Exoplanets, Breakthrough Initiatives and the Future of Discovery in Astronomy

Howard Isaacson
UC Berkeley

Nov 6th 2017

BREAKTHROUGH INITIATIVES
BREAKTHROUGH PRIZE FOUNDATION

BREAKTHROUGH LISTEN

BERKELEY SETI RESEARCH CENTER

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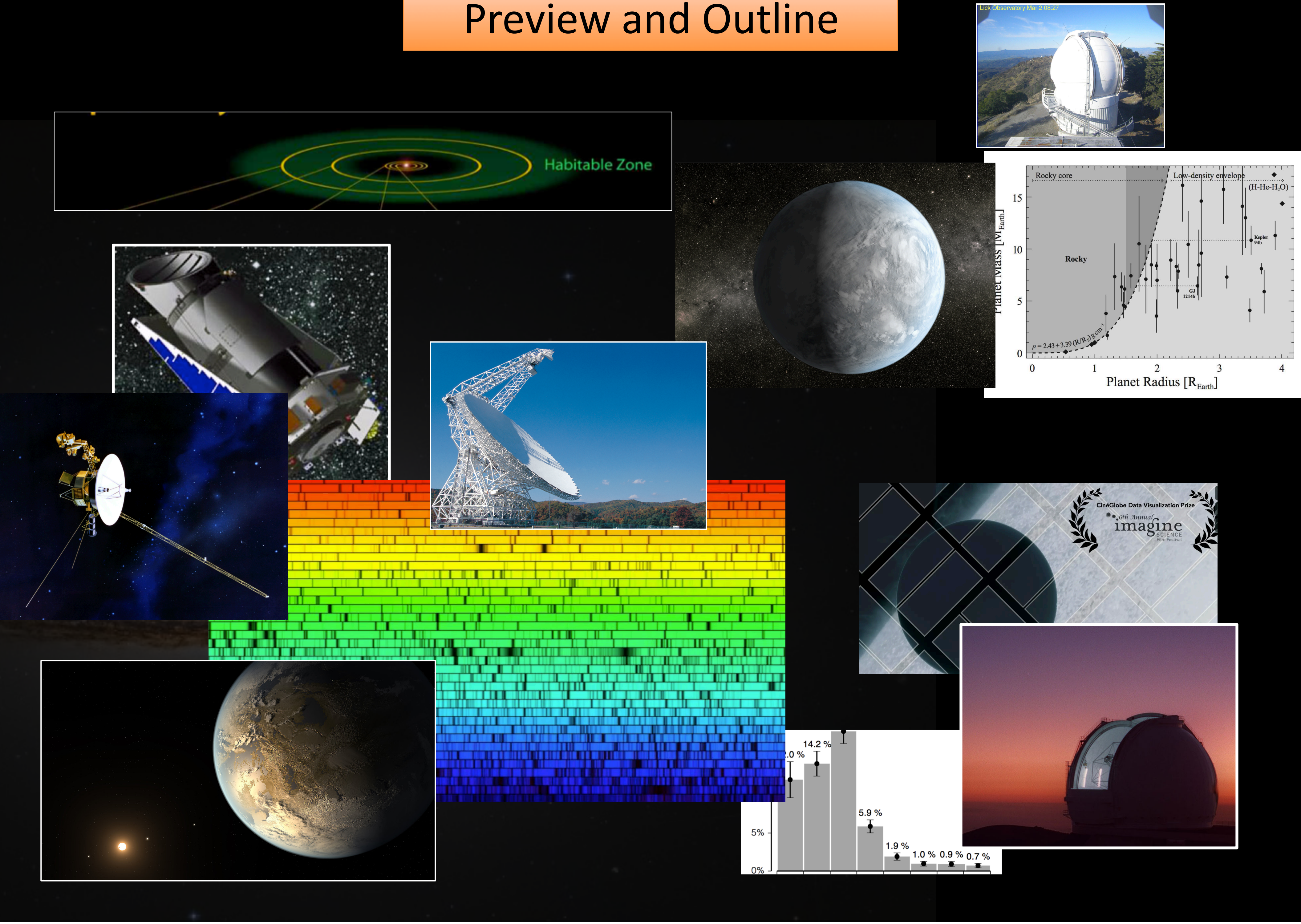
and many more…

Many graphics provided by NASA

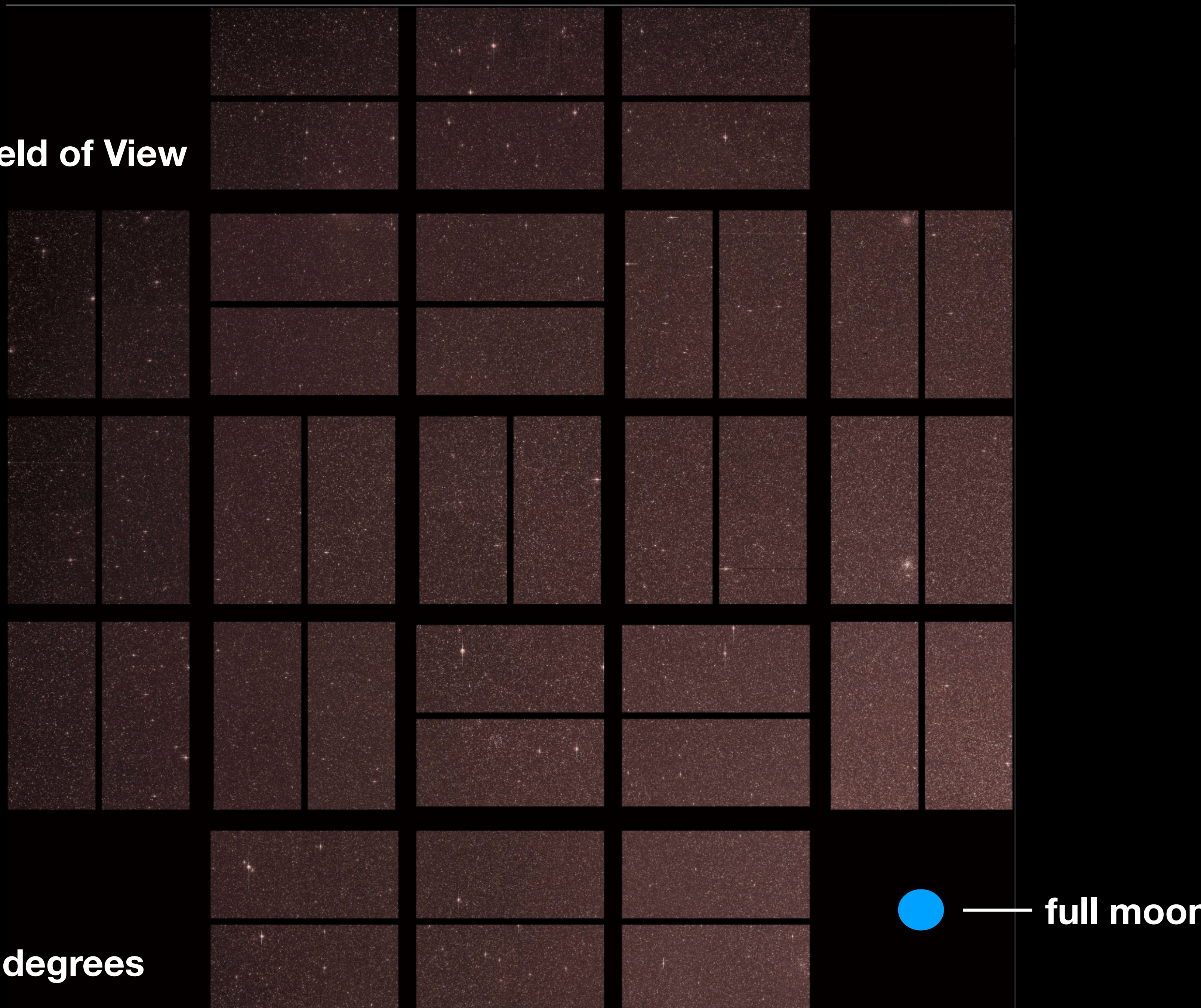
Preview and Outline



The Kepler Space Telescope

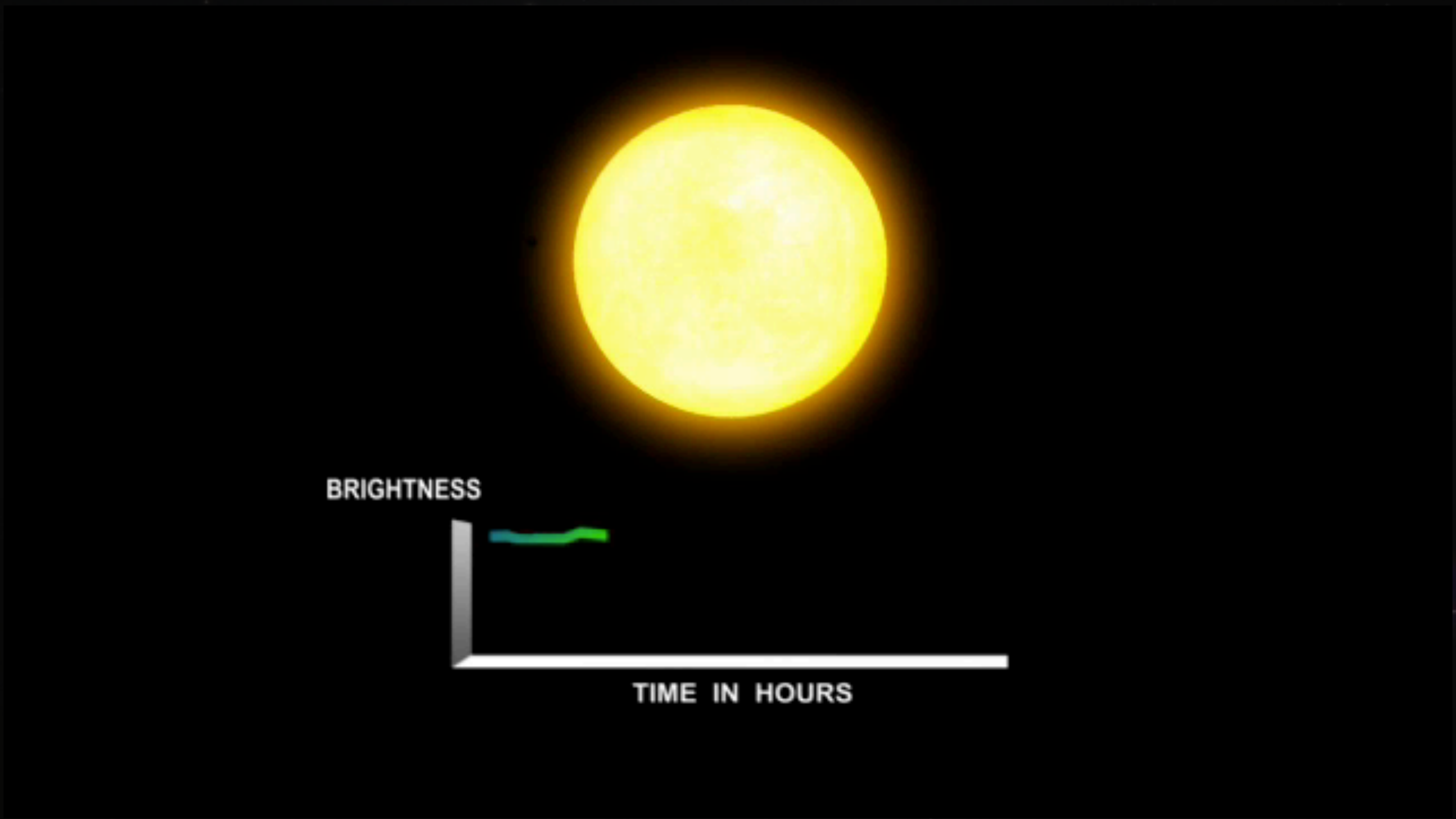
CCD Facts

95 Mega-pixels
6 sec readout binned
down to 1 min or 30 min
cadence
Precision: 20ppm in 6.5 hours

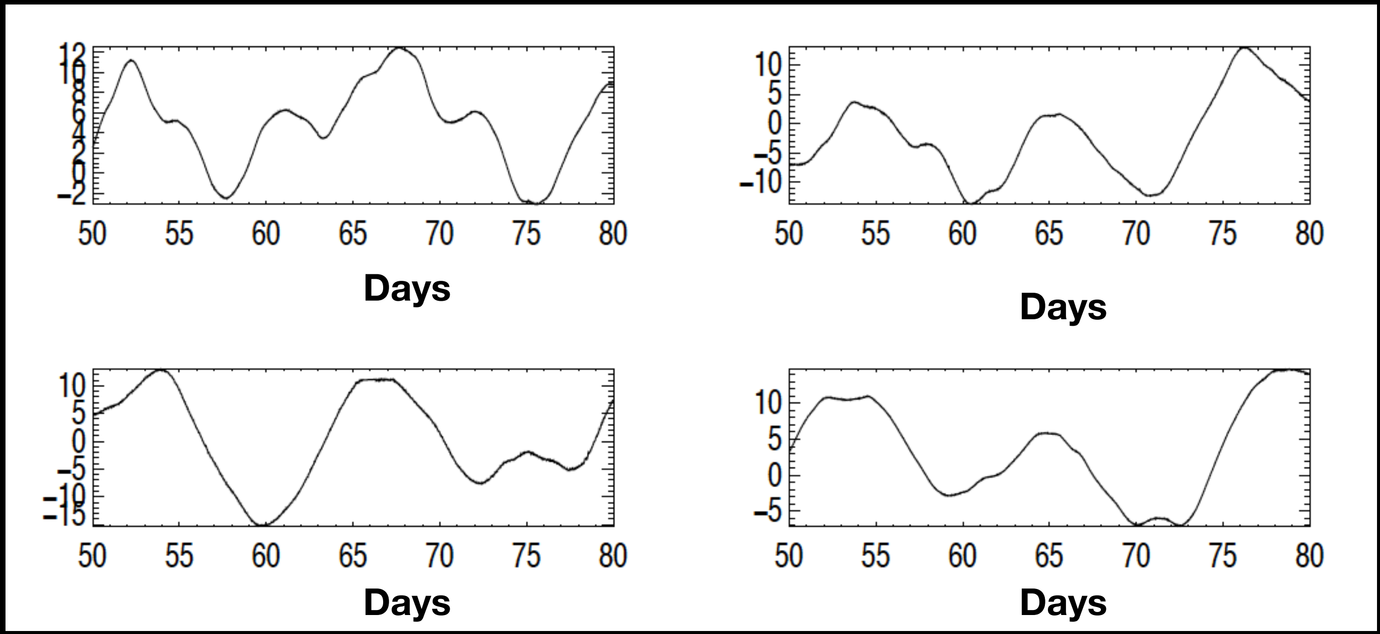

The Kepler Field of View
full moon
10 x 10 degrees

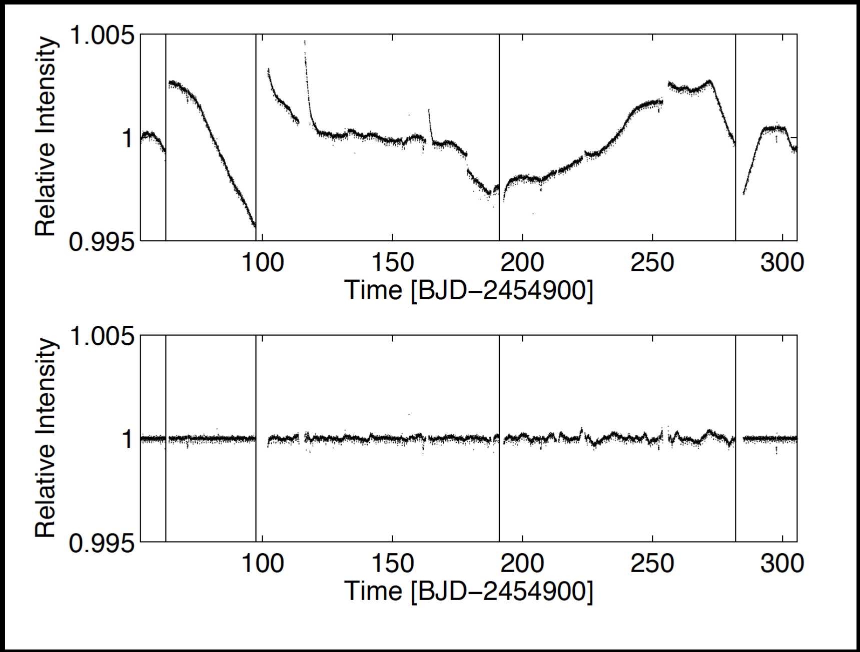
Small dips = small planets

Time between dips yields
period of the planet via Kepler’s Laws:
(orbital separation squared = orbital period cubed)



Kepler Light curves. Scale: pp thousand



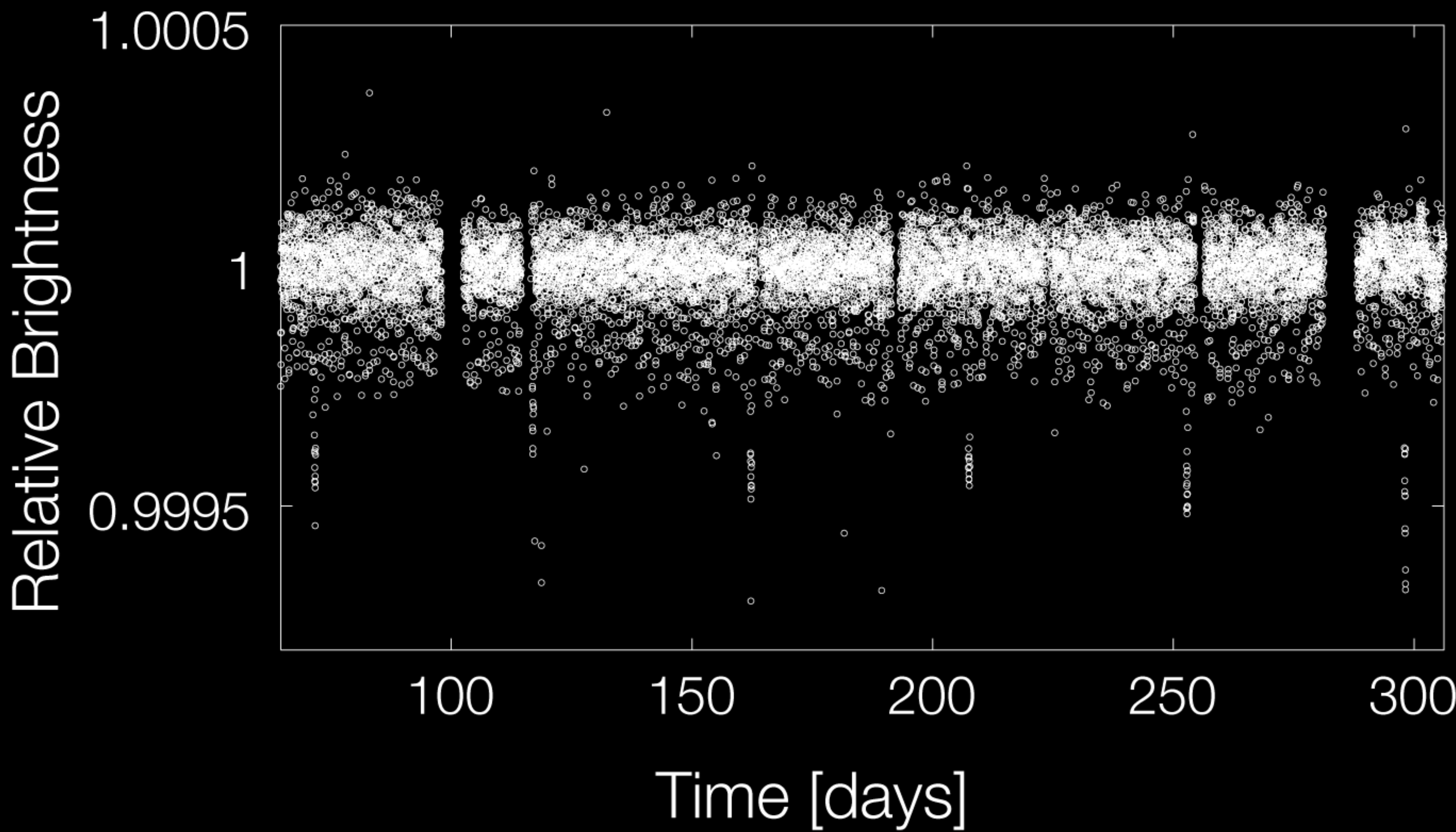


Kepler-10

Raw light curve

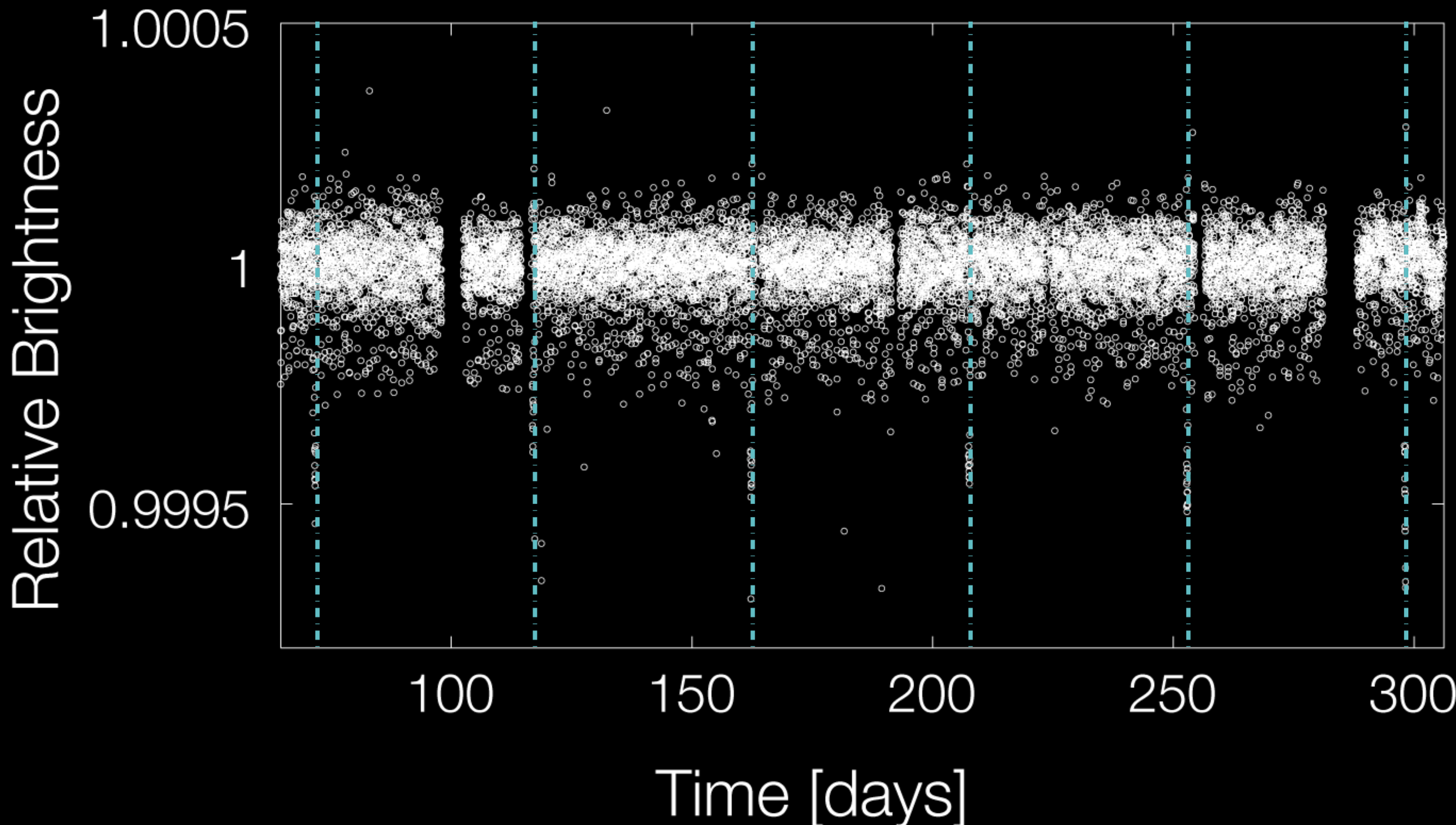
De-trended light curve

Kepler-10 Light Curve



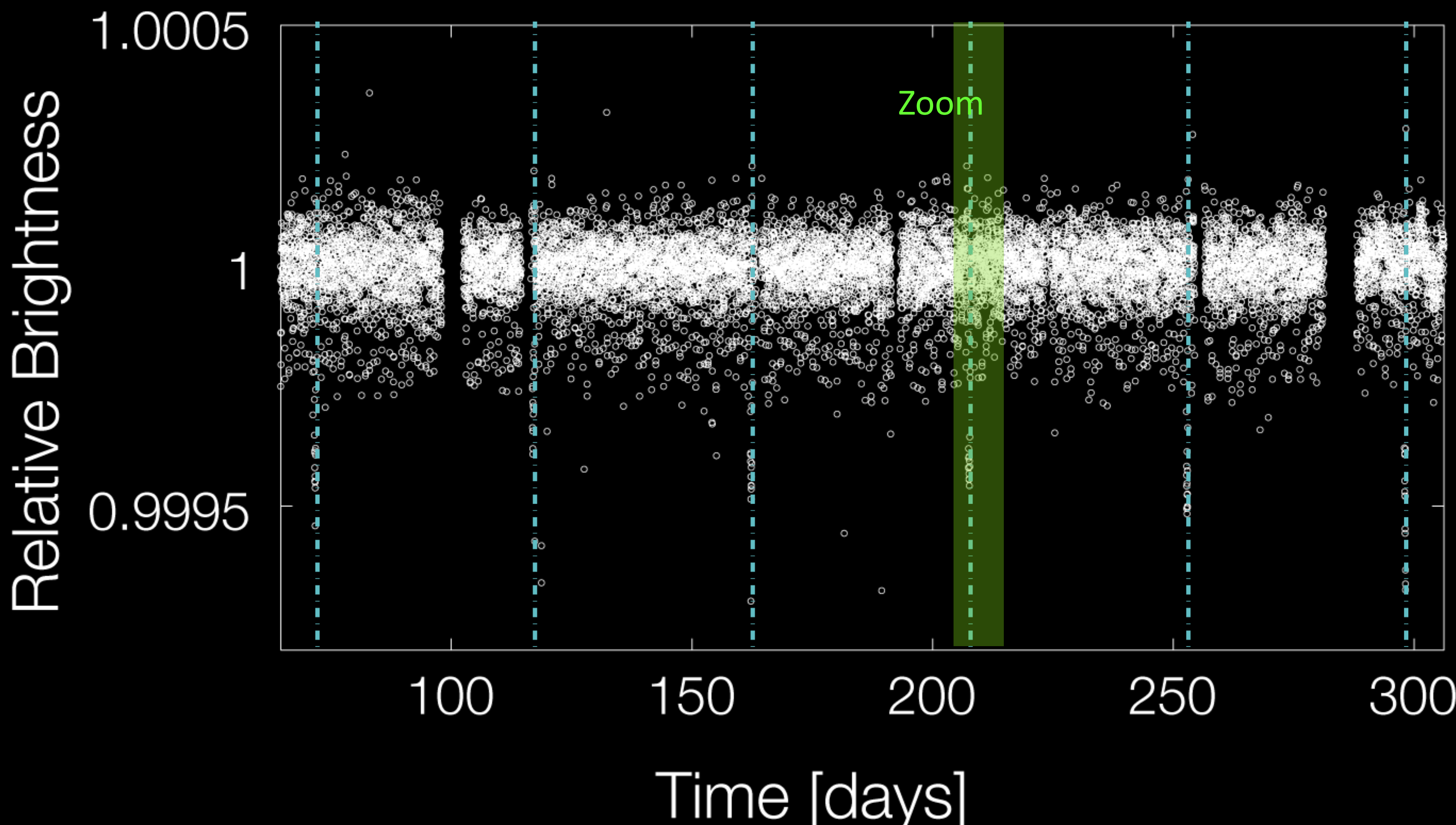
Kepler-10 Light Curve

Period = 45.29 days

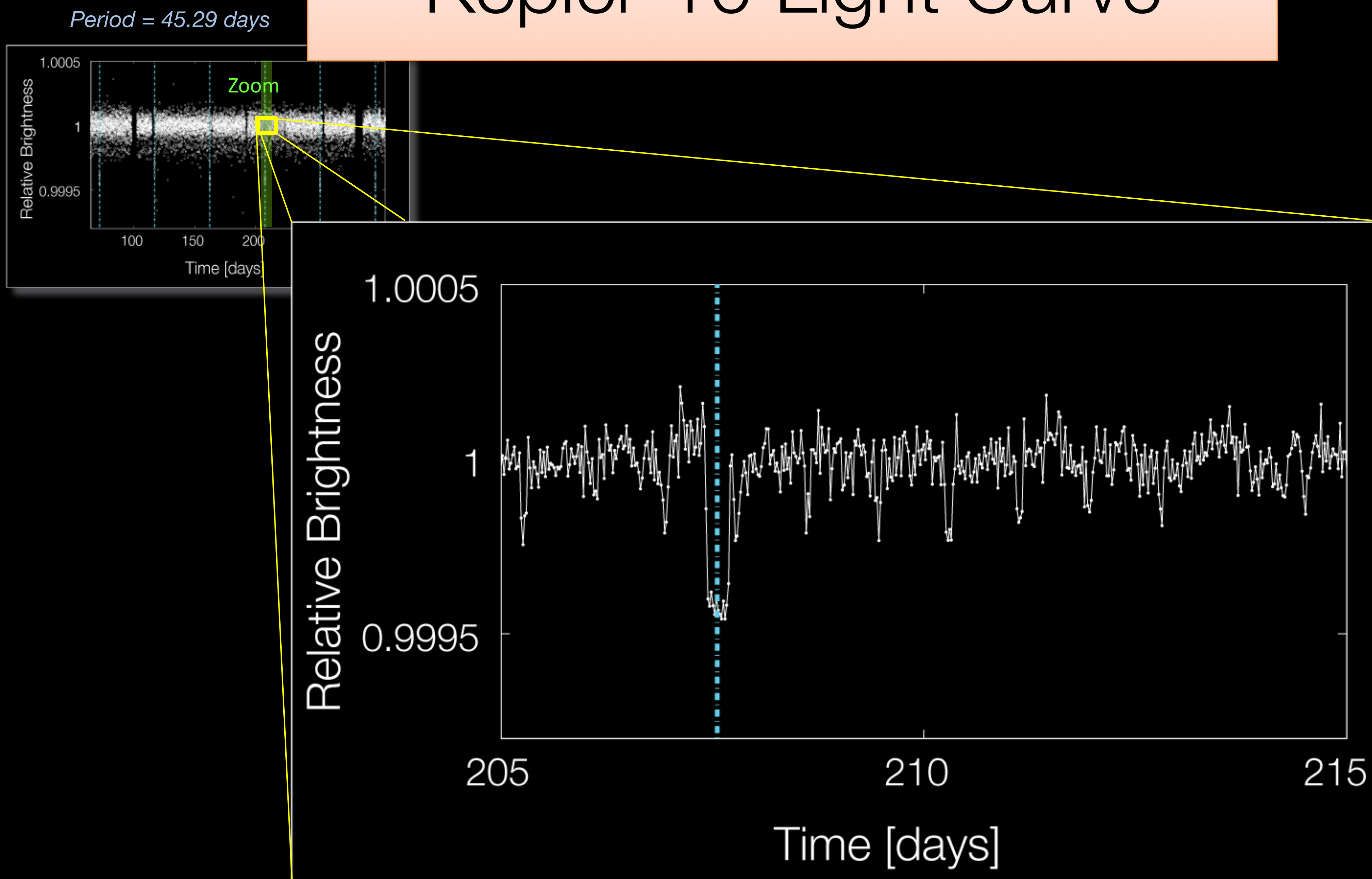


Kepler-10 Light Curve

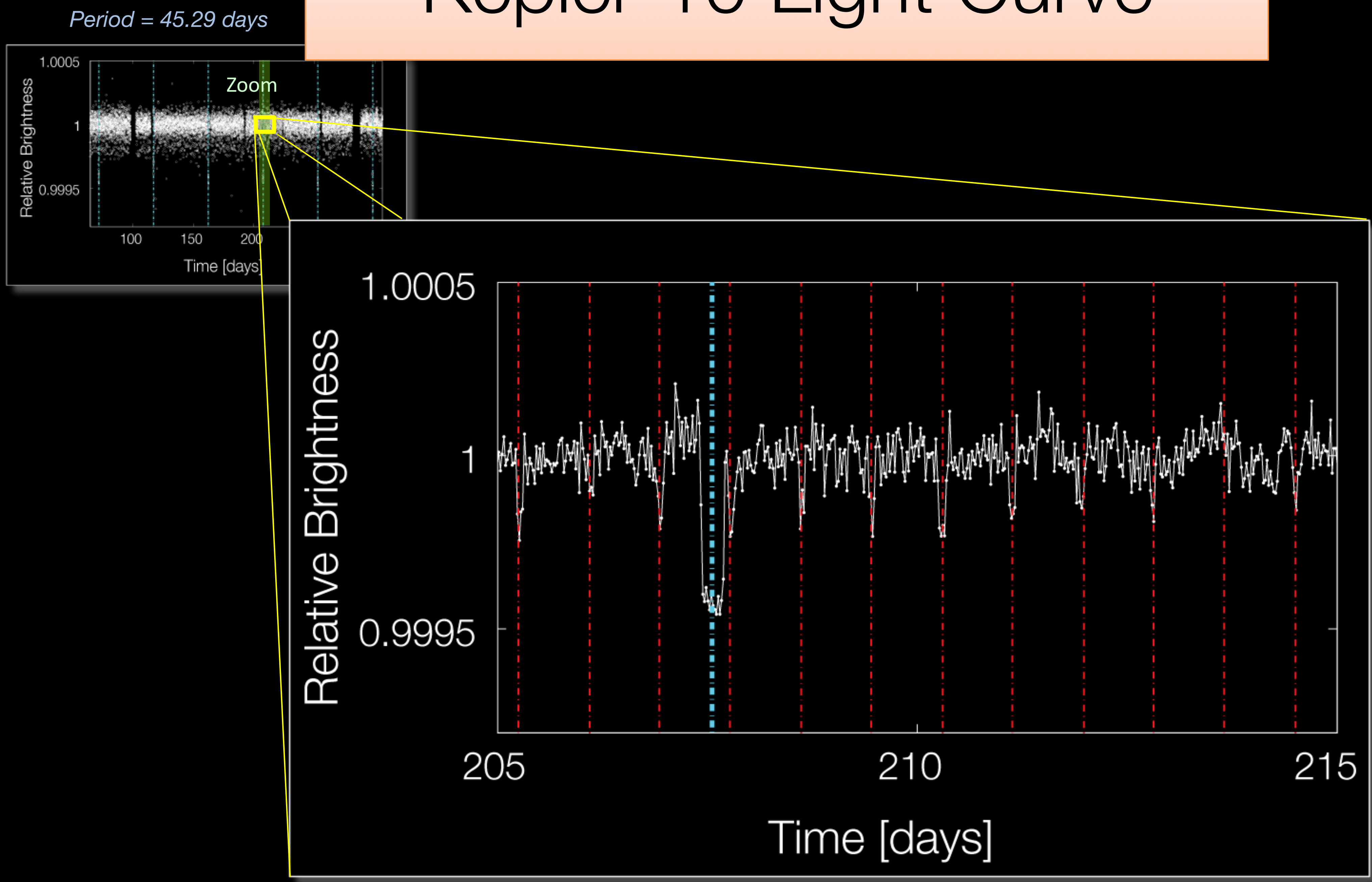
Period = 45.29 days



Kepler-10 Light Curve

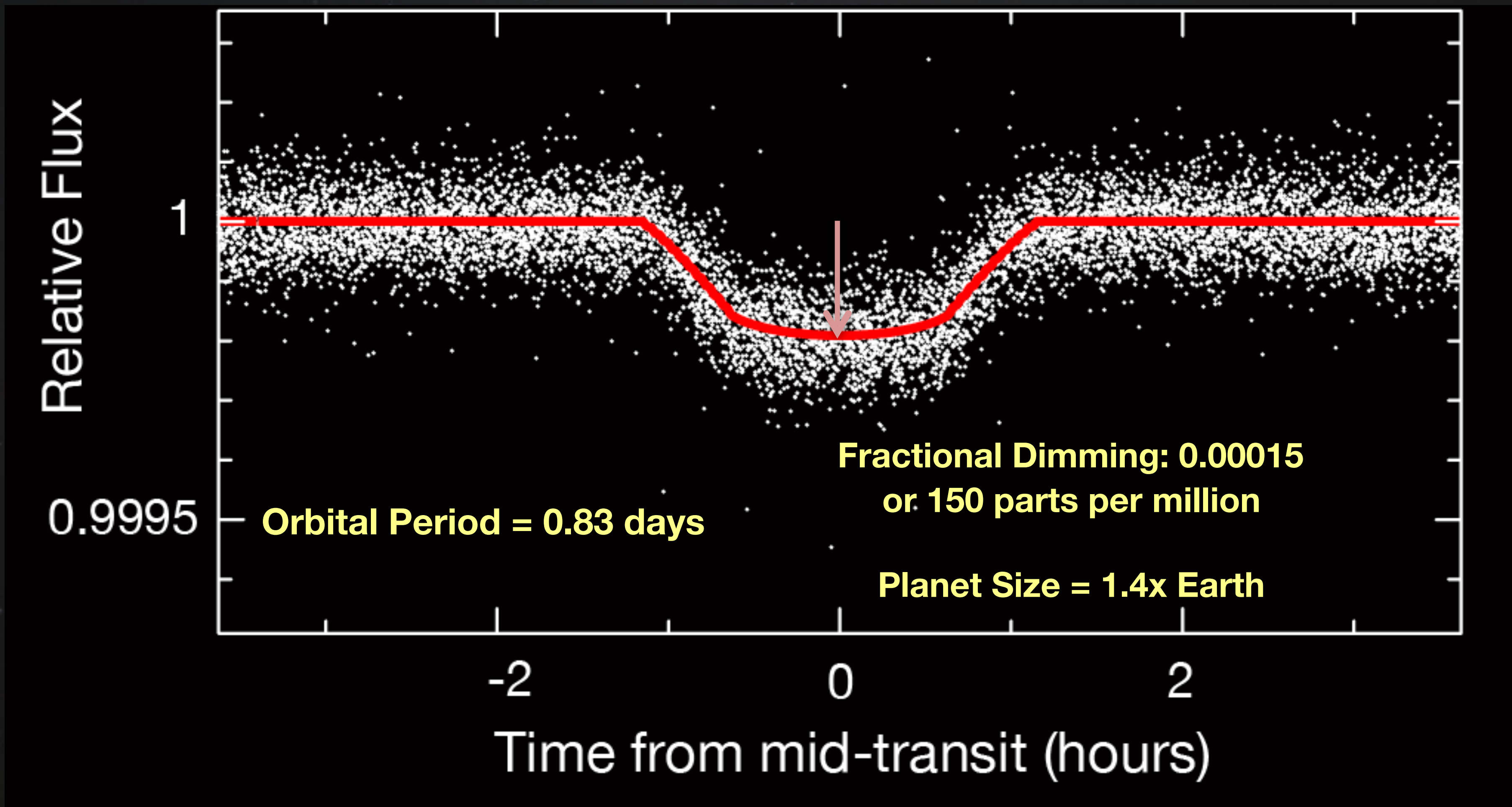


Kepler-10 Light Curve

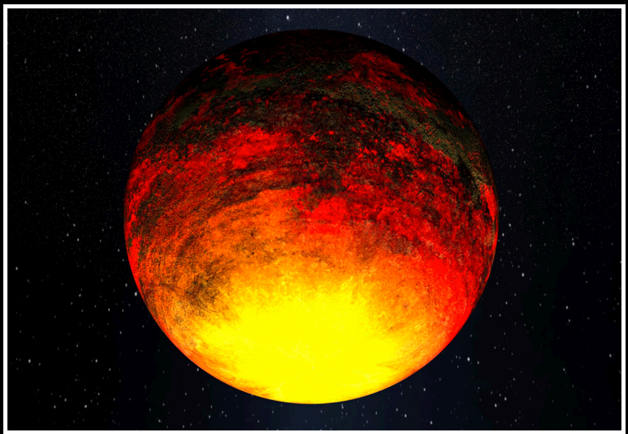


Planet 40% Larger than Earth

Kepler-10b Light Curve



Kepler-10b, the first Rocky Planet beyond the solar system



Orbital Period = 1 day
(Earth orbital period = 365 d)

Surface Temperature = 1500 C
(Earth Temp: 10 C)

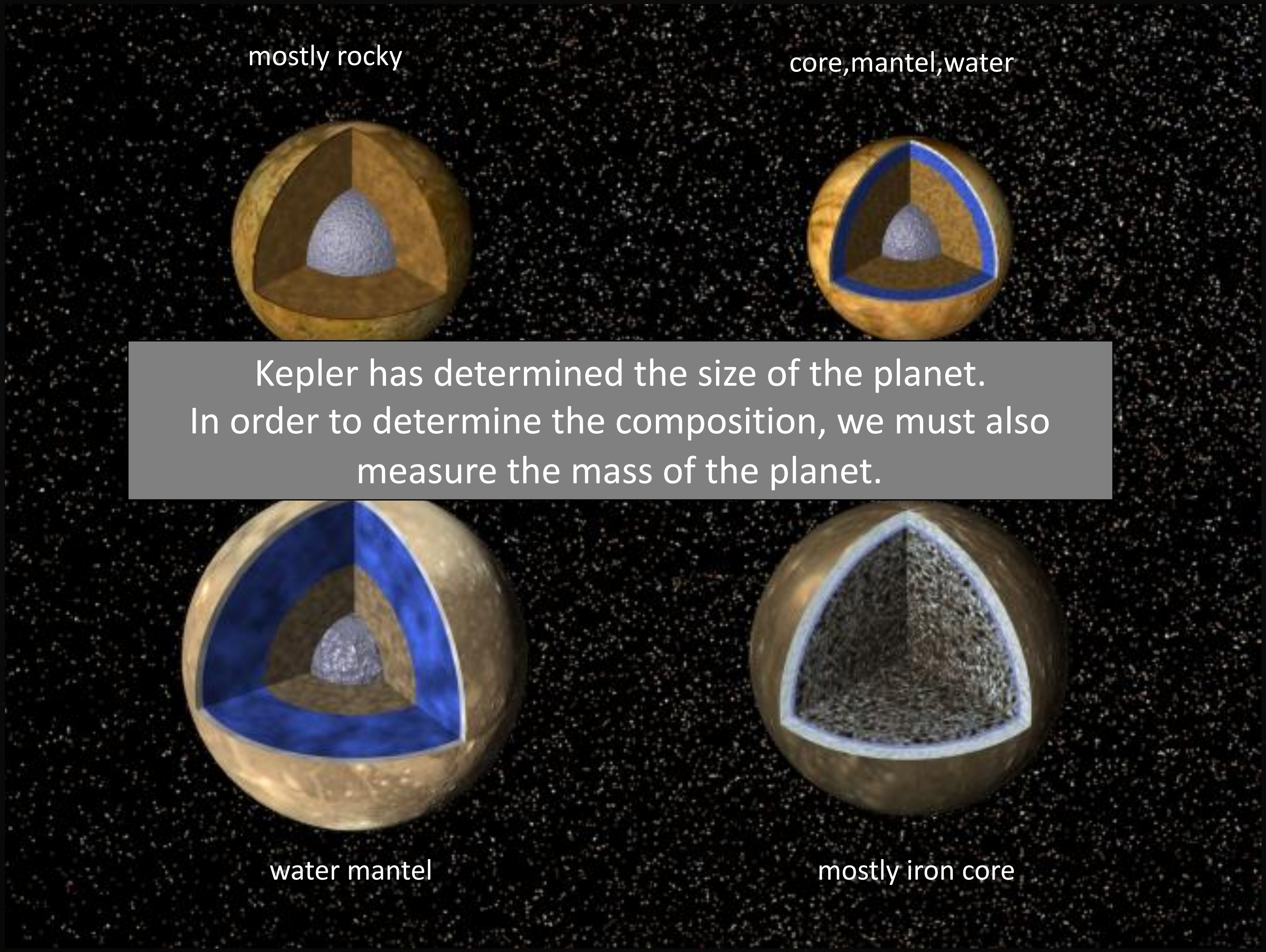
The surface of the planet is likely liquid lava rock

From Kepler-10b, the host star would appear 500 times larger than the sun

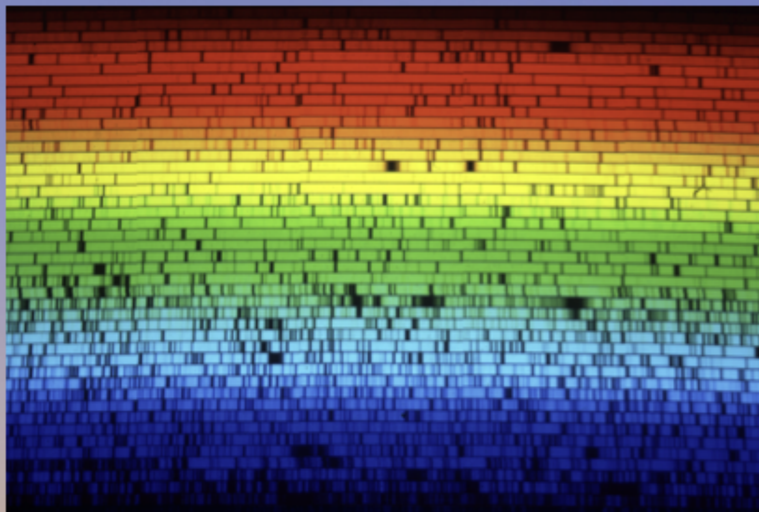
Artist Interpretations

Kepler's First Rocky Planet: Kepler-10b

What is Kepler-10b's composition?



Kepler has determined the size of the planet.
In order to determine the composition, we must also measure the mass of the planet.

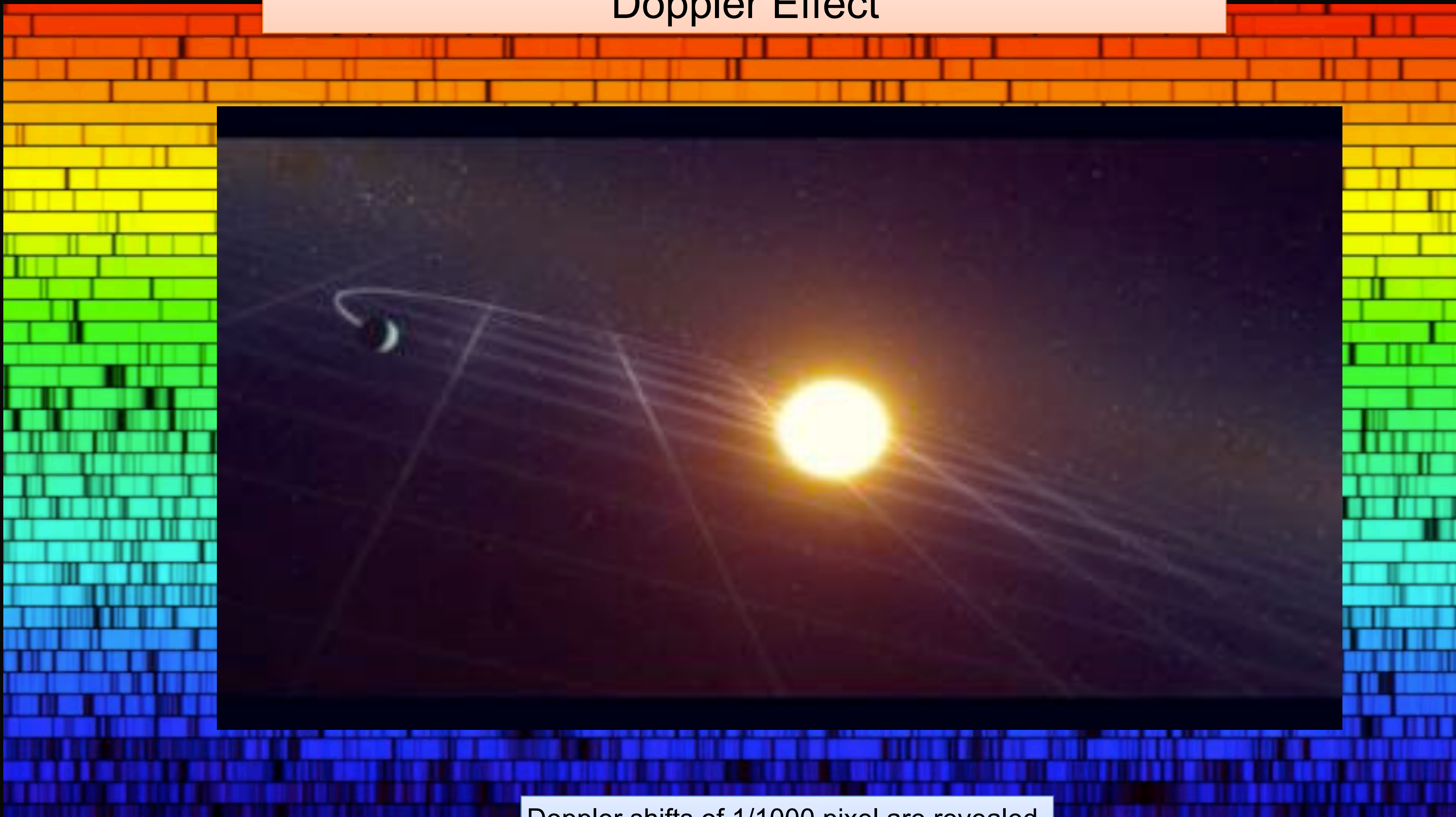


HIRES Echelle Spectrum

Iodine Absorption Cell

Photo Credit: Laurie Hatch

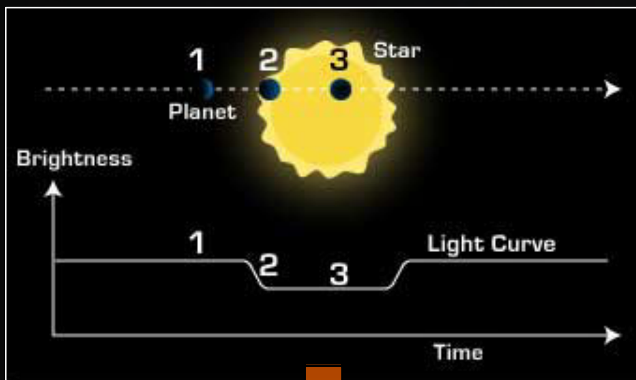
Detecting a Star's Reflex Motion via the Doppler Effect



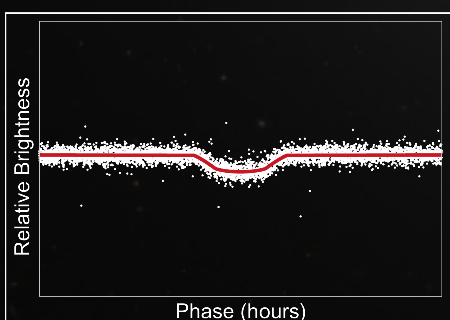
Doppler shifts of 1/1000 pixel are revealed as small displacements of the spectrum.
Doppler Precision: 1 meter / second

The Density of Kepler-10b

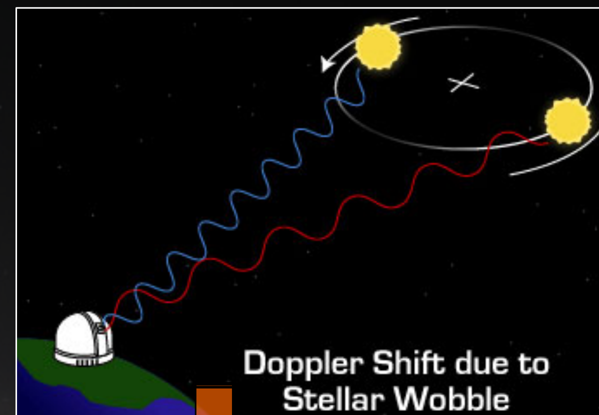
Star Dimming:
Size of the planet

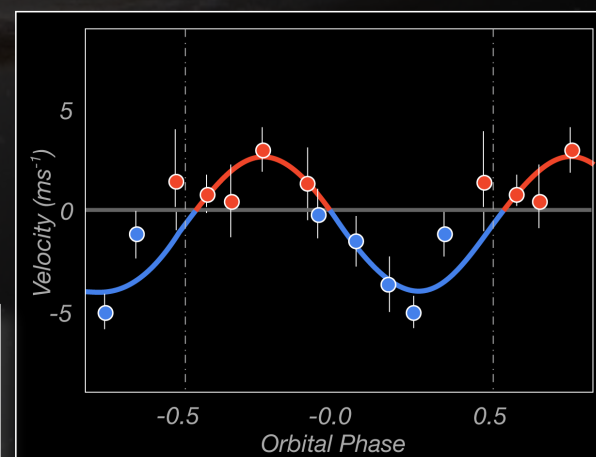


Size=1.4 R_{Earth}



Doppler of Star:
Mass of Planet

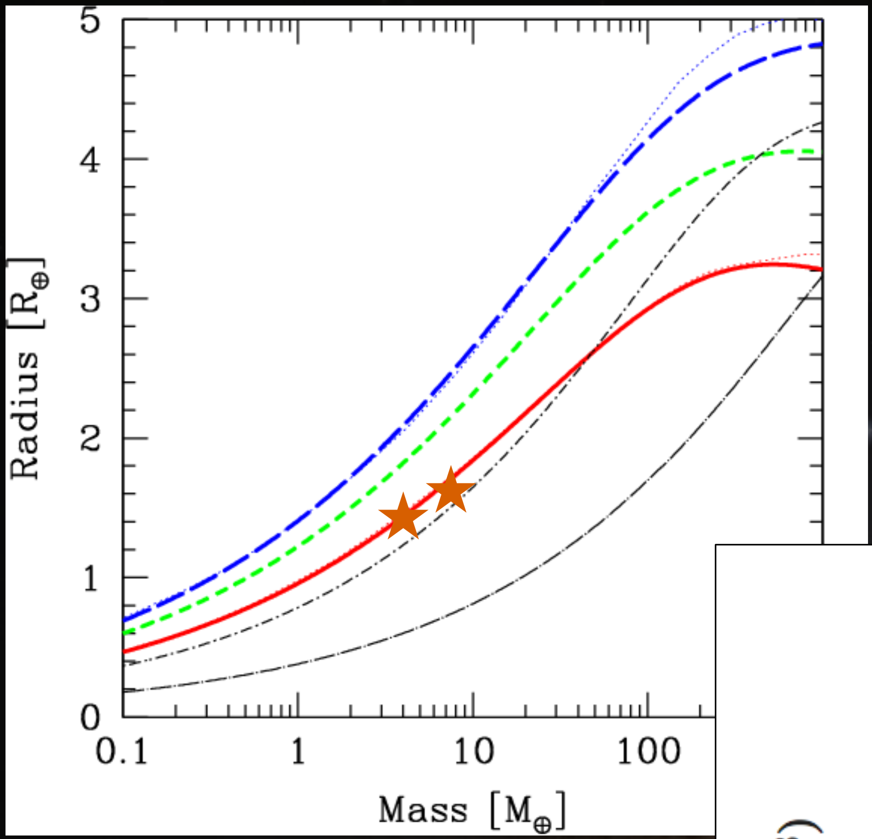




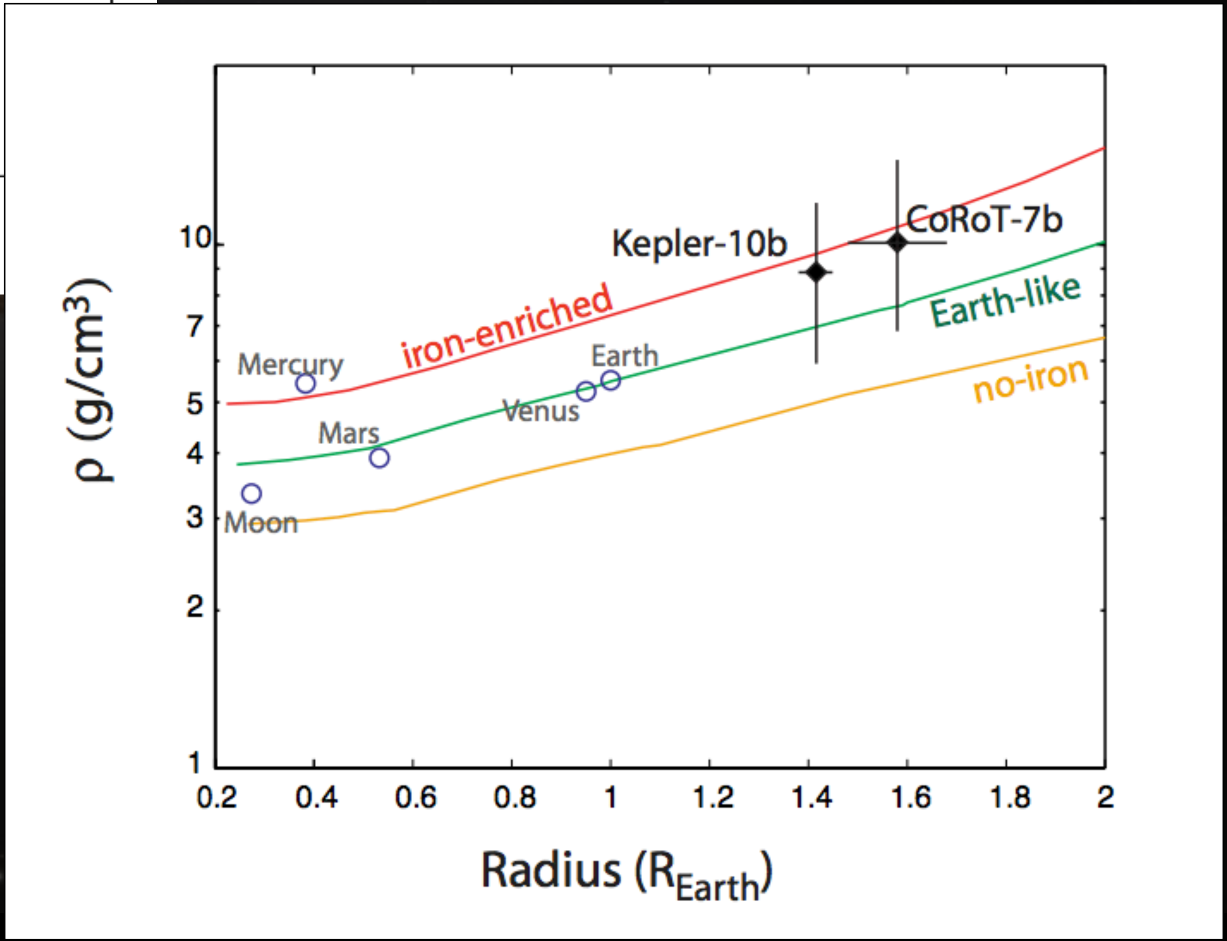
Planet Density:

$$\frac{\text{Mass}}{\text{Volume}} = 8.8\ \text{g/cm}^3$$

The Planet Mass vs Planet Radius Relation

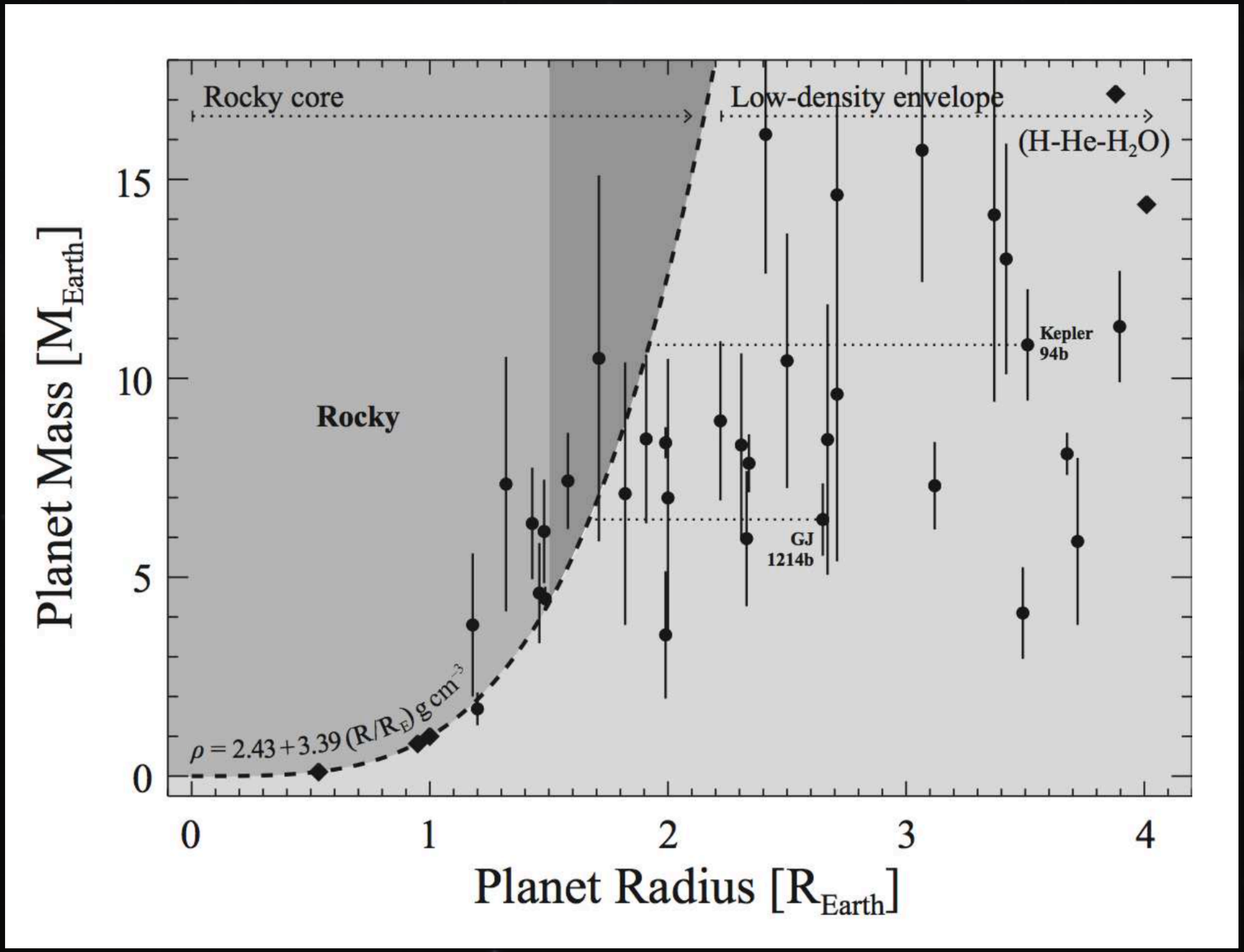


The Planet Mass vs Planet Density Relation




Jason Chu
Photography

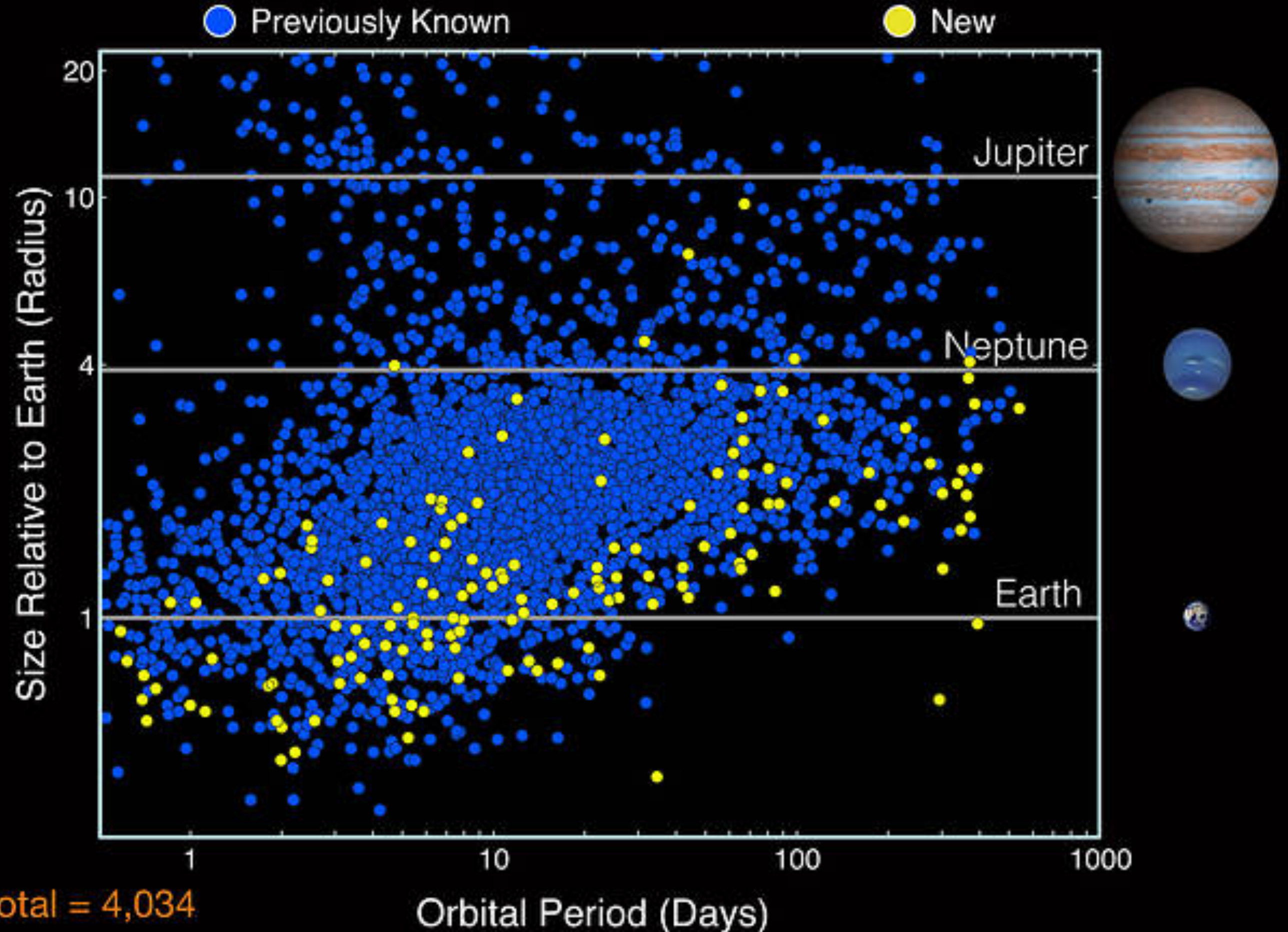
Using the Keck Telescope on Maunakea in Hawai'i, we measured the masses of 22 planetary systems holding 42 individual planets. Focusing on the range of planet radii between Earth and Neptune, (that is 1 and 4x the size of the Earth), we spent over 50 nights on the largest optical telescope in the world to measure the distribution of planet mass as a function of planet radii.



2014 !

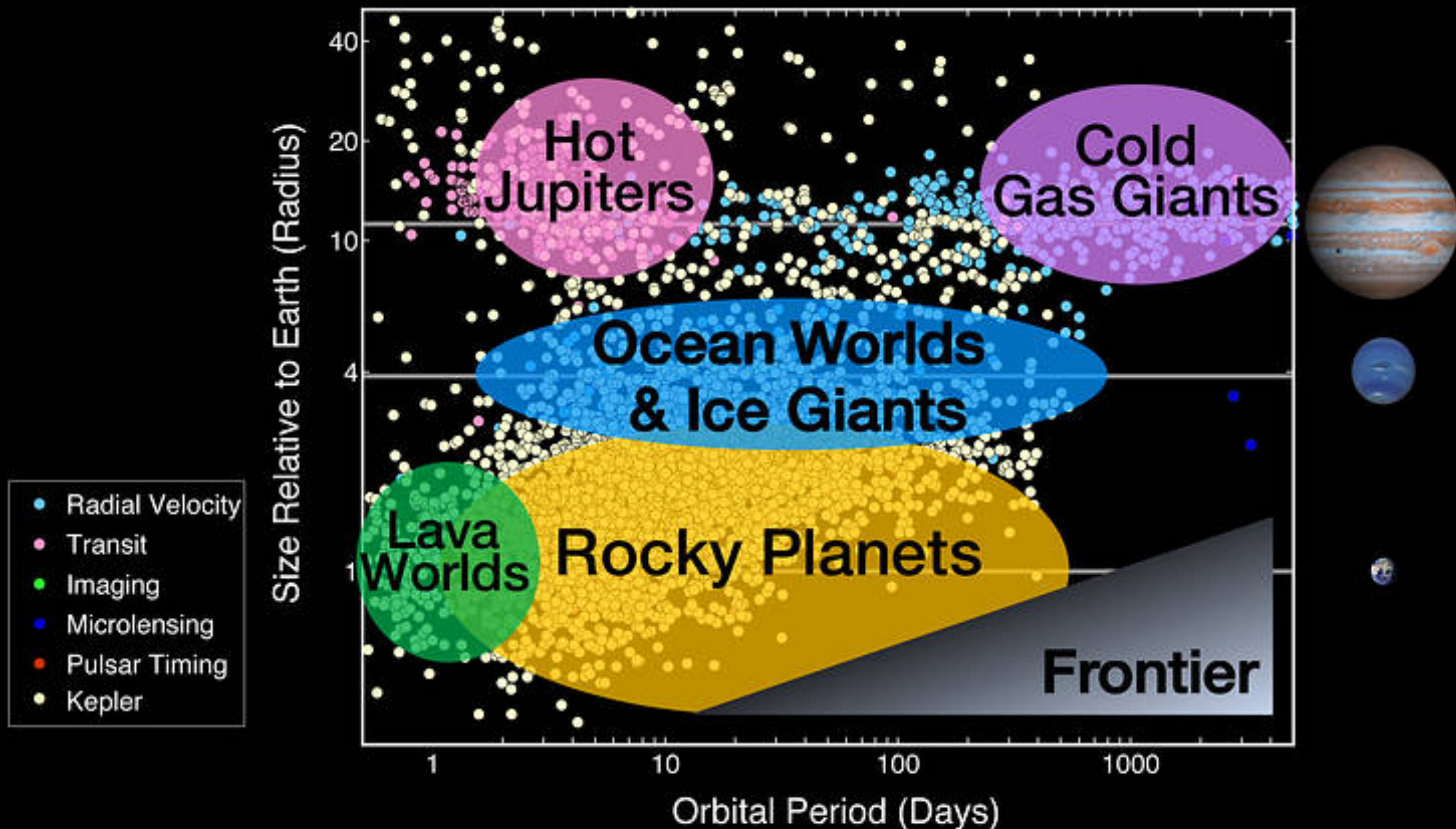
New Kepler Planet Candidates

As of June 2017



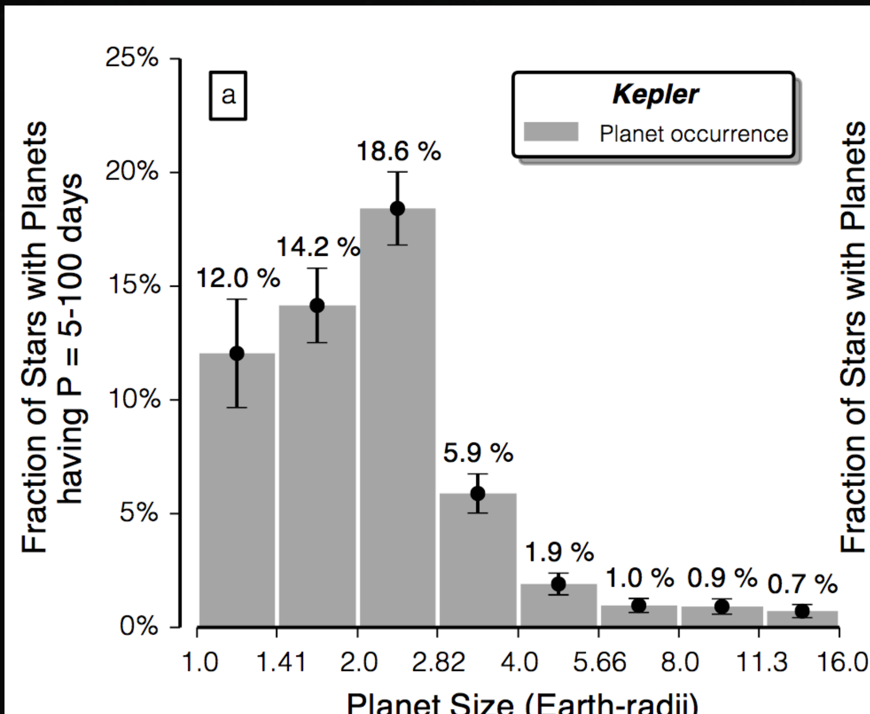
Total = 4,034

Exoplanet Populations



Courtesy: NASA

UC Berkeley (then) Graduate Student Erik Petigura, using Kepler Data, has given us the one of the first measurements of the occurrence of small planets…



Petigura et al (2013)

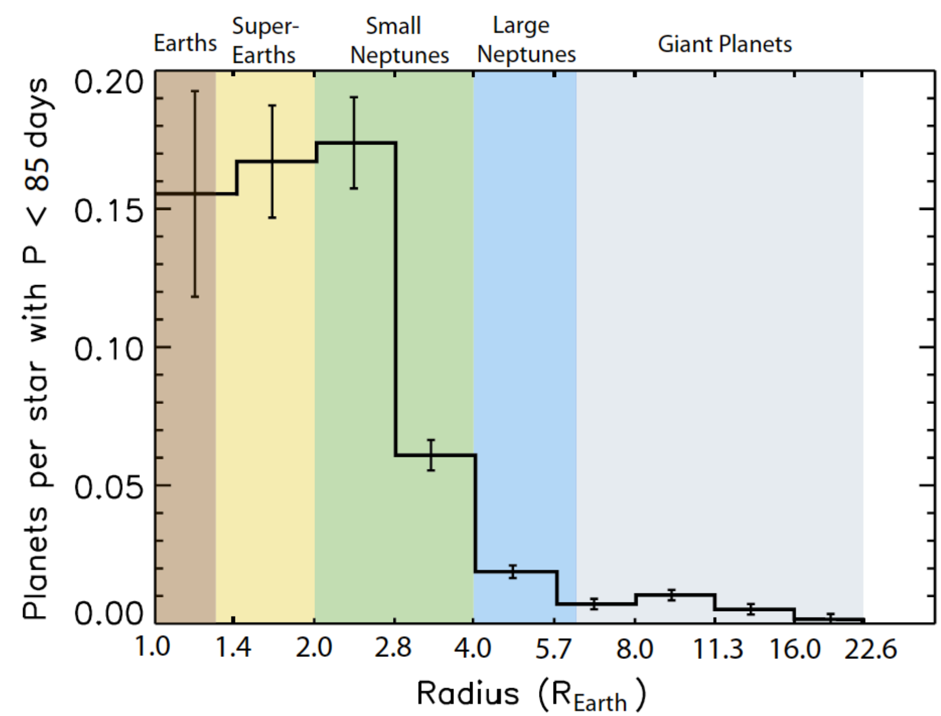
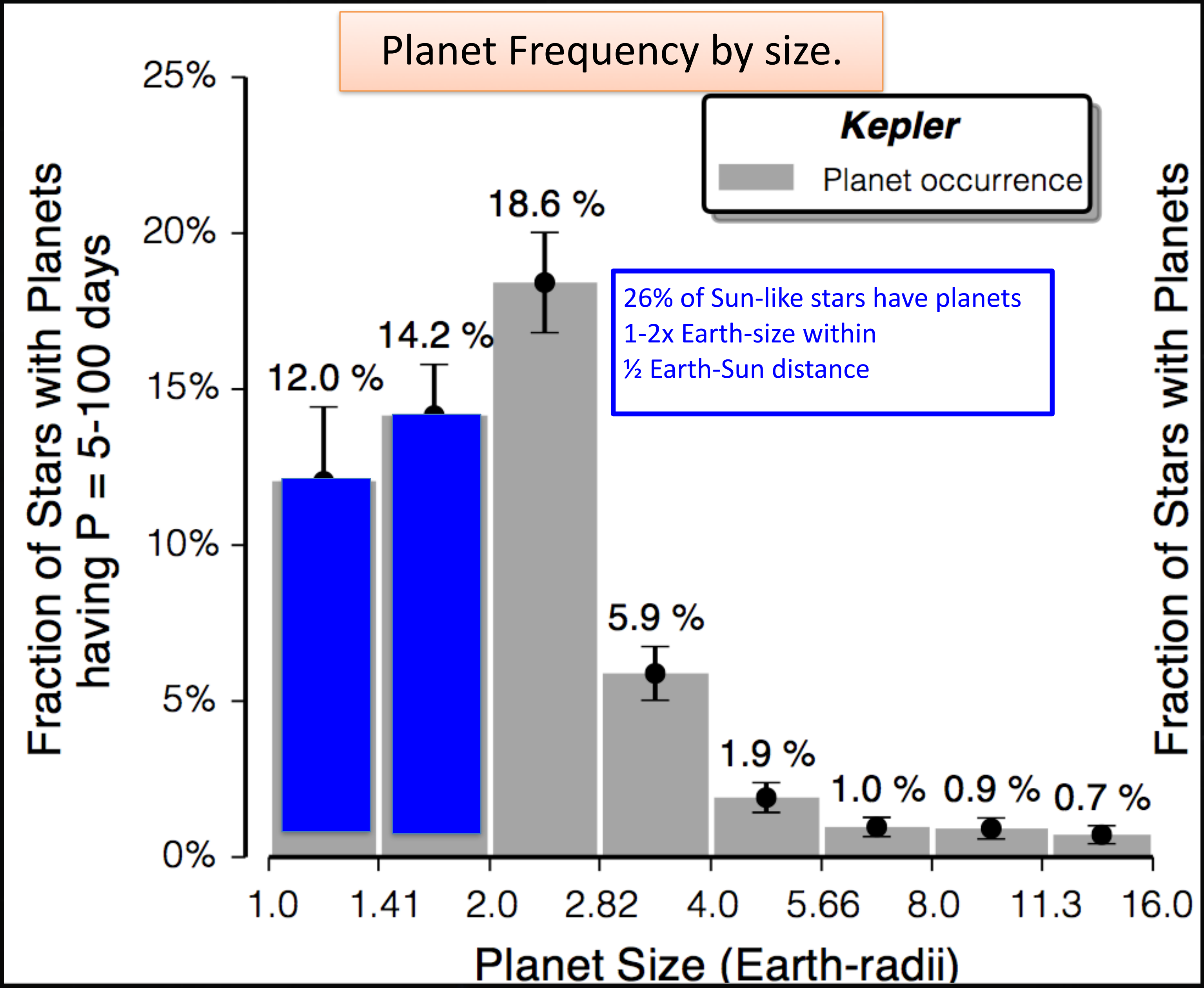


FIG. 7.— Average number of planets per size bin for main sequence FGKM stars, determined here from the Q1–Q6 *Kepler* data and corrected for false positives and incompleteness.

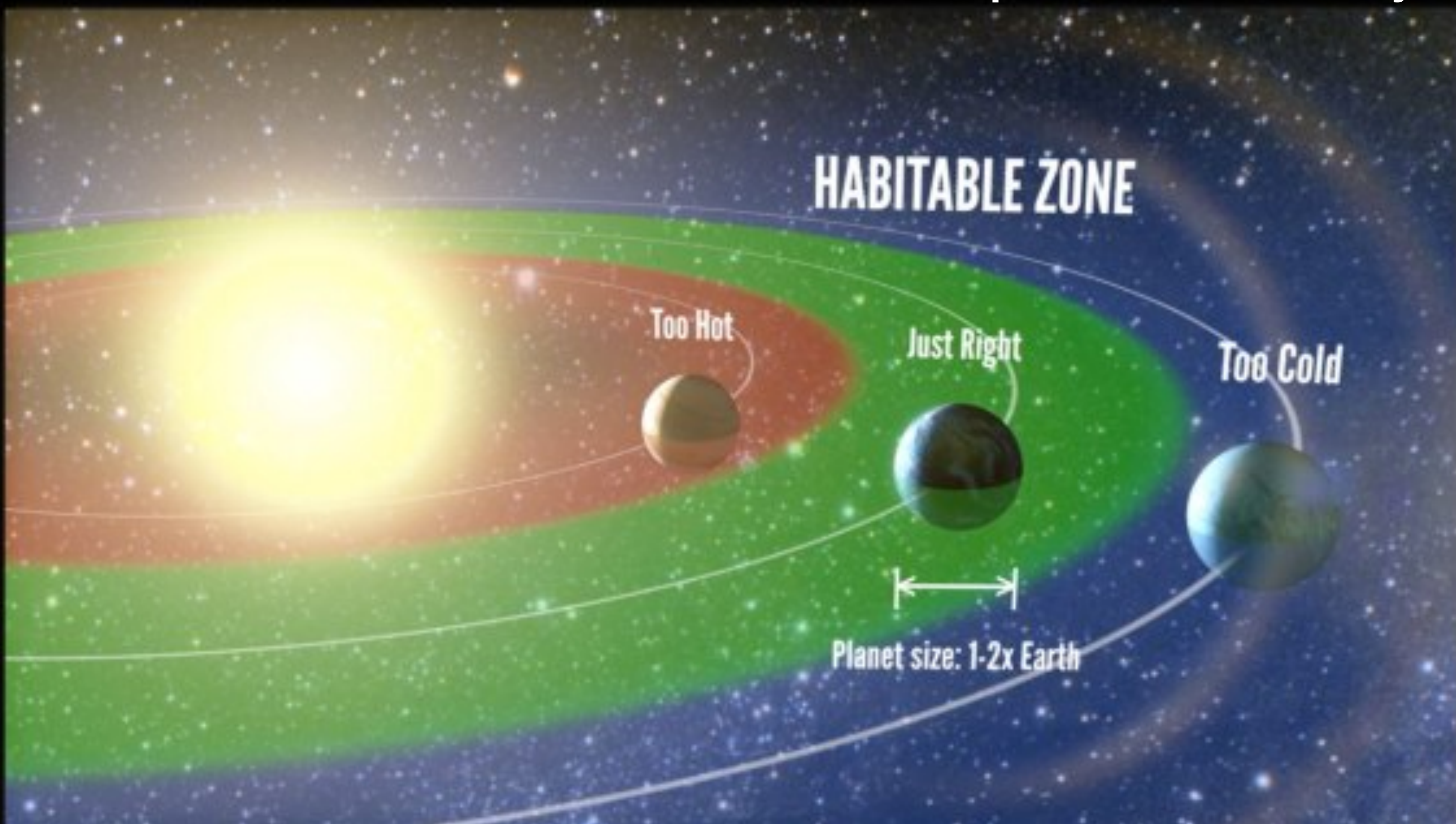
Fressin et al (2012)

…in the habitable zones of sun-like stars.



Kepler found that about 1 in 5 stars like the Sun has a planet like the Earth

This means there are BILLIONS of Earth like planets in our Galaxy



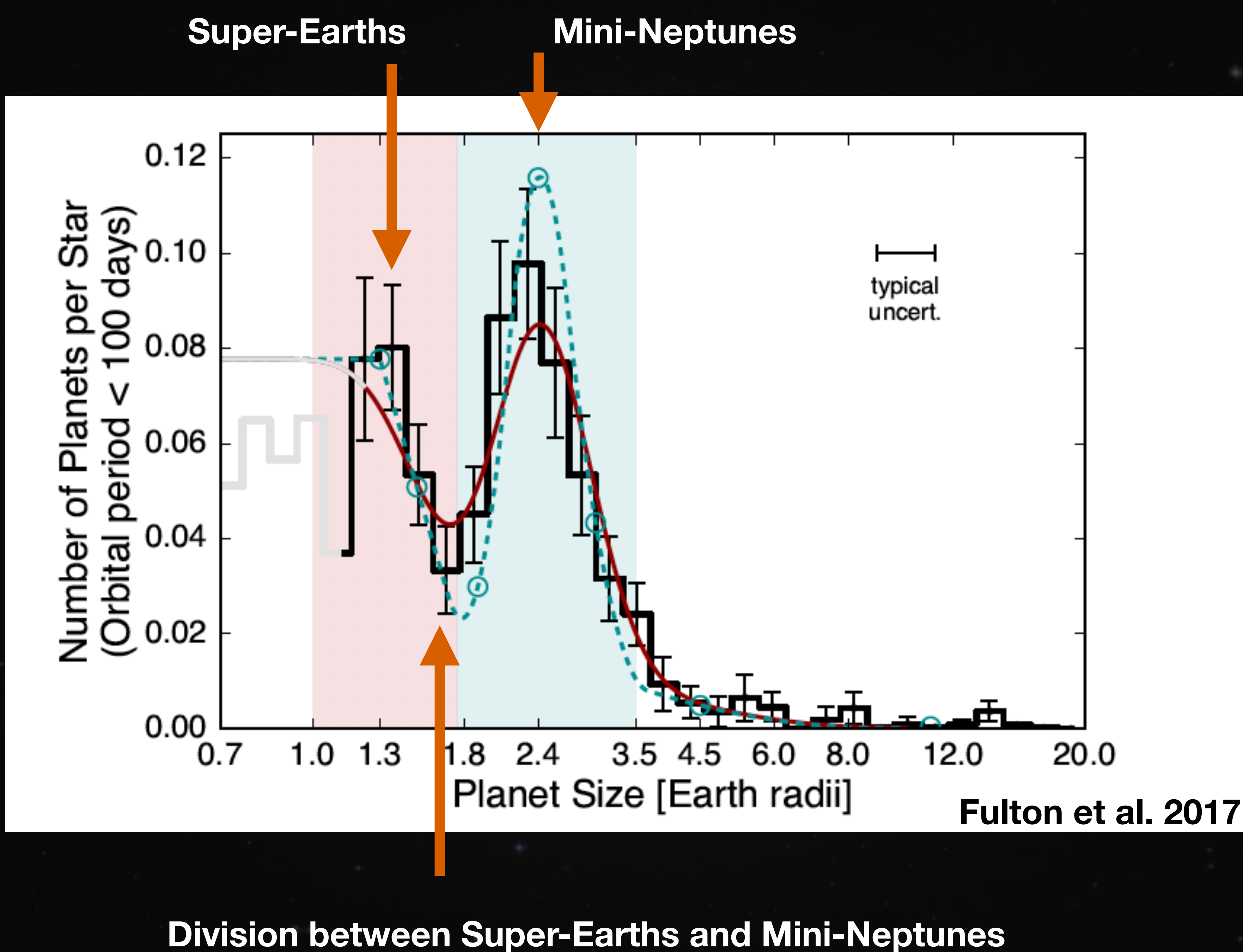
The habitable zone corresponds to the range of orbital distances where liquid water can exist on a planet's surface.

Erik A. Petigura

Kepler photometry alone is capable of determining the number of planets per star.

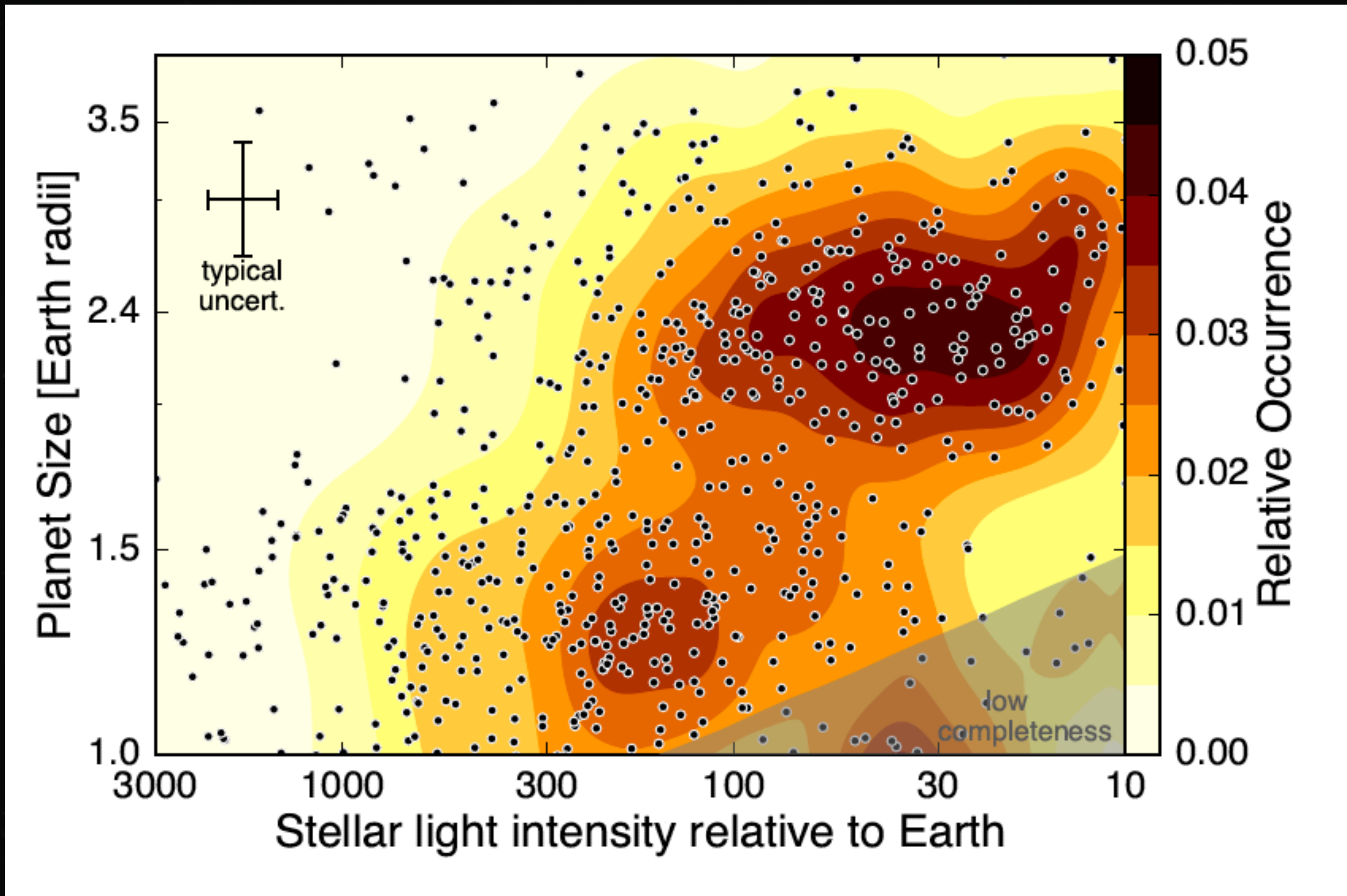
With the addition of ground based observations, we now know a little more.

So it's back to the telescope…



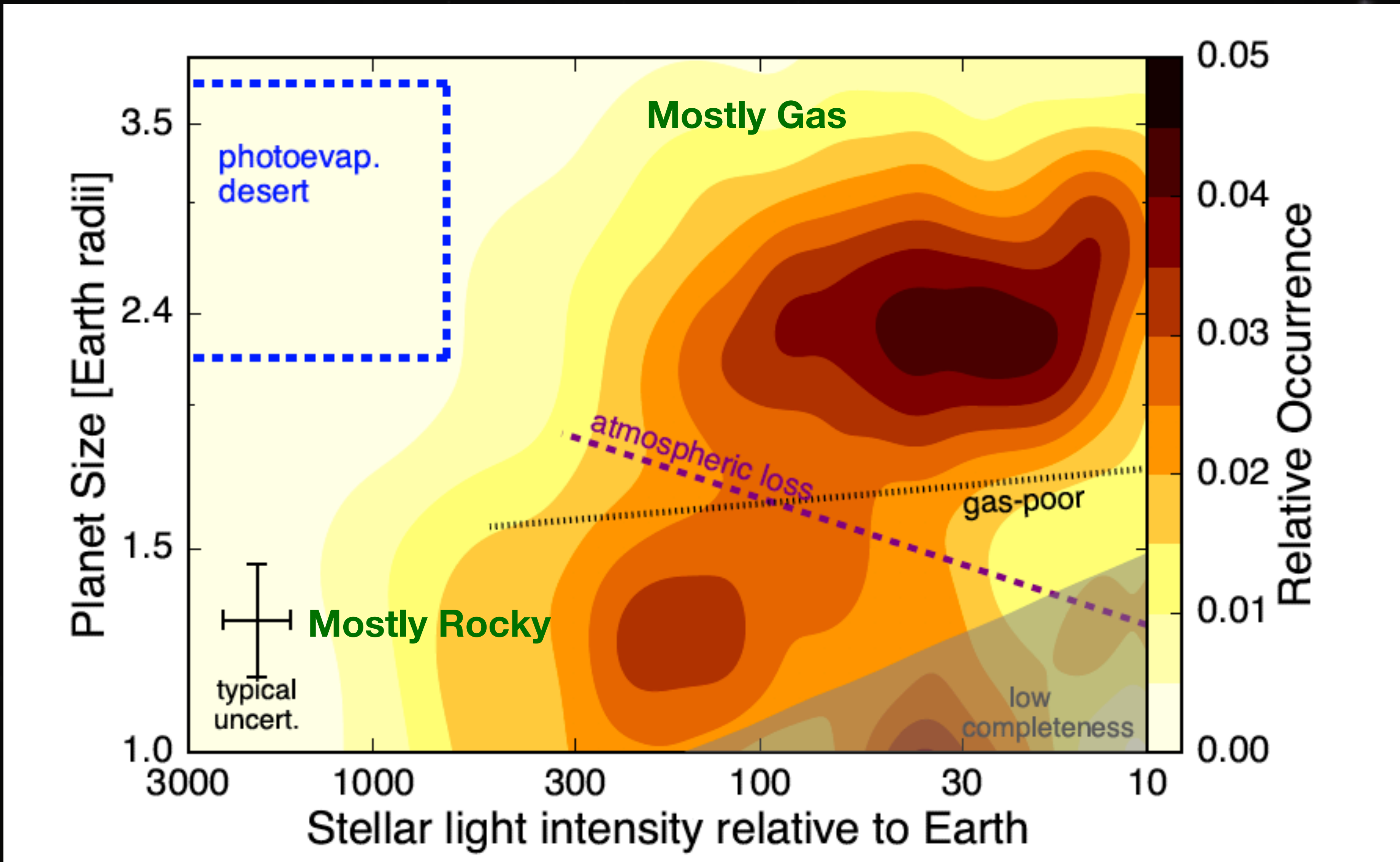
Super-Earths
Mini-Neptunes
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Number of Planets per Star
(Orbital period < 100 days)
typical
uncert.
0.7
1.0
1.3
1.8
2.4
3.5
4.5
6.0
8.0
12.0
20.0
Planet Size [Earth radii]
Fulton et al. 2017
Division between Super-Earths and Mini-Neptunes

Even with no measurements of the planets' masses we can learn about their populations, especially in relation to how much energy they receive from their host stars.

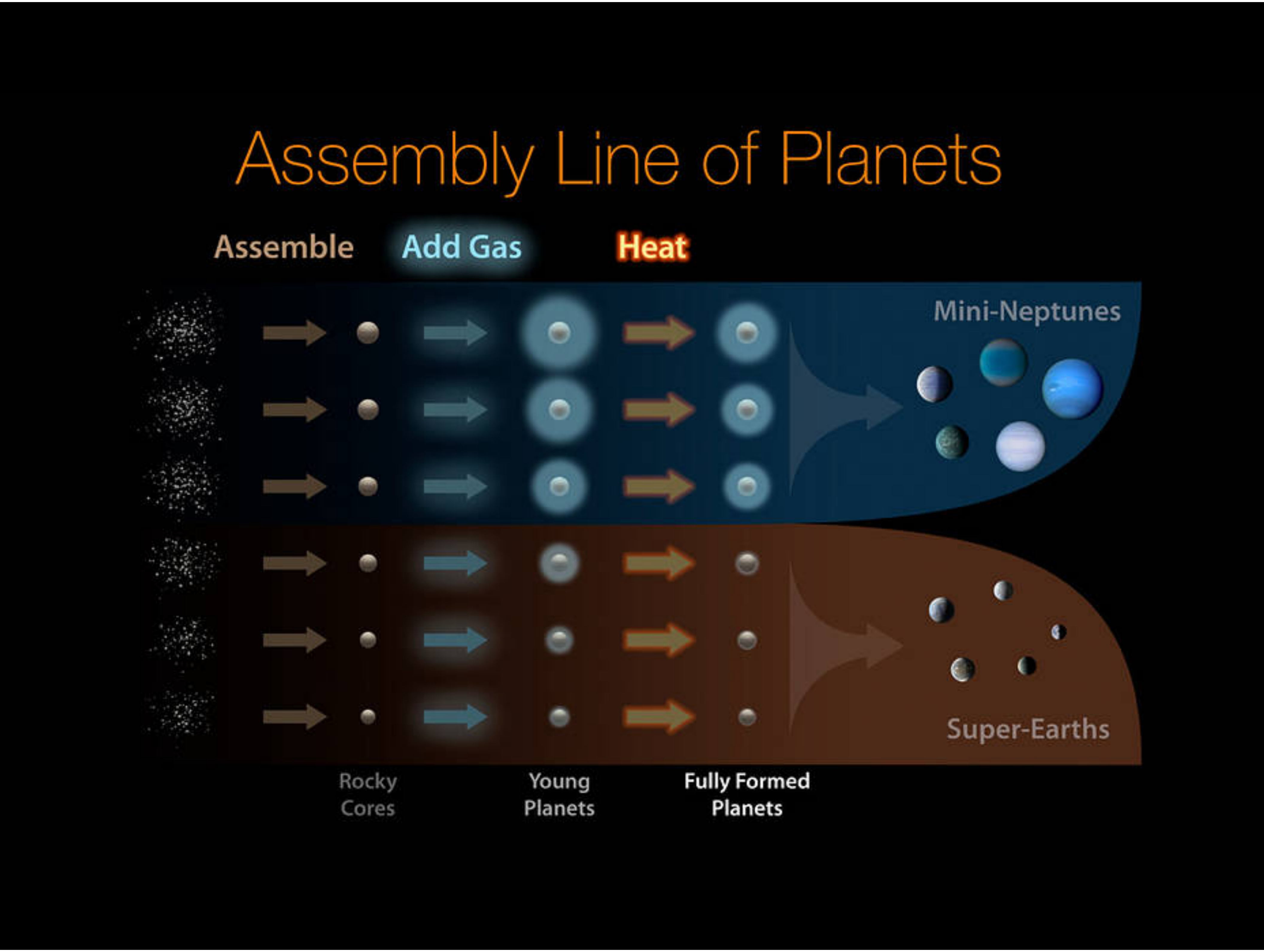


Hotter Planets → **Cooler Planets**

https://california-planet-search.github.io/cks-website/



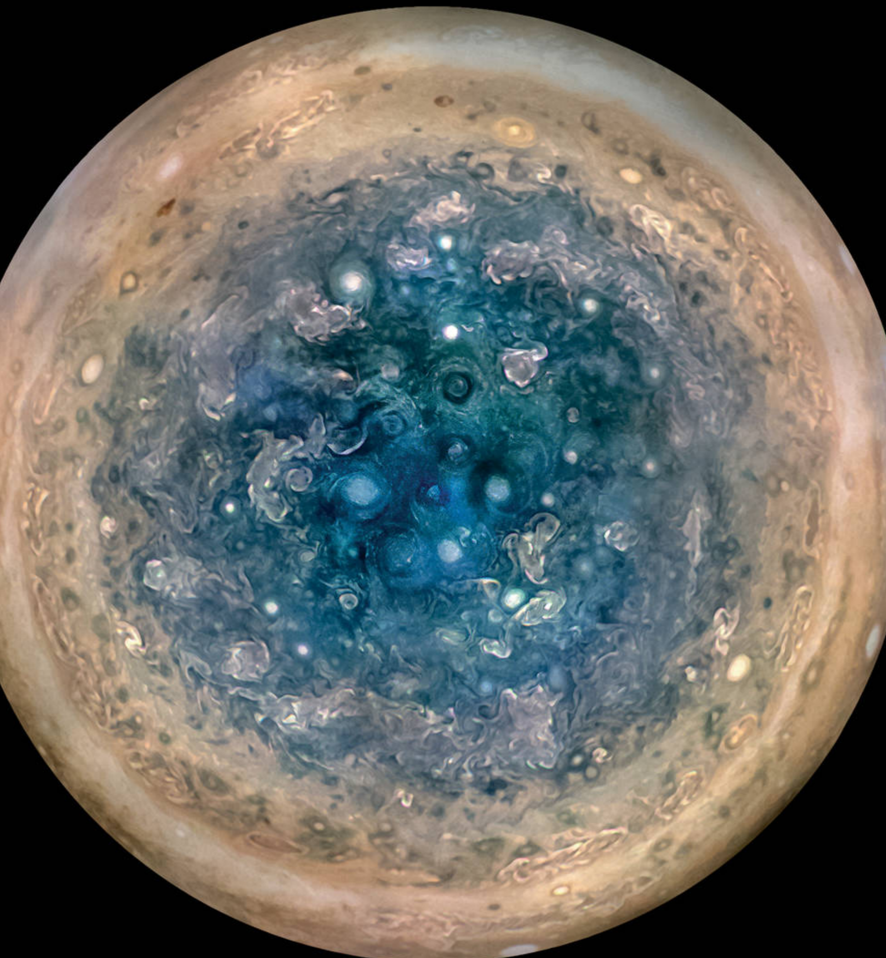
Hotter Planets → **Cooler Planets**


Assembly Line of Planets
Assemble
Add Gas
Heat
Mini-Neptunes
Super-Earths
Rocky Cores
Young Planets
Fully Formed Planets

Let’s move on from what we know to what the future holds.

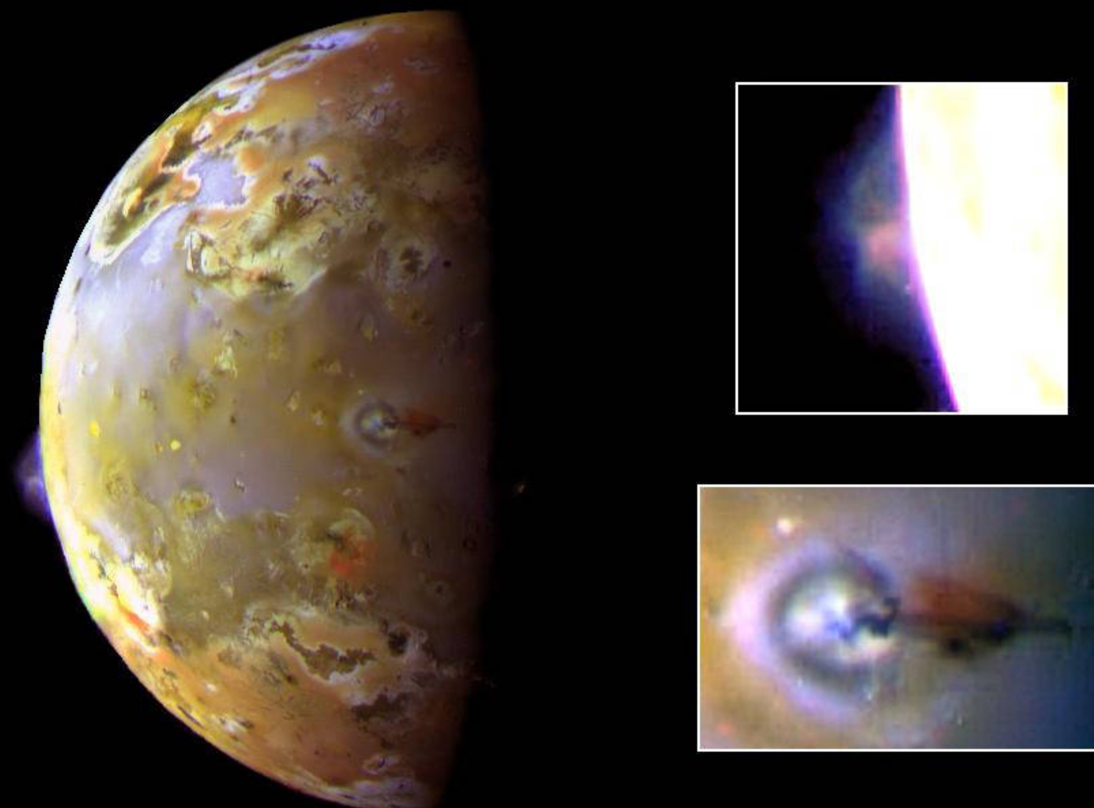
The three most sought after scientific discoveries regarding life beyond Earth

- **Detection of life on another body in the solar system**
- **Detection of bio-signatures on exoplanets**
- **Detection of electromagnetic radiation indicative of intelligent life beyond Earth — Breakthrough Listen**



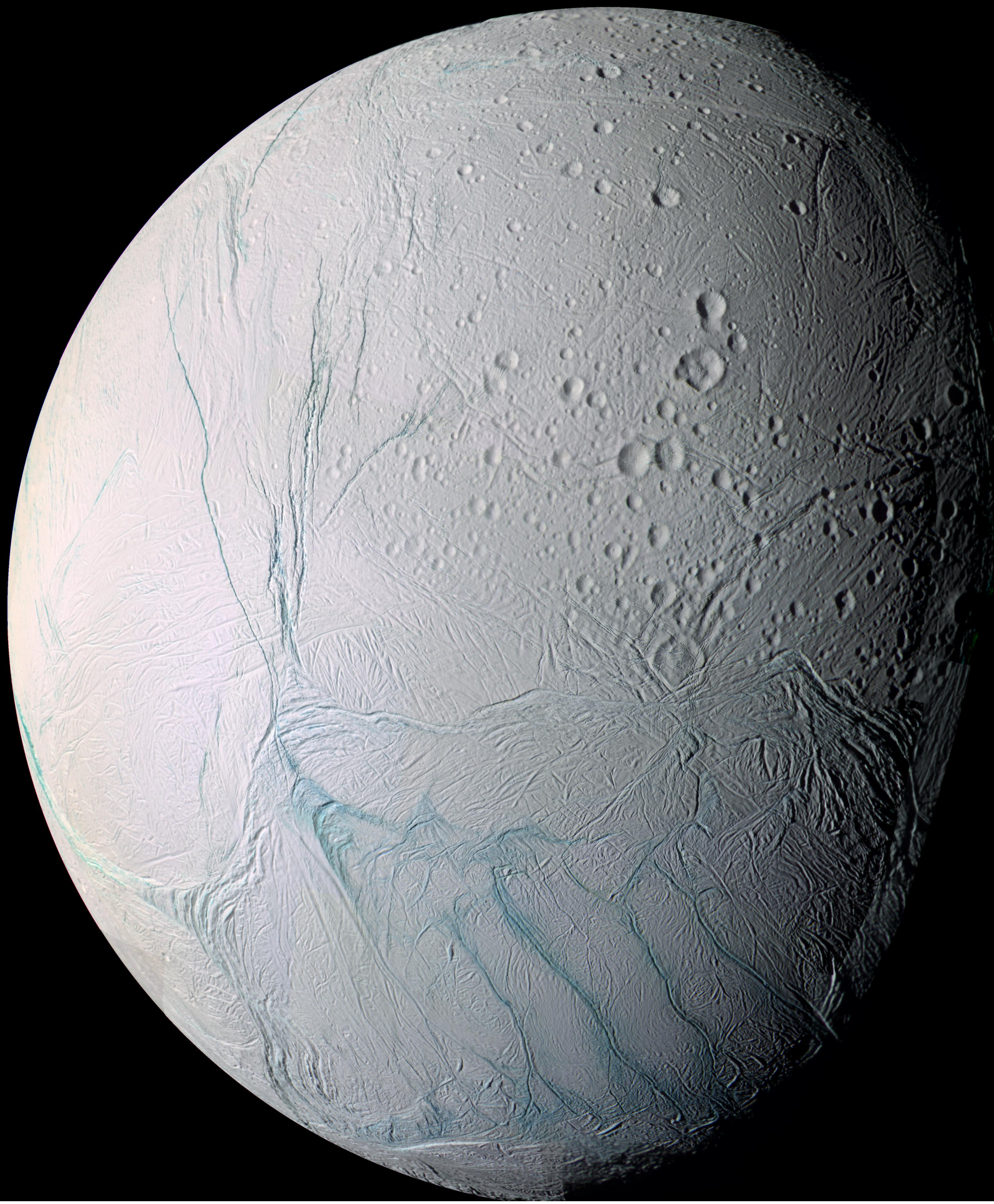
The southern pole of Jupiter
as seen from Juno

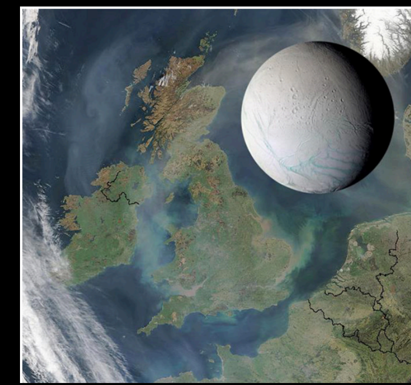
Jupiter’s moon Io seen erupting



In situ detection of life in the solar system.

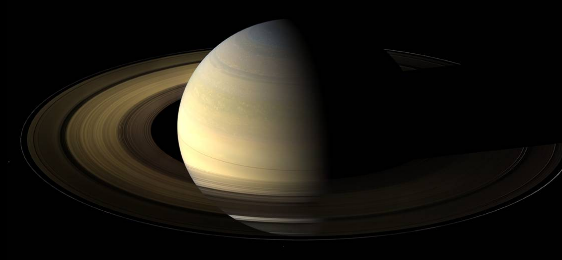
Io from NASA's New Horizon's spacecraft (movie)

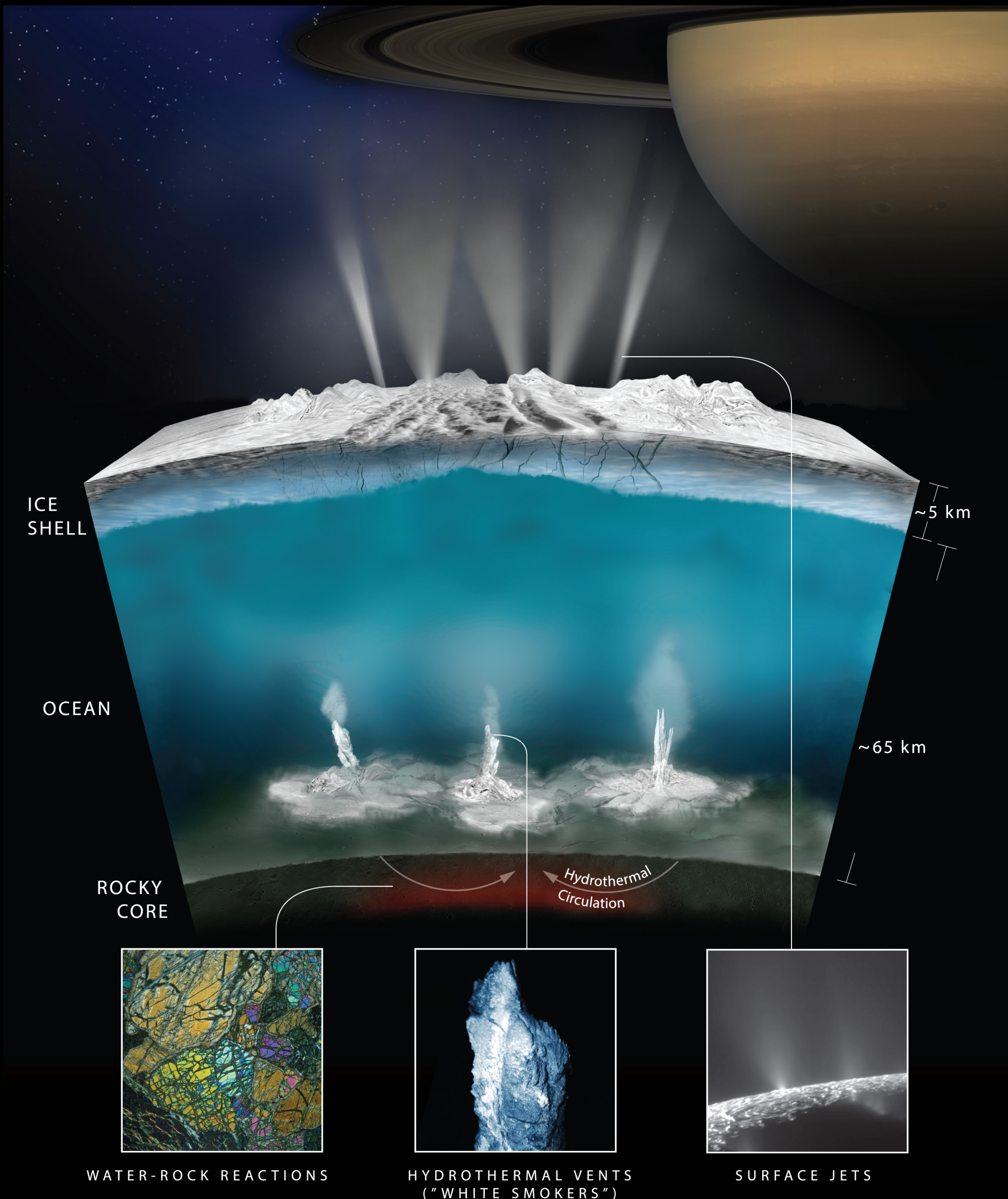




for Scale

Saturn’s moon Enceladus as seen by NASA’s Cassini spacecraft

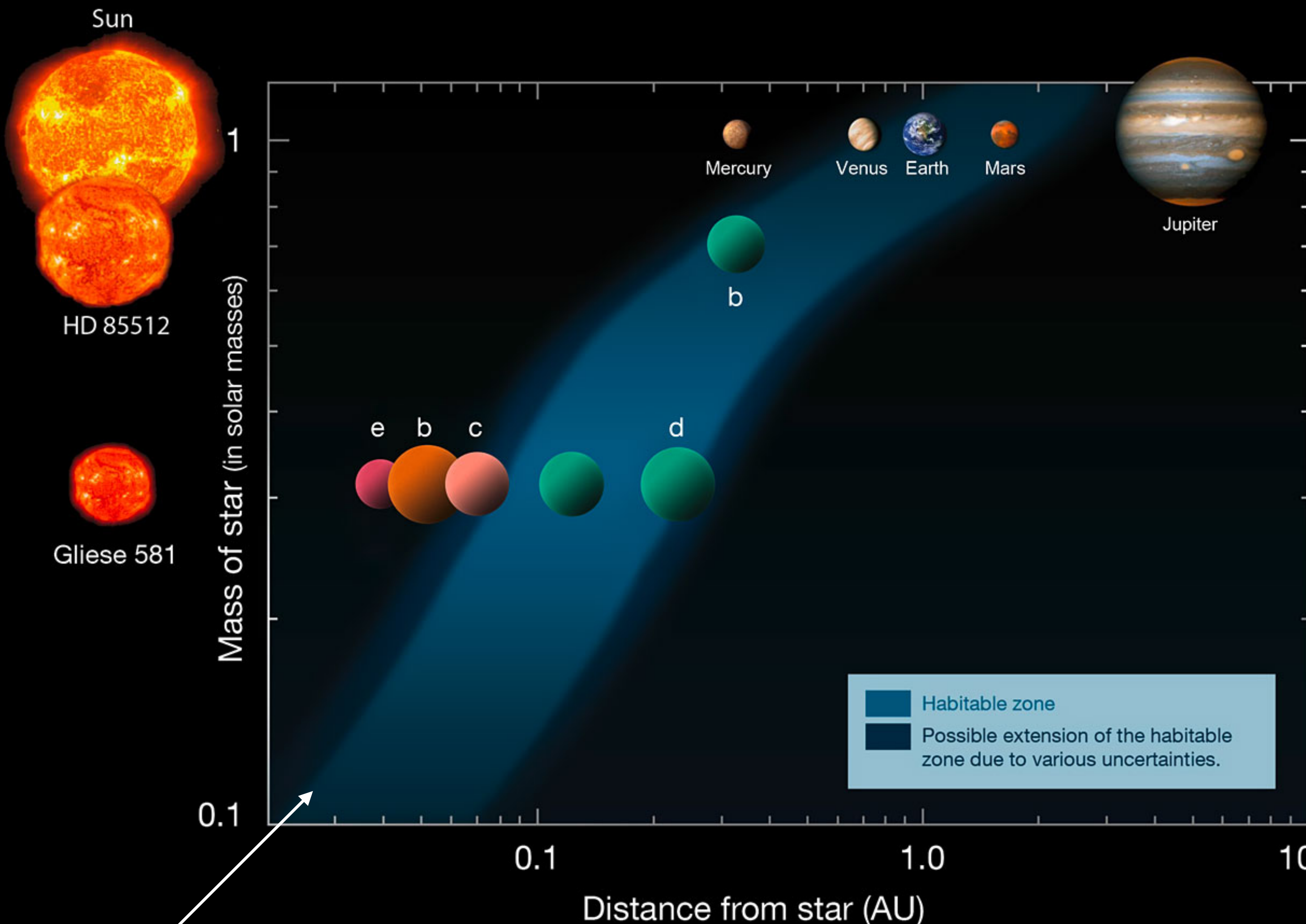




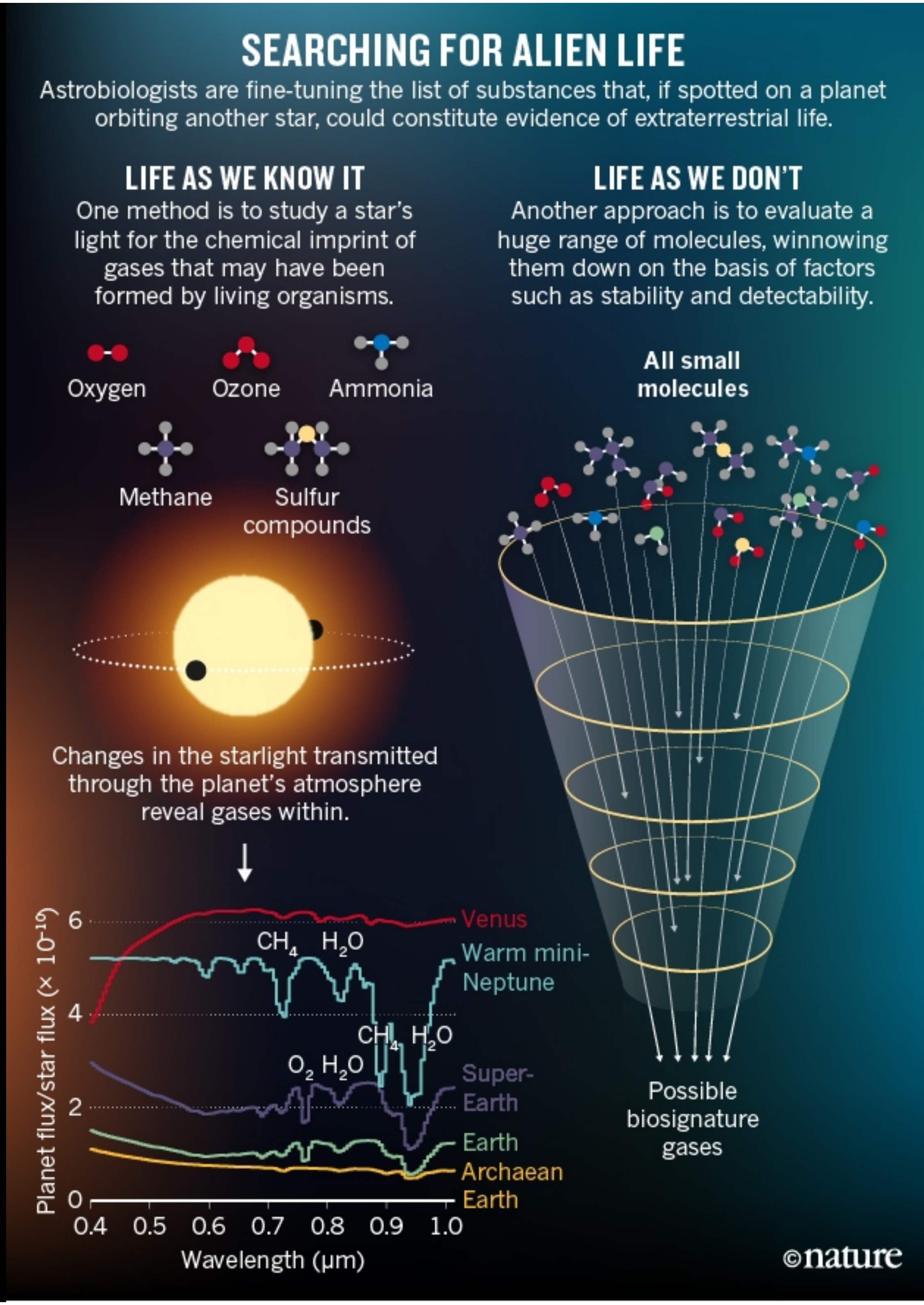
ENCELADUS

Image from Cassini

Bio-signatures in exoplanet atmospheres



Habitable Zone for cool stars


SEARCHING FOR ALIEN LIFE
Astrobiologists are fine-tuning the list of substances that, if spotted on a planet orbiting another star, could constitute evidence of extraterrestrial life.
LIFE AS WE KNOW IT
One method is to study a star's light for the chemical imprint of gases that may have been formed by living organisms.
Oxygen
Ozone
Ammonia
Methane
Sulfur compounds
Changes in the starlight transmitted through the planet's atmosphere reveal gases within.
Planet flux/star flux (× 10^{-10})
6
4
2
0
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Wavelength (µm)
CH_4
H_2O
CH_4
H_2O
O_2
H_2O
Venus
Warm mini-Neptune
Super-Earth
Earth
Archaean Earth
LIFE AS WE DON'T
Another approach is to evaluate a huge range of molecules, winnowing them down on the basis of factors such as stability and detectability.
All small molecules
Possible biosignature gases
©nature

Breakthrough Listen and the Search for Extra-Terrestrial Intelligence

"The universe is a pretty big place. If it's just us, seems like an awful waste of space."
— Carl Sagan, Contact

"We, all of us, are what happens when a primordial mixture of hydrogen and helium evolves for so long that it begins to ask where it came from."
— Jill Tarter

"We have a responsibility to not stop searching. It should always be happening in the background. This is the biggest question. We should be listening."
—Yuri Milner

BERKELEY SETI RESEARCH CENTER

breakthroughinitiatives.org

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—Yuri Milner

“It’s not crazy”

—Yuri Milner

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Detectable Signatures of Intelligence

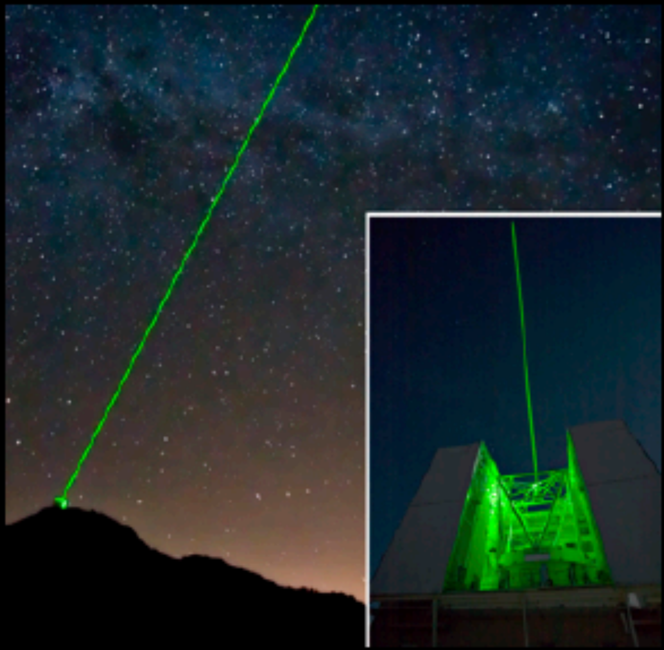
High-power TV and Radio

Hundreds of transmitters detectable at a few lightyears

Planetary Radar Systems

A few radar systems on Earth detectable across the galaxy

High-power Lasers

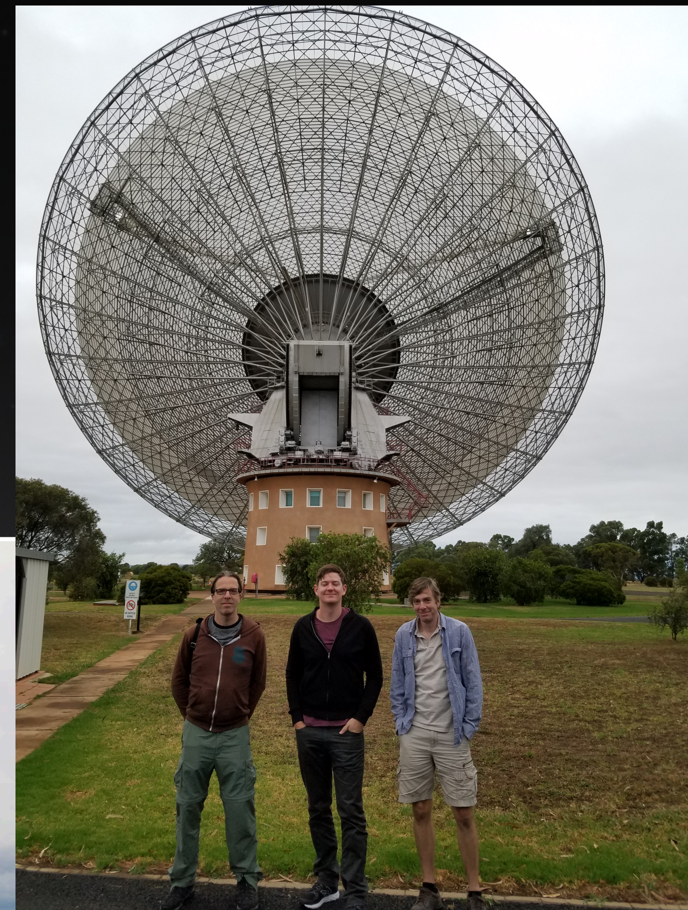


Lasers can outshine the Sun by thousands of times

Courtesy: Andrew Siemion

The 100m Green Bank Telescope

“The Dish” — Parkes 60m telescope



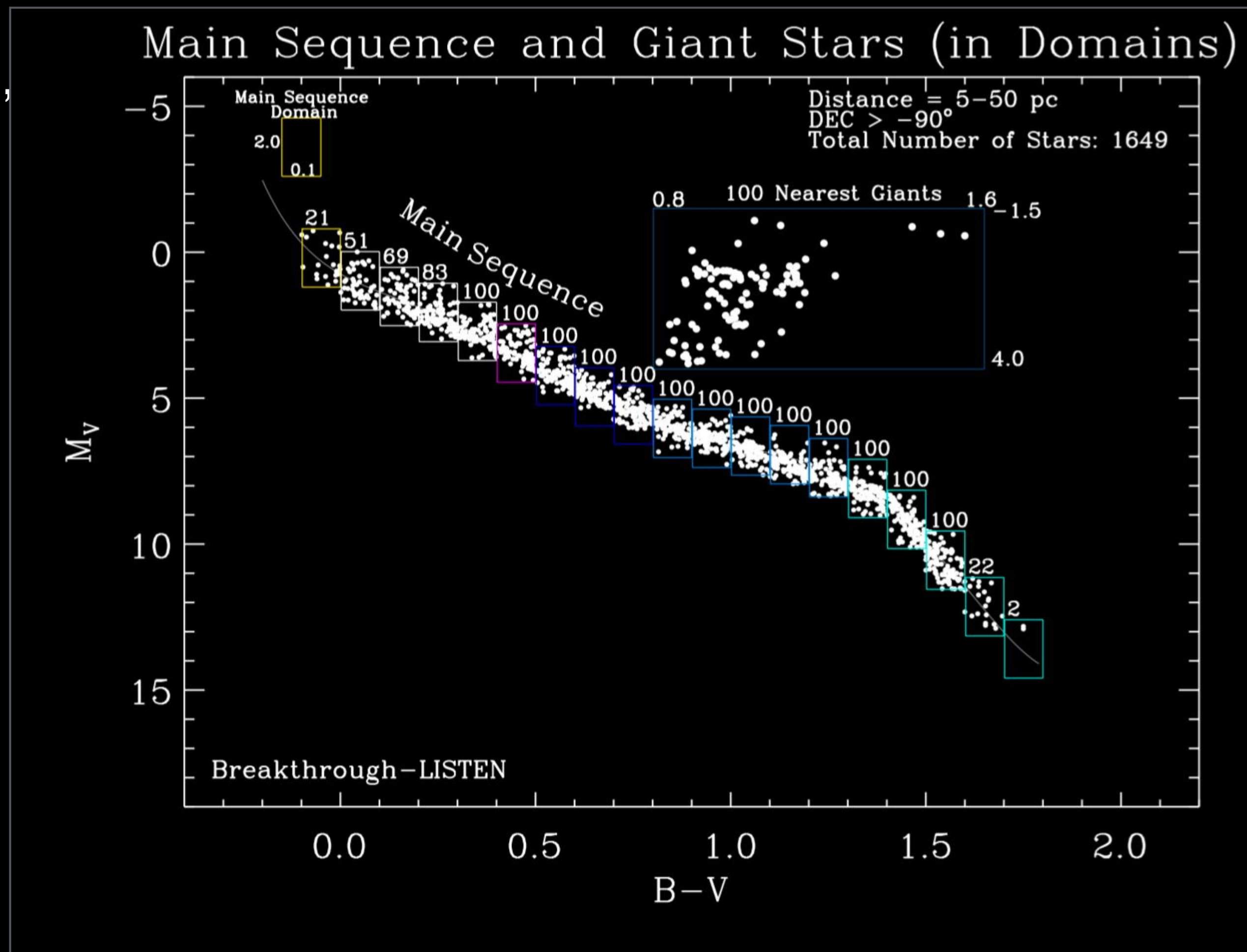
MeerKAT

The 2.4 Automated Planet Finder at Lick Observatory

On top of ~~the World~~ “The Dish”

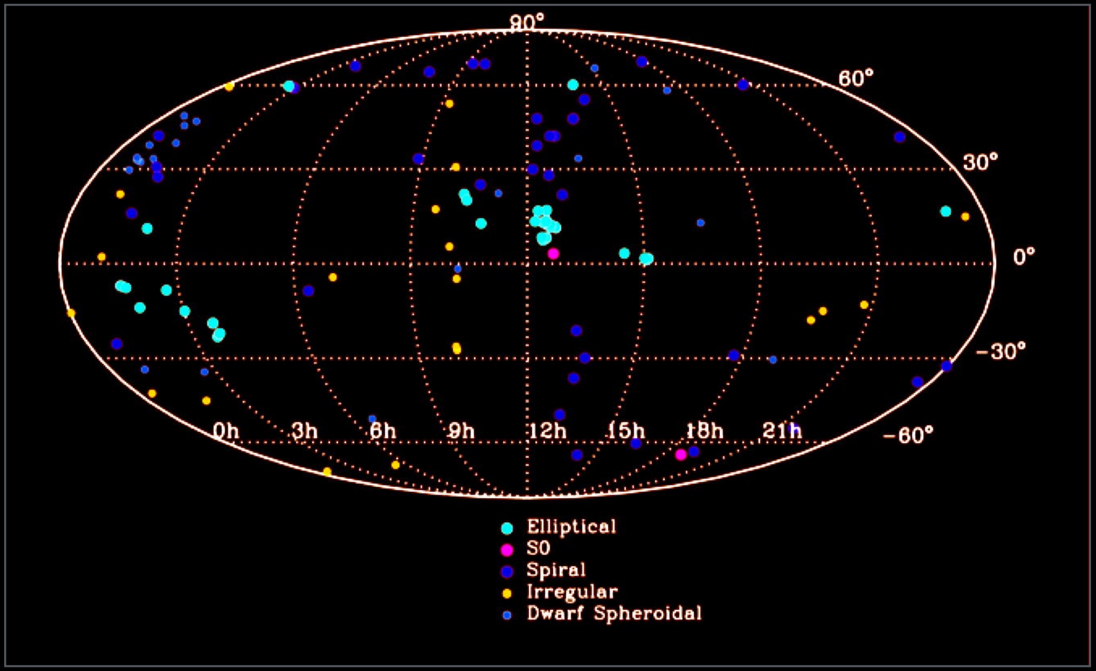
The 5-50 Parsec Spectral Type Complete Sample

- From the Hipparcos catalog, we have chosen 1709 stars across the main sequence and some giant stars in equal nearly measure.
- Proximity to the Earth is prioritized
- Such a broad sample of stars reduces bias in target selection

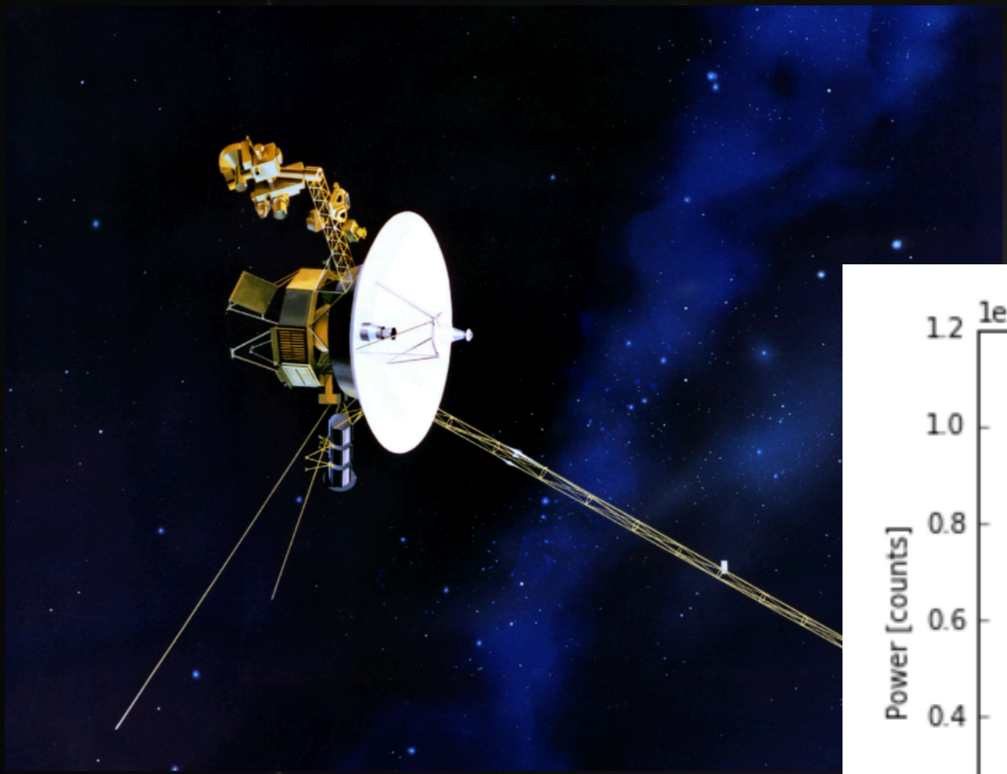


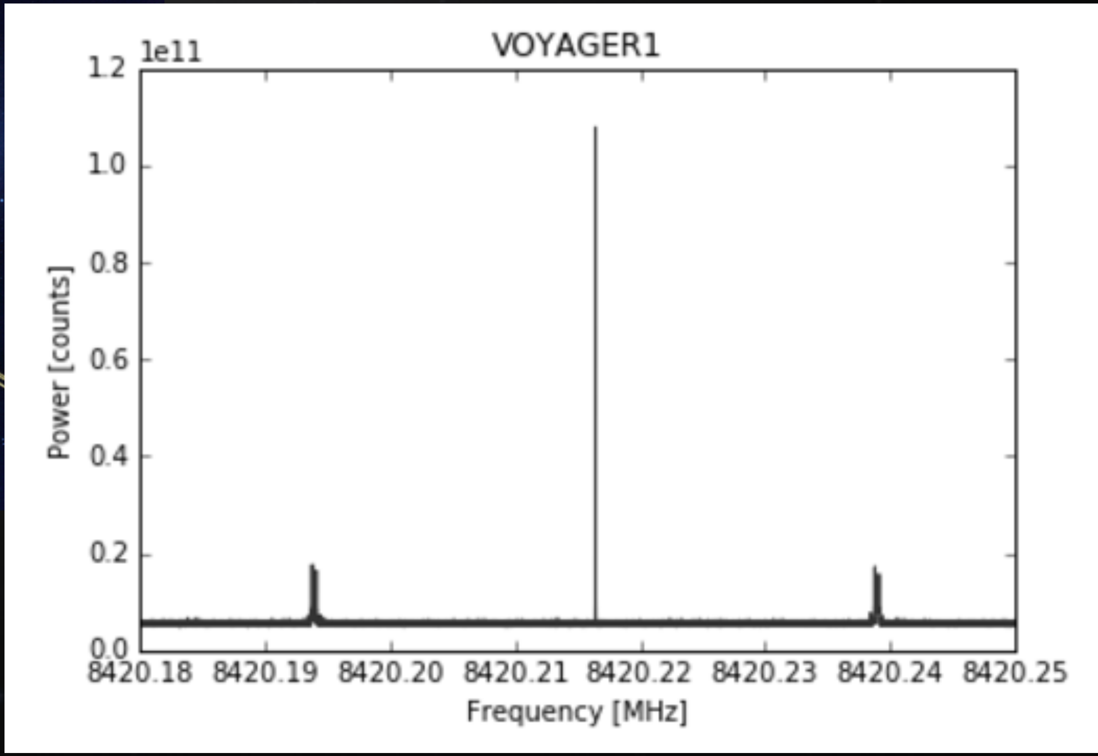
Morphologically Complete Sample of the Nearest Galaxies

- Our initial list of 123 galaxies consists of 40 spirals, 40 ellipticals, 20 dwarf spheroidal and 20 irregular galaxies.
- NEARGALCAT and Djorgovski & Davis provide a complete list of galaxies within 11 Mpc and 85 elliptical galaxies to choose from.



What are we looking for?





A Test case

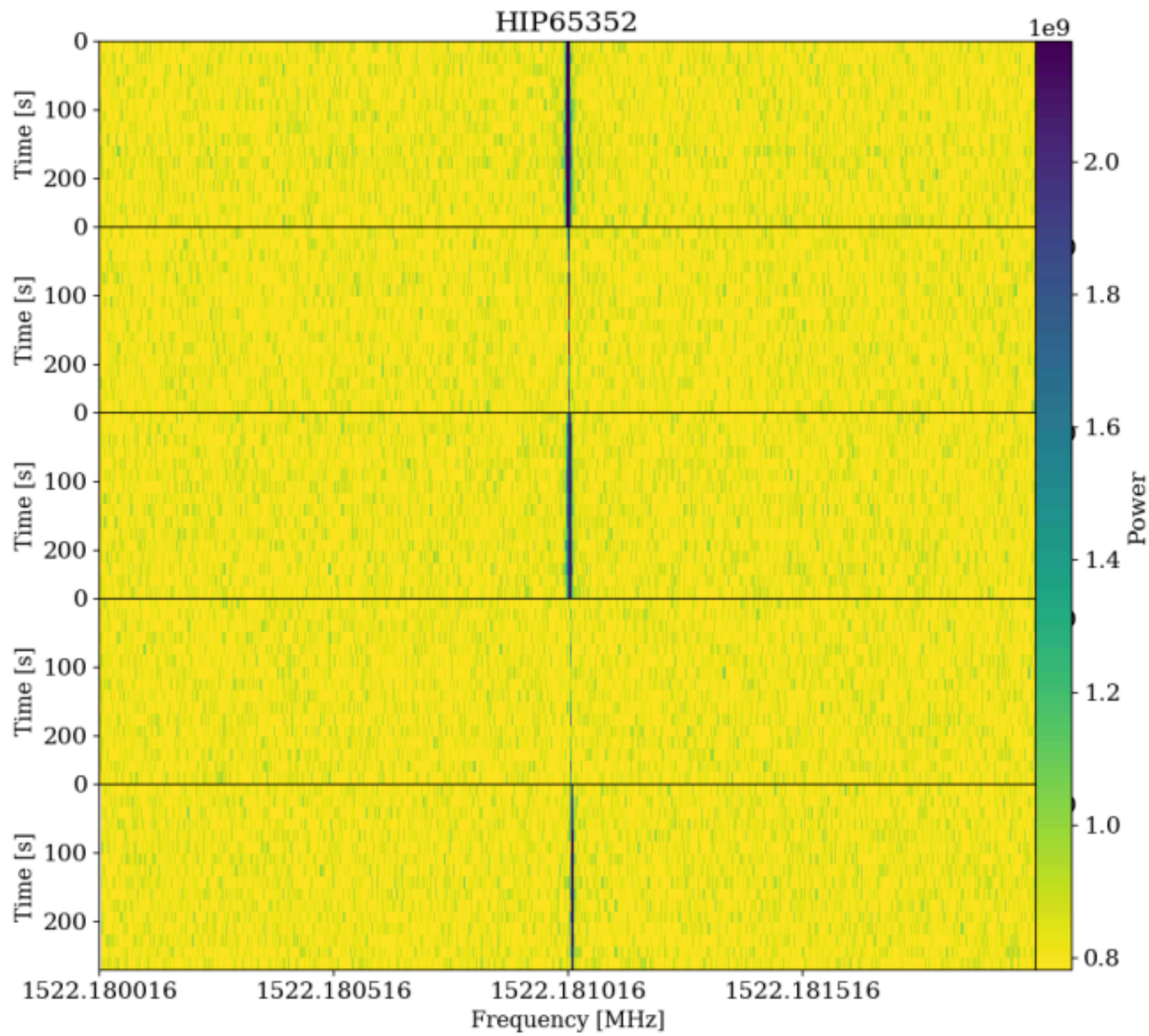


Figure 4. Series of 5 min "ON-OFF" observations of HIP65352 as described in Figure 1. This was reported as a significant event as the weaker signal in the "OFF" observation was not detected by the pipeline.

Enriquez 2017

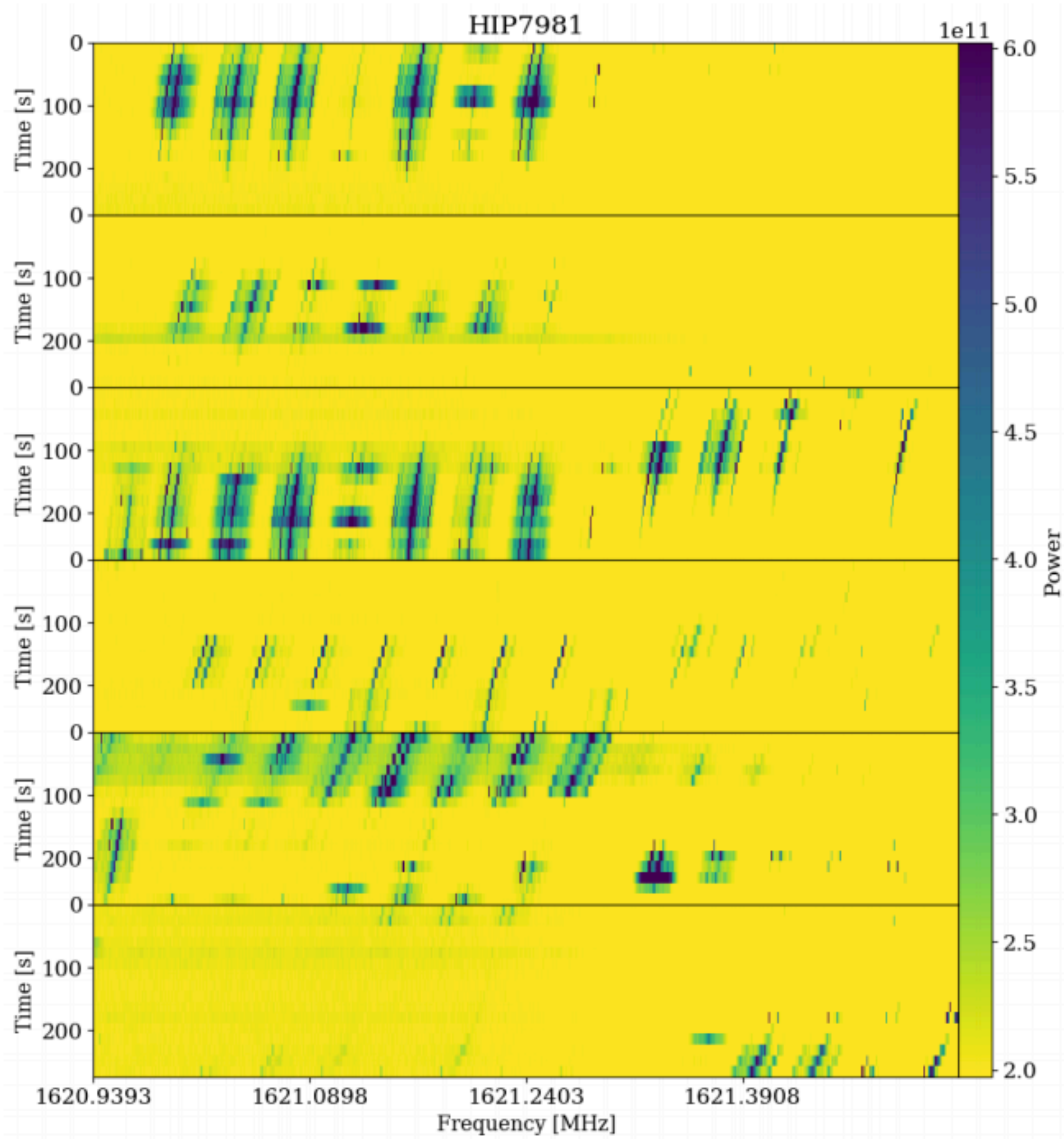


Figure 5. Series of 5 min "ON-OFF" observations of HIP7981 as described on Figure 1. The complex structure appears in both "ON" and "OFF" observations.

Enriquez 2017

MeerKat, a pre-cursor the Square Kilometer Array

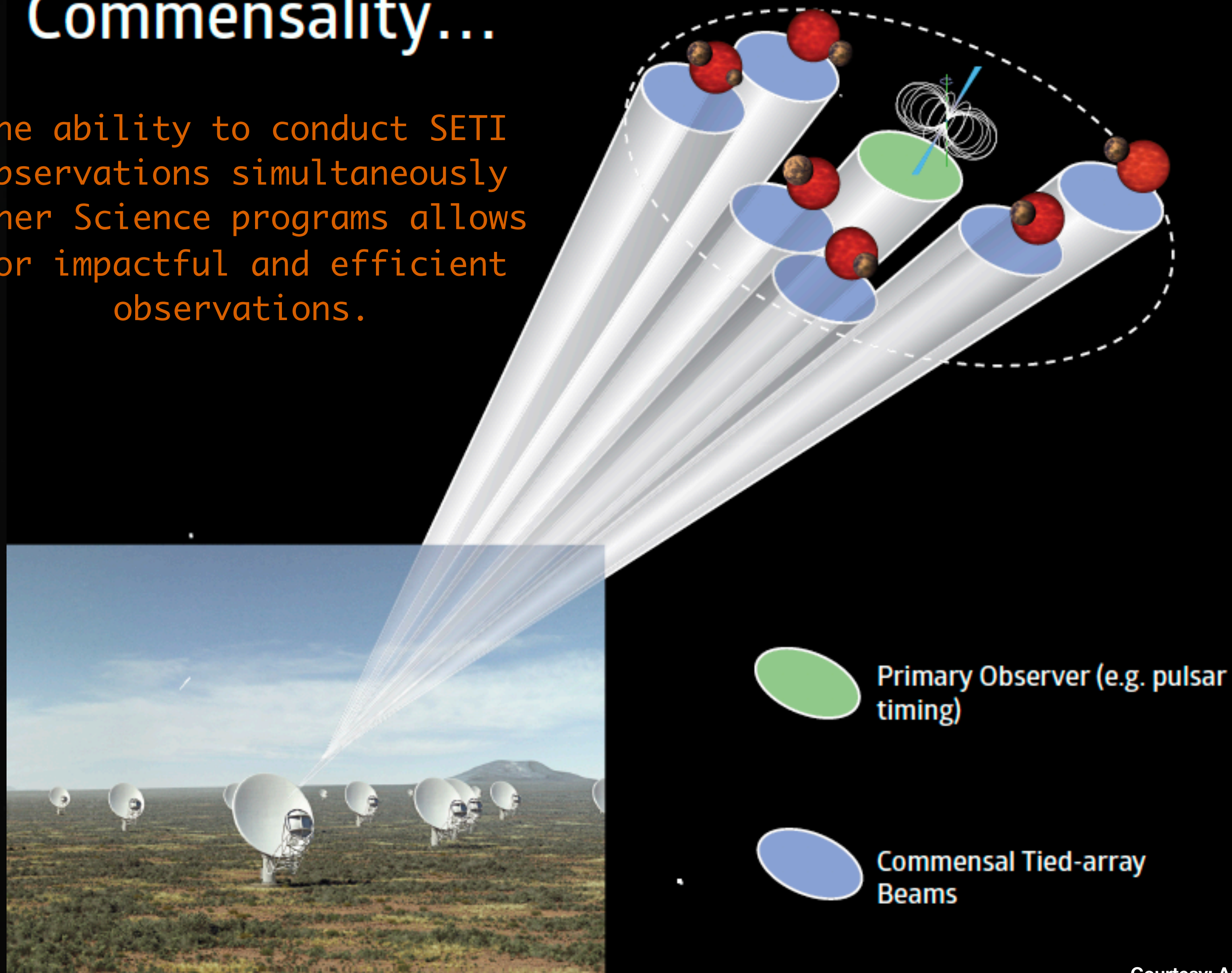
- Will be 64 dishes
- Each dish is 13.5 m
- Maximum Baseline: 8 km

Courtesey of SKA -South Africa

"Cradle of Life" initiative will include our SETI work as well as HZ studies

Commensality...

The ability to conduct SETI observations simultaneously other Science programs allows for impactful and efficient observations.



Courtesy: Andrew Siemion

The Search Continues…Breakthrough Listen offers unprecedented sensitivity in the Search for Intelligent Life beyond the Earth.

We will search a broader wavelength range and larger solid angle on the sky than ever.

We will use cutting edge signal processing tools including Machine Learning.

We will attempt to answer one of the most profound questions that humanity can ask.

Food for Thought

Before we knew where to look for exoplanets, we found none. Once we found the right place to look, they were everywhere.

Could the same be true about extra terrestrial intelligence, life within the solar system and life beyond it?

What are the chances of finding:

Electromagnetic signals from beyond the Earth?

Evidence of life on Io or Enceledeus?

Biosignatures on Earth-like planets around other stars?

In your opinion, is it worth it to spend money on projects like

Breakthrough Listen
Breakthrough Starshot
The Search for Biosignatures