The Quest for Other Worlds Like Earth - The Kepler Mission

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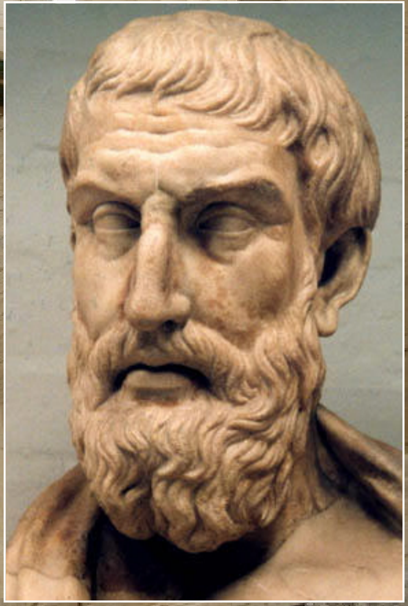
Speculation on the existence of other habitable worlds is age-old

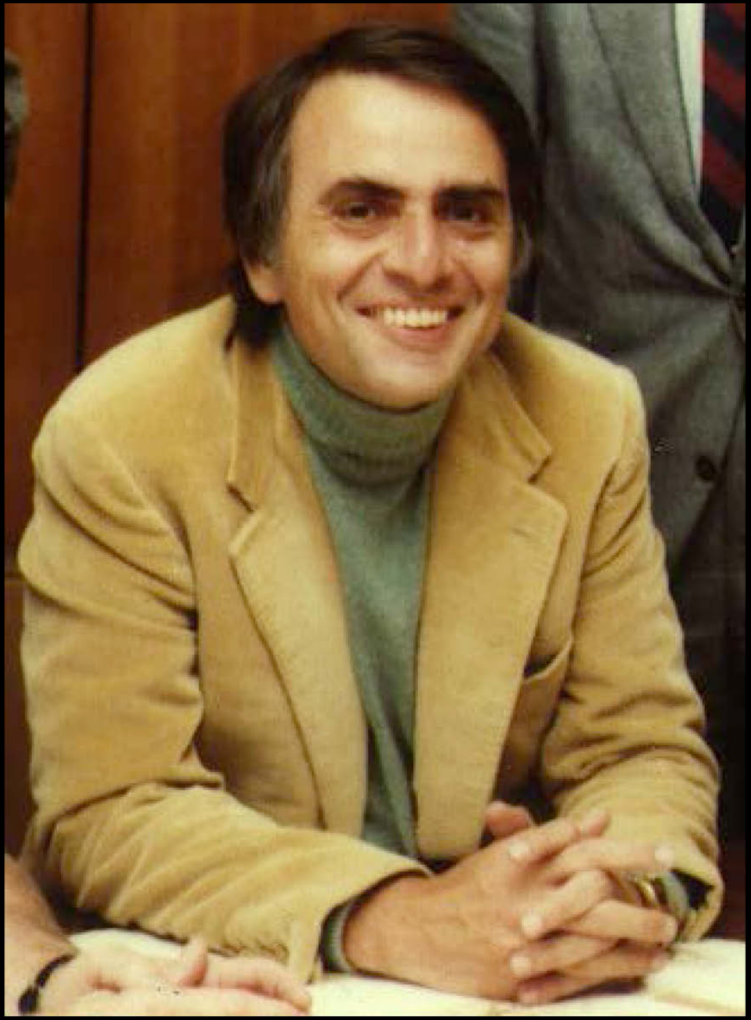
There are infinite worlds both like and unlike this world of ours ... we must believe that in all worlds there are living creatures and plants and other things we see in this world....

Epicurus (341-270 BC)



And modern …

- "There are perhaps as many as ten billion trillion [planets]. In the face of such overpowering numbers, what is the likelihood that only one ordinary star, the Sun, is accompanied by an inhabited planet?"
- "Why should we, tucked away in some forgotten corner of the Cosmos, be so fortunate? To me, it seems far more likely that the universe is brimming over with life."



Carl Sagan - Cosmos (1980)

There are 200 billion stars in our galaxy…

There ought to be some other Earths.

How do we look for them?

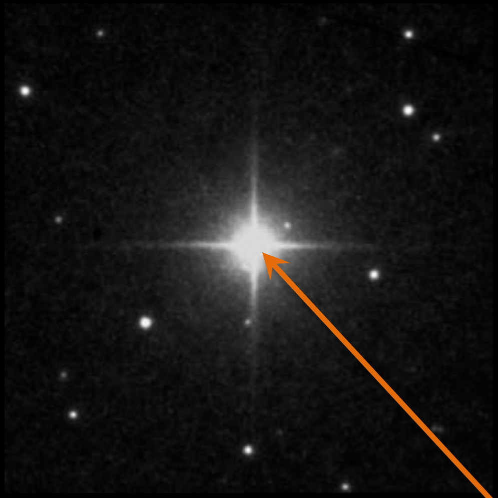
Take their pictures?

Problem: Stars are far away and REALLY bright.
Planets are dim and close to their star.

Taking pictures of extrasolar planets is hard.

Even then can't see close in ones like Earth.

What about other ways?



Solar type star
24 Sextans

2 known planets

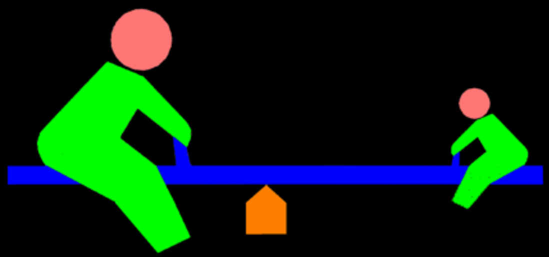
About the same distance as Mars and Jupiter from our Sun

Planets Move Stars

Planets and stars orbit each other, both circling their common center of gravity.

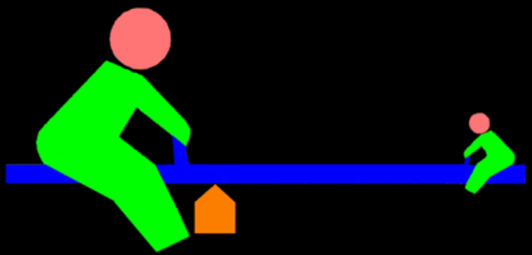
Larger planets pull the center of gravity farther from the star and make the star move in a larger orbit

Like kids on a see-saw:



Big kid (star) sits farther from balance point with medium size partner (planet).

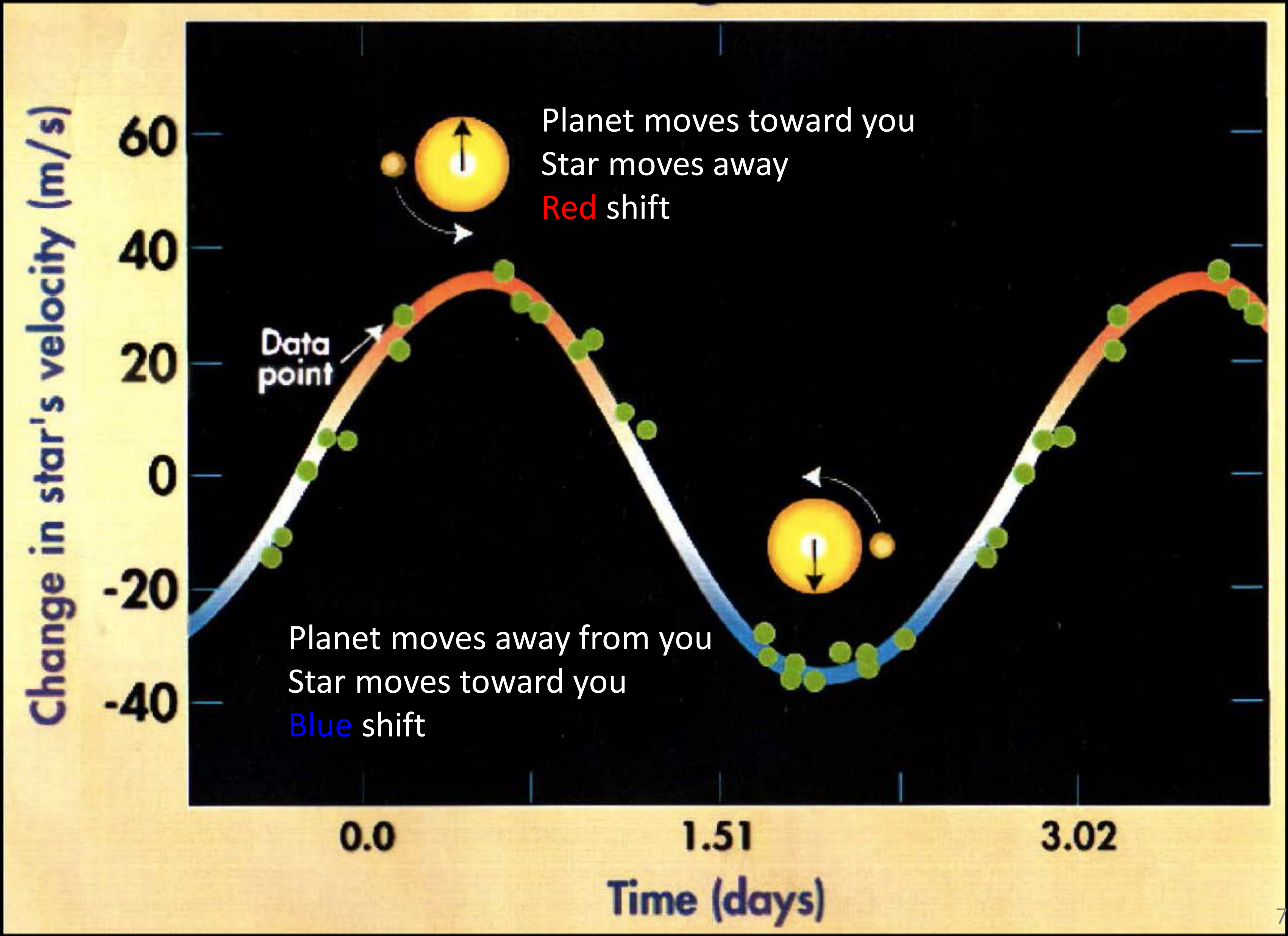
Moves more



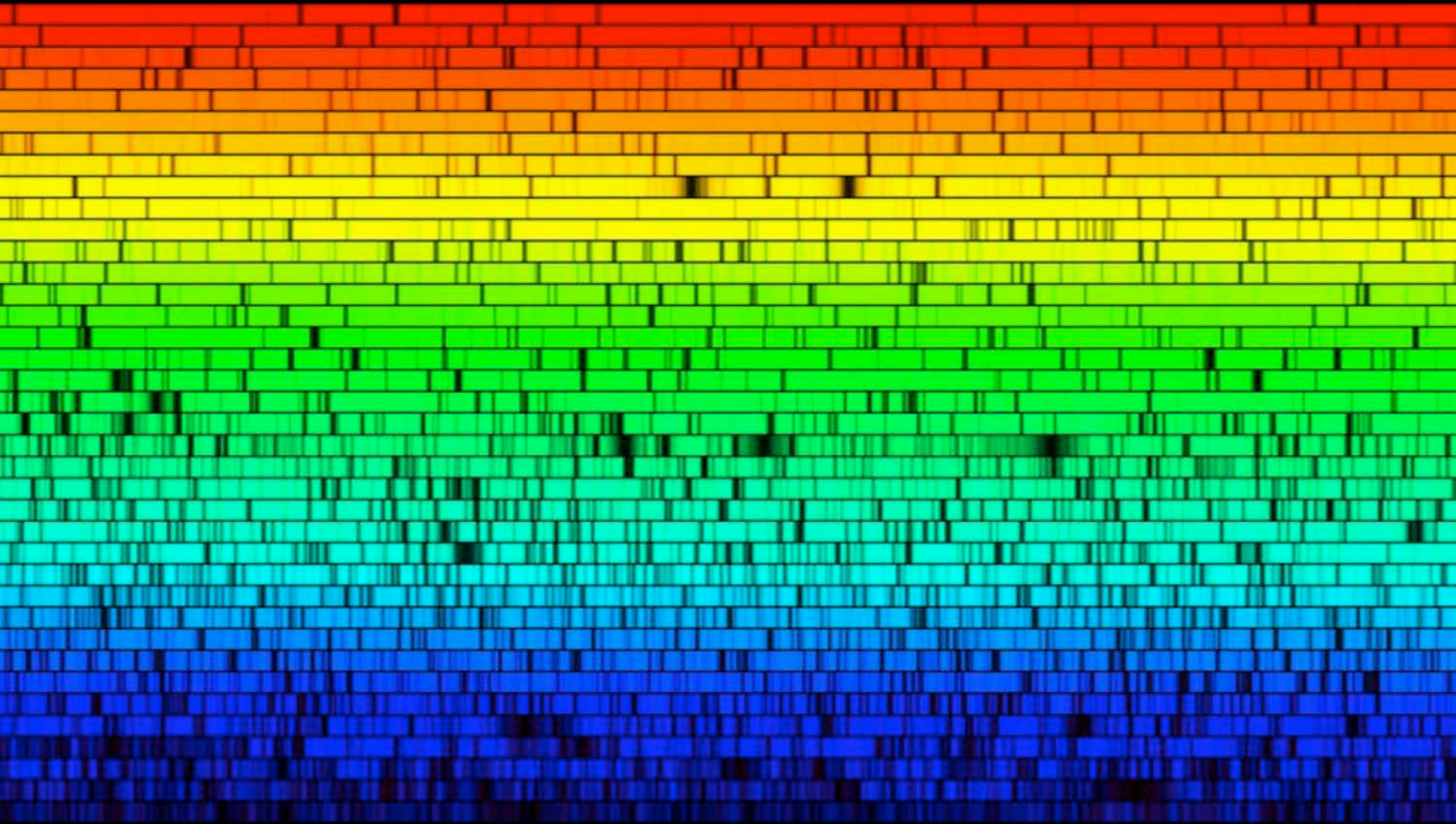
Big kid (star) sits closer to balance point with small size partner (planet).

Moves less

We See this Motion in the Star's Spectrum



Stellar Spectrum



Radial Velocity measurement can find planet's MASS

- And distance from its star but not its size

RV measurements good for finding large planets

- Also Earth-size around small, cool stars
- Not good enough to find Earths around Sun-like stars

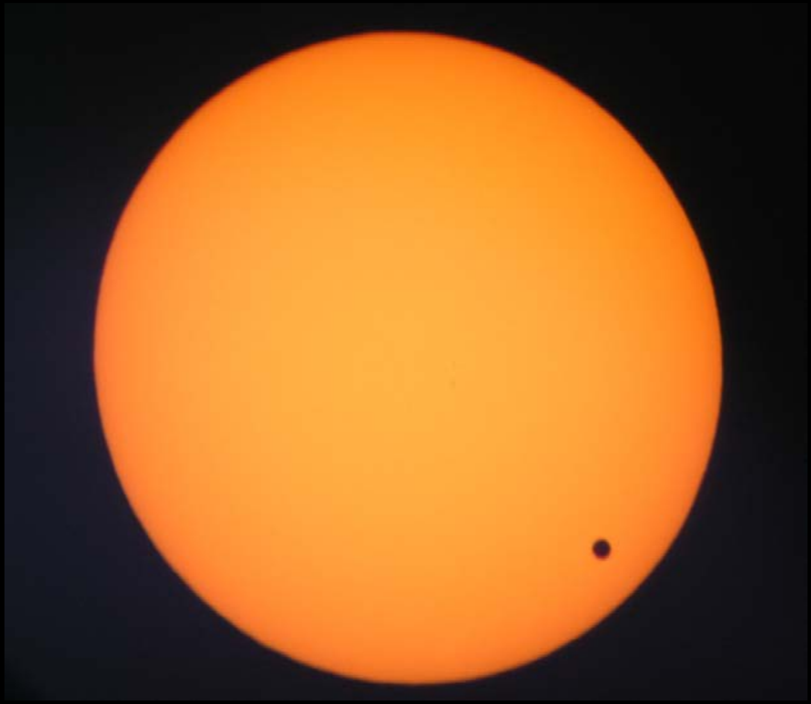
Also too slow.

- Can only do 1 star at a time.
- Need many measurements totaling, maybe, hundreds, of hours

Need another way to find Earths.

- But remember the RV method. It's important later.

Planets Cast Shadows



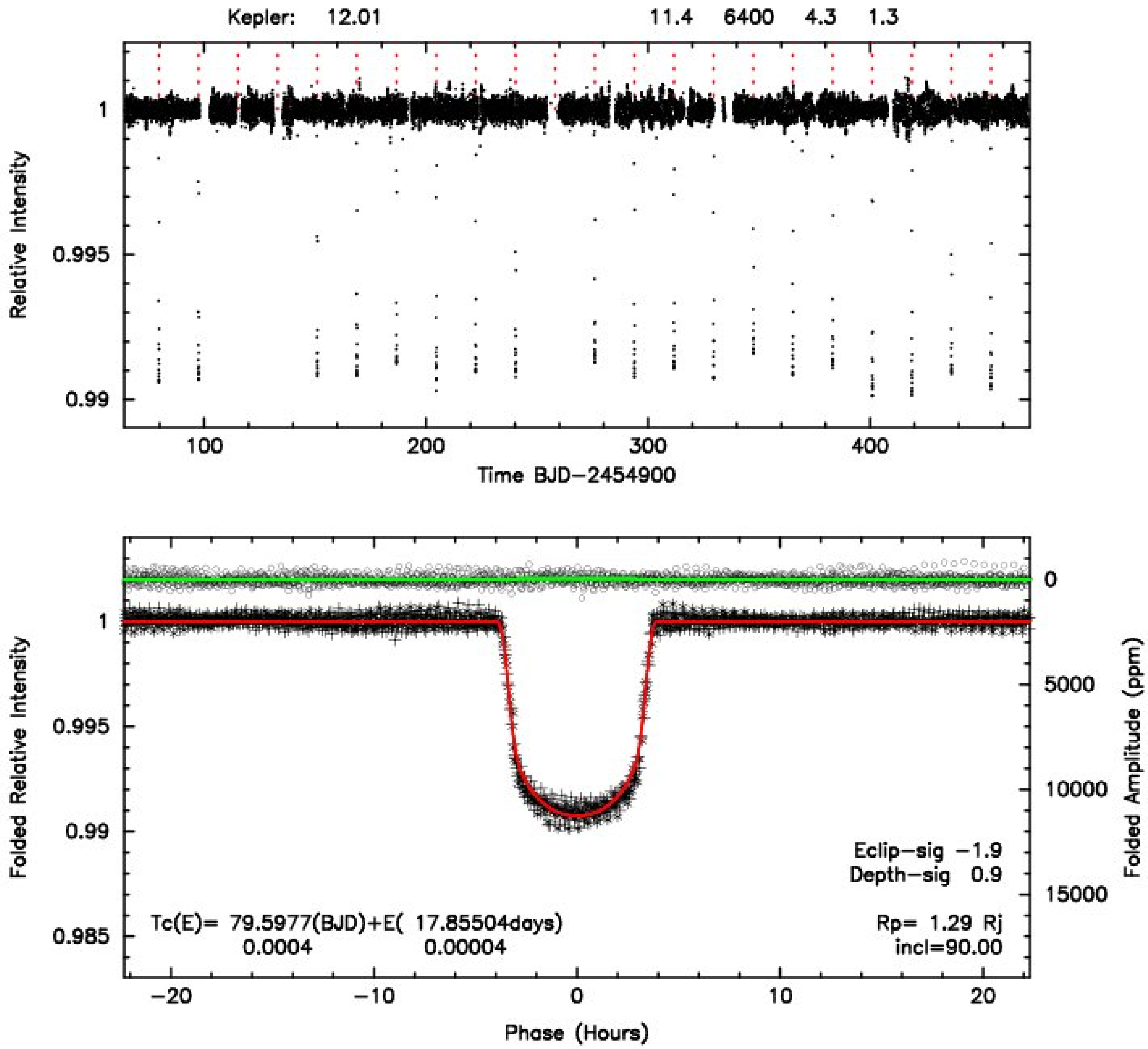
Planetary Transits

Sometimes a planet's orbit takes it in front of its star as seen from Earth.

For a few hours each orbit, it blocks a small amount of the star and making the star appear dimmer.

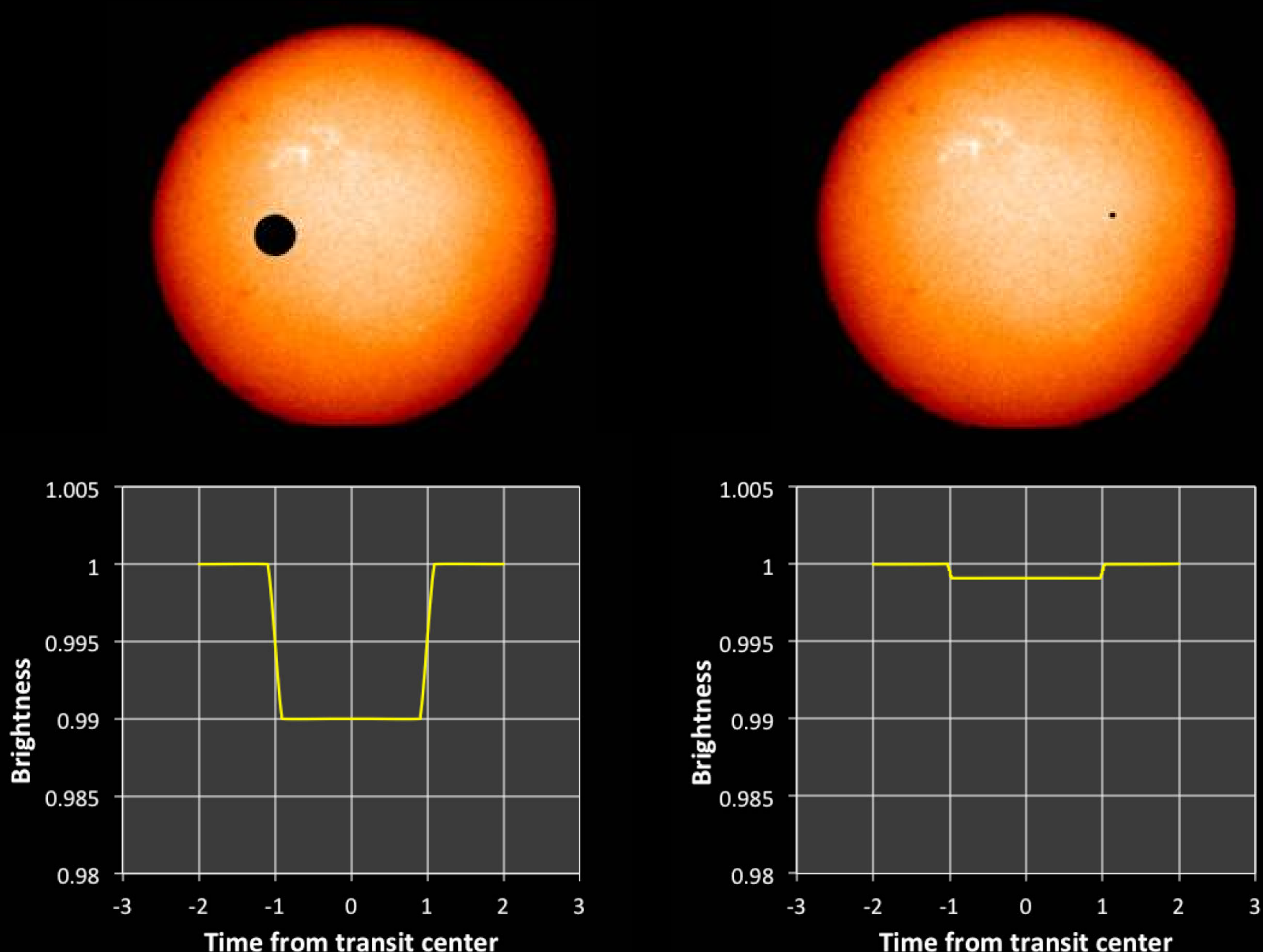
Transit measurements can find the size of the planet and distance from its star but not its mass.

Transit Photometry



Kepler: 12.01
11.4 6400 4.3 1.3
Relative Intensity
Time BJD−2454900
Folded Relative Intensity
Folded Amplitude (ppm)
Eclip−sig −1.9
Depth−sig 0.9
Tc(E)= 79.5977(BJD)+E(17.85504days)
0.0004 0.00004
Rp= 1.29 Rj
incl=90.00
Phase (Hours)

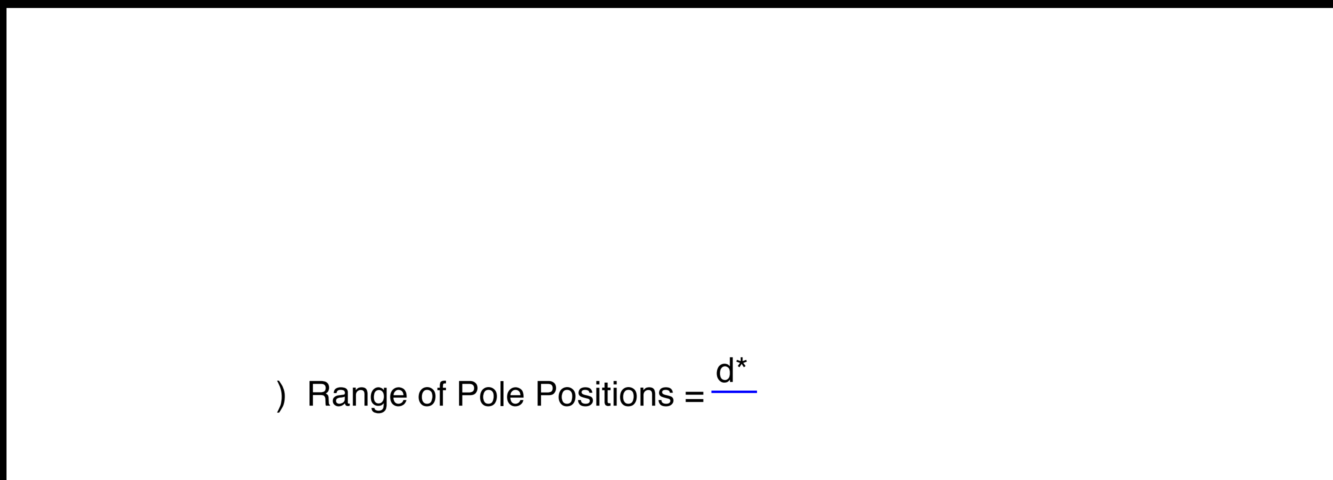
Transits Have Different Depths



Simulated light curves

Transits Won’t Find ALL Planets

Not all planetary orbits are aligned to produce a transit



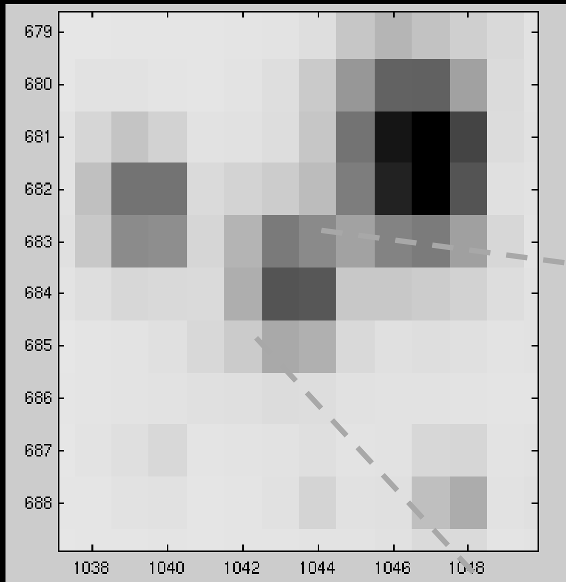
Only a few percent chance for a given planet to transit

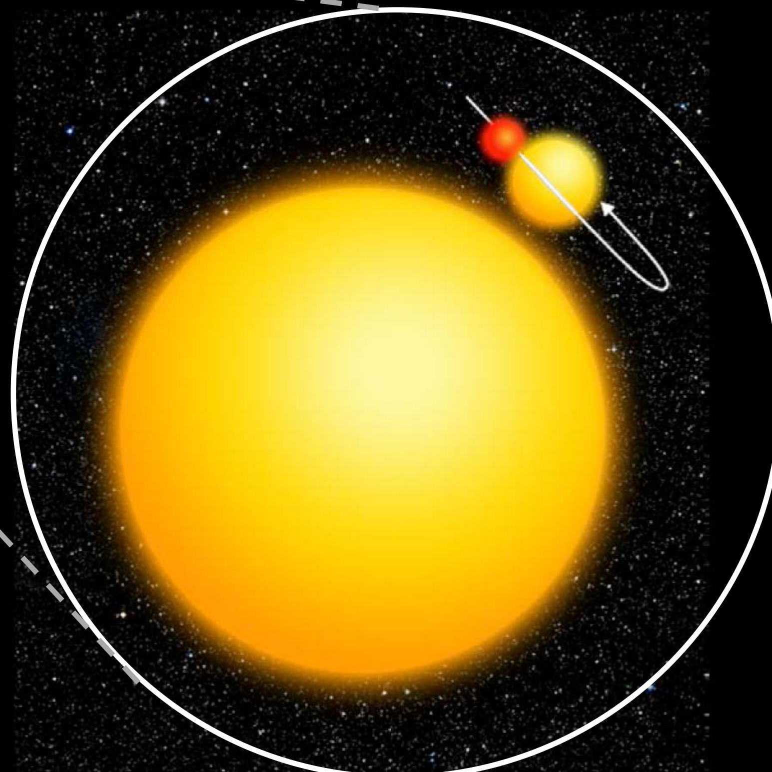
- Earth and Sun have only 0.5% chance

Transits last only a few hours each orbit

Must stare constantly at many thousands of stars to find many planets.

A pitfall: False Positives





Other things can look like transiting planets.

- Eclipsing binary stars behind target stars

Candidate transiting planets need to be carefully examined to look for false positives.

Ways to See Exoplanets

Star wobble (Radial Velocity) Mass, orbital period and shape: distance from star

Star dimming (Transit photometry) Size, orbital period: distance from star

With both mass and size get planet density. Then can tell if the planet is:

Gas : Low density

Ice : Medium density

Rock : High density

How do we know it when we find another Earth?

Perhaps a Habitable Planet?

- Right temperature
- Liquid water
- Atmosphere

Planets come is several types

Too big (about >10 M_{earth})

Holds onto light gases (Hydrogen and Helium) too well and turns into a gas giant. (Jupiter, Saturn, Uranus, Neptune)

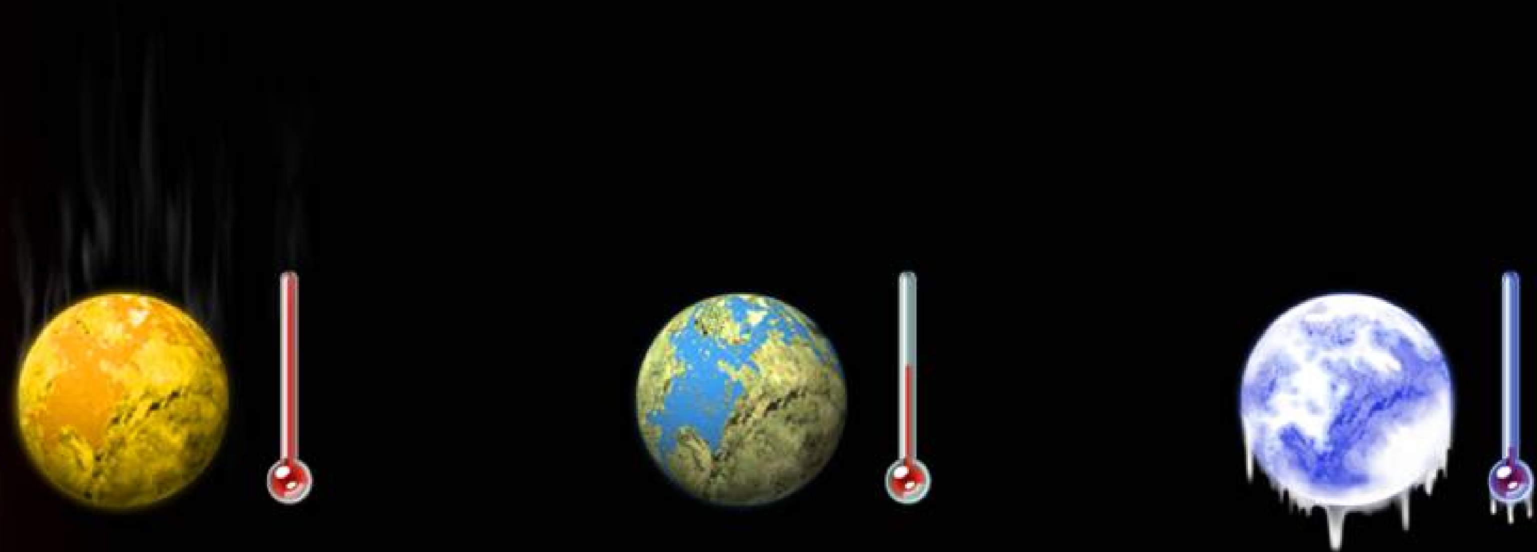
Just right (0.5 - 10 M_{earth})

Holds on to heavier gasses (Nitrogen, Oxygen) long enough to have a potentially habitable atmosphere (Earth, Venus)

Too small (about <0.5 M_{earth})

Can't hold onto a life sustaining atmosphere.
(Moon, Mercury)

And a range of temperatures



Too hot!

(too close)

Just right

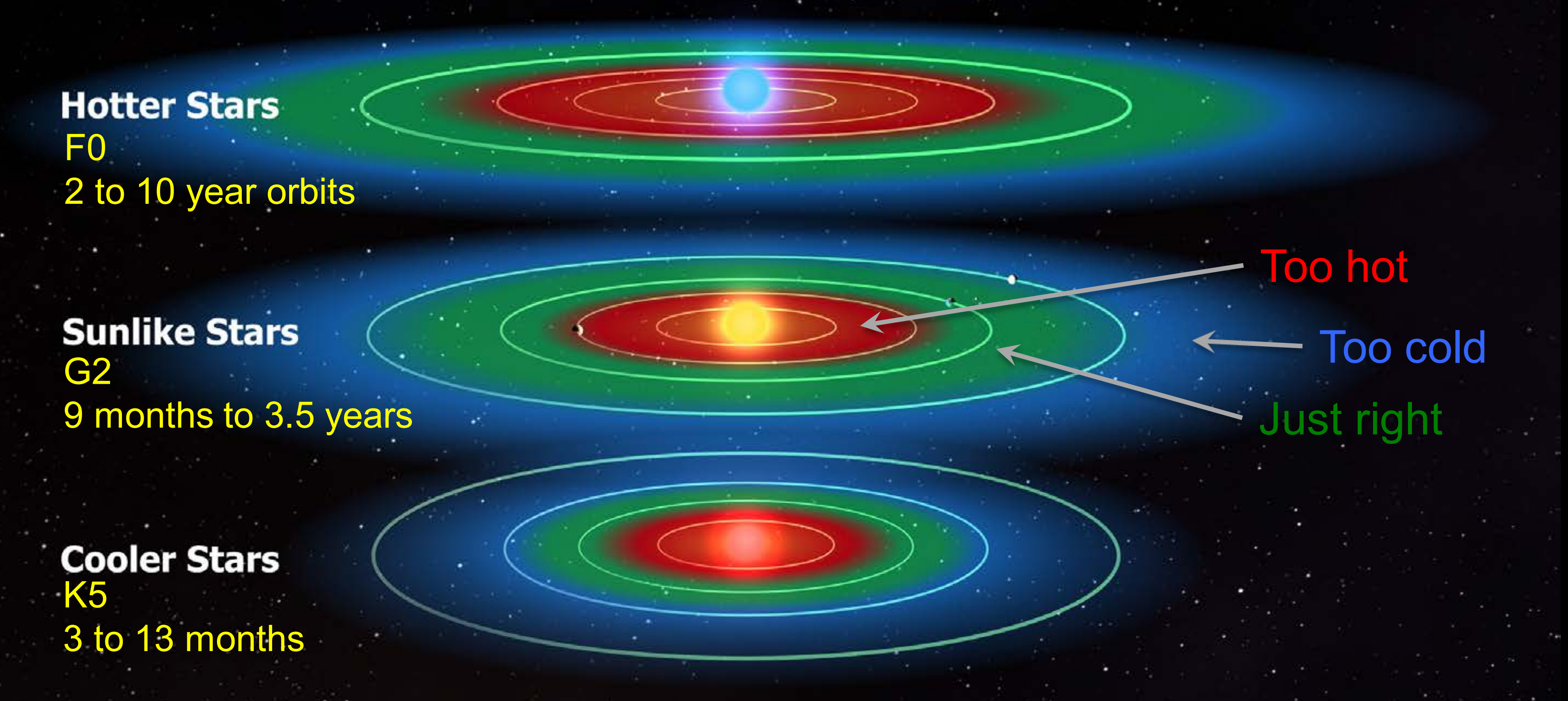
Too cold!

(too far)

The Habitable Zone

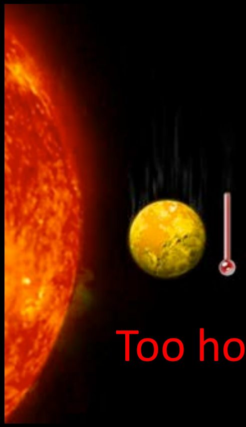
The region around a star where liquid water might exist on a planet's surface

The Goldilocks Zone



History of Exoplanet Discovery

- First surveys looked for wobble with RV
  - 1989: First exoplanet discovered
    - Very hot gas giant in close orbit around solar-like star



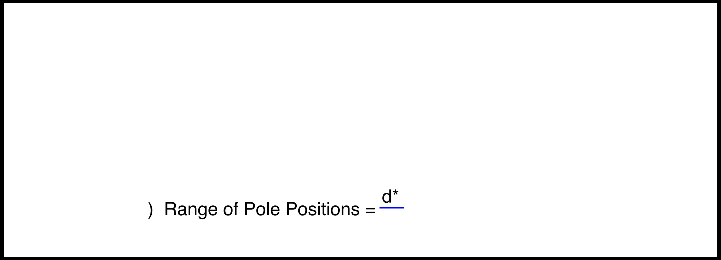
Too hot!

- Many more discoveries followed
  - More RV discoveries, ground based transit surveys, direct imaging, pulsar timing
  - By 2009: 332 exoplanets known, 61 with measured size and density
  - None like Earth. Mostly to big and too hot. Some too cold.

Why no Earths?

- Low sensitivity
  - RV wobble measurements not sensitive enough for low mass planets
  - Ground based transit surveys can’t see small enough planets

- Haven’t looked at enough stars
  - RV surveys are slow: one star at a time
  - Long periods required for habitable zones make planets hard to catch and make transit line-up probability low

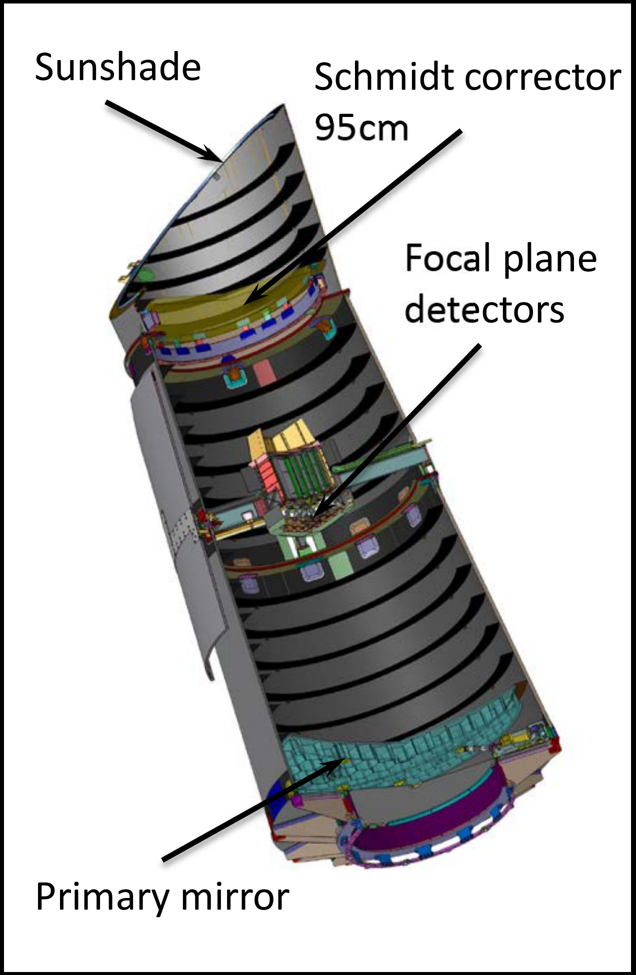


So, what to do?

Build a special transit detecting telescope with high sensitivity that can look at lots of stars at once –

Kepler

Kepler Telescope-Photometer



Wide field for lots of stars

15° diameter field

Monitor 150,000 stars at once

Big, to get enough light

95 cm aperture

Build it for use in space

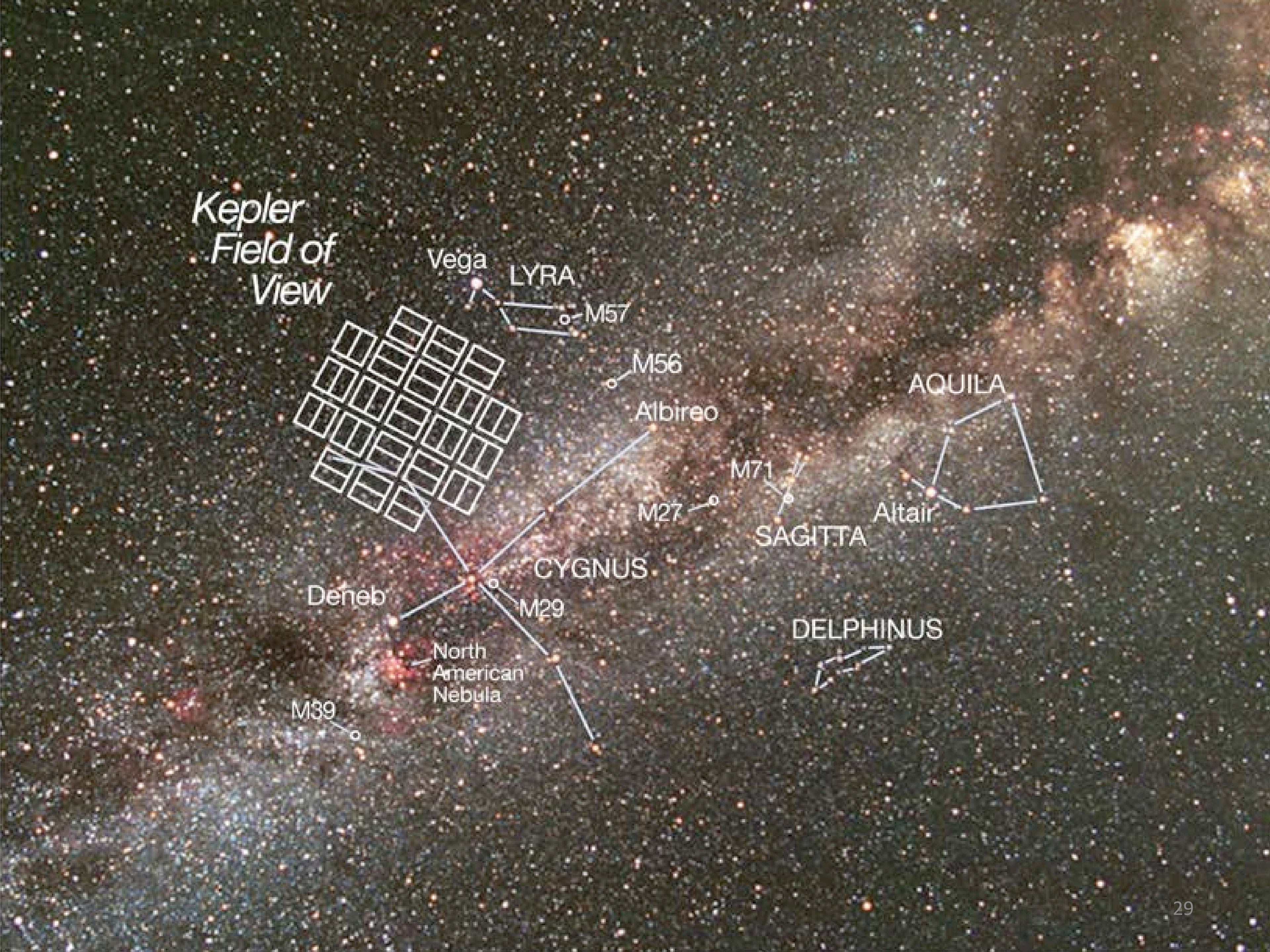
No variability from atmosphere to mask small transits

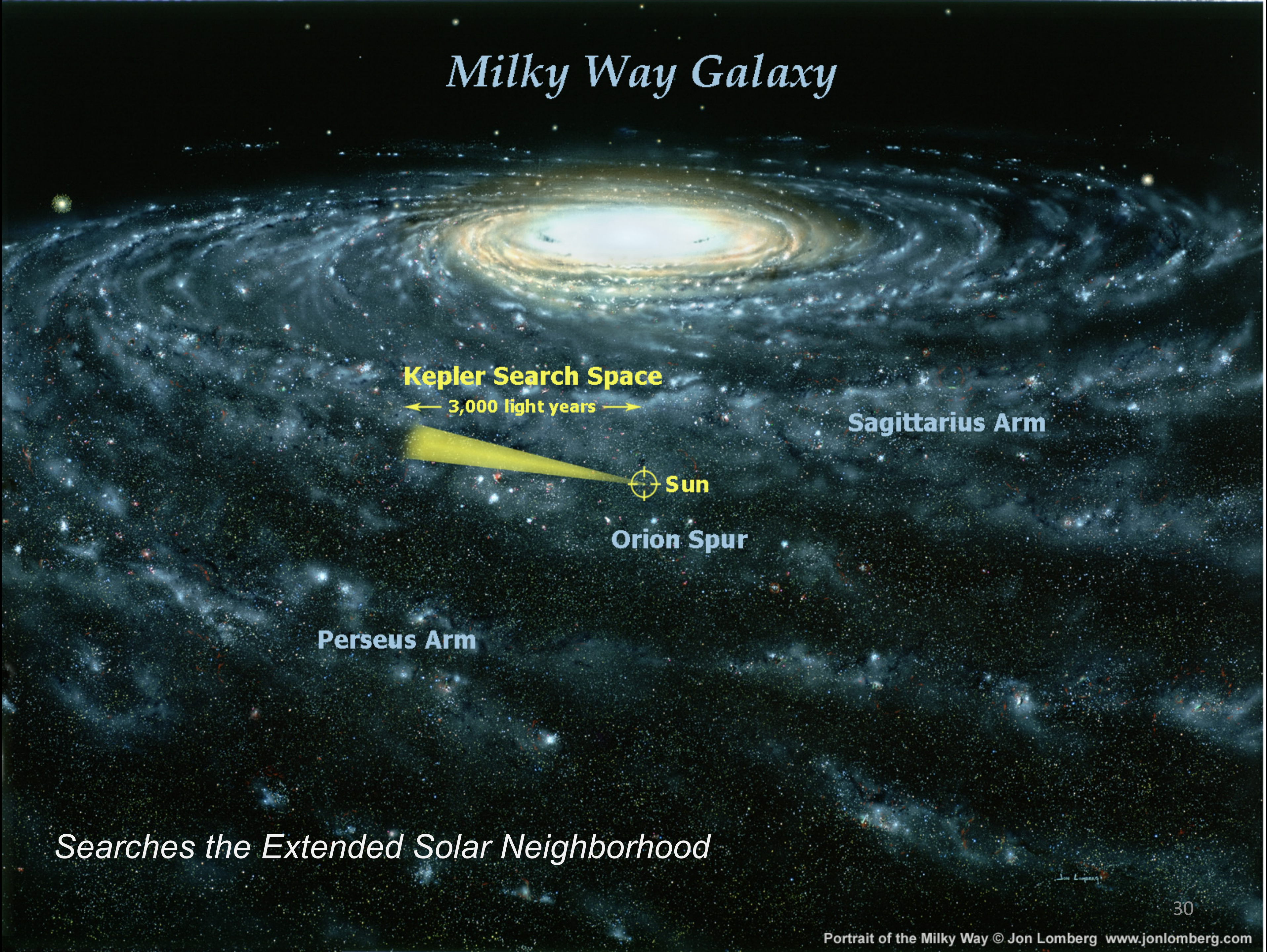
Kepler's 95 Megapixel Camera

>100 square degree field of view

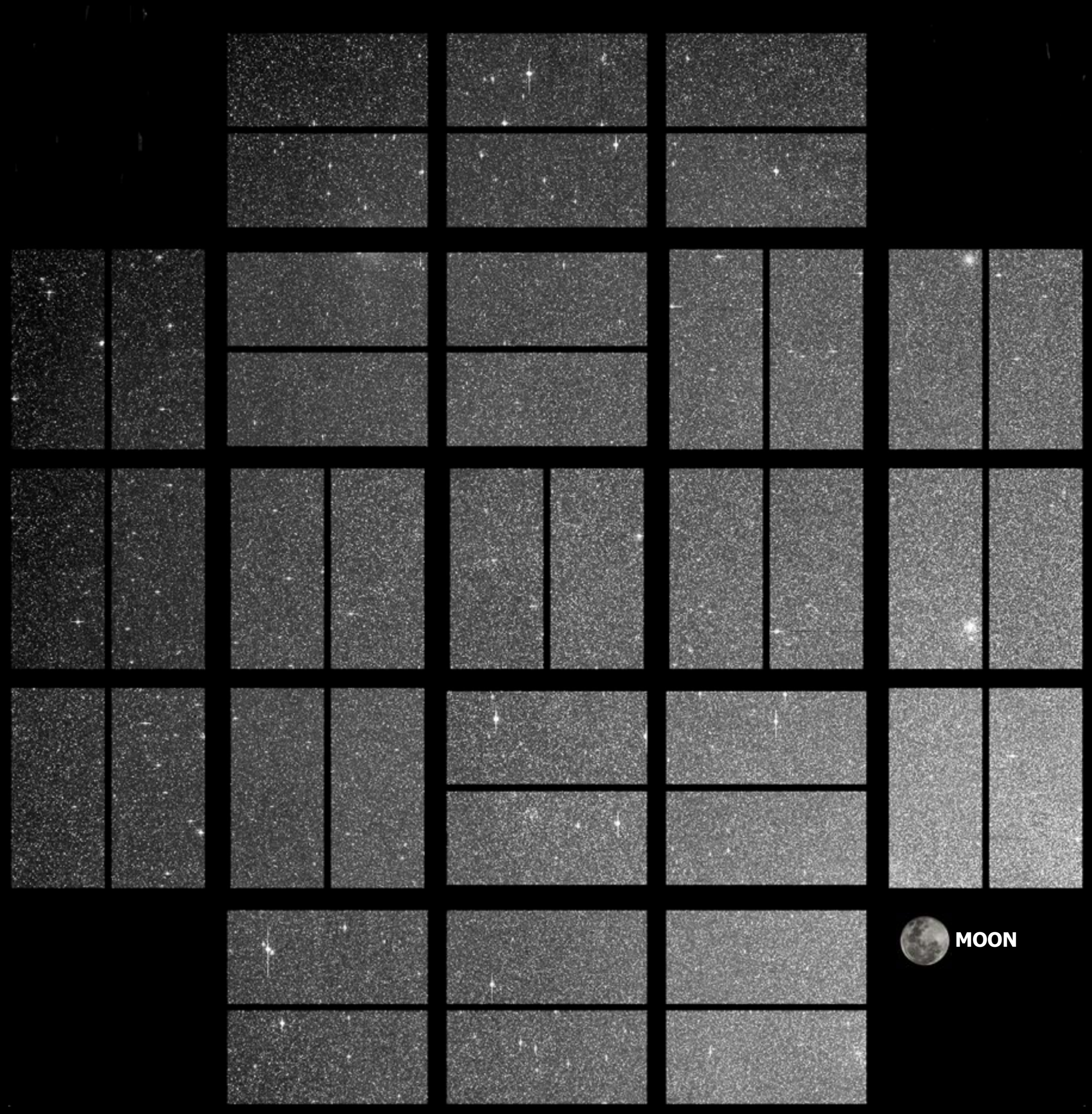
Kepler in final assembly

Kepler Launched March 6, 2009


Kepler Field of View
Vega
LYRA
M57
M56
Albireo
AQUILA
M71
M27
Altair
SAGITTA
CYGNUS
Deneb
M29
DELPHINUS
North American Nebula
M39


Milky Way Galaxy
Kepler Search Space
3,000 light years
Sagittarius Arm
Sun
Orion Spur
Perseus Arm
Searches the Extended Solar Neighborhood
Portrait of the Milky Way © Jon Lomberg www.jonlomberg.com

Kepler Full Field Image



What has Kepler found?

Yesterday 763 exoplanets were known. 70 of those from Kepler observations

Still no habitable zone Earth-size planets

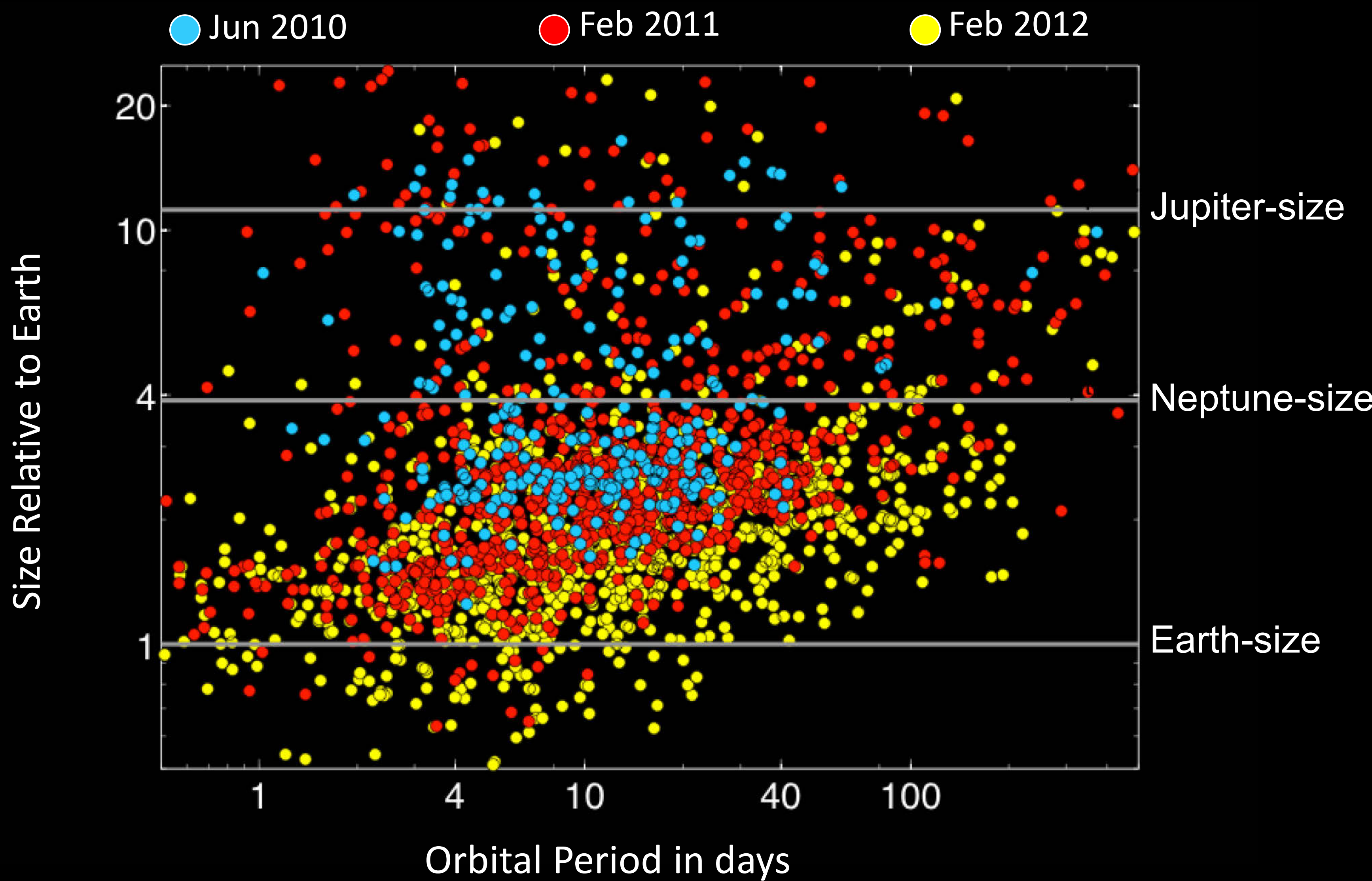
But, Kepler has found LOTS more planet candidates: Over 3000 with more coming

90% of candidates are expected to be real planets

Expect Kepler to announce ~800 new confirmed planets by fall.

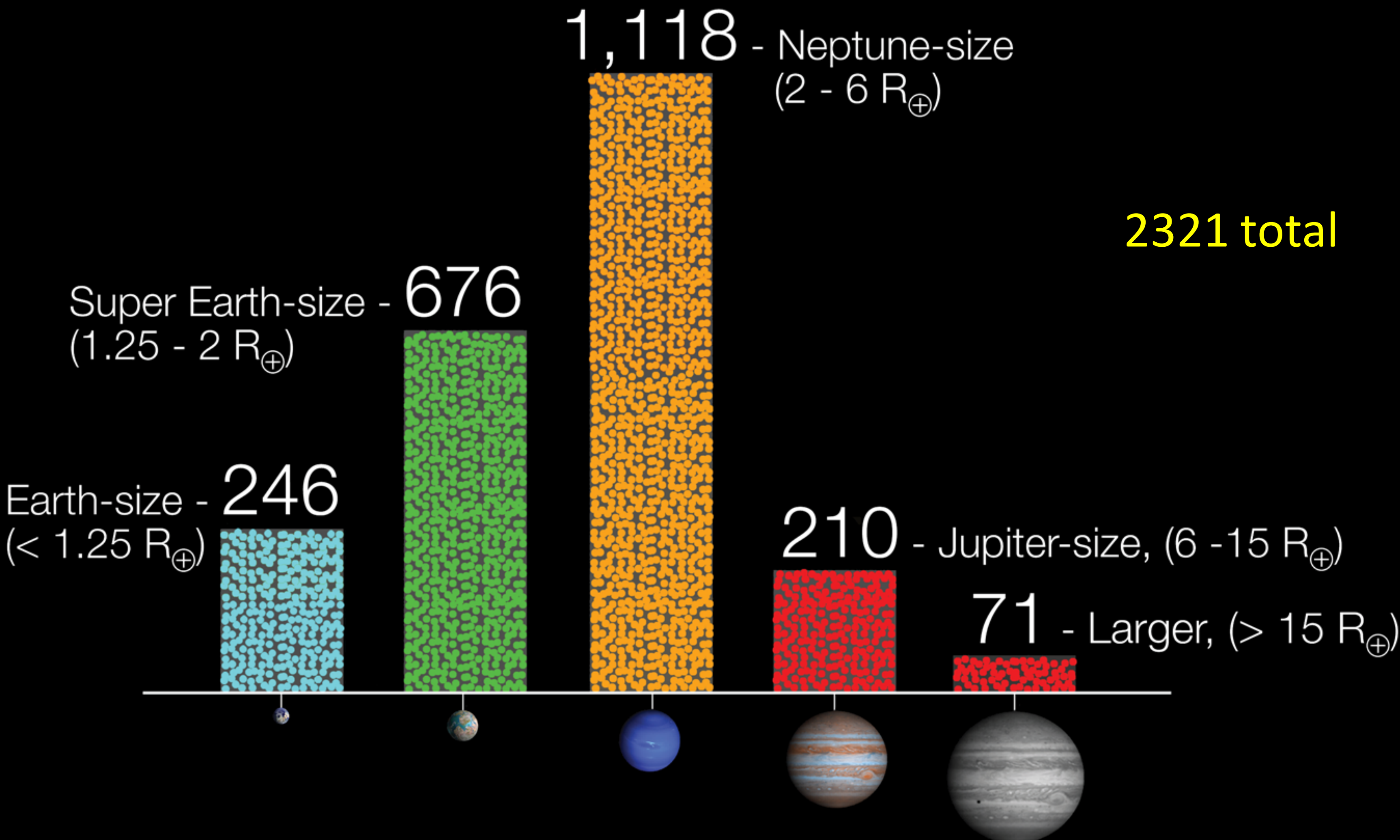
Candidates as of Feb 2012

2312 total



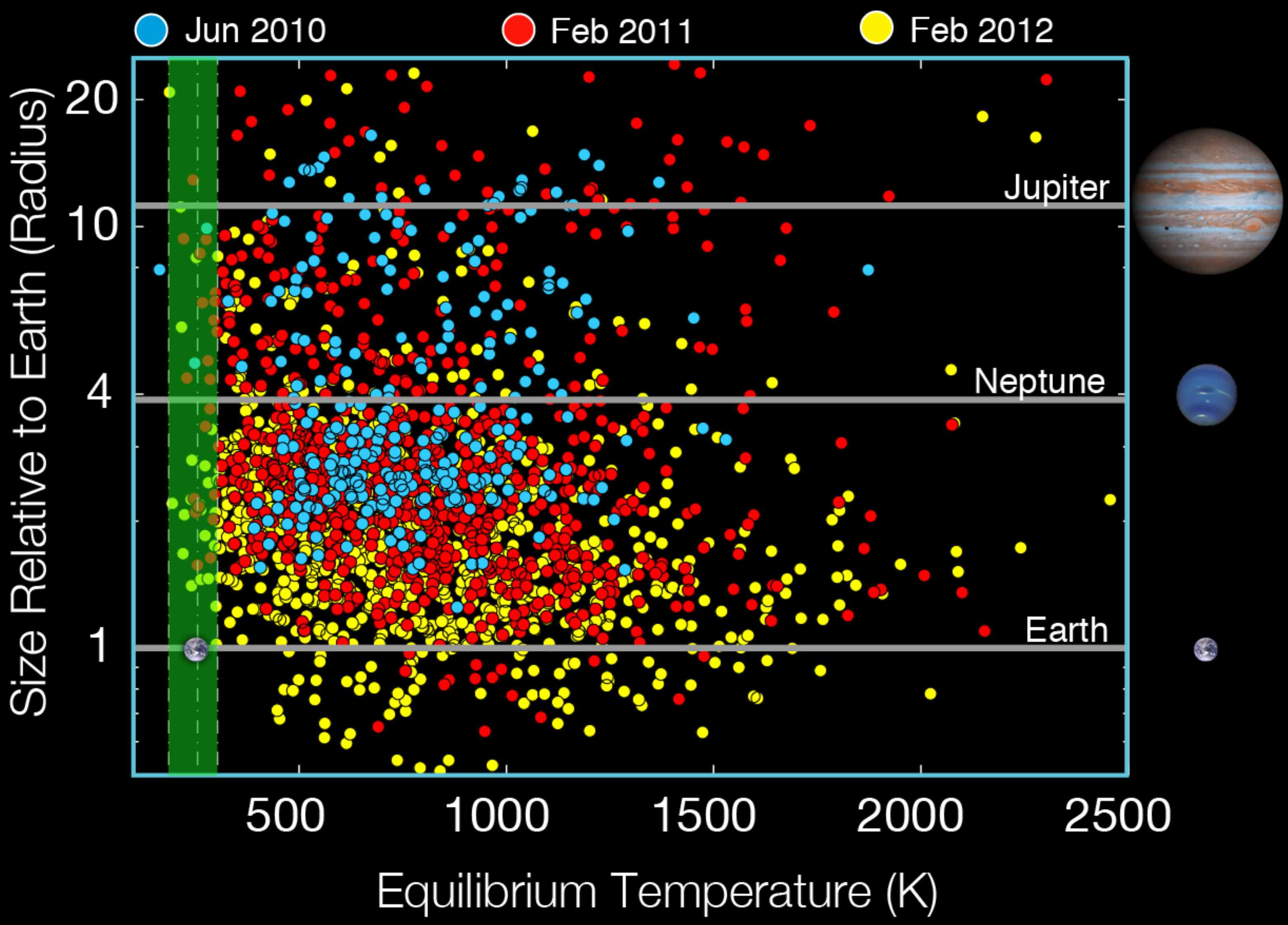
Numbers of Planet Candidates

As of February 27, 2012



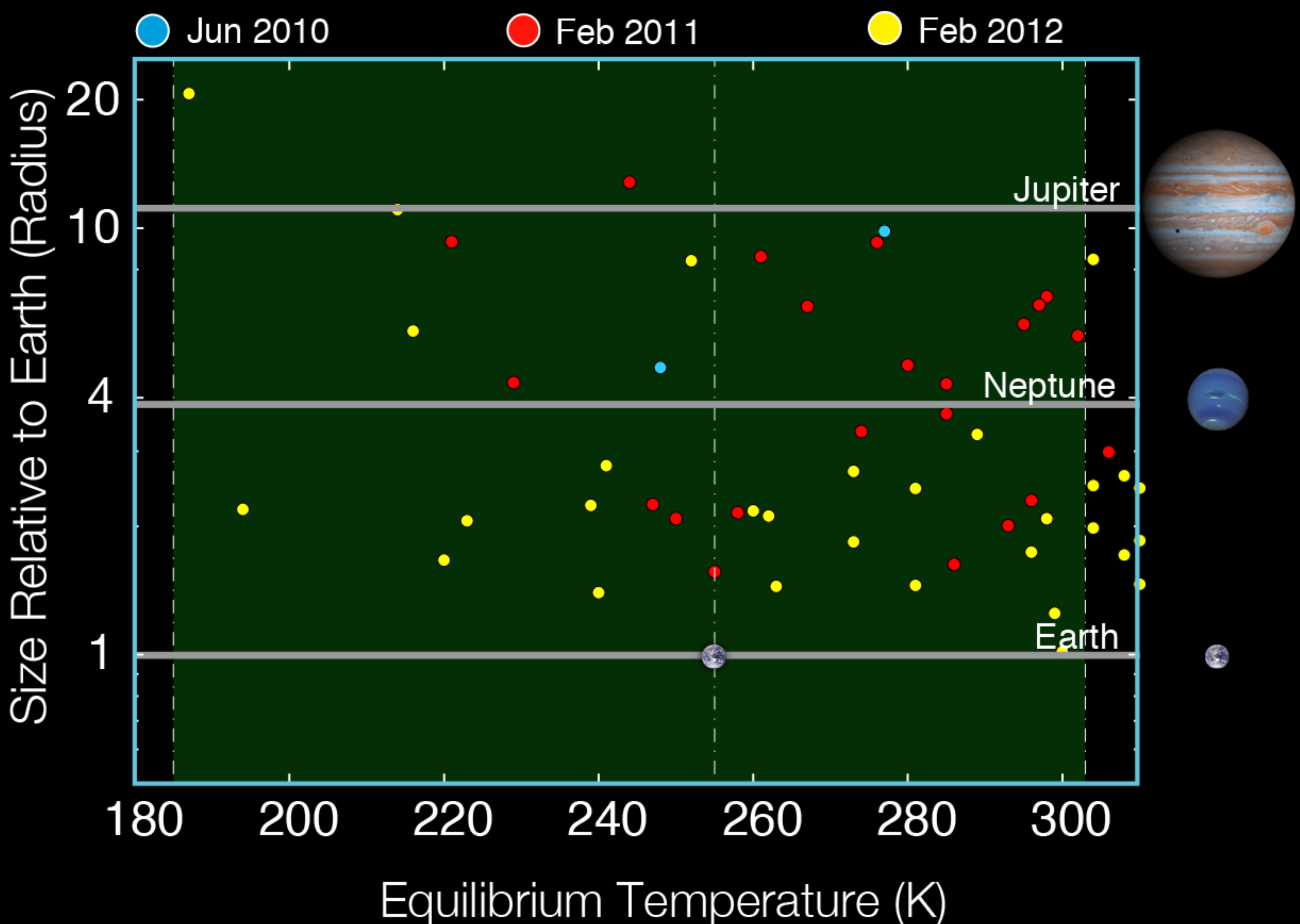
Candidates in the Habitable Zone

As of February 27, 2012



HZ Candidates

48 with T_{eq} between 185 and 303 K



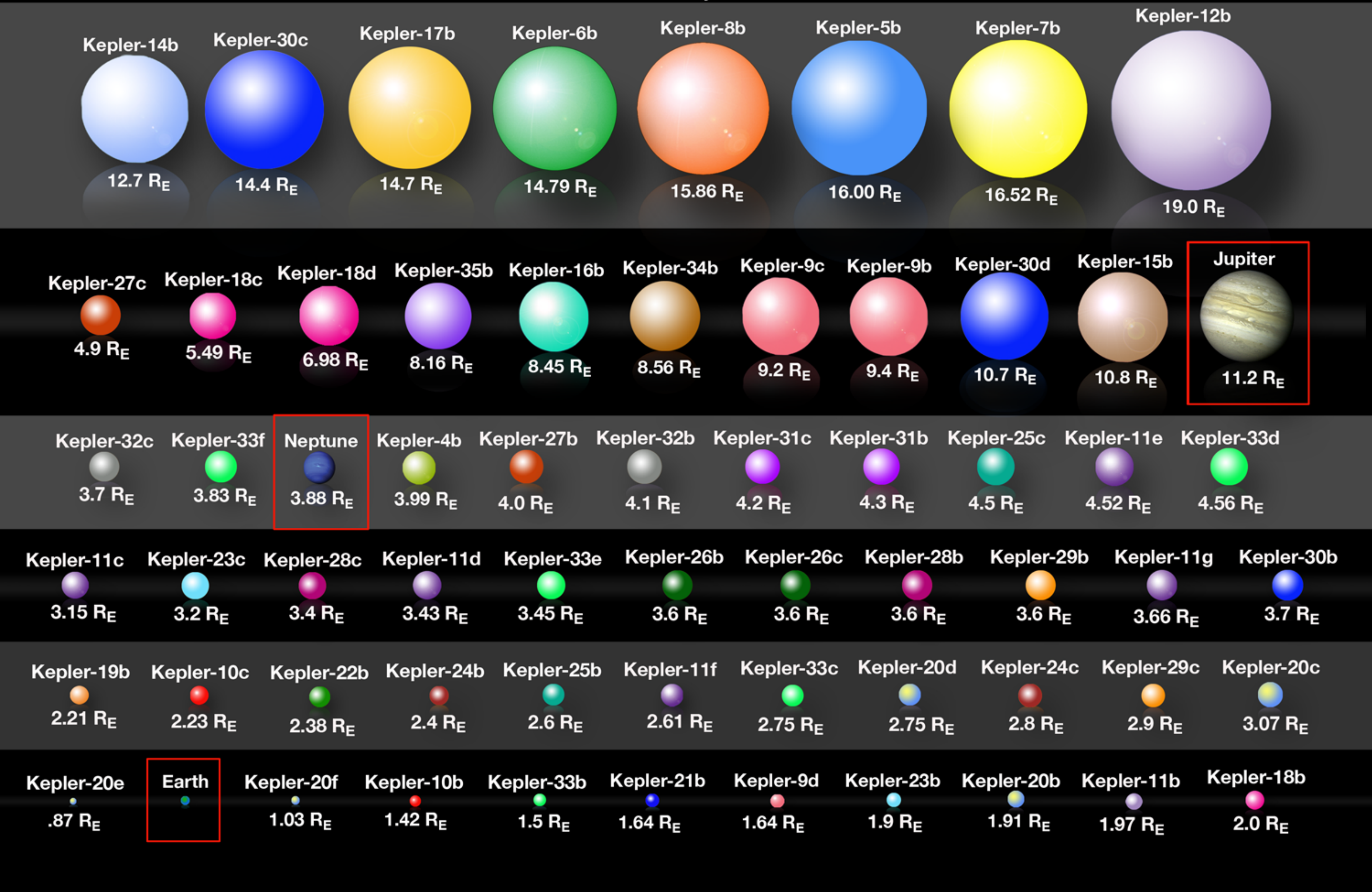
Earth: Our Reference Planet

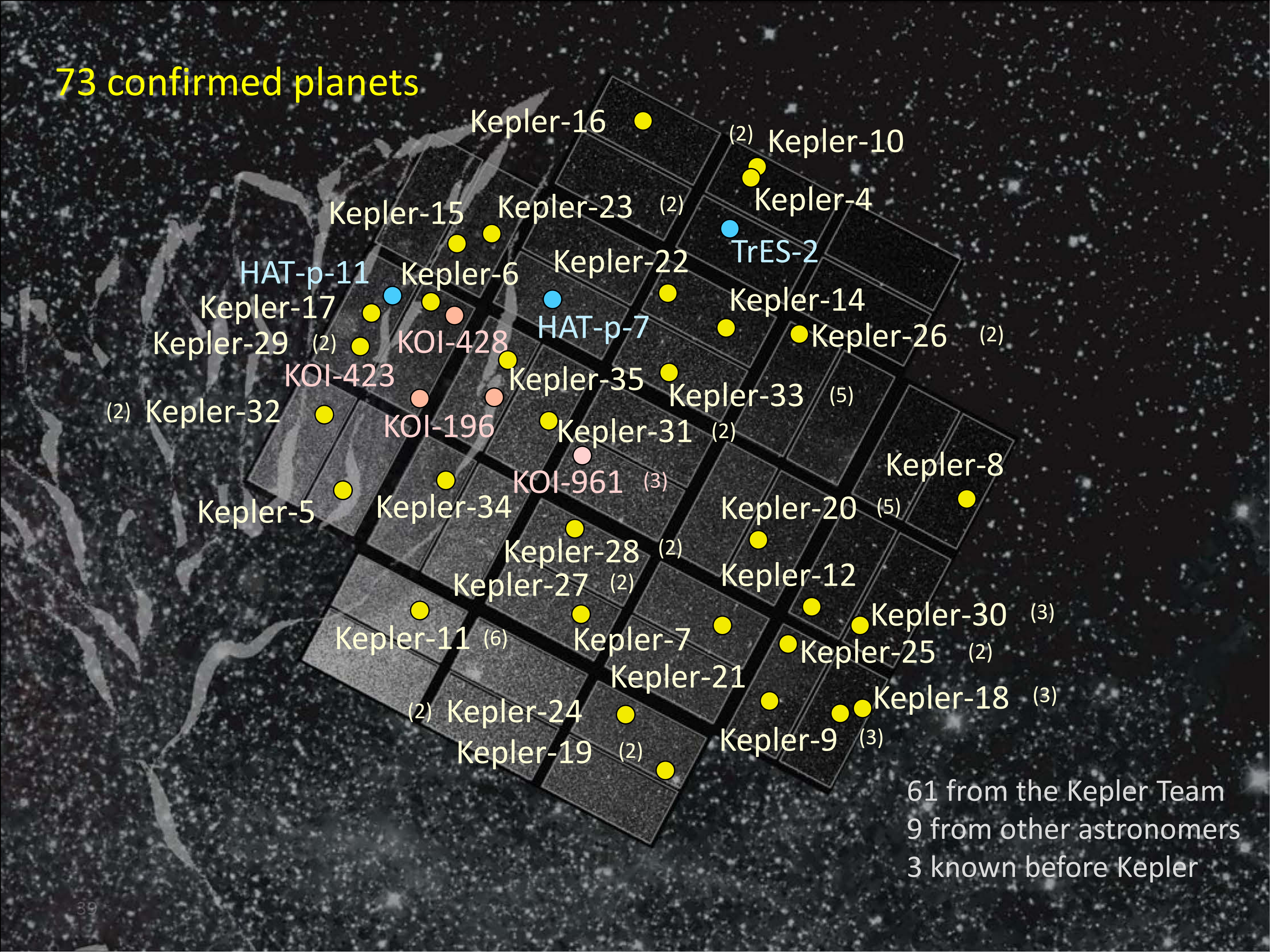
Known habitable

Size:	1.0 R_{Earth}
Density:	5.5 g/cm^2
Surface:	rocky/water
Atmosphere:	thin
Location:	habitable zone
Temperature:	57F (287K)

Kepler Planets

As of February 27, 2012





73 confirmed planets
Kepler-16
(2) Kepler-10
Kepler-4
Kepler-15
Kepler-23 (2)
TrES-2
HAT-p-11
Kepler-6
Kepler-22
Kepler-17
Kepler-14
Kepler-29 (2)
KOI-428
HAT-p-7
Kepler-26 (2)
KOI-423
Kepler-35
Kepler-33 (5)
(2) Kepler-32
KOI-196
Kepler-31 (2)
Kepler-8
KOI-961 (3)
Kepler-5
Kepler-34
Kepler-20 (5)
Kepler-28 (2)
Kepler-12
Kepler-27 (2)
Kepler-30 (3)
Kepler-11 (6)
Kepler-7
Kepler-25 (2)
Kepler-21
Kepler-18 (3)
(2) Kepler-24
Kepler-19 (2)
Kepler-9 (3)
61 from the Kepler Team
9 from other astronomers
3 known before Kepler

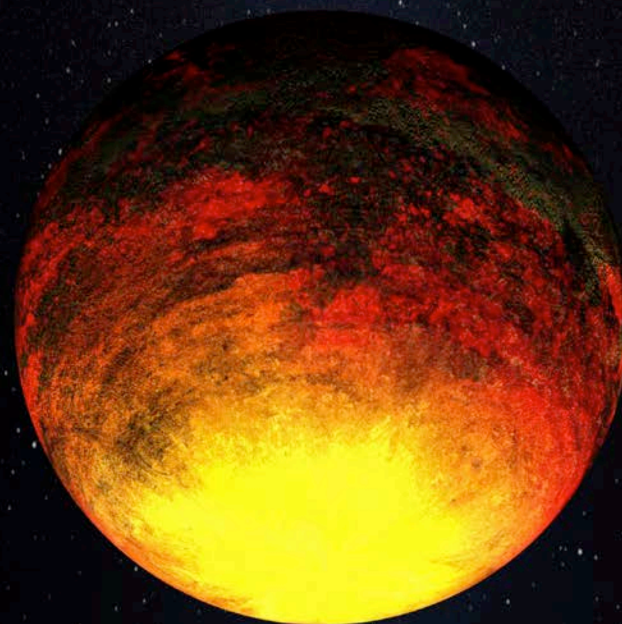
Kepler-16

(2) Kepler-10

Kepler-10b

Rocky planet around a star a lot like the Sun
560 light-years away

1.4 x Earth size
4.6 x Earth mass
Definitely rocky
(8.8 g/cm², denser than iron)

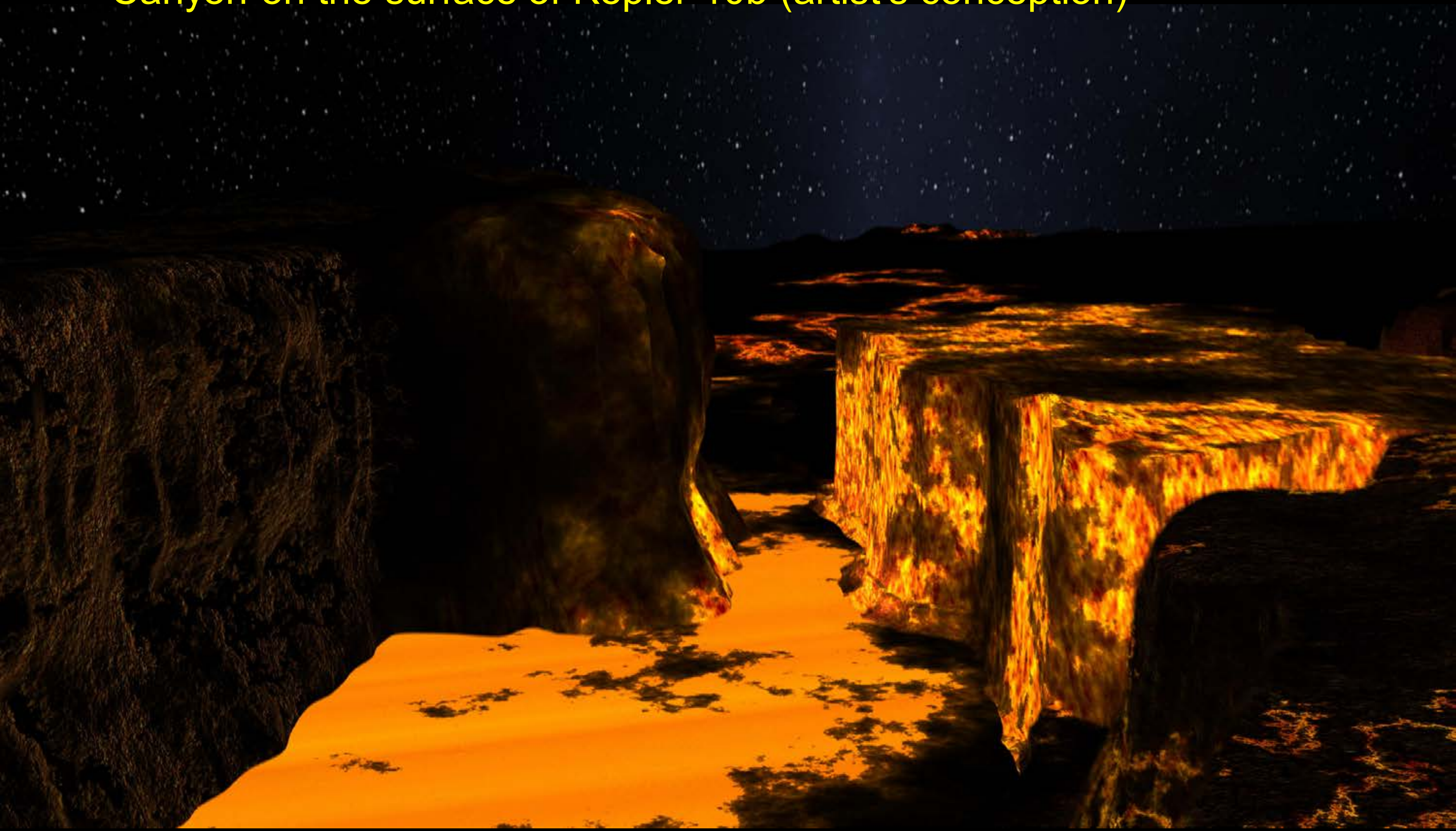


(3)

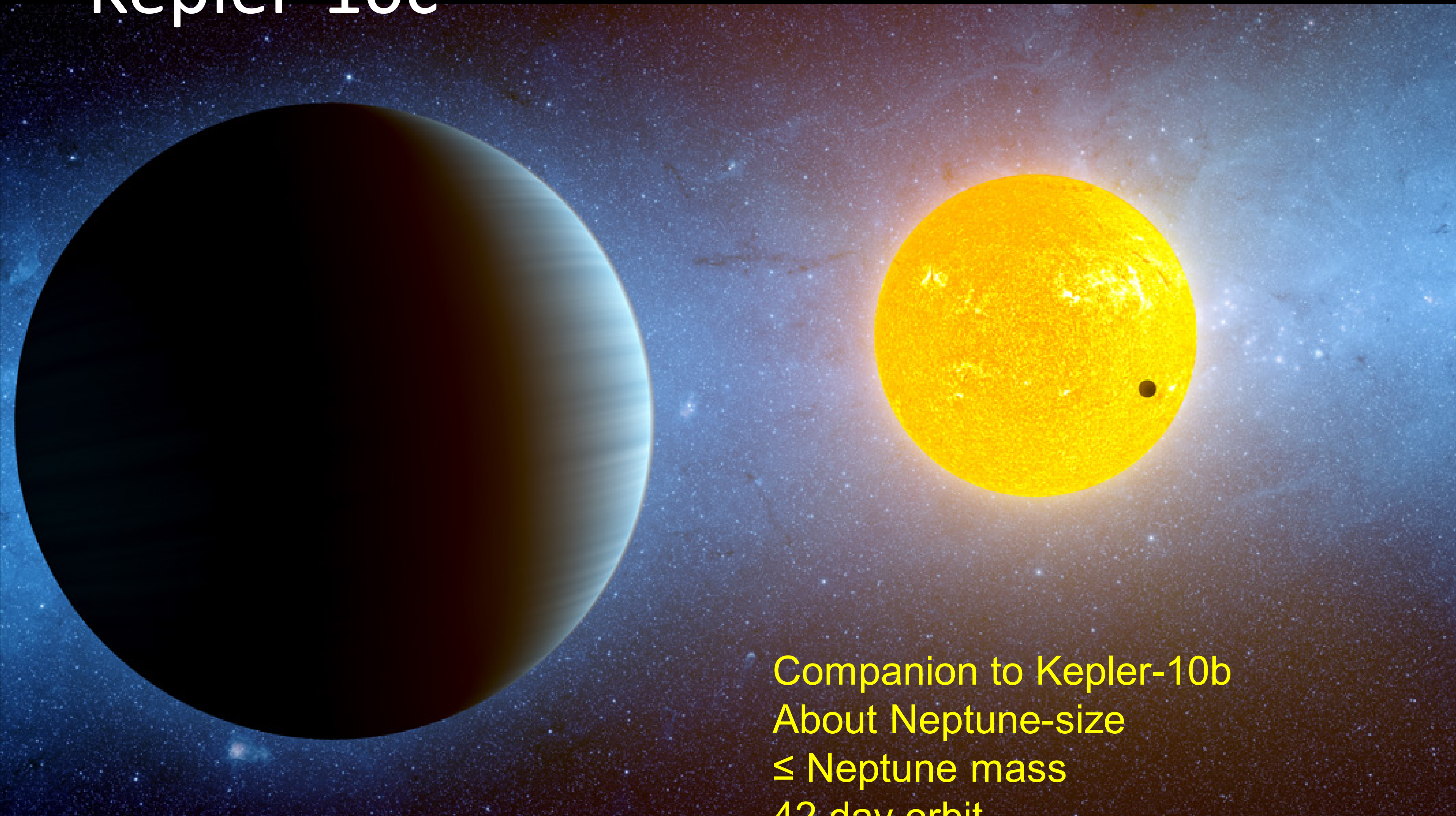
(3)

70 x closer to its star than Earth
19 hour orbit
Scorching hot 2800 F (1833K) surface temperature

Canyon on the surface of Kepler 10b (artist's conception)



Kepler-10c



Companion to Kepler-10b
About Neptune-size
≤ Neptune mass
42 day orbit
410 F temperature

Kepler-16

(2) Kepler-10

Kep

(2) Kep

Kepler-16b

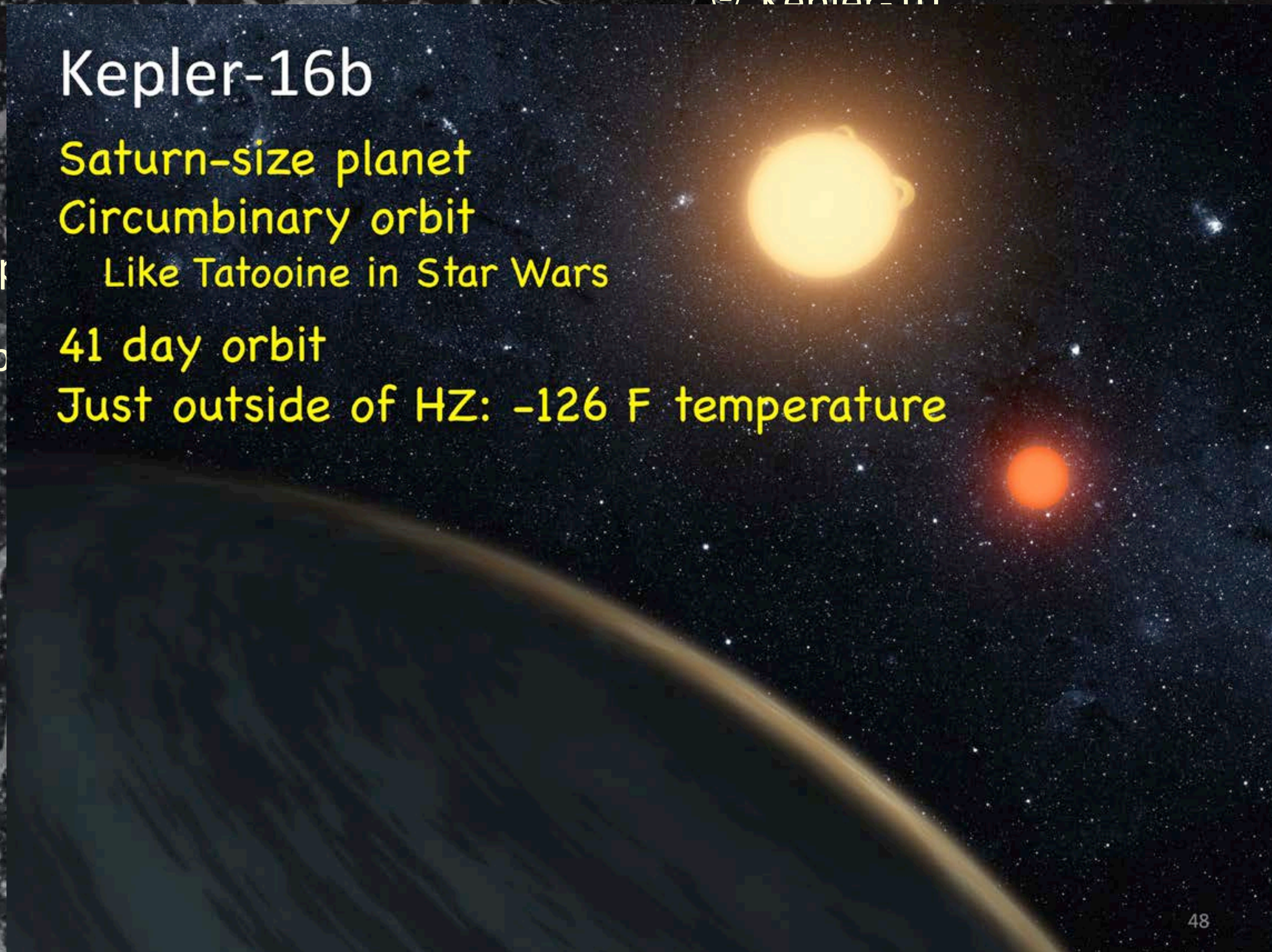
Saturn-size planet

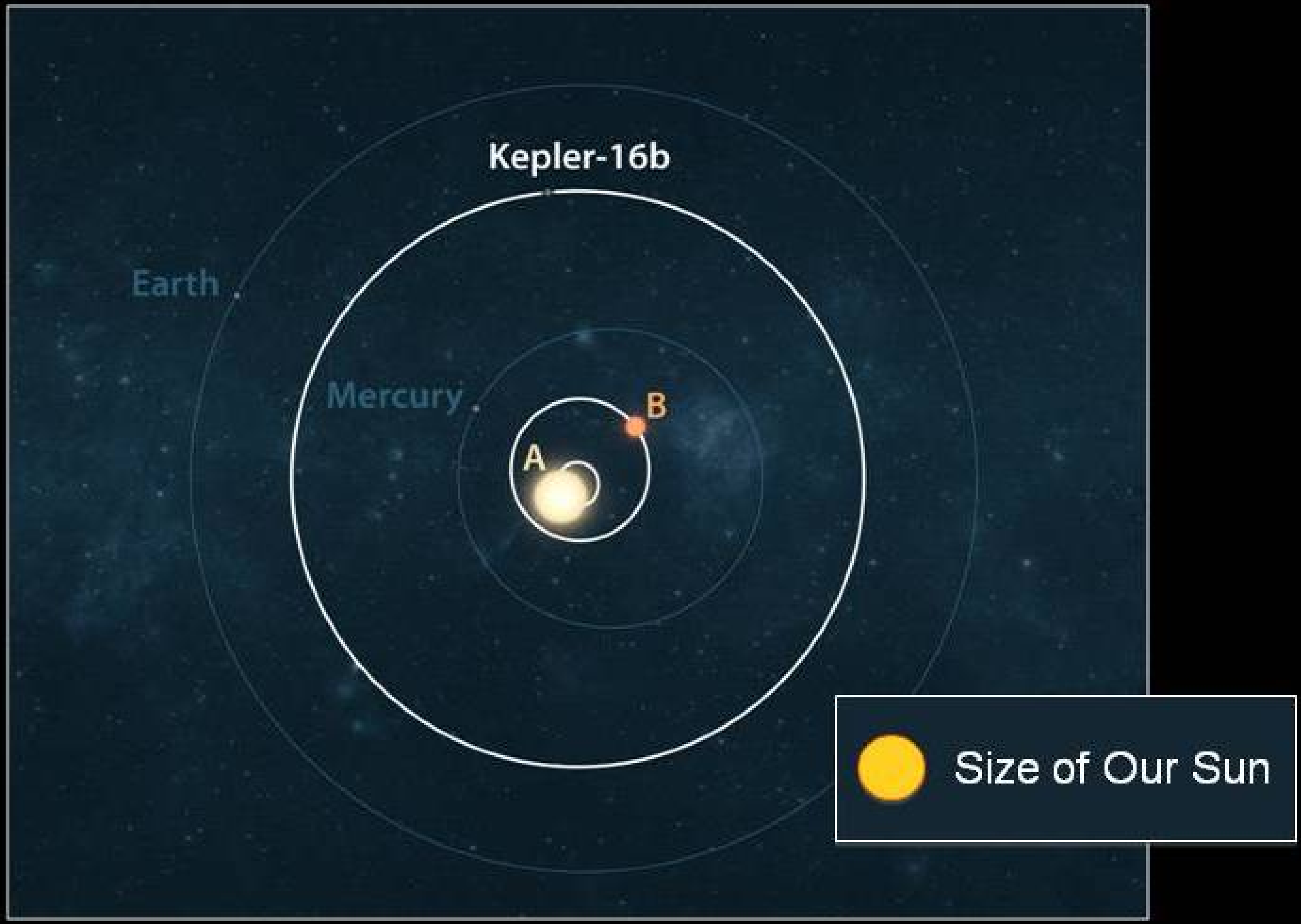
Circumbinary orbit

Like Tatooine in Star Wars

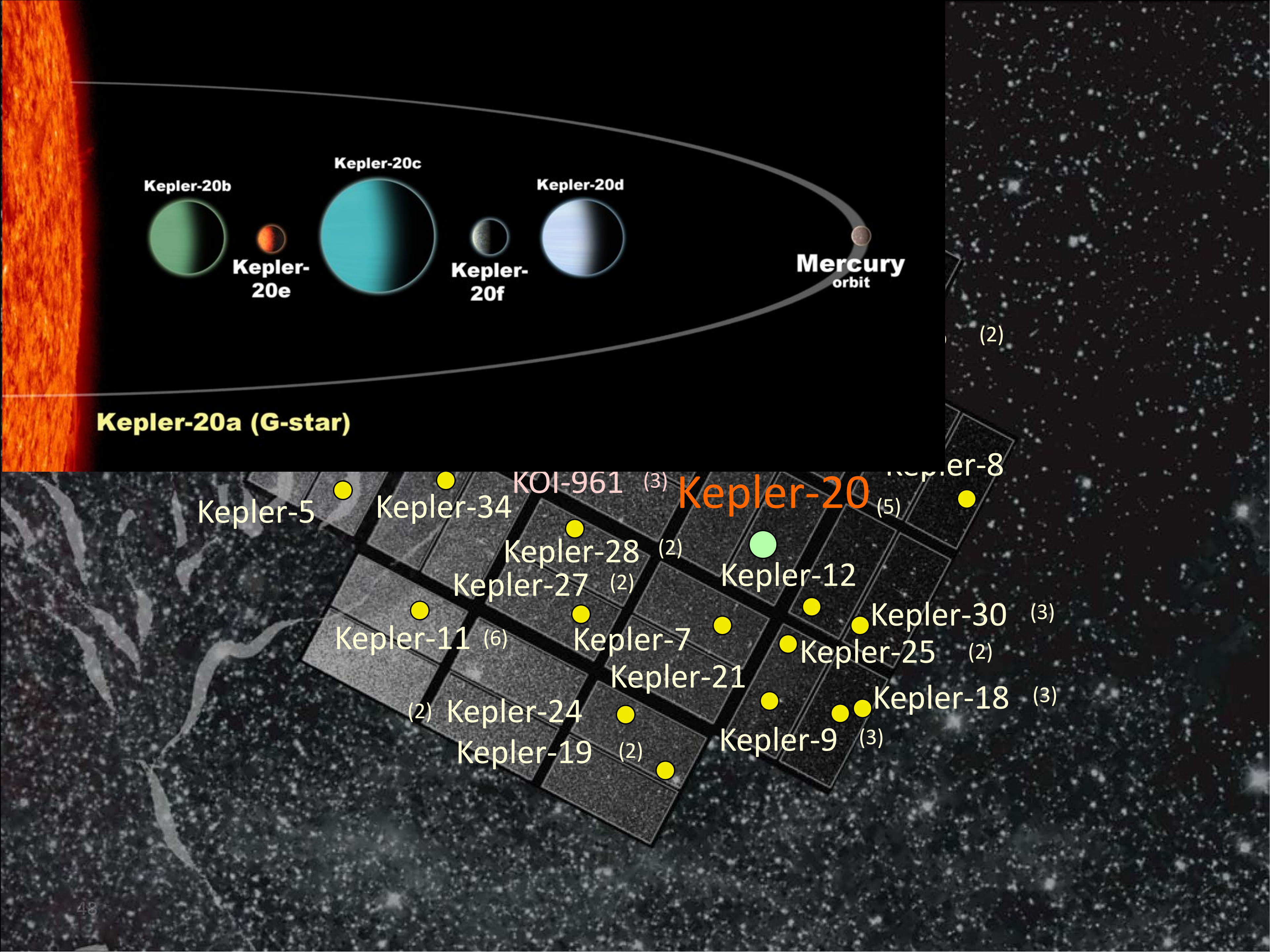
41 day orbit

Just outside of HZ: -126 F temperature



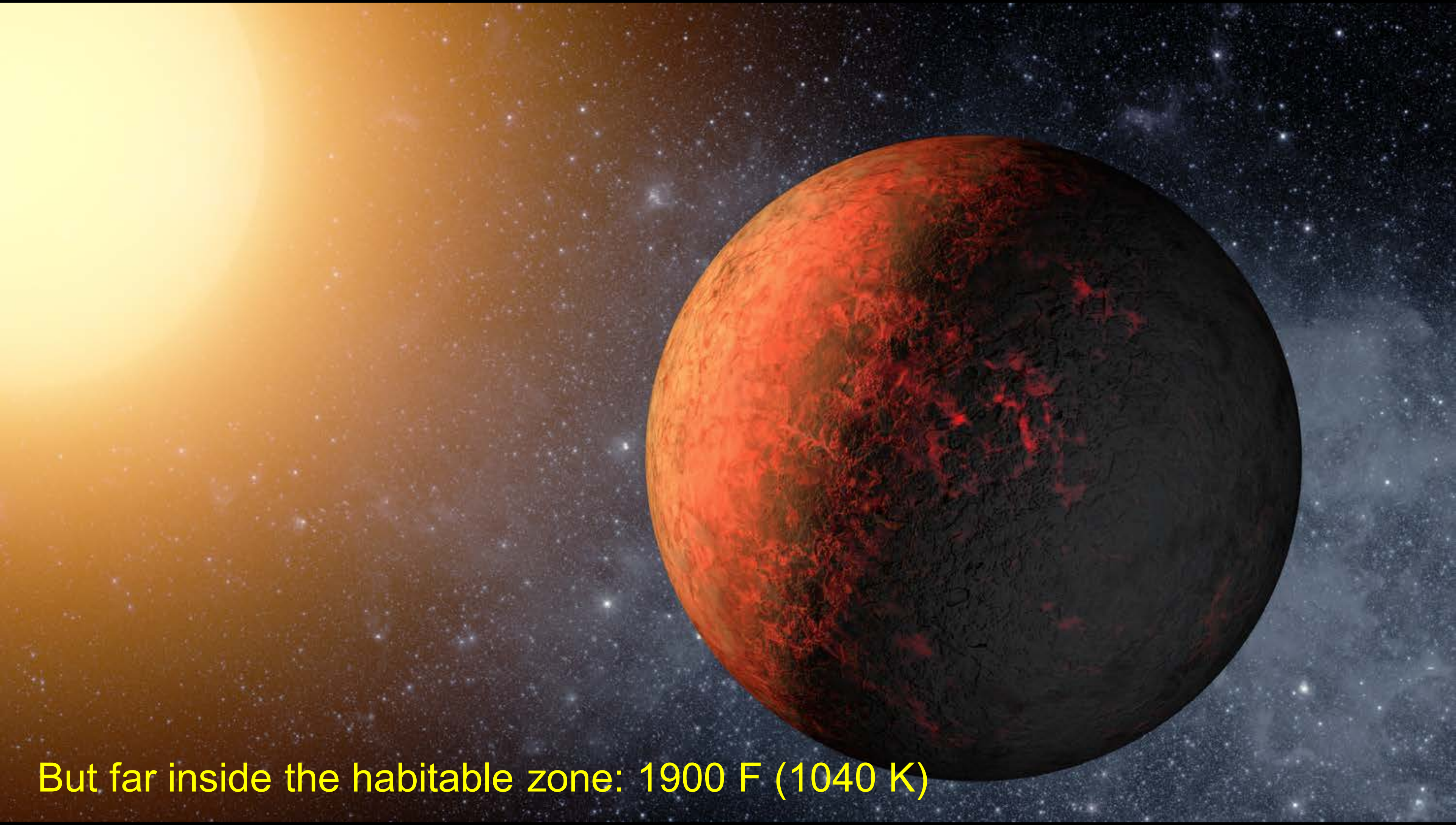

Kepler-16b
Earth
Mercury
A
B
Size of Our Sun

Sunset on Kepler 16b



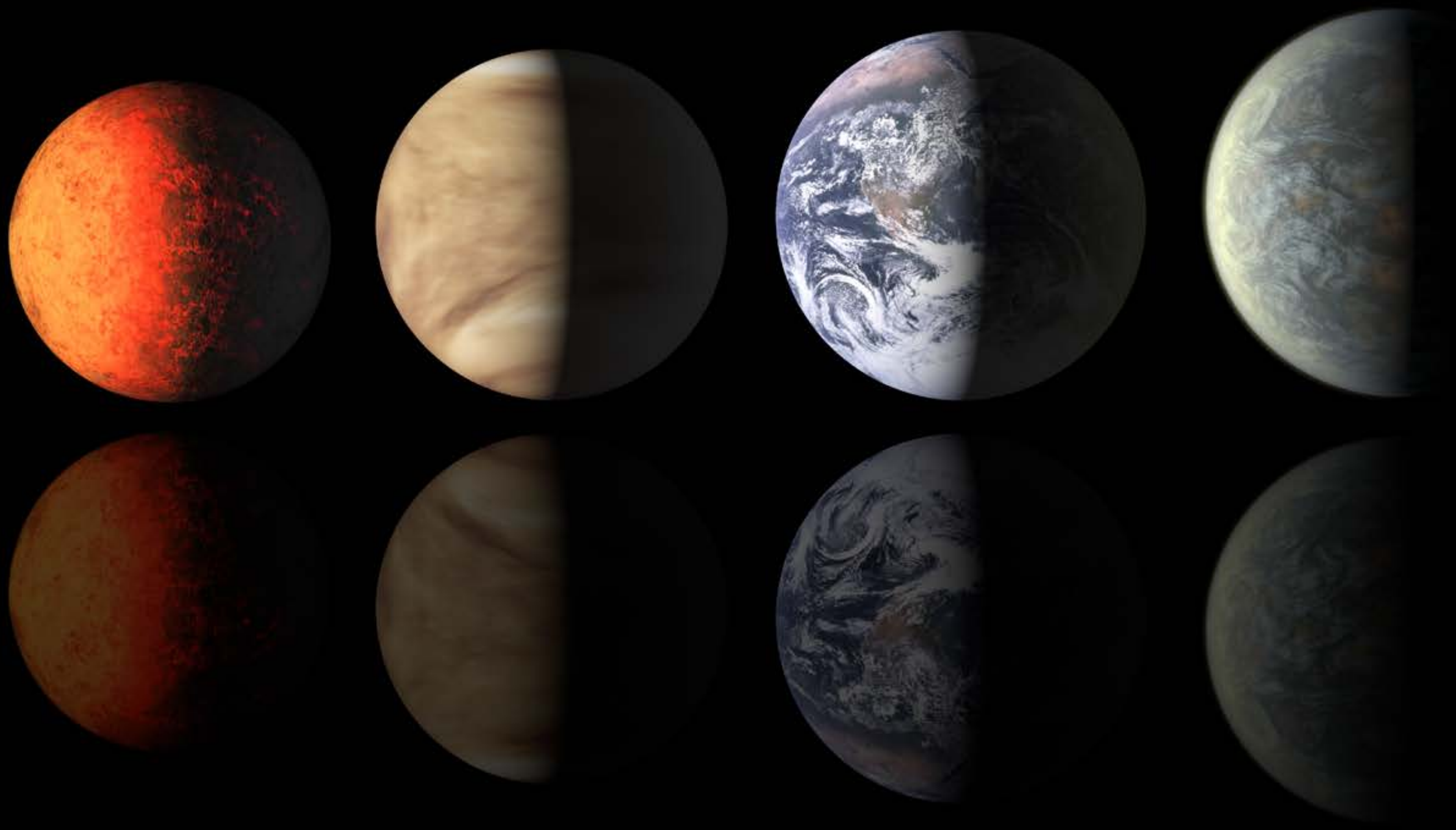
Kepler-20b
Kepler-20c
Kepler-20d
Kepler-20e
Kepler-20f
Mercury orbit
Kepler-20a (G-star)
(2)
KOI-961 (3)
Kepler-20 (5)
Kepler-5
Kepler-34
Kepler-28 (2)
Kepler-12
Kepler-27 (2)
Kepler-30 (3)
Kepler-11 (6)
Kepler-7
Kepler-25 (2)
Kepler-21
Kepler-18 (3)
(2) Kepler-24
Kepler-9 (3)
Kepler-19 (2)

Kepler 20e: a world smaller than Earth around a Solar type star

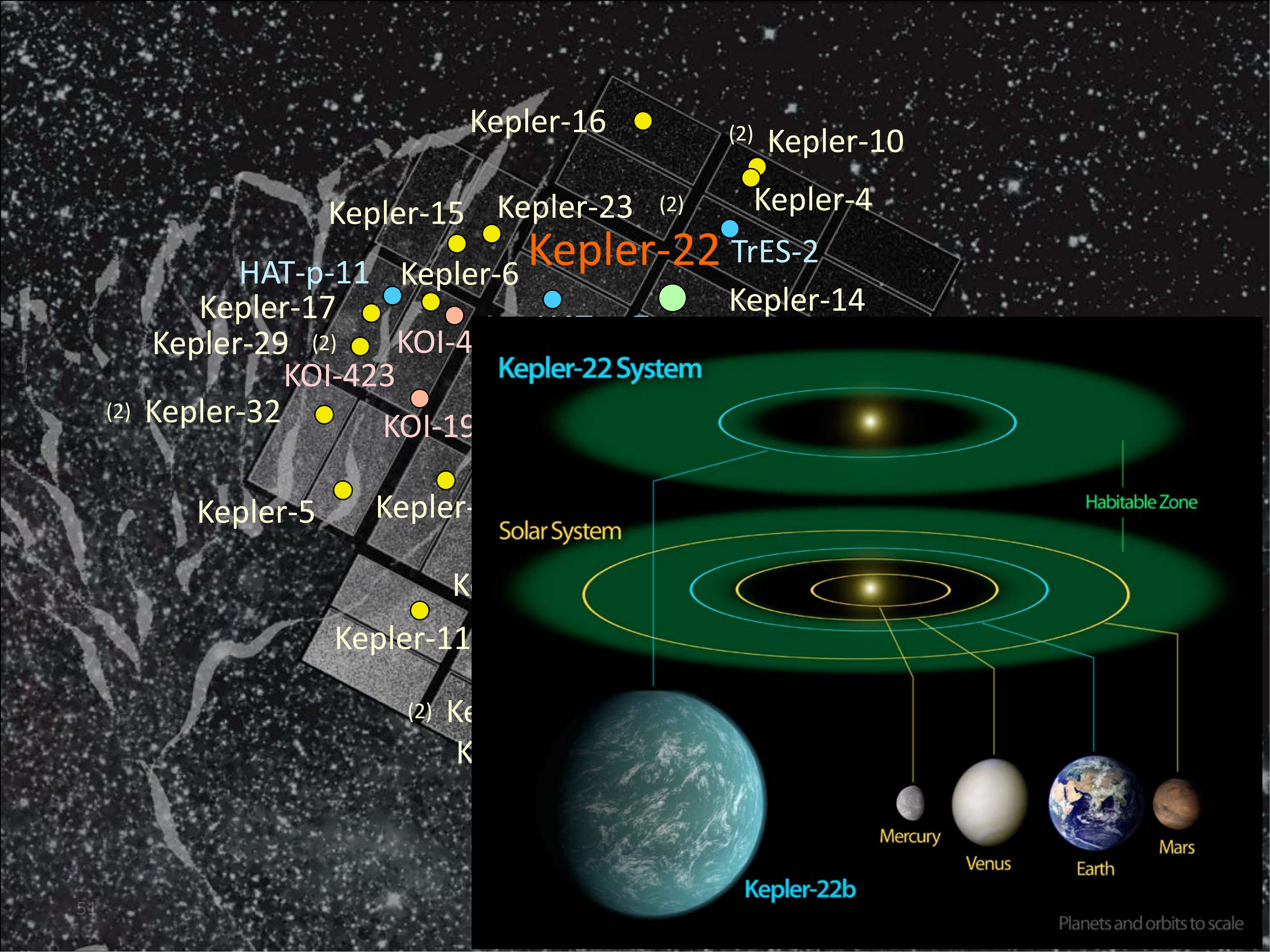


But far inside the habitable zone: 1900 F (1040 K)

Kepler-20e	Venus	Earth	Kepler-20f
1040 K	299/753 K	255/288 K	705 K



Kepler 20 small planet lineup

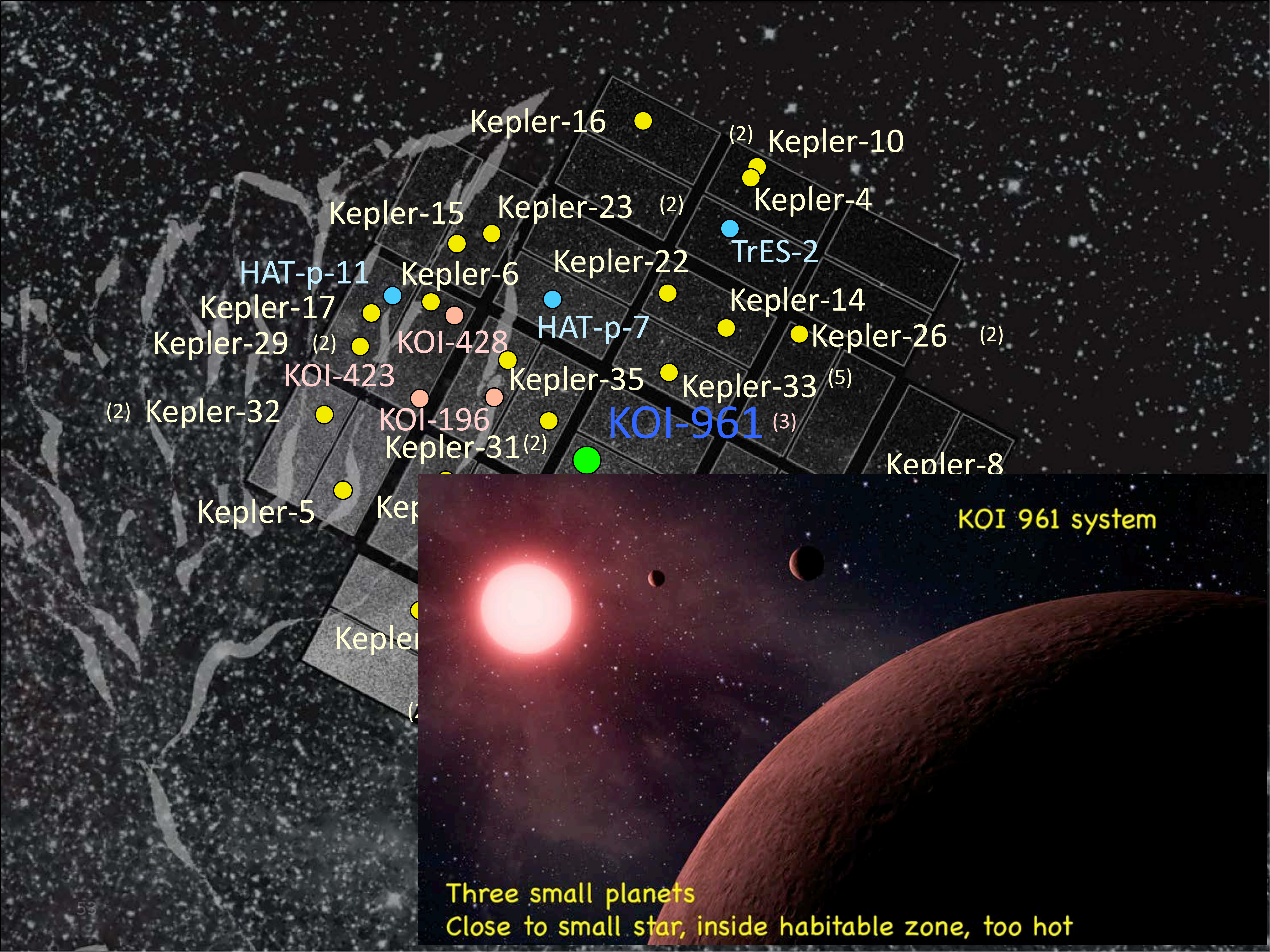

Kepler-16
(2) Kepler-10
Kepler-4
Kepler-15
Kepler-23 (2)
Kepler-22
TrES-2
HAT-p-11
Kepler-6
Kepler-14
Kepler-17
Kepler-29 (2)
KOI-423
(2) Kepler-32
Kepler-5
Kepler-11
(2)
Kepler-22 System
Habitable Zone
Solar System
Kepler-22b
Mercury
Venus
Earth
Mars
Planets and orbits to scale

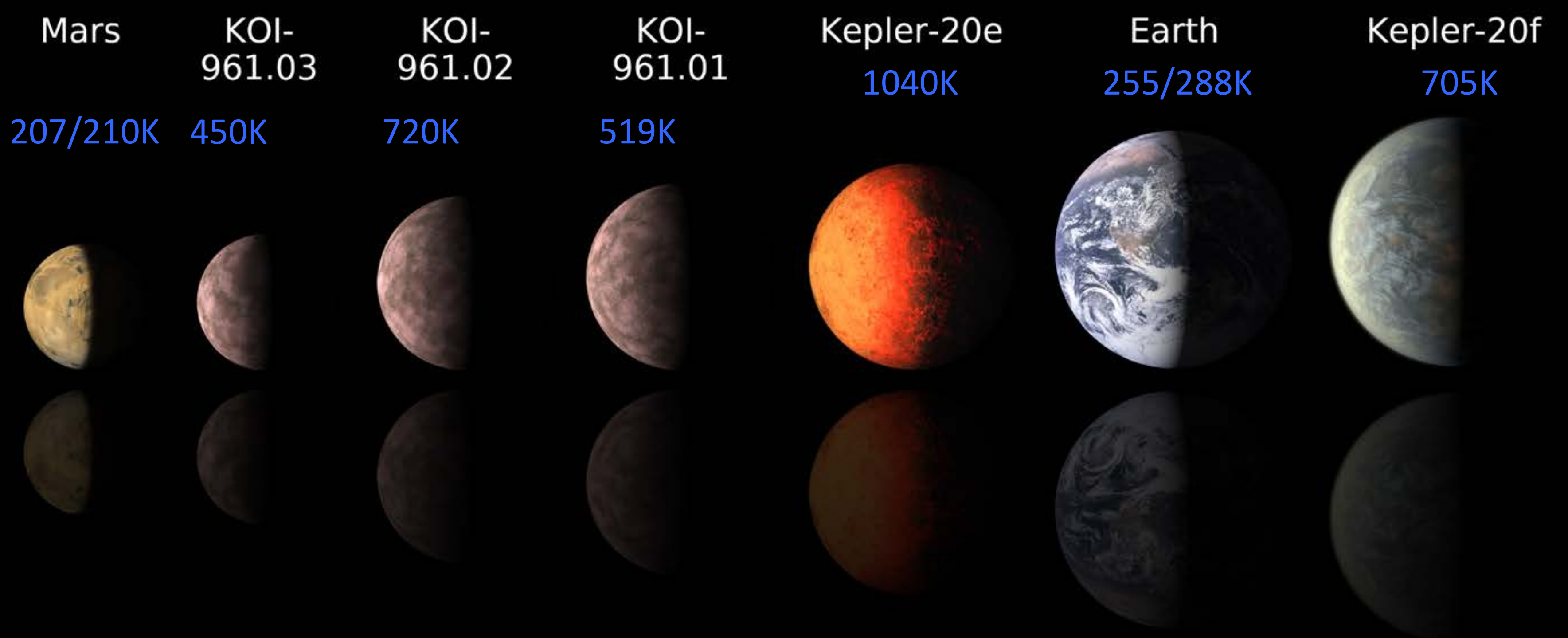
Kepler 22b

In the habitable zone of a Solar-like star
but 2.4 times the size of Earth

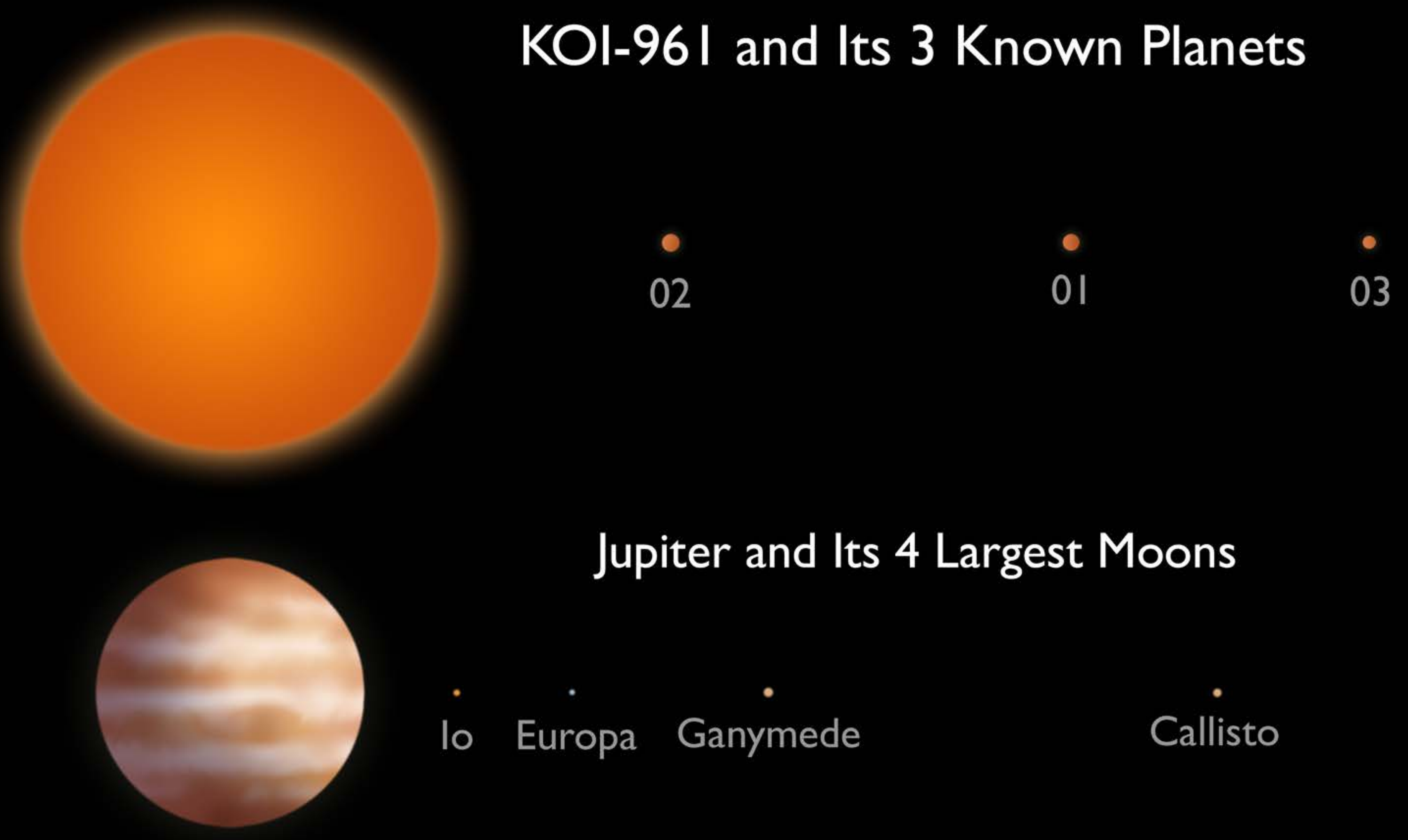
Temperature 14 F
(but warmer with an atmosphere)

Water planet?   Rocky surface?   Deep atmosphere?

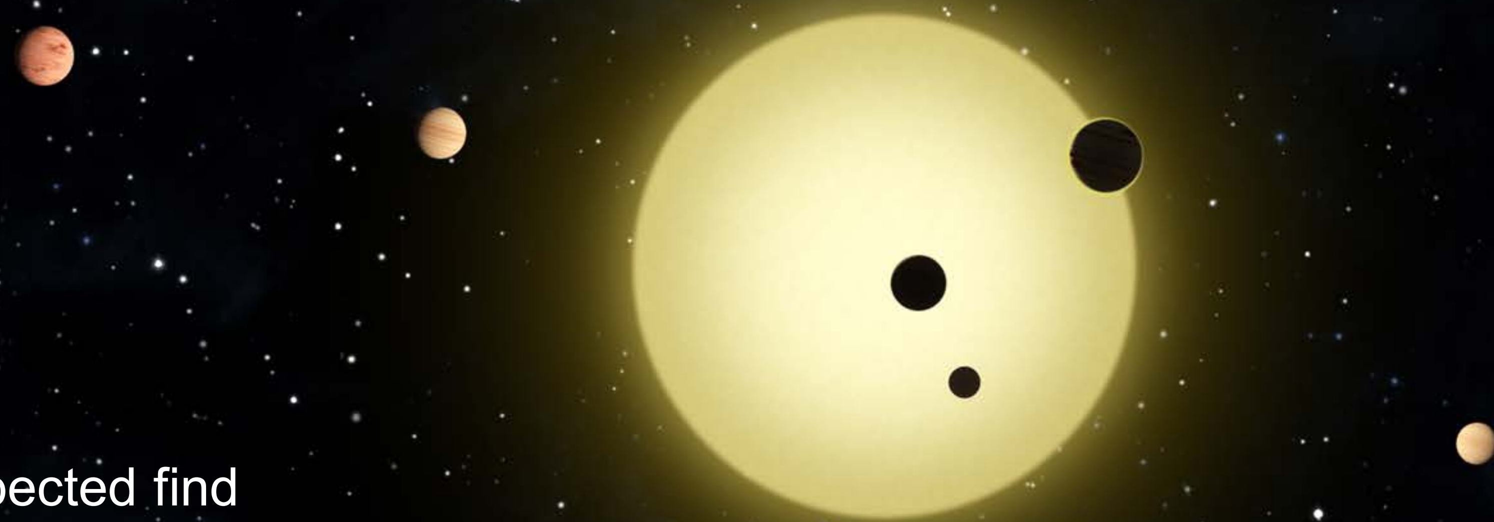

Kepler-16
(2) Kepler-10
Kepler-4
Kepler-15
Kepler-23 (2)
TrES-2
HAT-p-11
Kepler-6
Kepler-22
Kepler-17
Kepler-14
HAT-p-7
Kepler-29 (2)
KOI-428
Kepler-26 (2)
KOI-423
Kepler-35
Kepler-33 (5)
(2) Kepler-32
KOI-196
KOI-961 (3)
Kepler-31 (2)
Kepler-8
Kepler-5
KOI 961 system
Three small planets
Close to small star, inside habitable zone, too hot



KOI 961 planet lineup

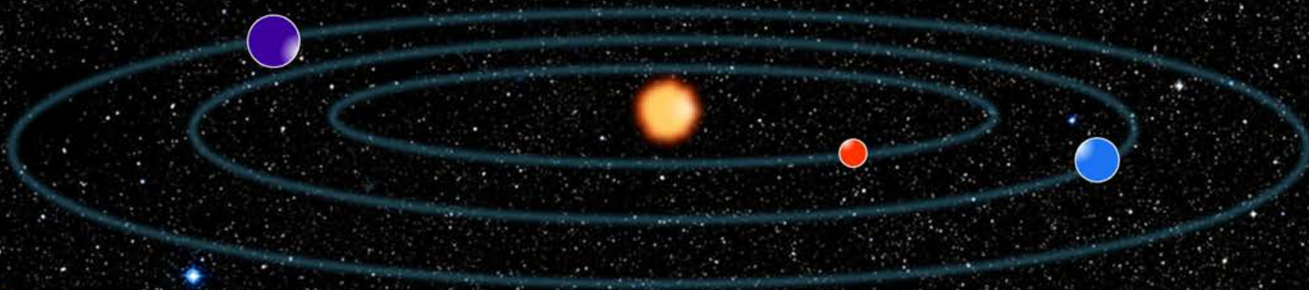

KOI-961 and Its 3 Known Planets
02
01
03
Jupiter and Its 4 Largest Moons
Io
Europa
Ganymede
Callisto

Multiple Planet Systems

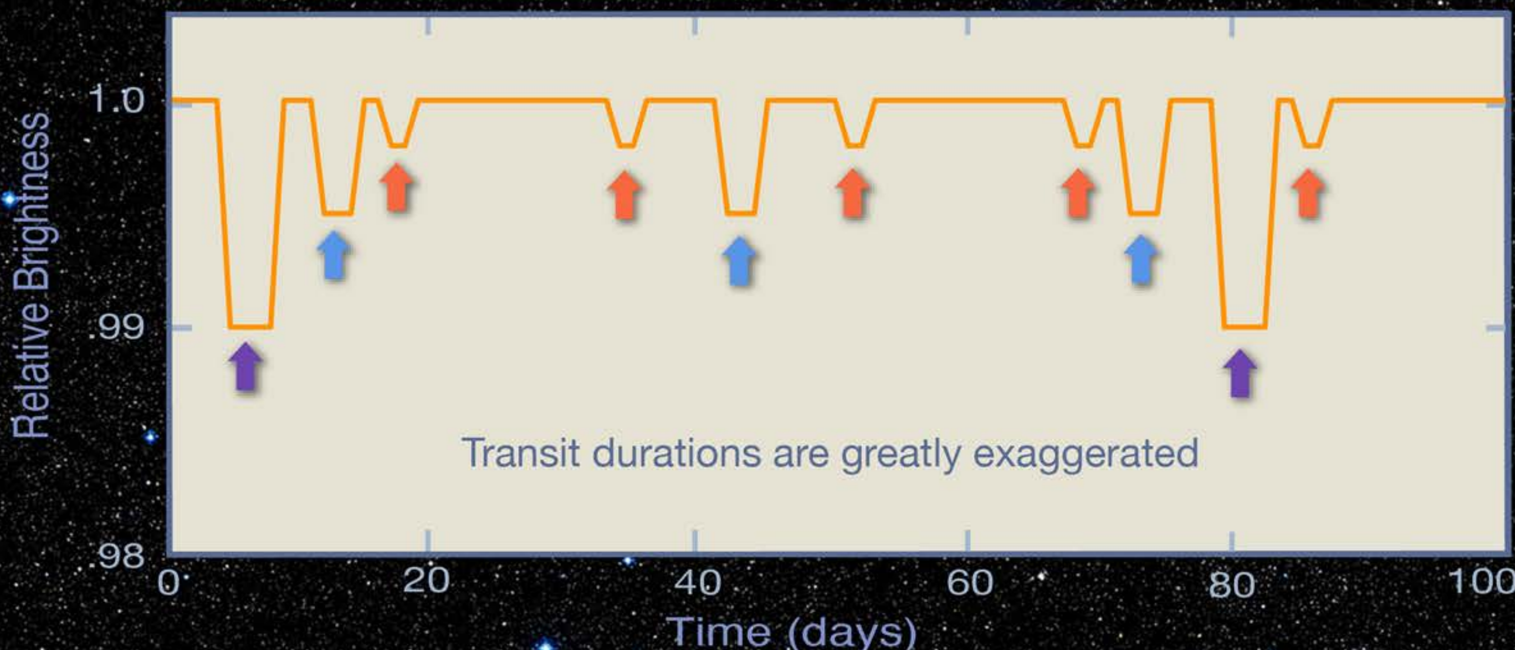


- Unexpected find
- Tells us about planet system, not just planets
- Self confirming because multiple occurrence of false positives is really unlikely

Transit Signature of a Multiple-Planet System



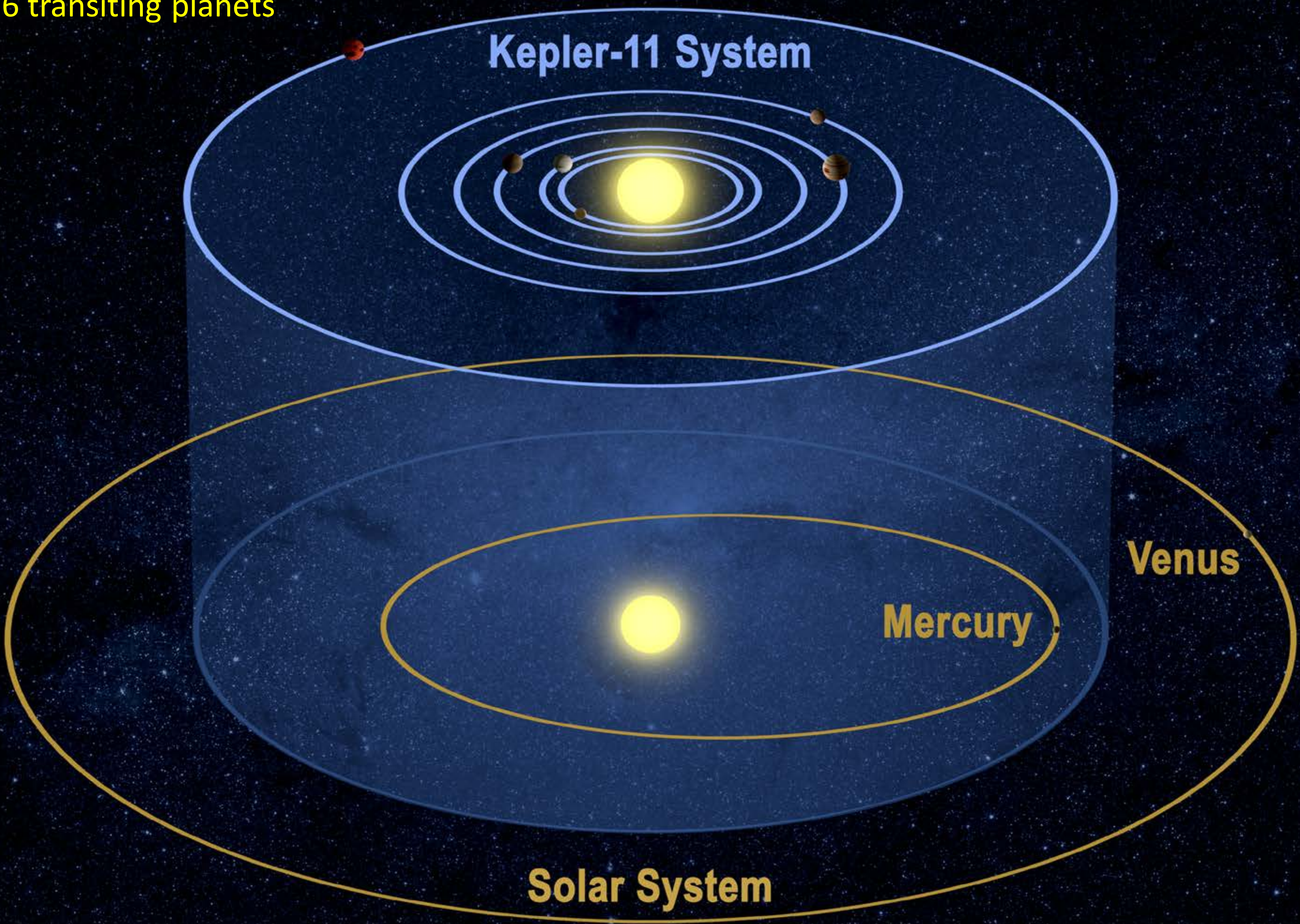
Planets can be distinguished by:
- Different periods
- Different depths
- Different durations



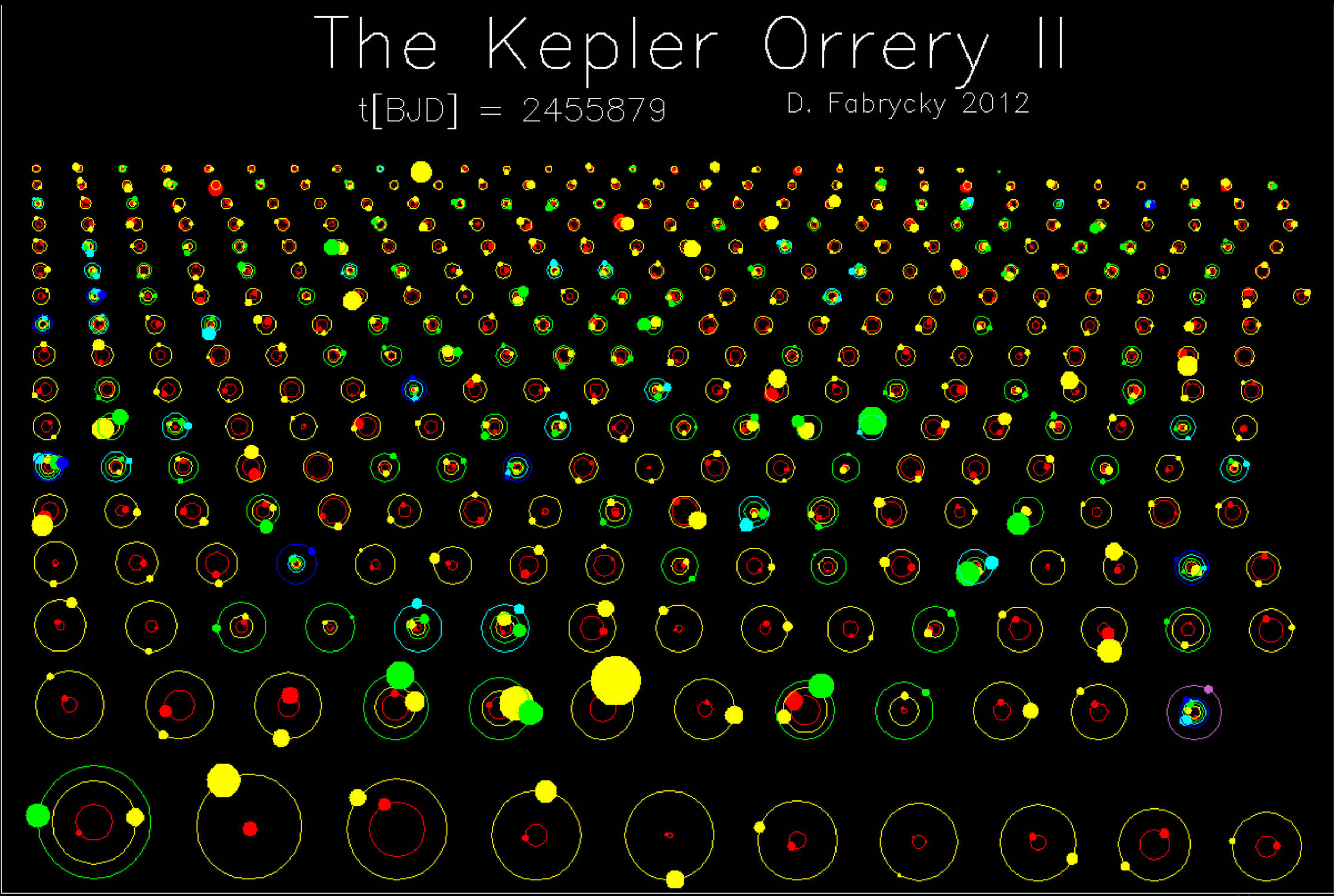
Kepler’s Confirmed Multiple Planet Systems

>150 more multiple planet systems with >800 planet candidates

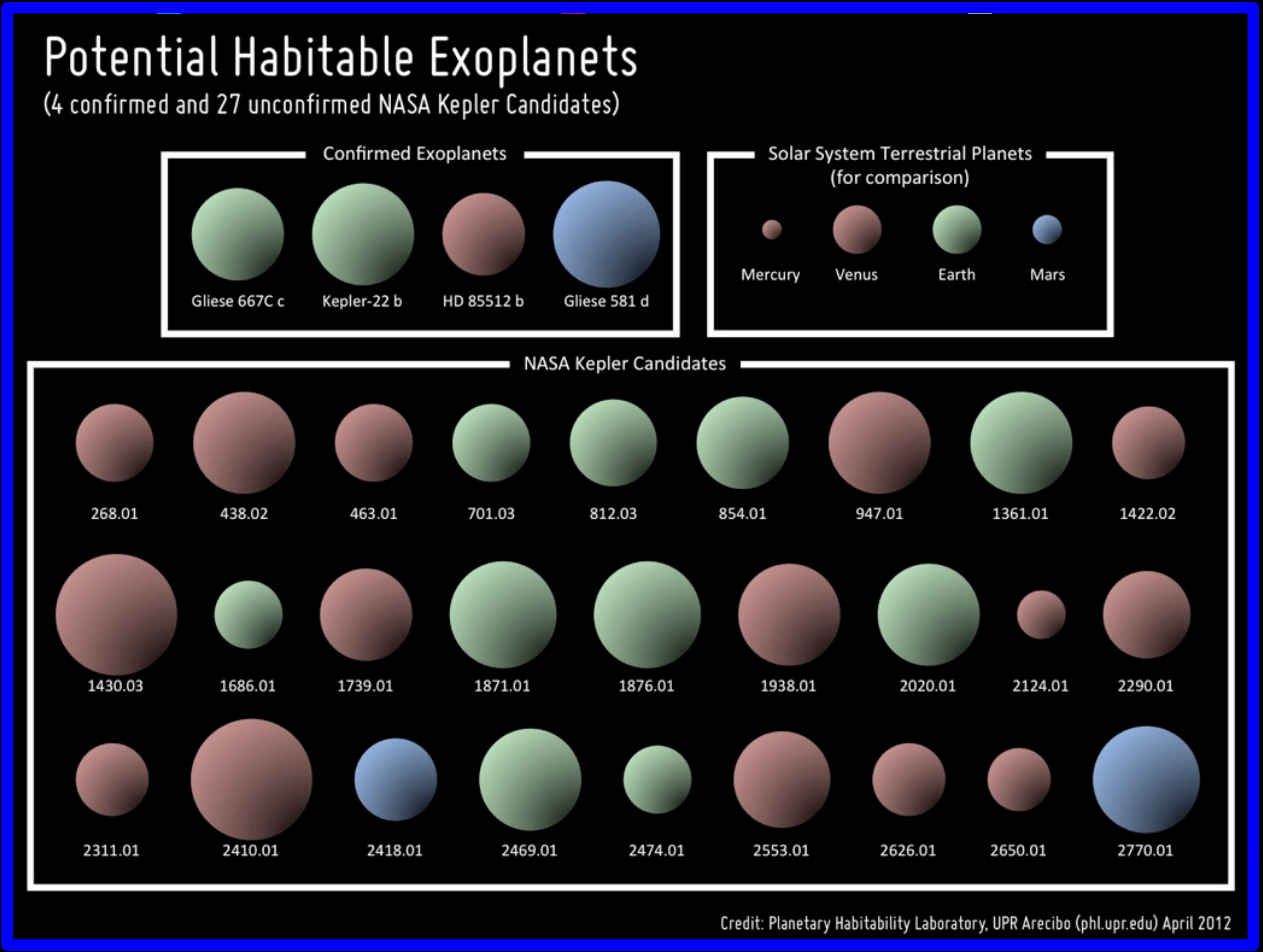
6 transiting planets



Lissauer, et al., Nature v470, pp 53–58 (03 February 2011)


The Kepler Orrery II
t[BJD] = 2455879
D. Fabrycky 2012

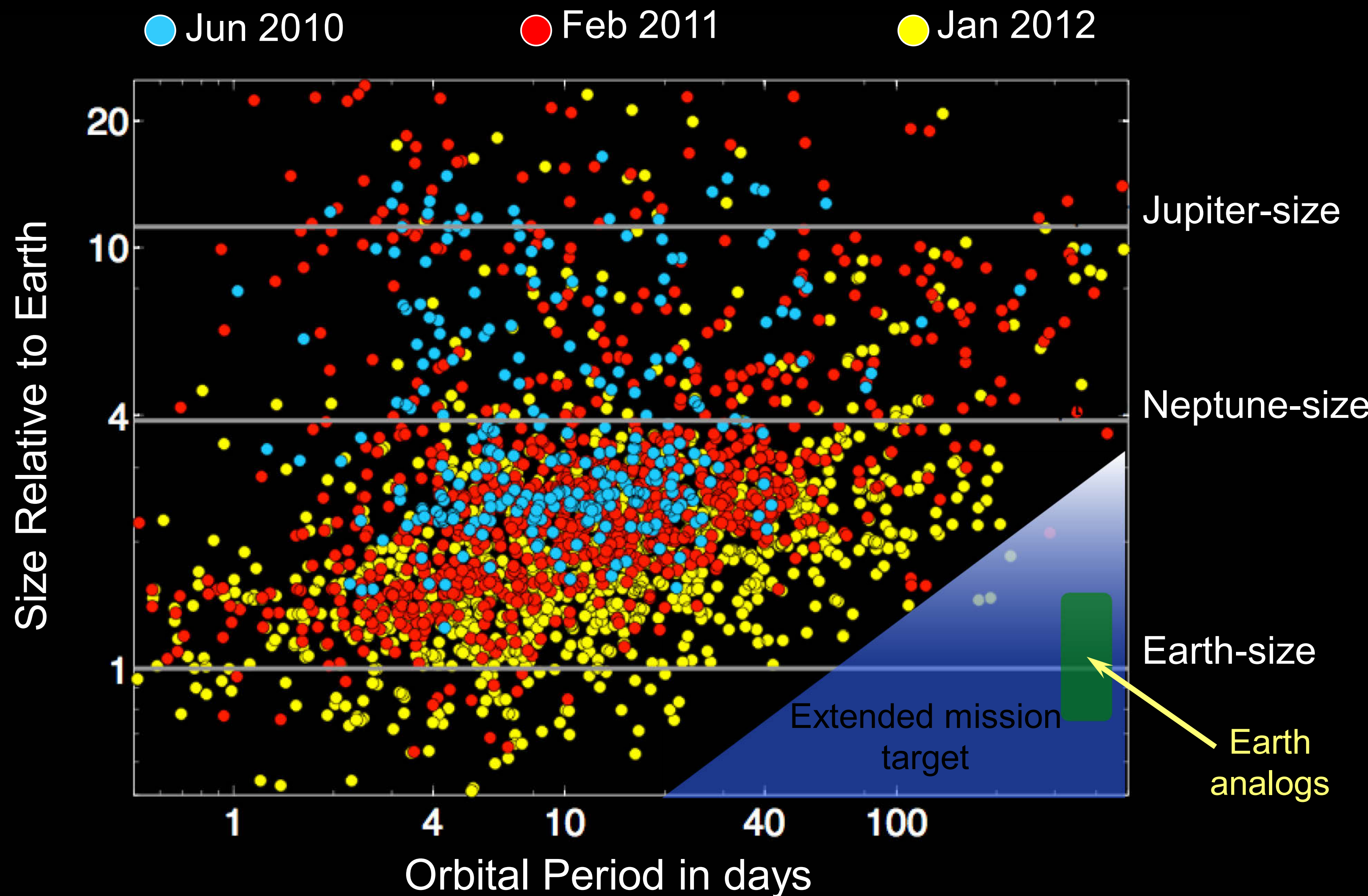
Many habitable zone planets.
Lots of Earth-size planets.
No confirmed Earth-size HZ planet yet. But soon!



Batalha et al. 2012, arXiv: 1202.5852

Kepler Extended Mission Target:

Habitable Zone Earths



What about life?

Habitable zone planets (or their moons) COULD have life.

But DO they?

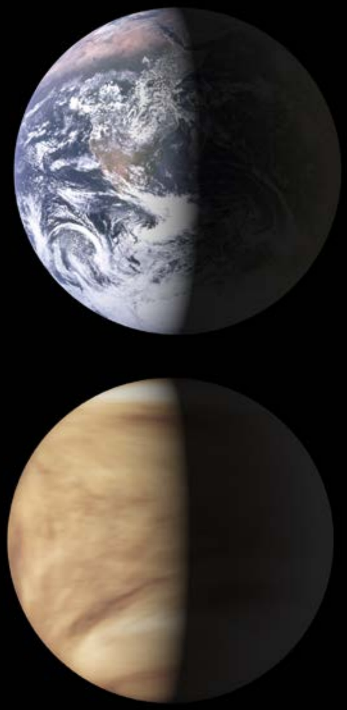
Compare Earth and Venus.
  Same size
  Both in the habitable zone

Earth: Surface temperature that melts water
  Life

Venus: Surface temperature that melts lead
  Probably no life

Can't tell the difference between Earth-like and Venus-like habitable zone exoplanets.

Need new telescopes to measure exoplanet atmospheres. (FINESS)

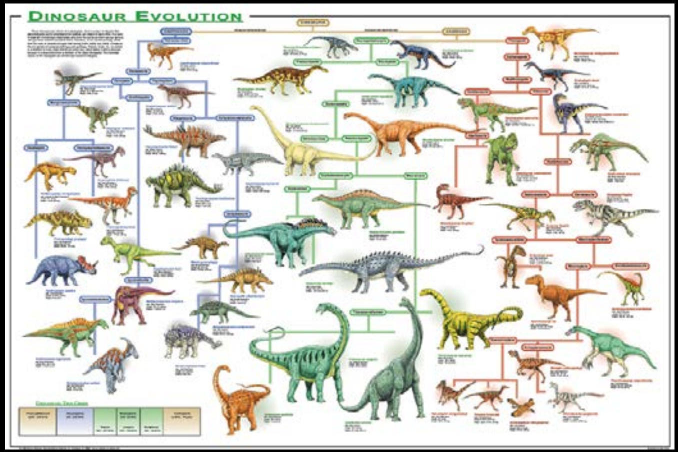


Intelligent Life?

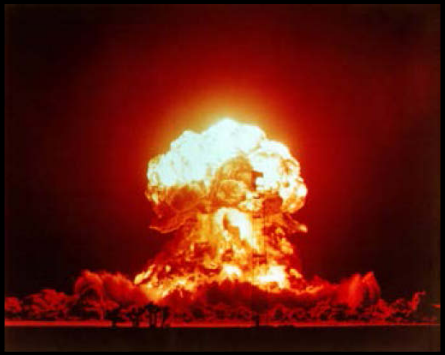
Another matter altogether

Deep ocean
worm feeds on
methane eating
bacteria

Life is probably frequent
How often does it become intelligent?
How long does intelligent life last?
We are now performing this experiment.



200 million years of evolution
Walnut-size brains
No tools



or

Are we alone ?

<u>We don’t know!</u>

(But we’re working on it.)


"One day, from the shores of a new world, we'll gaze at the sea that took us there. And its waves will be stars."
http://kepler.nasa.gov/education/sagan