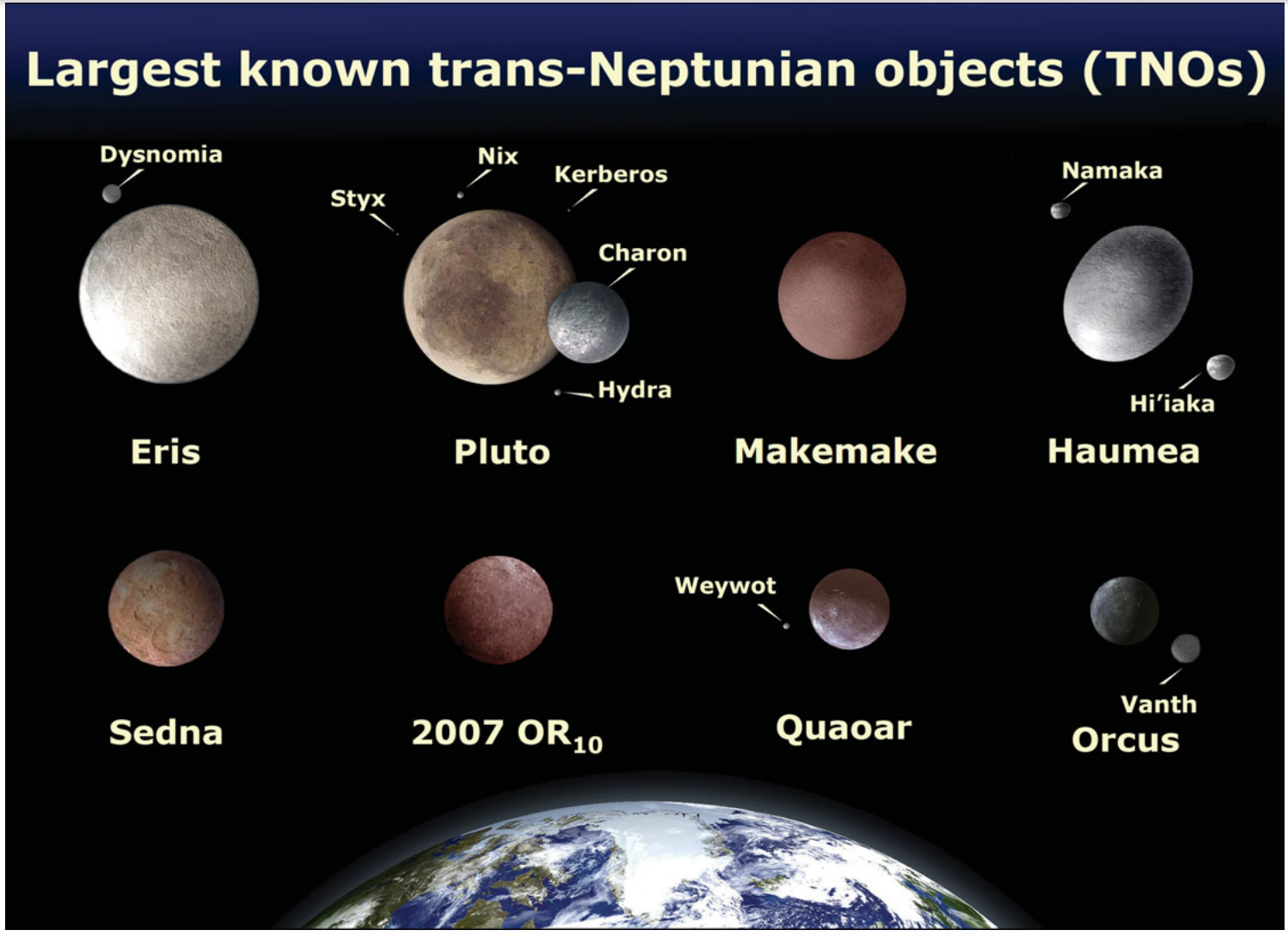
Pluto is Demoted

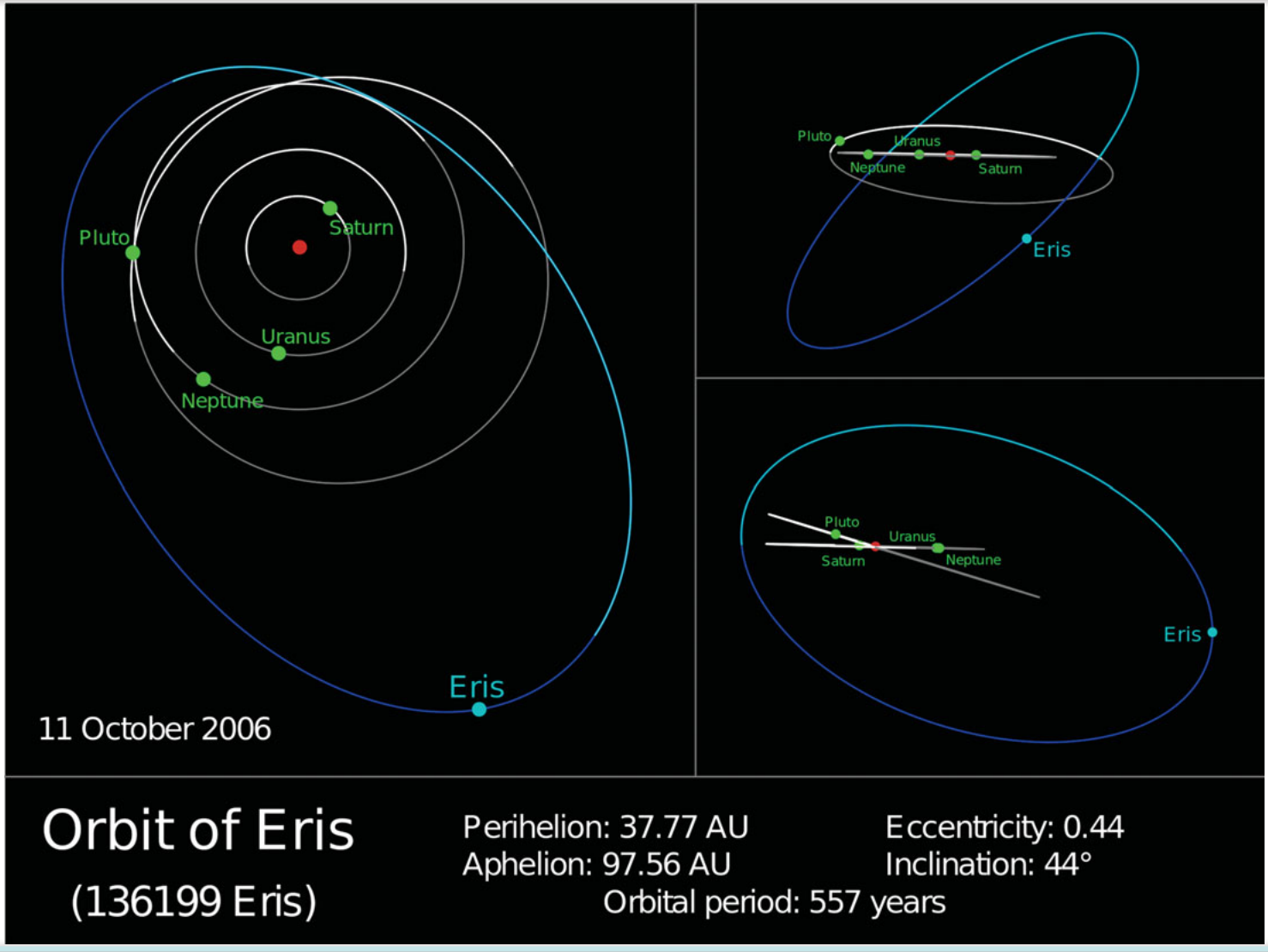


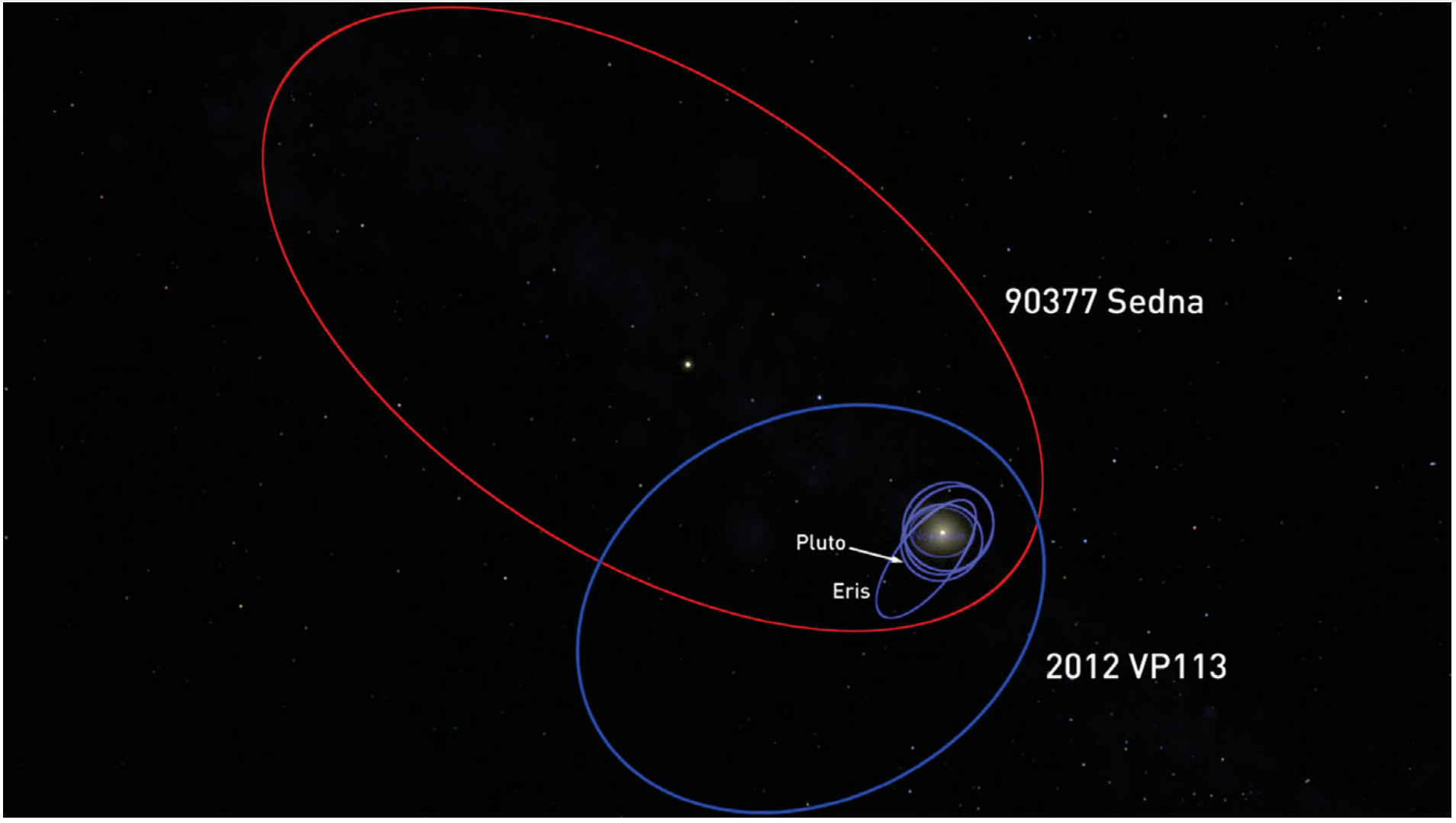
- Eris discovery in 2005 – 27% more massive than Pluto
- 2006 – IAU definition of a planet excludes Pluto, now a minor planet
- New Horizons (2016) probe imagery shows rich, complex topography

New Horizons Shows Pluto Also Has An Atmosphere

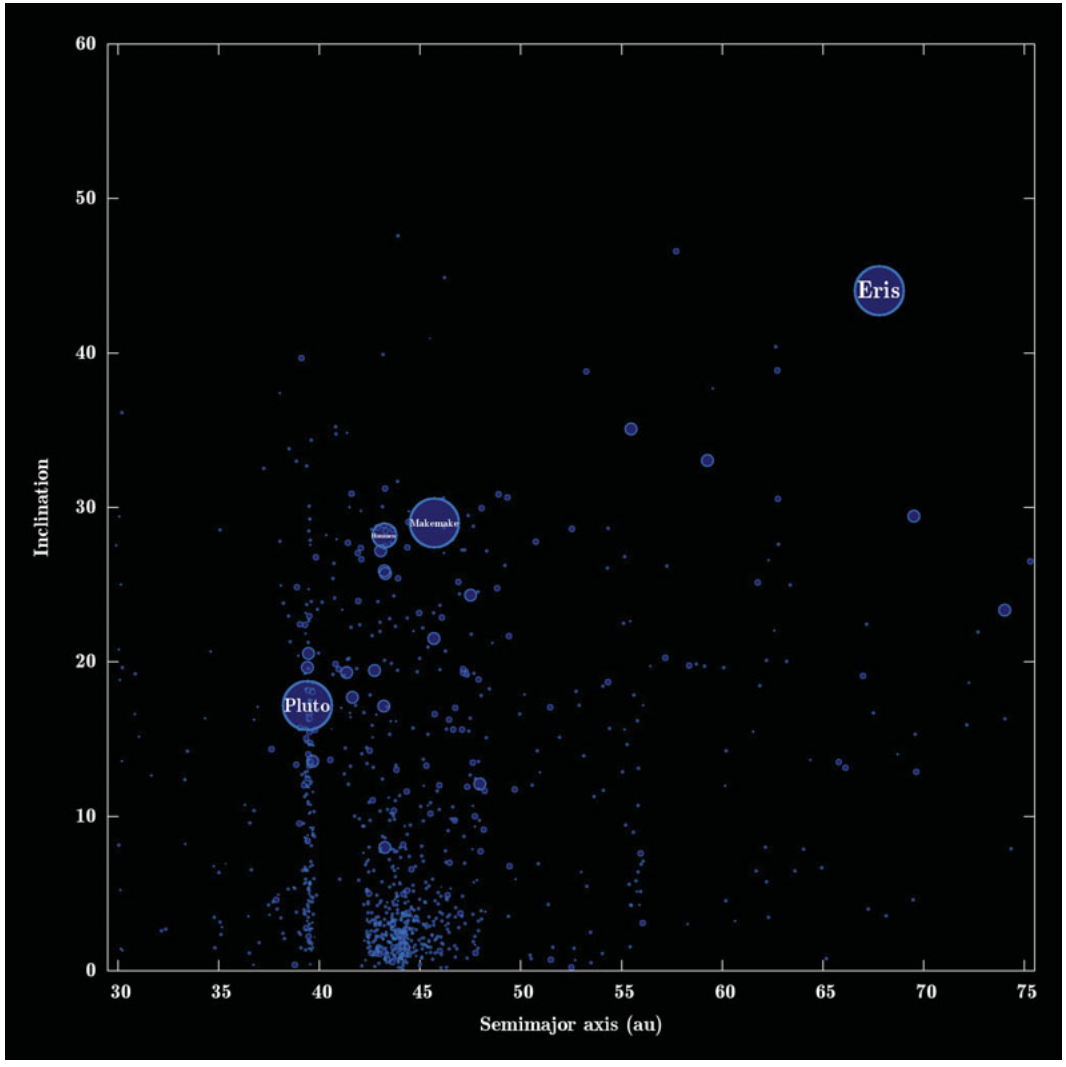



Largest known trans-Neptunian objects (TNOs)
Dysnomia
Eris
Nix
Kerberos
Styx
Charon
Hydra
Pluto
Makemake
Namaka
Hi'iaka
Haumea
Sedna
2007 OR10
Weywot
Quaoar
Vanth
Orcus

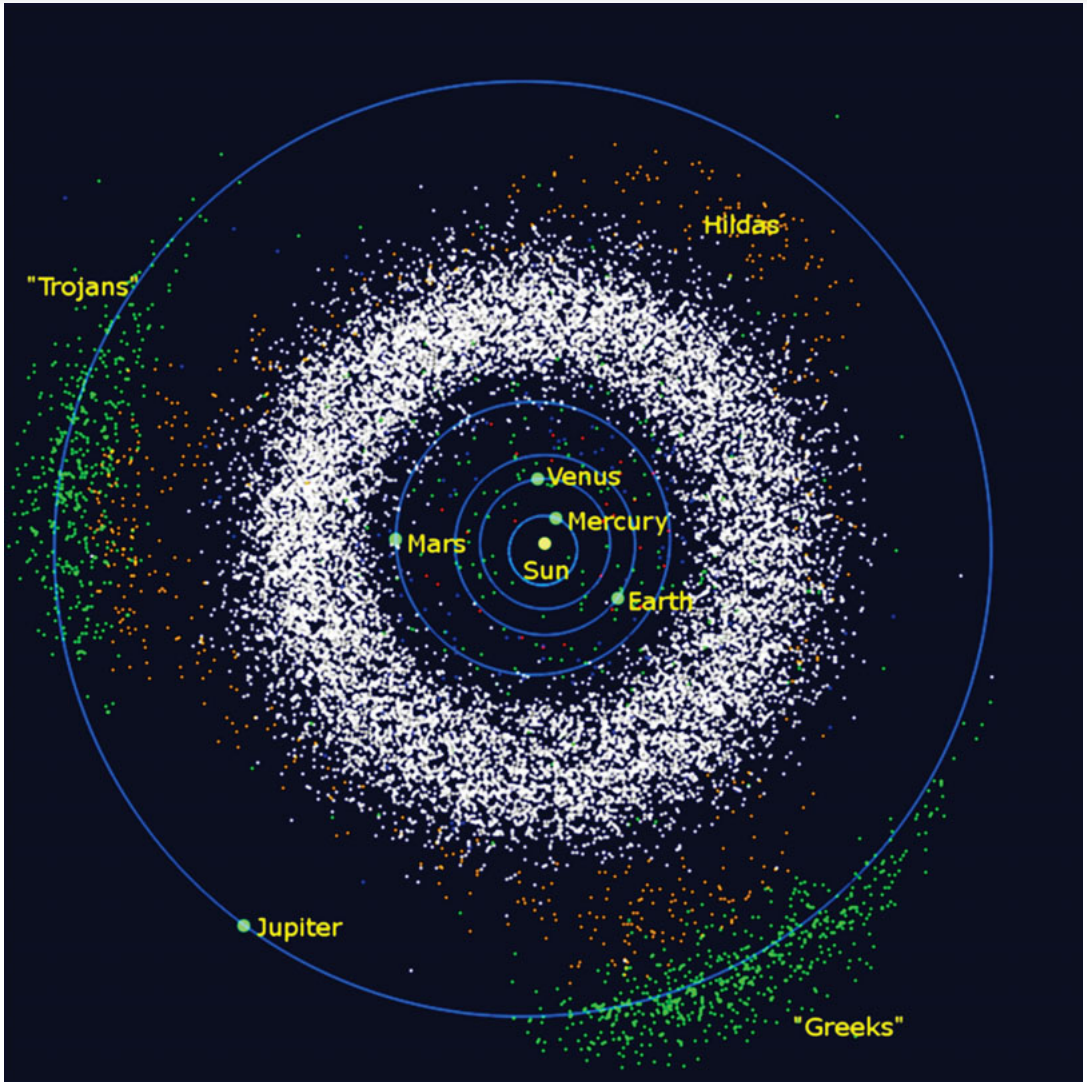

Pluto
Saturn
Uranus
Neptune
Eris
11 October 2006
Pluto
Uranus
Neptune
Saturn
Eris
Pluto
Uranus
Saturn
Neptune
Eris
Orbit of Eris
(136199 Eris)
Perihelion: 37.77 AU
Aphelion: 97.56 AU
Eccentricity: 0.44
Inclination: 44°
Orbital period: 557 years


90377 Sedna
Pluto
Eris
2012 VP113

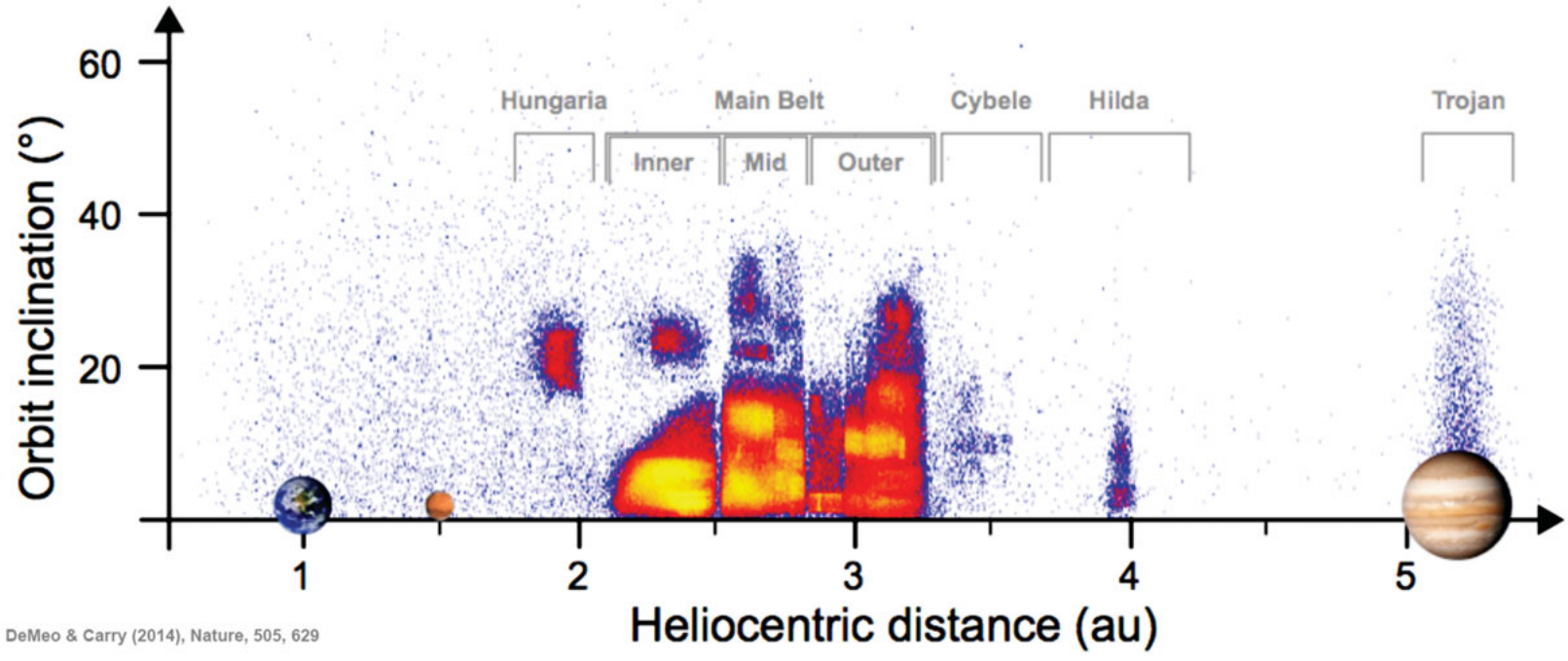
TNOs Have A Wide Range of Eccentricities& Incliantions



Asteroid “Live” Between Jupiter and Mars

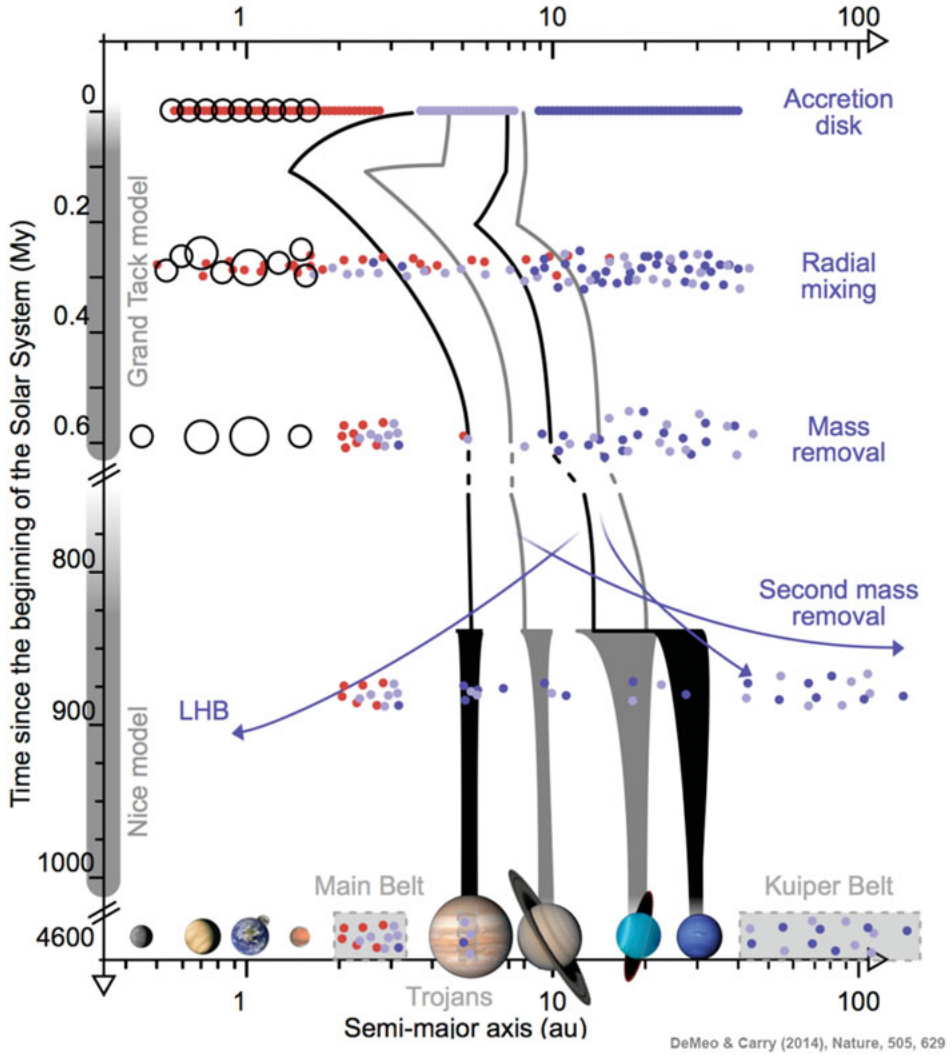


Asteroid Belt Taxonomy

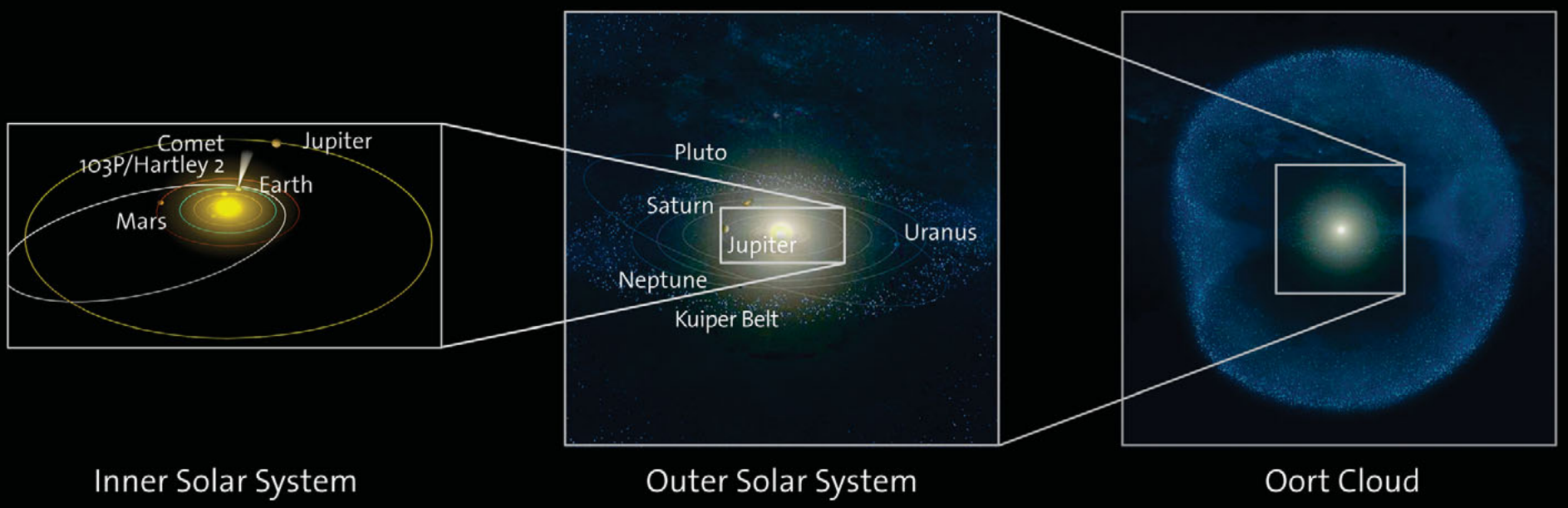


DeMeo & Carry (2014), Nature, 505, 629

A Migration History of the Solar System

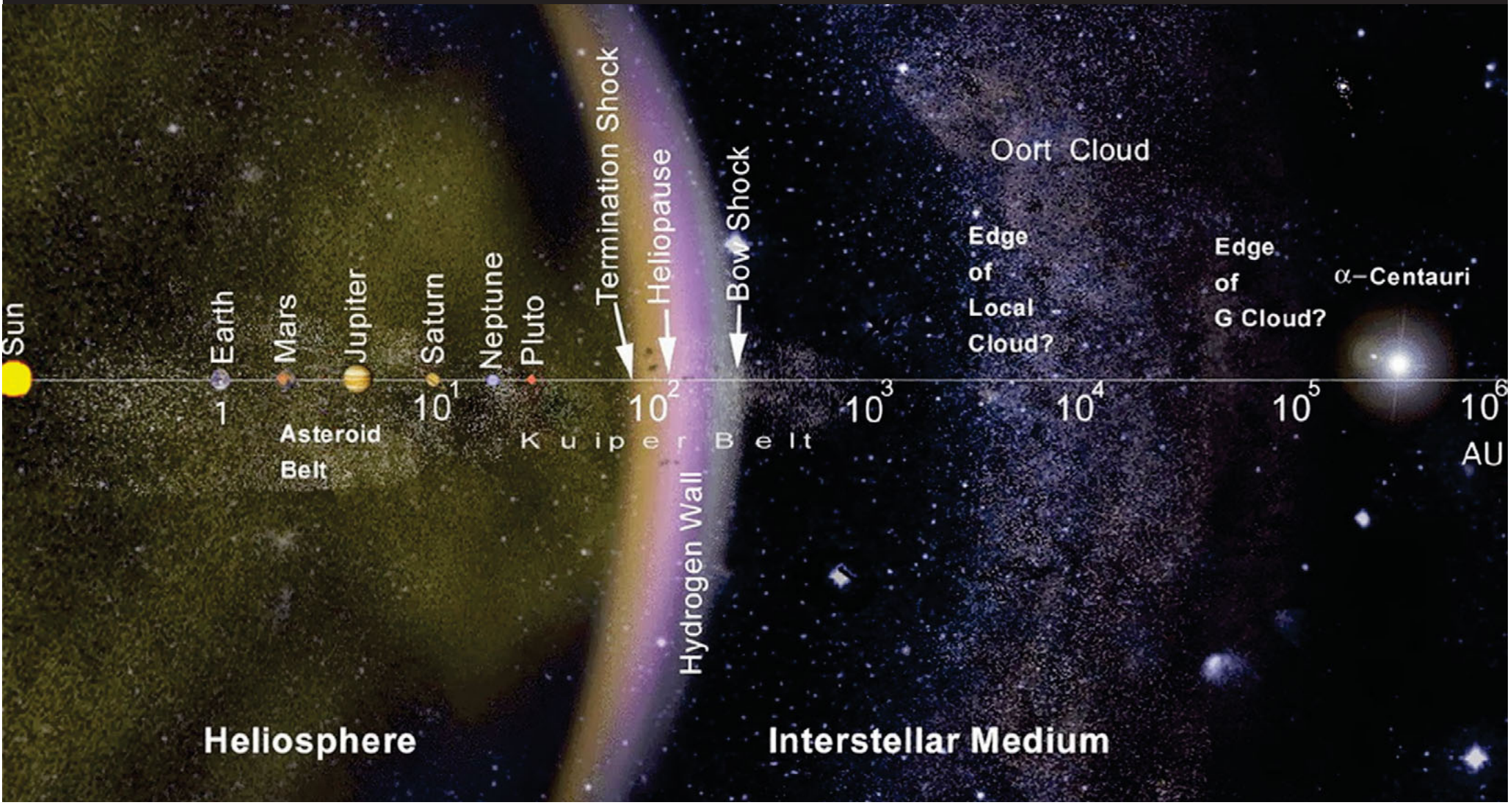


The Oort Cloud is an Unseen Swarm of Comets

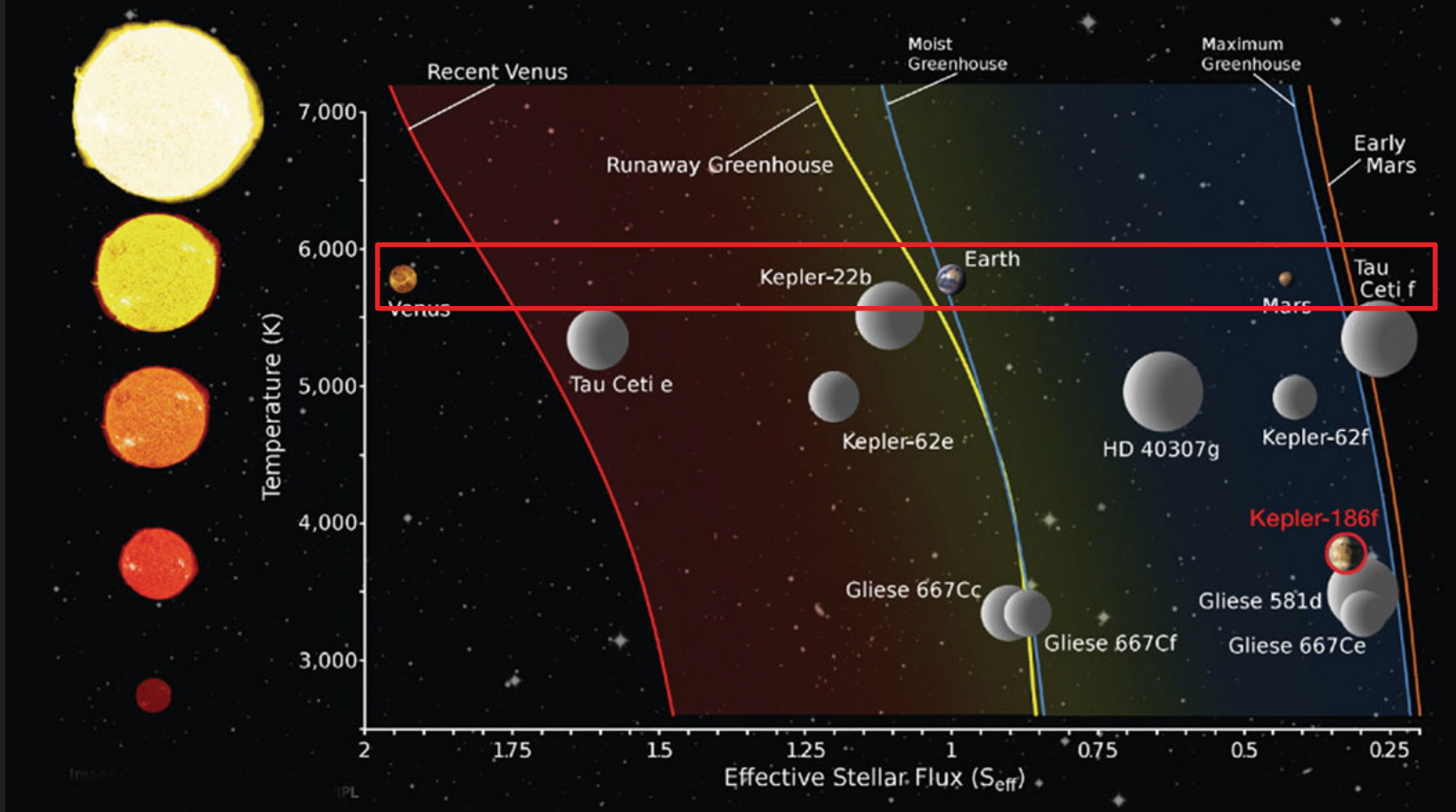


Comets supplies water to Earth during “Grand Tack” in the “Grand Tack” model

The Space Between the Stars



The Habitable Zone



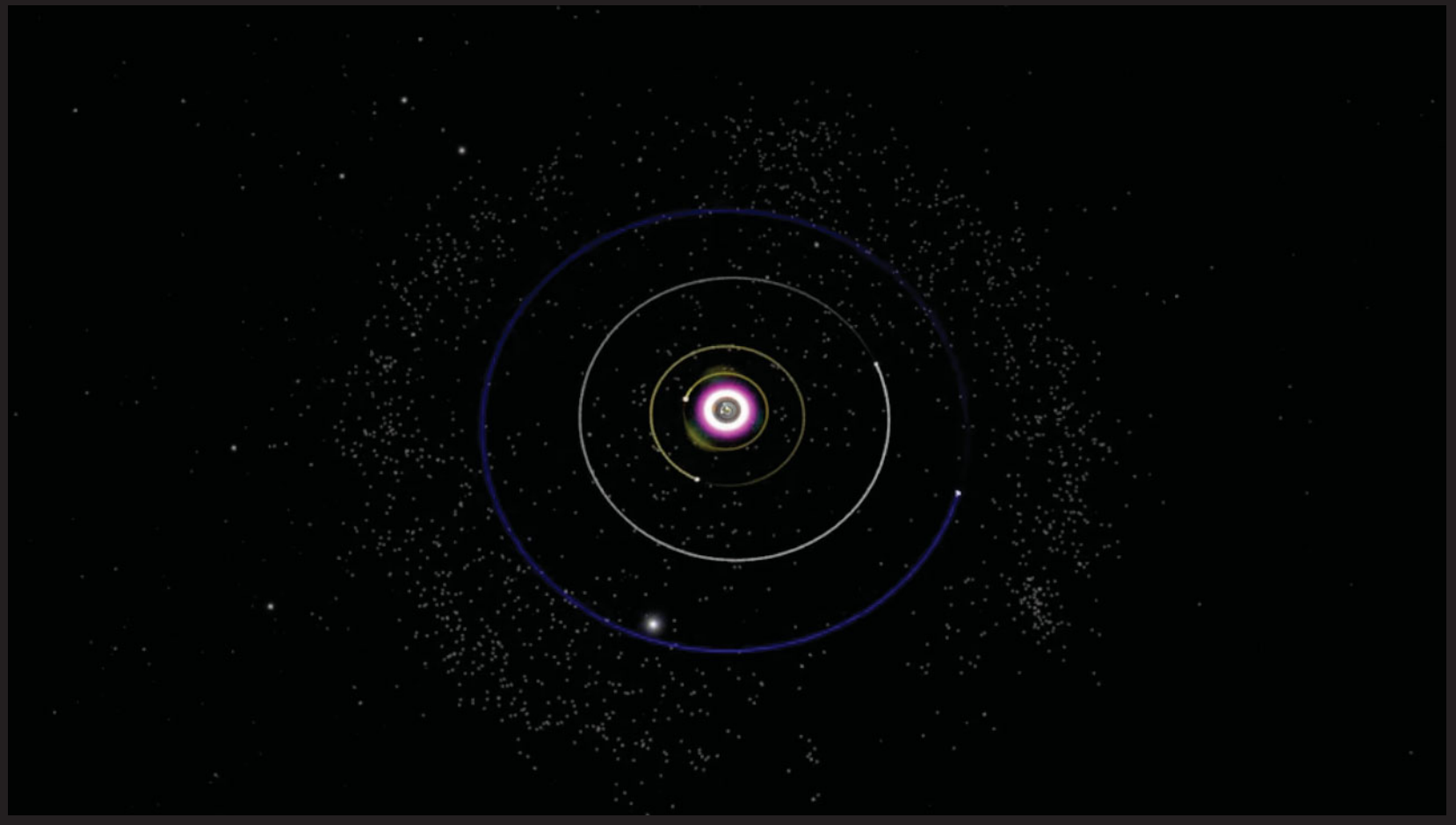
Exoplanet Science Today, in a Little More Detail

Pluto Kicked Our of Planet Club

- 2006 – IAU definition of a planet excludes Pluto, now a minor planet

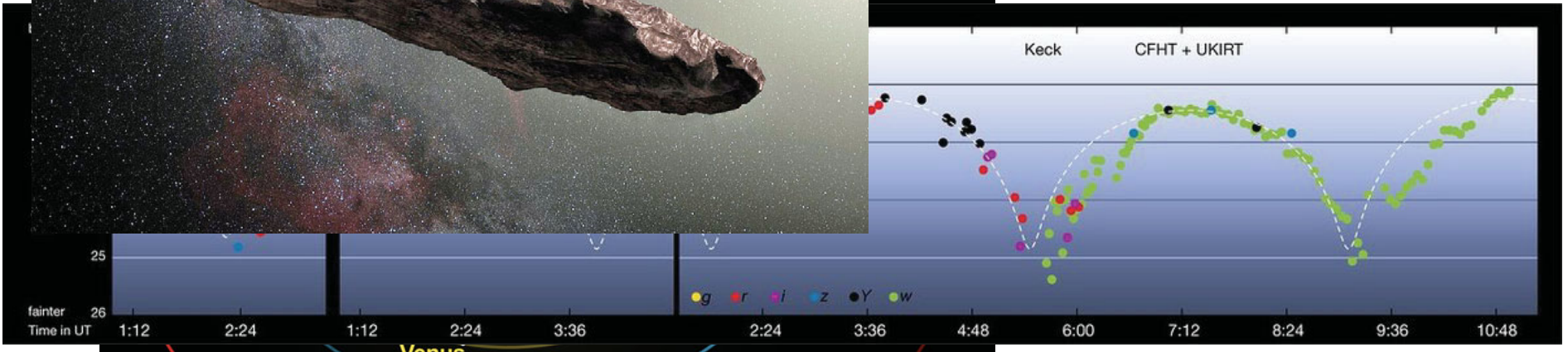
But is there another Planet 9?

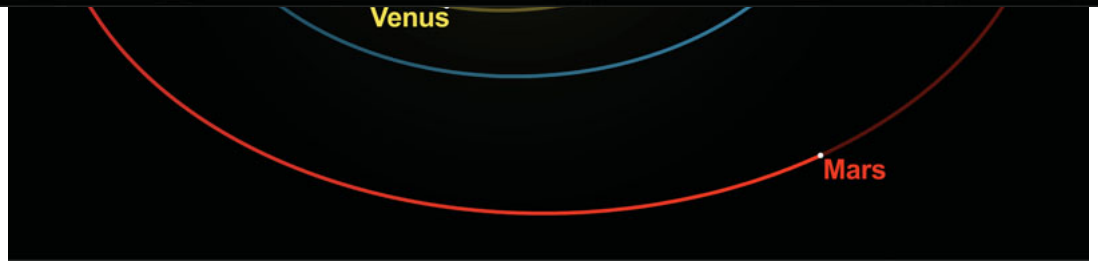
Caption



A Least One Solar System Object is a “Visitor”

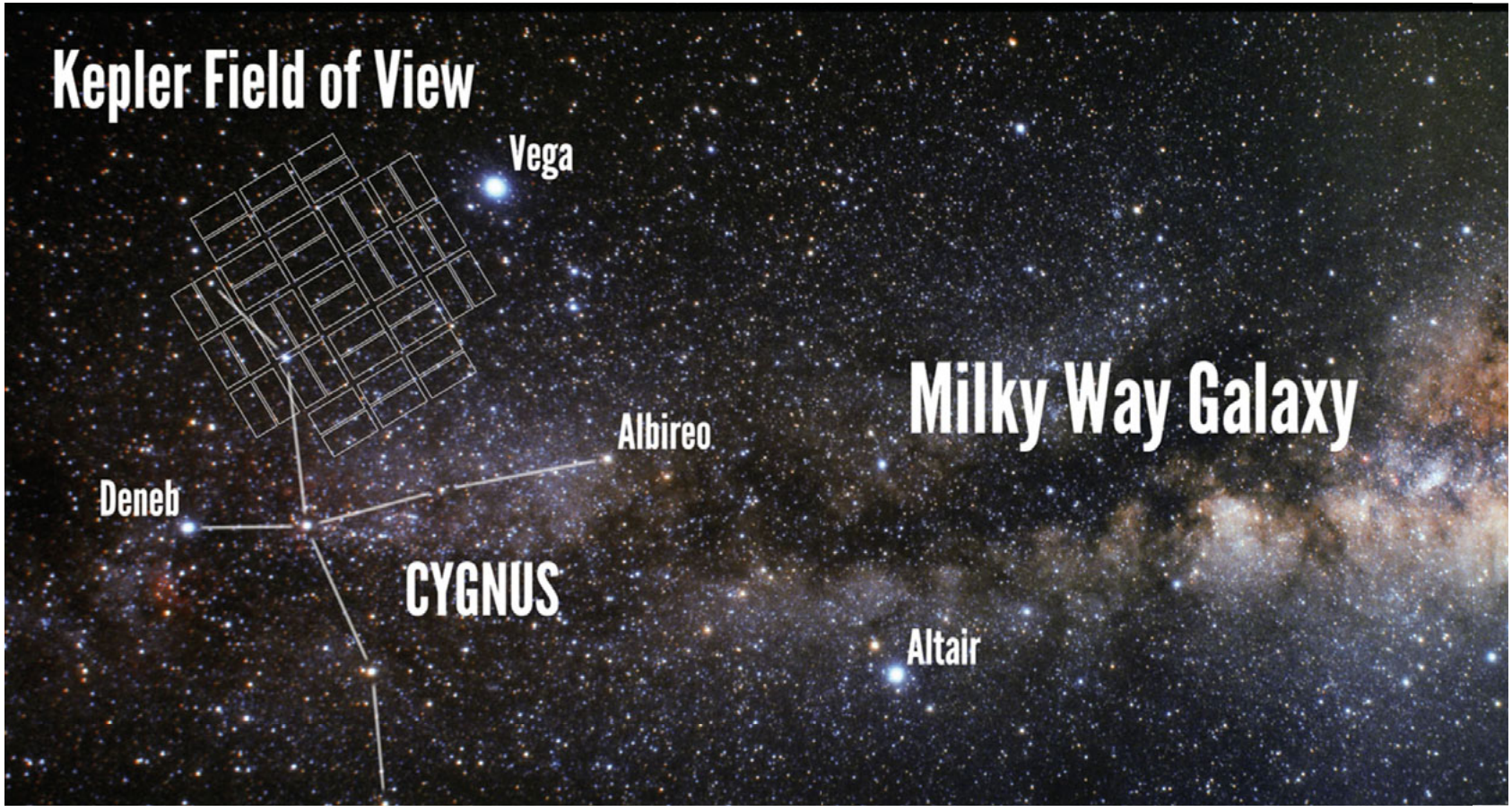
- Oumuamau
- Orbital ccentricity 1.2 > Parabolic (1.0)
- No cometary tail
- Very low albedo





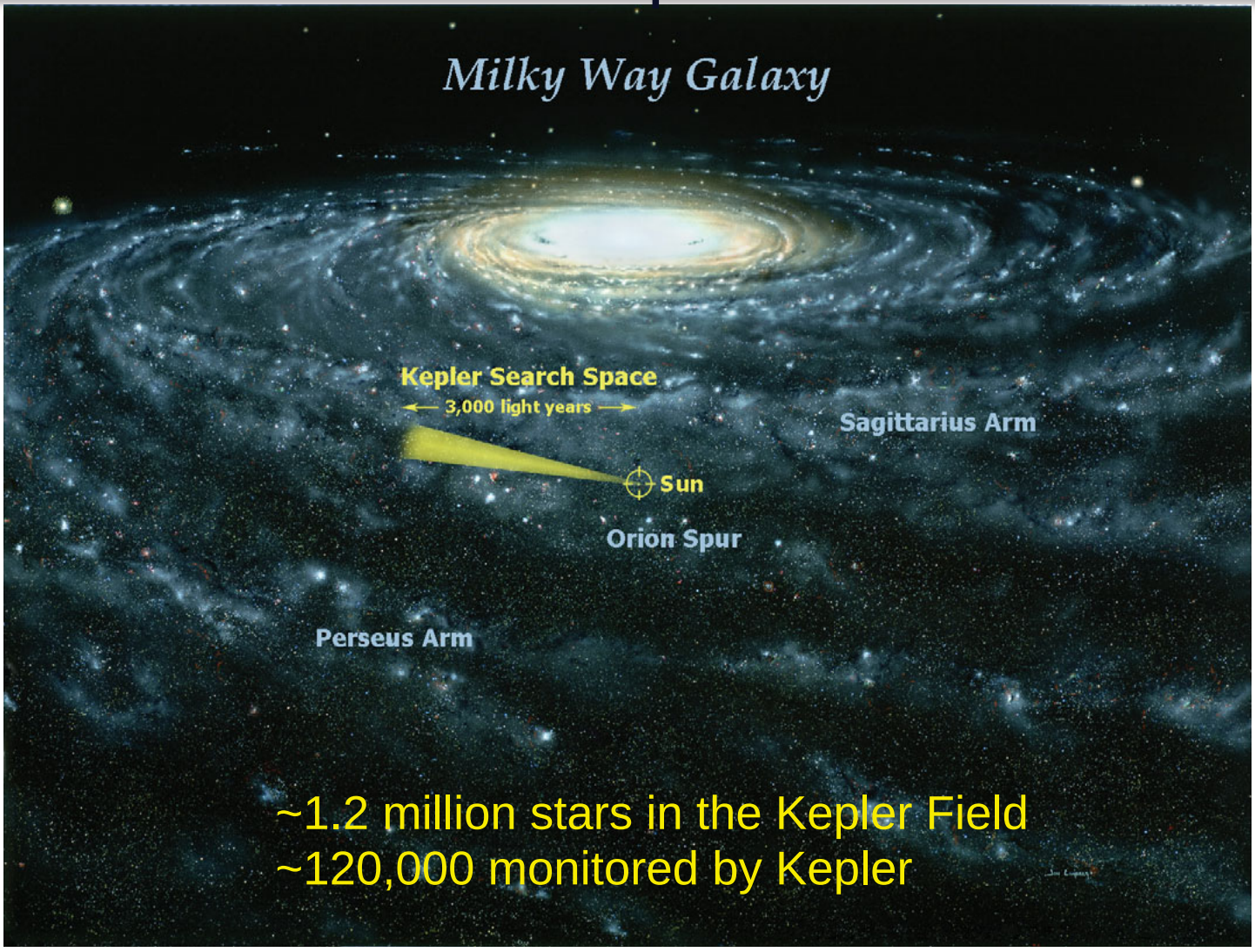
- Light curve indicates tumbling
- Multiperiodic and variable amplitude
- Not rotating about principle axis
- Aspect ratio ~ 10:1
- 230 m × 35 m × 35 m

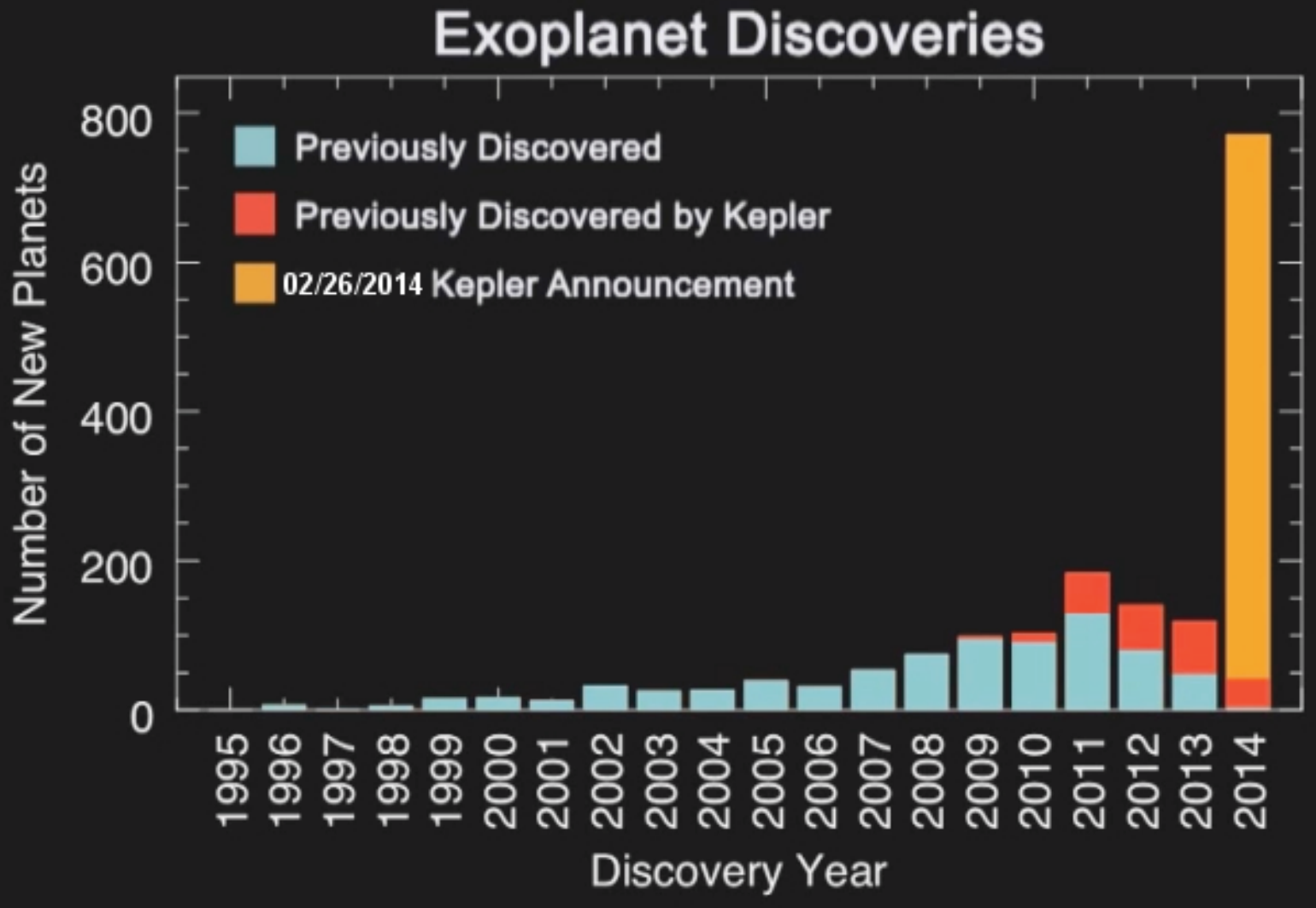
The Kepler Mission has Discovered Most of the Known Exoplanets



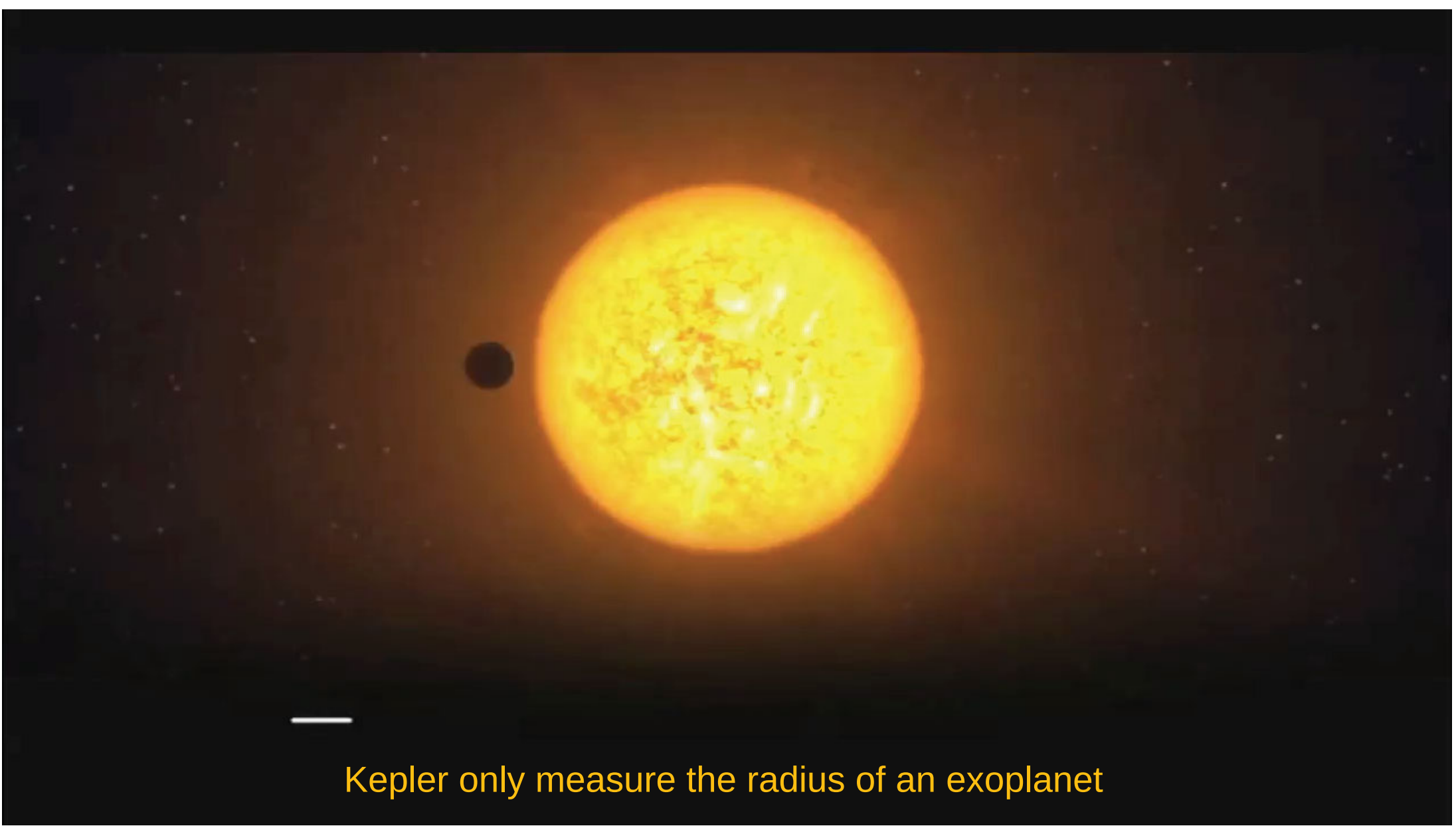
Kepler "Stared" at a ~100^2 deg field of view for ~3 years

Where Kepler Searched





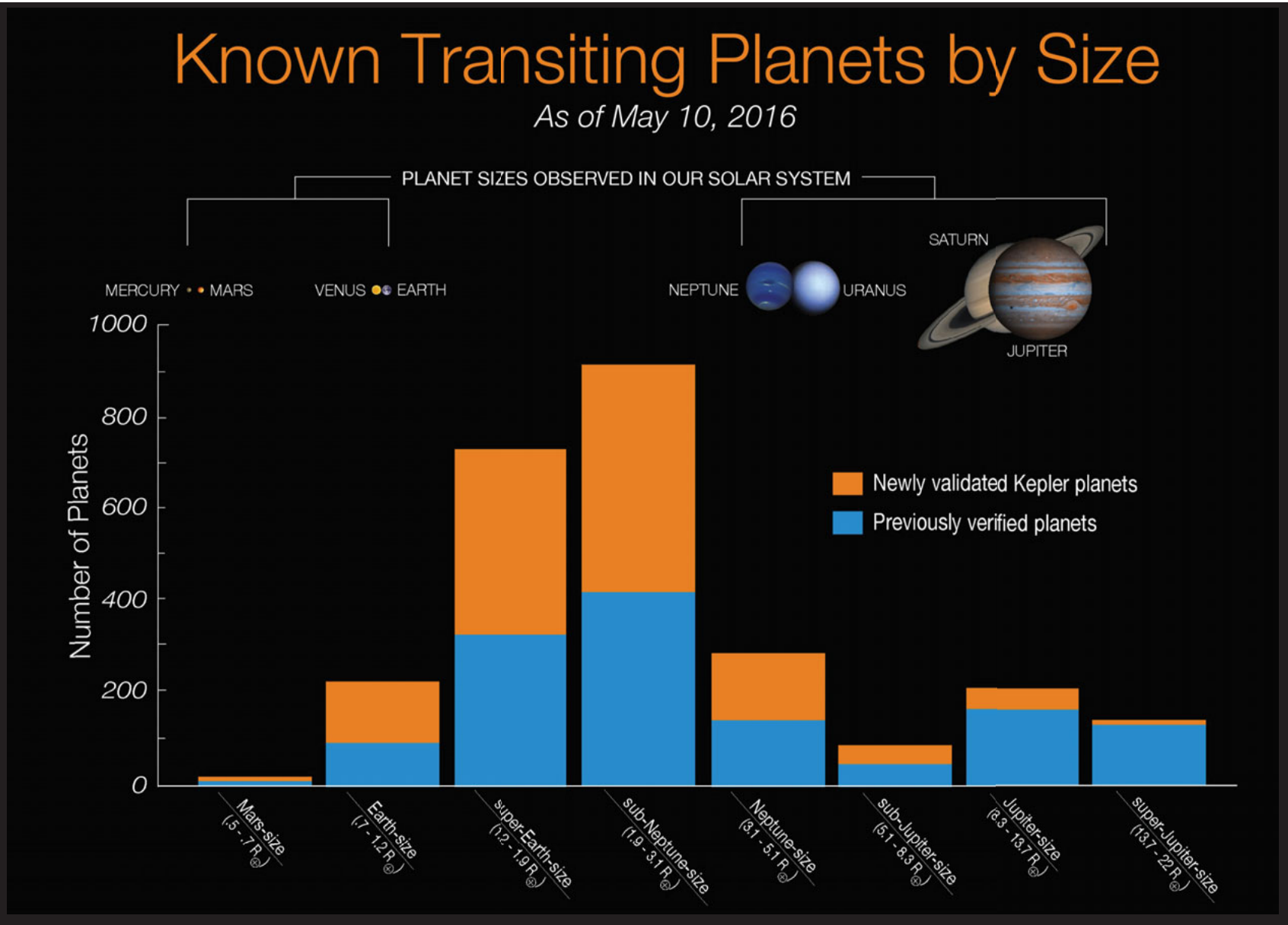
Kepler only measure the radius of an exoplanet



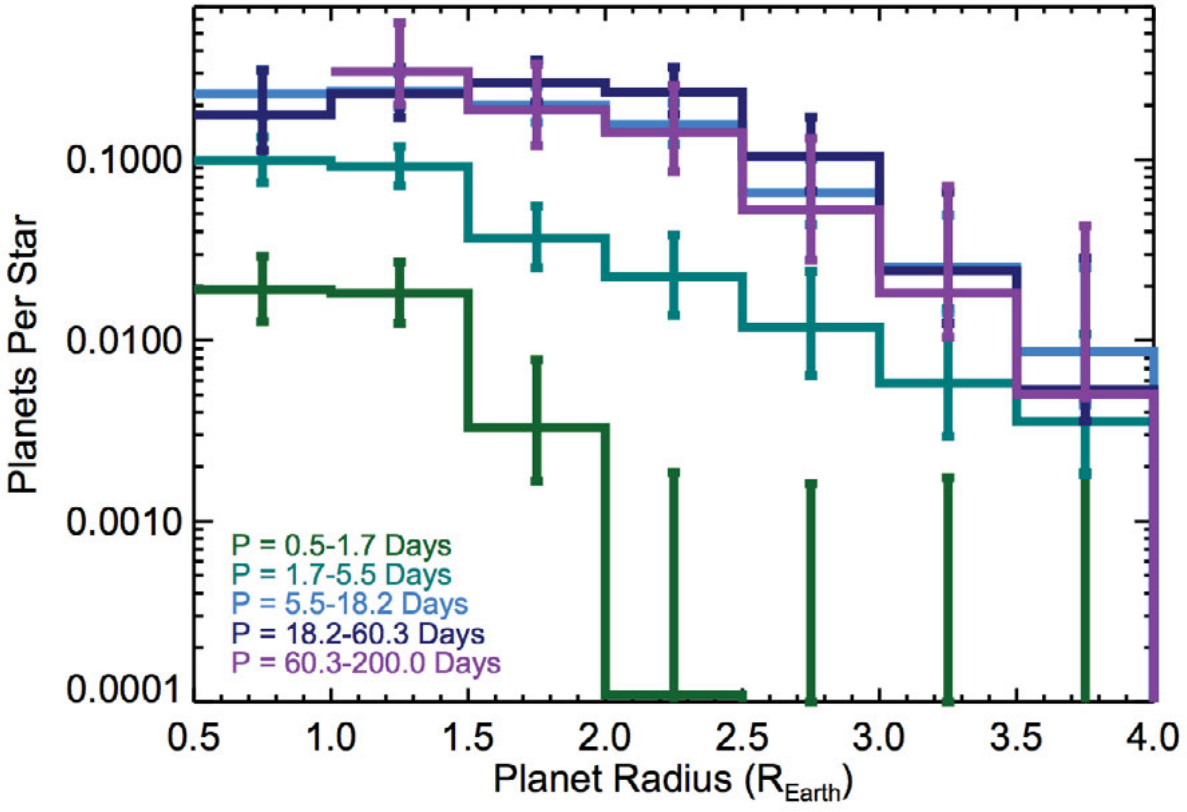
Kepler only measure the radius of an exoplanet

Known Transiting Planets by Size

As of May 10, 2016



Most Exoplanets are Earth size, many in habitable zone.

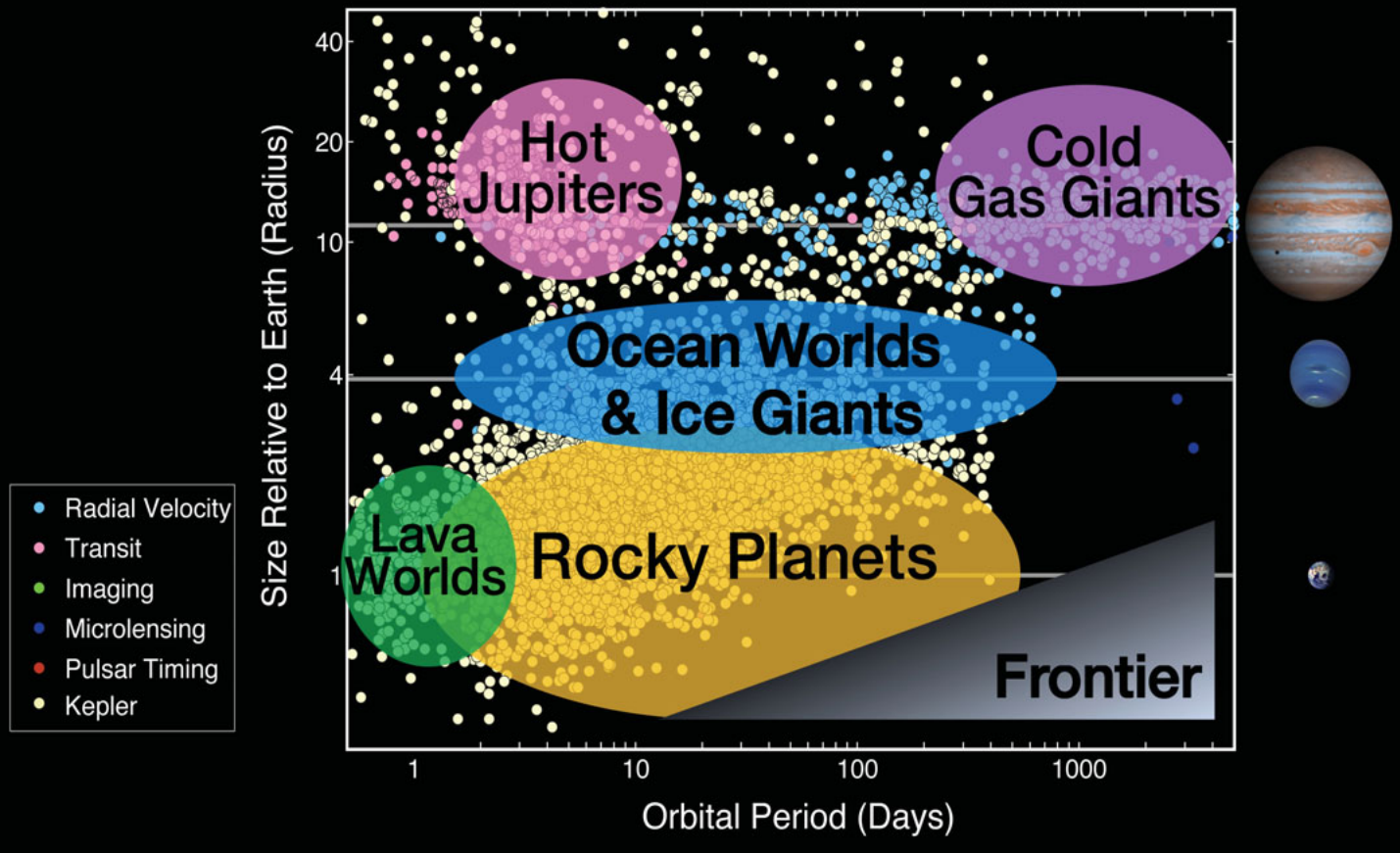


Dressing & Charbonneau, 2013, ApJ, 767, 95

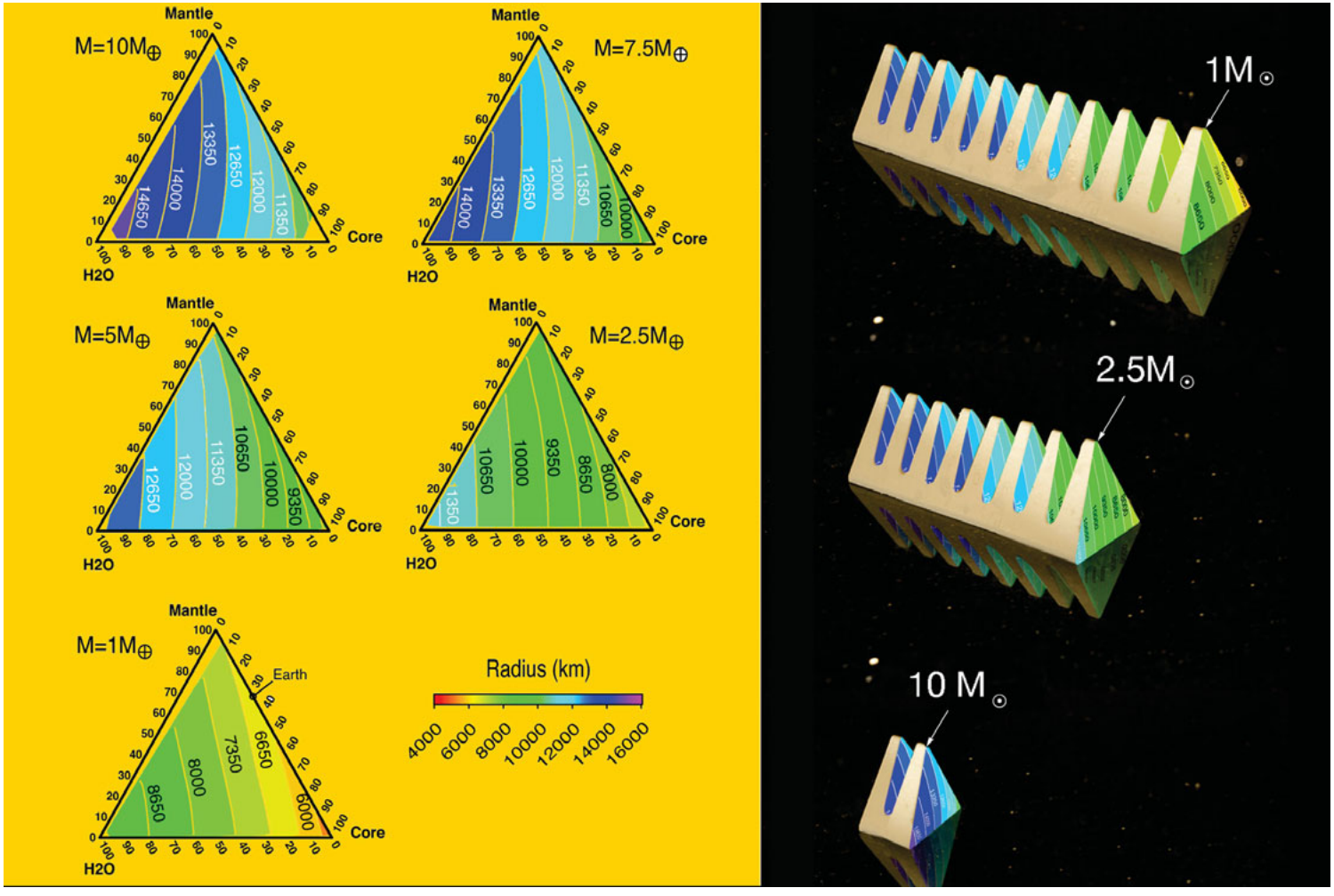
Extreme Exoplanets

Planet	Characteristic
HD10180 System	System with most exoplanets (≧ 7 planets, = 9?)
Kepler 64 b	In circumbinary orbit with 4 star system
NY Virginis b	Jupiter mass planet orbiting binay with B dwarf
HD 208527 b	Host star is a M1III red giant
HD 106906 b	650 AU from host star (Pluto 49.3 at aphelion)
V830 Tau b	Orbits 2 million year old T Tauri star (Youngest Host Star)
GJ 1214 b	”Waterworld”

Exoplanet Populations

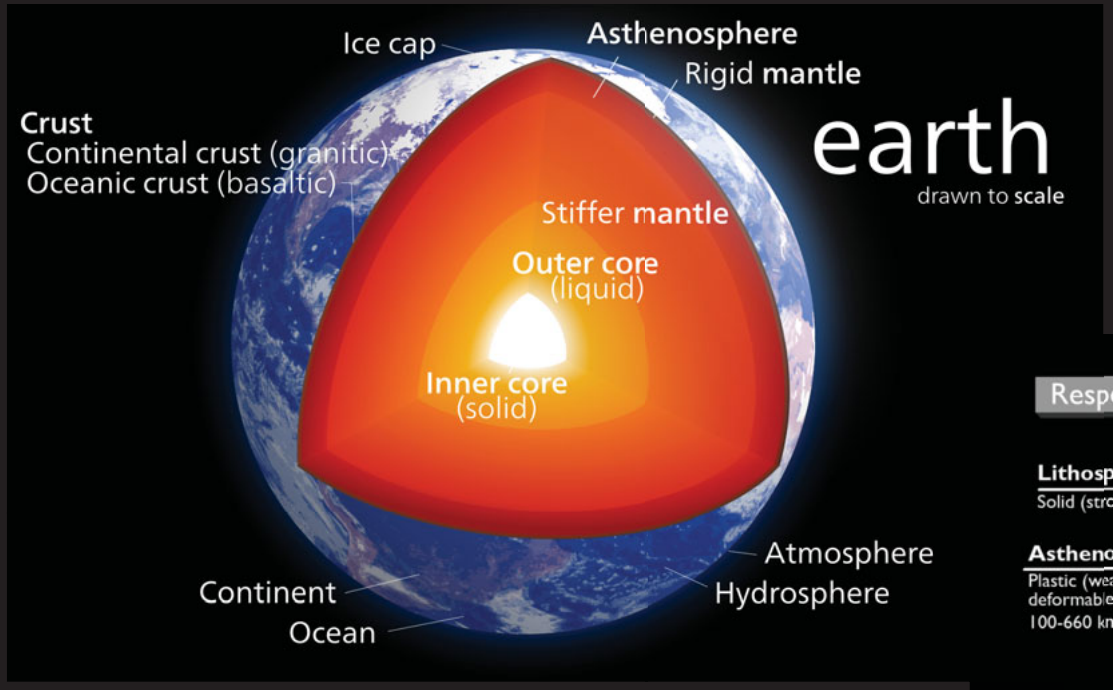


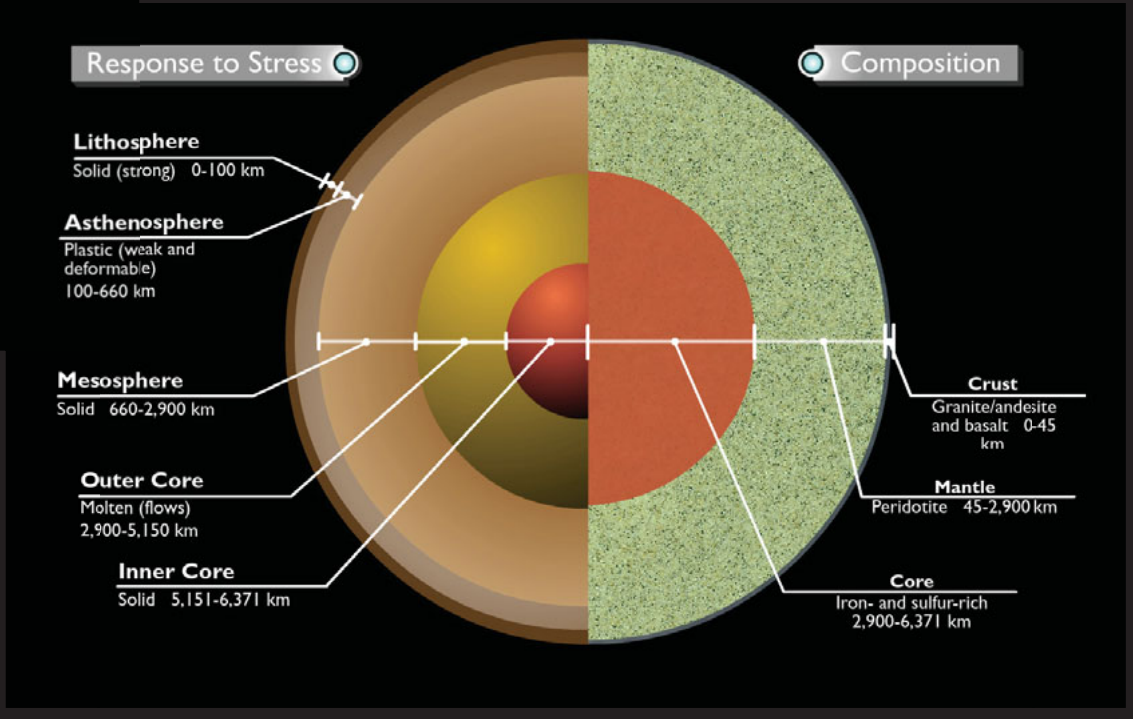
Ternary (“Toblerone”) Representation of Density and Composition



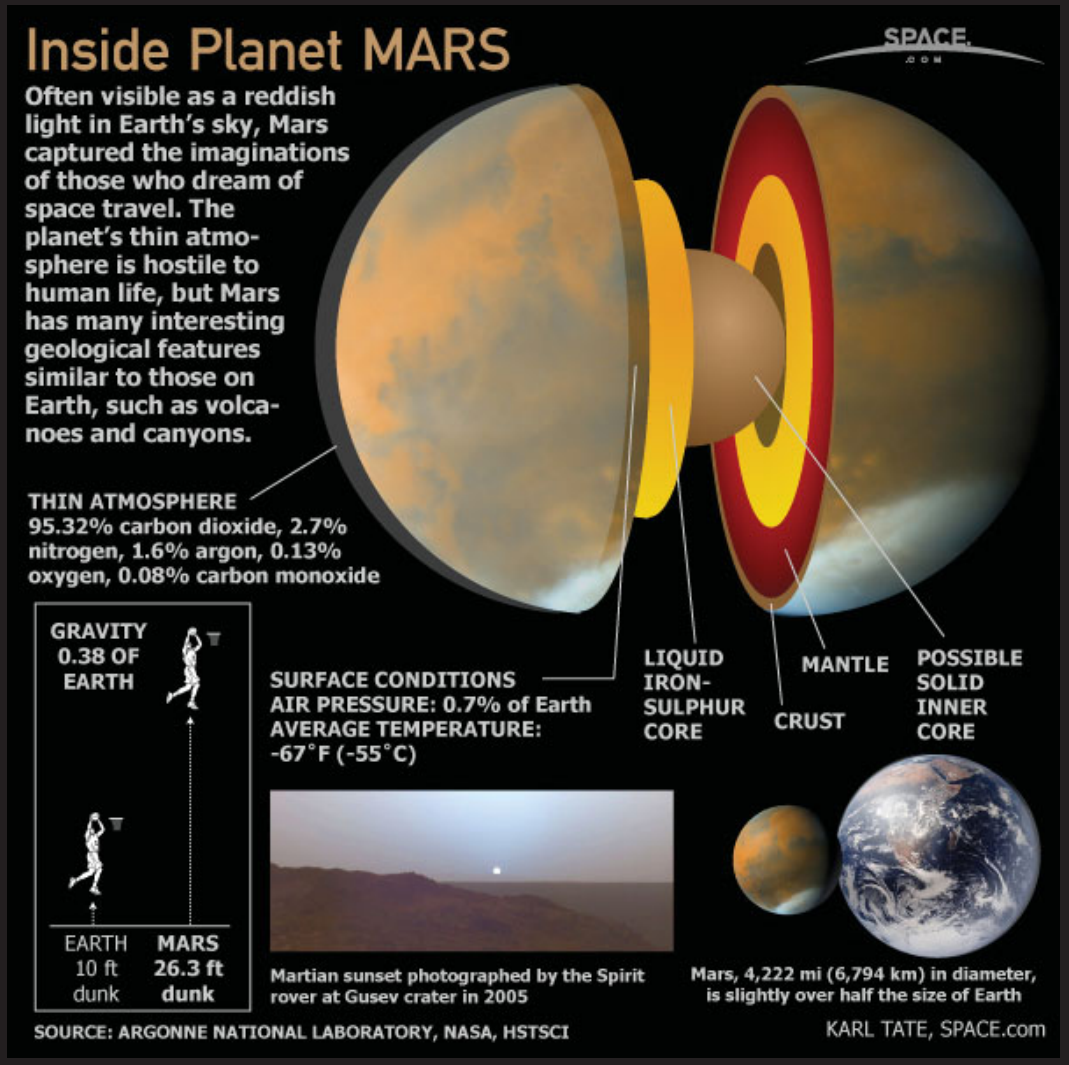
Composition seems to determine radius and mass, or vice versa.

The Earth is a Rocky Exoplanet

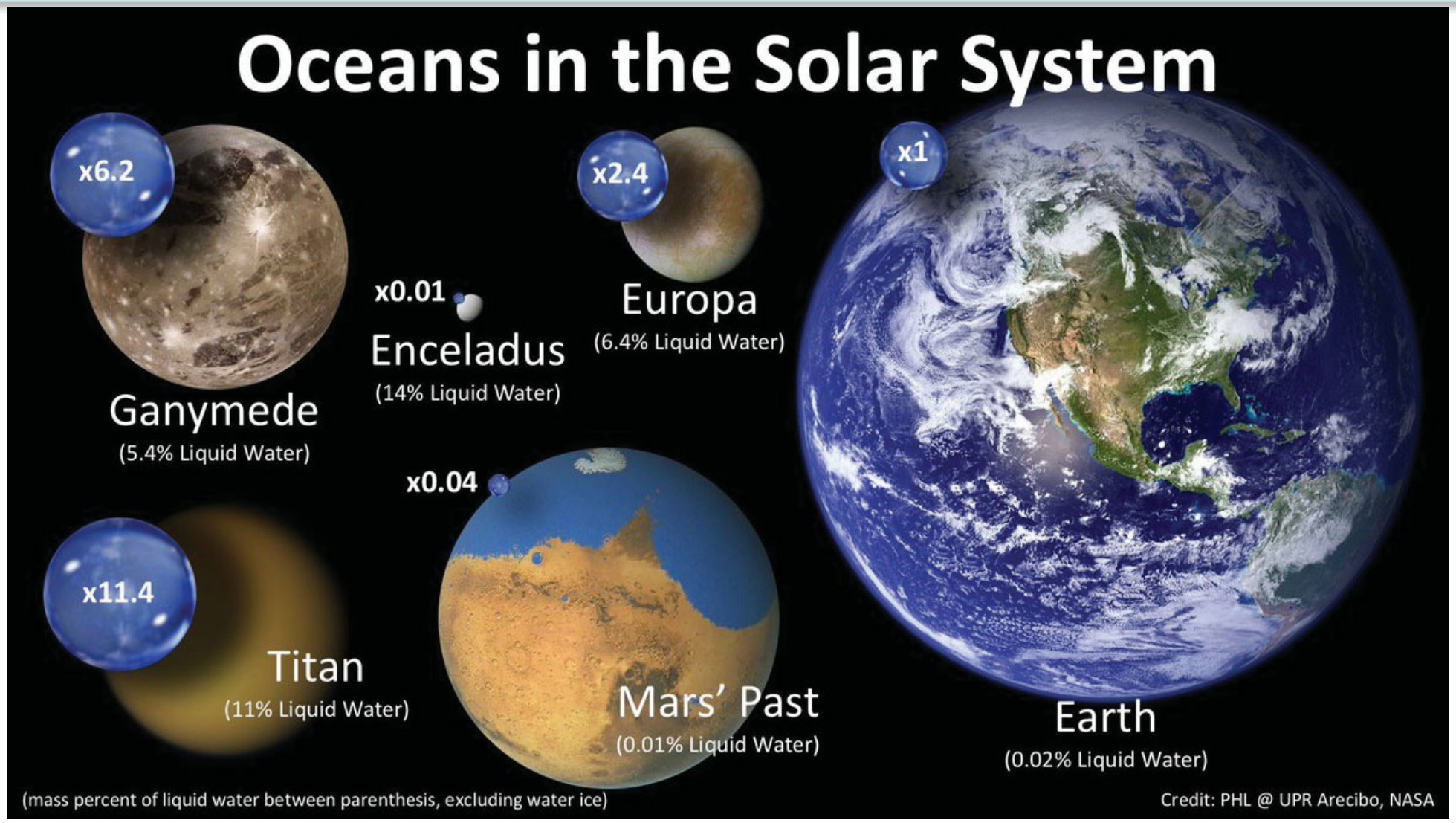




MARS is a Rocky Exoplanet TOO



The Earth is not “Wet”



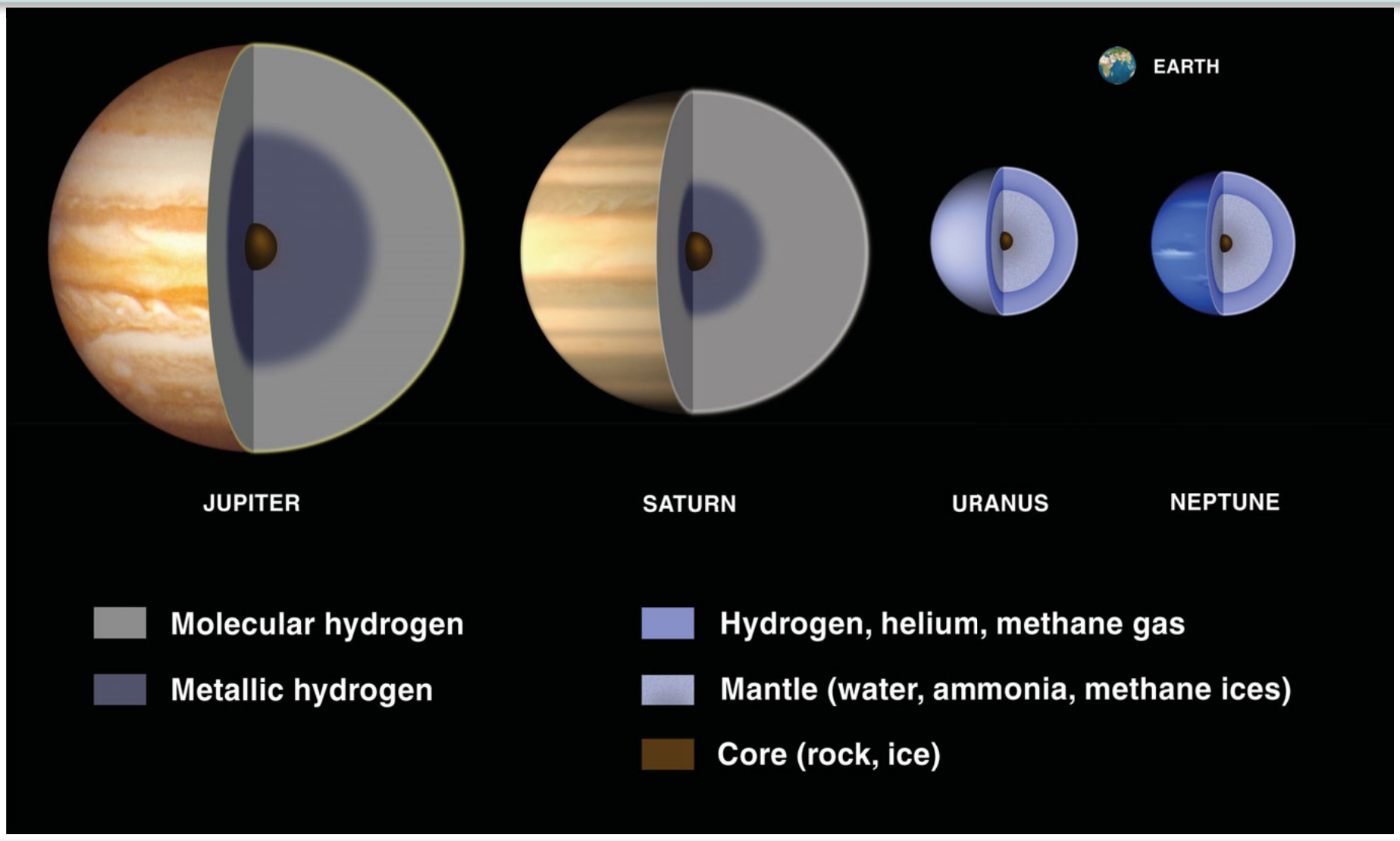
The Search for Earth 2.0

Name	Earth masses ($M_\oplus$)	Earth radii ($R_\oplus$)	Note
Kepler-69c	0.98	1.7	Originally thought to be in the circumstellar habitable zone (CHZ), now thought to be too hot.
Kepler-9d	>1.5[27]	1.64	Extremely hot.
COROT-7b	<9	1.58	Extremely hot.
Kepler-20f	< 14.3[25]	1.03[25]	Slightly larger and likely more massive, far too hot to be Earth-like.
Tau Ceti b	2		Extremely hot. Not known to transit.
Alpha Centauri Bb	1.1[28]		Closest known mass to Earth but much hotter. NOTE: May not exist (NYT, June 10, 2013).[29]
Kepler-186f		1.1[30]	Orbits in CHZ.
Earth	1	1	Orbits in habitable zone.
Venus	0.815	0.949	Much hotter.
Kepler-20e	< 3.08[24]	0.87[24]	Too hot to be Earth-like.
Proxima b	>1.27	>1.1	Closest exoplanet to Earth.

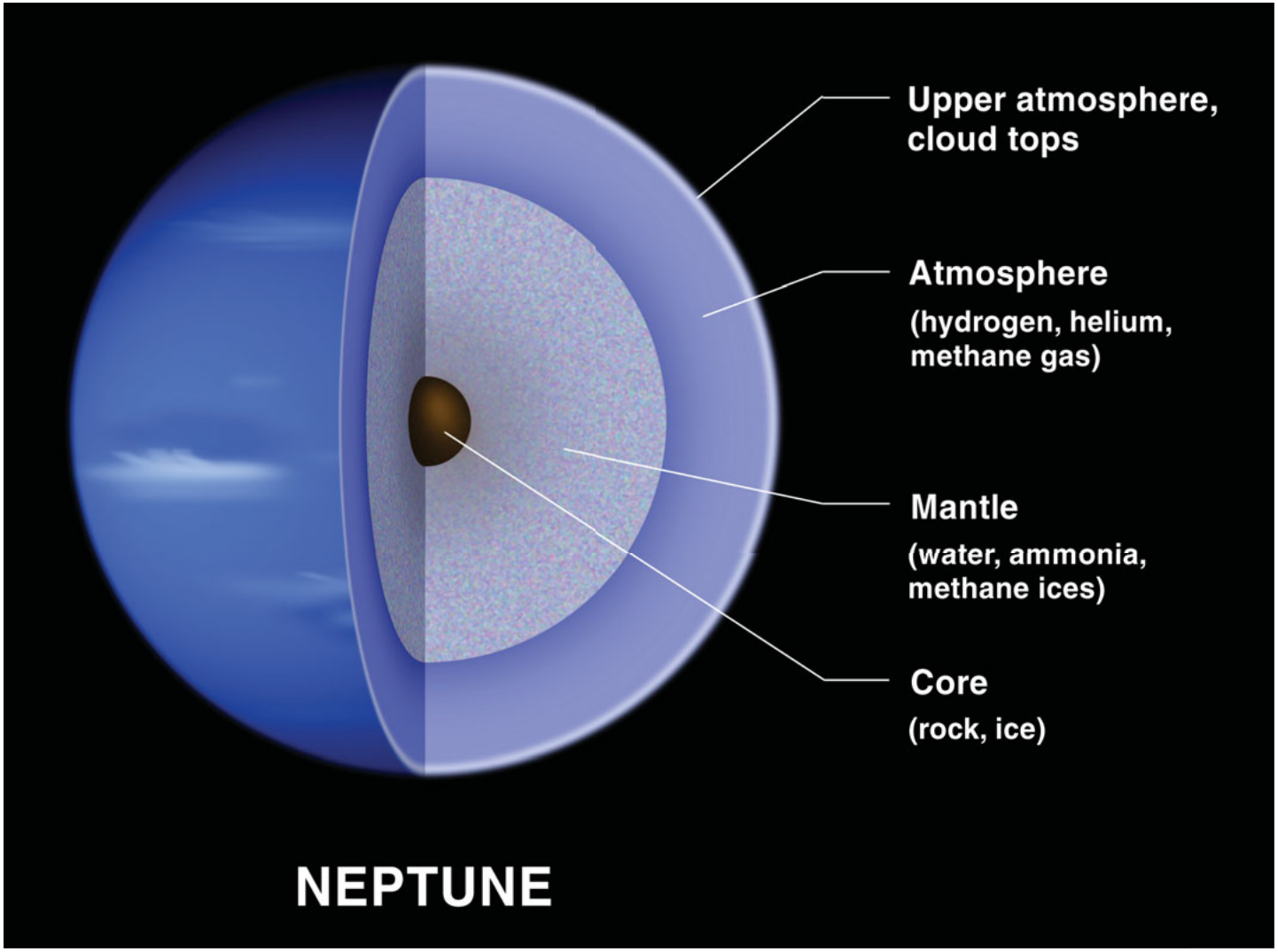
Planet	ESI	Notes
Earth	1.00	
Gliese 581 g	0.89	unconfirmed
Kepler-438b	0.88	
Ross 128 b	0.86	
Gliese-3323b	0.86	
Kepler-62e	0.83	[10]
Gliese 832 c	0.81	
Gliese 581 d	0.74	
Gliese 581 c	0.70	
Mercury	0.60	
HD 69830 d	0.60	
55 Cnc c	0.56	
Moon	0.56	
Gliese 581 e	0.53	

No “true” analogue has been found to date.

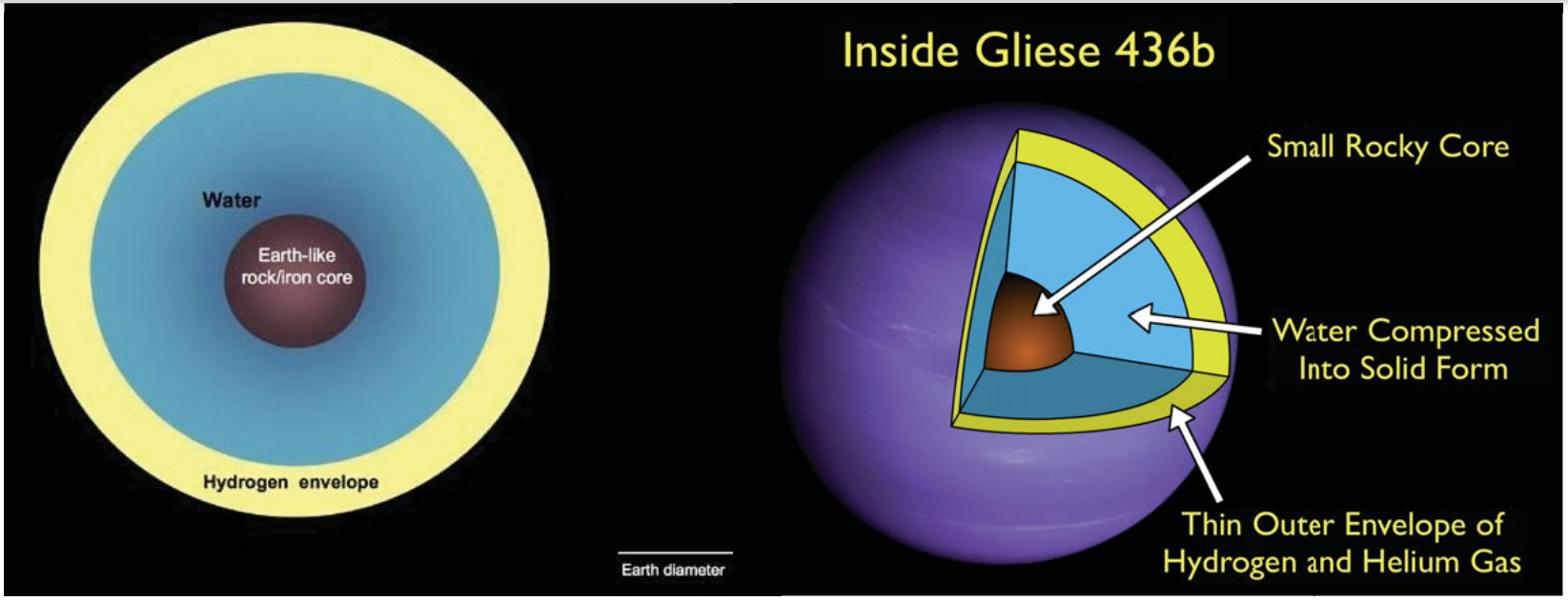
”Gas Bag” Planets (Jupiters) and Water Worlds



Neptune is a Frozen Waterworlds

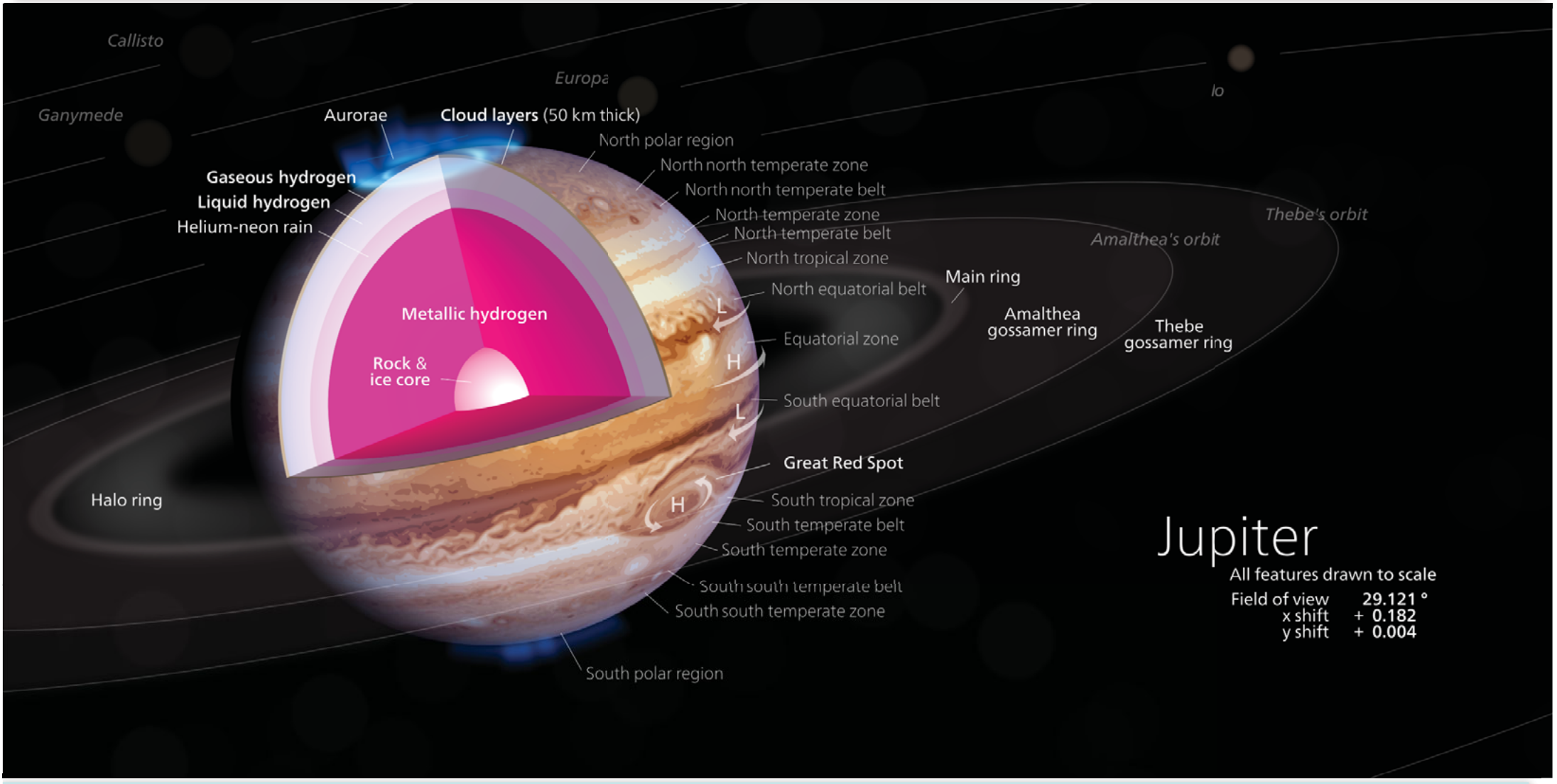


Gliese 436b is a Liquid Waterworld



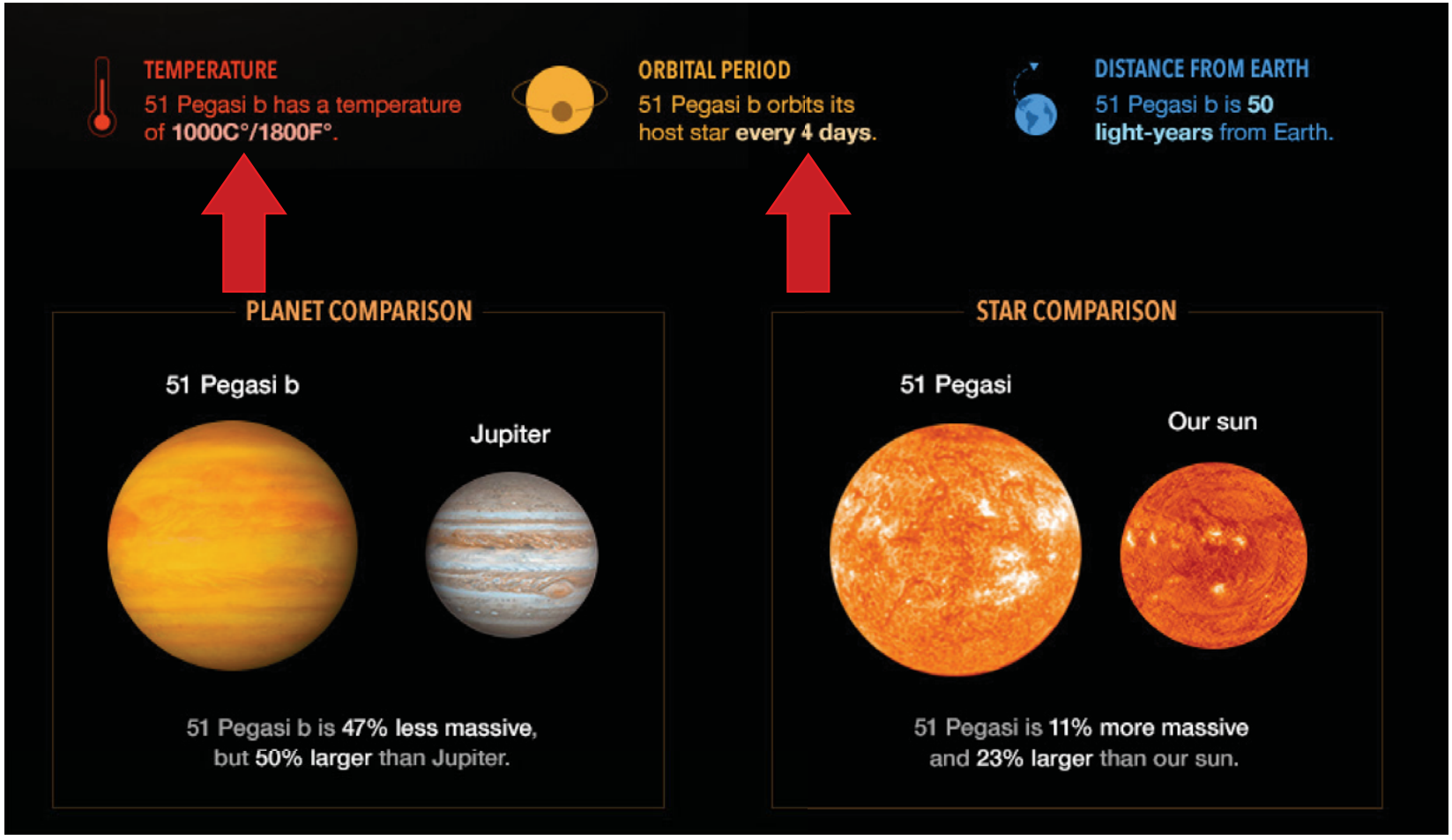
Stellar Type	M2.5V
Orbital Period	2.64d
Orbital Radius	0.0291 AU
Mass	22.2 $M_{\oplus}$
Radius	4.33 $R_{\oplus}$
Temperature	712K

Jupiter is Mostly Metallic Hydrogen



51 Peg b is a Jupiter Analogue

The first exoplanet was a Jupiter analogue!



Solar system fact-sheet

	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792.4	14,2984	120,536	51,118	49,528	2,390
Mass (10^{24} kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013
Density (kg.m^3)	5.41	5.19	5.51	3.35	3.93	1.33	0.69	1.27	1.64	1.86

Rocky Planets

Gas Giants

Ice Giants

Axial tilt (°)	——														
Surface gravity (m.s^2)	274.0														
Escape velocity (km.s^{-1})	617.7														
Surface area (10^6 km^2)	6,087														
Volume (10^{12}	1,412,200	0.06	0.9	1.1	0.02	0.16	0.0005	1431	827	68	63	0.007	~0.002		0.009
Density (kg.m^3)	1.41	5.41	5.19	5.51	3.35	3.93	1.89	1.33	0.69	1.27	1.64	1.86	~2	~3	~2
Albedo	——	0.11	0.65	0.37	0.12	0.15	0.09	0.52	0.47	0.51	0.41	0.58	?	0.6	0.86
Apparent magnitude (V)	–26.7	–1.9	–4.6	——	–12.9	–2.9	6.9	–2.9	–0.2	5.3	7.8	13.7	16.7	17.5	18.7
Angular diameter, max. (")	1,962.0	13.0	66.0	——	2,046	25.1	0.8	50.1	20.1	4.1	2.4	0.1	0.02	0.02	0.04
Rings	——	no	no	no	no	no	no	yes	yes	yes	yes	no	no	no	no
Satellites	billions!	0	0	1	no	2	0	63	60	27	13	3	0	2	1
Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun
Perihelion (10^6 km)	——	46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650
Aphelion (10^6 km)	——	69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600
Semimajor axis (AU)	——	0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7
Eccentricity	——	0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44
Inclination (°)	——	7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2
Orbital period (days)	——	88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600
Orbital period (years)	——	0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4
Orbital velocity (km.s^{-1})	——	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)	——	——	——	——	——	1801	——	——	——	1781	1846	1930	2005	2004	2003

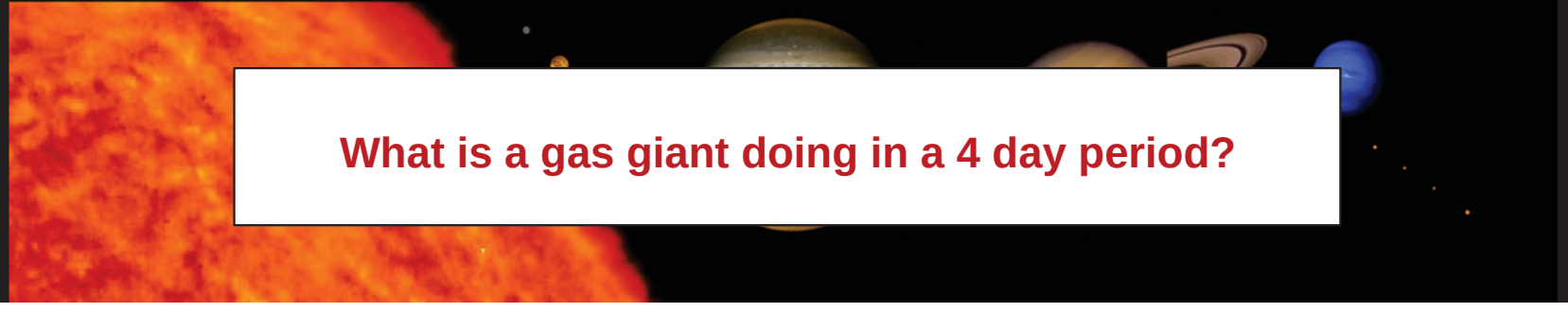
Rocky Planets

Solar system fact-sheet

	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792.4	14,2984	120,536	51,118	49,528	2,390
Mass (10^{24} kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013
Density (kg.m^3)	5.41	5.19	5.51	3.35	3.93	1.33	0.69	1.27	1.64	1.86
Satellites	0	0	1	no	2	63	60	27	13	3
Rotation period (days)	58.6	–243.0	1.0	27.3	1.0	0.4	0.4	–0.7	0.7	–6.4
Axial tilt (°)	0.04	177.3	23.4	6.7	25.2	3.1	26.7	97.8	28.3	119.6
Semimajor axis (AU)	0.4	0.7	1.0	0.003	1.5	5.2	9.6	19.2	30.1	39.5

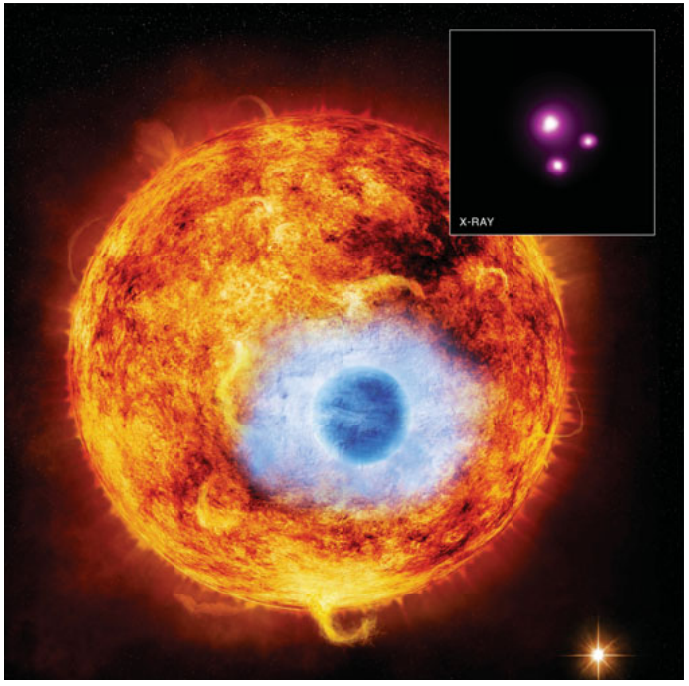
- Rocky planets are all inside ~1.5 AU.
- Gas giants @ ~5 AU or greater?
- Gas giants must form beyond the “Ice/ Snow Line where water, ammonia, methane, CO2, &c. freeze out

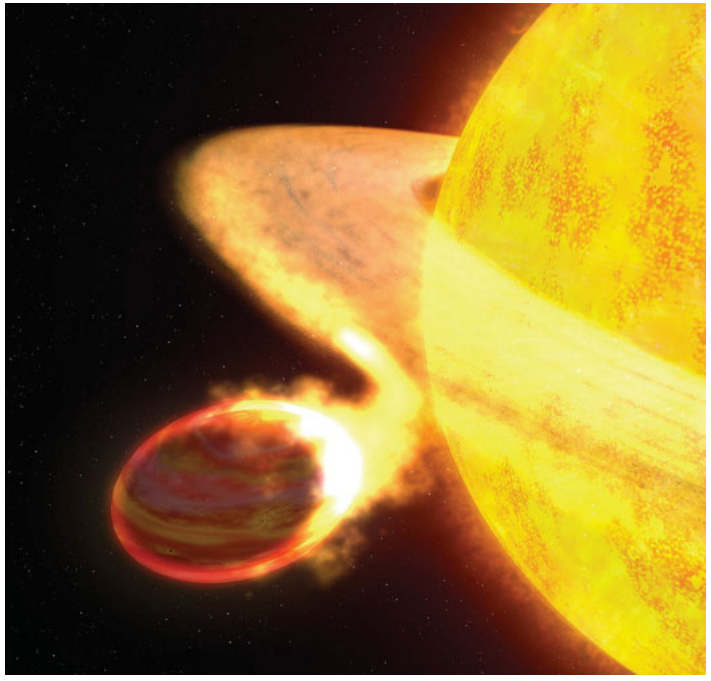
Orbits the:														Sun	Sun
Perihelion (10^6 km														5,260	5,650
Aphelion (10^6 km)														7,708	14,600
Semimajor axis (A														43.3	67.7
Eccentricity														0.19	0.44
Inclination (°)														28.2	44.2
Orbital period (day														104,234	203,600
Orbital period (yea														285.4	557.4
Orbital velocity (kn														4.5	3.4
Discovery (year)	—	—	—	—	—	1801	—	—	—	1781	1846	1930	2005	2004	2003



What is a gas giant doing in a 4 day period?

Hot vs. Cold Jupiters





Hot Jupiters like HD18977 - b and WASP-12b are probably evaporating

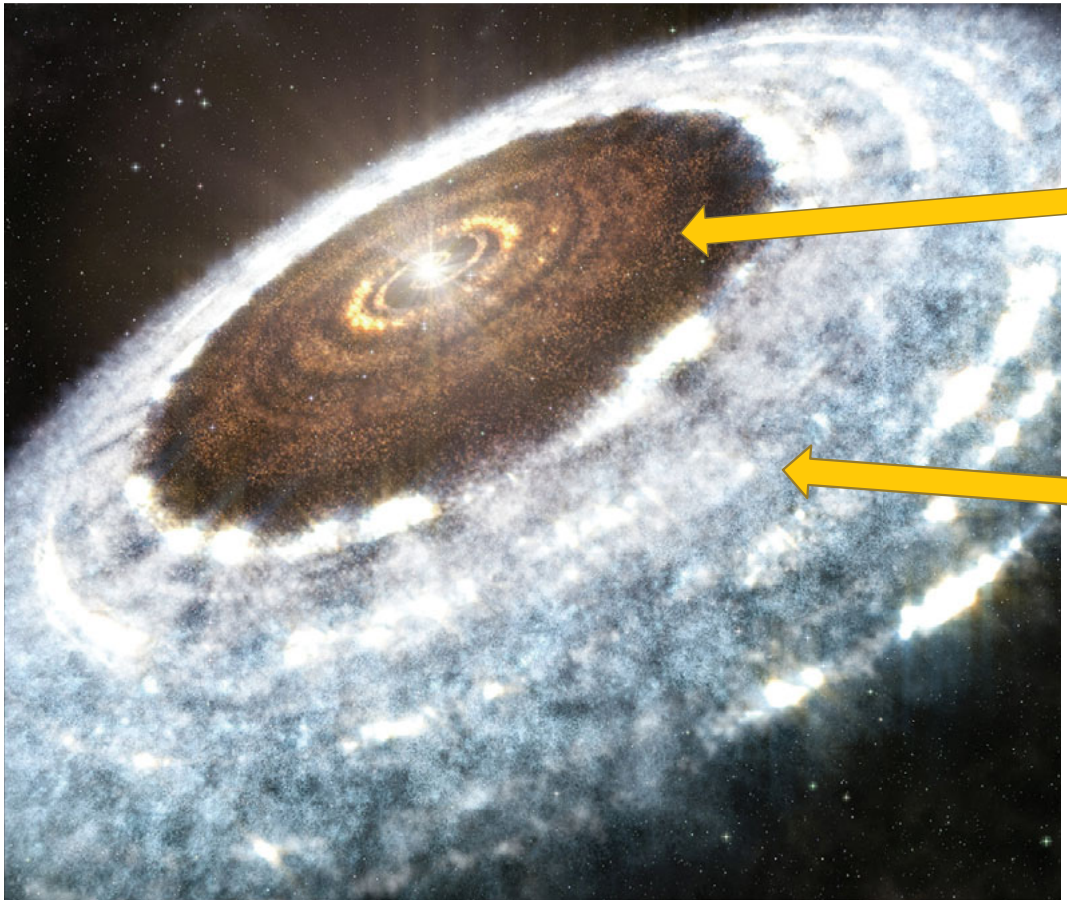
Jupiter	
Period	1,680 d
Orb. Rad.	2.8 AU
Temp	Complicated

HD189733-b	
Period	2.22 d
Orb. Rad.	0.03 AU
Temp	1117 K

WASP-12b	
Period	1.09 d
Orb. Rad.	0.023 AU
Temp	2525 K

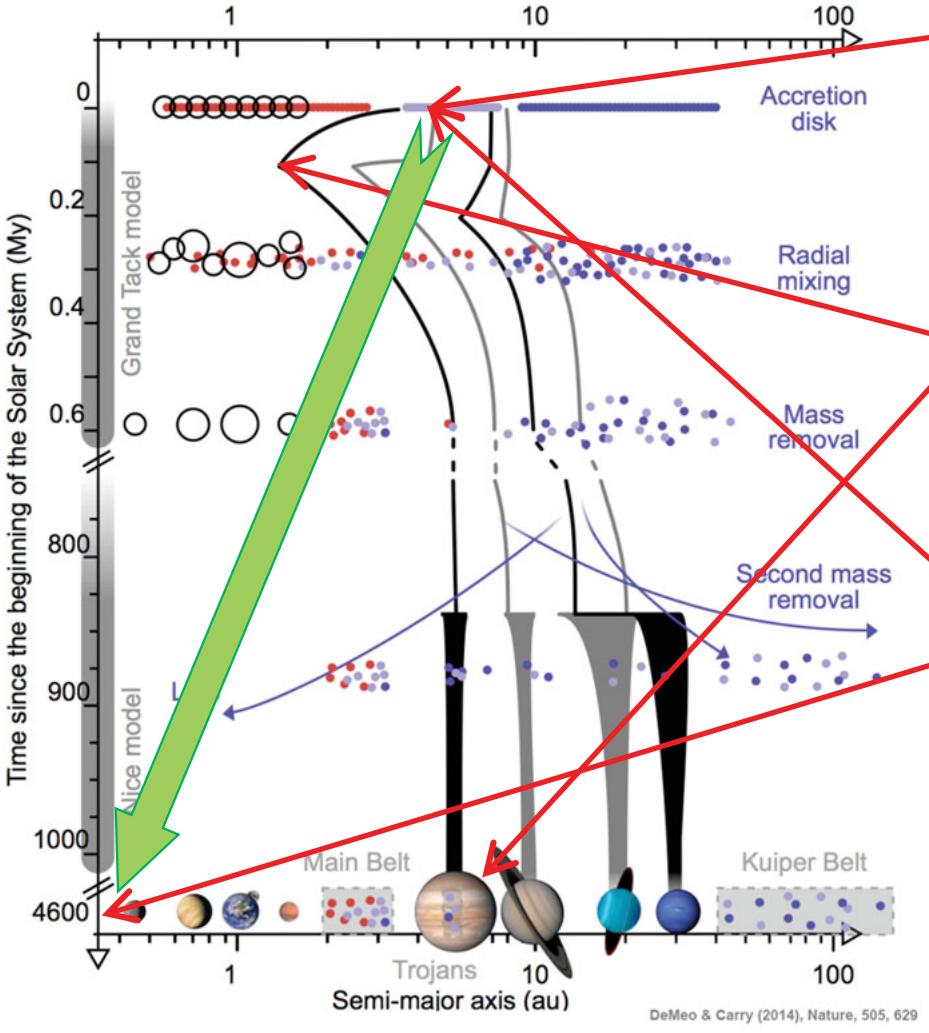
Mercury	
Period	2.22 d
Orb. Rad.	0.466 AU
Temp	~350 K

The Exoplanet ”Ice Line”

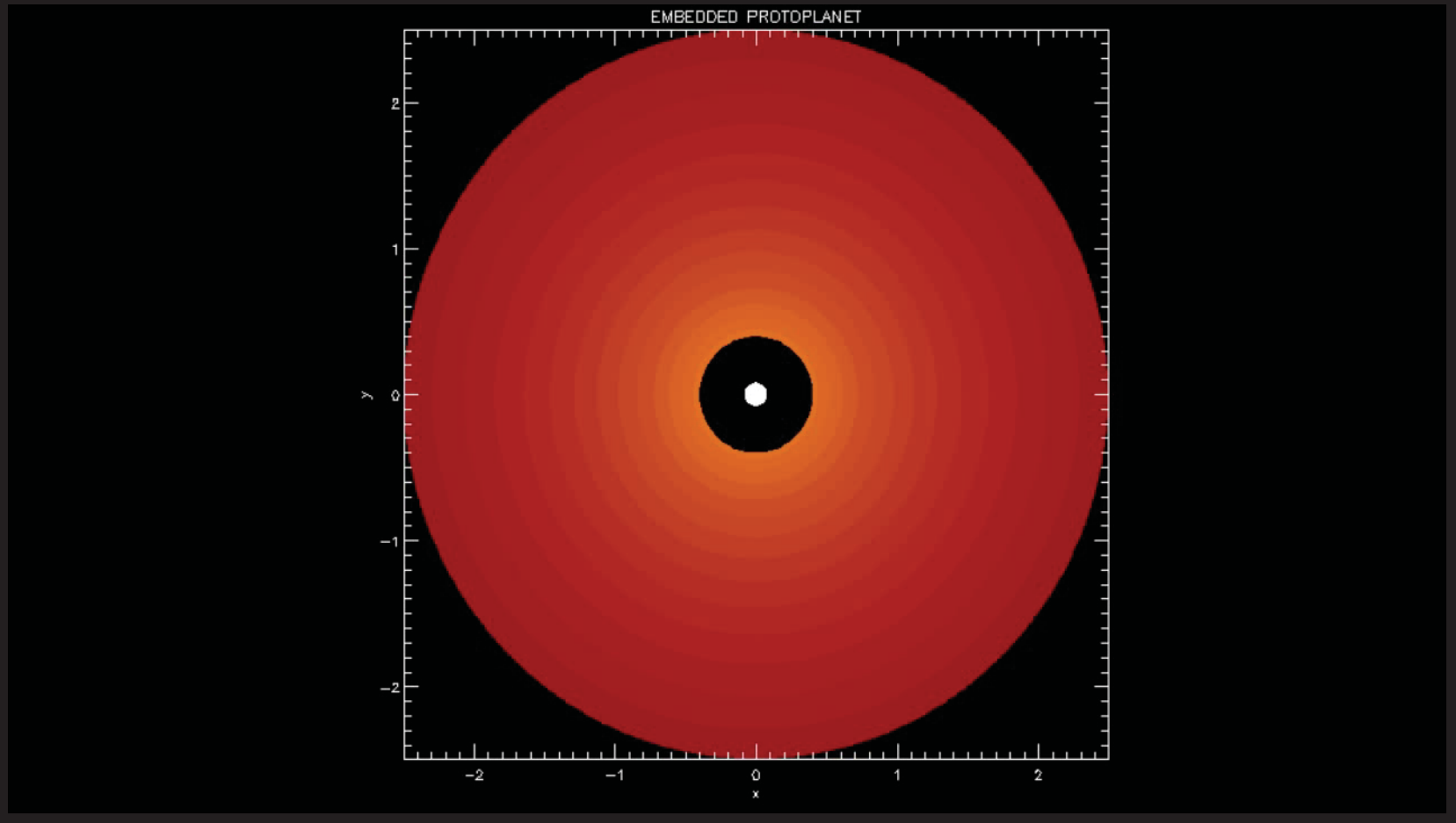


Artist’s impression of a protoplanetary disk with warm inner circle of dust and outer ring of “snow”

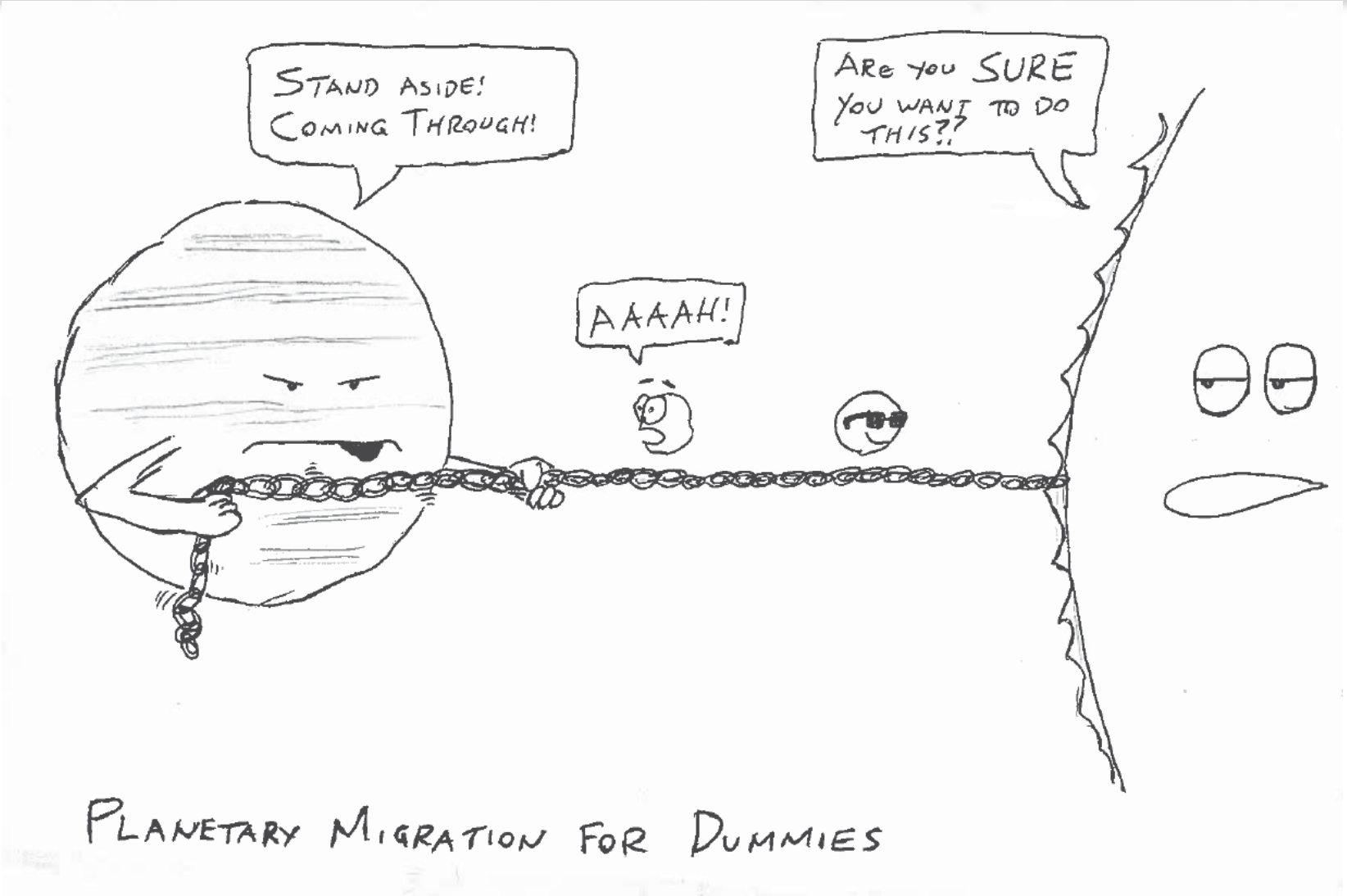
A Migration History of the Solar System



- Jupiter had to be made outside the Ice Line
- Jupiter ended up outside the Ice Line
- But there is strong evidence that Jupiter migrated well within the Ice Line
- Hot Jupiters end up here
- But the have to be born here
- **The process of planetary migration is mysterious, but seems inevitable**


EMBEDDED PROTOPLANET
2
1
0
−1
−2
y
−2
−1
0
1
2
x

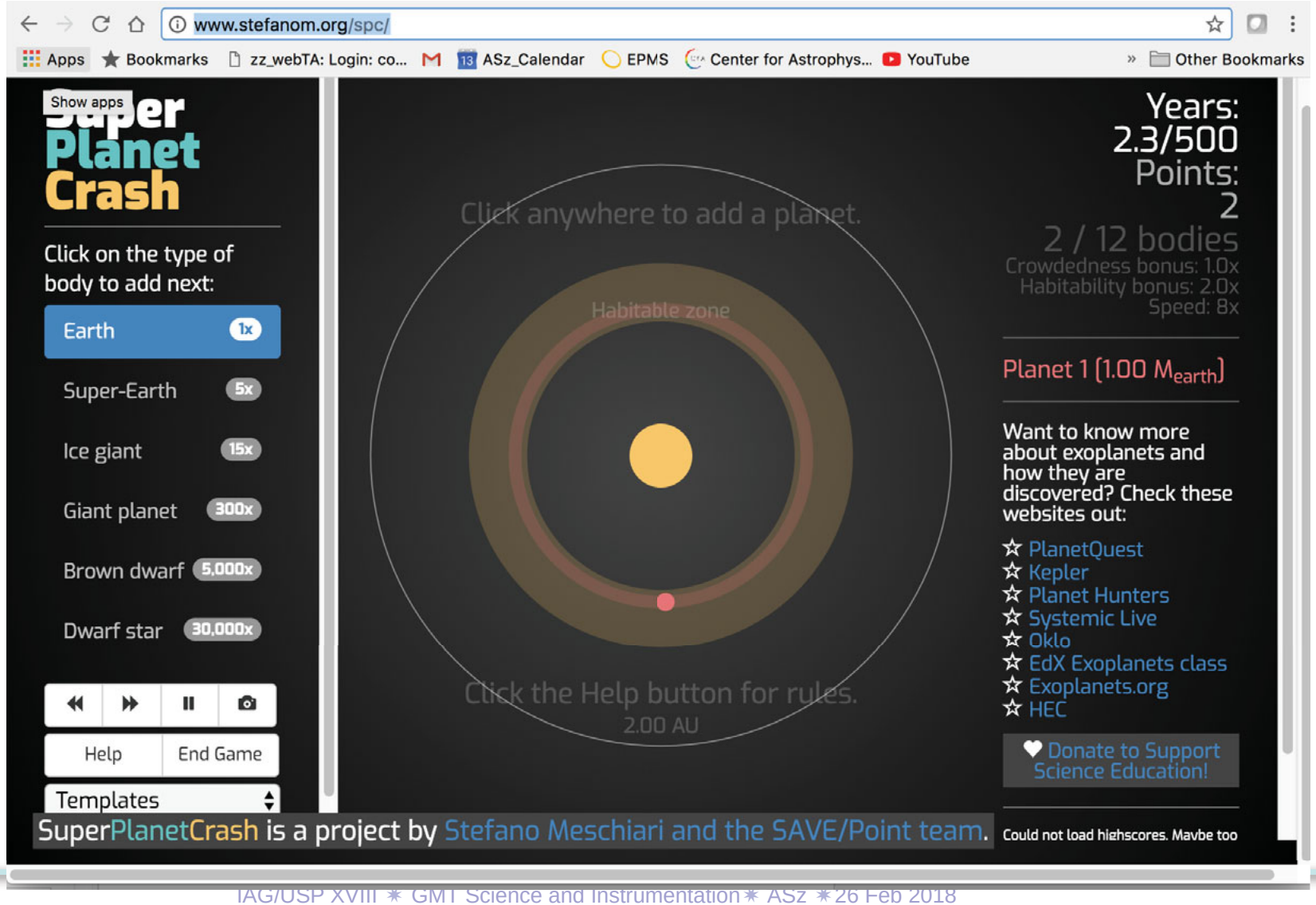
The Solar System Grand Tack in Manga



But Dynamical Interations Are Important Too

Let's simply play the game!

http://www.stefanom.org/spc/



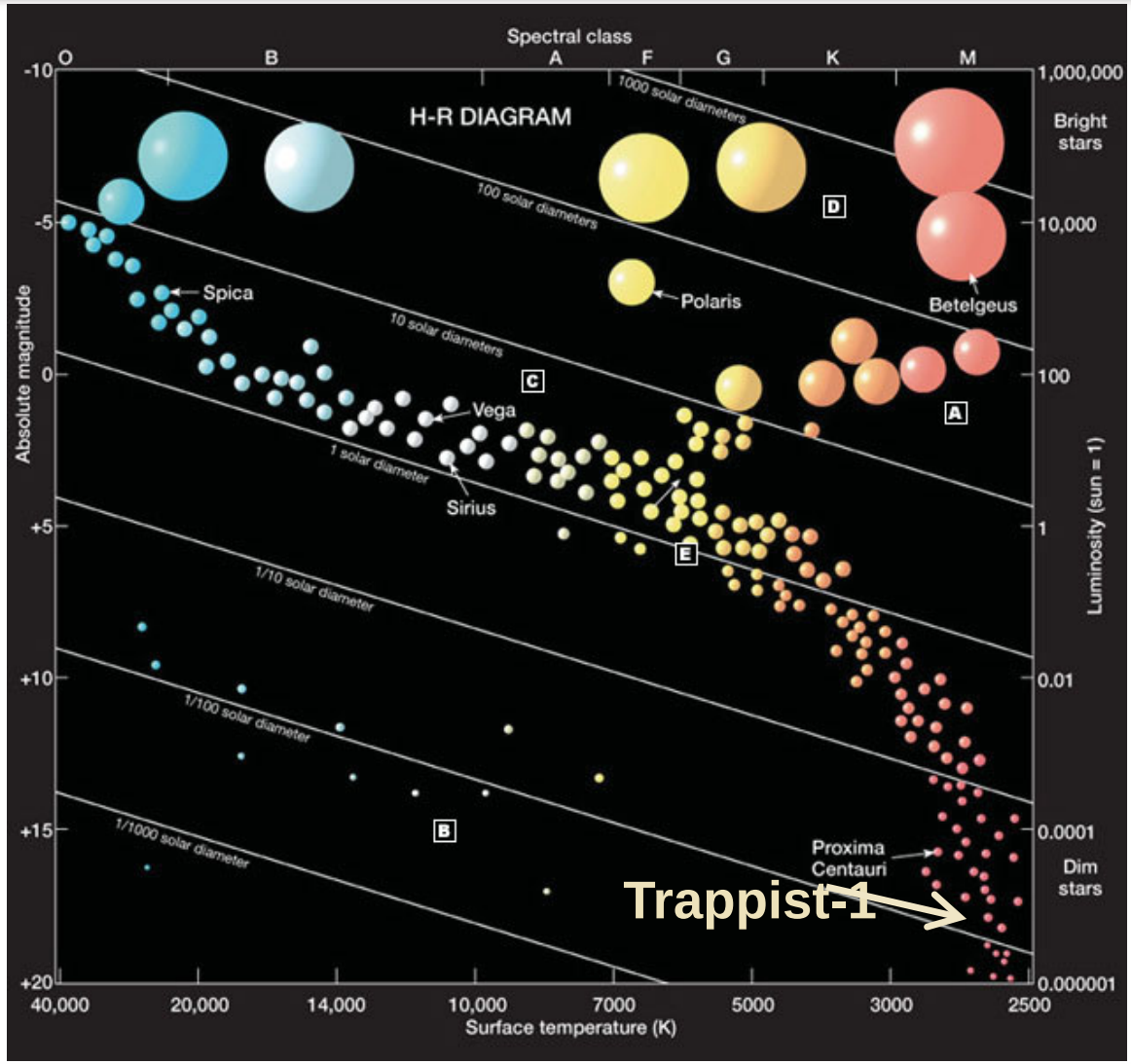
A Paradigm-Shifting Exoplanet System – Trappist-1

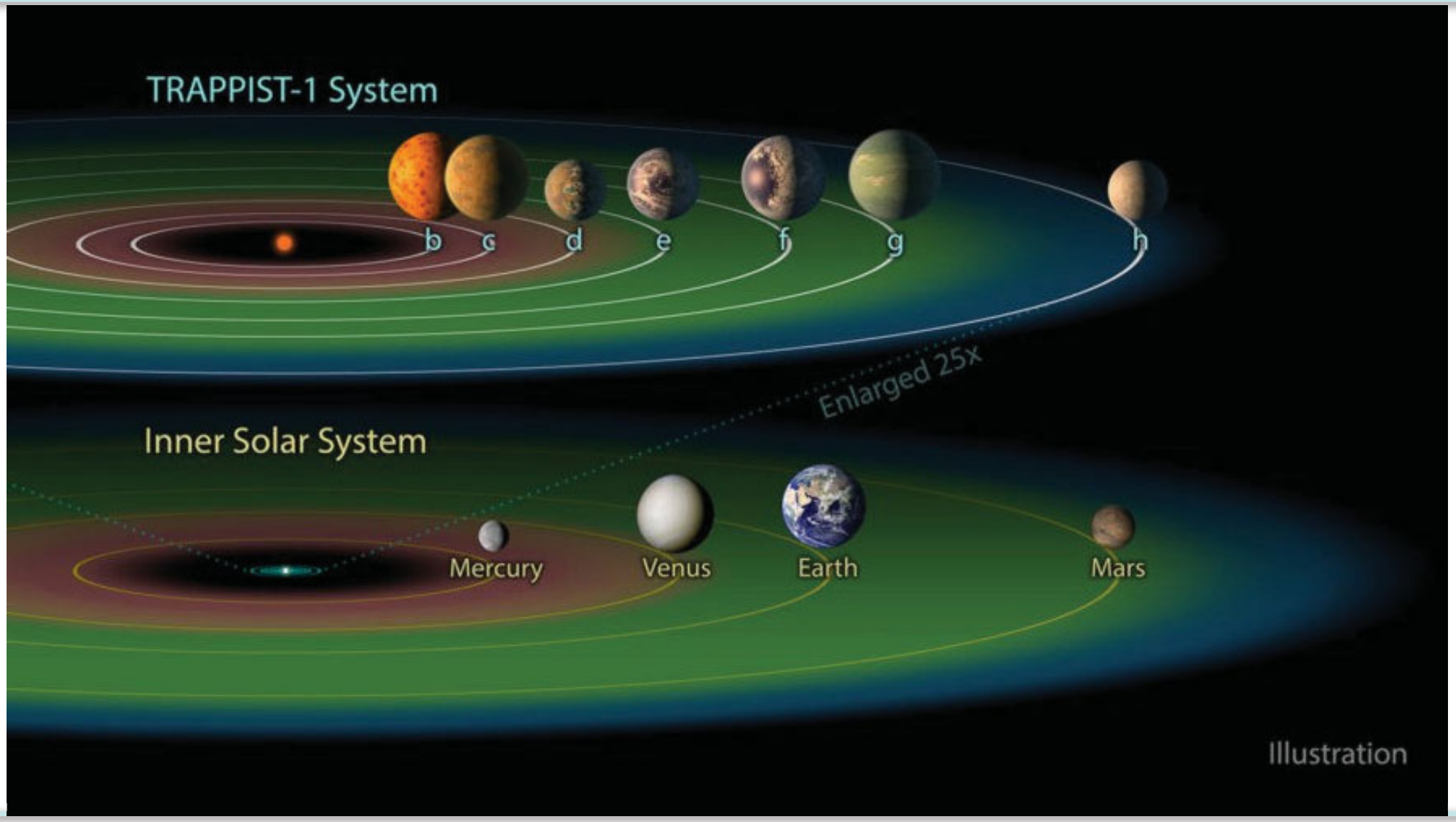
The TRAPPIST-1 planetary system

Companion (in order from star)						Radius[6][33]
b	0					1.086 ±0.035 $R_\oplus$
c	1					1.056 ±0.035 $R_\oplus$
d	0					0.772 ±0.030 $R_\oplus$
e						0.918 ±0.039 $R_\oplus$
f	0					1.045 ±0.038 $R_\oplus$
g	0.					1.127 ±0.041 $R_\oplus$
h	0.		(8.92 million km)			0.715 $^{+0.047}_{-0.043}$ $R_\oplus$

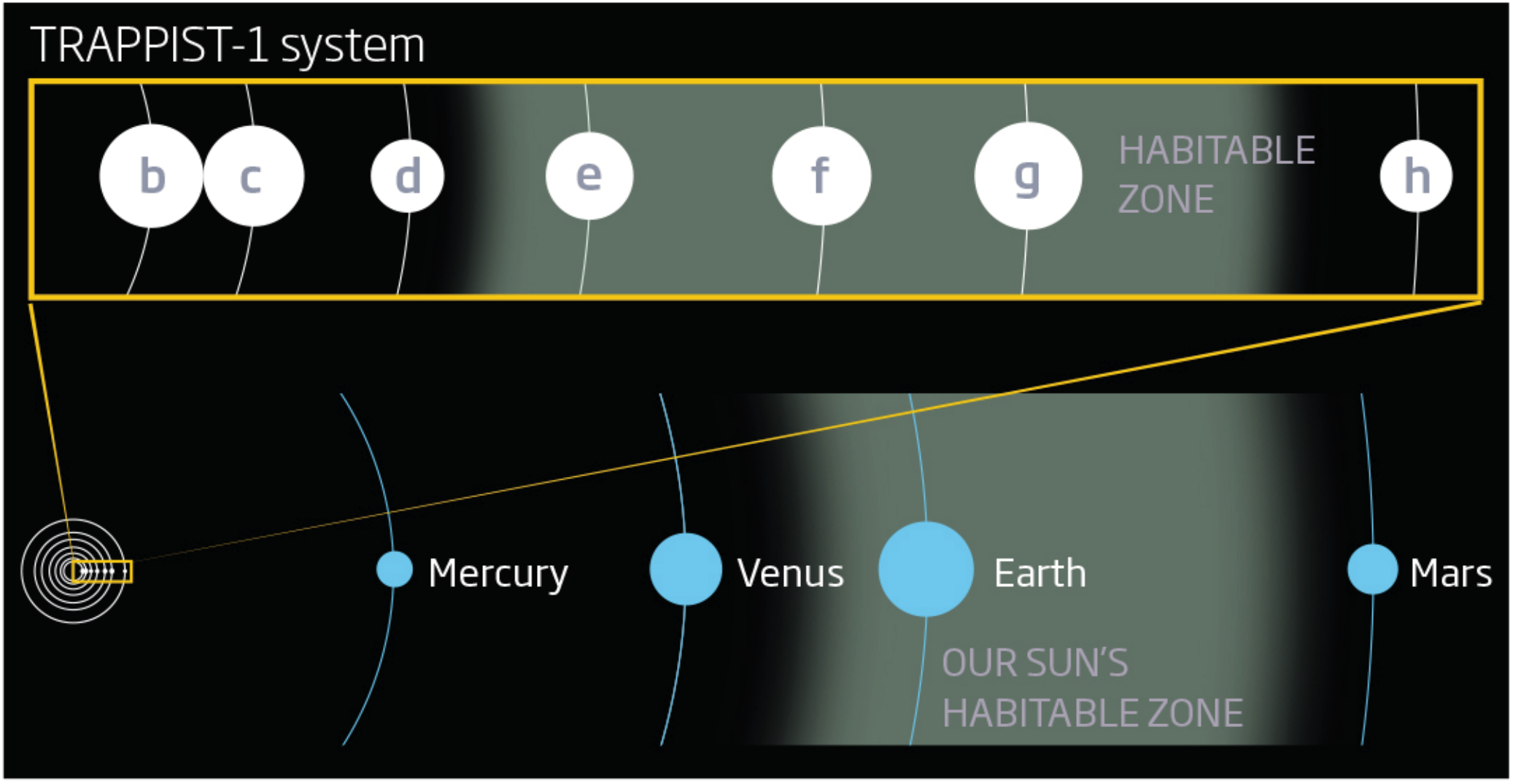
Spectral Type	M8V
Evolutionary Type	Main Sequence
Apparent V Magnitude	18.8
Distance	12.1 pc
Mass	0.08 $M_\odot$
Radius	0.114 $R_\odot$
Temperature	2550K
Age	3-8 Gyr
	Flares & Spot

Trappist-1 in the The HR Diagram

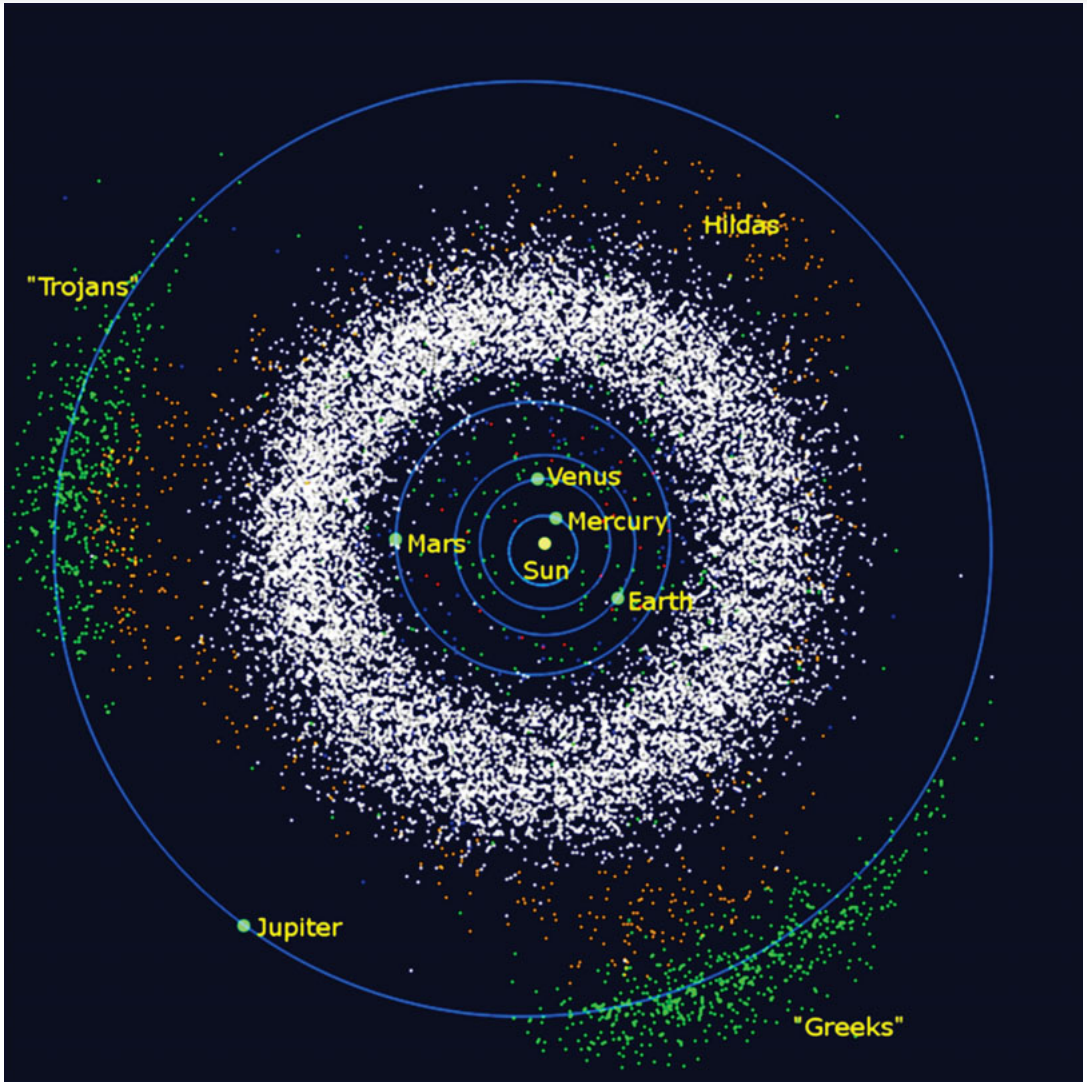



TRAPPIST-1 System
b
c
d
e
f
g
h
Enlarged 25x
Inner Solar System
Mercury
Venus
Earth
Mars
Illustration

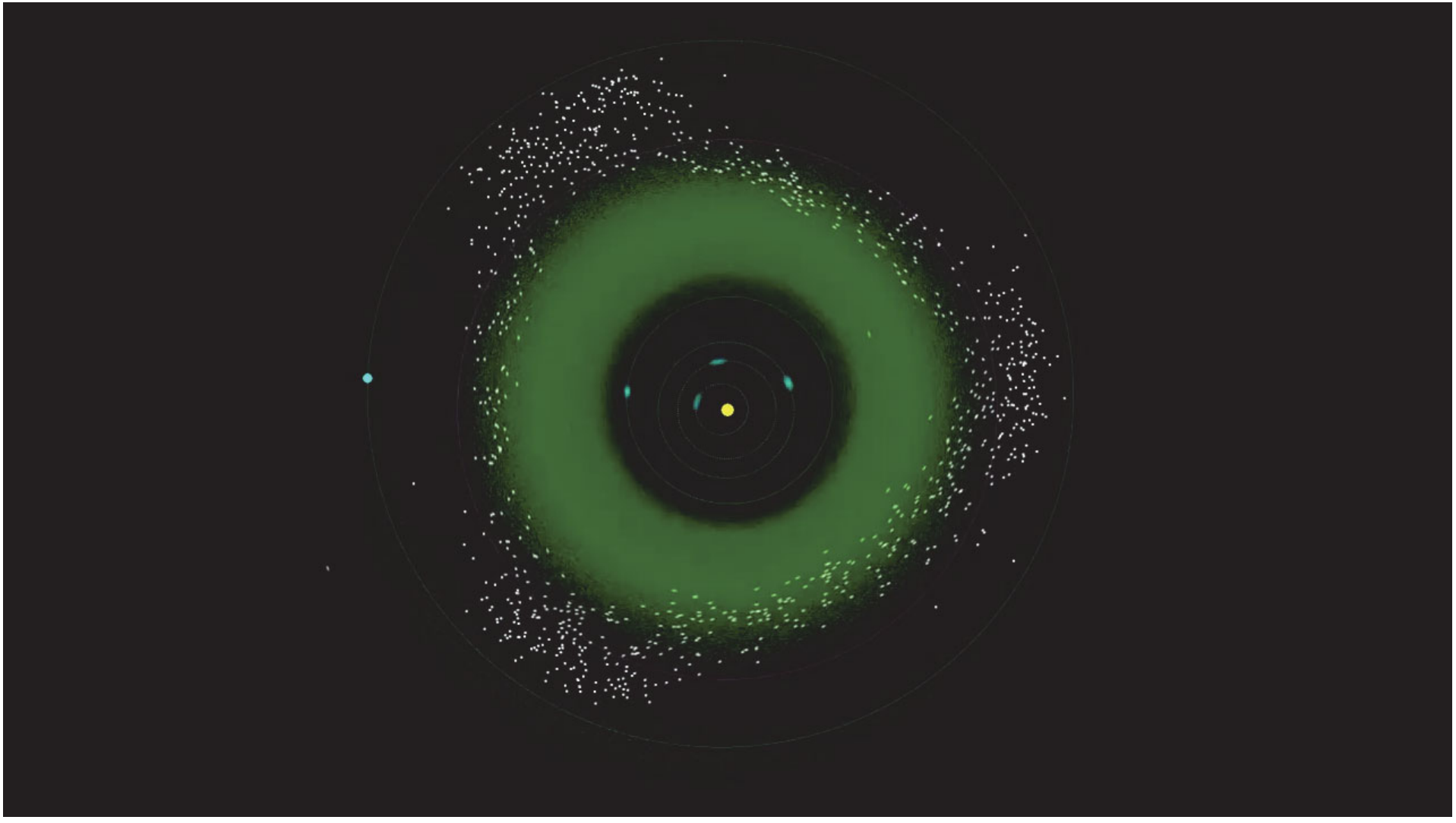
Trappist-1 Has 3 Planets in Its Habitable Zone!



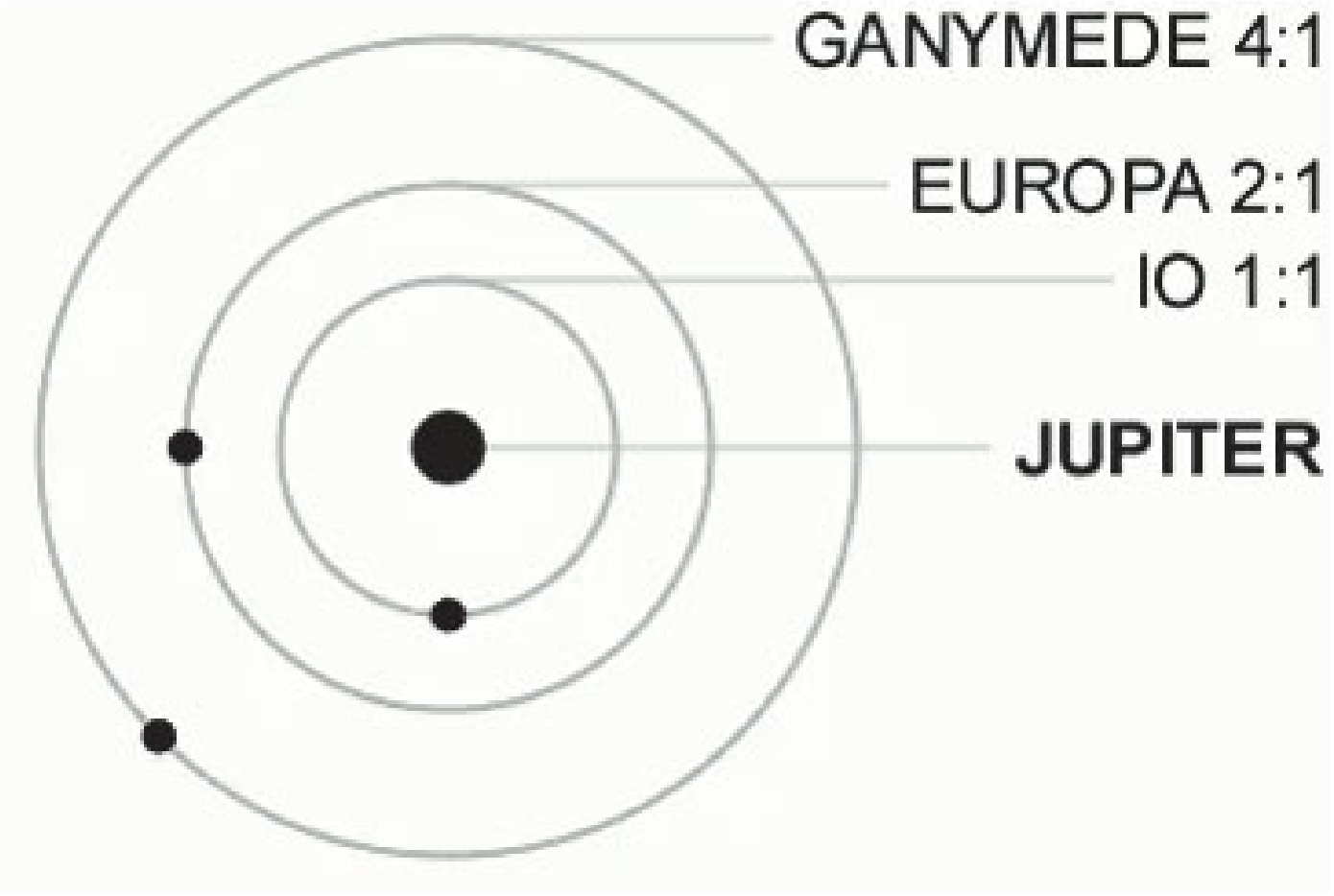
Mean Motion Resonance (MMR) ”Herds” the Asteroid Belt

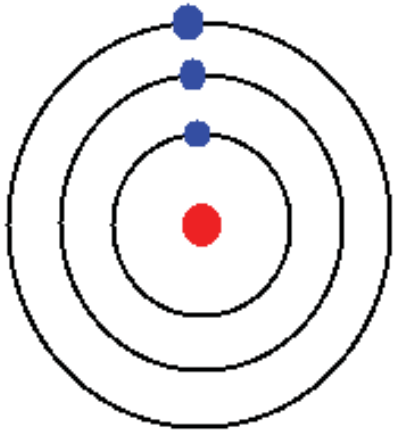


Mean Motion Resonance: The Asteroid Movie

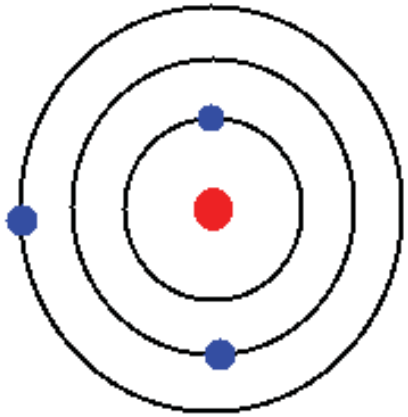


MMR − Multiples of Small Integers

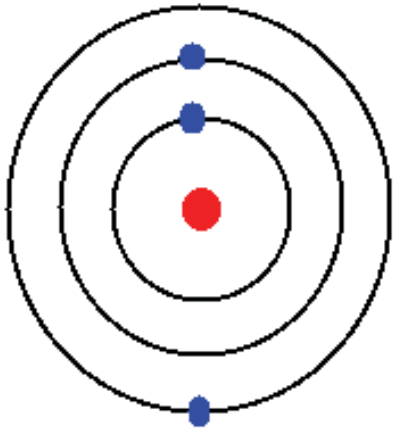




Start

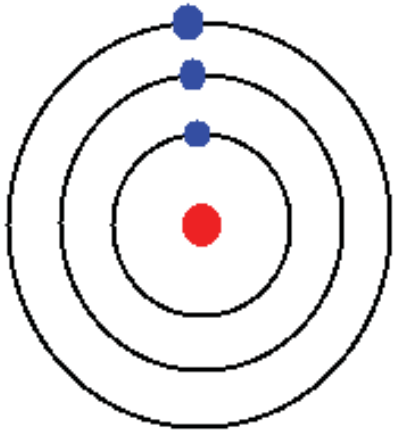


1 Io orbit later



2 Io orbits later

4 Io orbits later:



Resonances in Trappist-1 Are Very Complex!

The relative orbital periods (proceeding outward) approximate whole integer ratios of:

24/24, 24/15, 24/9, 24/6, 24/4, 24/3, and 24/2, respectively,

or nearest-neighbor period ratios of about:

8/5, 5/3, 3/2, 3/2, 4/3, and 3/2 (1.603, 1.672, 1.506, 1.509, 1.342, and 1.519)

The Nearest Star Hosts Exoplanets

- The star nearest the Sun hosts an exoplanet
- It is conceivable to send probes to that planet

NATURE | LETTER

日本語要約

A terrestrial planet candidate in a temperate orbit around Proxima Centauri

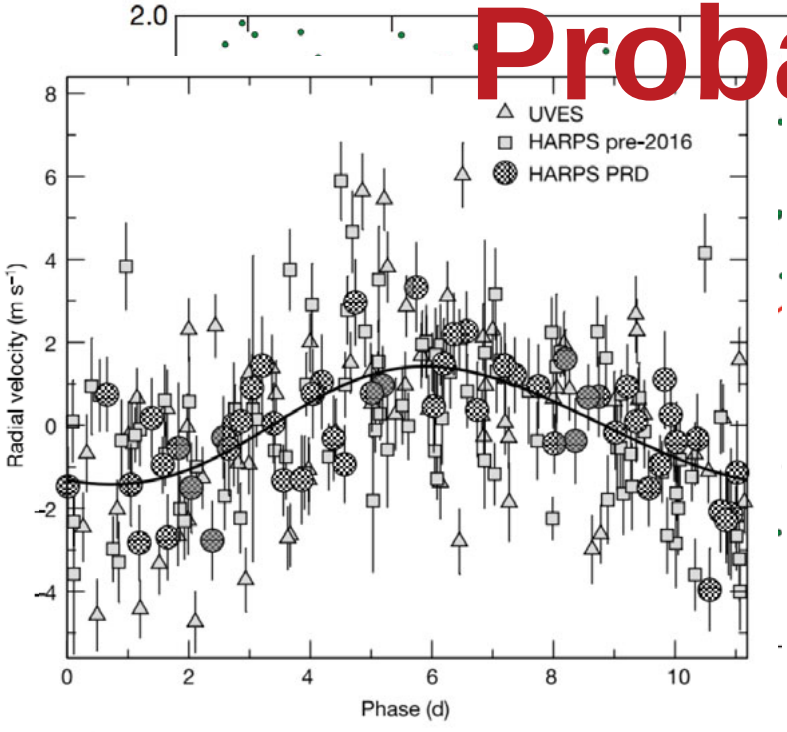
Guillem Anglada-Escudé, Pedro J. Amado, John Barnes, Zaira M. Berdiñas, R. Paul Butler, Gavin A. L. Coleman, Ignacio de la Cueva, Stefan Dreizler, Michael Endl, Benjamin Giesers, Sandra V. Jeffers, James S. Jenkins, Hugh R. A. Jones, Marcin Kiraga, Martin Kürster, María J. López-González, Christopher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

A terrestrial planet candidate in a temperate orbit around Proxima Centauri

Anglade-Escude et al (2016) Nature, 536, 437.

Nature, 2012,491, 207

Probably spurious ….



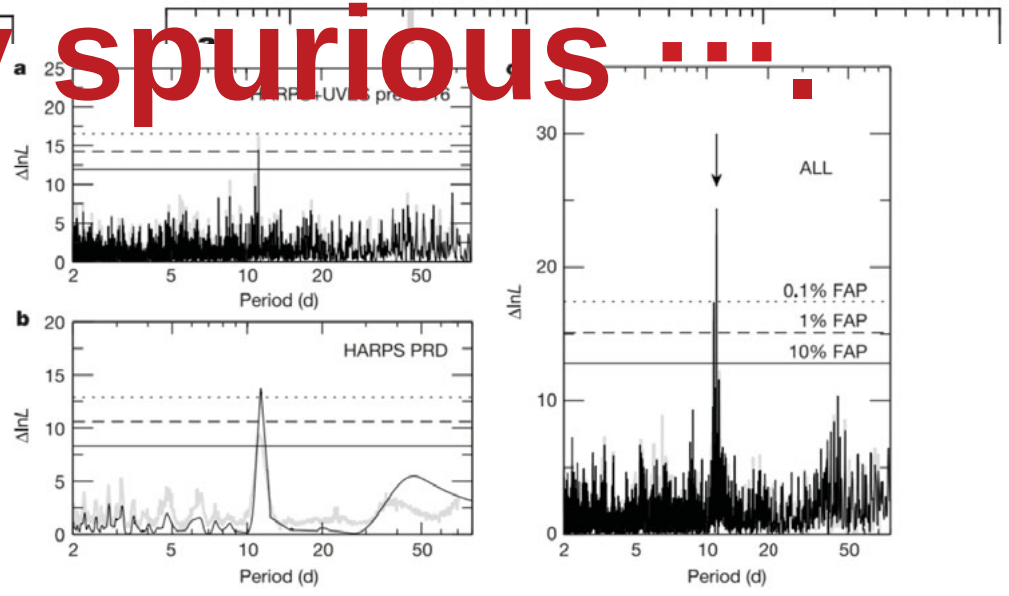
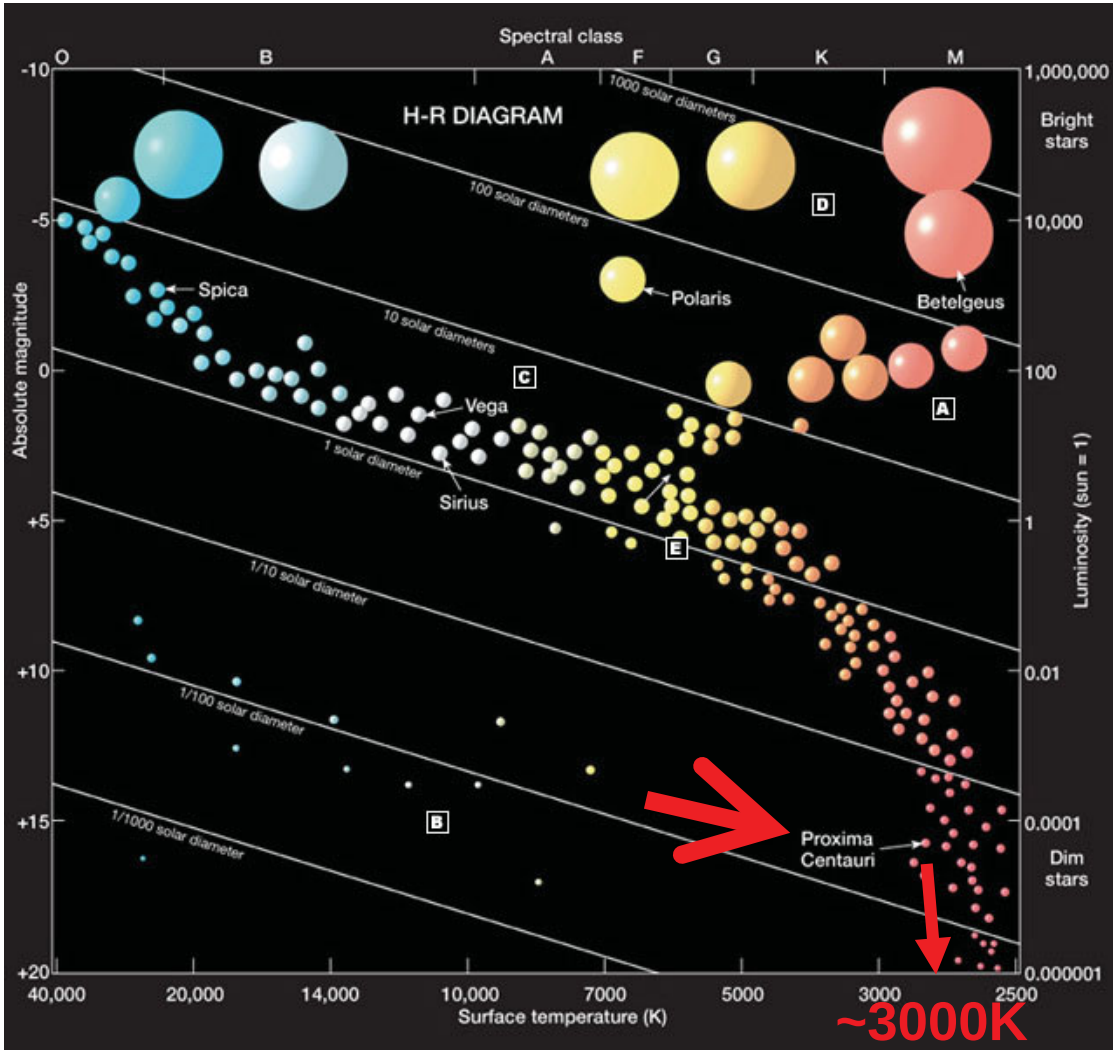


Figure 1 | Detection of a Doppler signal at 11.2 d. a, b, Detection periodograms of the 11.2 d signal in the HARPS+UVES pre-2016 data (**a**) and the HARPS PRD campaign only (**b**). **c,** The periodogram obtained after combining all of the data sets. Black lines correspond to the Δ ln*L* statistic, whereas the grey thick lines represent the logarithm of the Bayesian posterior density (see text, arbitrary vertical offset applied for visual comparison of the two statistics). The horizontal solid, dashed and dotted lines represent the FAP thresholds of the frequentist analysis.

Proxima Cen in the The HR Diagram



Sunset at your beach house on Proxima Cen b

* T of Quartz-Halogen Lamp is 3100K

Breakthrough Starshot takes its first step toward interstellar travel

First ... low Earth orbit. But eventually, these chip-sized spacecraft could explore Proxima Centauri.