What is hEARTH and why should we care?

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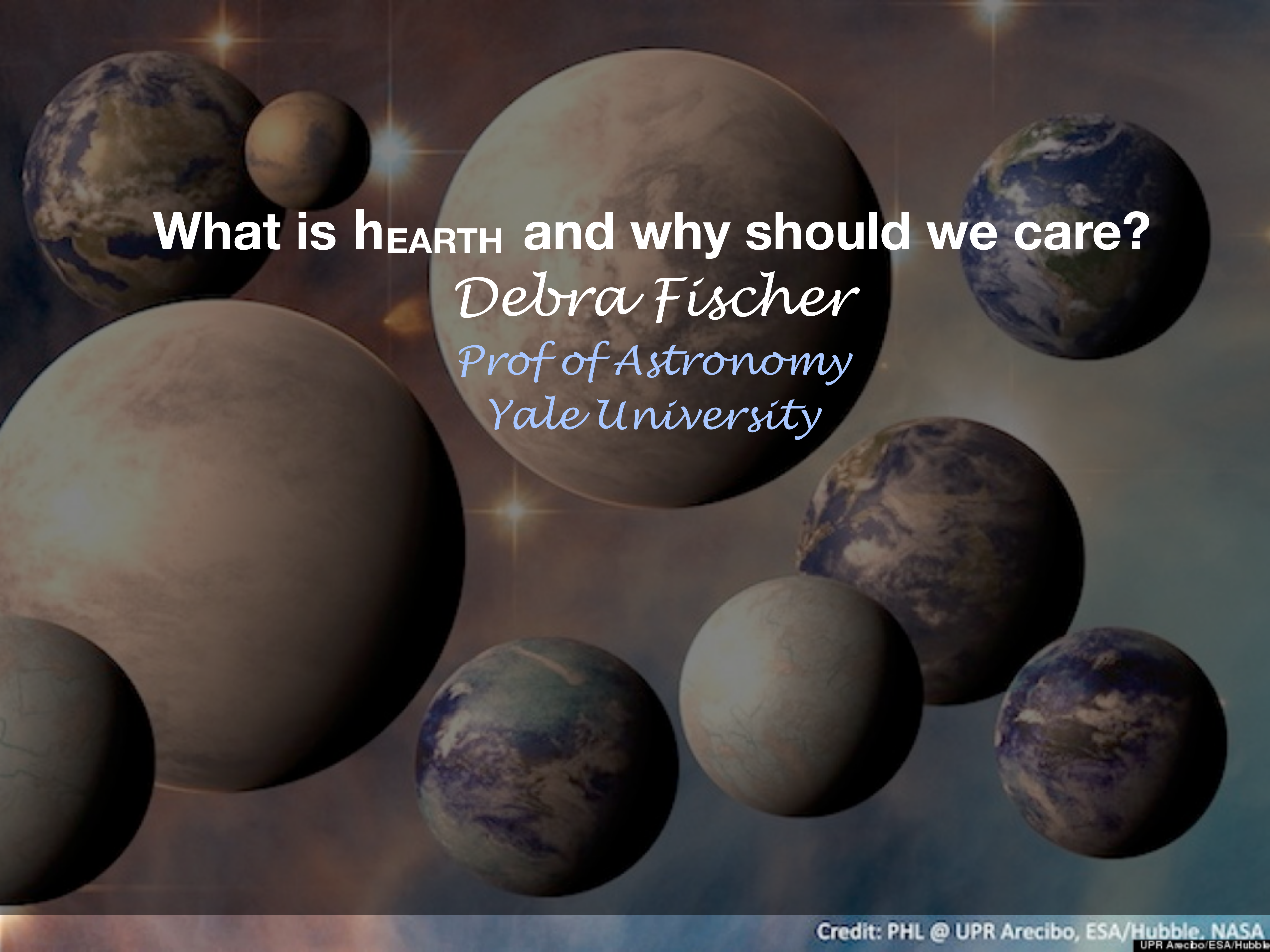
Prof of Astronomy
Yale University



Credit: PHL @ UPR Arecibo, ESA/Hubble, NASA

h_{Earth} as defined by the *Kepler* science team is the fraction of stars with Earth-sized planets in the habitable zone.

Why do we want that number?
It tells us the number of stars we need to survey to find habitable planets => what size space telescopes needed.

No, really why do we want that number?
Because we think that a sample of Earth analogs will be an alien-enriched set of planets.


The Press
NASA and its scientists are hell-bent on finding Earth 2.0, and with the new James Webb Space Telescope that is set to launch in the year 2018, this is very much possible. Within the next 20 years, we could very well come across Earth-like planets or even alien life somewhere out there in the Universe.
TECH TIMES
The Scientists
"Imagine the moment that the news breaks we've discovered Earth 2.0,"
TECH TIMES
Matt Mountain, Director STScI
The Public Response
“Seems to me that NASA is angling for more money....”
TECH TIMES
The Public Response
Hasn’t this already been done?
TECH TIMES

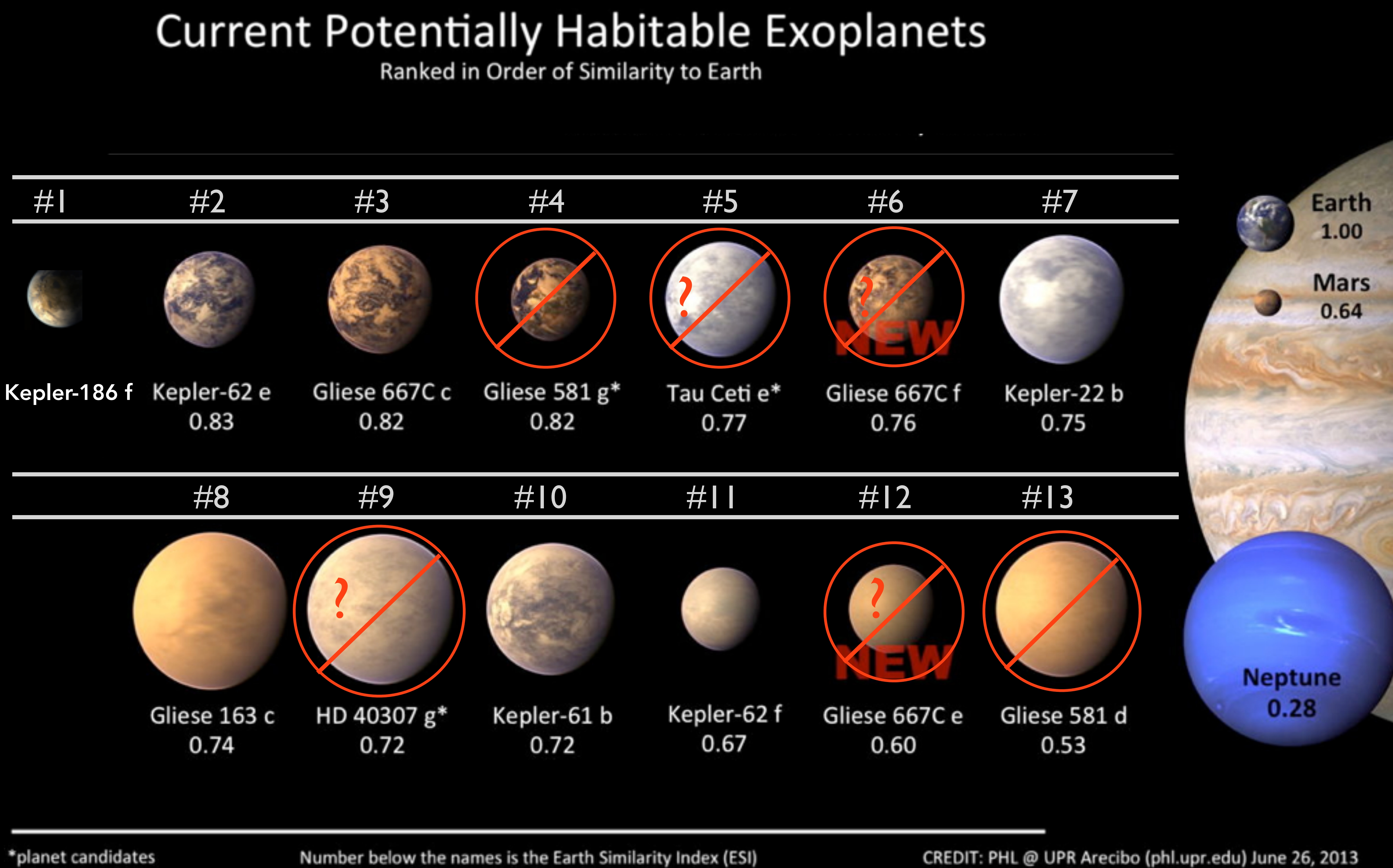
The Problem: The signals for these planets are tenuous and there are disagreements about the statistical analysis.

At least for RV detections: precision is not yet good enough.

The other Problem: each detection has been the "first" - even the reporters are confused about what new detections of "the first" really means.

Corollary to "the other problem:" press-release science provides advertising that can give scientists an edge in times of tight funding.

The normal scientific process of confirmation and rejection of our hypotheses is being carried out in full view of the public, who does not know how to interpret these scientific disagreements.



Current Potentially Habitable Exoplanets
Ranked in Order of Similarity to Earth
#1
Kepler-186 f
#2
Kepler-62 e
0.83
#3
Gliese 667C c
0.82
#4
Gliese 581 g*
0.82
#5
?
Tau Ceti e*
0.77
#6
?
NEW
Gliese 667C f
0.76
#7
Kepler-22 b
0.75
#8
Gliese 163 c
0.74
#9
?
HD 40307 g*
0.72
#10
Kepler-61 b
0.72
#11
Kepler-62 f
0.67
#12
?
NEW
Gliese 667C e
0.60
#13
Gliese 581 d
0.53
Earth
1.00
Mars
0.64
Neptune
0.28
*planet candidates
Number below the names is the Earth Similarity Index (ESI)
CREDIT: PHL @ UPR Arecibo (phl.upr.edu) June 26, 2013

What makes a planet "Earth like" ?

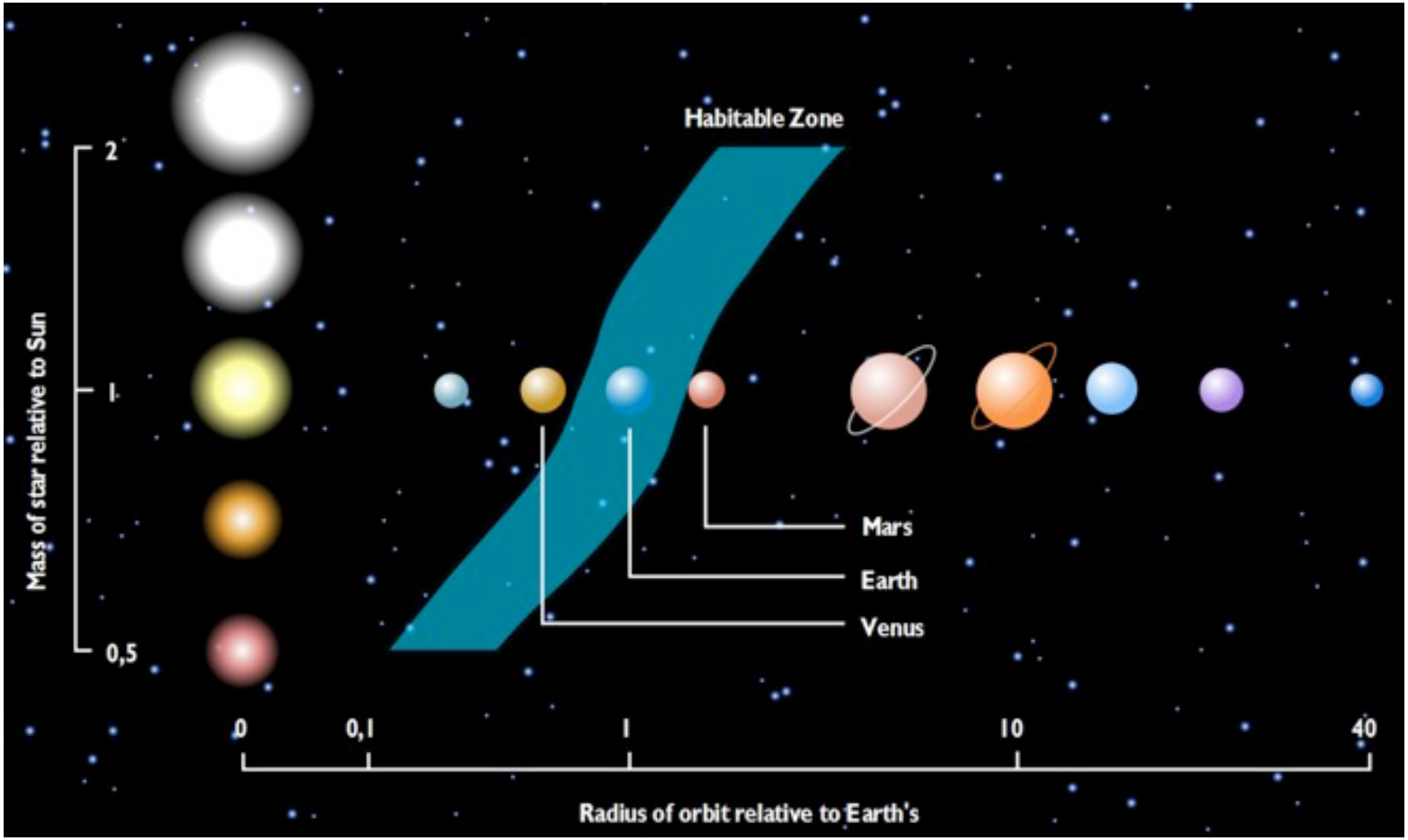
Similar mass

Interior structure

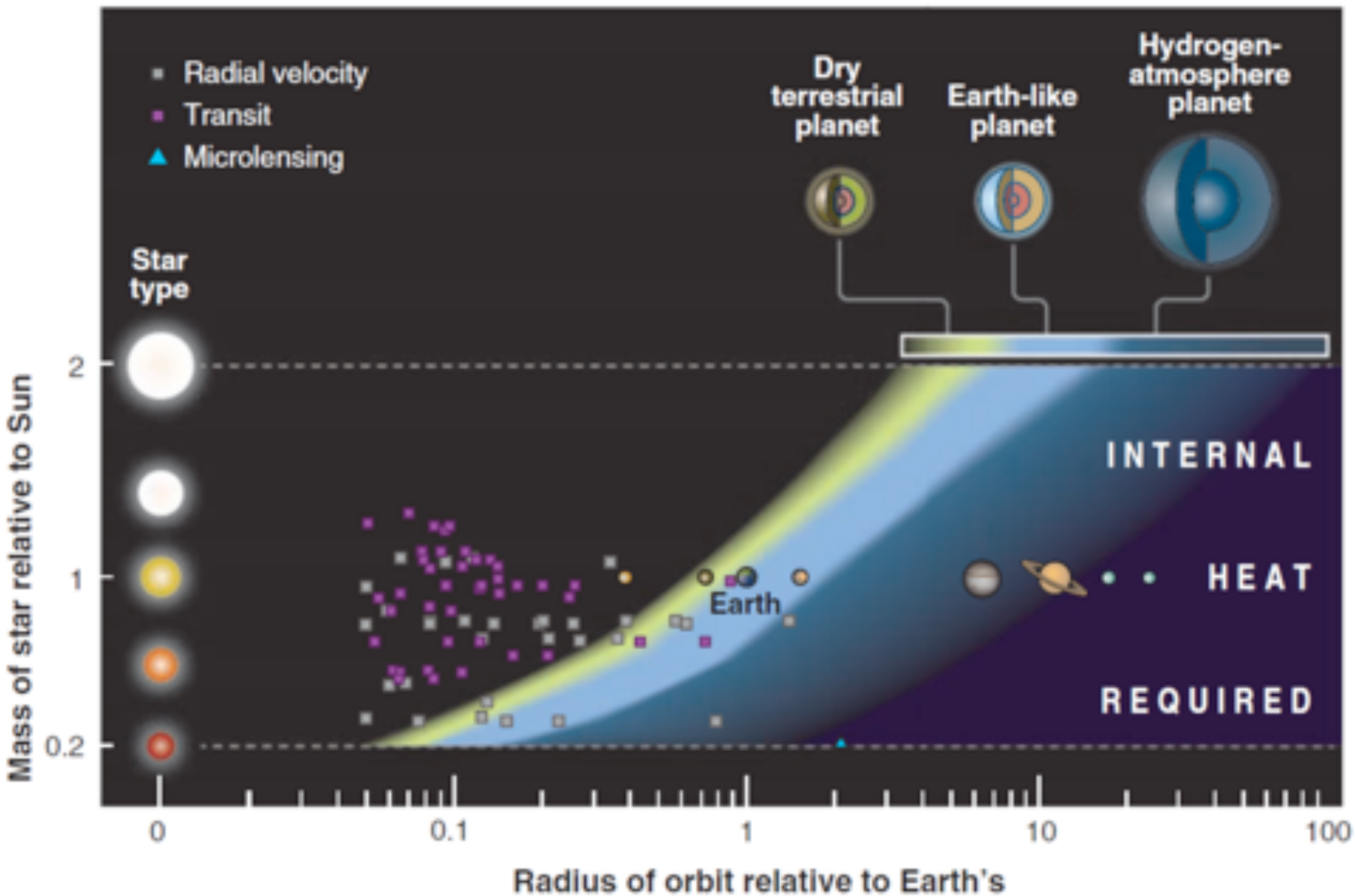
- differentiated for liquid core and global magnetic field
- plate tectonics

Surface water

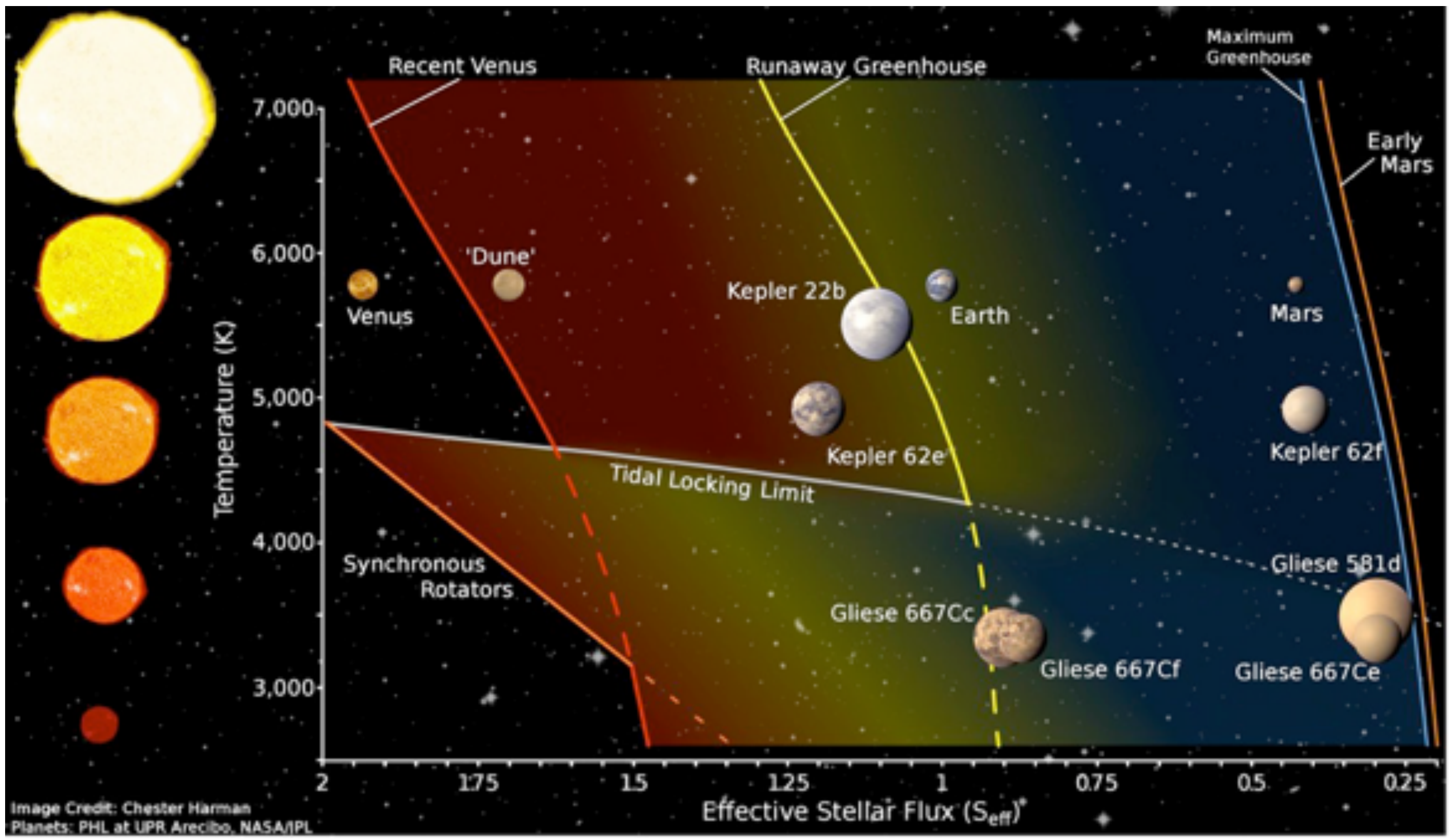
Conditions for similar prebiotic chemistry



HZ is the circumstellar region where a terrestrial planet can maintain liquid water on the surface.

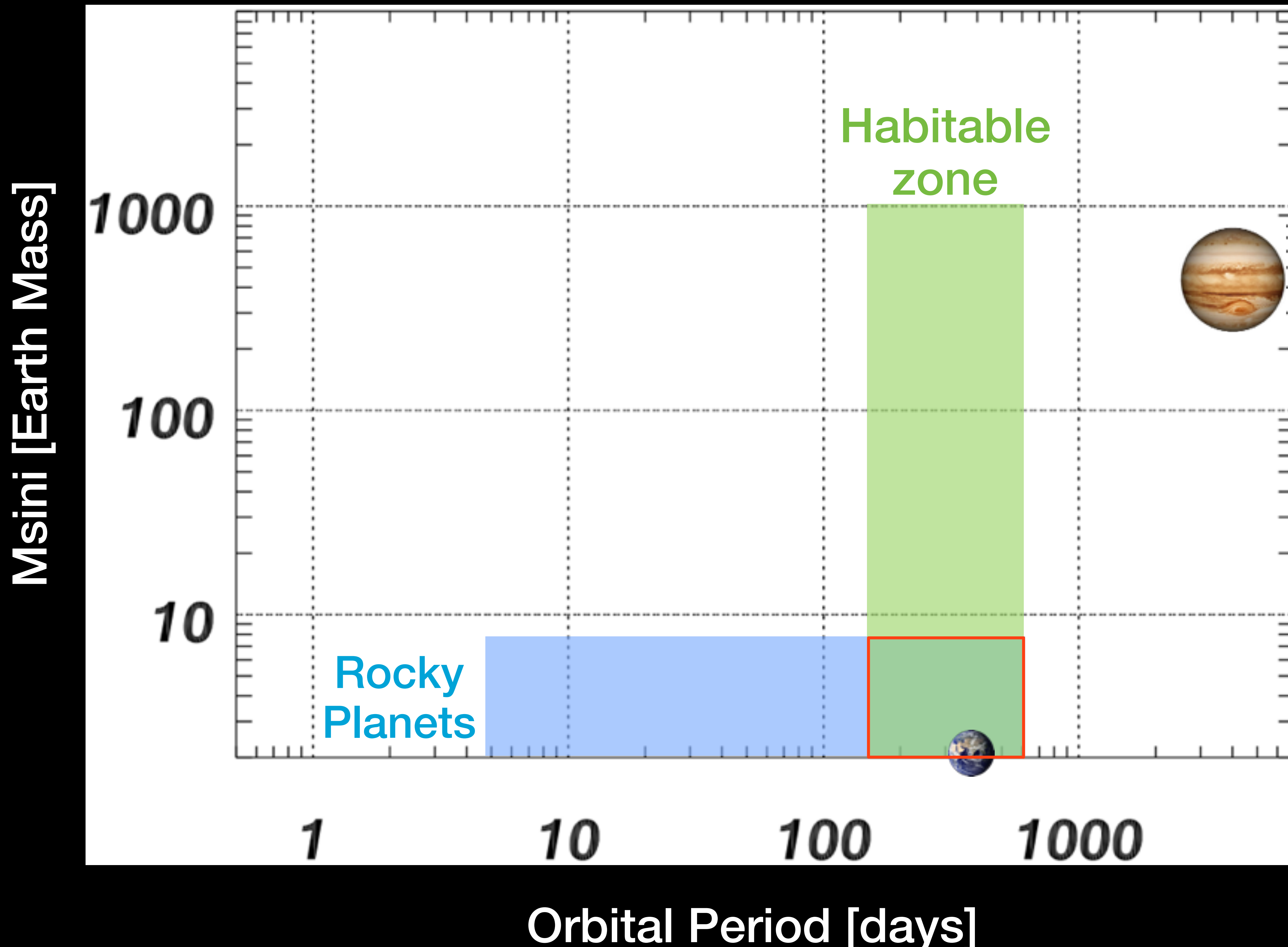


Dry “land” planets have an advantage over planets with oceans. They can re-emit more IR radiation because air is unsaturated and the dry stratosphere limits hydrogen escape.

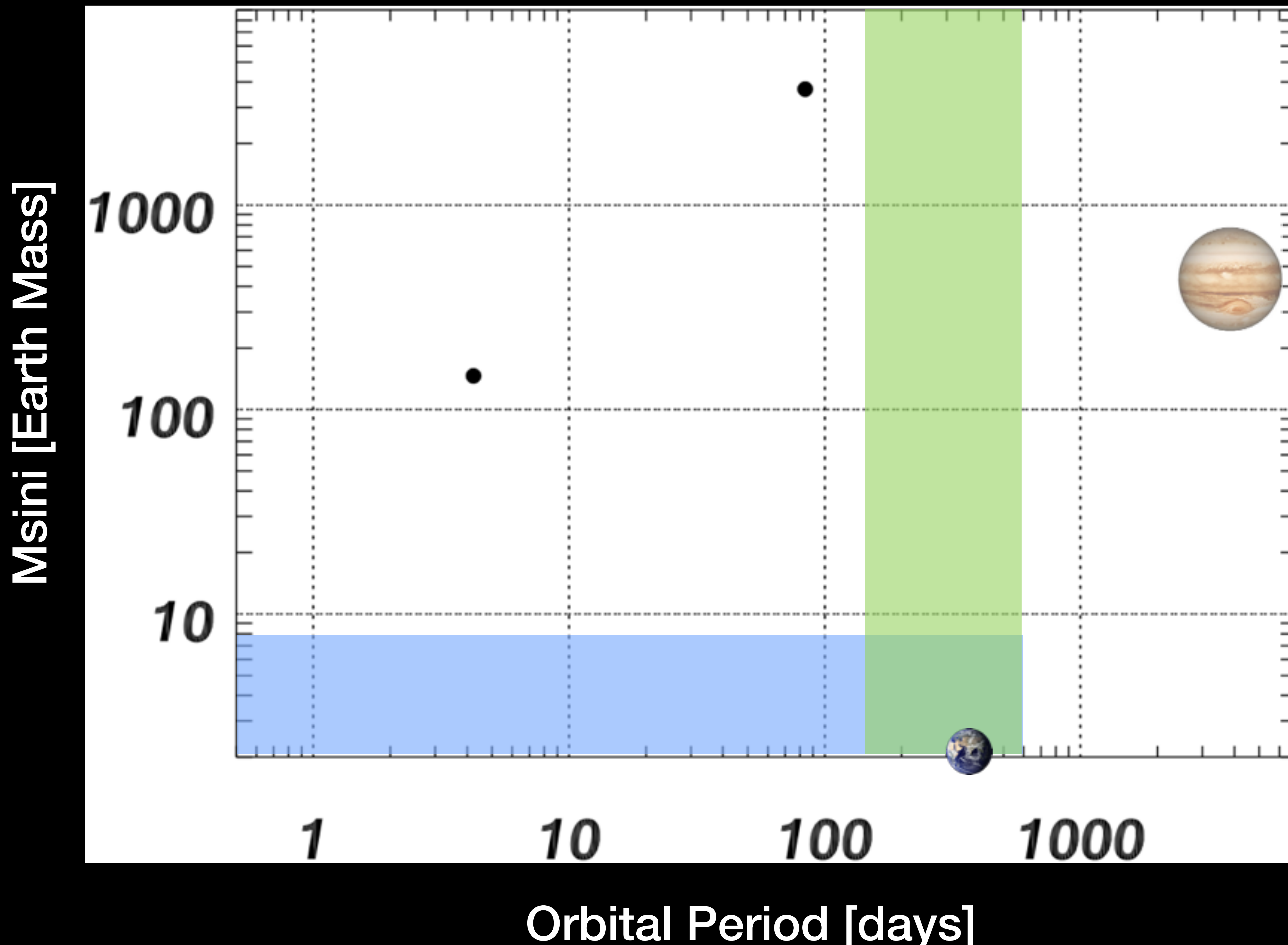


Because of uncertainties in planetary albedo, Kopparapu et al. (2013) revise the HZ as f(L_{STAR})

Inner and outer boundaries are empirical:
Venus lost water ~1 Gya and Mars lost water 3.8 Gya


Habitable zone
Rocky Planets
1000
100
10
1
10
100
1000
Msini [Earth Mass]
Orbital Period [days]

1995


Msini [Earth Mass]
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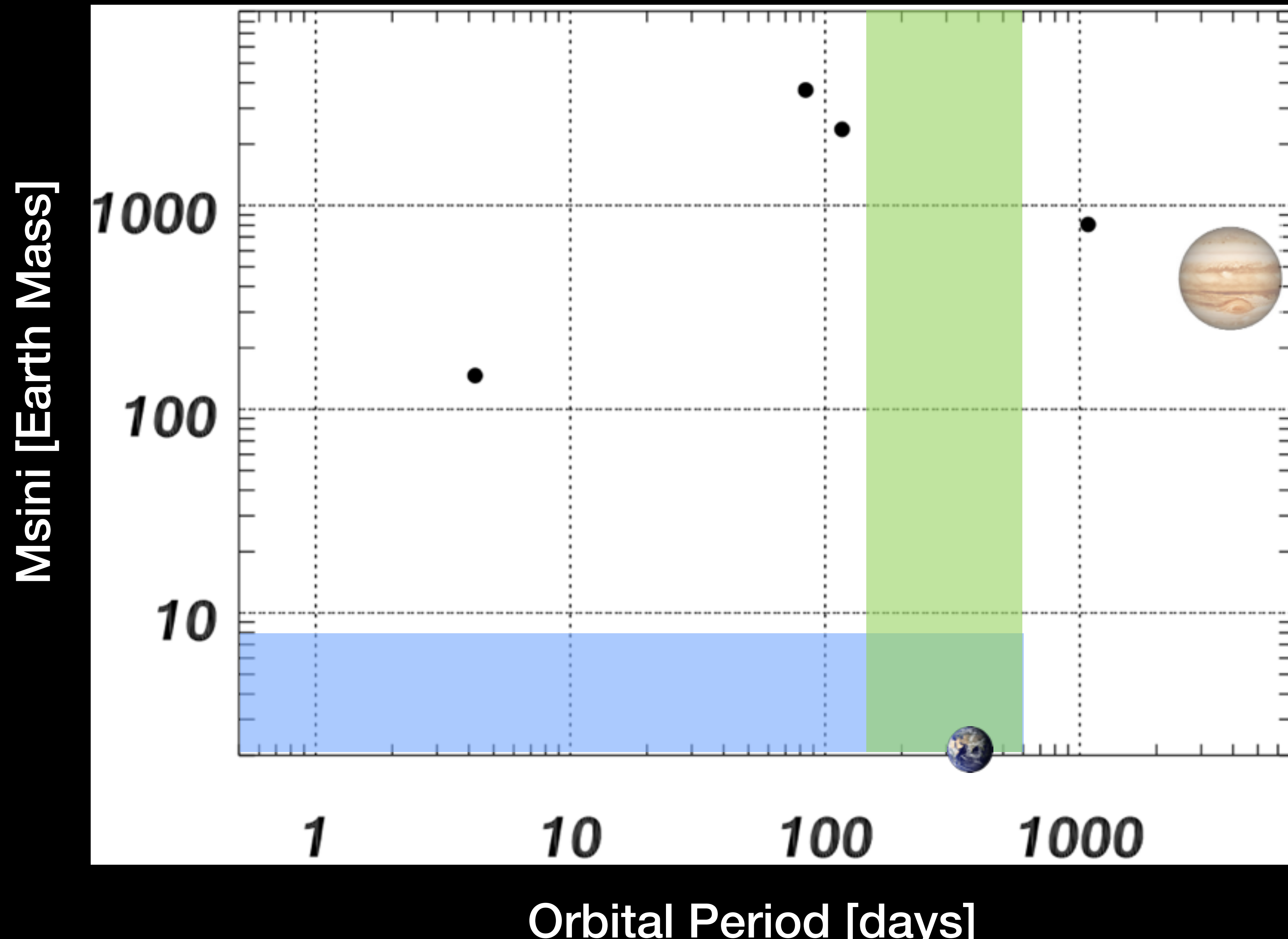
Orbital Period [days]

1996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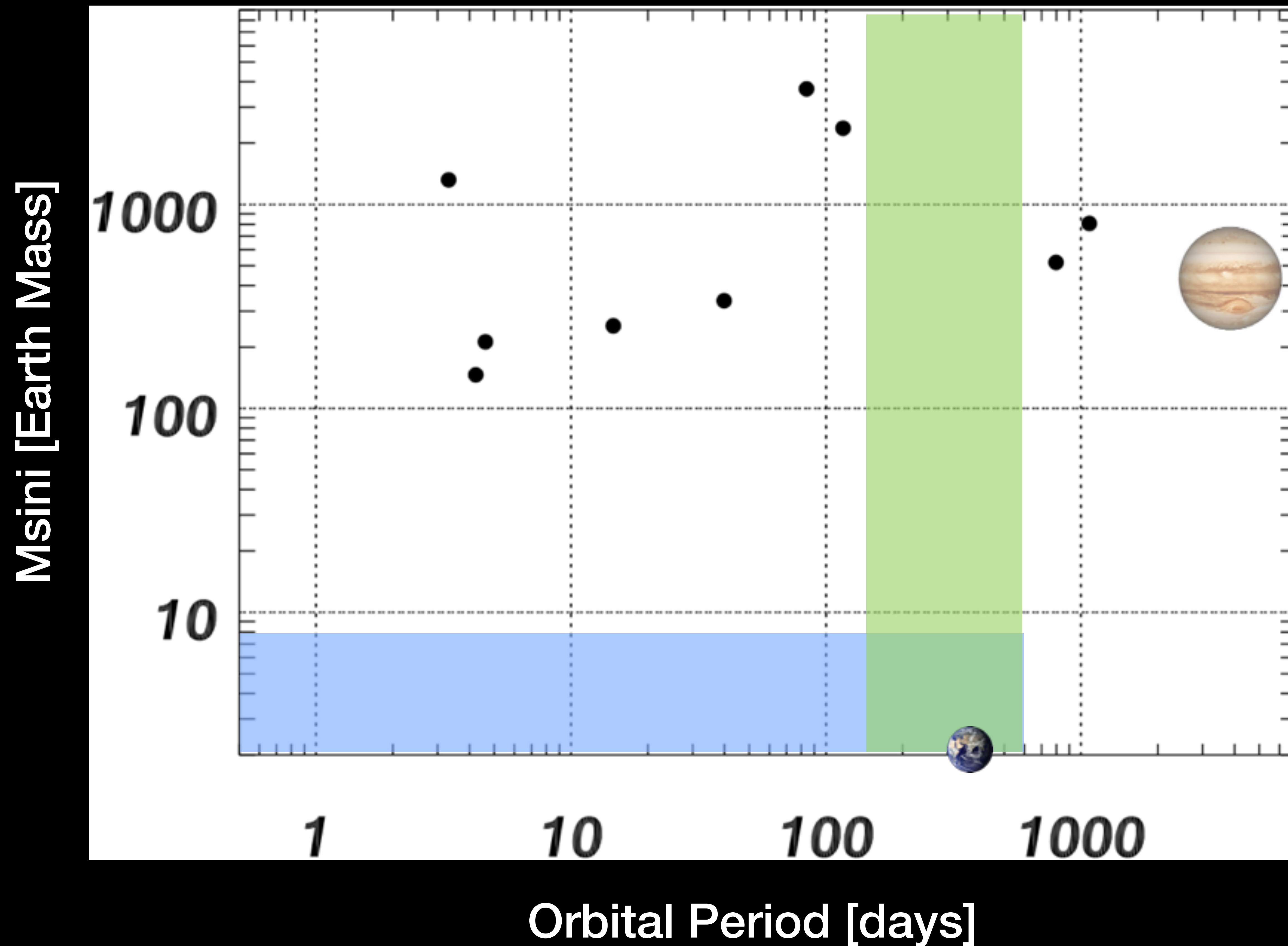
Msini [Earth Mass]
Orbital Period [days]

1997


Msini [Earth Mass]
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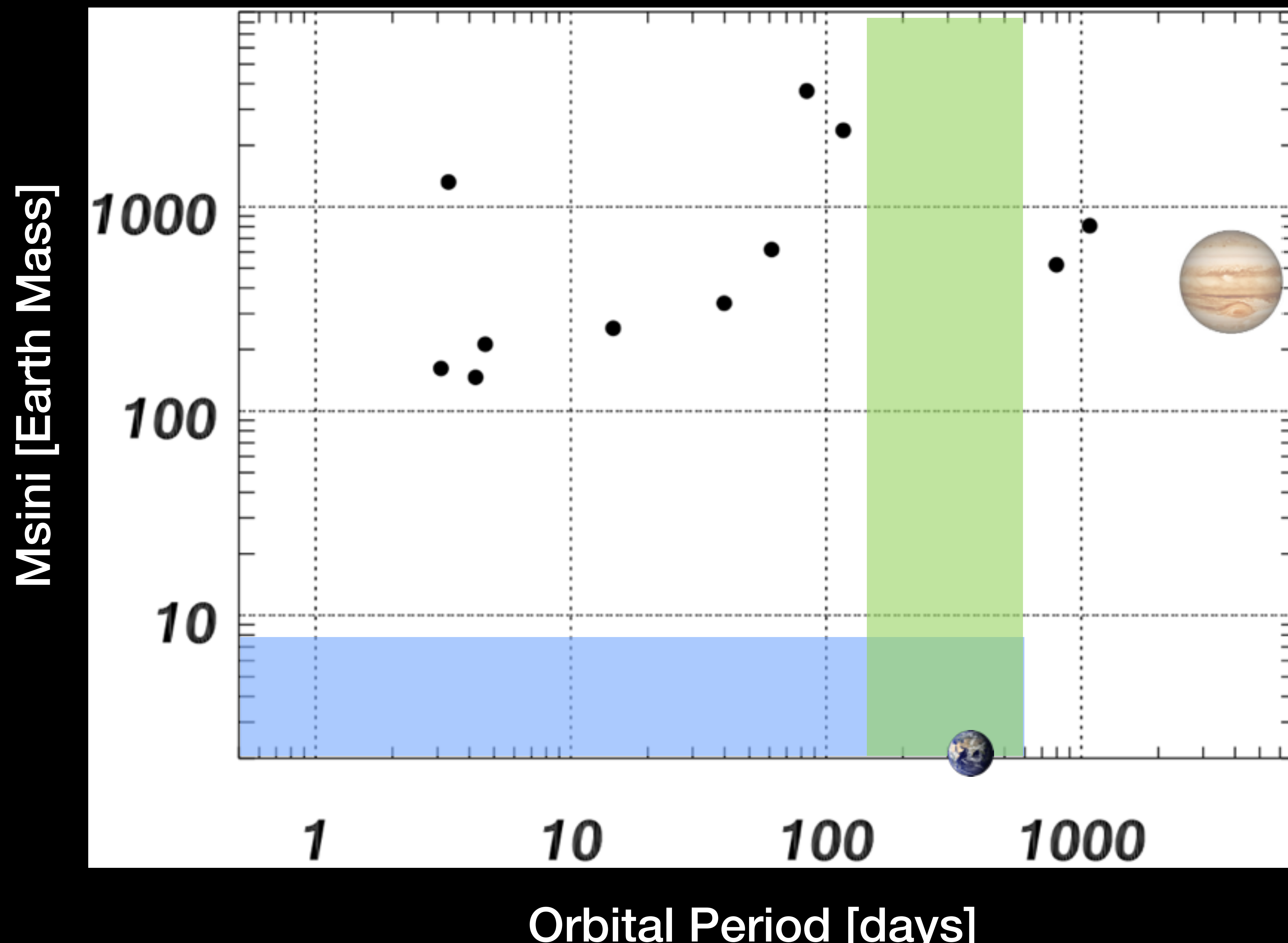
Orbital Period [days]

1998



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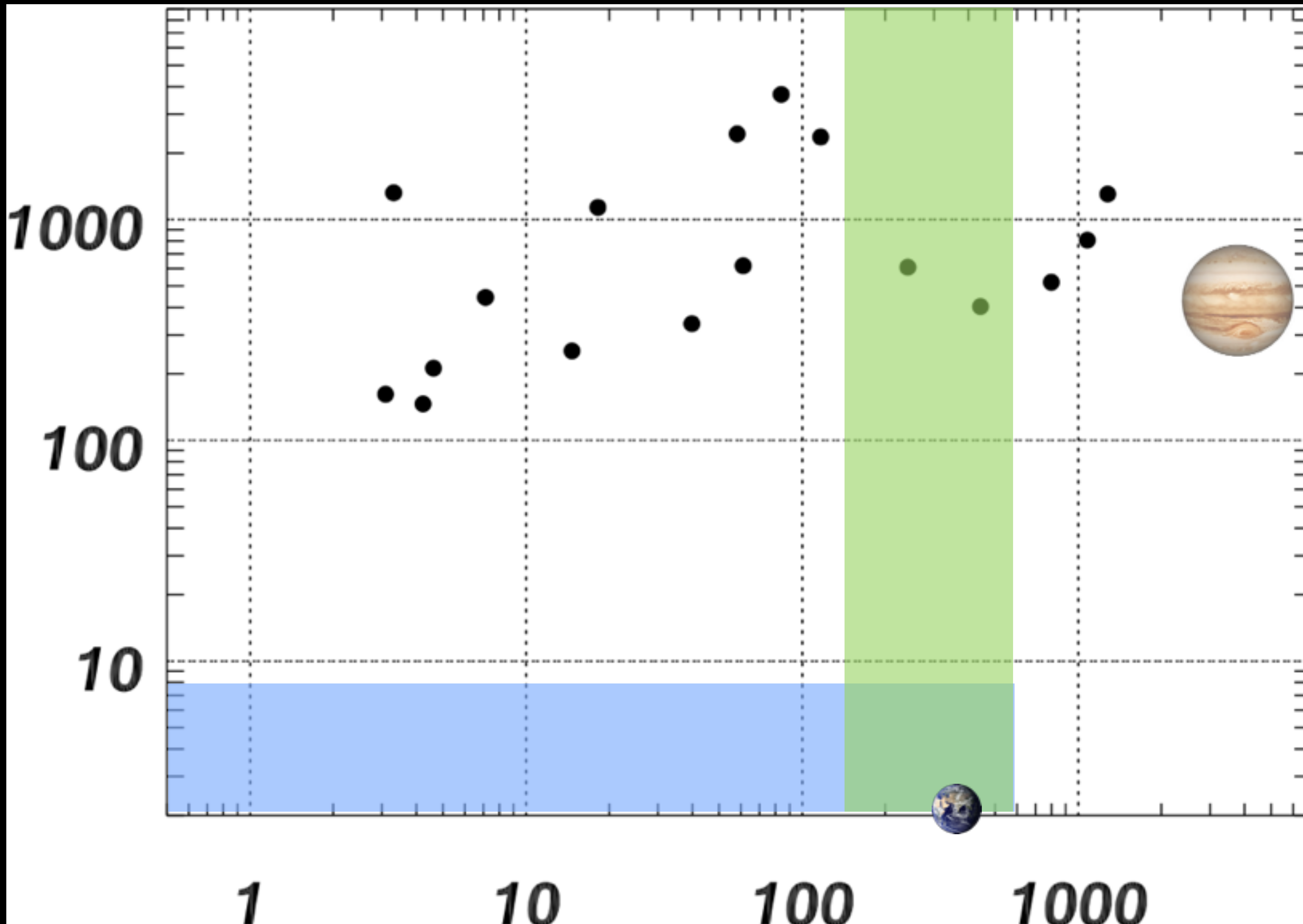
Msini [Earth Mass]
Orbital Period [days]

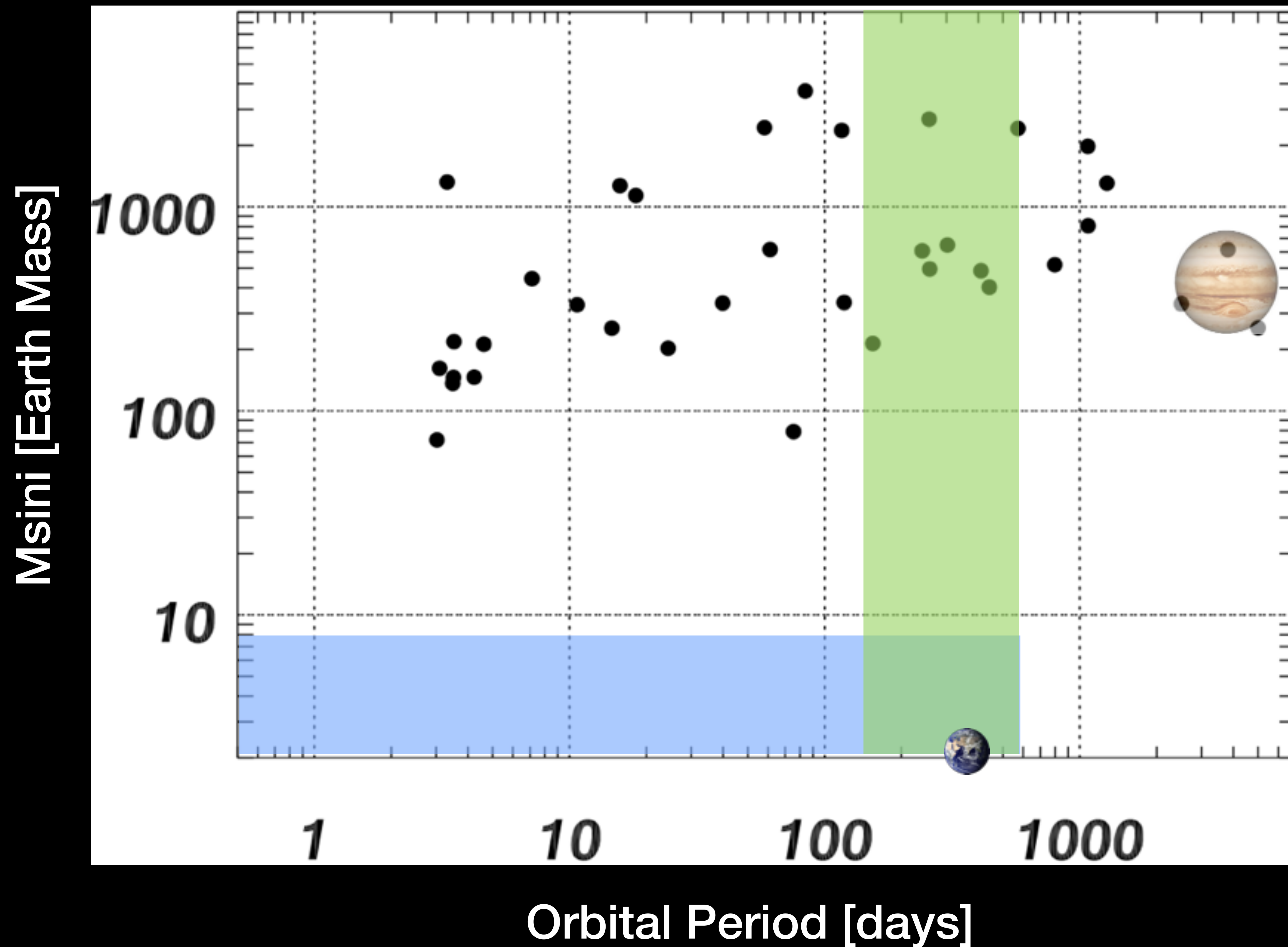
1999



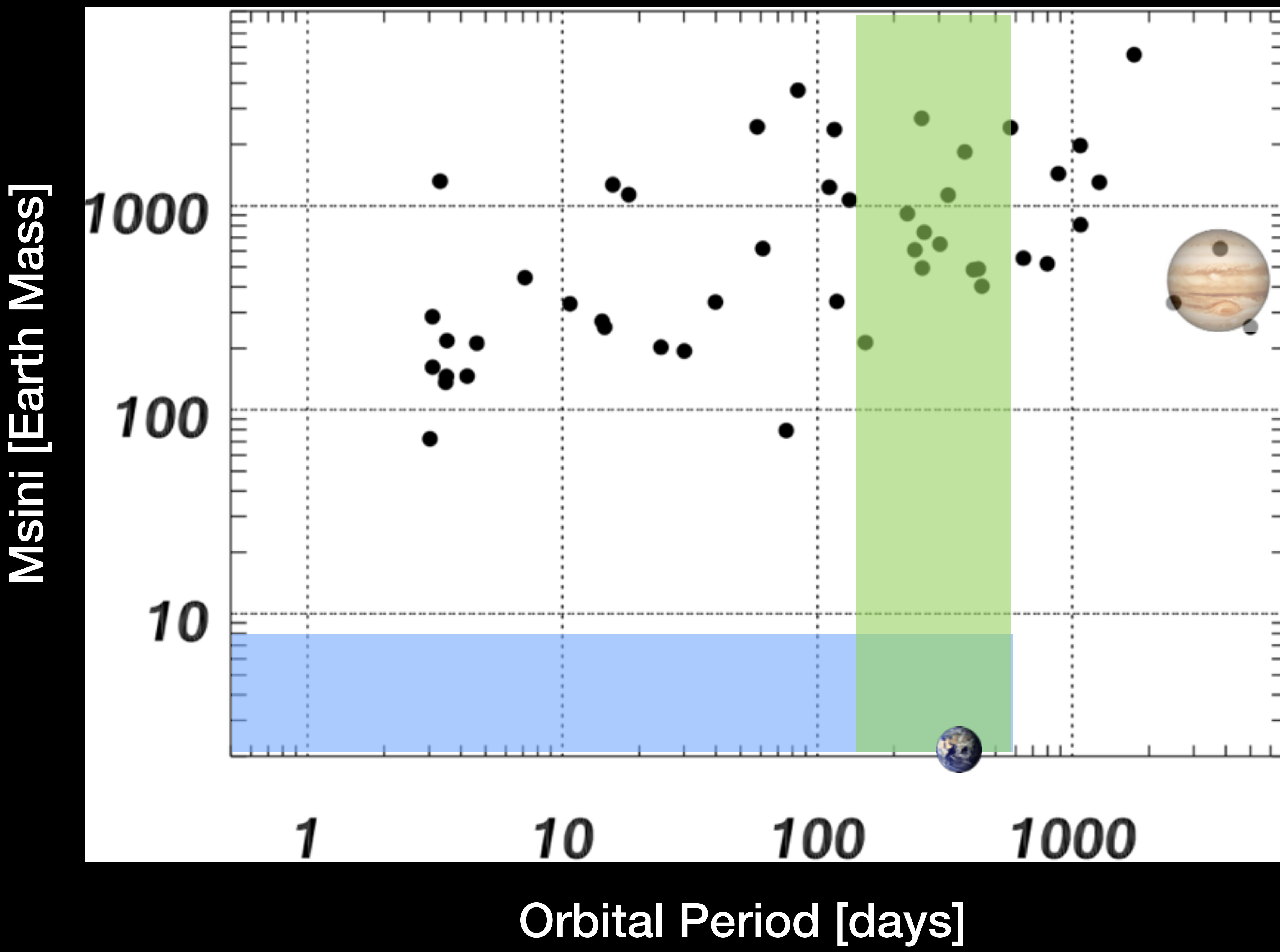
Msini [Earth Mass]

Orbital Period [days]

2000


Msini [Earth Mass]
1000
100
10
1
10
100
1000
Orbital Period [days]

2001



Msini [Earth Mass]
1000
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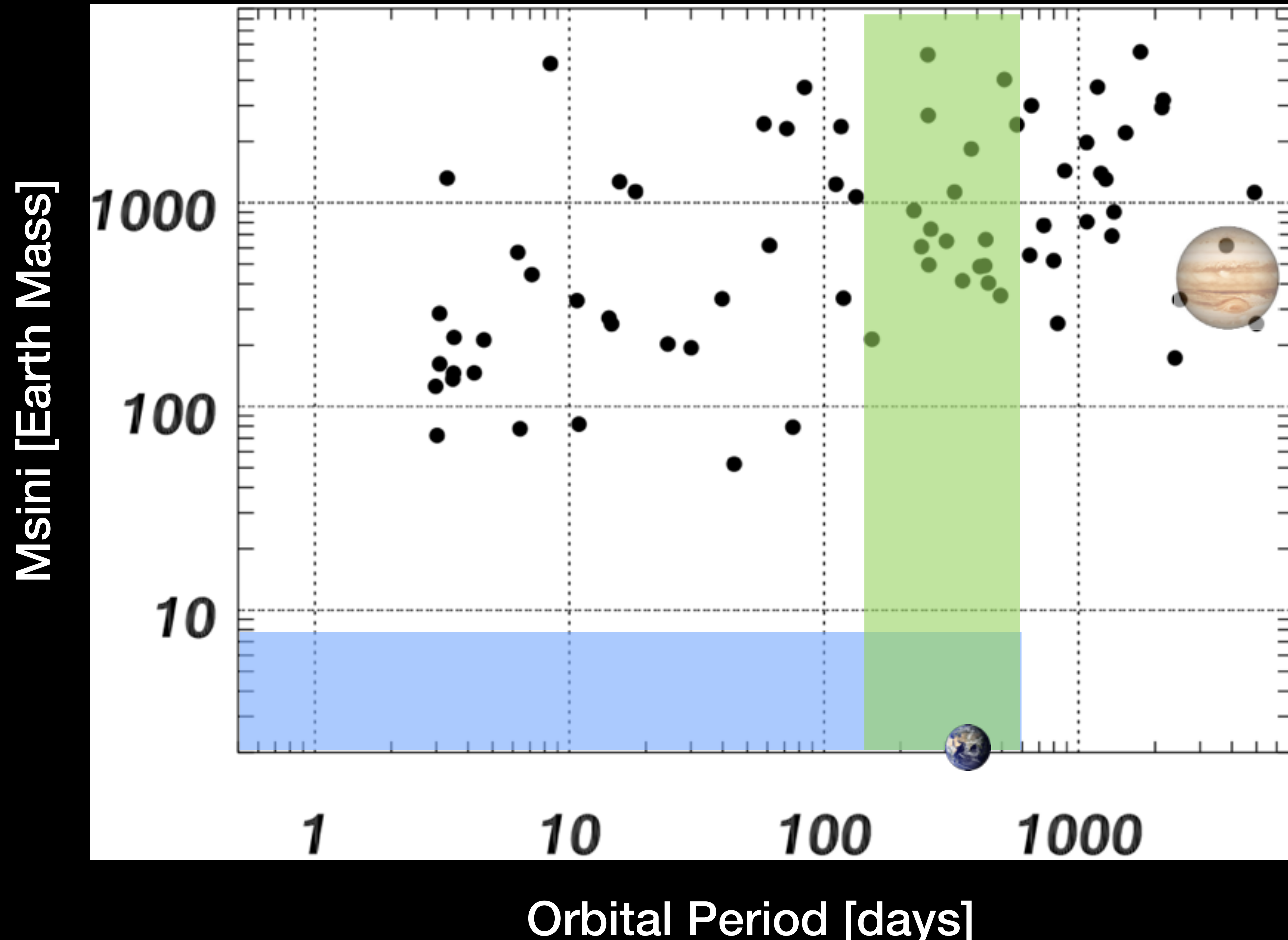
1
10
100
1000
Orbital Period [days]

2002



Msini [Earth Mass]
1000
100
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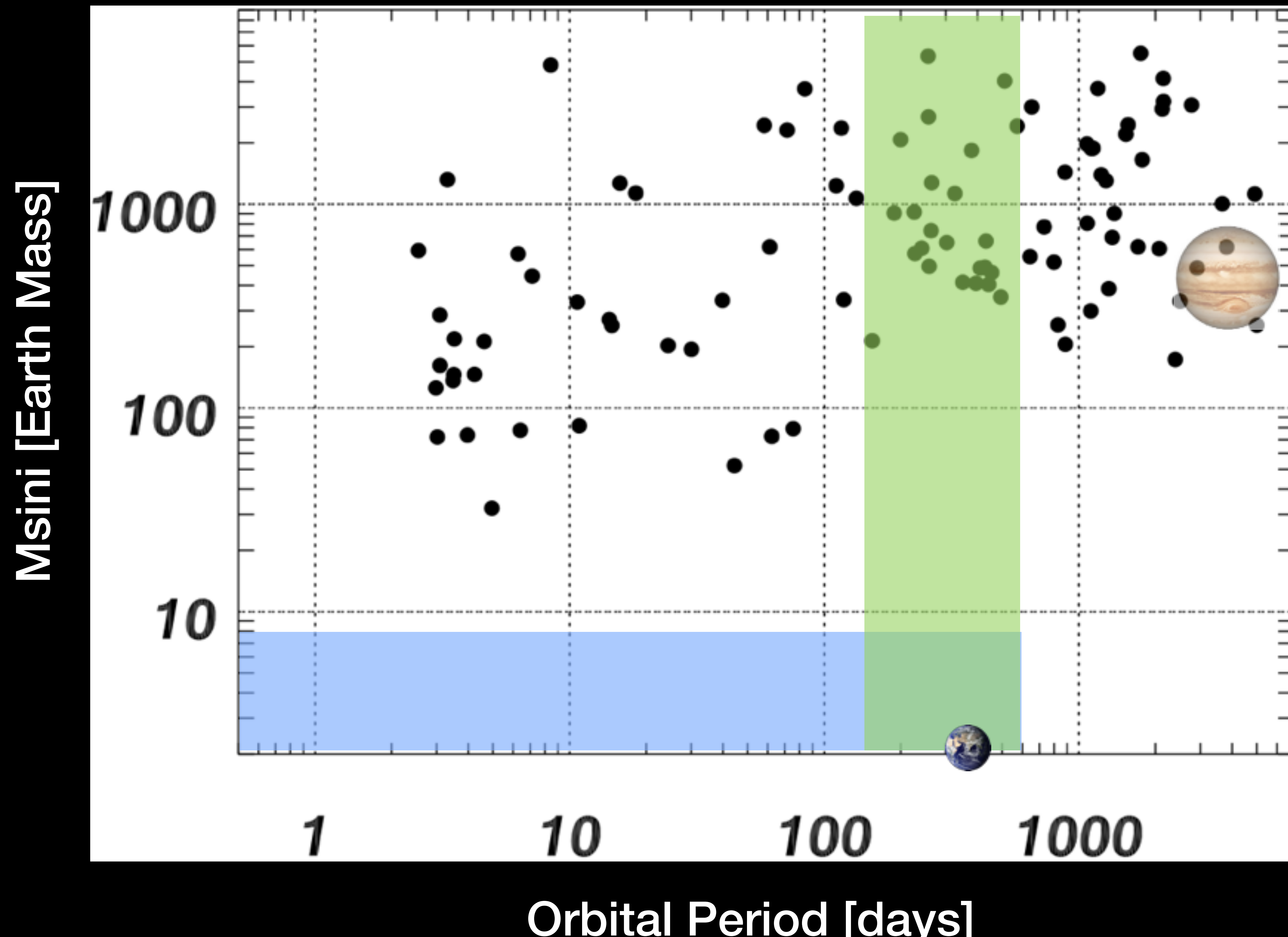
1
10
100
1000
Orbital Period [days]

2003



Msini [Earth Mass]
1000
100
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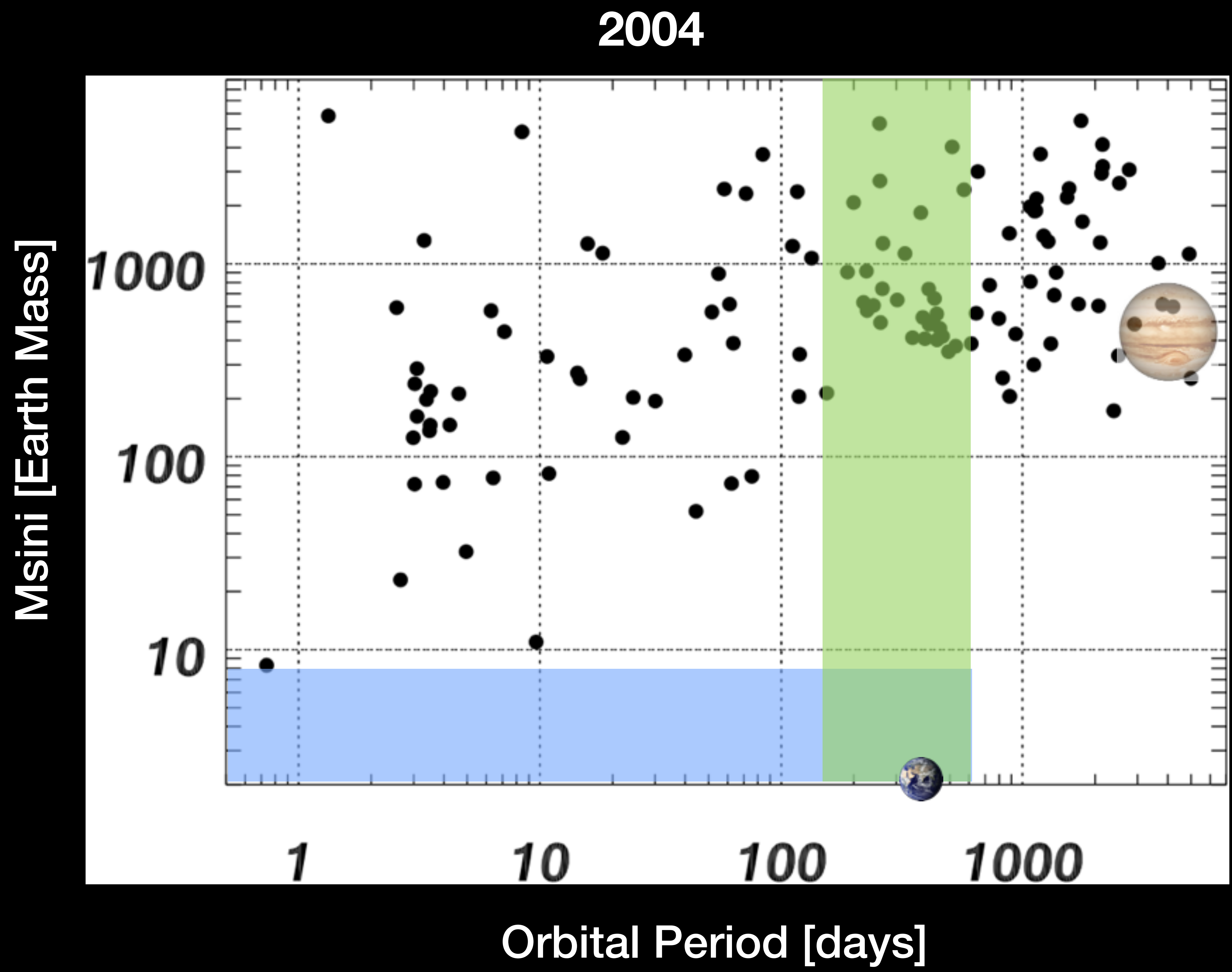
1
10
100
1000
Orbital Period [days]



2004
Msini [Earth Mass]
1000
100
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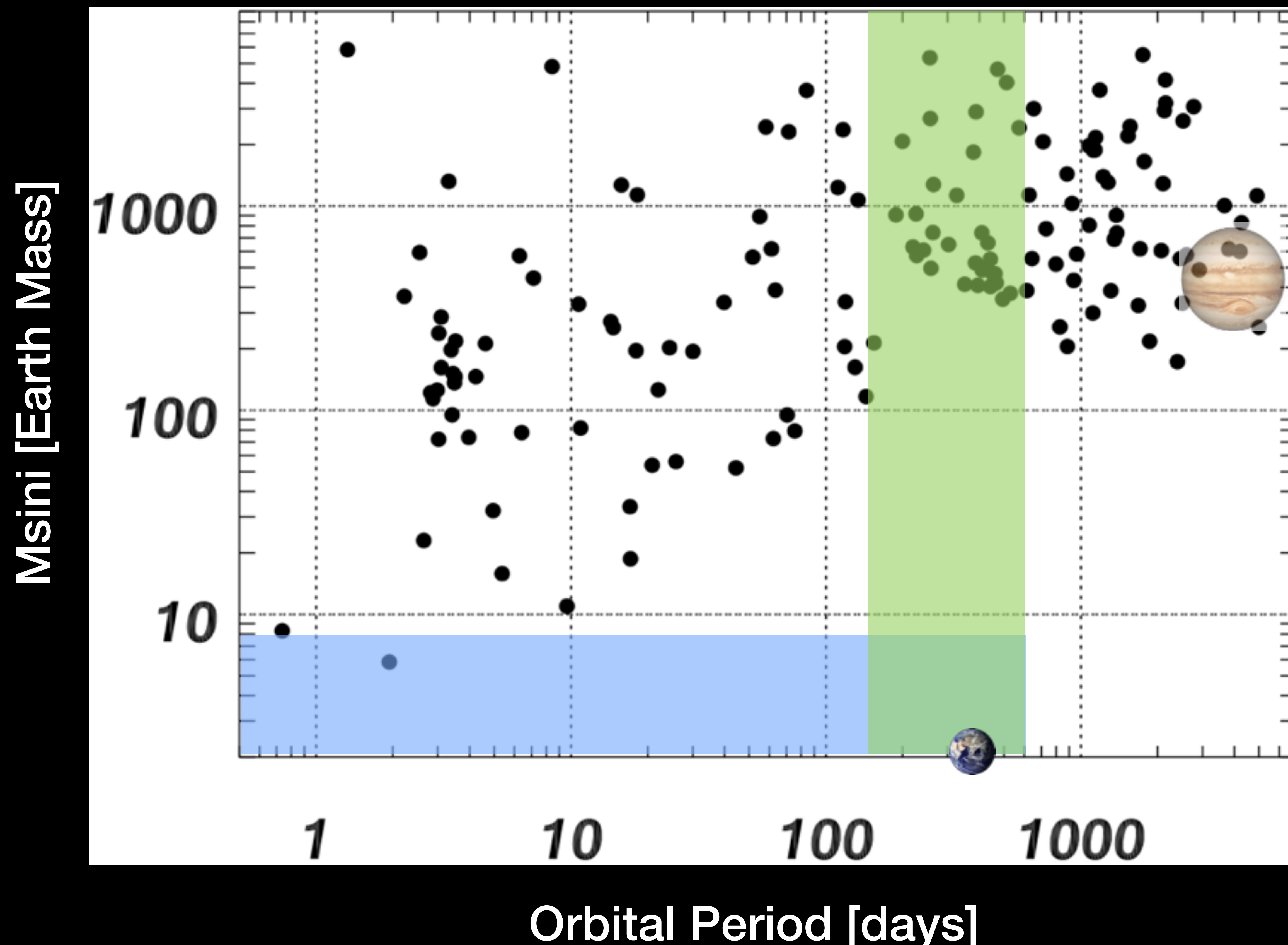
1
10
100
1000
Orbital Period [days]

2005


Msini [Earth Mass]
1000
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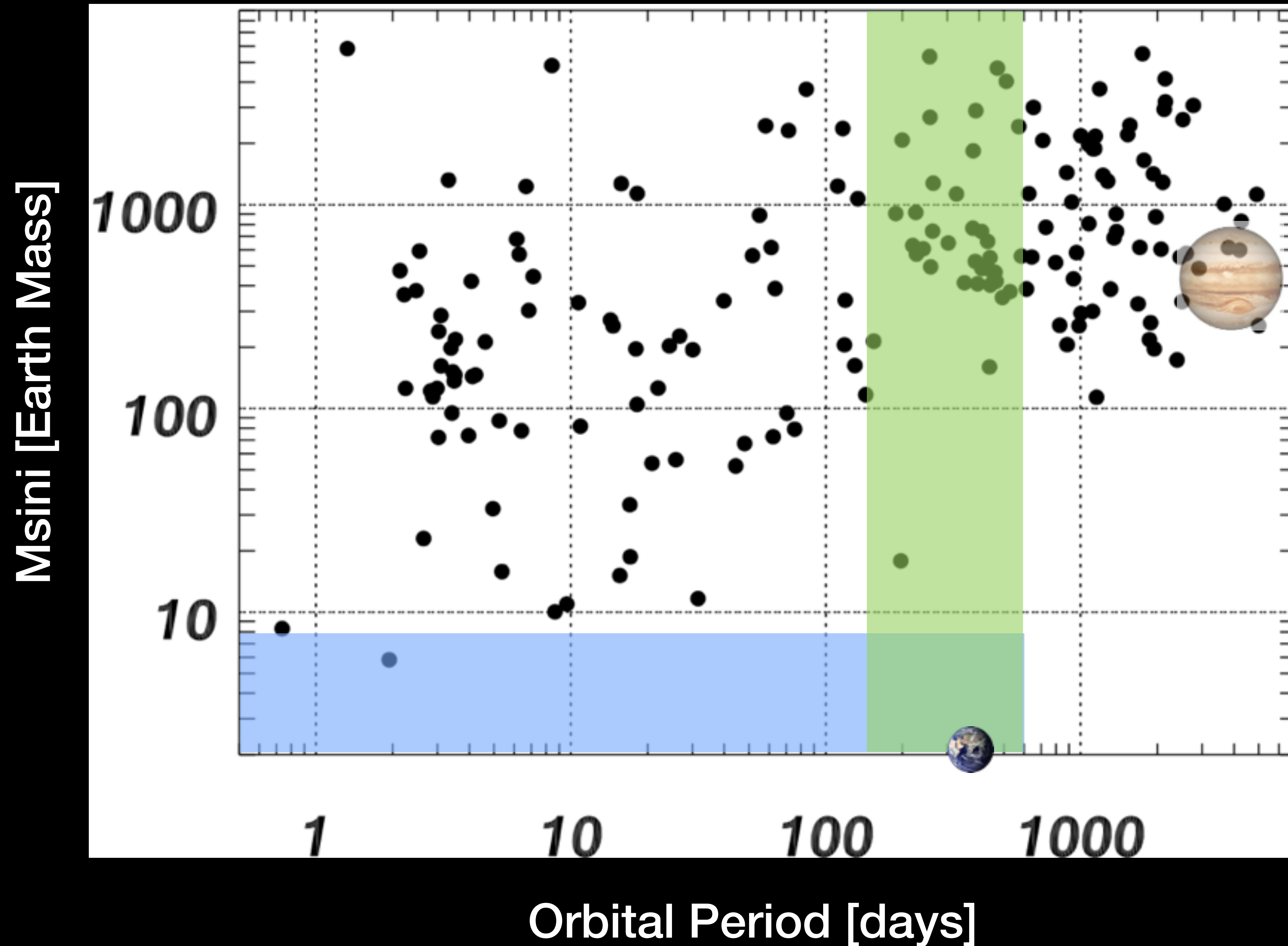
100
1000
Orbital Period [days]

2006


Msini [Earth Mass]
1000
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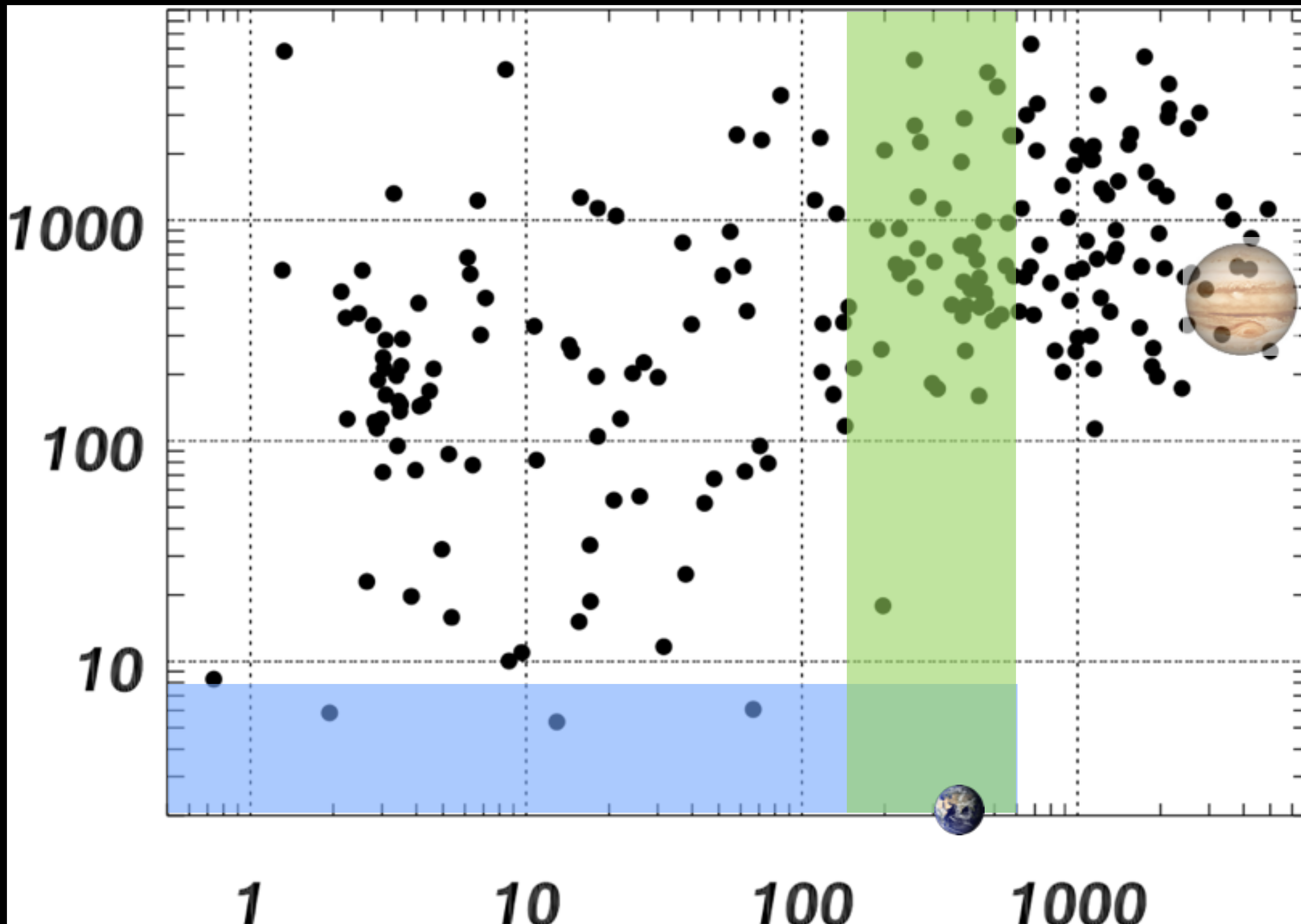
100
1000
Orbital Period [days]

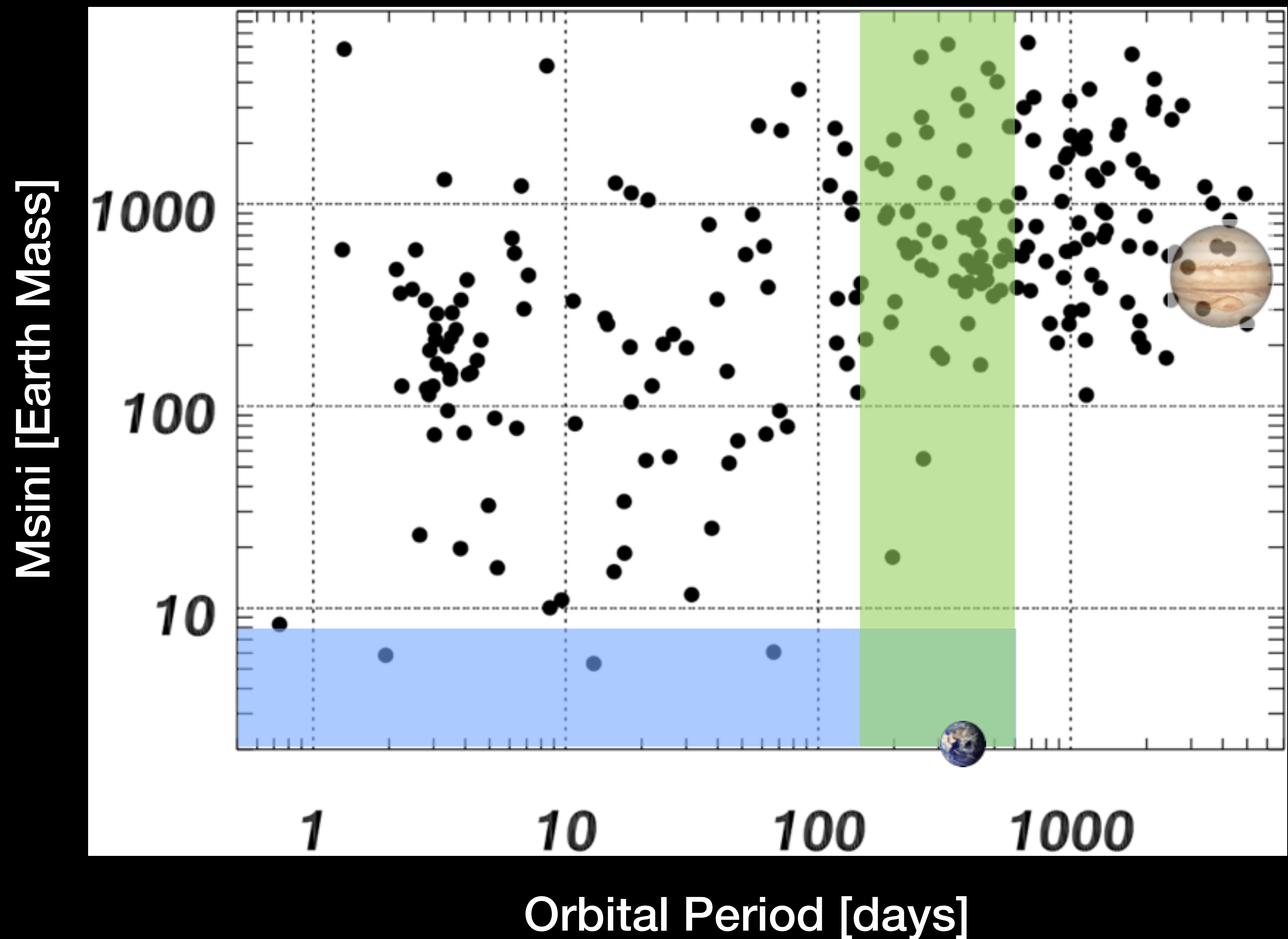
2007



Msini [Earth Mass]

Orbital Period [days]

2008



Msini [Earth Mass]
1000
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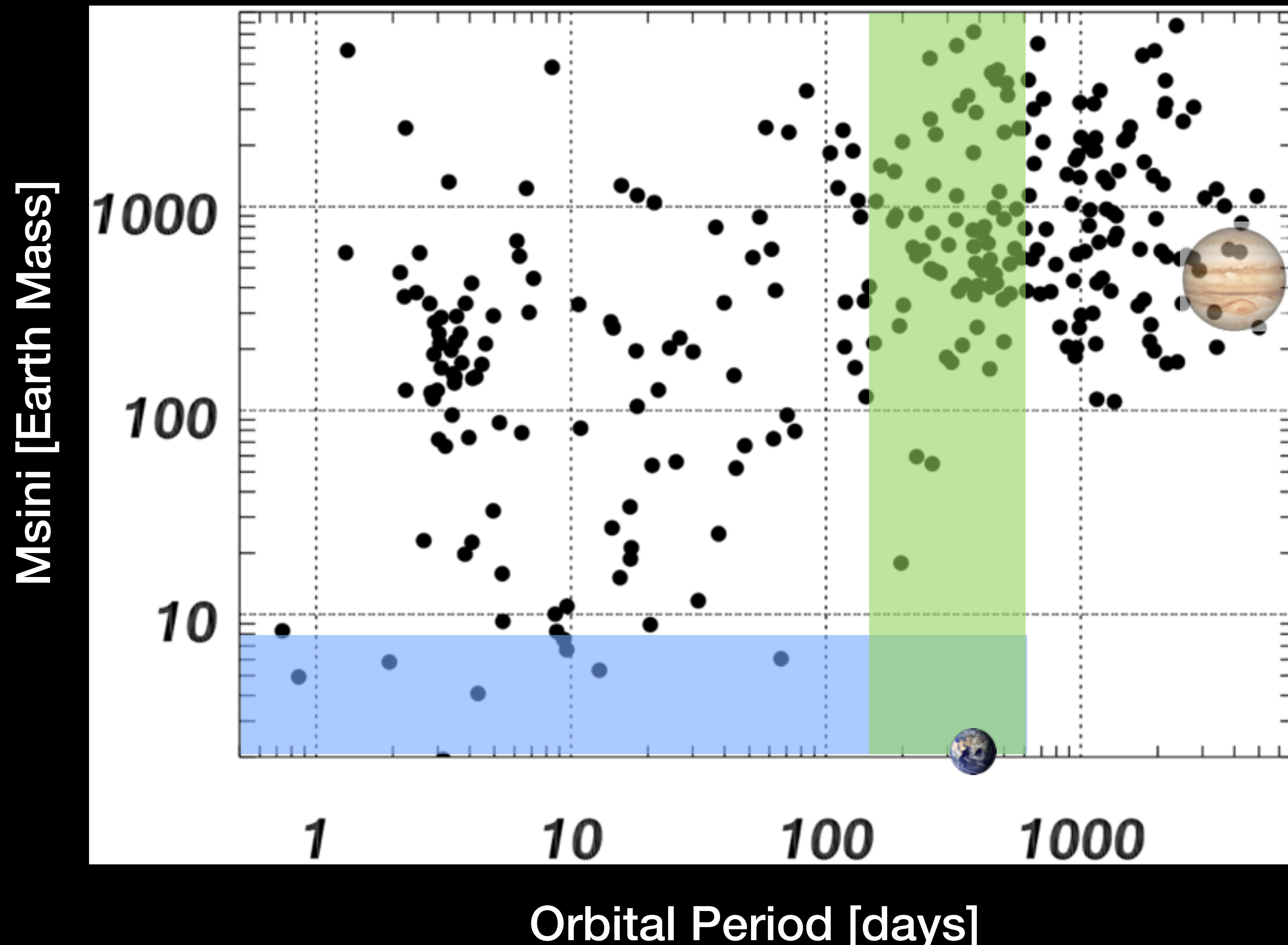
1
10
100
1000
Orbital Period [days]

2009



Msini [Earth Mass]
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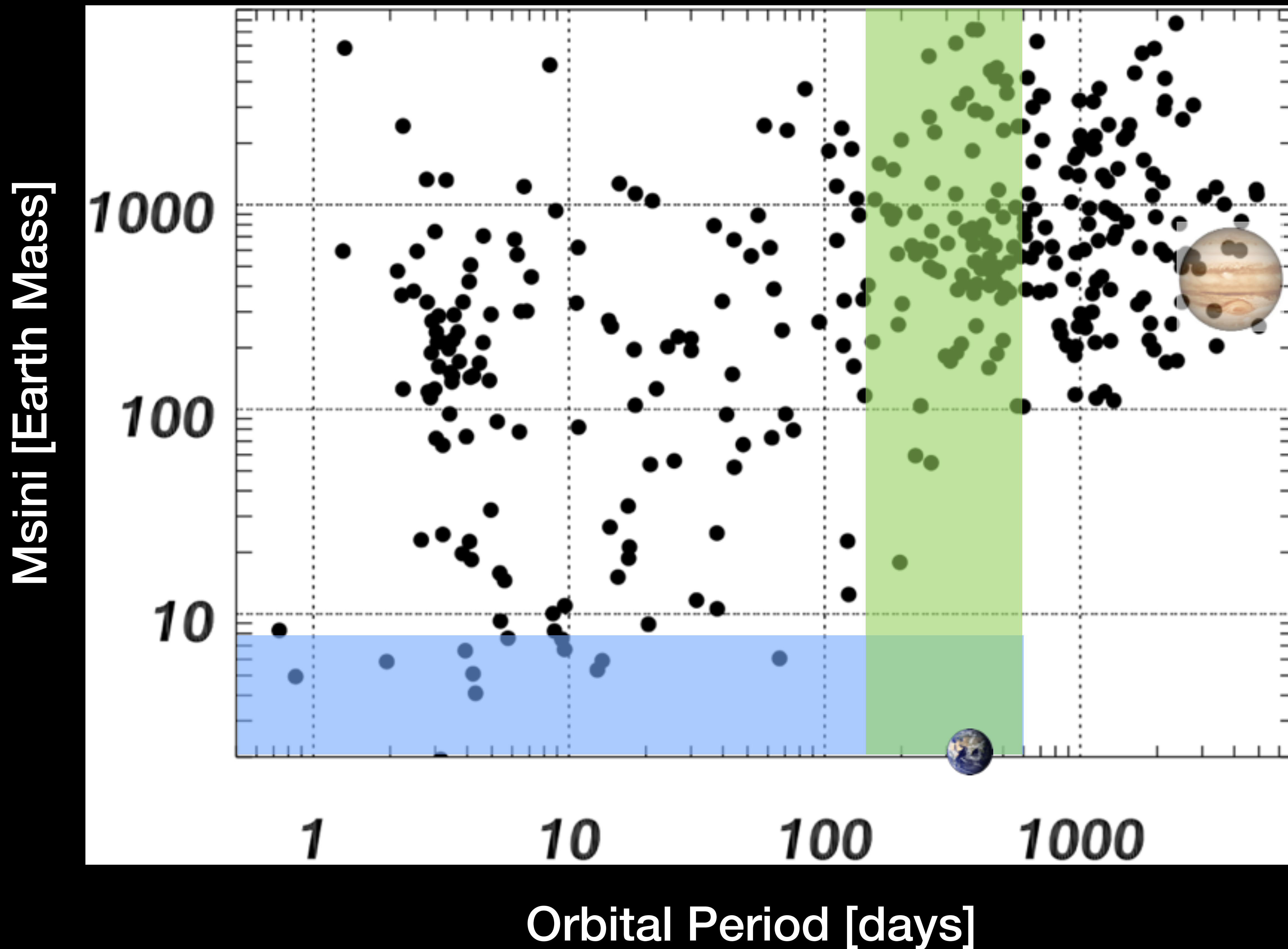
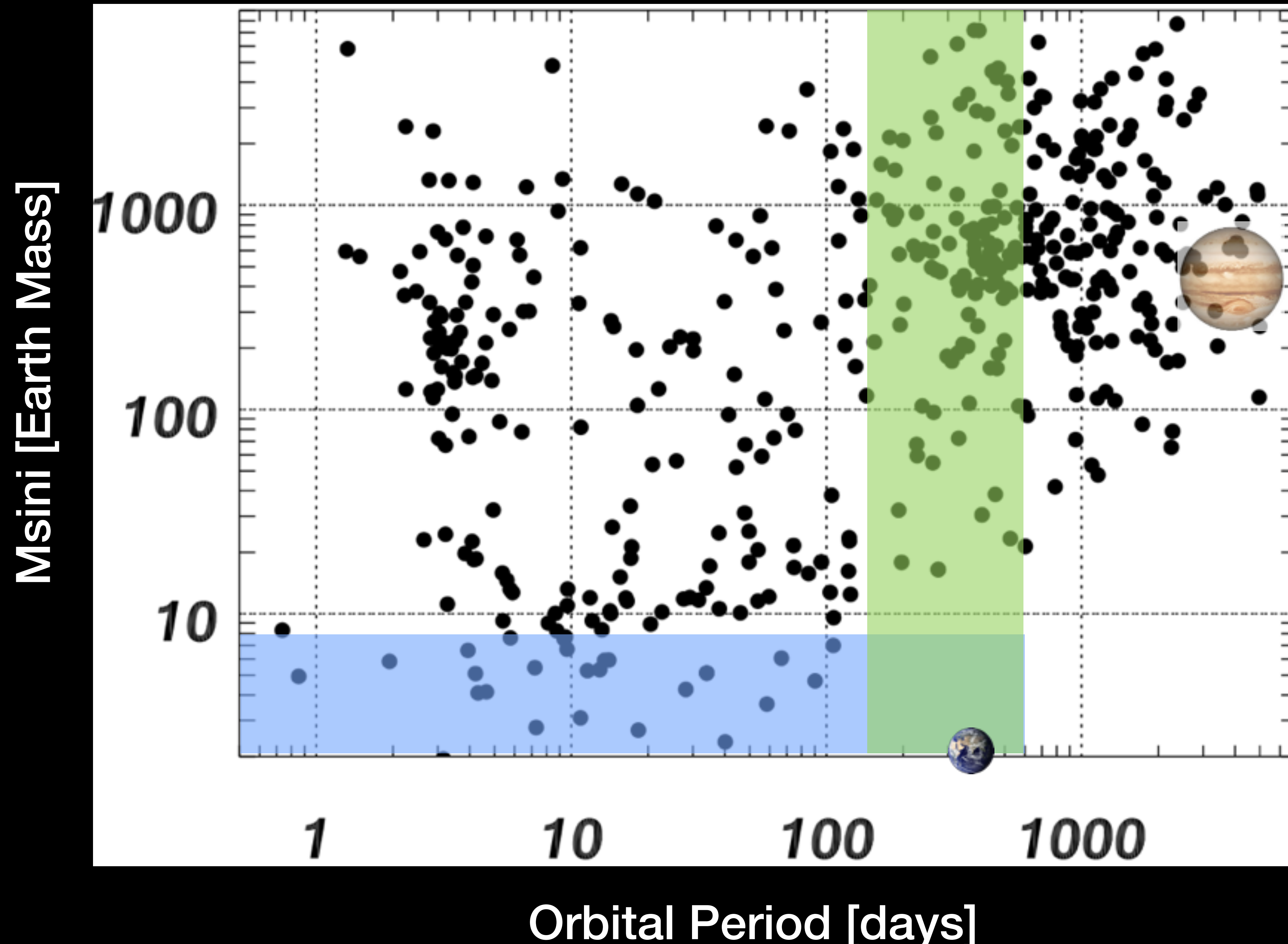
1000
Orbital Period [days]

2010



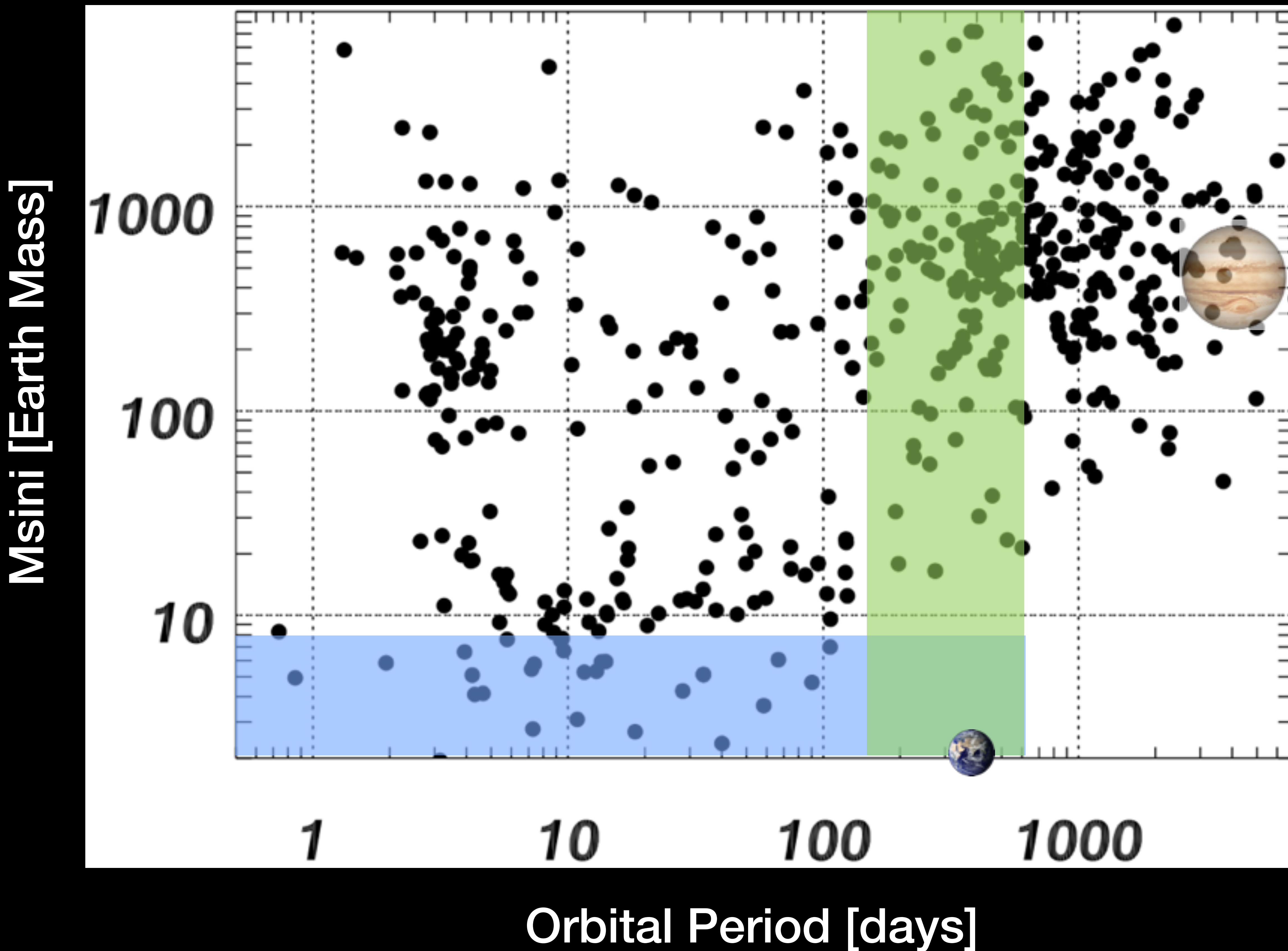
Msini [Earth Mass]
1000
100
10
1
10
100
1000
Orbital Period [days]

2011



Msini [Earth Mass]
1000
100
10
1
10
100
1000
Orbital Period [days]

2012



Msini [Earth Mass]
1000
100
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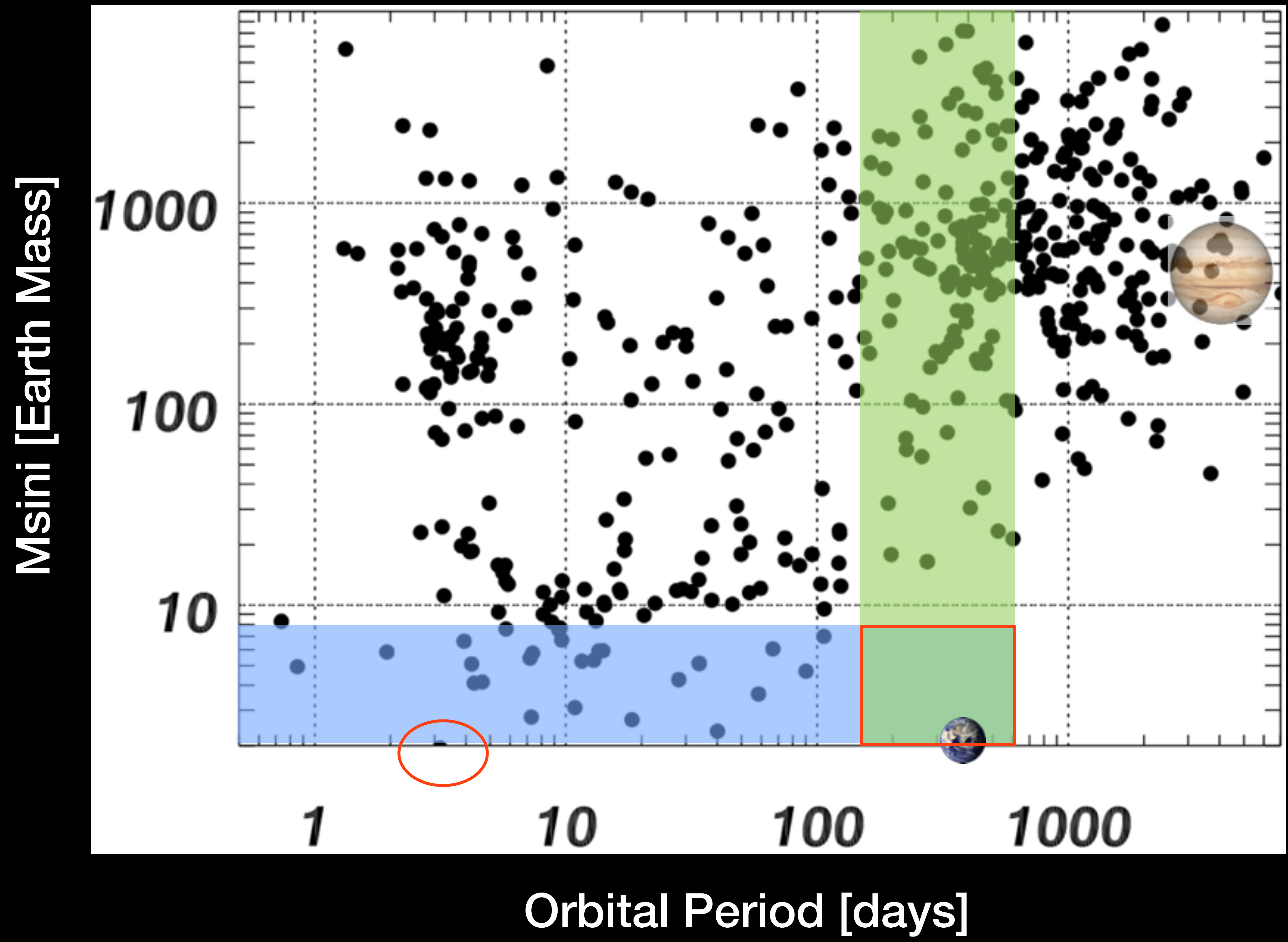
1
10
100
1000
Orbital Period [days]

2013



1000
100
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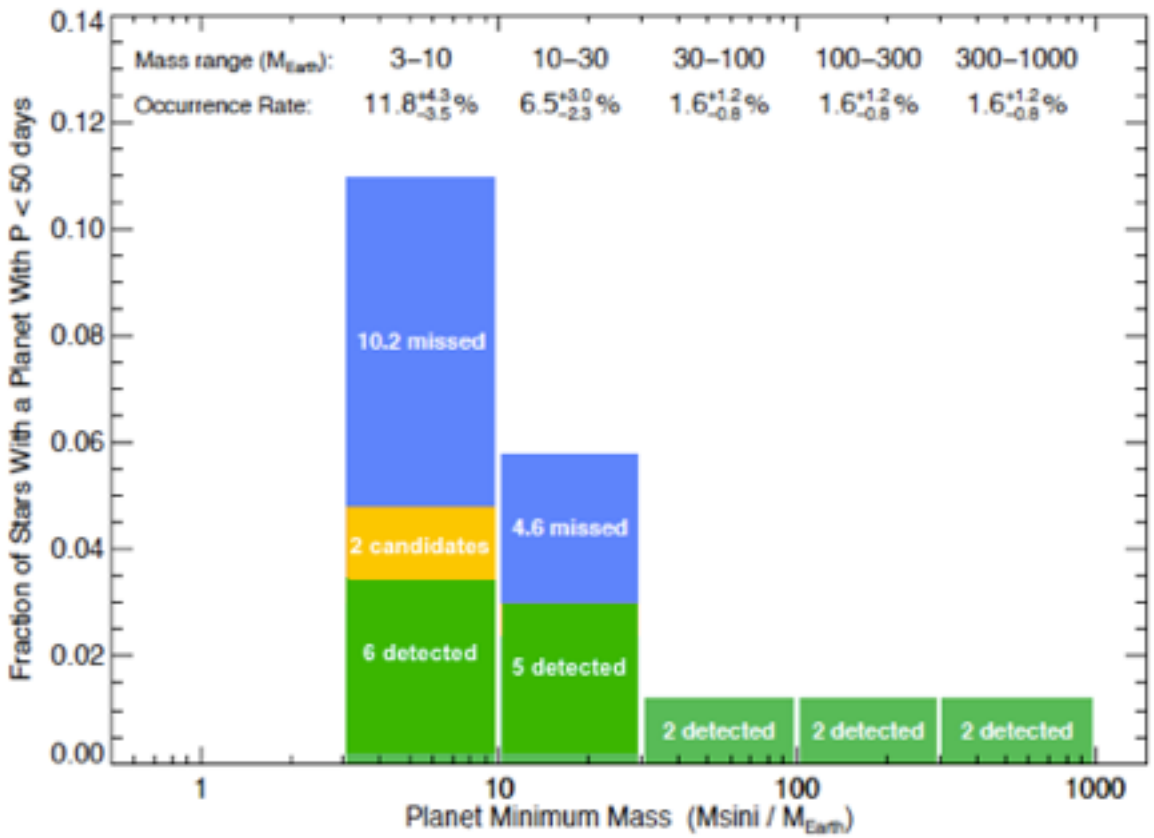
1000
Msini [Earth Mass]
Orbital Period [days]

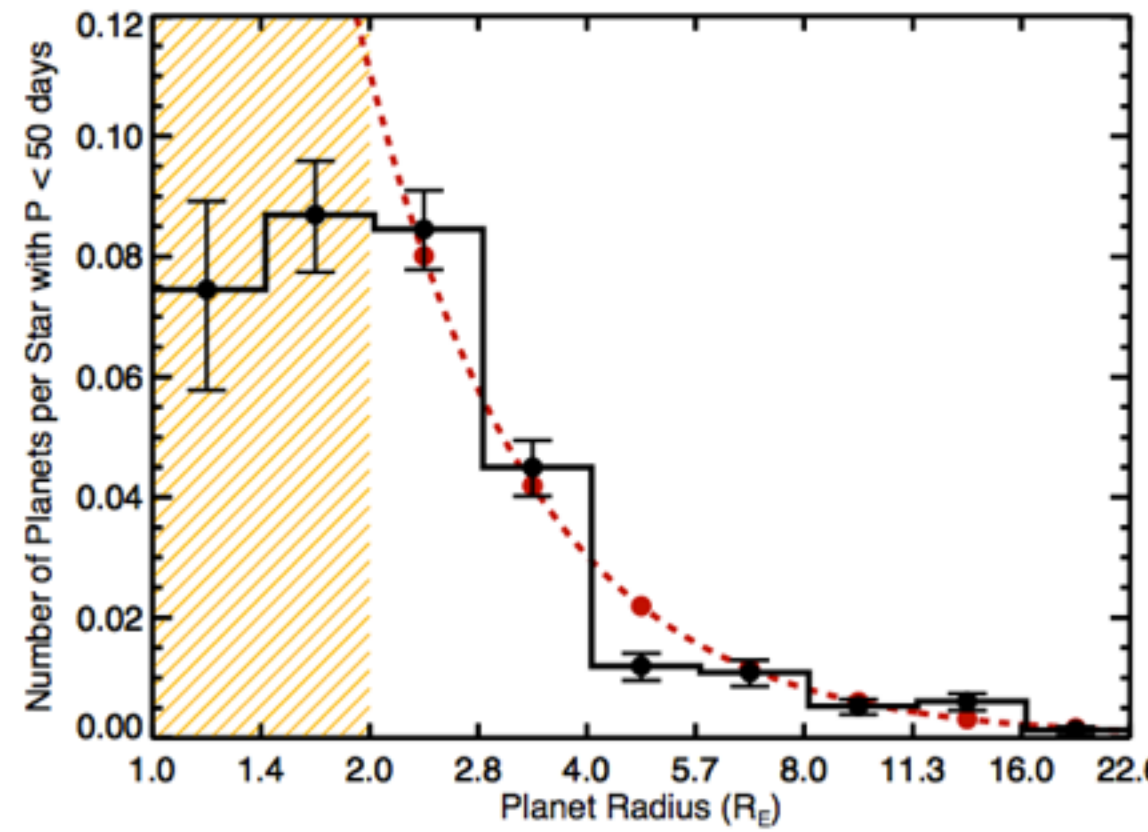
For short-period (< 50 day) planets

RV's: low mass planets common



Howard et al. 2010
Science 330, 653

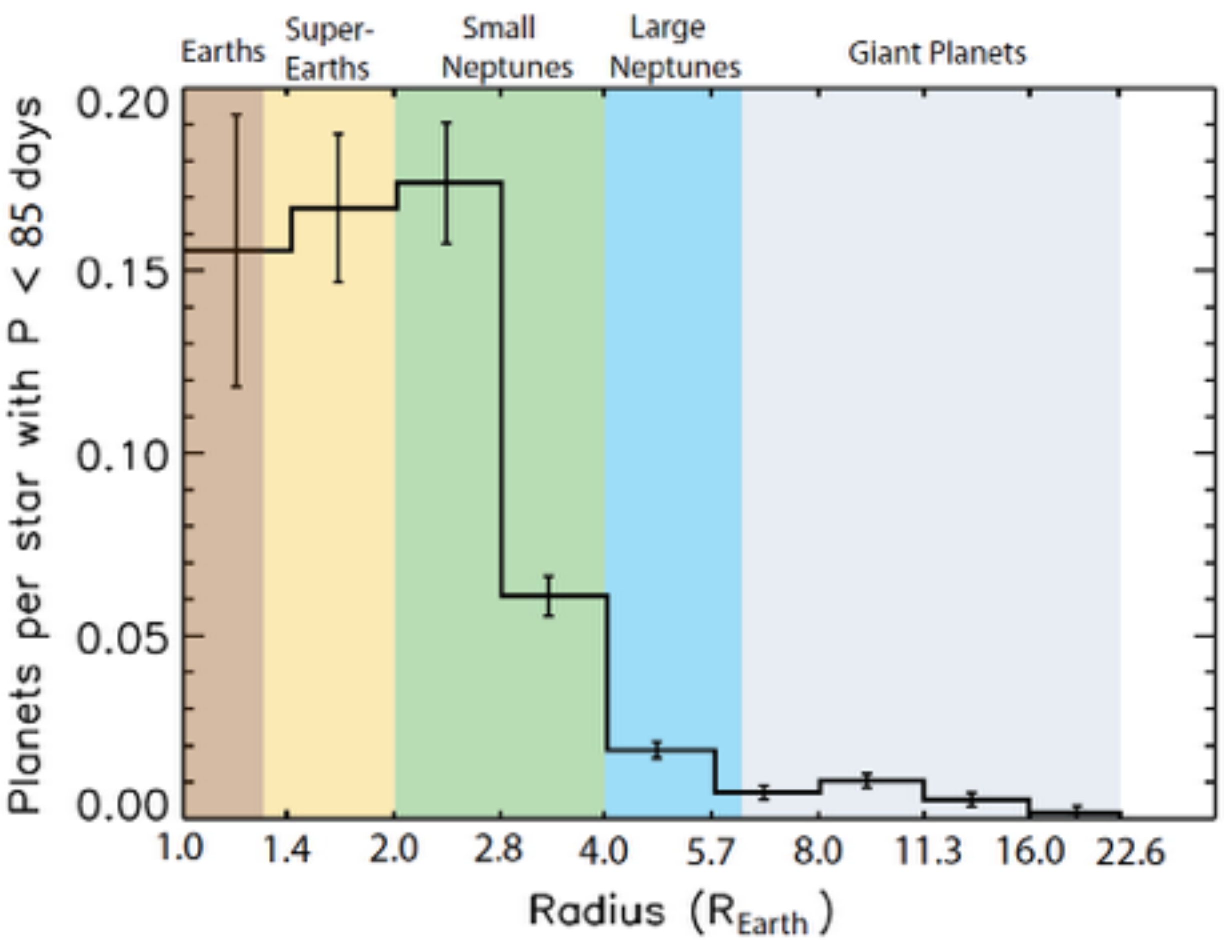
Kepler: Small planets common



Howard et al. 2012

Four times as many Neptunes as Jupiters.
Seven times as many super-Earths as Jupiters!
Only P< 50 days, so no estimate of η_{Earth}

For short-period (< 85 day) planets

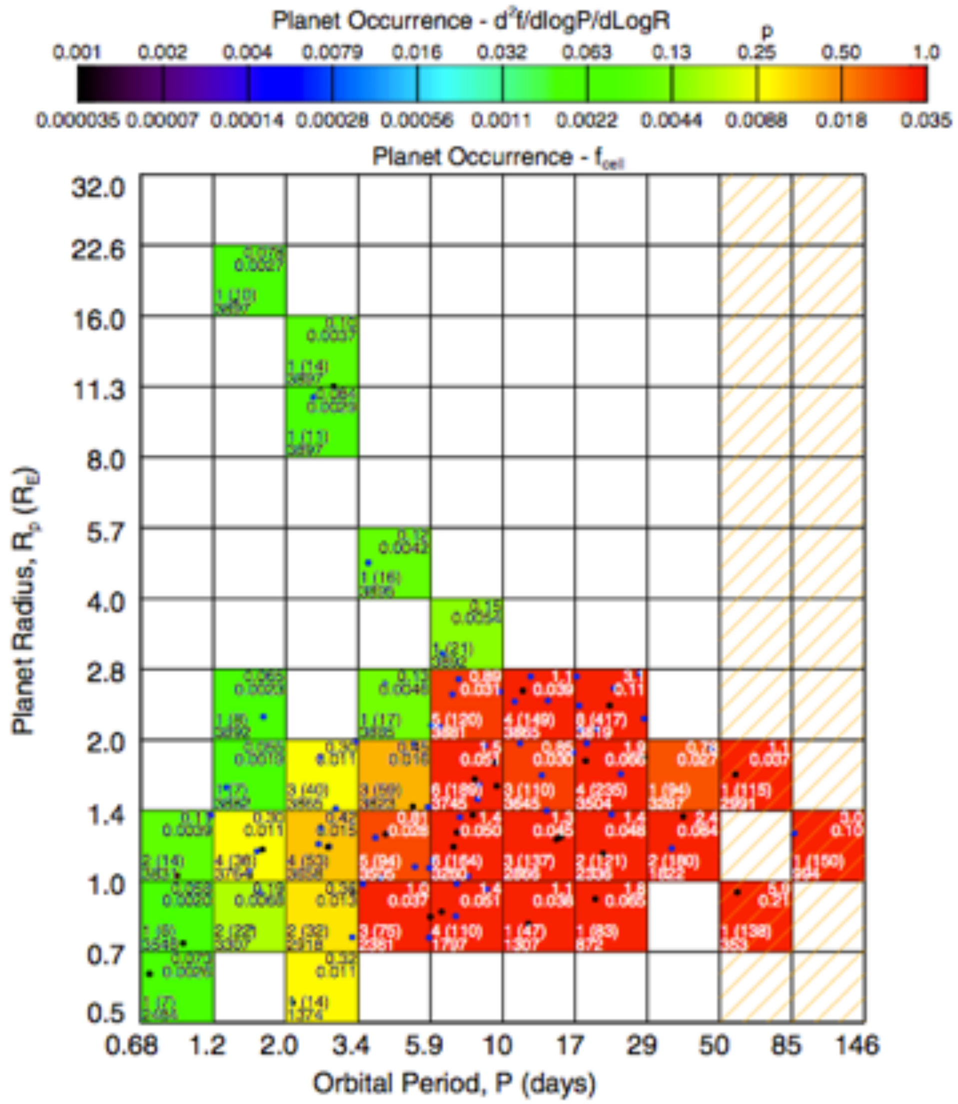


Fressin et al. 2013 ApJ 766, 81

Strength: better FP estimate f(radius).
Simulate transits for planets of different sizes and run extraction code to correct for incompleteness.

Relatively low detection of simulated Earth-size planets; hard to find Earths. Only P< 85, so no calculation of h_{Earth}

Planet Occurrence rates



Mdwarfs make up 70% of MW stars.
Mdwarf size advantage.
HZ is closer so 5 transits per year instead of one.
Added geometric advantage since P(transit) is greater for close-in planets.
Strength: revised stellar parameters.
No correction for FP rates.

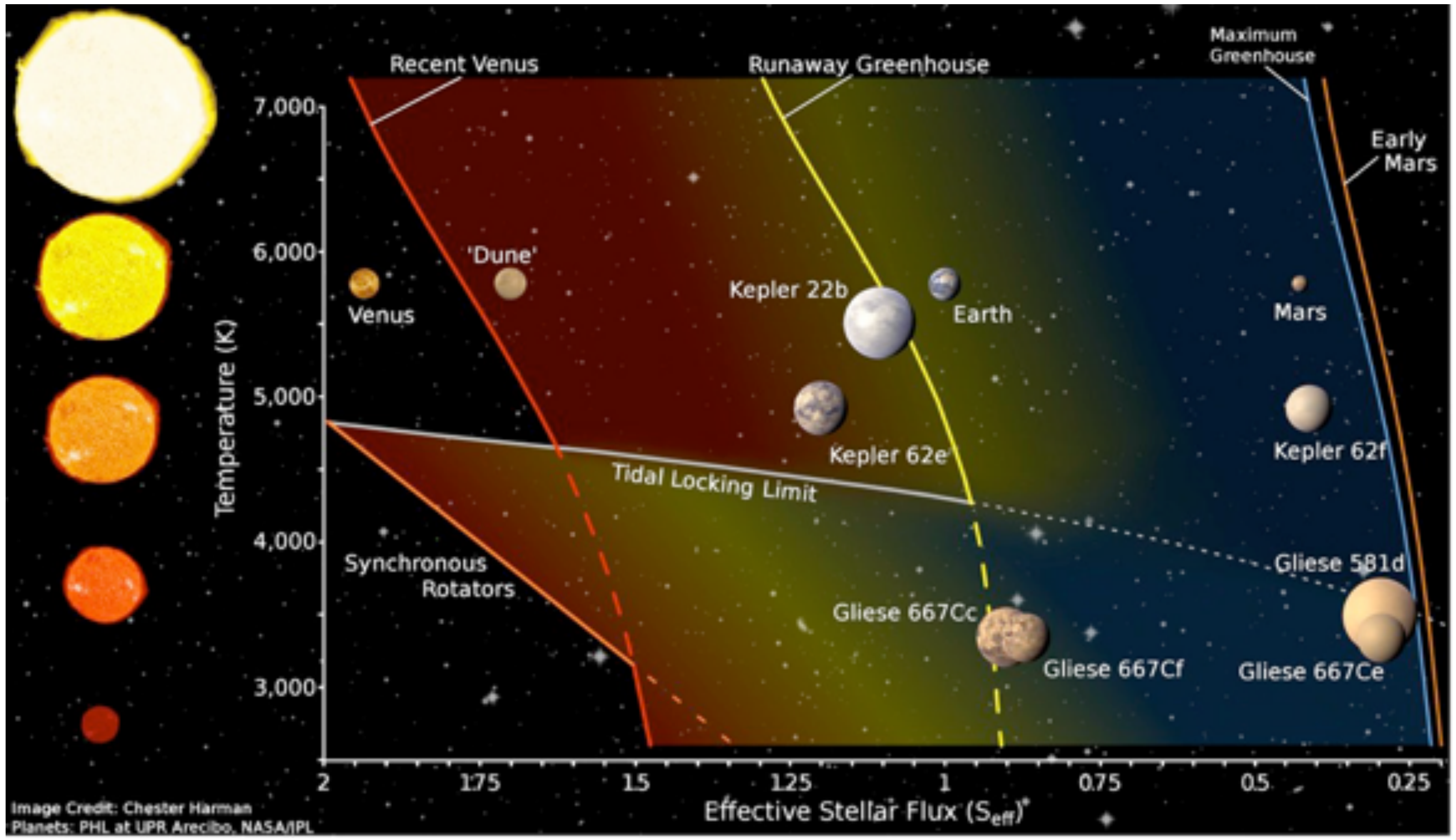
h_{Earth} ~ 15% around M dwarfs

Dressing & Charbonneau 2013 ApJ 767, 95

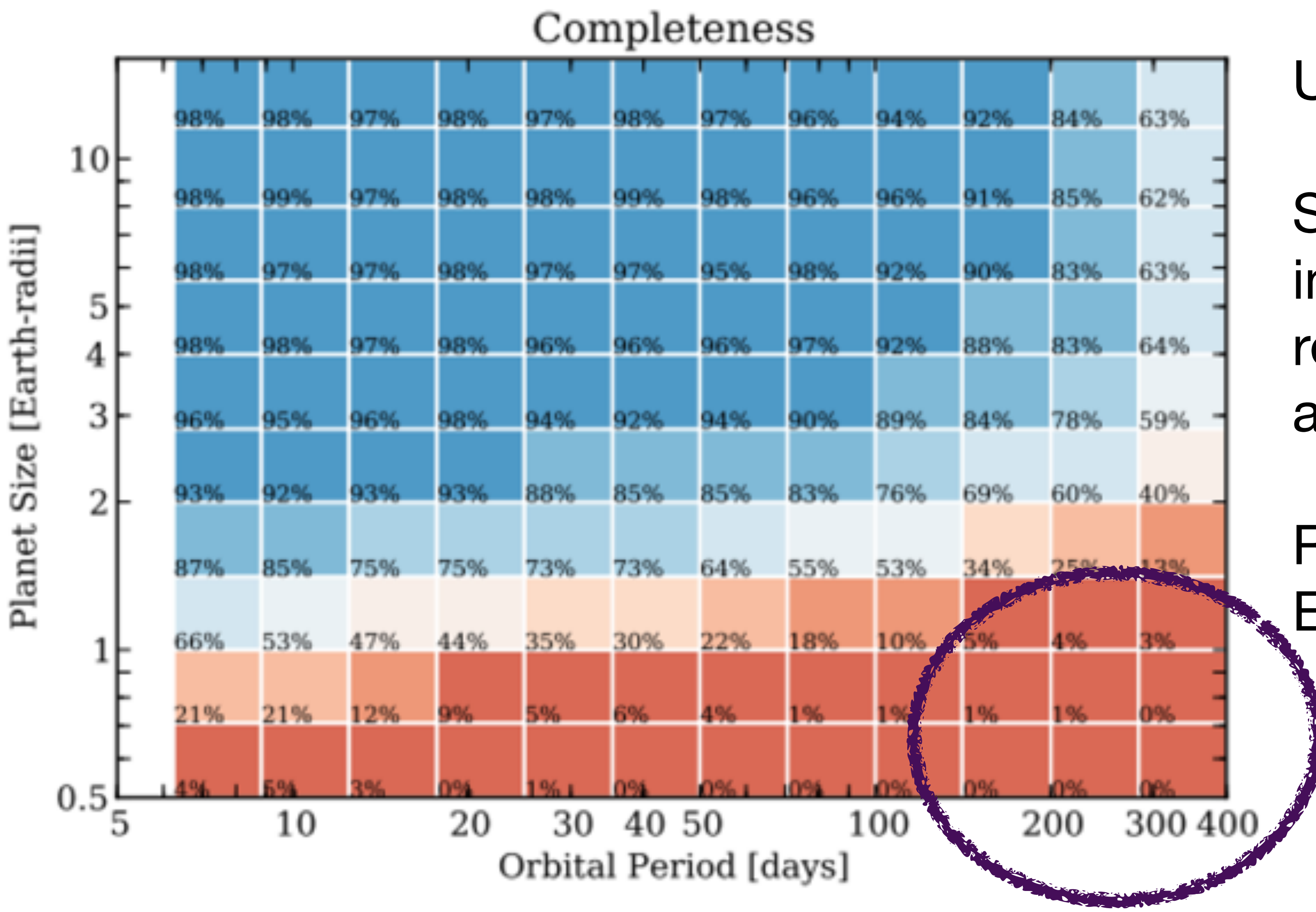
Colors: planet occurrence within bin

- 0.51 planets per star (0.5 - 1.4 R_e)
- 0.39 planets per star (1.4 - 4 R_e)

HZ around Mdwarfs



Greenhouse gases absorb and re-emit much of the outgoing IR.
The Wien peak for Mdwarfs is in the IR, making their HZ wider than it would be based on stellar flux.

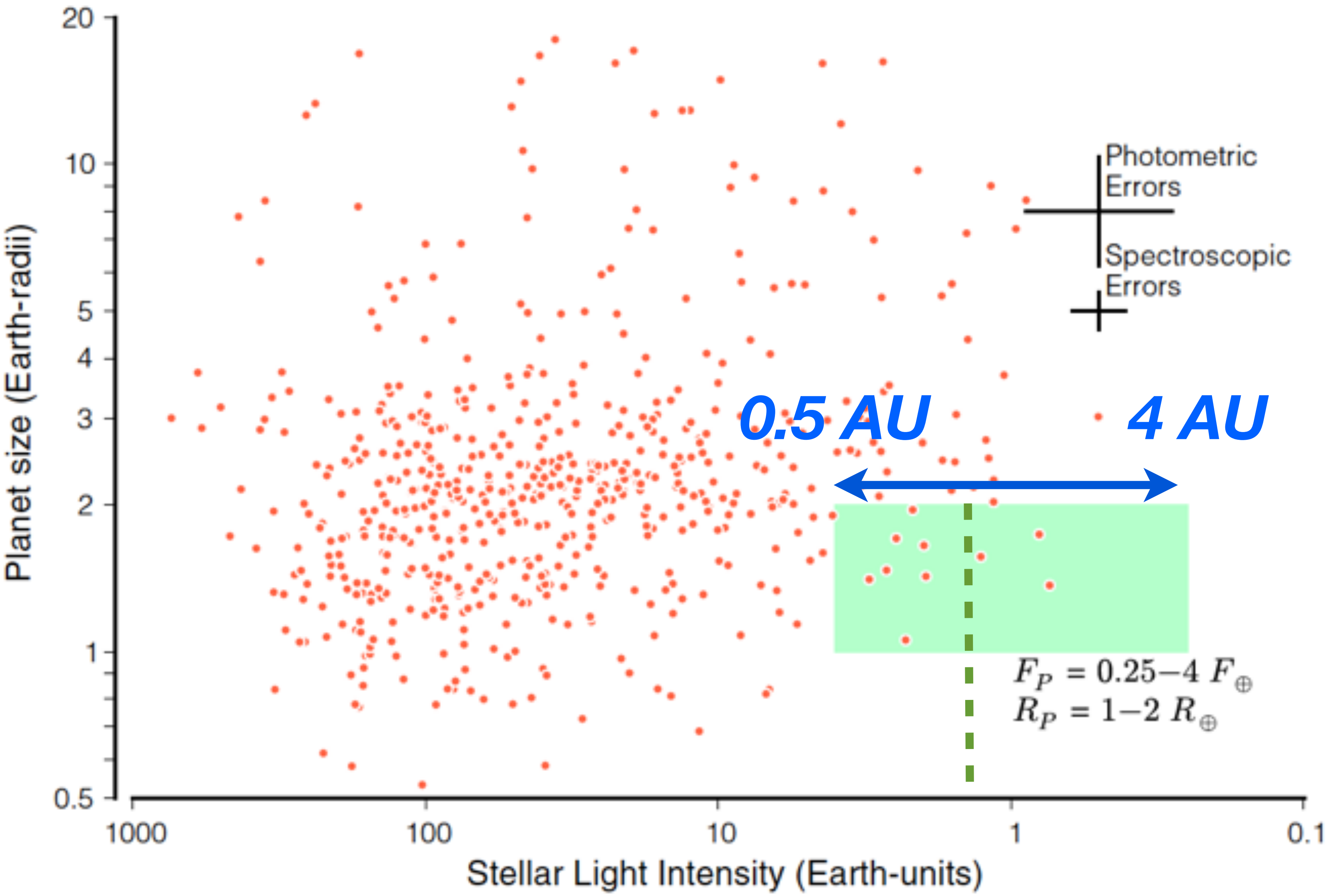


Use their own TERRA pipeline.

Strength: Completness analysis - they inject transiting planets and calculate recovery rate for both the planet radius and the semi-major axis.

Relatively low detection of simulated Earth-size planets; hard to find Earths!

Petigura et al. (2013) PNAS



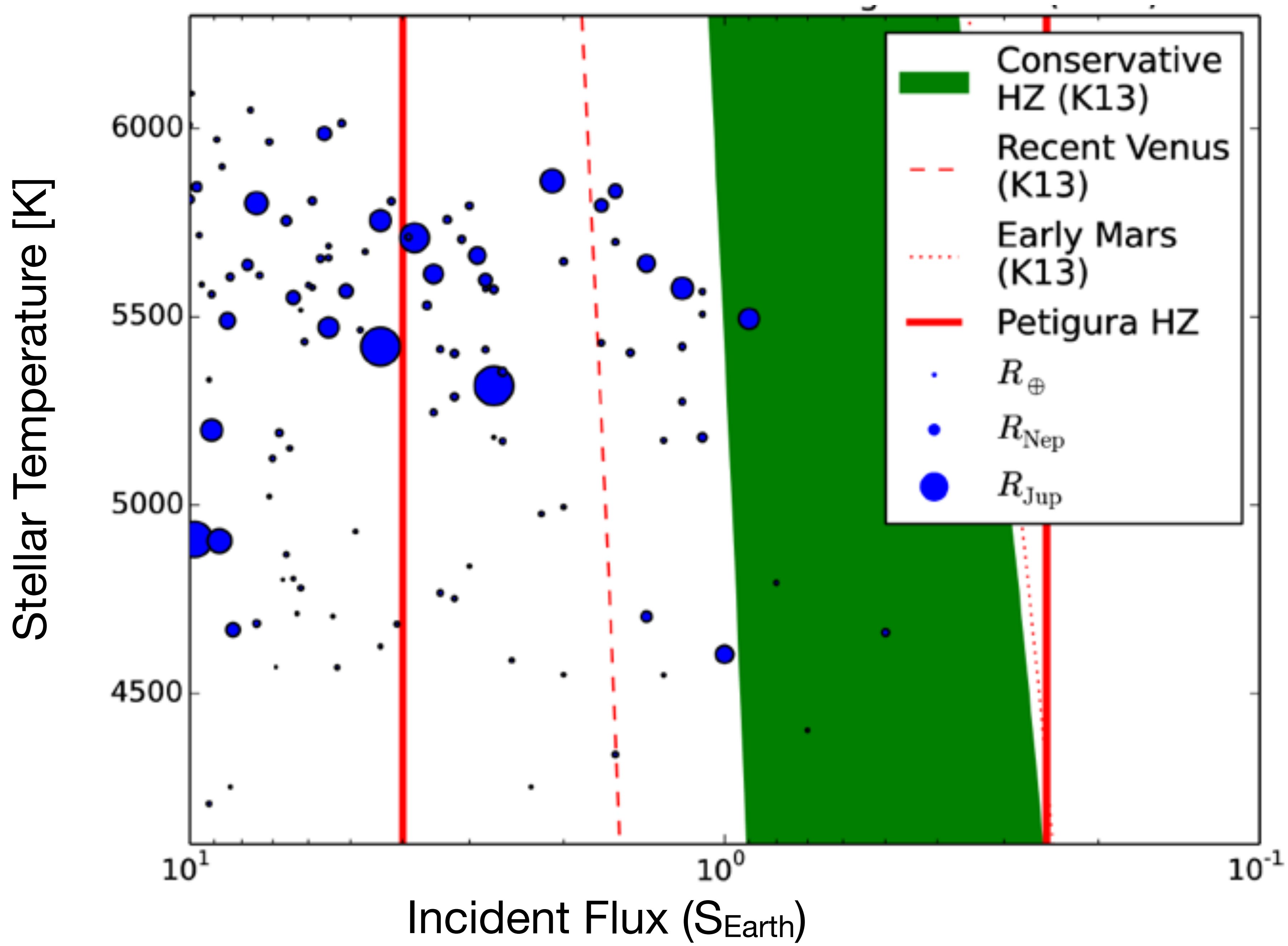
Count the fraction of planets in bins where R_p = 1-2 R_e and F_p = 0.25 - 4 F_e

Correct for observational incompleteness
Correct for transit geometry

Based on detections at shorter periods, an extrapolation is made for occurrence of Earth-sized planets in their HZ bins
η_{Earth} = 22%

Petigura et al. (2013) PNAS

Perhaps somewhere between 10 - 40% depending on extrapolation assumptions.



Schmitt et al. (in prep)

Do we know h_{EARTH}?

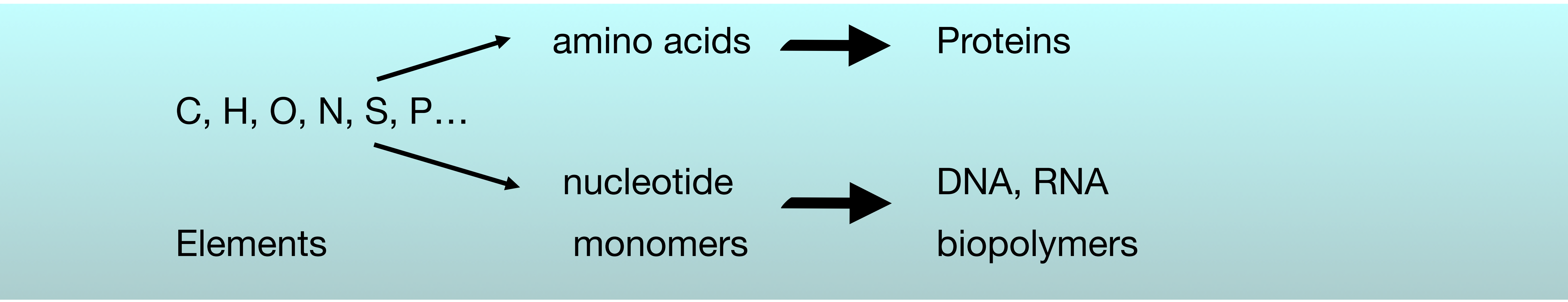
Probably not. We do know:

- Earth-sized planets do exist
- Almost every star has planets
- Small planets more common than gas giants
- Most systems are multi-planet

And that is quite a lot to know!

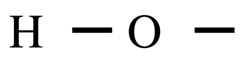
So, why should we care?
What do we know about the origin of Life on Earth?
Is it safe to generalize? Probably not, but baby steps....

Underpinnings of life lies in the bonding properties and behavior of electrons.
Carbon is exceptionally versatile (single, double, triple bonds, long hydrocarbon chains)

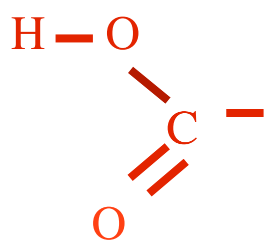


Life on Earth is carbon-based; 96% of the human body is CHON
By mass: C (18%), H (9.5%), O (65%), N (3.3%)

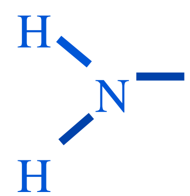
Prebiotic Molecules



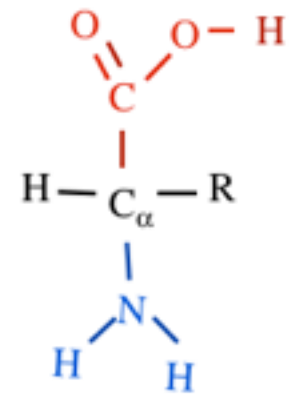
hydroxyl group



carboxyl group



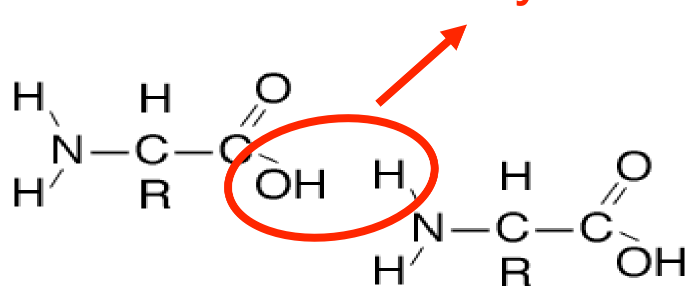
amino group

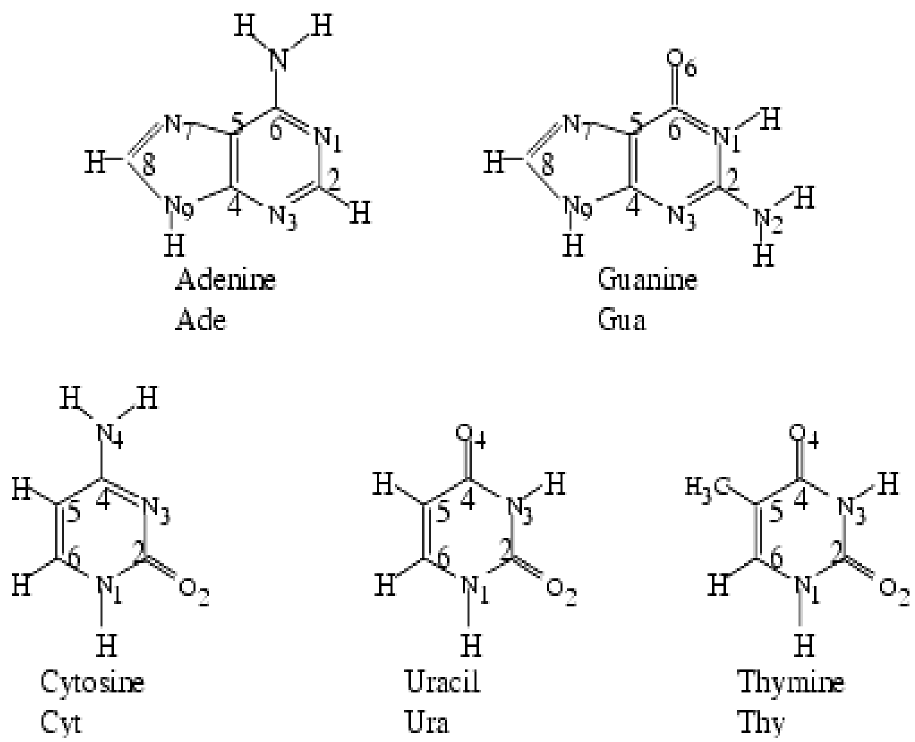


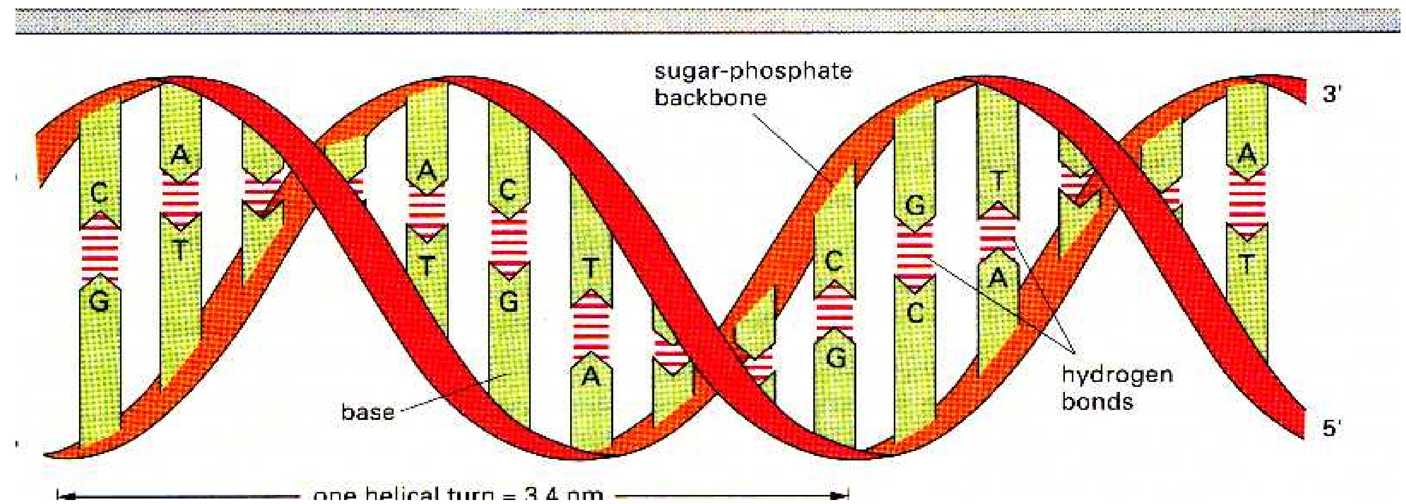
Amino acid: amino group with a central carbon Cα, that is bonded to a carboxyl end group, an R group and a H atom.

Hundreds of amino acids all distinguished by unique R “side chain.”
From all these possibilities, only 20 amino acids are used by extant life forms.

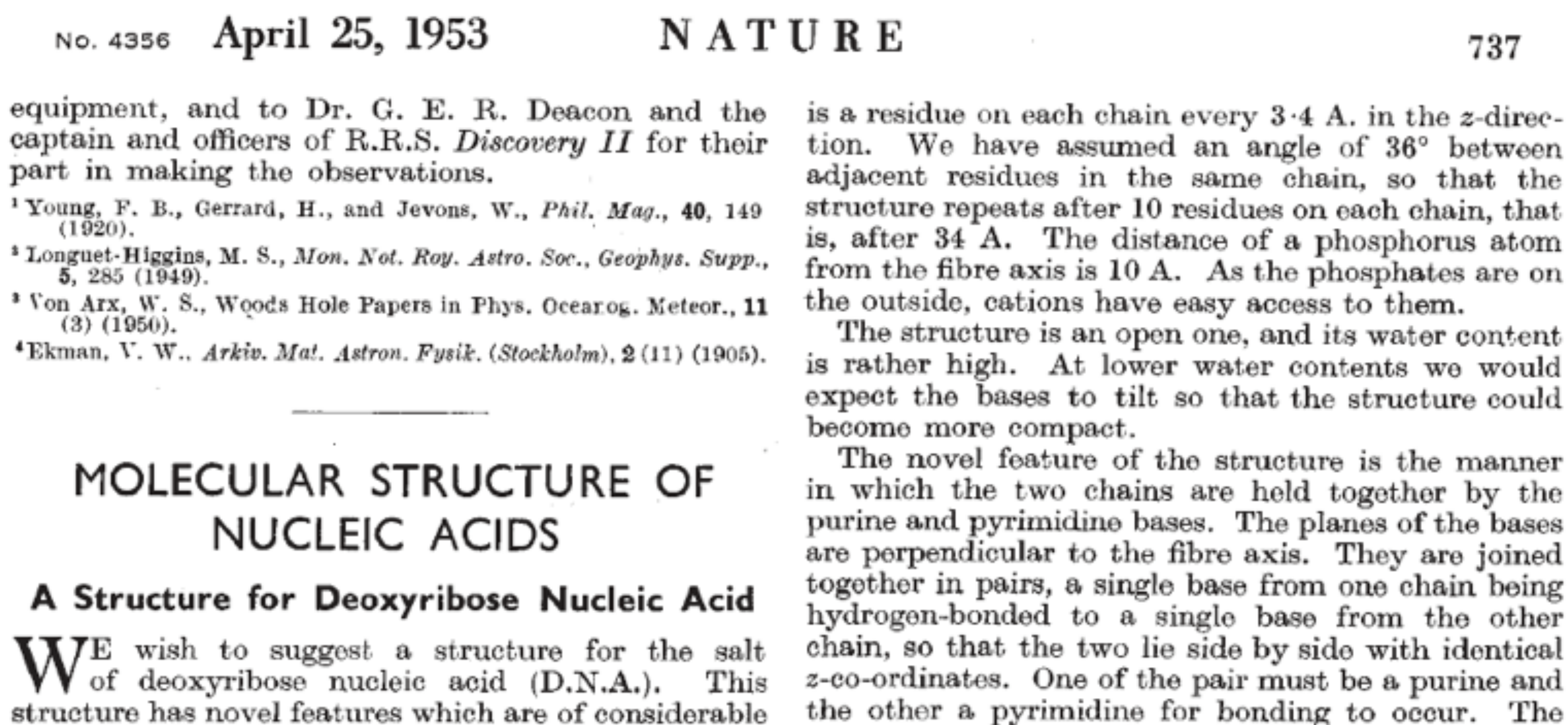
Dehydration forms a dipeptide - chain like assembly of thousands of amino acids build proteins.








Watson Crick


No. 4356 April 25, 1953 NATURE 737

equipment, and to Dr. G. E. R. Deacon and the captain and officers of R.R.S. *Discovery II* for their part in making the observations.

[1] Young, F. B., Gerrard, H., and Jevons, W., *Phil. Mag.*, **40**, 149 (1920).

[2] Longuet-Higgins, M. S., *Mon. Not. Roy. Astro. Soc., Geophys. Supp.*, **5**, 285 (1949).

[3] Von Arx, W. S., Woods Hole Papers in Phys. Oceanog. Meteor., **11** (3) (1950).

[4] Ekman, V. W., *Arkiv. Mat. Astron. Fysik. (Stockholm)*, **2** (11) (1905).

MOLECULAR STRUCTURE OF NUCLEIC ACIDS

A Structure for Deoxyribose Nucleic Acid

WE wish to suggest a structure for the salt of deoxyribose nucleic acid (D.N.A.). This structure has novel features which are of considerable

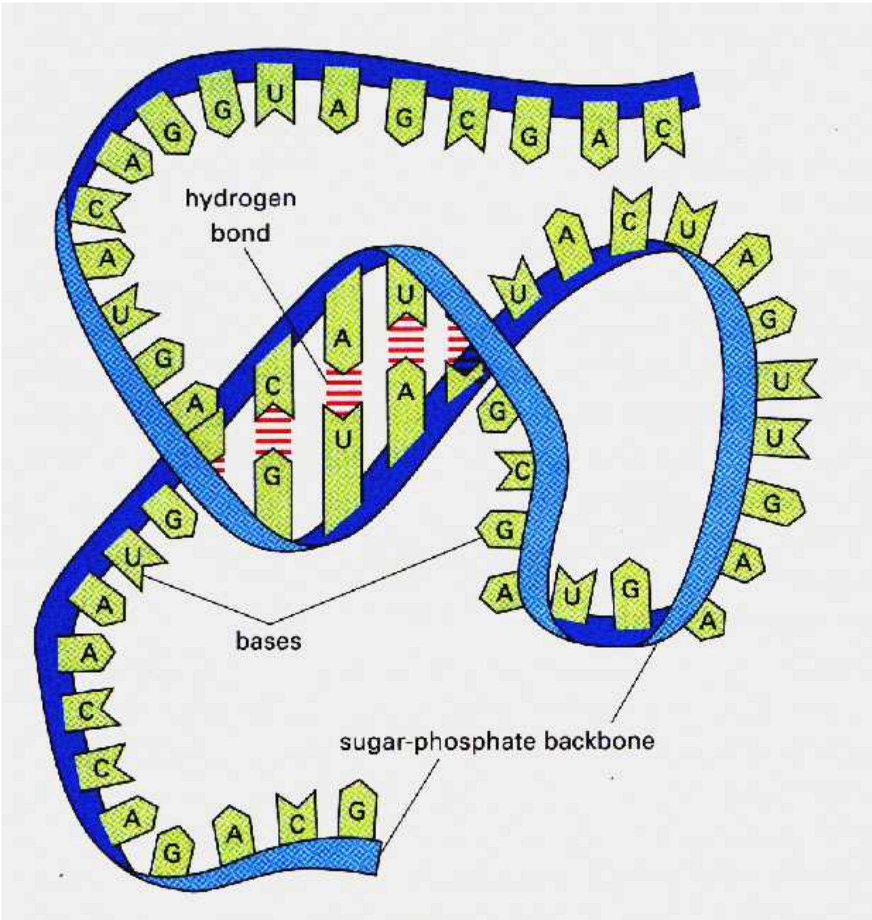
is a residue on each chain every 3·4 A. in the *z*-direction. We have assumed an angle of 36° between adjacent residues in the same chain, so that the structure repeats after 10 residues on each chain, that is, after 34 A. The distance of a phosphorus atom from the fibre axis is 10 A. As the phosphates are on the outside, cations have easy access to them.

The structure is an open one, and its water content is rather high. At lower water contents we would expect the bases to tilt so that the structure could become more compact.

The novel feature of the structure is the manner in which the two chains are held together by the purine and pyrimidine bases. The planes of the bases are perpendicular to the fibre axis. They are joined together in pairs, a single base from one chain being hydrogen-bonded to a single base from the other chain, so that the two lie side by side with identical *z*-co-ordinates. One of the pair must be a purine and the other a pyrimidine for bonding to occur. The

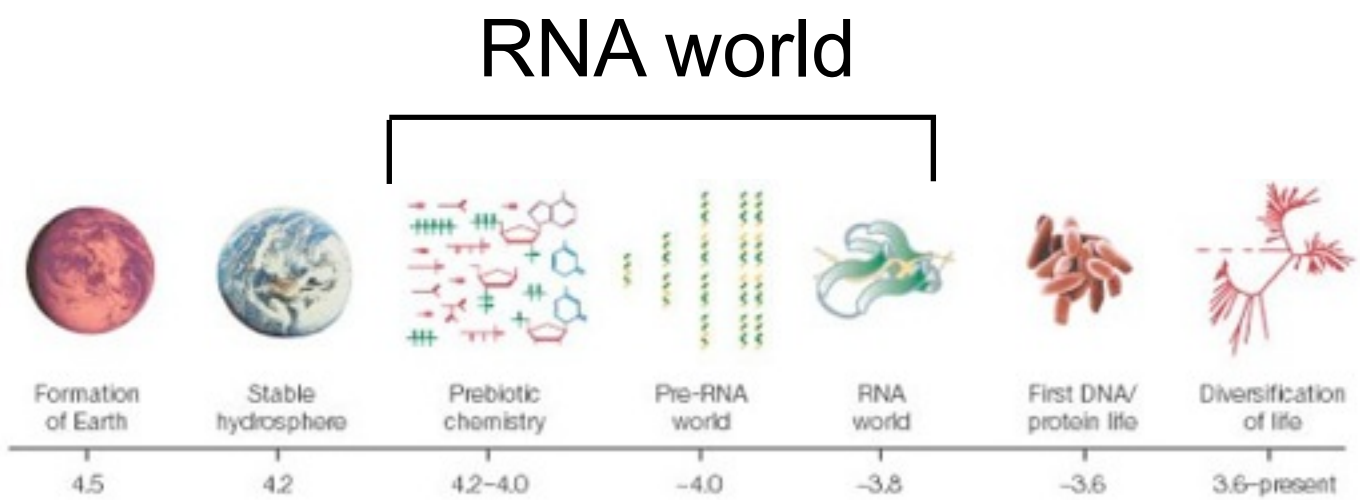
<u>"Molecular structure of DNA"</u>

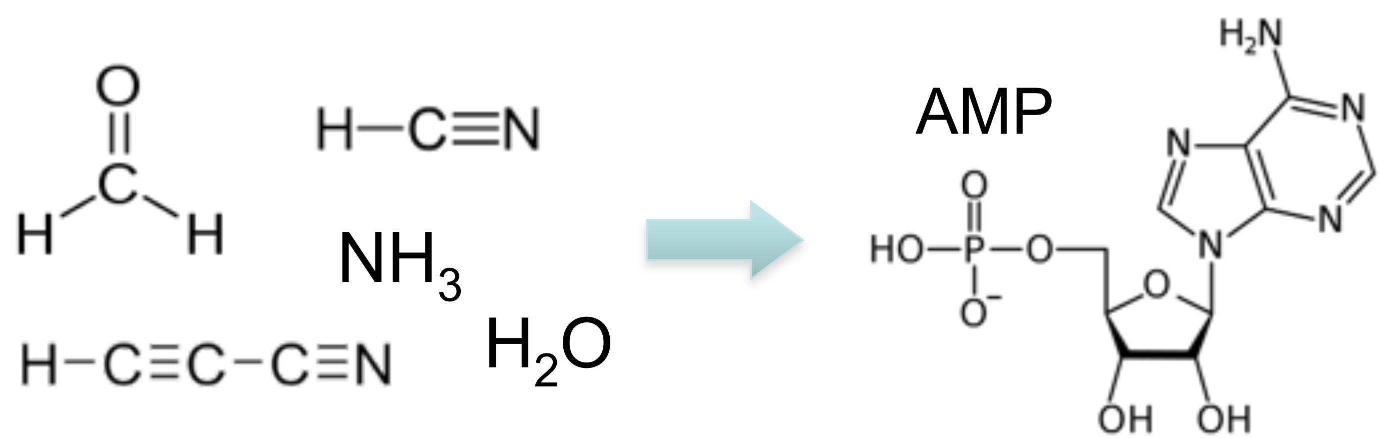
1. In 1953, Watson and Crick announced a double helix structure for DNA.
2. Helix chain held together by weak H-bonds between nucleic bases.
3. Only specific pairs can bind together: A-T and G-C
   - experimentally, ratio of A:T and G:C is nearly unity
   - geometrically: had to be one purine and one pyrimidine base
4. Could not build DNA with ribose sugar because the extra oxygen atom would make too close a van der Waals contact - need deoxyribose sugar
5. It did not escape their attention that the specific pairings suggested a code: a possible copying mechanism



RNA is a single strand with catalytic properties.
(Like DNA, but using Uracil in place of Thymine - b/c of the bonding properties of ribose vs deoxyribose)

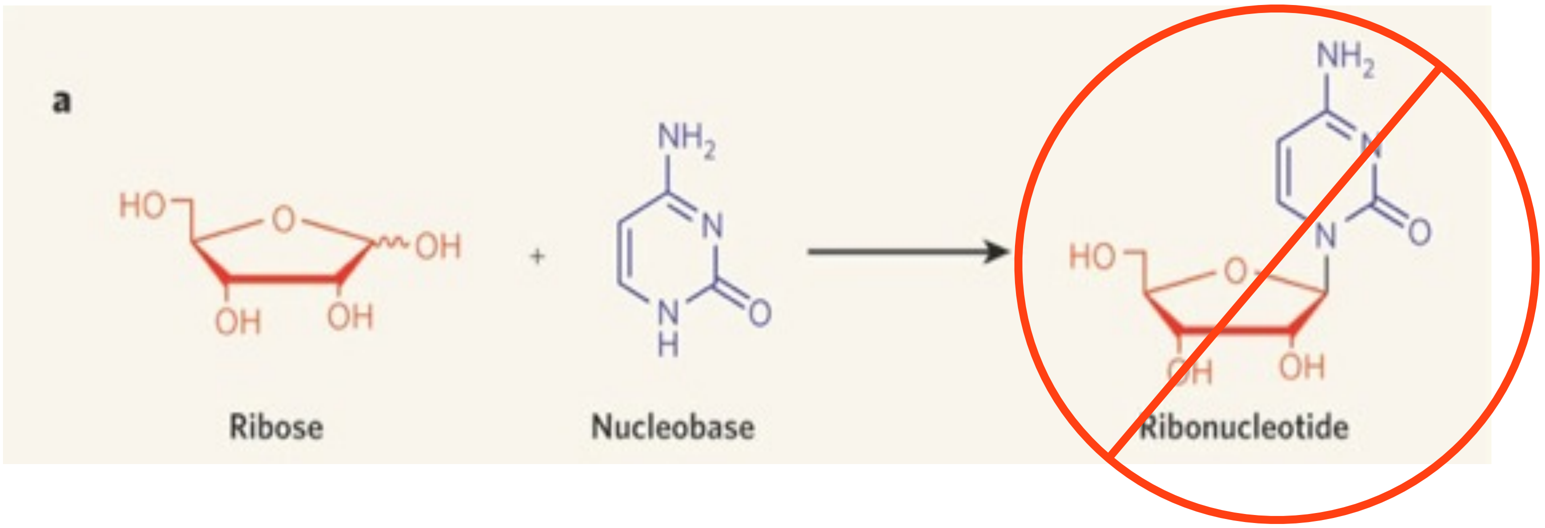
RNA is the simplest molecule with coded genetic material and the ability to replicate. This lead to the idea that RNA might be the link to the origin of life on Earth...





This idea started with the Miller-Urey experiment (1953). Take the pre-assembled subcomponents of RNA and mix them in a test tube... and for 50 years....

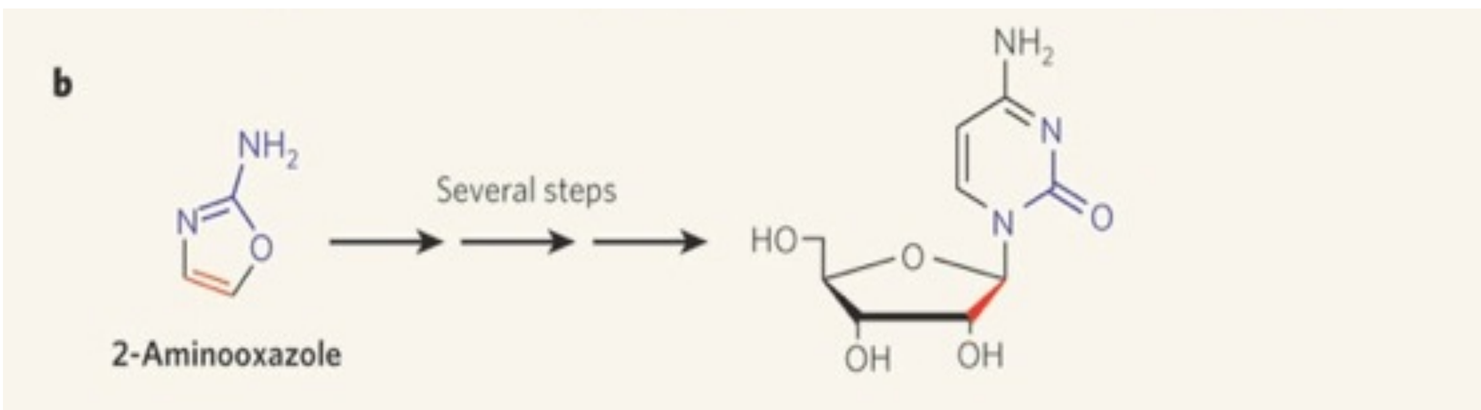
Prebiotic road block

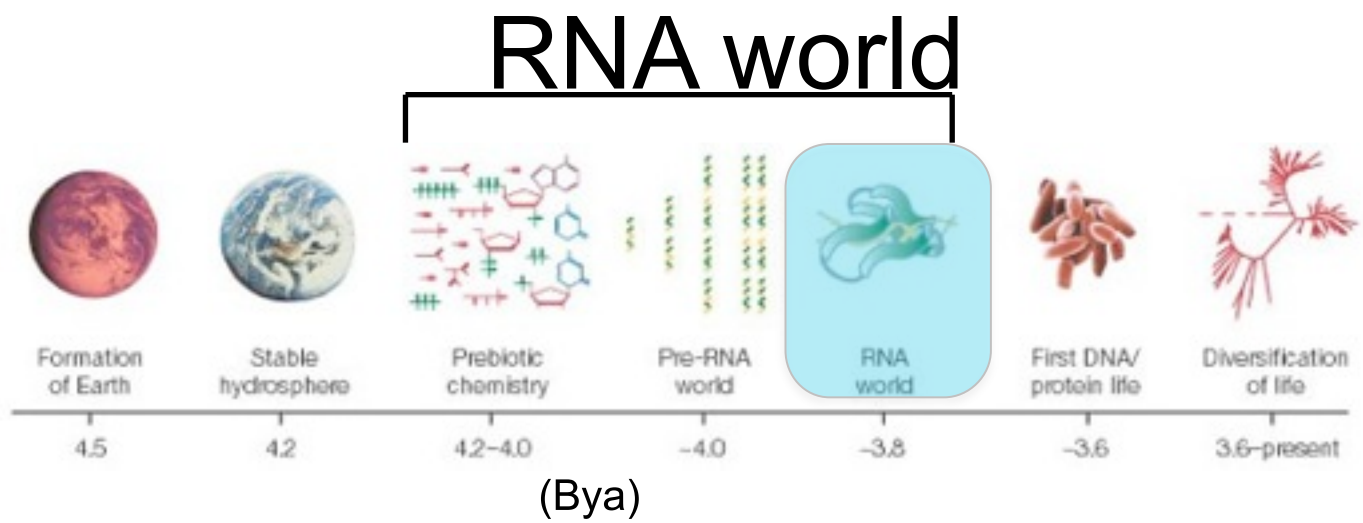


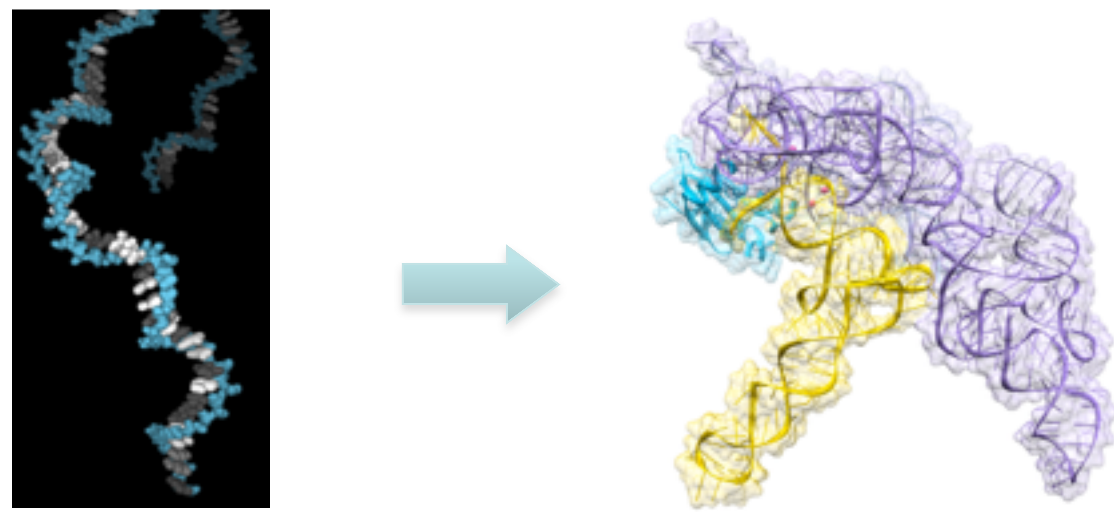
50 years of synthesizing ⟶ **tar**

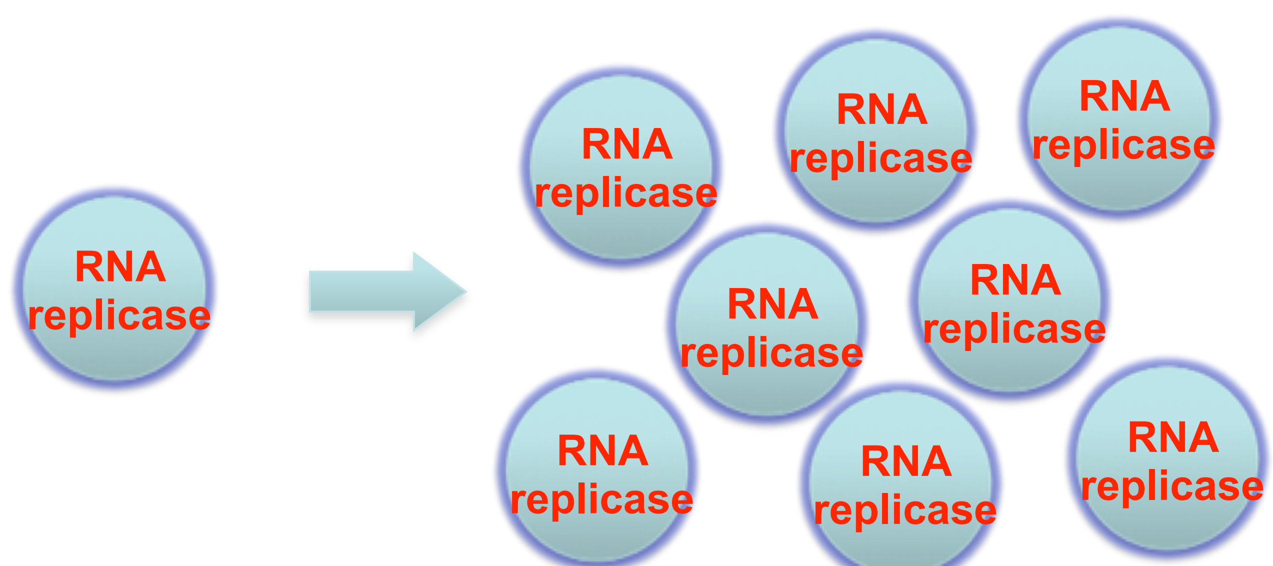
Prebiotic road block

In 2009, John Sutherland discovered an efficient pathway for nucleotide synthesis under prebiotically plausible conditions, using phosphate as a catalyst that is later incorporated into ATP




RNA world
Formation of Earth
Stable hydrosphere
Prebiotic chemistry
Pre-RNA world
RNA world
First DNA/ protein life
Diversification of life
4.5
4.2
4.2–4.0
~4.0
~3.8
~3.6
3.6–present
(Bya)




RNA replicase
RNA replicase
RNA replicase
RNA replicase
RNA replicase
RNA replicase
RNA replicase
RNA replicase
RNA replicase

What is Life?

How Chemistry Becomes Biology

Addy Pross

Living things are made of the same “dead” molecules as non-living things. These molecules interact in a holistic ensemble in organisms. Until we understand how life emerged, we will not understand what life is.

Richard Feynman “What I cannot create, I do not understand.”

Nature pushes systems toward equilibrium; disorder; chaos. Life resists that tendency by expending energy.

What is Life?

How Chemistry Becomes Biology

Addy Pross

Life is cell-based.
Genetic information is stored in DNA.
Proteins for all of life's functionality are coded in DNA.
Universal energy storage for life: ATP molecules.

All of this tells us that life today was derived from a last common ancestor.
It does not tell us what life is.

Chemical stability: $H_2O \rightleftarrows H + OH$

1. Rxns occur if more stable products are produced from less stable reactants.
2. Rxns may not proceed if there is an energy barrier.
3. Auto-catalytic self replication can lead to exponential amplification until resources are exhausted.

Origin of Life:

Was the emergence of life on Earth a freak accident or inevitable, given the laws of physics and chemistry?

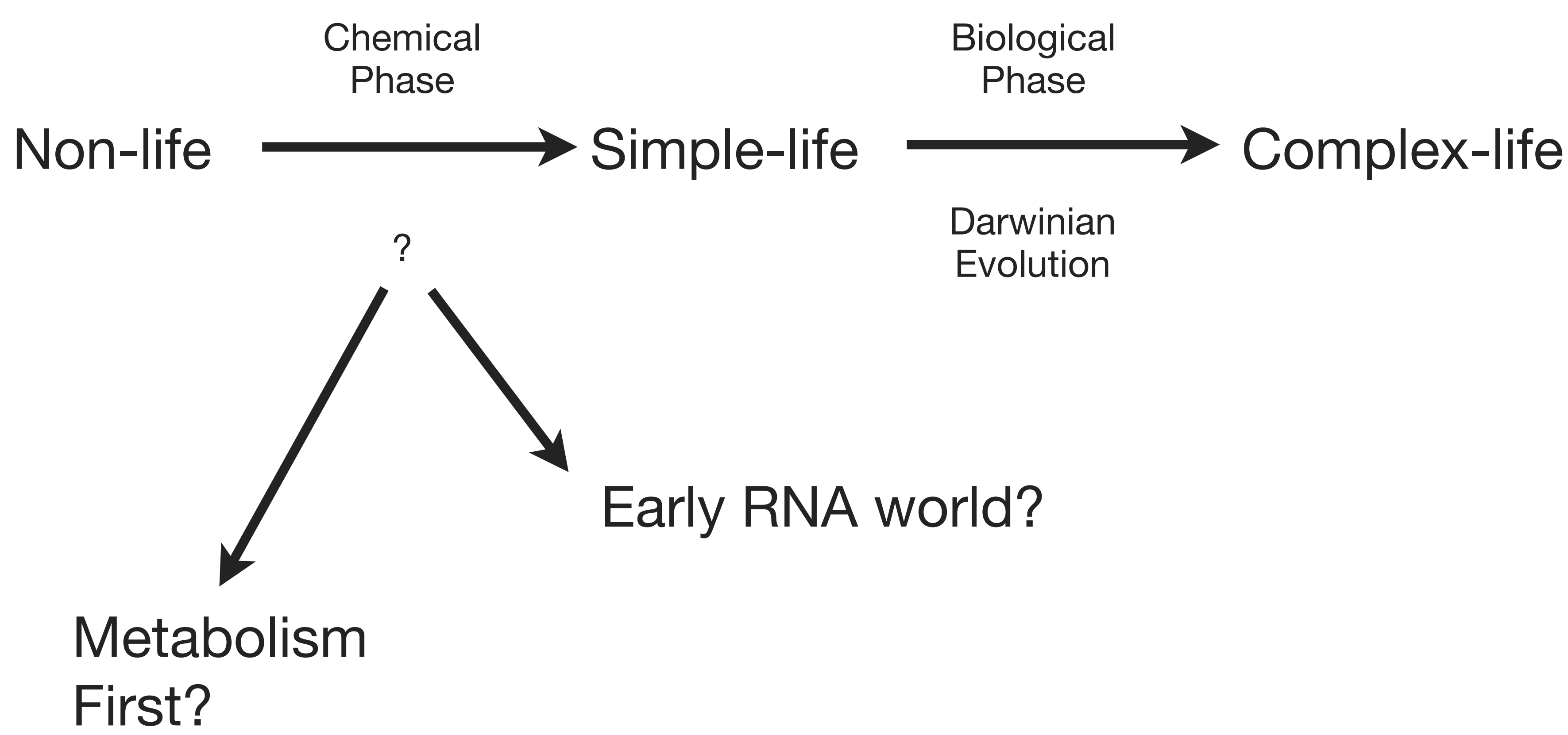
Frustrating state of ignorance. Our survey is limited to a sample of one. Even though the number of Earth-like planets is likely to be spectacularly large, we do not have evidence for life on any other worlds (nor have we had the capability of searching in the past).

Woese (famous for work on the tree of life): “Biology today is no more fully understood in principle than physics was a century or so ago.”

What is Life?

How Chemistry Becomes Biology

Addy Pross



What is Life?

How Chemistry Becomes Biology

Addy Pross

Study of autocatalytic RNA dates back to the late 1980’s (Nobel prize for Czech and Altman)

Spiegelman: molecular replication in a test tube (using an enzyme to catalyze rxns. Used an RNA strand with free floating building blocks of the RNA

Longer RNA strands evolved into shorter ones (faster replication)

replication - mutation - selection - evolution

- later it was shown that this process can be autocatalytic (no enzymes)

Gerald Joyce (2009): *competitive exclusion principle*
“Complete competitors cannot exist”

Two non-breeding species cannot exist in the same ecological niche; the better adapted species will drive the other one to extinction.

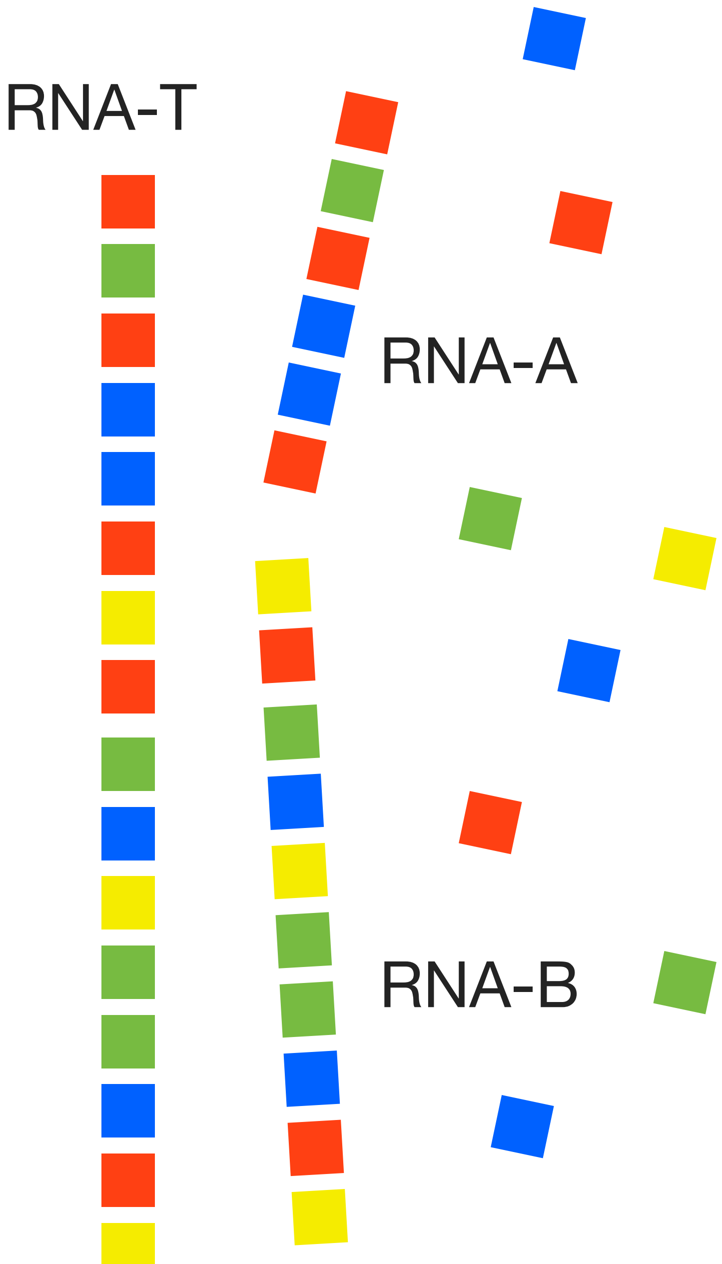
Galapagos Islands: variety of finches that differ in their beaks -> ground finches; tree finches, etc, coexist b/c they evolved to make use of other resources.

Joyce: RNA-1 and RNA-2 in the same essential substrate; one drives the other to extinction. Switch the substrate and the same thing may happen to the other RNA.

What is Life?

How Chemistry Becomes Biology

Addy Pross



Joyce was able to make an autocatalytic RNA:

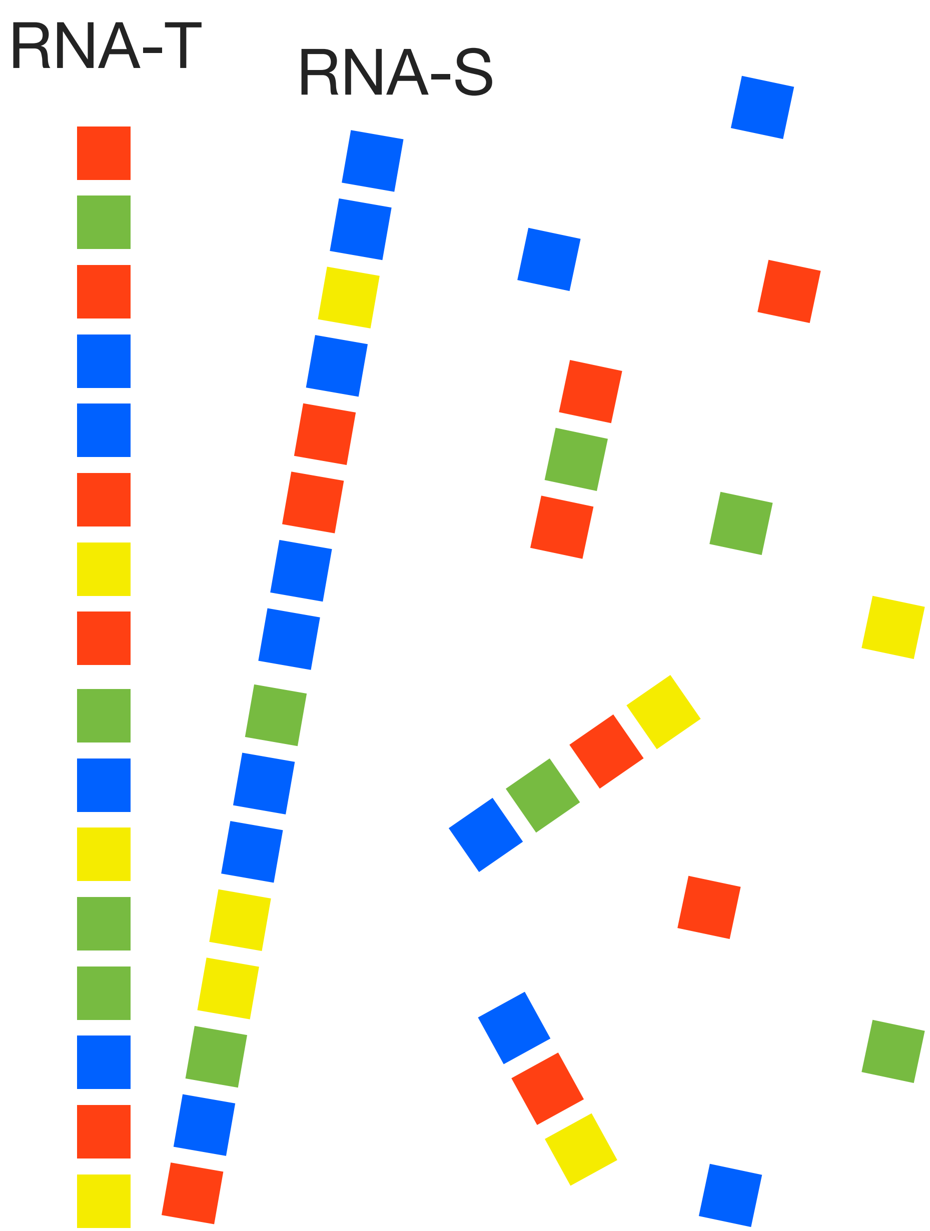
RNA-T composed of RNA-A and RNA-B.
Put A and B in solution with T and a single T molecule will make copies of itself.

1. slow process (17 hours...)
2. replication process only proceeded for 2 rounds

What is Life?

How Chemistry Becomes Biology

Addy Pross



Joyce repeated the experiment with 2 RNA molecules:

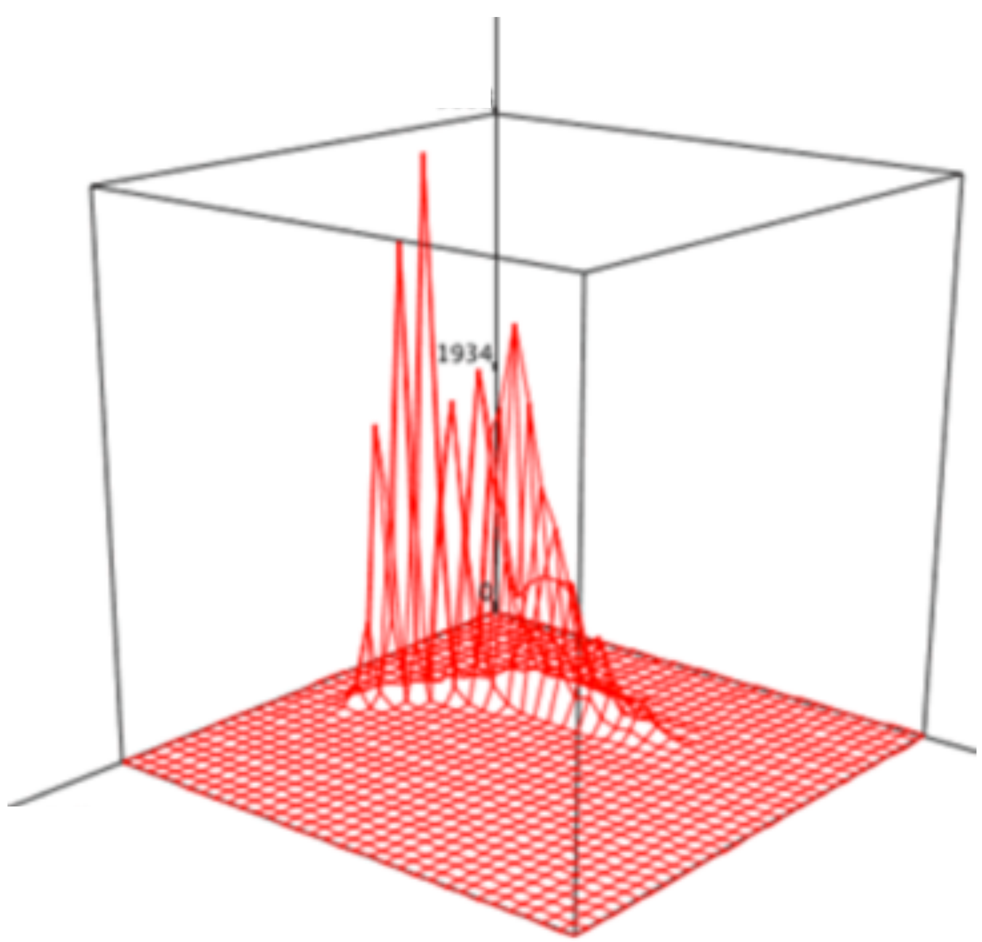
1. fast process (1 hour)
2. replication proceeded indefinitely!

- each component is not making independent copies
- RNAs evolve into cross-catalytic system: one RNA catalyzes formation of the other!
- The system as a whole is self-replicating.
- Rapid replication is energetically favored. Faster processes win... and the faster process involves cross-catalysis.

The population of replicating RNAs explores the fitness landscape (by trial and error). The activity of the population of RNA is centered on the most successful sequence.

Not the fittest individual that is selected for, but the fittest population.

Change the reaction conditions and the evolutionary course changes - the winner is likely to be an entirely different set of RNA molecules.



What is Life?

How Chemistry Becomes Biology

Addy Pross

replication - mutation - complexification - selection = evolution

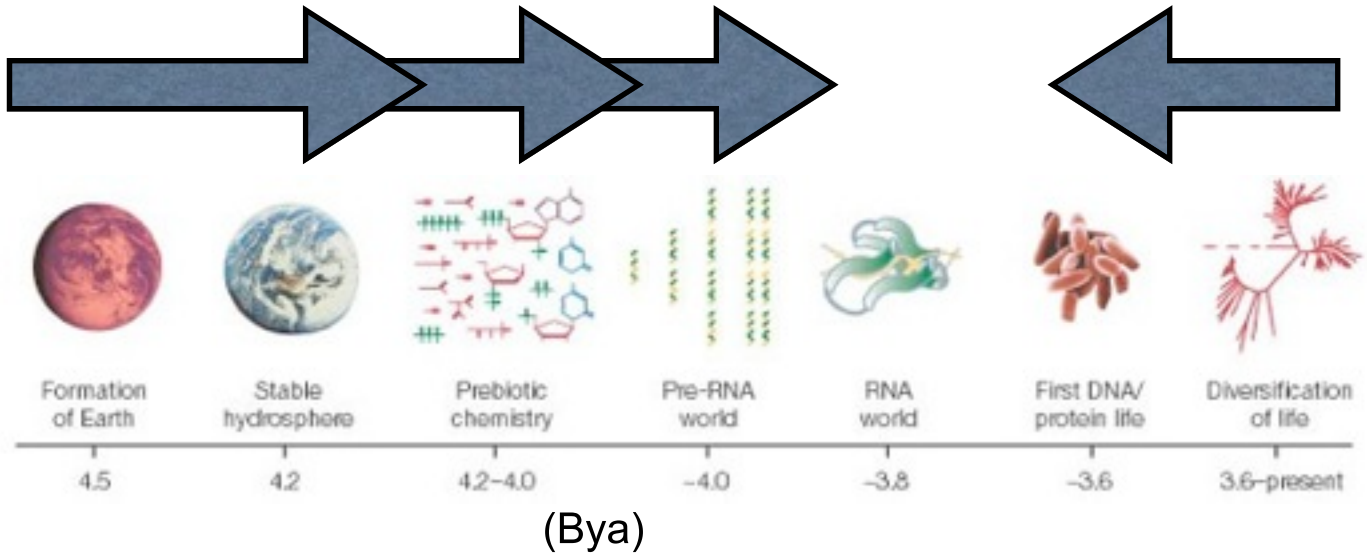
RNA that undergoes chance mutation to develop an energy-gathering capability (photosynthesis) can outcompete the non-metabolic replicator by providing “activation energy” for rxns to proceed more efficiently.

“metabolic complexification”

The evolution from prebiotic chemistry to evolving RNA does not appear to be a freak accident. It is the energetically favored outcome of system chemistry. Given the right temperature, pressure, chemical composition, this process may be typical.

ExoEarths may be intrinsically good Petrie dishes for life...

There is a chaotic quality to this process - vary the initial conditions even slightly and the outcome could be different.



In the past decade there have been significant advances in understanding the origin of life on Earth:

- pathways to synthesizing RNA monomers
- a new field of system chemistry
- understanding that Darwinian evolution starts at the molecular level

Astrobiologists are still limited by:
1. incomplete understanding of Earth life
2. lack of data about alternative biochemistries

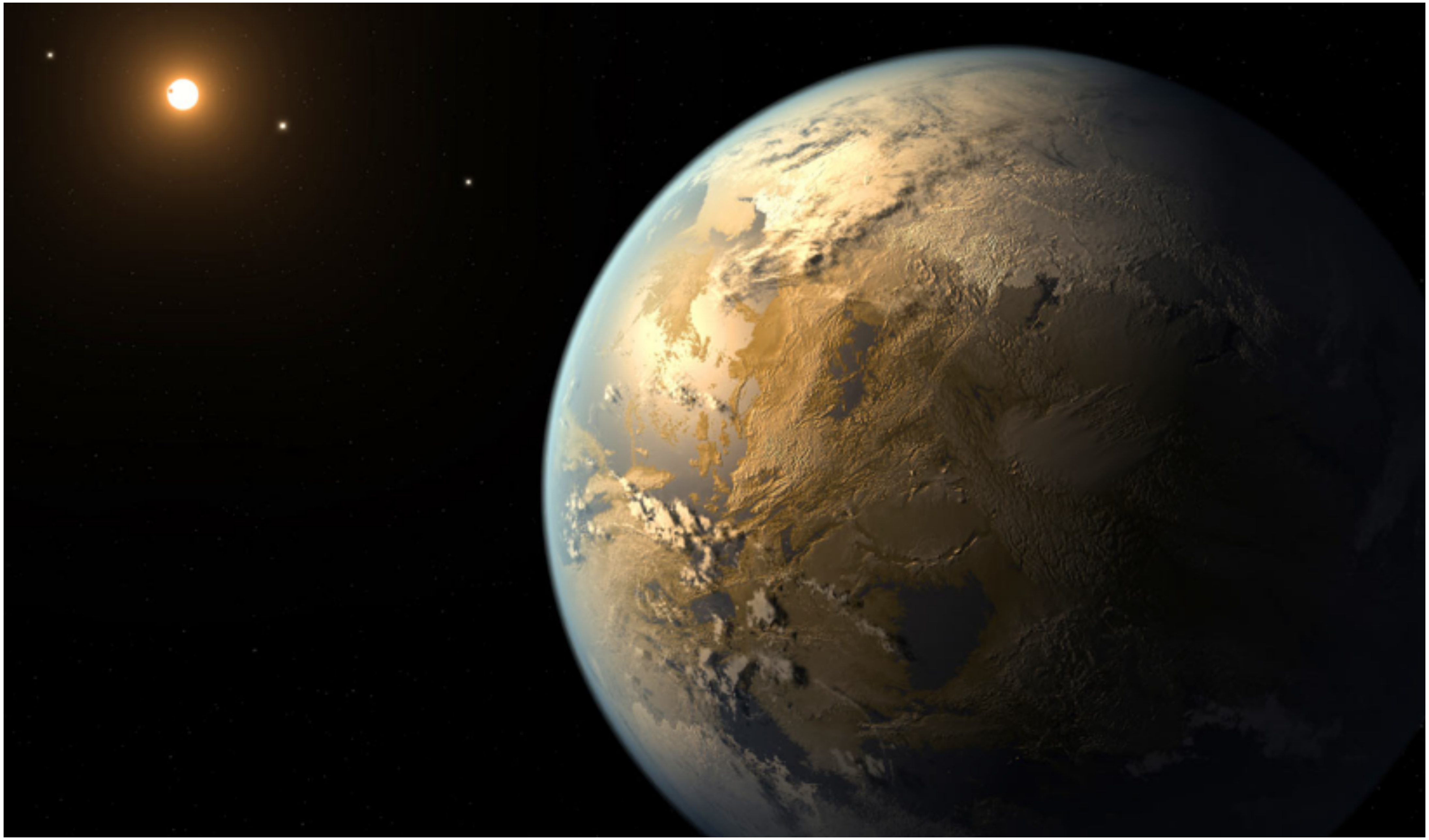
Less than 1% of microbial population in deep sediments and in seawater has been cultured.

Good arguments for carbon and water-based life on Earth, but what about environments (e.g., temperature and pressures) not on our planet?

What are the limitations of carbon-based life?

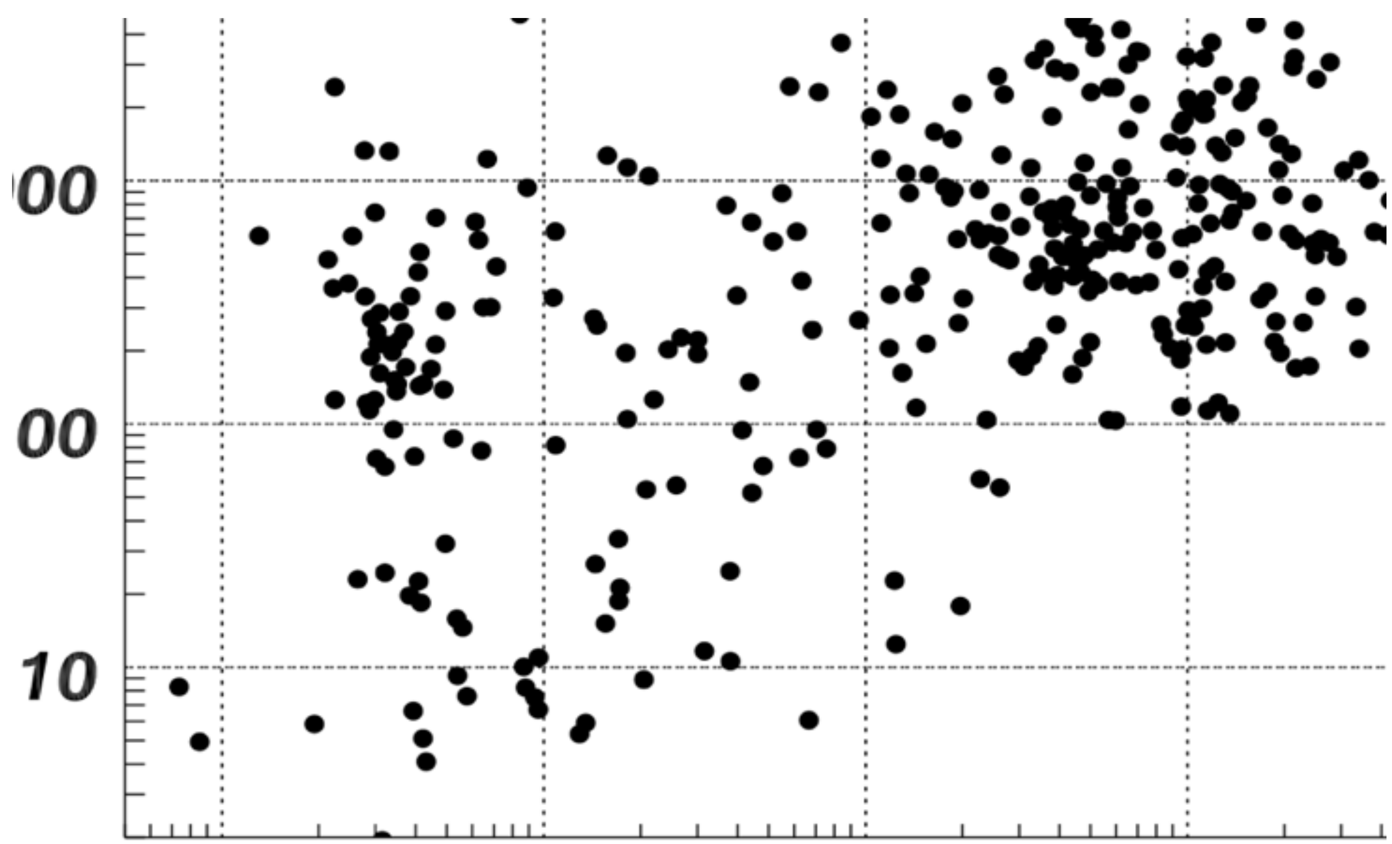
Paradigm shifts:

Kepler discoveries: “Practically all Sun-like stars have planets”
Biochemistry: Life may be a natural outcome of system chemistry on Earthlike planets.

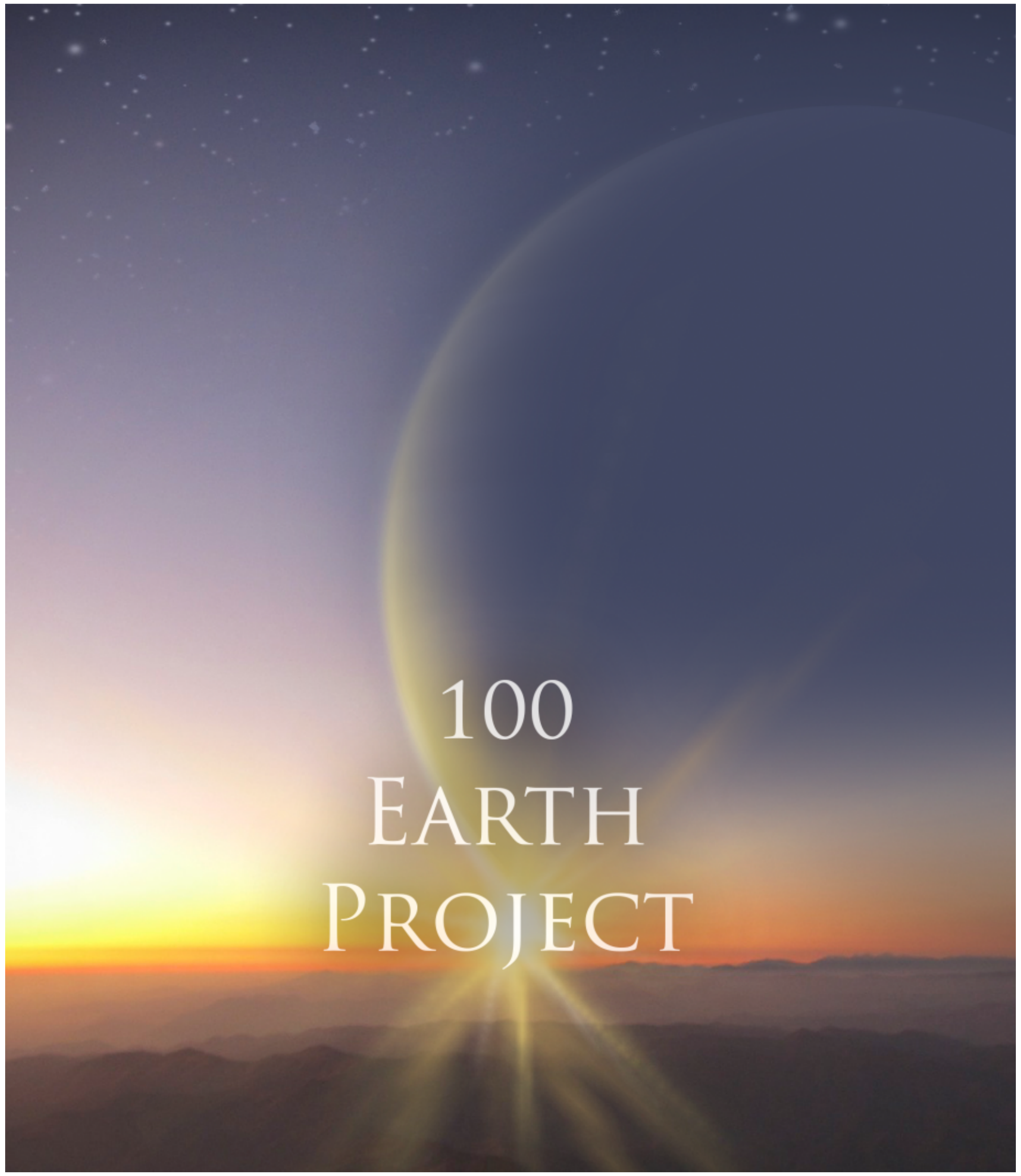


2010 Decadal Survey: "Our view of the universe has changed dramatically. Hundreds of planets of startling diversity have been discovered orbiting distant suns."

Recommended technology development to improve Doppler precision to 10 cm/s.



100 Earths Project

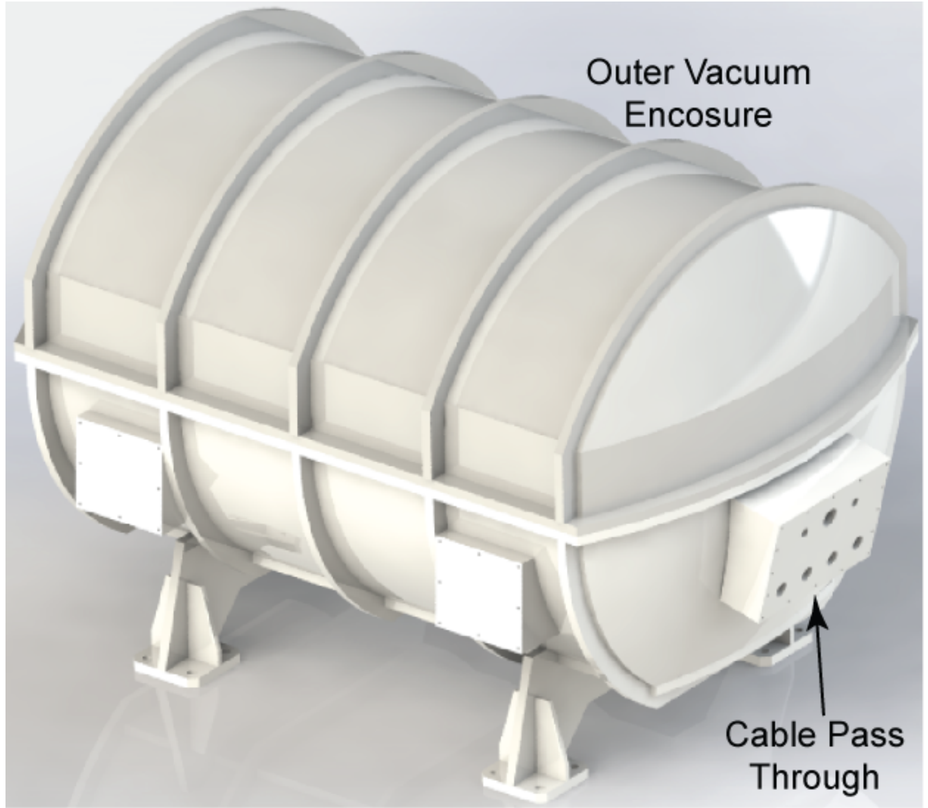


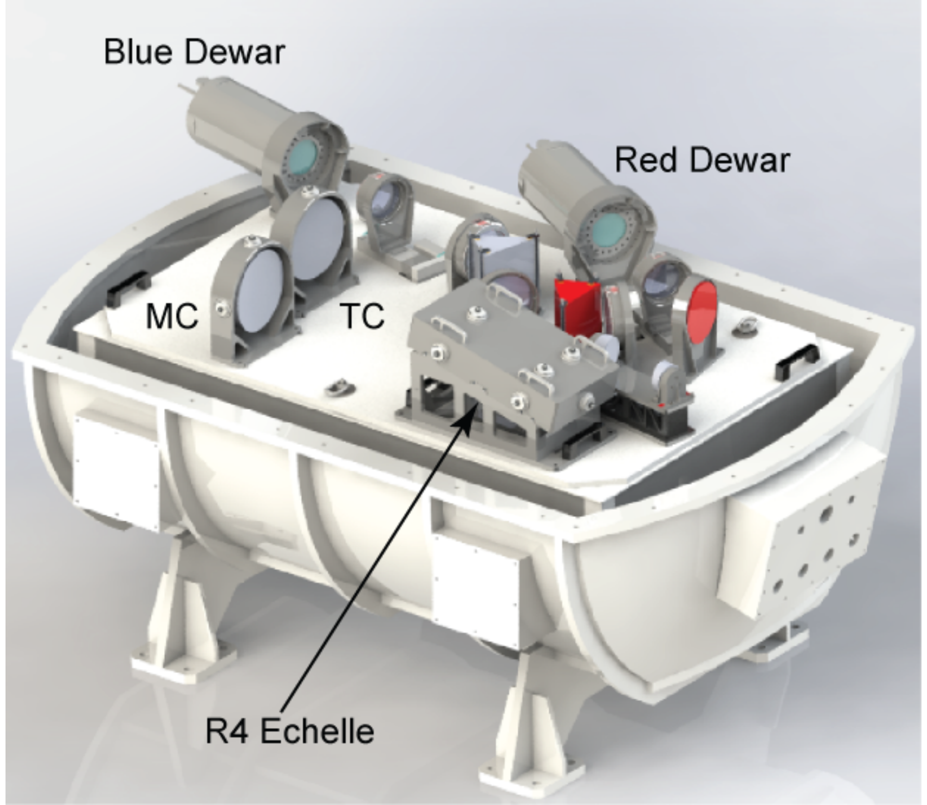
If we keep using the same instruments we've used in the past, we will get the same results (1 m/s precision).

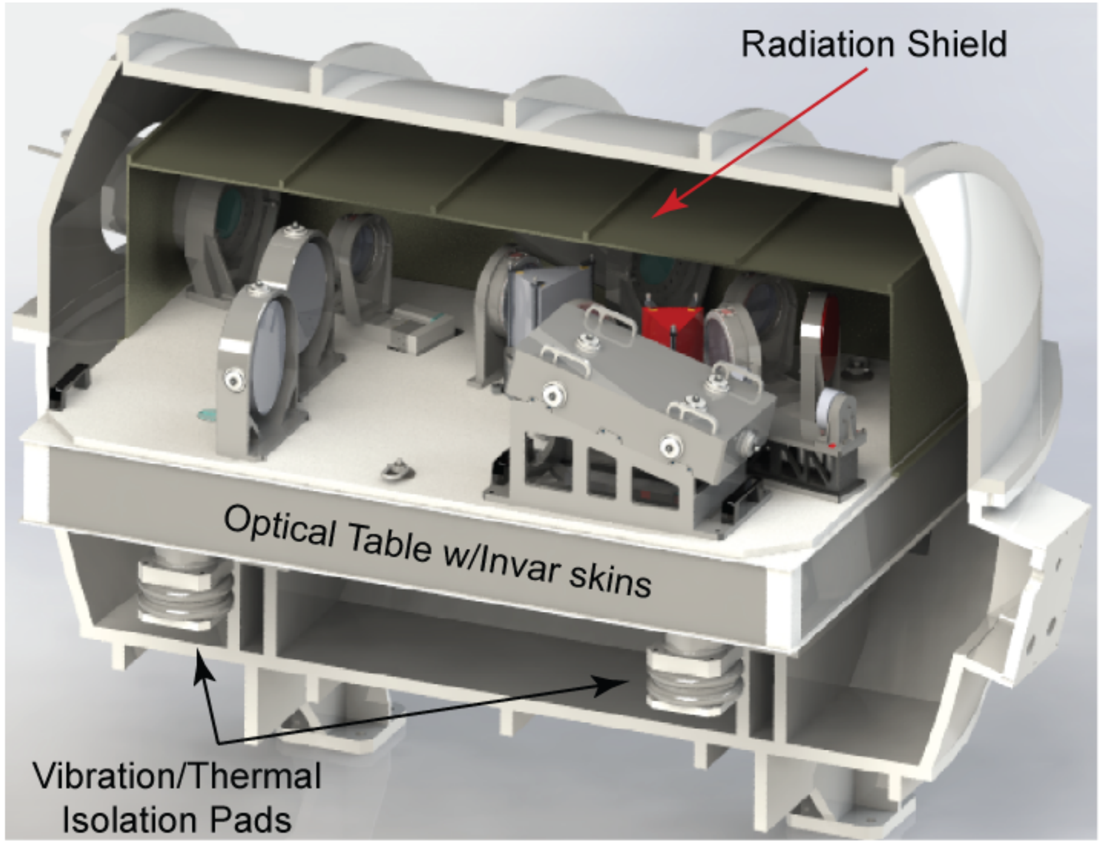
Time to design instruments that are fundamentally different for Doppler searches.

100 Earths Project: EXPRES-0

The goal is to build an instrument that can distinguish stellar “noise” from Doppler line shifts. NSF MRI proposal was just selected for funding.

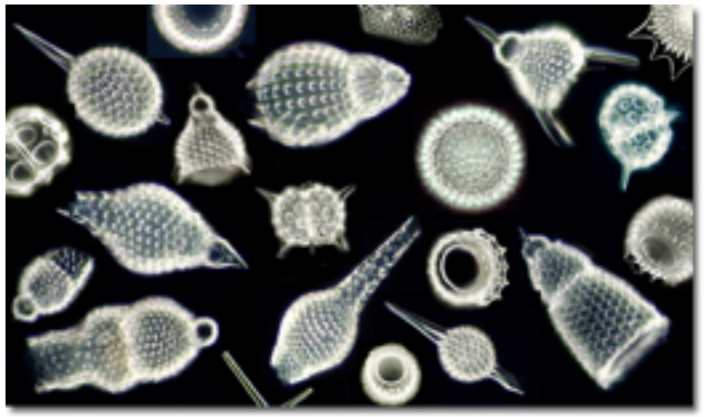






100 Earths Project: at the DCT (target for commissioning 2016)

Extra Slides



Why not silicon-based life? Silicon has 4 valence shell electrons like Carbon.

No silicon-based analog for DNA. Silicon atoms are larger and far more difficult to form double or triple bonds.

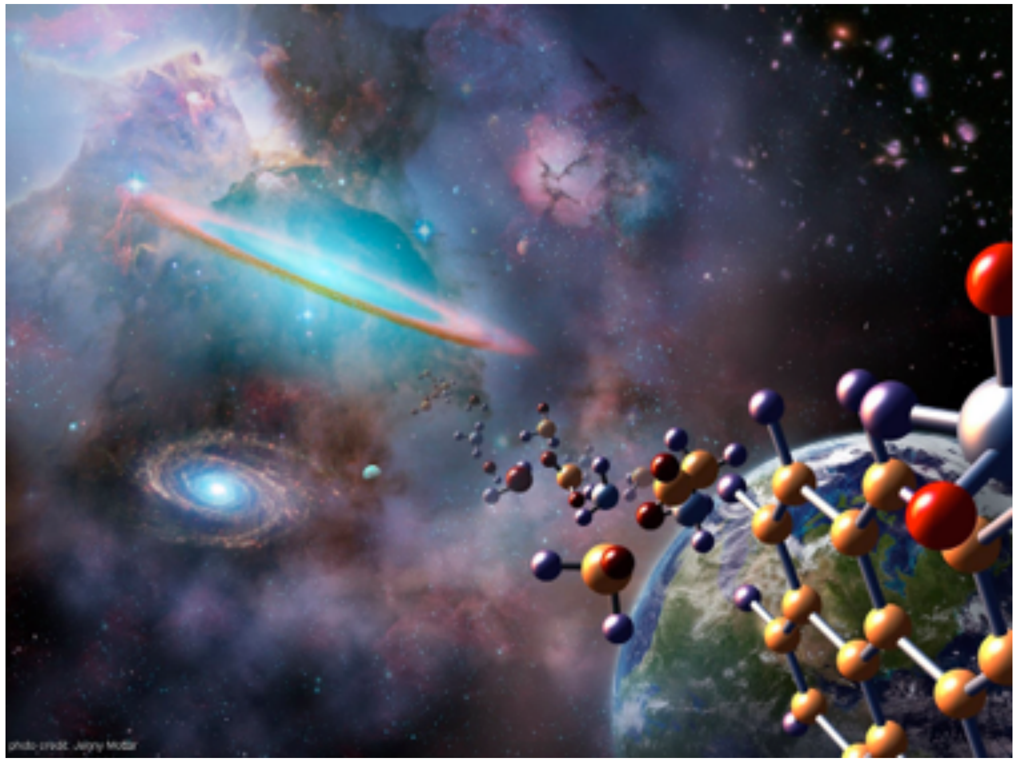
Polysilicon analogs highly reactive in water - need a different solvent. Likely to be more fragile with slower metabolism than carbon.

Carbon has a greater cosmic abundance, though silicon is more common (by a factor of 1000) in the Earth mantle.

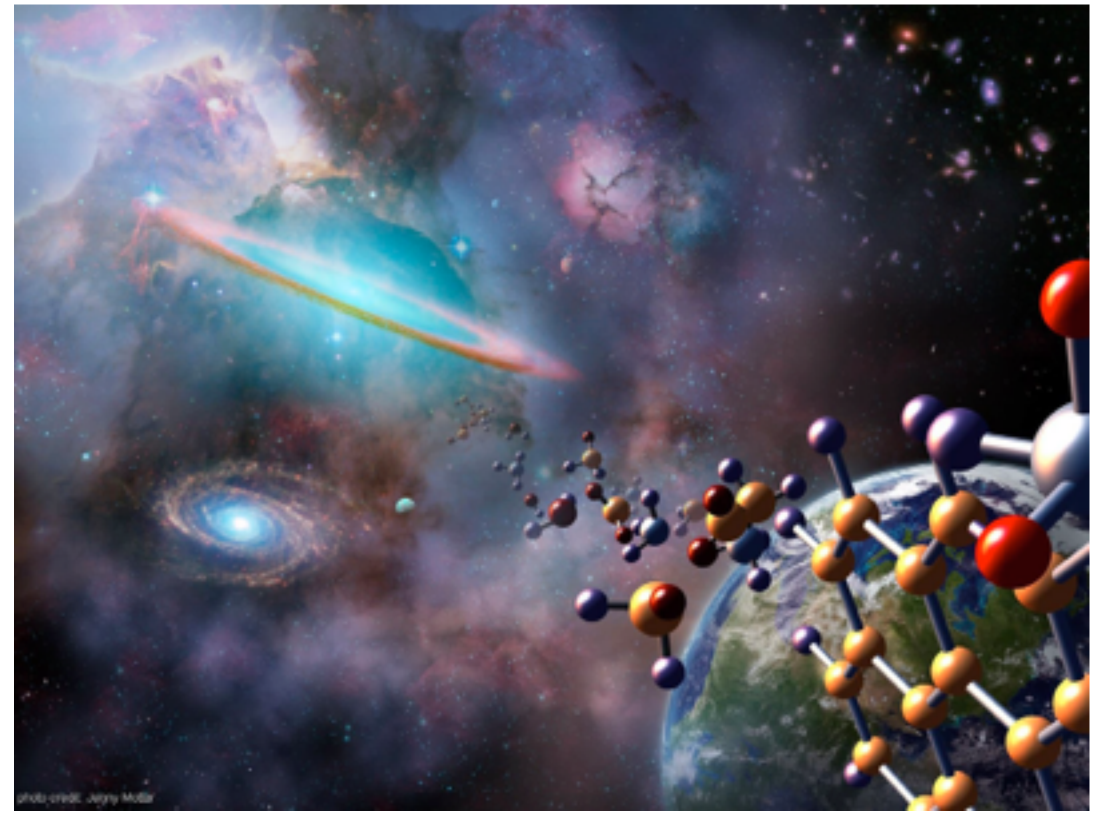
Carbon and biochemistry

Carbon produced by stars and hydrogen that was present near the origin of the Universe can combine to form a vast number of organic molecules.

Carbon bonds (C-C, C-H, C-O, C-N) are strong and will survive for thousands of years at liquid water temperatures.



Carbon and biochemistry



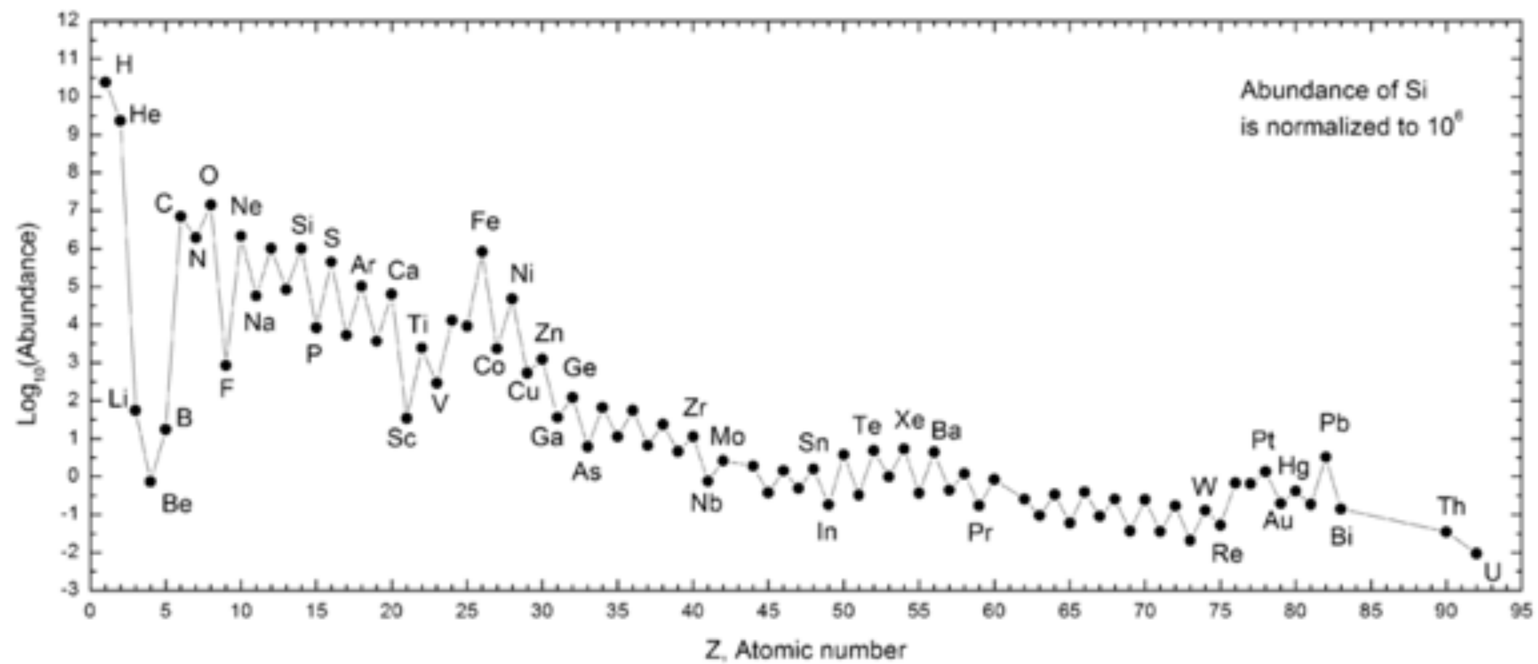
N-N, O-O, S-S and other single bonds of identical elements are weak and fall apart at liquid water temperatures.

$N \equiv N$ bonds are strong, but by using all valence electrons for the nitrogen bond, not possible for extended chains to form.

Carbon and biochemistry

On a cosmic scale, carbon is more ubiquitous than silicon.

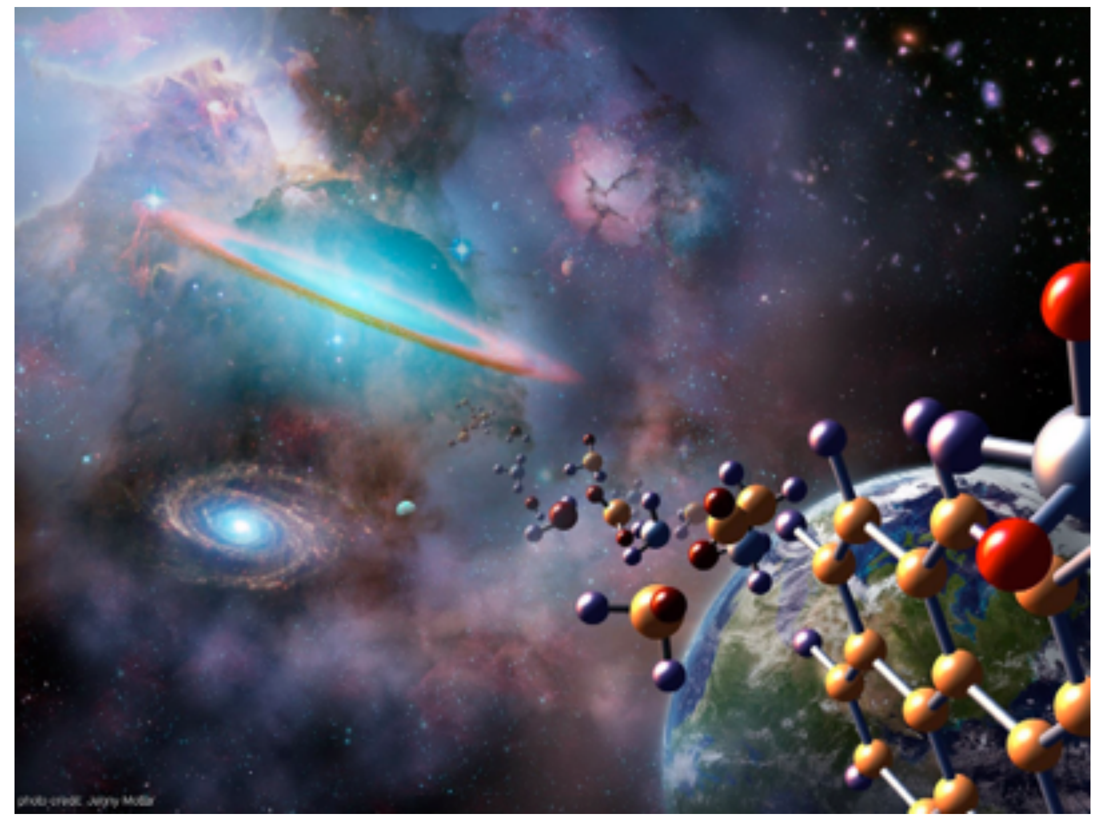
However, silicon is 1000 times more common in the Earth mantle than carbon. If life could use Si instead of C, the Earth has plenty of raw materials (maybe not the right pressure or temperatures?)



Carbon and biochemistry

CHON are volatile elements; did they come from the planetesimals that built up to form planets?

More likely: meteorites that fall to Earth deliver the organic constituents at a later stage.



Murchison meteorite

The Murchison meteorite fell in 1969 in Australia. Quickly recovered, so little contamination.

Contains organic material and 70 amino acids (many not known to exist on contemporary Earth) with different enantiomeric ratios than Earth, supporting extraterrestrial origins.

Murchison meteorite

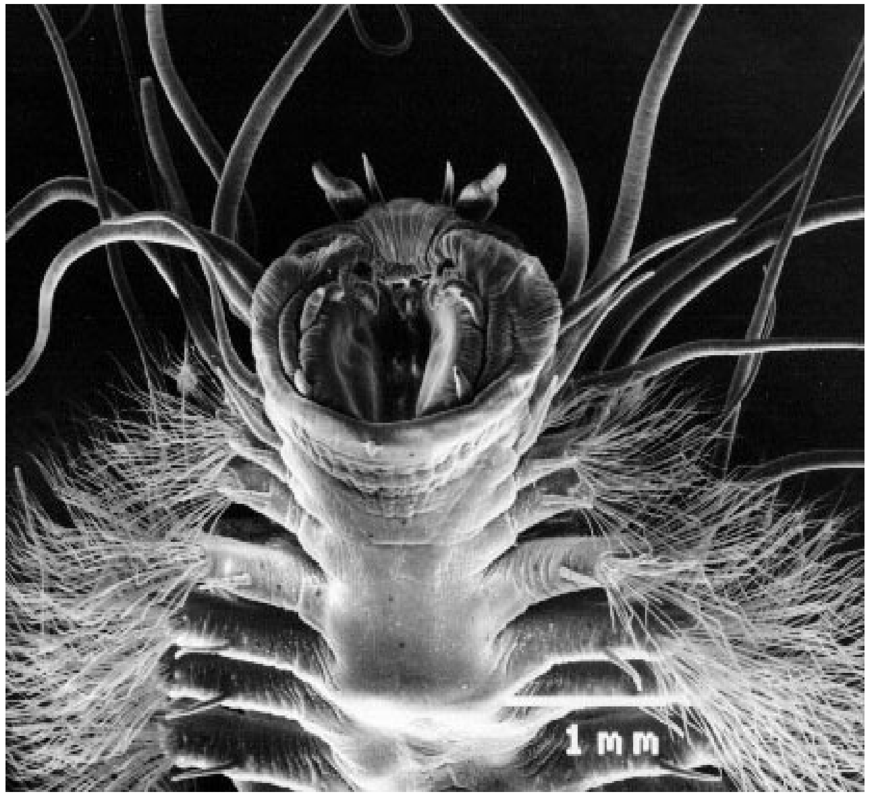
Chemical fragments of DNA and RNA found: the Murchison meteorite contains trace amounts of adenine, guanine and uracil.

Also contains reduced and oxidized forms of ribose and phosphate-containing minerals.

No nucleosides (nucleic bases bound to sugar) or nucleotides (nucleic bases bound to a phosphate).



Archea are the most extreme of the extremophiles, including sulfur-metabolizing hyperthermophiles and acidophiles, found in hot sulfur springs, hydrothermal sea vents, volcanoes or methanogenic anaerobes.



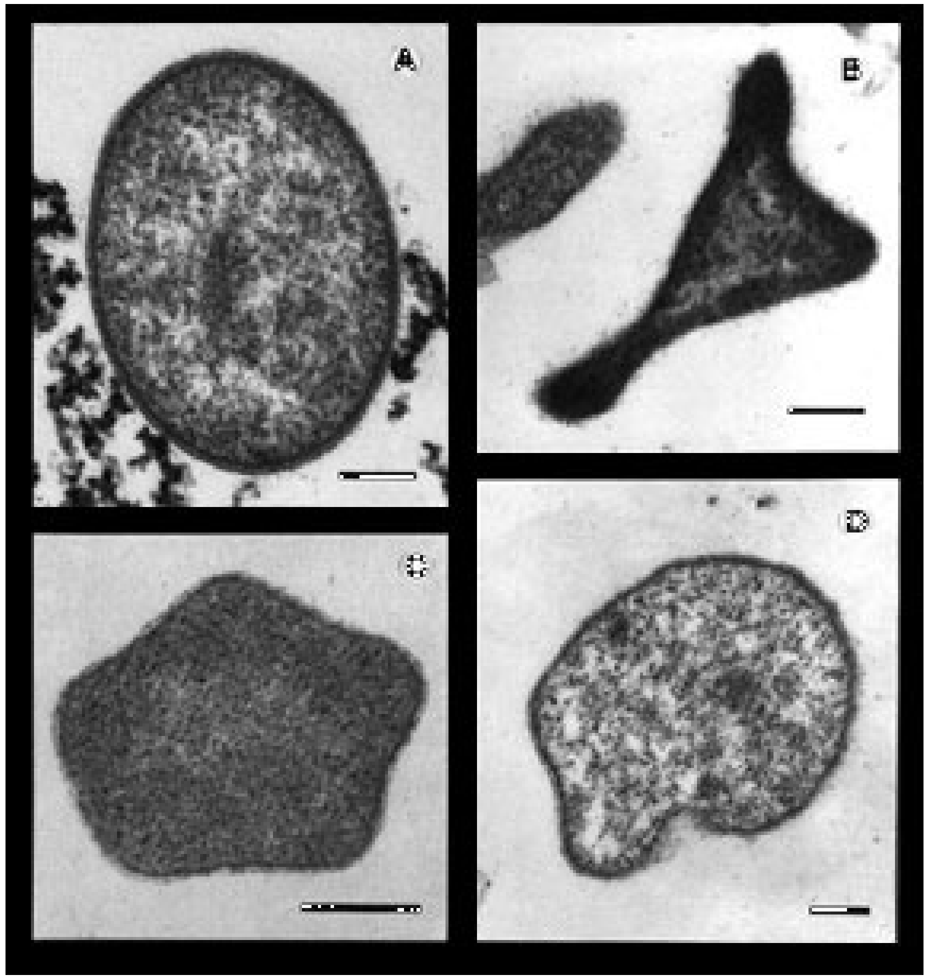
Methane Ice Worms
Gulf of Mexico, 80 miles off the coast of Louisiana

Hydrothermal vent communities
First discovered on the Galapagos Rift off the coast of Ecuador

Most of the Earth's biosphere is not exposed to light. Chemosynthesis may be supporting the dominant fraction of living cells on our planet.

The deepest...

Bacillus infernus
Johannesburg, South Africa
New species of bacteria have been discovered in caves and gold mines as deep as 2 miles underground. These species are known as thermophiles, or heat lovers, because they thrive in high-temperature environments.



The hottest...
Archaea Strain 121
Hot springs at Yellowstone National Park, Wyoming
This microbe belongs to a class called "hyperthermophiles," which live in extremely hot or acidic water. Some species can survive temperatures over 235 degrees Fahrenheit -- hot enough to boil an egg in minutes.

Most acidic...
Acidophiles
Lechuguilla Cave, Carlsbad, New Mexico
These hardy organisms have been found living in a number of caves under conditions of pH of 0.0 -about as acidic as battery acid!

Highest radiation environments...
D. radiodurans
Hanford nuclear waste storage site, Washington
"Conan the Bacterium." It's the most radiation-resistant organism known. These guys can withstand 1.5 million rads (units of radiation) - a thousand times more than any other life form on Earth.

Wangiella dermatitdis
Chernoble nuclear reactor chambers

The coldest...

Microbial activity measured at -20C in ice and photosynthesis takes place in Antarctic lichen.

The driest: Atacama

Atacama Desert (Chile): driest place on Earth. Average rainfall of 1 mm / yr. High altitude (UV radiation). So far, no life identified!