Title: Exoplanets and the Search for Habitable Worlds

Date: Jun 23, 2015 04:10 PM

URL: http://pirsa.org/15060043

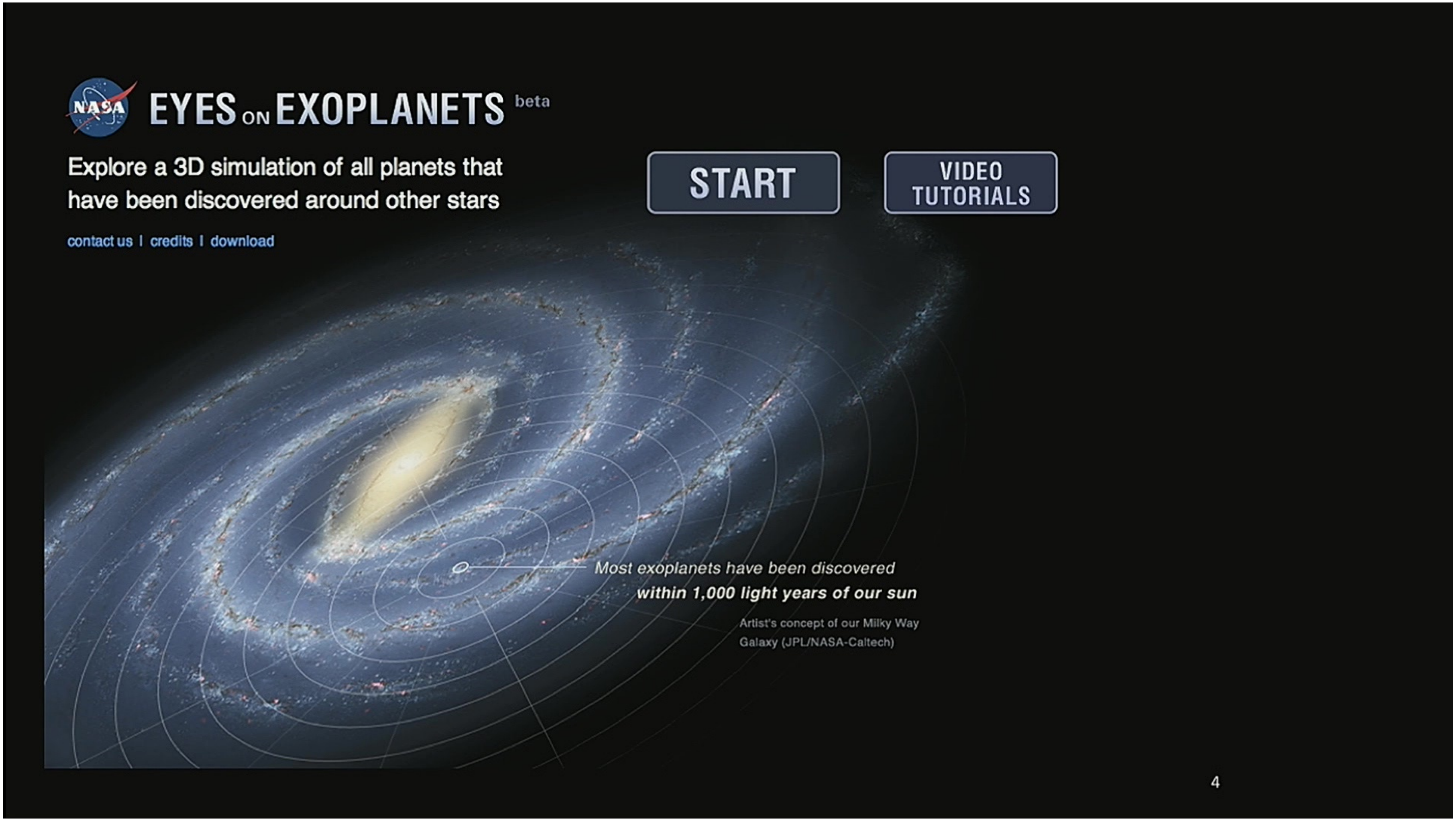
Abstract: Thousands of exoplanets are known to orbit nearby stars, with further evidence that every star in our Milky Way Galaxy has planets. Beyond their discovery, a new era of â€œexoplanet characterizationâ€• is underway with an astonishing diversity of exoplanets driving the fields of planet formation and evolution, interior structure, atmospheric science, and orbital dynamics to new depths. The push to find smaller and smaller planets down to Earth size is succeeding and motivating the next generation of space telescopes to have the capability to find and identify planets that may have suitable conditions for life or even signs of life by way of atmospheric biosignature gases. After thousands of years of people wondering â€œAre we alone?â€•, we are the first generation in human history to be able to make quantitative progress in answering this age-old question.

The Search for Habitable Worlds

✓Thousands of exoplanets are known and small (rocky) planets are common

✓Habitable planets are anticipated

✓The next generation telescopes will each have a chance at finding and/or identifying a habitable world



NASA
EYES ON EXOPLANETS beta
Explore a 3D simulation of all planets that have been discovered around other stars
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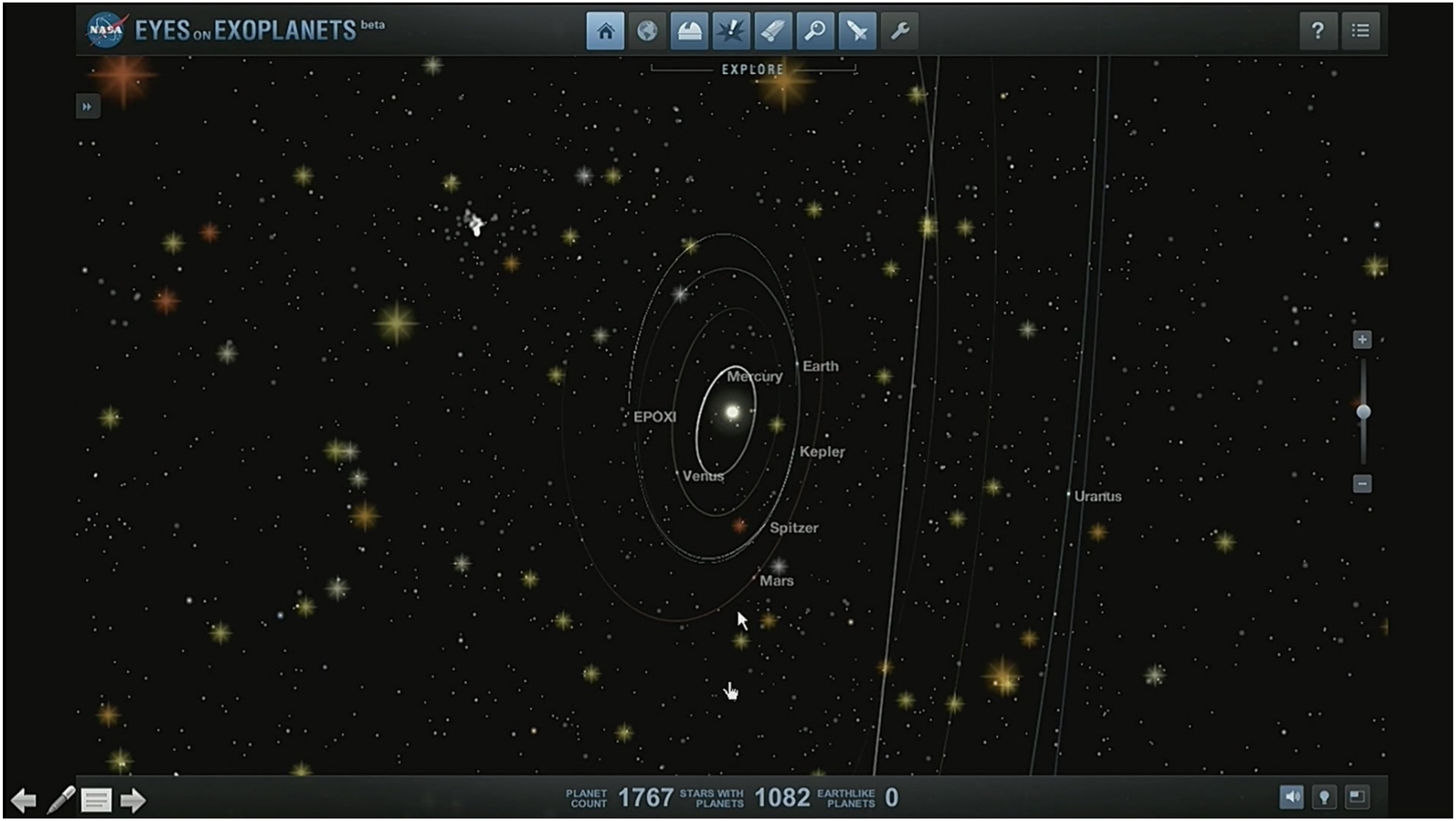
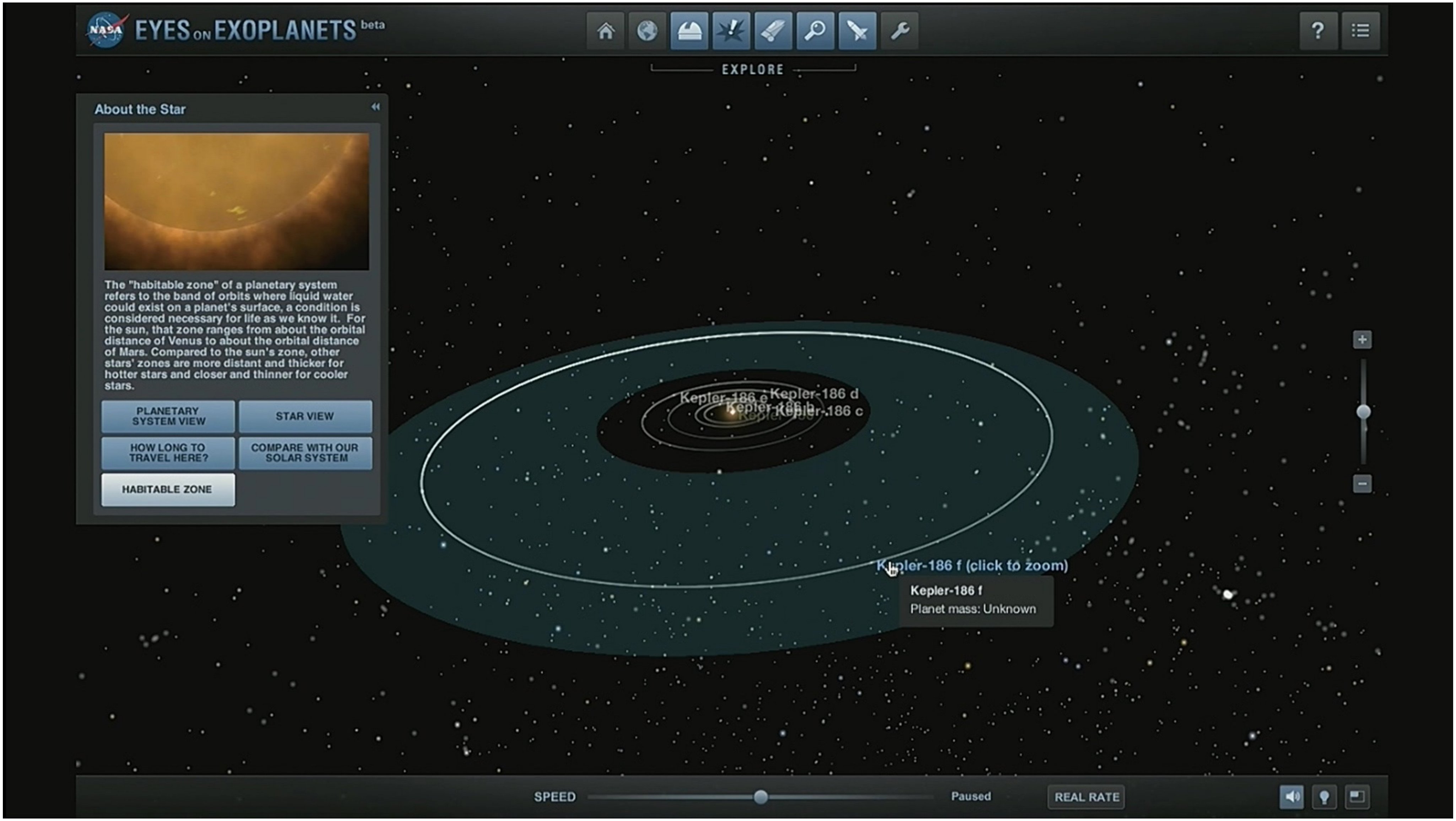
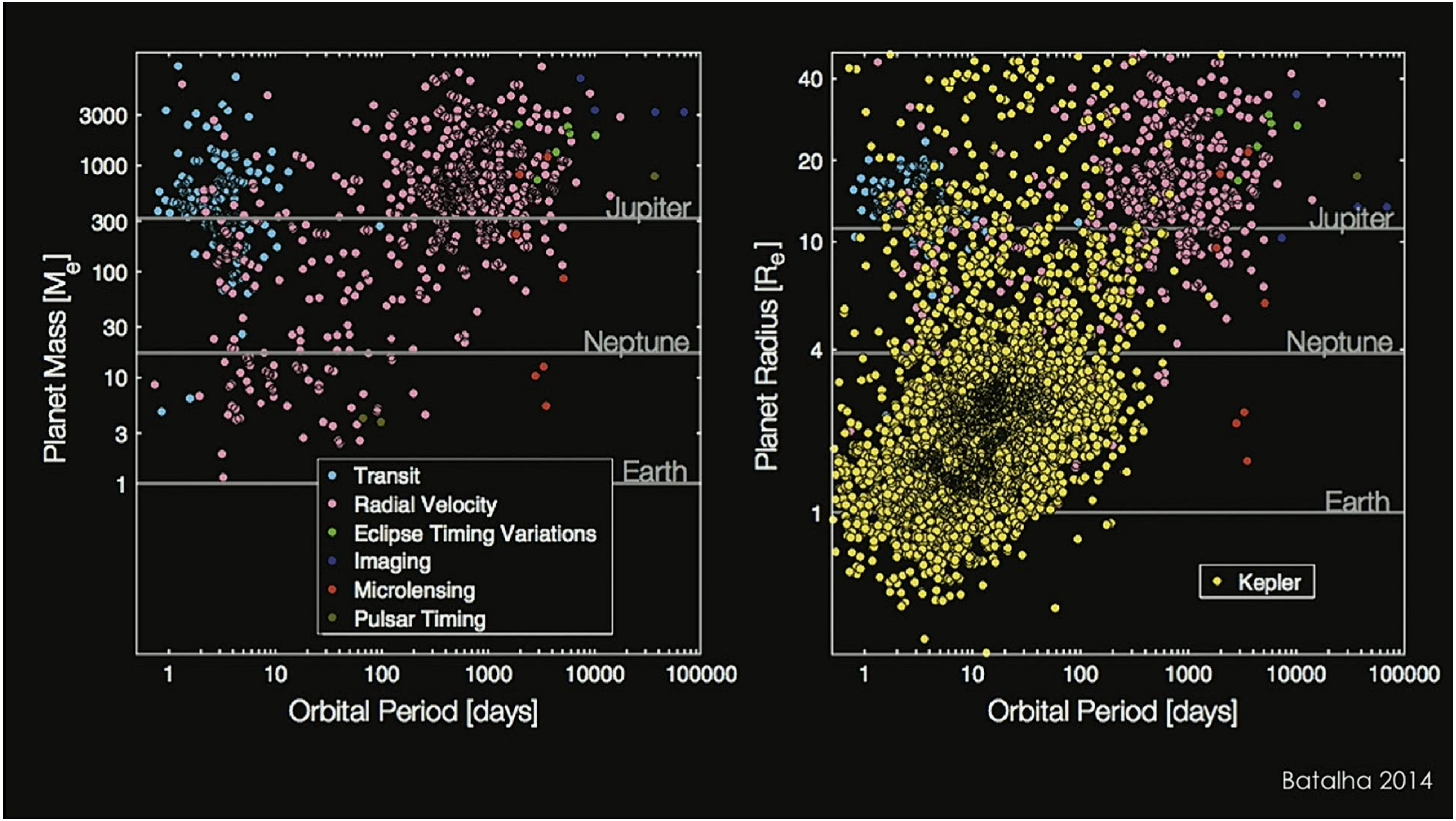
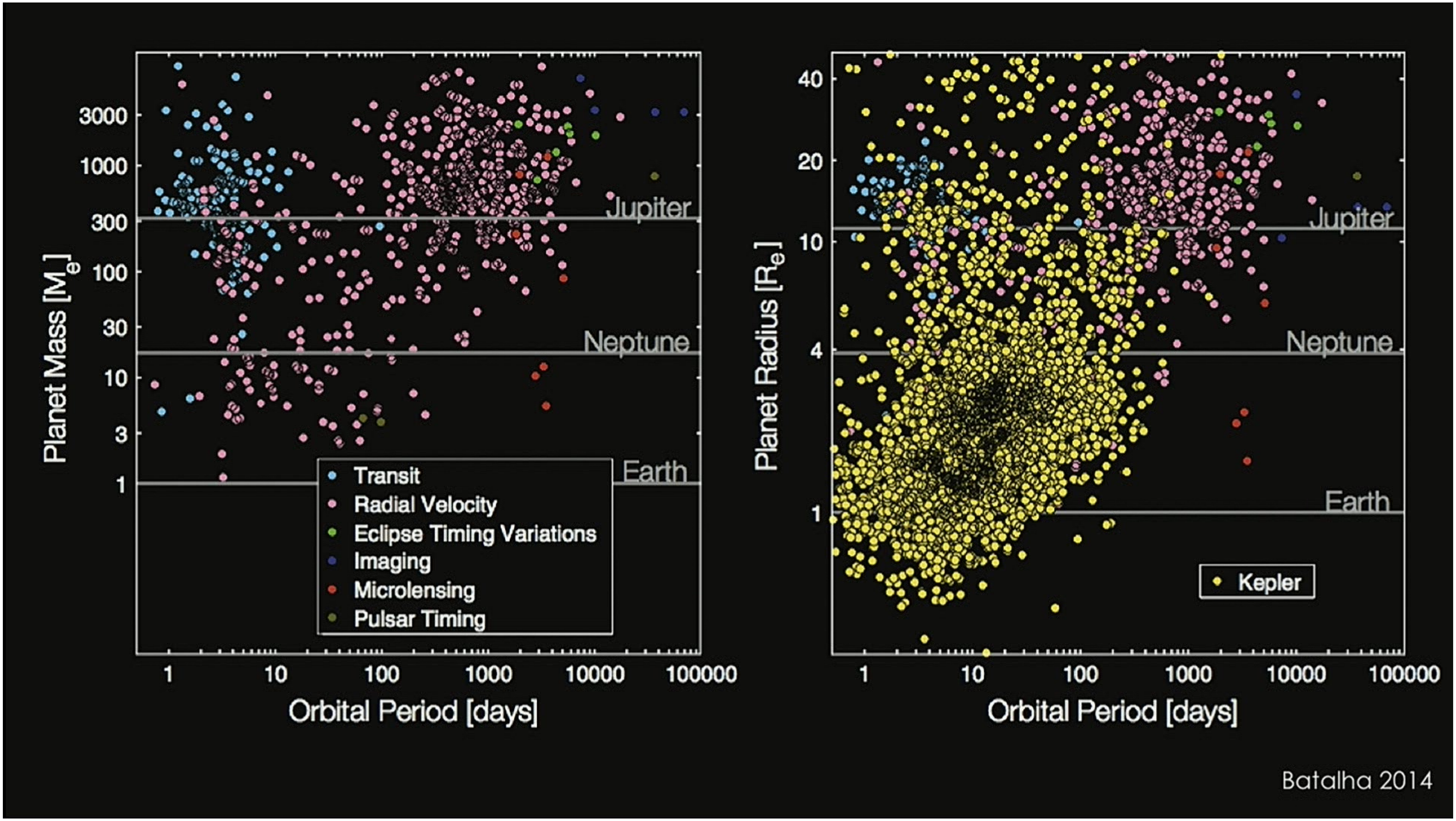
START
VIDEO TUTORIALS
Most exoplanets have been discovered within 1,000 light years of our sun
Artist's concept of our Milky Way Galaxy (JPL/NASA-Caltech)
4


EYES ON EXOPLANETS beta
EXPLORE
Earth
Mercury
EPOXI
Kepler
Venus
Uranus
Spitzer
Mars
PLANET COUNT 1767
STARS WITH PLANETS 1082
EARTHLIKE PLANETS 0


EYES ON EXOPLANETS beta
EXPLORE
About the Star
The "habitable zone" of a planetary system refers to the band of orbits where liquid water could exist on a planet's surface, a condition is considered necessary for life as we know it. For the sun, that zone ranges from about the orbital distance of Venus to about the orbital distance of Mars. Compared to the sun's zone, other stars' zones are more distant and thicker for hotter stars and closer and thinner for cooler stars.
PLANETARY SYSTEM VIEW
STAR VIEW
HOW LONG TO TRAVEL HERE?
COMPARE WITH OUR SOLAR SYSTEM
HABITABLE ZONE
Kepler-186 e
Kepler-186 d
Kepler-186 c
Kepler-186 f (click to zoom)
Kepler-186 f
Planet mass: Unknown
SPEED
Paused
REAL RATE


Planet Mass [M_e]
3000
1000
300
100
30
10
3
1
Jupiter
Neptune
Earth
Transit
Radial Velocity
Eclipse Timing Variations
Imaging
Microlensing
Pulsar Timing
1
10
100
1000
10000
100000
Orbital Period [days]
Planet Radius [R_e]
40
20
10
4
1
Jupiter
Neptune
Earth
Kepler
1
10
100
1000
10000
100000
Orbital Period [days]
Batalha 2014



Planet Mass [M_e]
3000
1000
300
100
30
10
3
1
Jupiter
Neptune
Earth
Transit
Radial Velocity
Eclipse Timing Variations
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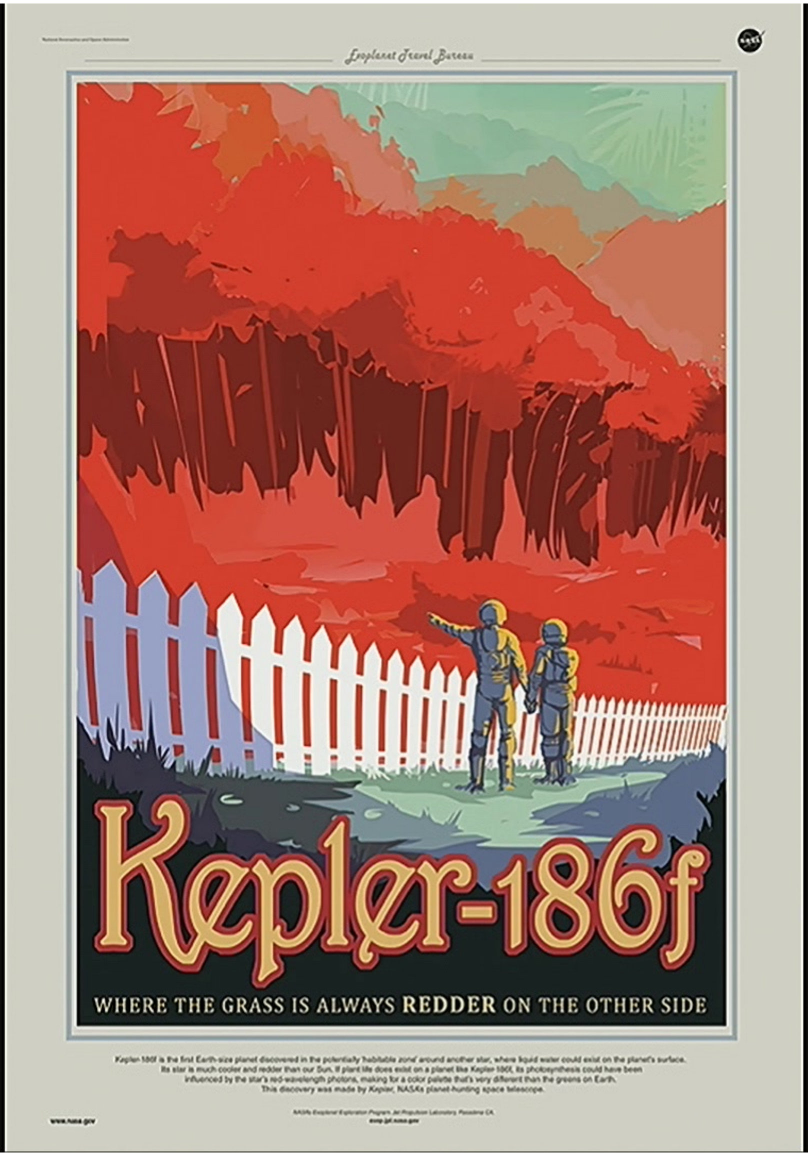
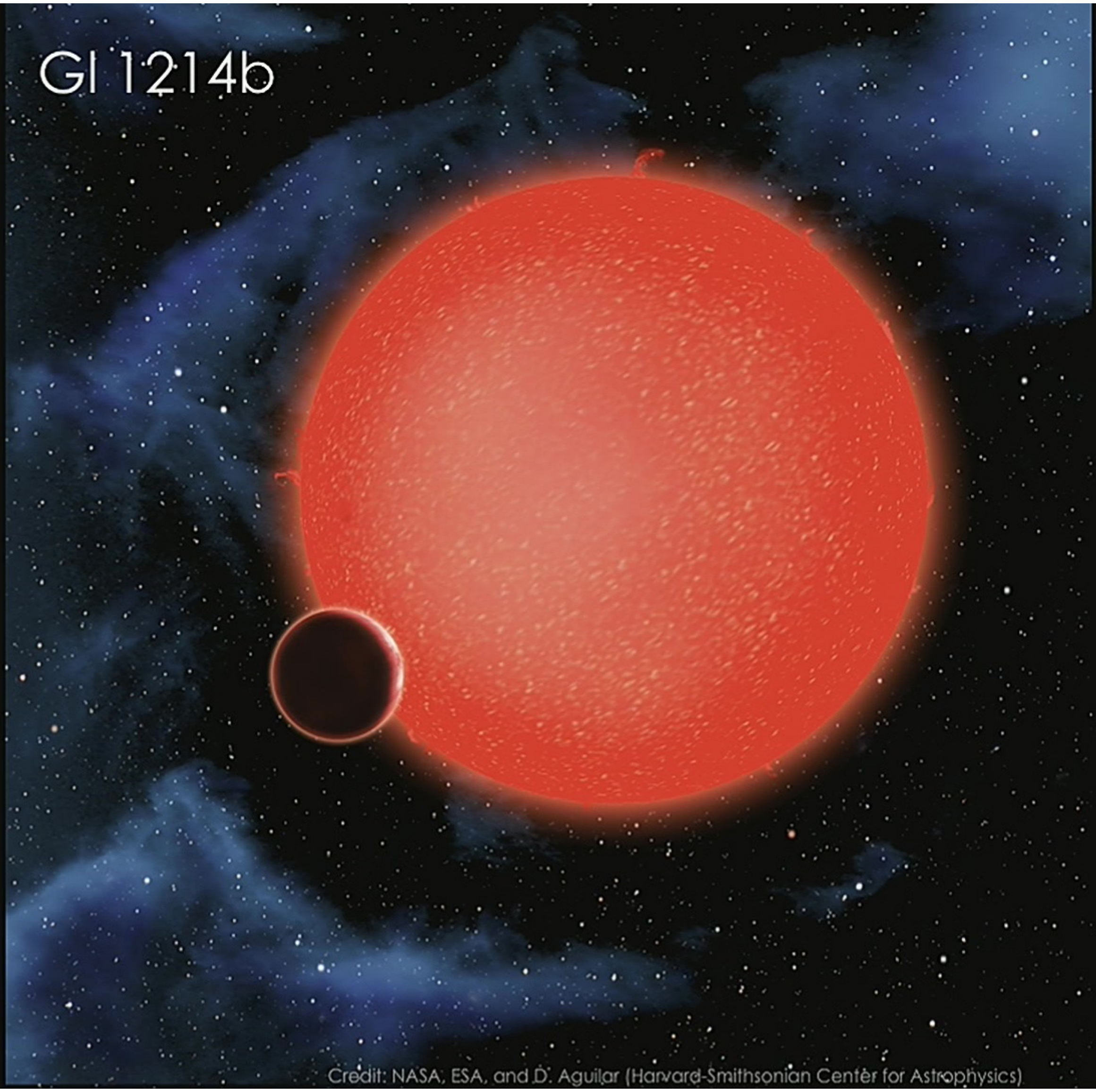
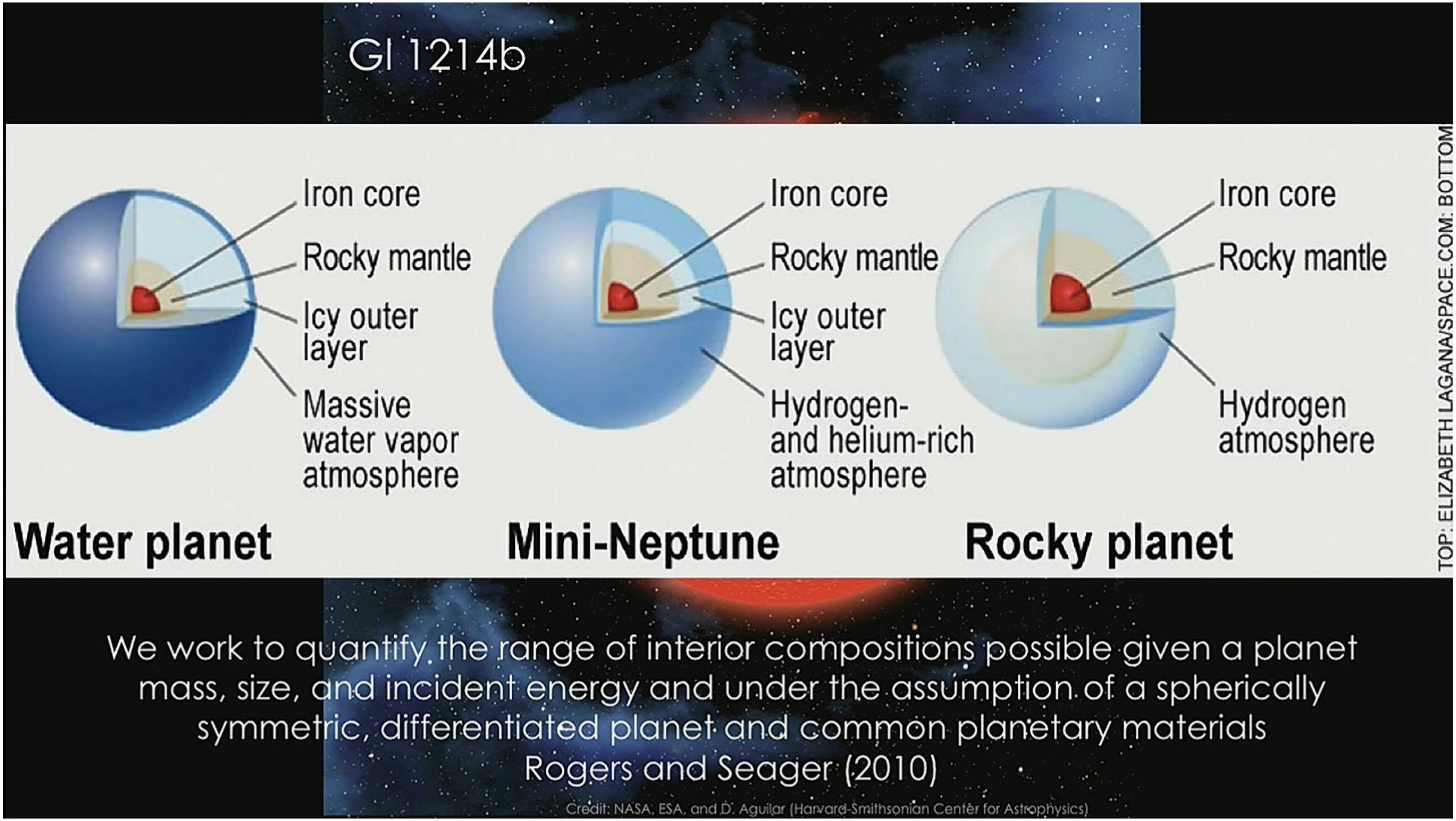
1
10
100
1000
10000
100000
Orbital Period [days]
Batalha 2014

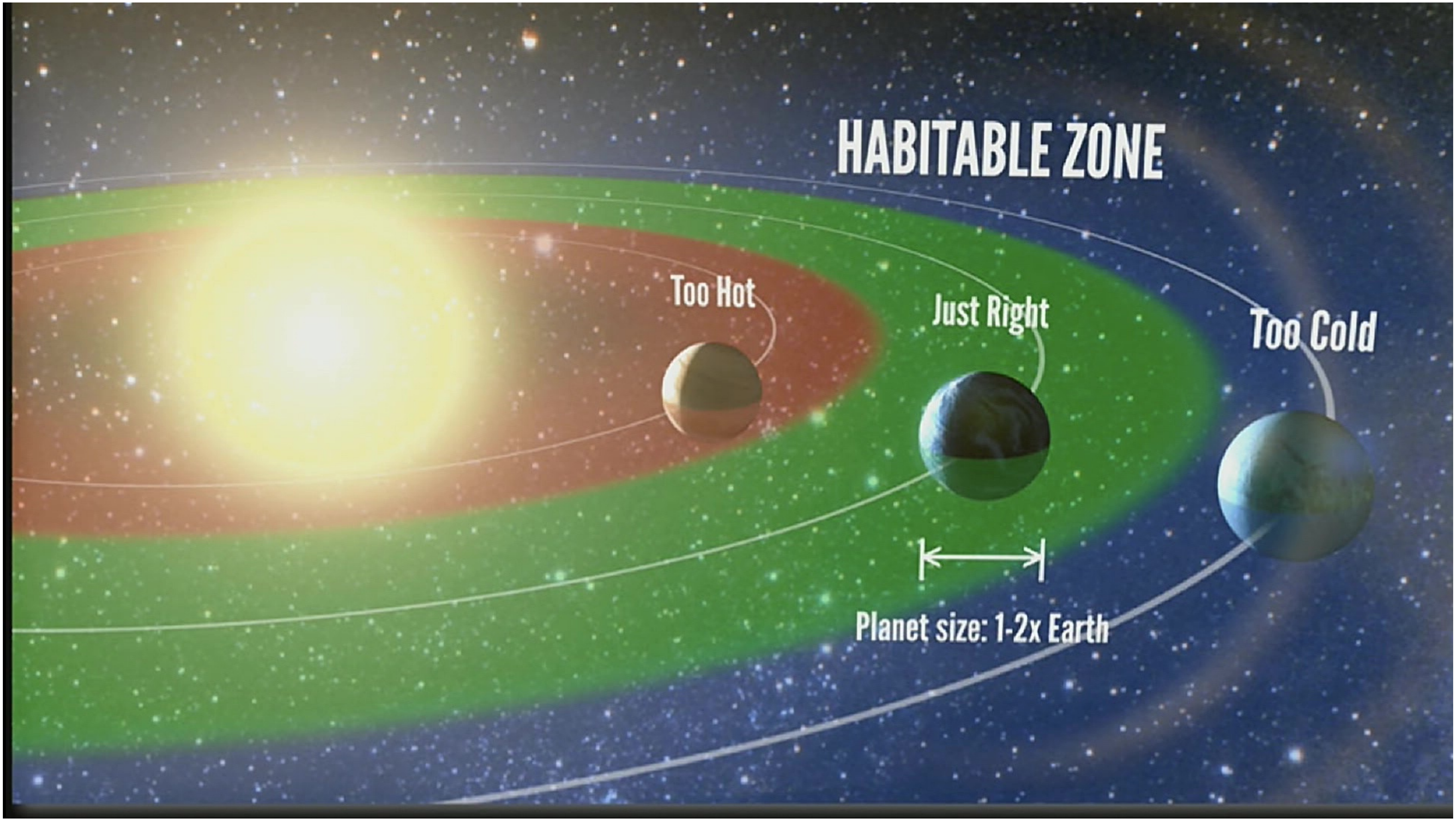

Exoplanet Travel Bureau
Kepler-186f
WHERE THE GRASS IS ALWAYS REDDER ON THE OTHER SIDE
Kepler-186f is the first Earth-size planet discovered in the potentially 'habitable zone' around another star, where liquid water could exist on the planet's surface.
Its star is much cooler and redder than our Sun. If plant life does exist on a planet like Kepler-186f, its photosynthesis could have been
influenced by the star's red-wavelength photons, making for a color palette that's very different than the greens on Earth.
This discovery was made by Kepler, NASA's planet-hunting space telescope.
NASA's Exoplanet Exploration Program, Jet Propulsion Laboratory, Pasadena CA.
exep.jpl.nasa.gov
www.nasa.gov

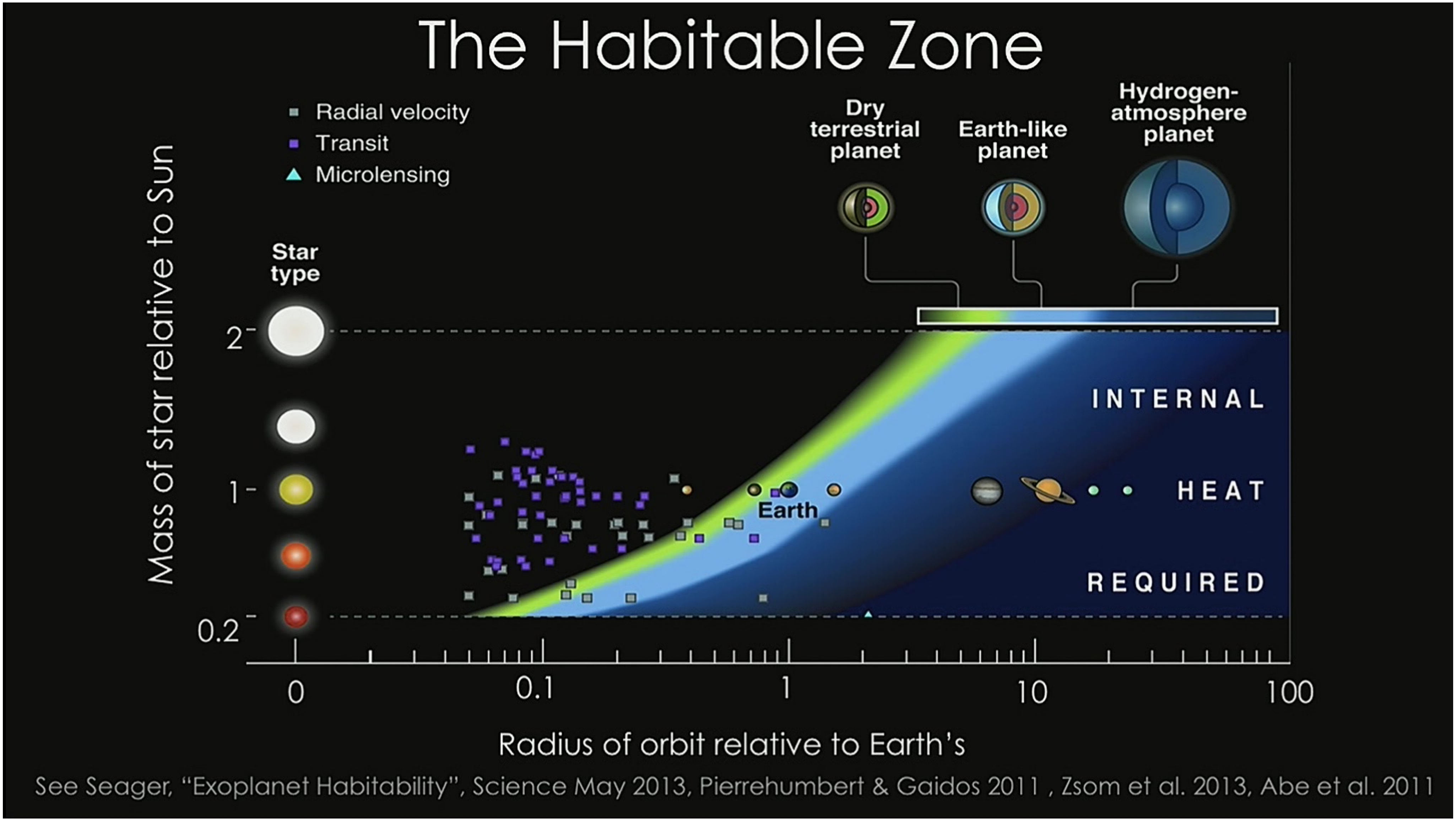

Gl 1214b
Credit: NASA, ESA, and D. Aguilar (Harvard-Smithsonian Center for Astrophysics)

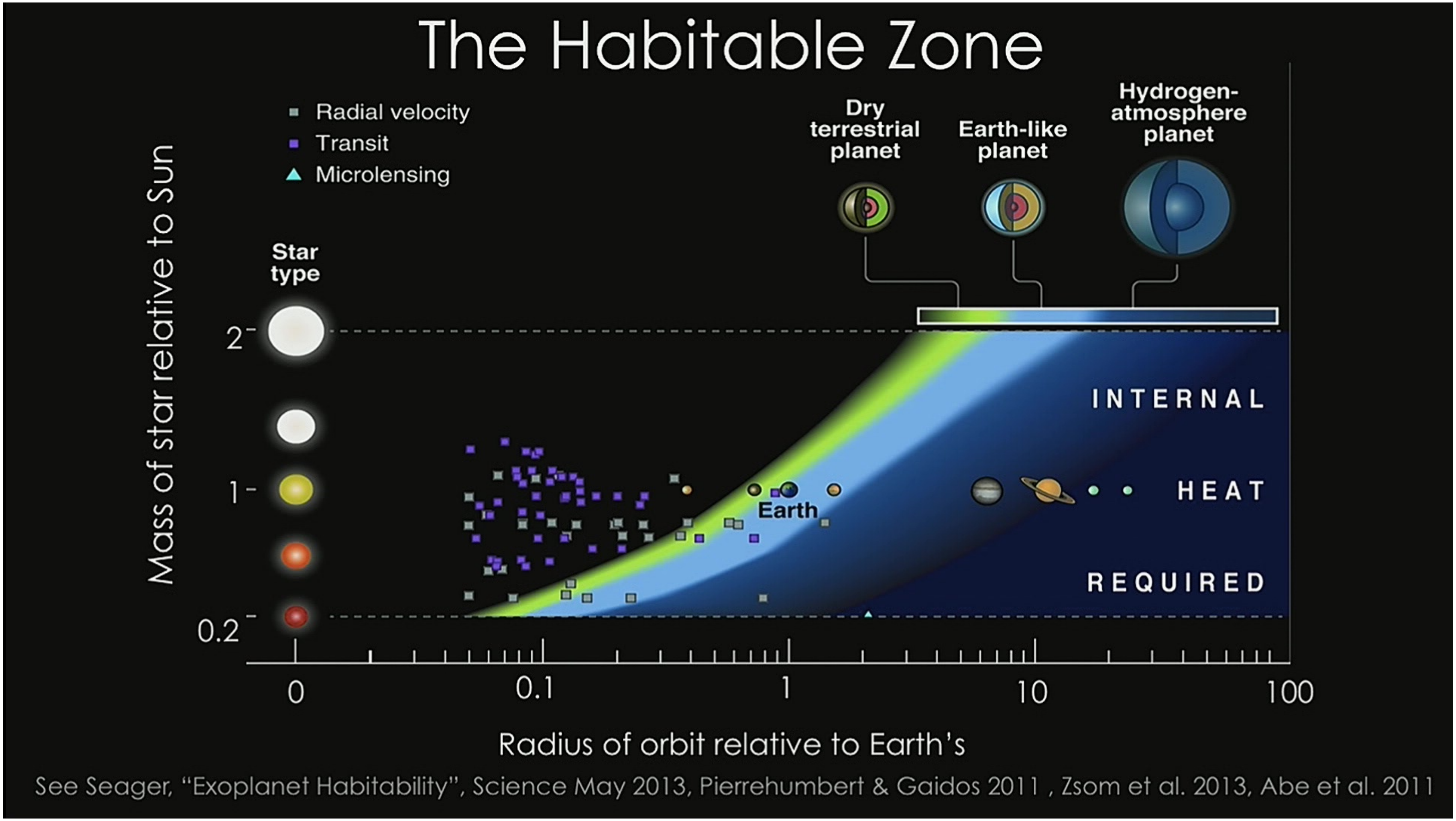

Gl 1214b
Iron core
Rocky mantle
Icy outer layer
Massive water vapor atmosphere
Water planet
Iron core
Rocky mantle
Icy outer layer
Hydrogen- and helium-rich atmosphere
Mini-Neptune
Iron core
Rocky mantle
Hydrogen atmosphere
Rocky planet
TOP: ELIZABETH LAGANA/SPACE.COM; BOTTOM
We work to quantify the range of interior compositions possible given a planet mass, size, and incident energy and under the assumption of a spherically symmetric, differentiated planet and common planetary materials
Rogers and Seager (2010)
Credit: NASA, ESA, and D. Aguilar (Harvard-Smithsonian Center for Astrophysics)

Thousands of exoplanets are known

- Exoplanets are diverse, covering nearly all masses, sizes, orbits possible
- Small planets (~twice Earth's size) are nearly ten times as common as Jupiter-size planets, challenging formation theory
- For many planets, despite having measured masses and radii, ambiguity remains


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


The Habitable Zone
Radial velocity
Transit
Microlensing
Mass of star relative to Sun
Star type
2
1
0.2
Dry terrestrial planet
Earth-like planet
Hydrogen-atmosphere planet
INTERNAL
HEAT
REQUIRED
Earth
0
0.1
1
10
100
Radius of orbit relative to Earth's
See Seager, "Exoplanet Habitability", Science May 2013, Pierrehumbert & Gaidos 2011 , Zsom et al. 2013, Abe et al. 2011


The Habitable Zone
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Dry terrestrial planet
Earth-like planet
Hydrogen-atmosphere planet
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Mass of star relative to Sun
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0
0.1
1
10
100
Radius of orbit relative to Earth's
See Seager, "Exoplanet Habitability", Science May 2013, Pierrehumbert & Gaidos 2011 , Zsom et al. 2013, Abe et al. 2011


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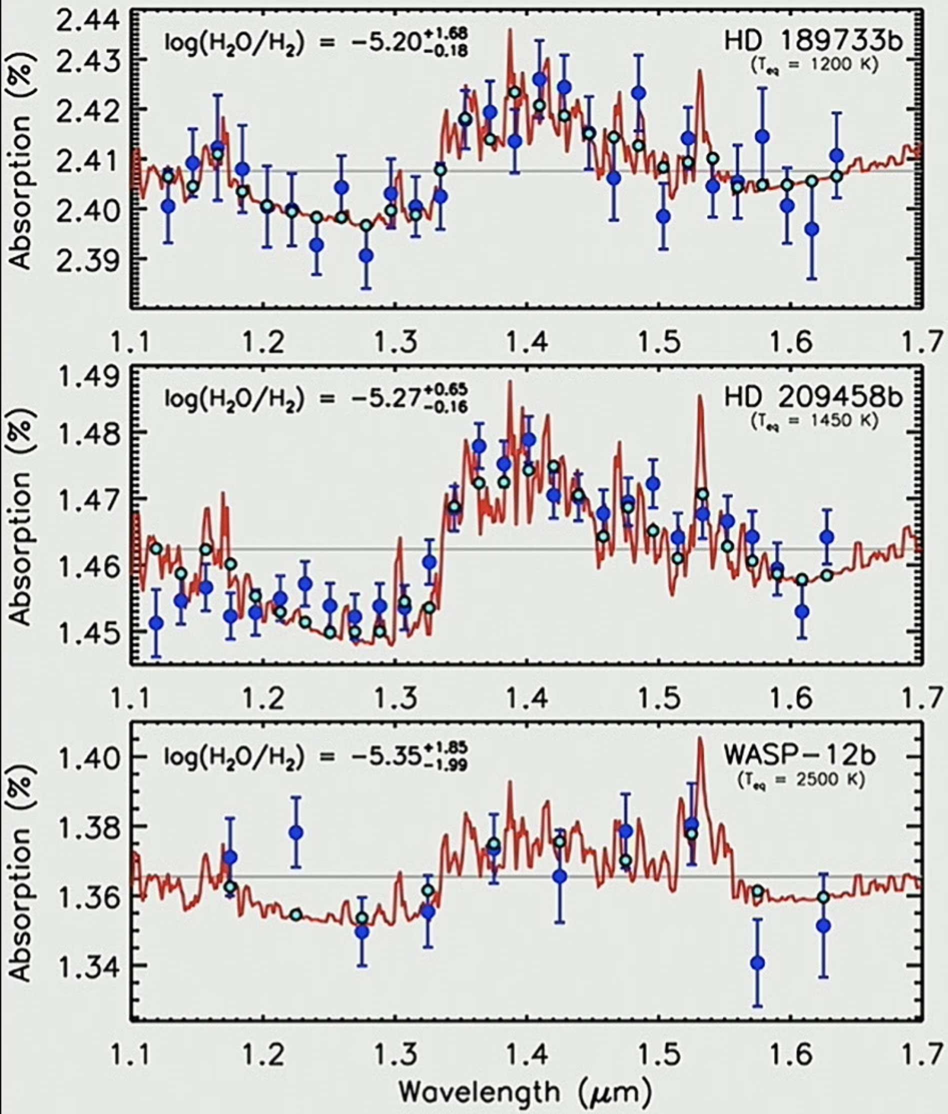
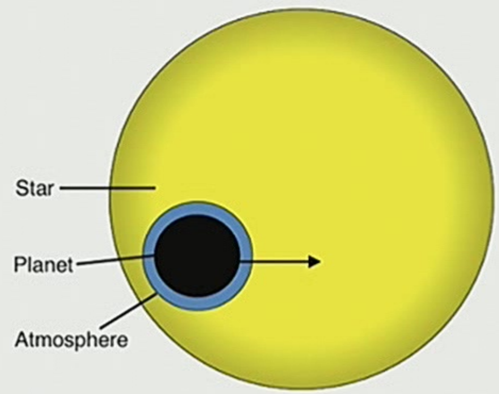
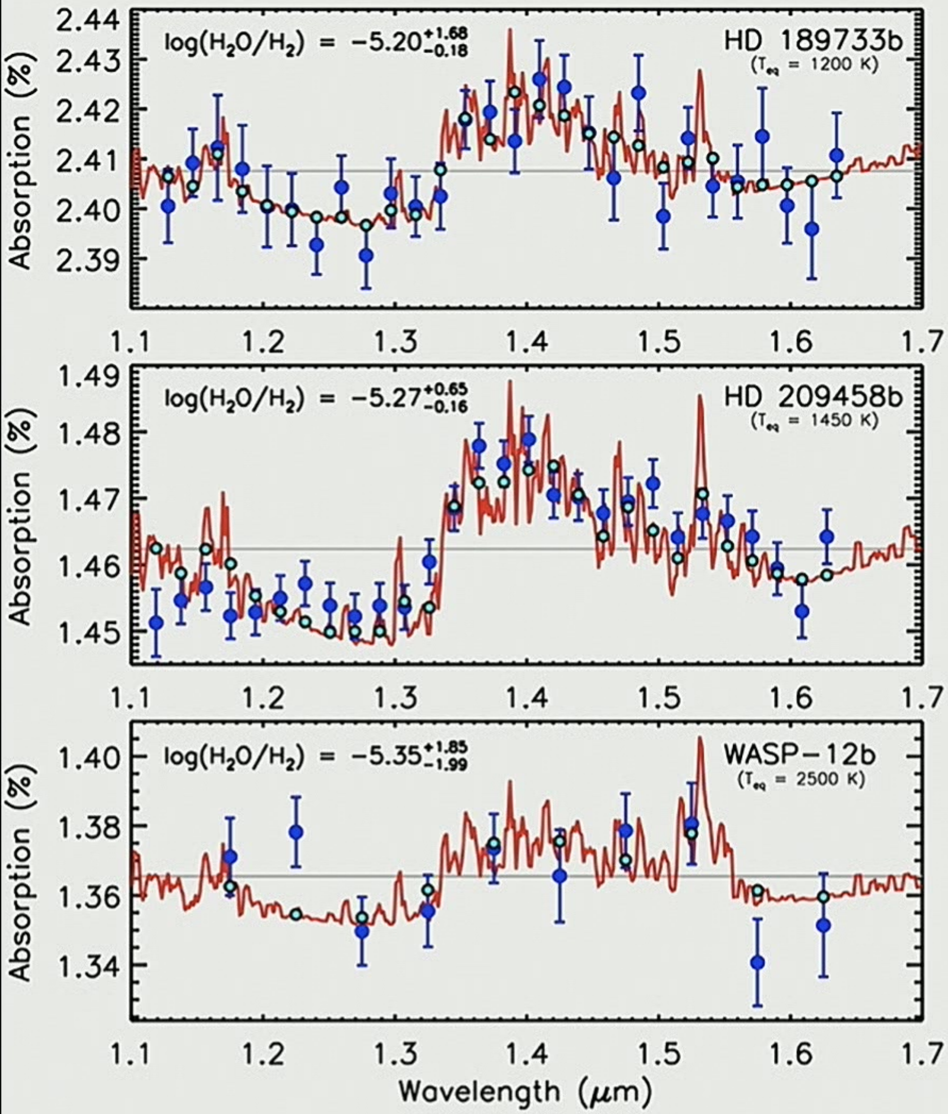


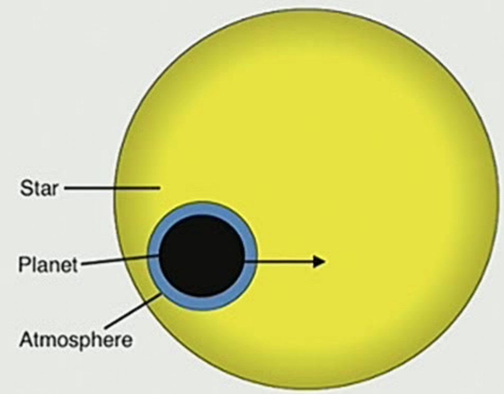
Water Vapor in Three Hot Jupiters



Madhusudhan et al. 2014

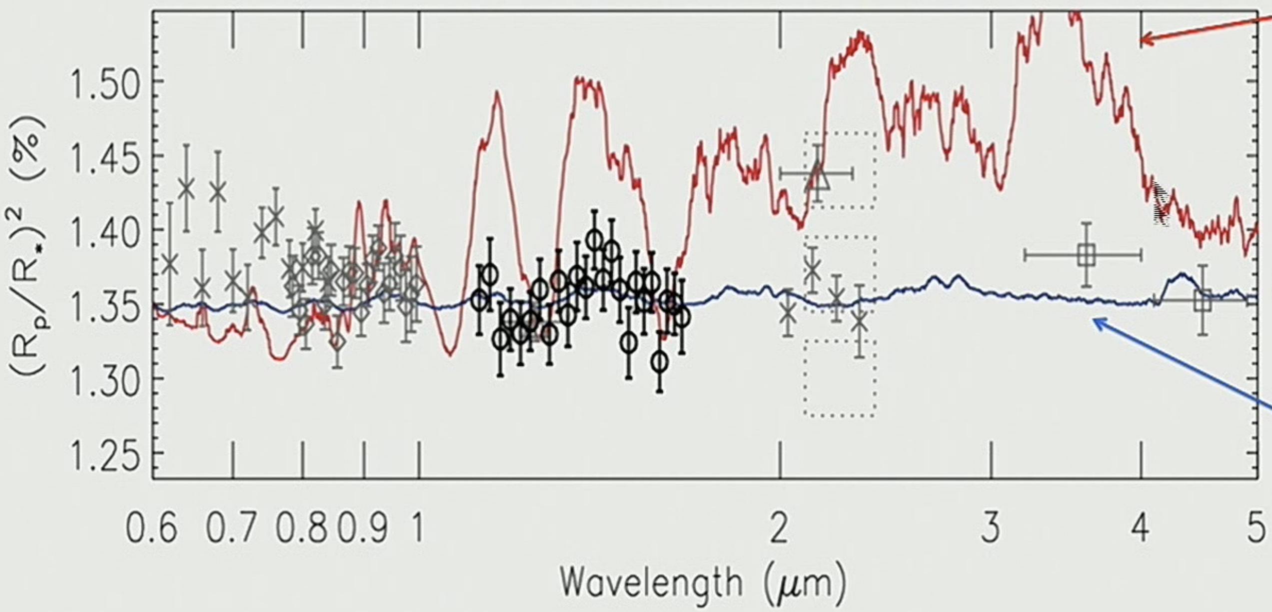
Water Vapor in Three Hot Jupiters

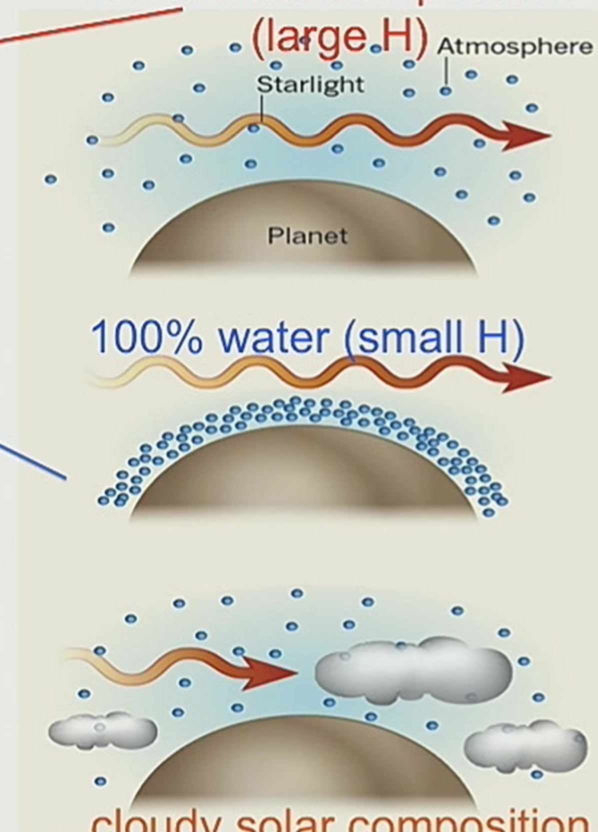




Madhusudhan et al. 2014

GJ1214b: A Current Mystery



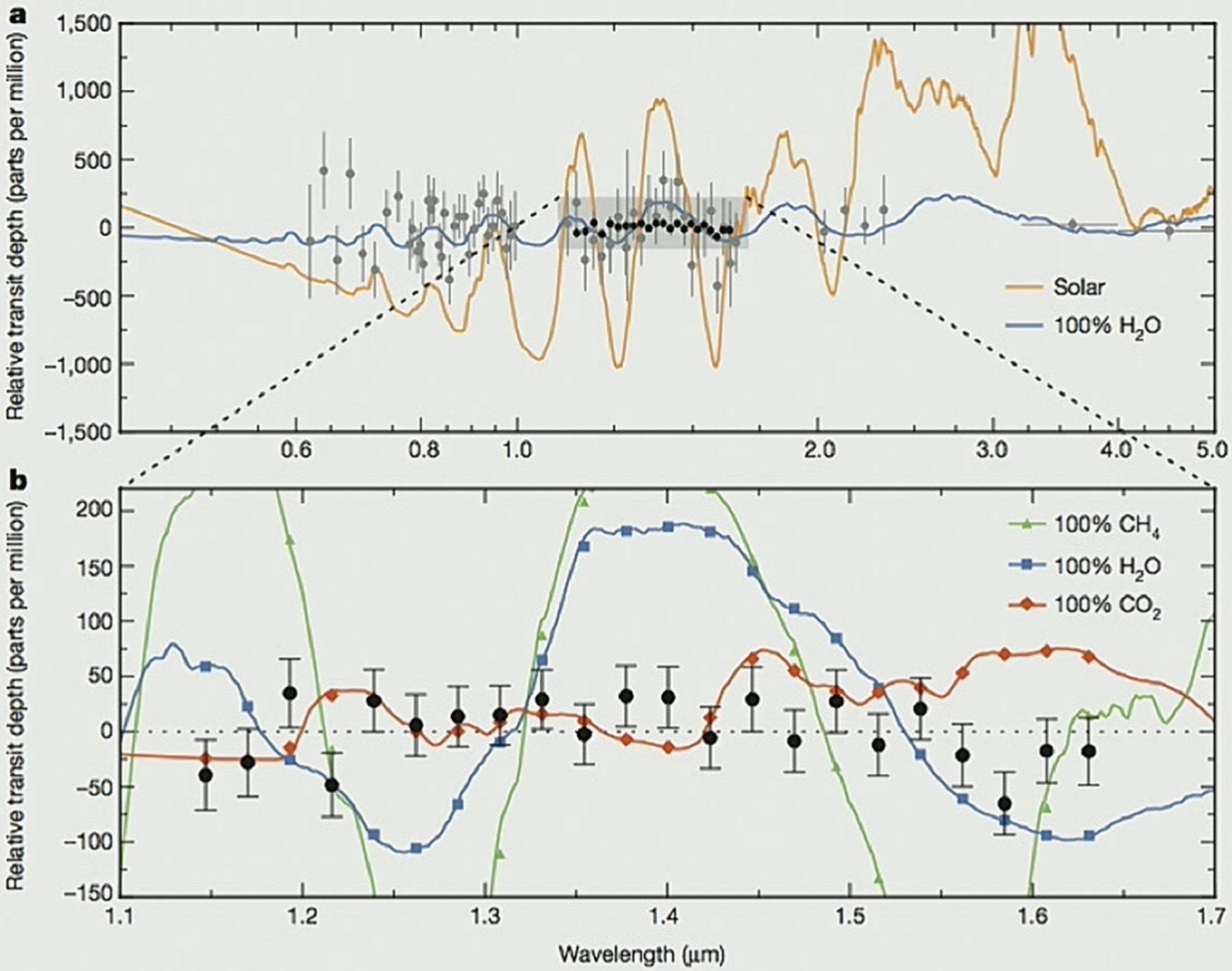


◇ VLT (Bean et al. 2010)
□ Spitzer (Désert et al. 2011)
△ CFHT (Croll et al. 2011)
⋯ Keck (Crossfield et al. 2011)
× VLT/Magellan (Bean et al. 2011)
O WFC3 (this work)

strength of spectral features:

$$\Delta D \sim \frac{5HR_p}{R_*^2} \quad H = \frac{kT}{\mu m_H g}$$

Courtesy J. Bean



Kreidburg et al. 2014

GJ 1214b
HST WFC3

A permanent mystery?

For many exoplanets, ambiguity remains in bulk interior or atmospheric compositon or both. Interpretation will remain limited even with precision measurements

Compound name	Formula	Typical atmospheric concentration	Primary terrestrial atmospheric source	Example of biological production
Nitrogen	N_2	78%	-	Denitrifying bacteria
Oxygen	O_2	21%	Photosynthesis	Photosynthesis
Water	H_2O	1% - 4%	Evaporation	Respiration
Argon	Ar	9340 ppm	Outgassing	*Not produced*
Carbon dioxide	CO_2	350 ppm	Outgassing, biology, anthropogenic	Respiration
Neon	Ne	18.18 ppm	Outgassing	*Not produced*
Helium	^4He	5.24 ppm	Outgassing	*Not produced*
Methane	CH_4	1.7 ppm	Biology	Methanogenesis
Krypton	Kr	1.14 ppm	Outgassing	*Not produced*
Hydrogen	H_2	0.55 ppm	H_2O photolysis	Hydrogenase H_2 production in phototrophs
Nitrous Oxide	N_2O	320 ppb	Biology	Ammonia oxidation (nitrification)
Carbon monoxide	CO	125 ppb	Photochemistry	Mammalian CO signaling
Xenon	Xe	87 ppb	Outgassing	*Not produced*
Ozone	O_3	10 – 100 ppb	Photochemistry	Inflammation in animals
Hydrogen chloride	HCl	~1 ppb	Sea salt	Halocarbon metabolism (as chloride)
Isoprene	C_5H_8	1 – 3 ppb	Plants	Trees
Ethane	C_2H_6	0.2 – 3 ppb	Fires, oceans, anthropogenic	Oceanic bacterial metabolism
Benzene	C_6H_6	0.1 – 1 ppb	Anthropogenic	Made by mushrooms, trees
Ammonia	NH_3	0.1 – 3 ppb	Biology	Nitrogen fixation by many bacteria
Nitric acid	HNO_3	0.04 – 4 ppb	Photochemistry	Nitrifying bacteria (as nitrate)
Methyl chloride	CH_3Cl	612 ppt	Biology	Oceanic bacteria
Carbonyl sulfide	OCS	500 ppt	Biology	Lichens in soils
Nitric oxides	NO, NO_2	30 – 300 ppt	Biology	Ammonia oxidizing bacteria
Difluorodichloro methane	CCl_2F_2	300 ppt	Entirely anthropogenic	Anthropogenic
Trichlorofluorom ethane	$CClF_3$	178 ppt	Entirely anthropogenic	Anthropogenic
Trichloroethane	CH_3CCl_3	157 ppt	Anthropogenic	Seaweed
Tetrachlorometh ane	CCl_4	121 ppt	Anthropogenic	Seaweed
Tetrafluorometha ne	CF_4	69 ppt	Entirely anthropogenic	Anthropogenic
Chlorodifluorom ethane	$CHClF_2$	59 ppt	Entirely anthropogenic	Anthropogenic
Hydrogen sulfide	H_2S	30 – 100 ppt	Biology	Sulfide reducing bacteria
F113	$C_2Cl_3F_3$	30 – 40 ppt	Entirely anthropogenic	Anthropogenic
(...)				

All gases present in Earth's atmosphere to ppt levels(except noble gases) are produced by life.

O_2 is the most robust biosignature gas

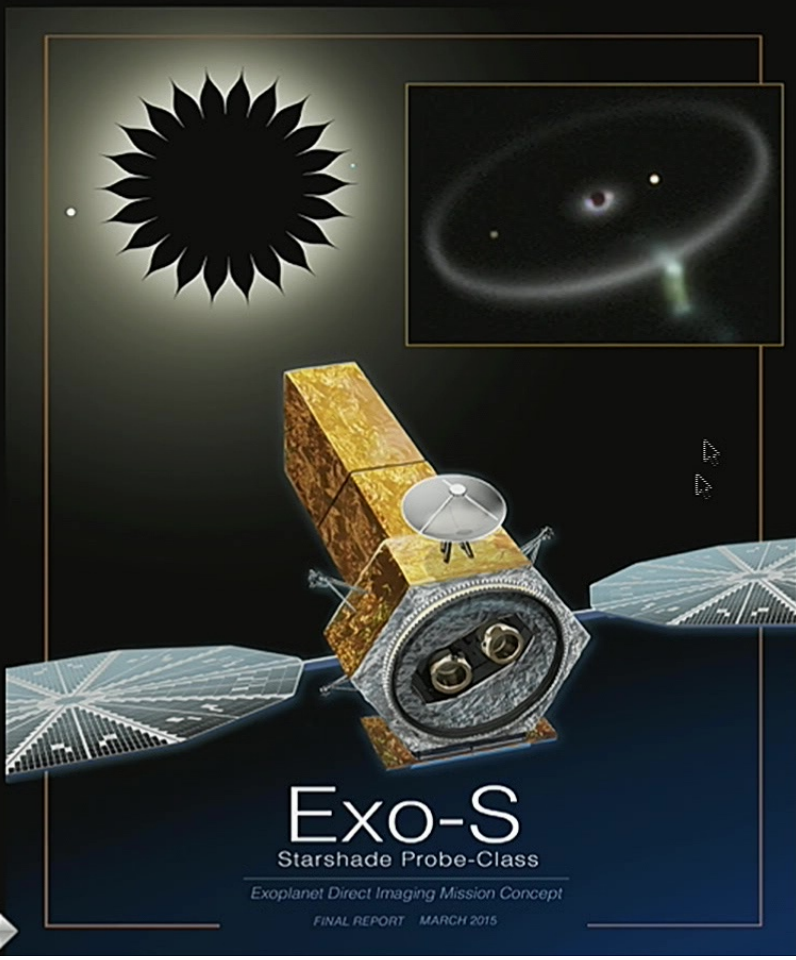
CH_4, N_2O, and other "abundant" gases have false positives

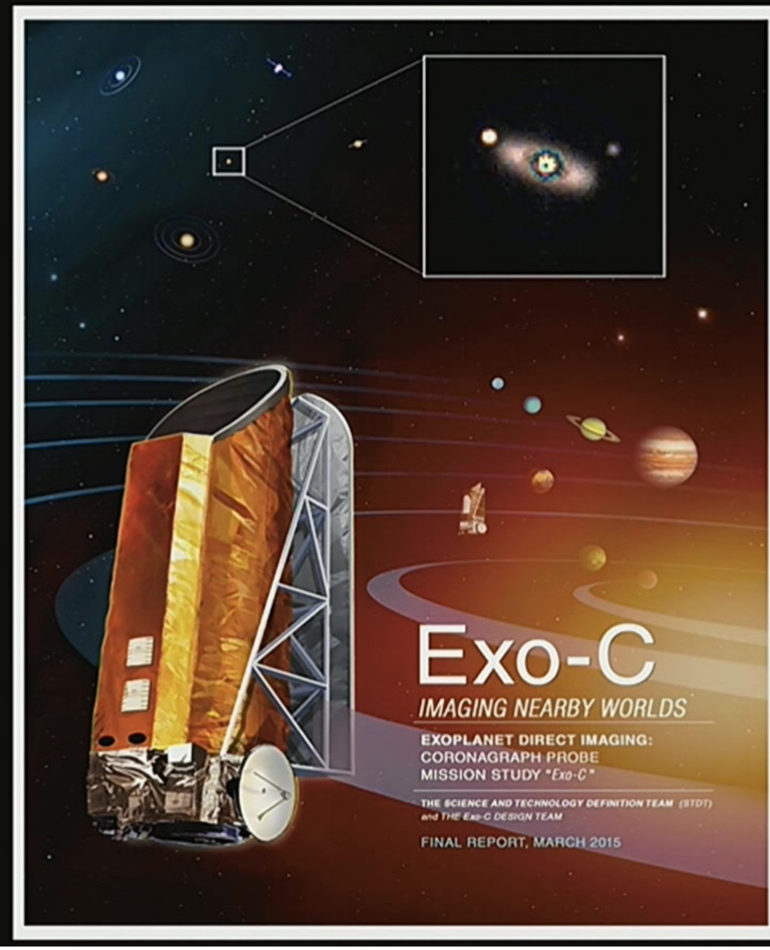
CH_3Cl, DMS, and many others are produced in tiny quantities

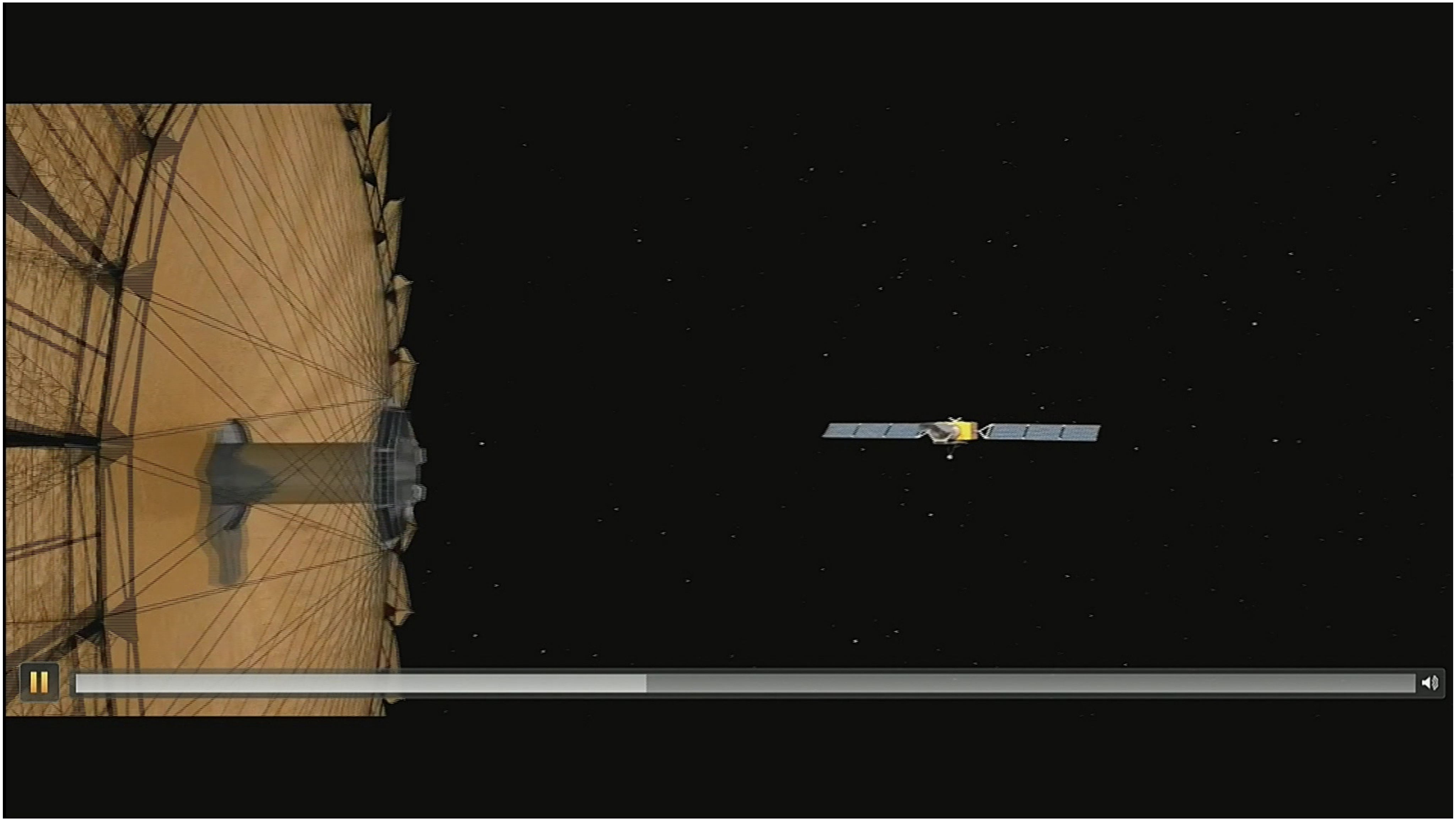
	C3H6O2	388368	O=C[C@@H](O)C
	C3H6O2	103073	CC1(OO1)C
	C3H6O2	388473	O=C[C@H](O)C
	C3H6O2	388368	O=C[C@@H](O)C
	C3H6O2	4573978	OC[C@H]1OC1
	C3H6O2	388473	O=C[C@H](O)C
	C3H6O2	8117729	C1C(CO1)O
	C3H6O2	4573978	OC[C@H]1OC1
	C3H6O2	24590984	C/C=C\OO
	C3H6O2	8117729	C1C(CO1)O
	C3H6O2	8009645	OC1OCC1
	C3H6O2	24590984	C/C=C\OO
	C3H6O2	67601	O=CCCO
	C3H6O2	8009645	OC1OCC1
	C3H6O2	832	O=CC(O)C
	C3H6O2	67601	O=CCCO
C3H6O2	C3H6O2	82676	COCC=O
	C3H6O2	832	O=CC(O)C
	C3H6O2	10303481	O\C=C\OC
C3H6O2	C3H6O2	82676	COCC=O
	C3H6O2	28705258	C(C=CO)O
	C3H6O2	10303481	O\C=C\OC
	C3H6O2	9301293	O/C(OC)=C
	C3H6O2	28705258	C(C=CO)O
	C3H6O2	121835	O1OCCC1
	C3H6O2	9301293	O/C(OC)=C
	C3H6O2	8488625	O\C=C\CO
	C3H6O2	121835	O1OCCC1
	C3H6O2	21106125	CC(=O)CO
	C3H6O2	8488625	O\C=C\CO
	C3H6O2	10303281	CC1COO1
	C3H6O2	21106125	CC(=O)CO
	C3H6O2	9157685	O(O)C\C=C
	C3H6O2	10303281	CC1COO1
	C3H6O2	4417663	OC(O)\C=C
	C3H6O2	9157685	O(O)C\C=C
	C3H6O2	141532	OC1(O)CC1
	C3H6O2	4417663	OC(O)\C=C
	C3H6O2	26667354	C(/C=C\O)O
	C3H6O2	141532	OC1(O)CC1
	C3H6O2	5344354	OC[C@@H]1OC1
	C3H6O2	26667354	C(/C=C\O)O
	C3H6O2	14823306	C\C=C\OO
	C3H6O2	5344354	OC[C@@H]1OC1
	C3H6O2	13472118	C=C(O)CO
	C3H6O2	14823306	C\C=C\OO
	C3H4O3	857	CC(=O)C=O
	C3H6O2	13472118	C=C(O)CO

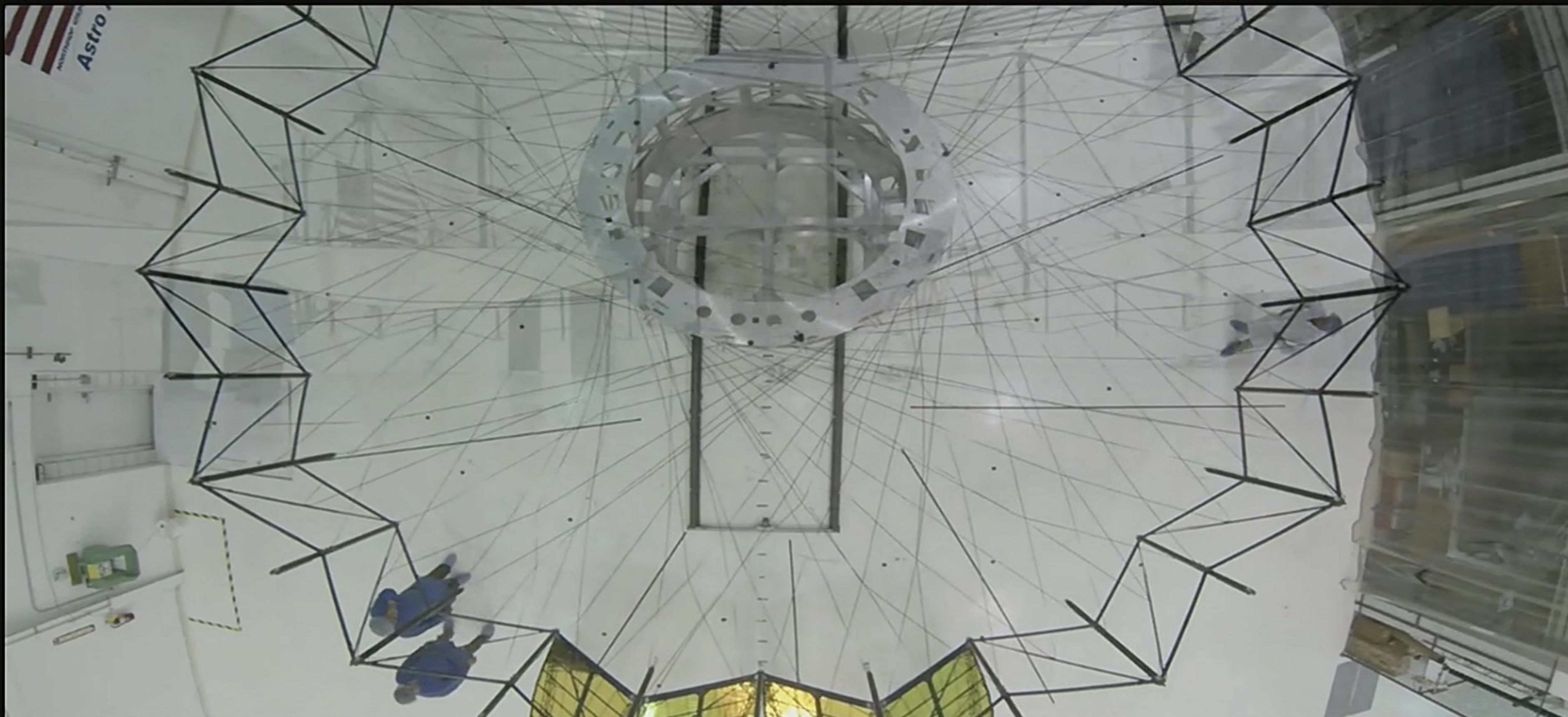

Direct Imaging:
Suppress Starlight to Find Planets

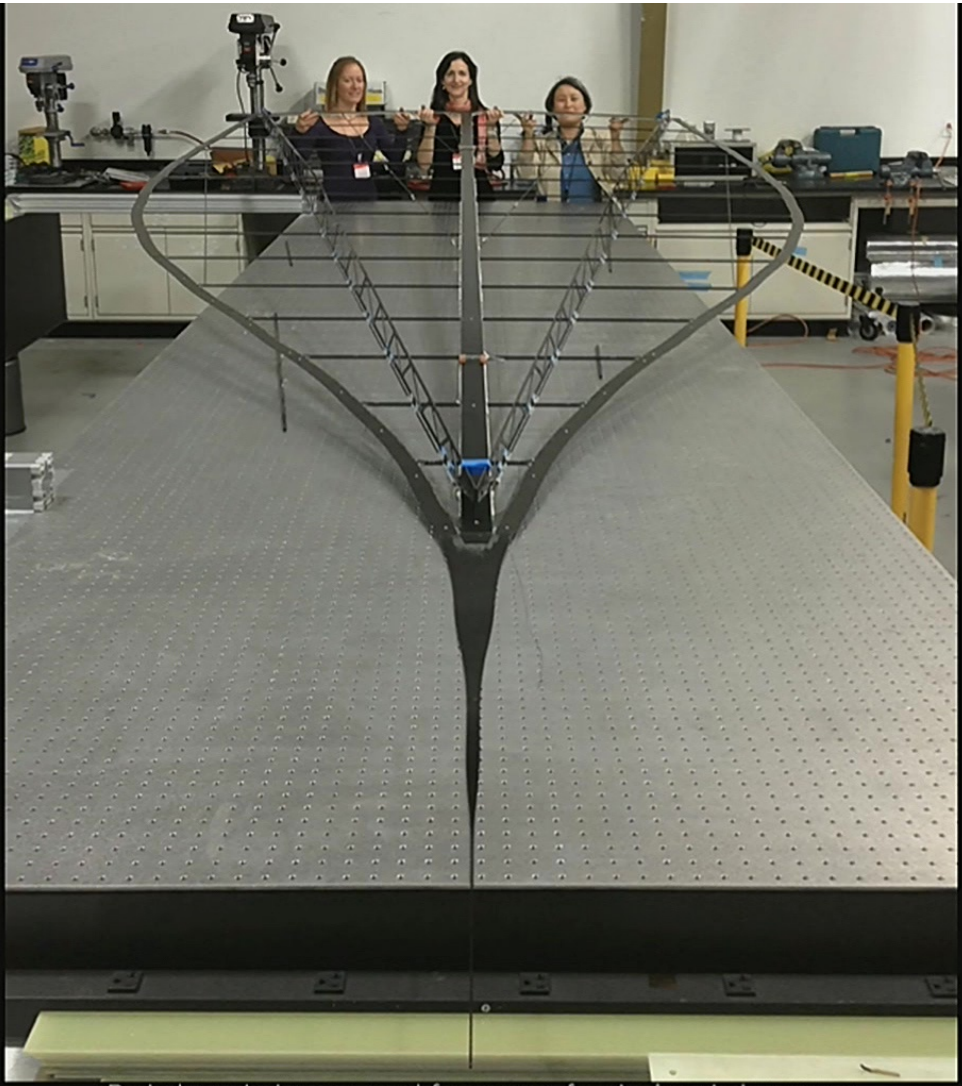
NASA Probe-Class Studies 2015











Petal prototype used for manufacturing tolerance verification tests. Credit: NASA/JPL