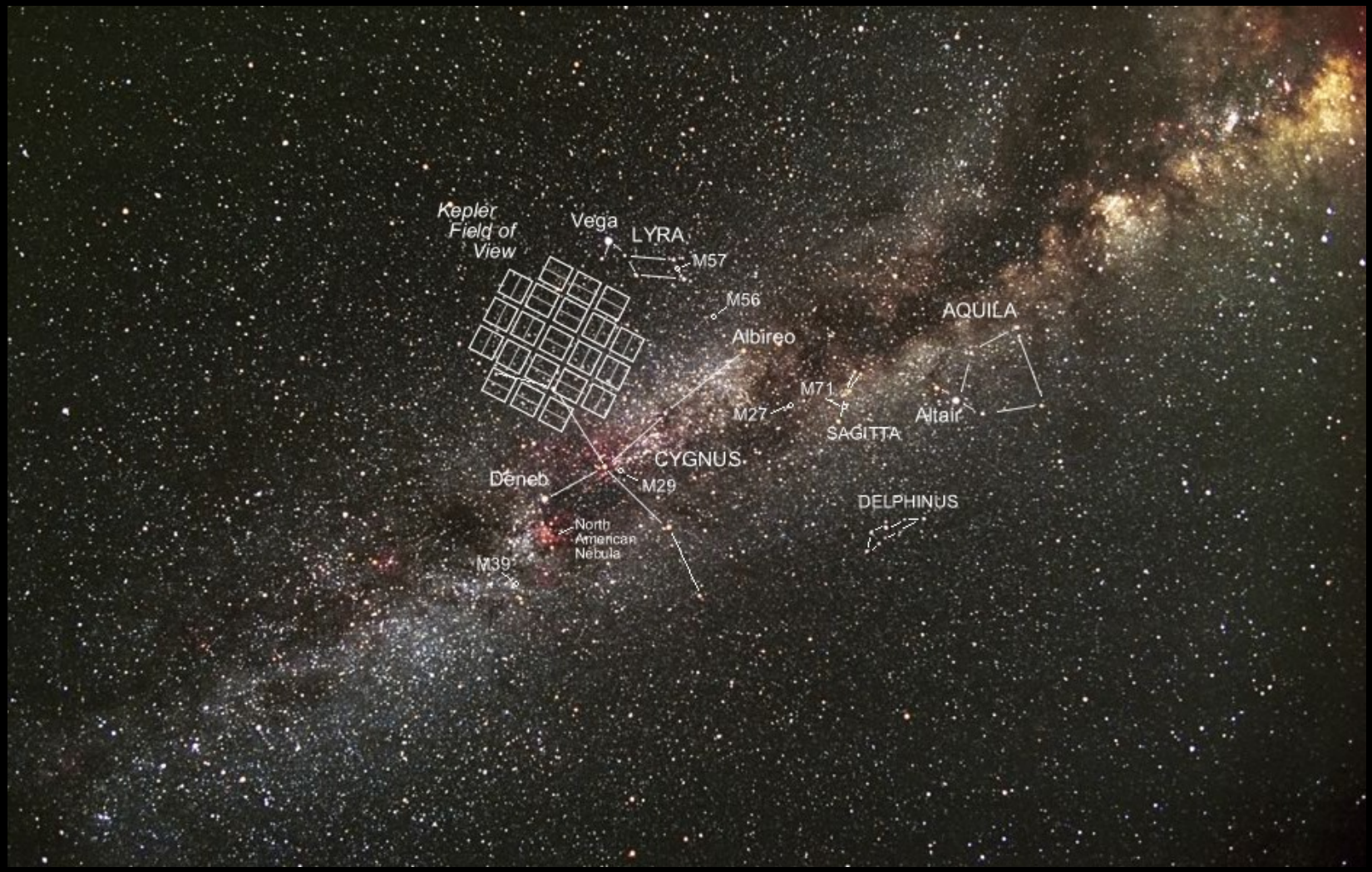
# The Search for Extrasolar Planets




A Presentation and Discussion for the Osher Life-Long-Learning Institute
Our Place in the Universe
Mitzi Adams and Dr. Allyn Tennant

# Why Do We Care?

Frank Drake, 1961

$$N = R^* \times f_p \times n_e \times f_e \times f_i \times f_c \times L$$

N = Total number of civilizations in Milky Way
R* = Rate of Star Formation
$f_p$ = fraction of R that have planetary systems
$n_e$ = number of planets in those systems with habitable zones
$f_e$ = the fraction of those with life
$f_i$ = the fraction of those with intelligent life
$f_c$ = the fraction of those which create civilizations that advertise their existence
L = the time those civilizations send signals into space (I Love Lucy)

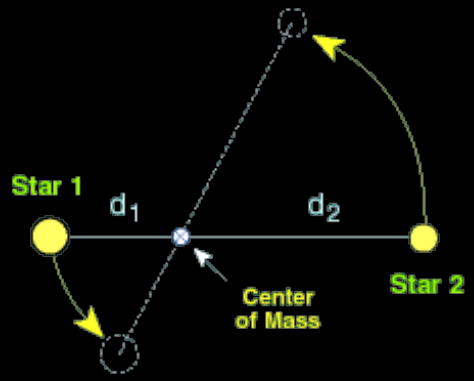
Sara Seager, 2013

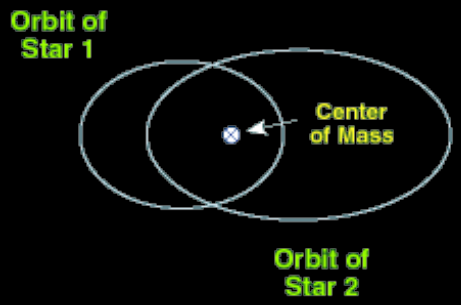
$$N = N^* \times f_Q \times f_{HZ} \times f_O \times f_L \times f_S$$

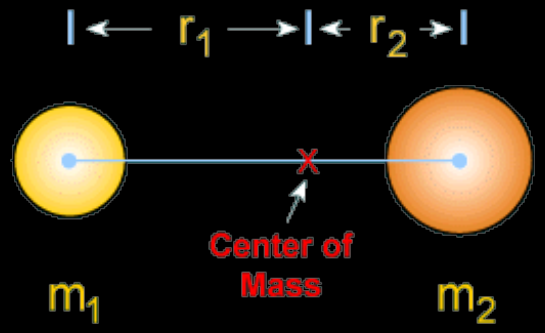
N = Number of planets with detectable signs of life
N* = Number of stars observed
$f_Q$ = fraction of those that are quiet
$f_{HZ}$ = the fraction of stars with rocky planets in the habitable zone
$f_O$ = the fraction of those planets that can be observed
$f_L$ = the fraction of those that have life
$f_S$ = the fraction of those on which that life produces a detectable signature gas

# History -- Wobbles, Proper Motion

For stars that are too far away or are too close to each other

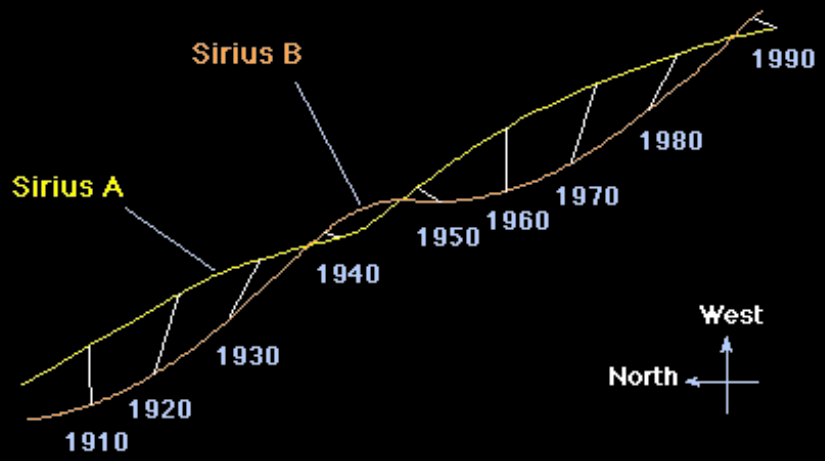



$$( m_1 + m_2 ) P^2 = ( r_1 + r_2 )^3 = R^3 \qquad R=r_1+r_2$$

Knowing period and average distance, solve for total mass.



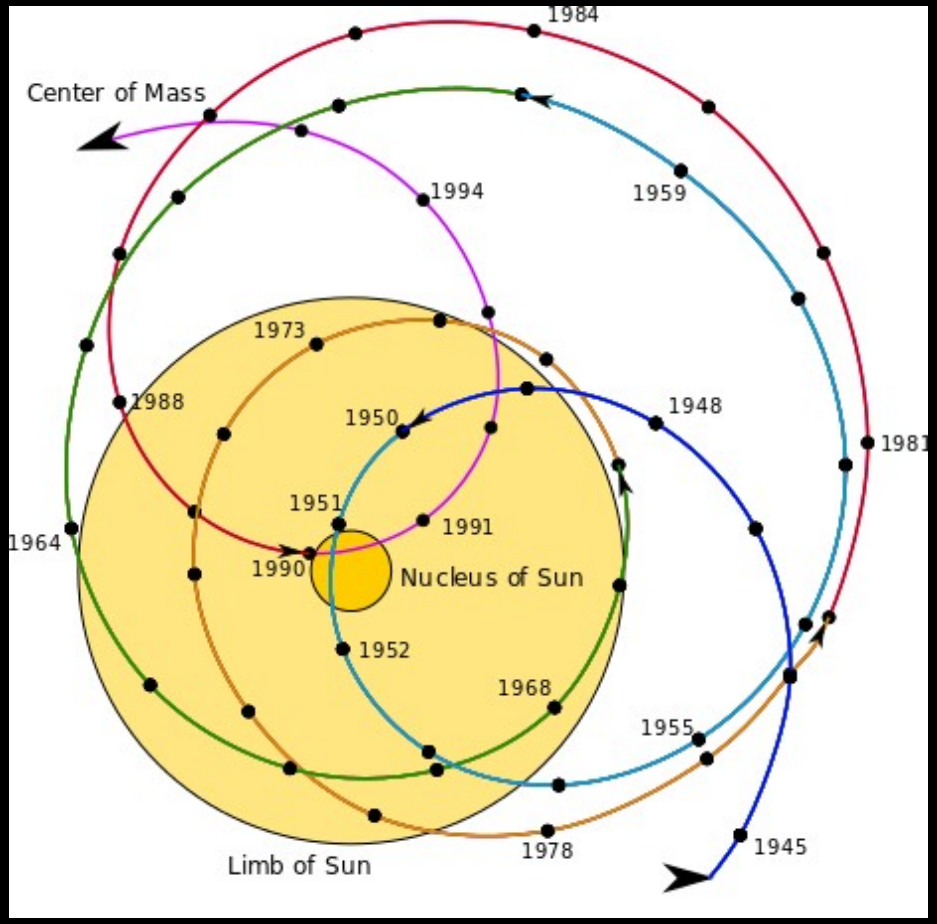

from
http://csep10.phys.utk.edu/astr162/lect/binaries/astrometric.html

# Solar System's Barycenter

$\Phi \sim 1.5$ lt_sec/ 4_lt_year = $1.5/(4*\pi*1e^{7}) = 10^{-8}$ radians

$\Phi = 10^{-8}$ radians * 57 deg/radian * 3600 arcsec/deg = 2 marcsec

Need dedicated workers
for 30 years
AND
Stable equipment




Earth/Moon barycenter is
inside Earth, ~ 4671 km
from center

By Solarsystembarycenter.gif: Carl Smithderivative work: Rubik-wuerfel (talk) - http://s173.photobucket.com/user/CarlSmith_2007/media/Sun%20SSB/ssb-orbit-col.gif.html GIF, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=9952653

# History -- Wobbles, Doppler Shifts

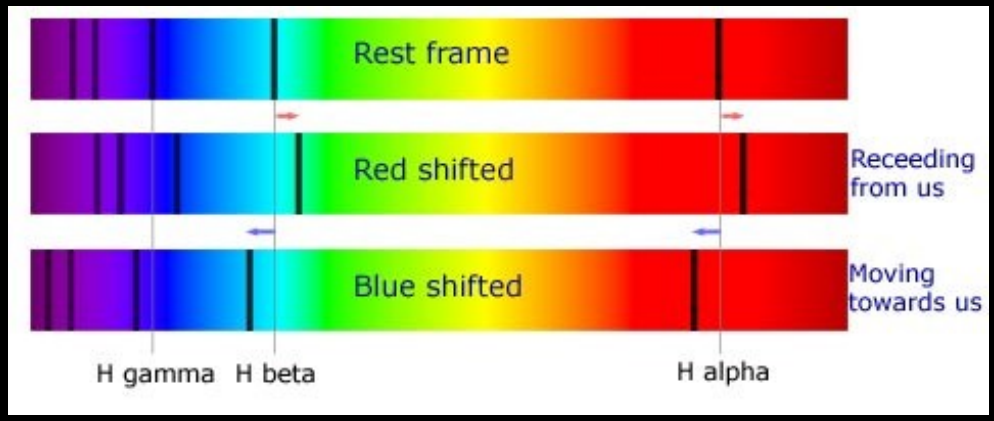
Light source moving away from the observer, the observed wavelength will get longer, and hence REDSHIFTED

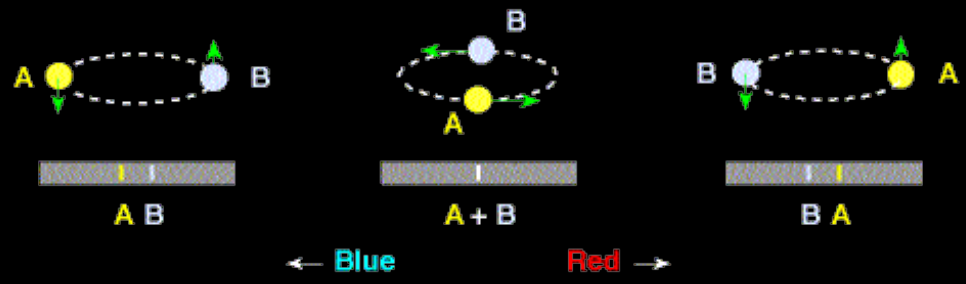
Light source moving towards the observer, the observed wavelength will get shorter, and hence BLUESHIFTED

$$\frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}} = v/c$$

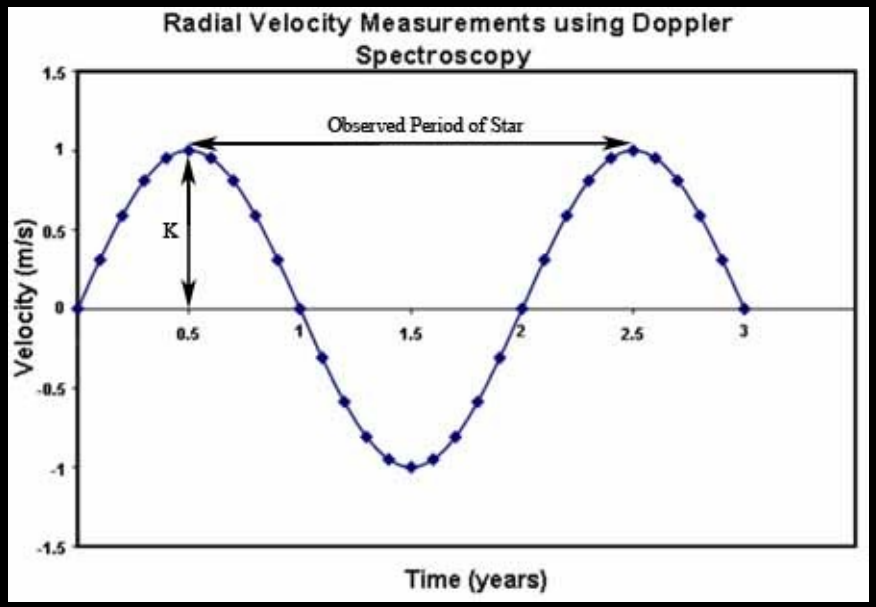
$\lambda_{obs}$ = wavelength observed

$\lambda_{em}$ = wavelength emitted



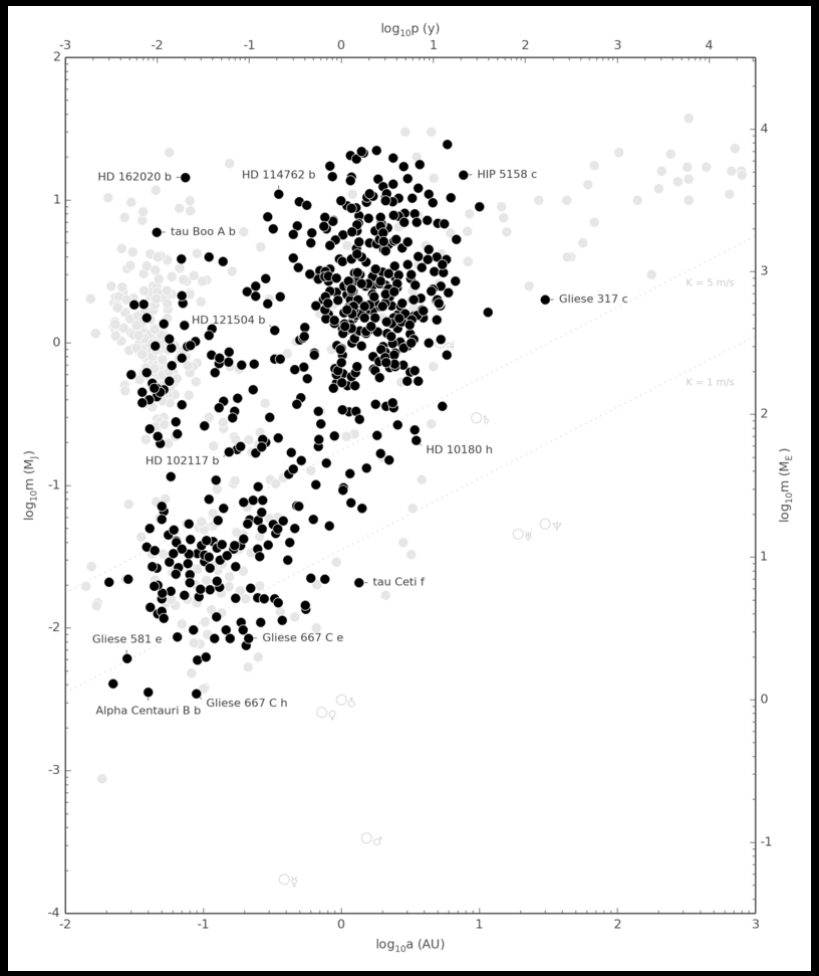



# Doppler Spectroscopy
(continued)



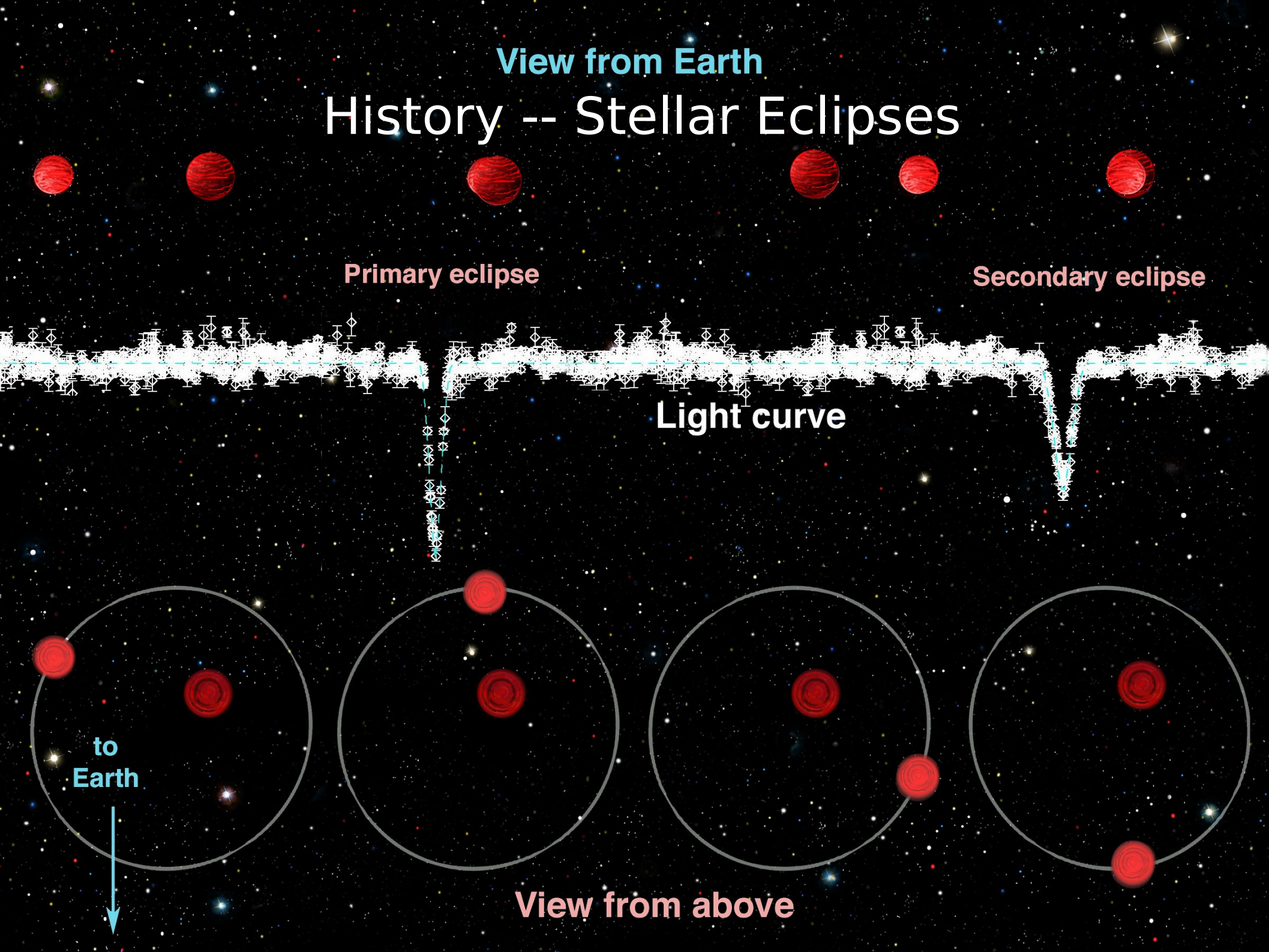

# Doppler Spectroscopy

$V \sim 2*\pi* 1e^6 \text{ km} / (10*\pi*1e^7 \text{ sec}) = 20 \text{ m/sec}$




Mass and distance from parent star of planets discovered through 2013 using radial velocity. Light gray dots are planets discovered using other methods.

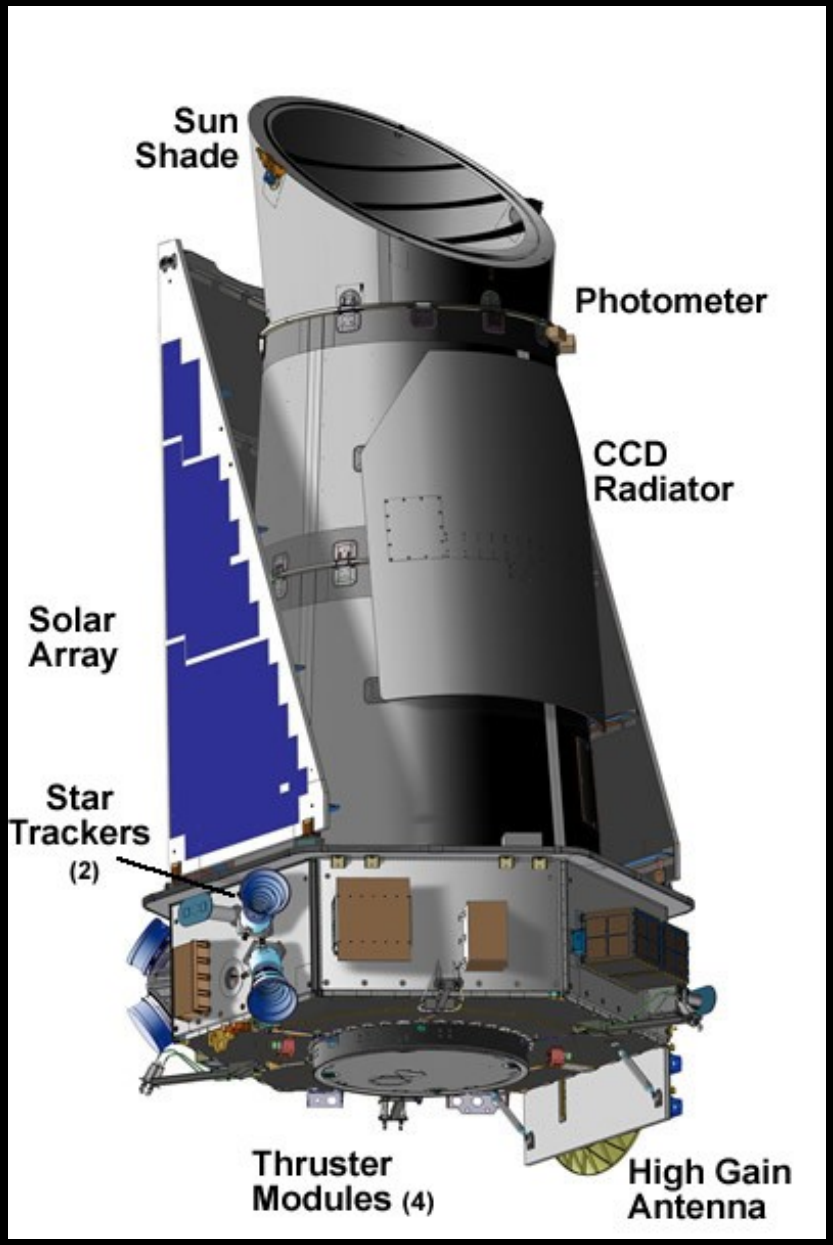
| Planet Mass | Distance AU | Radial velocity ($v_{radial}$) |
|---|---|---|
| Jupiter | 1 | 28.4 m/s |
| Jupiter | 5 | 12.7 m/s |
| Neptune | 0.1 | 4.8 m/s |
| Neptune | 1 | 1.5 m/s |
| Super-Earth (5 M⊕) | 0.1 | 1.4 m/s |
| Alpha Centauri Bb (1.13 ± 0.09 M⊕) | 0.04 | 0.51 m/s |
| Super-Earth (5 M⊕) | 1 | 0.45 m/s |
| Earth | 1 | 0.09 m/s |


View from Earth
History -- Stellar Eclipses
Primary eclipse
Secondary eclipse
Light curve
to Earth
View from above

# Mercury Transit, May 9, 2016


From http://spaceweathergallery.com, taken by Nunzio Micale in Vieste, Italy.

# Kepler Mission




Launched March 6, 2009

- Monitor 100,000 main-sequence stars
- Mission lifetime of 3.5 yrs to 6 yrs
- In Earth-trailing heliocentric orbit
- Stares at same fov over lifetime

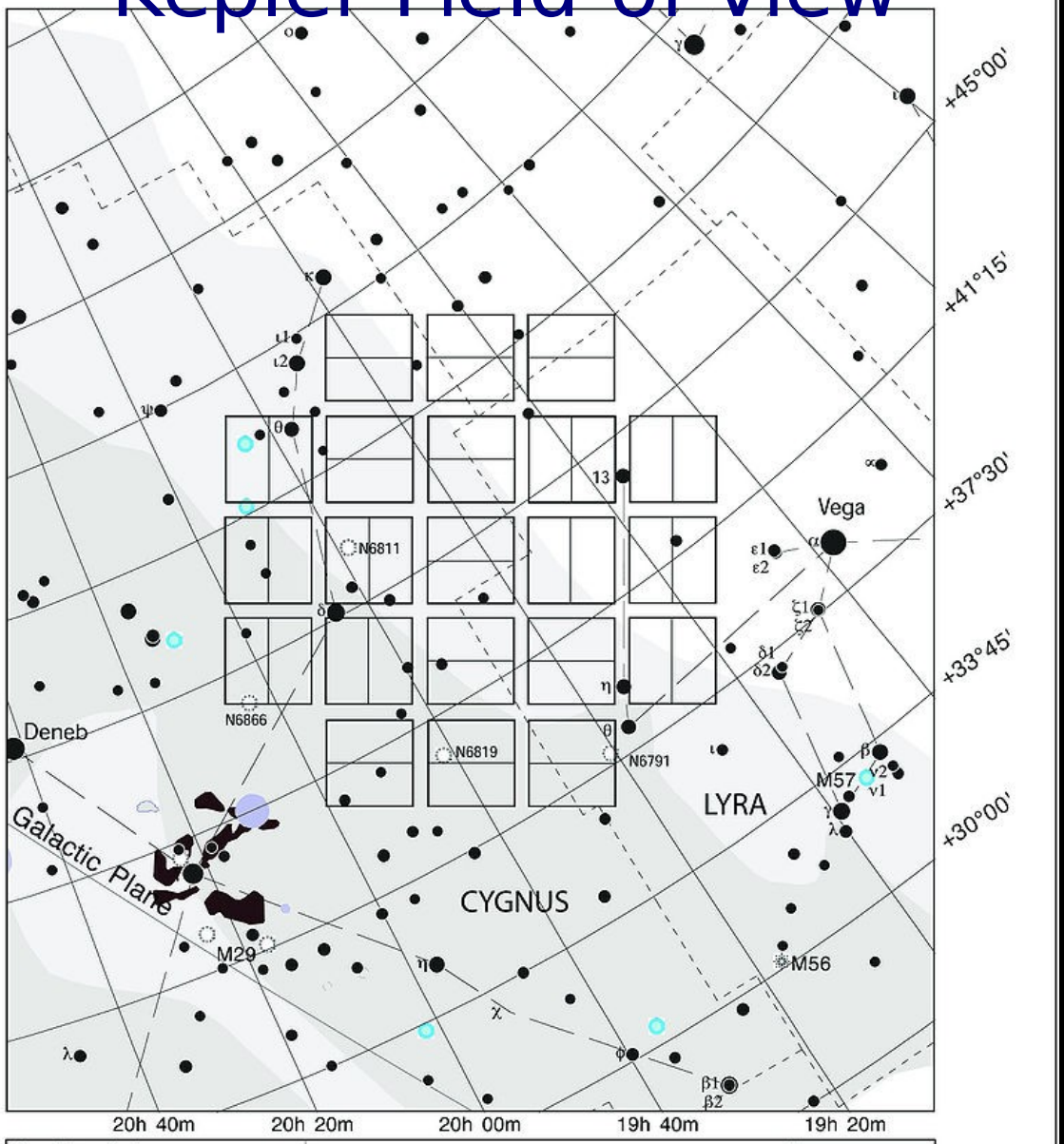
- Has a 0.95 m photometer
- Primary mirror: 1.4 m
- Bandpass: 4300-8900 Angstroms

- Extra-solar planet must be edge on to us
- To reliably detect planets in habitable zone, transits are once per year...must have four

- Second reaction wheel failed 2013 May 11, ending the primary mission.

# Kepler Field-of-View

95 Megapixel detector
42 CCDs
2200x1024 pixels



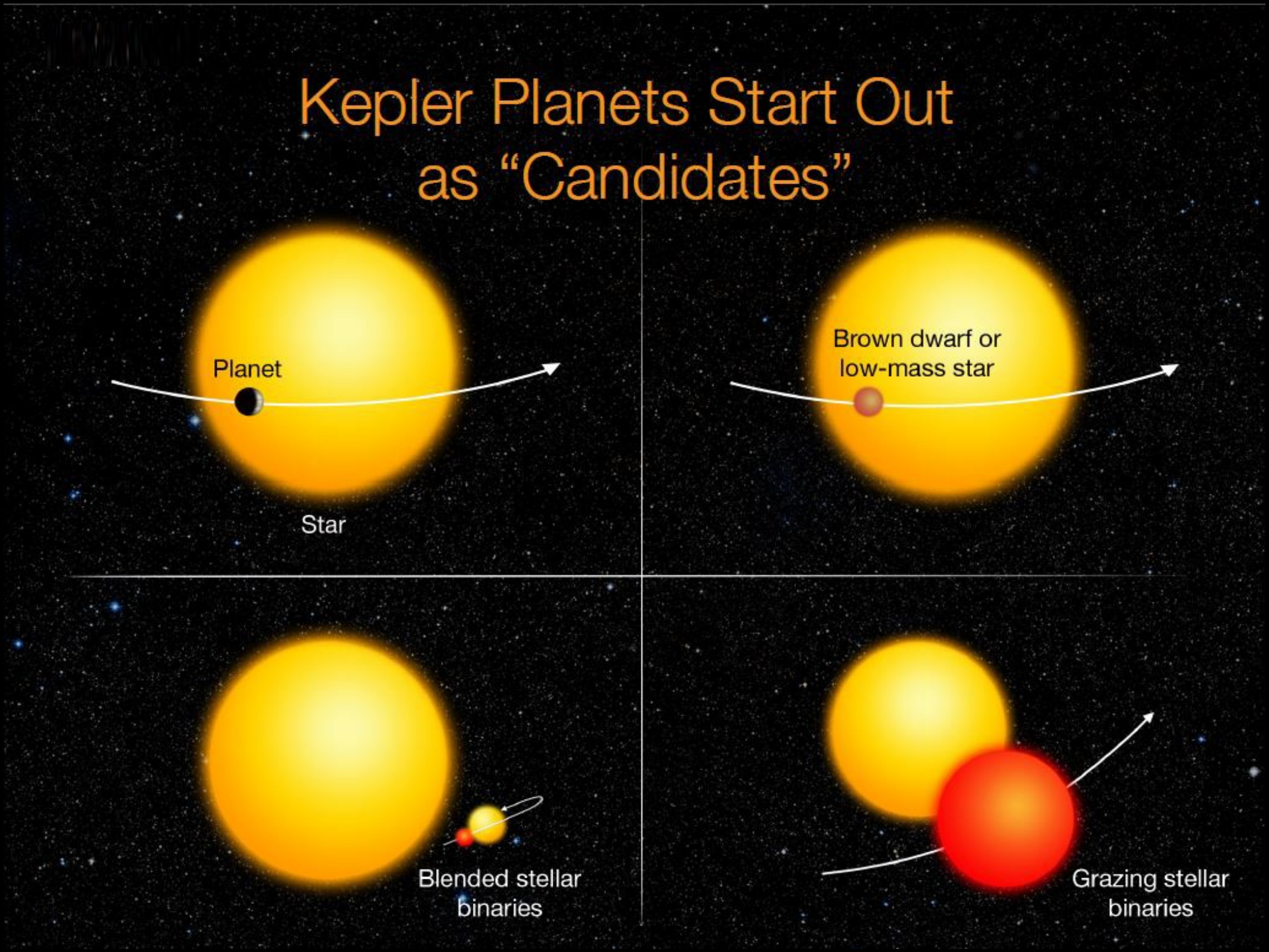

CCDs read out every six seconds

co -added for ~60s (short cadence)

co-added for ~29 min (long cadence)

12 GB download per month

# Kepler Planets Start Out as "Candidates"

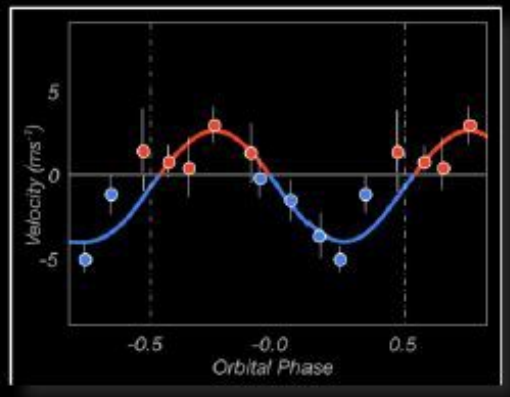


# Planet Verification

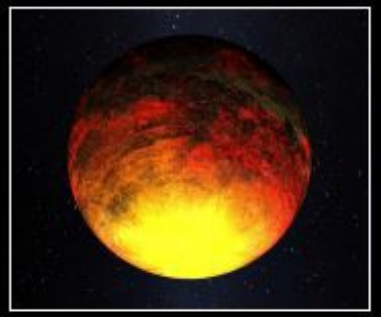
*Often requires extensive follow-up observations*

*W. M. KECK OBSERVATORY*

*RADIAL VELOCITY*

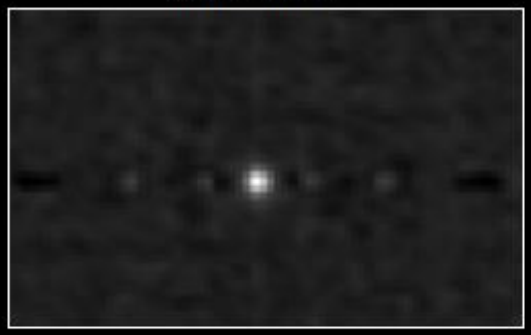



*KEPLER-10b*



*GEMINI NORTH OBSERVATORY*

*IMAGING*



*KEPLER-186f*

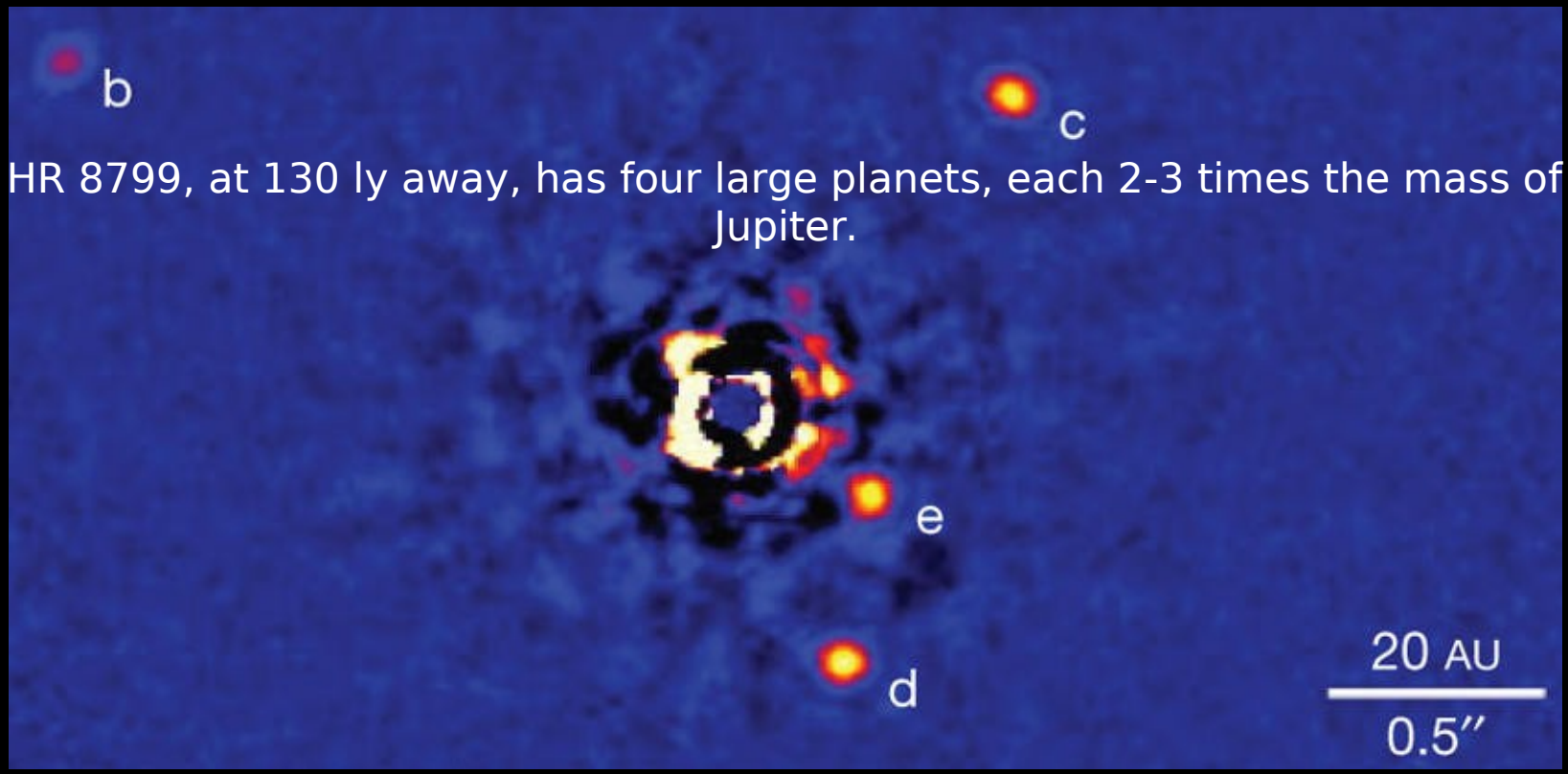
# Intriguing Exoplanets

Kepler-186f, the first rocky planet to be found within the habitable zone, ~500 ly away.

HD 209458b (Osiris), the first exoplanet to be seen in transit. A hot Jupiter, it is 150 ly away.

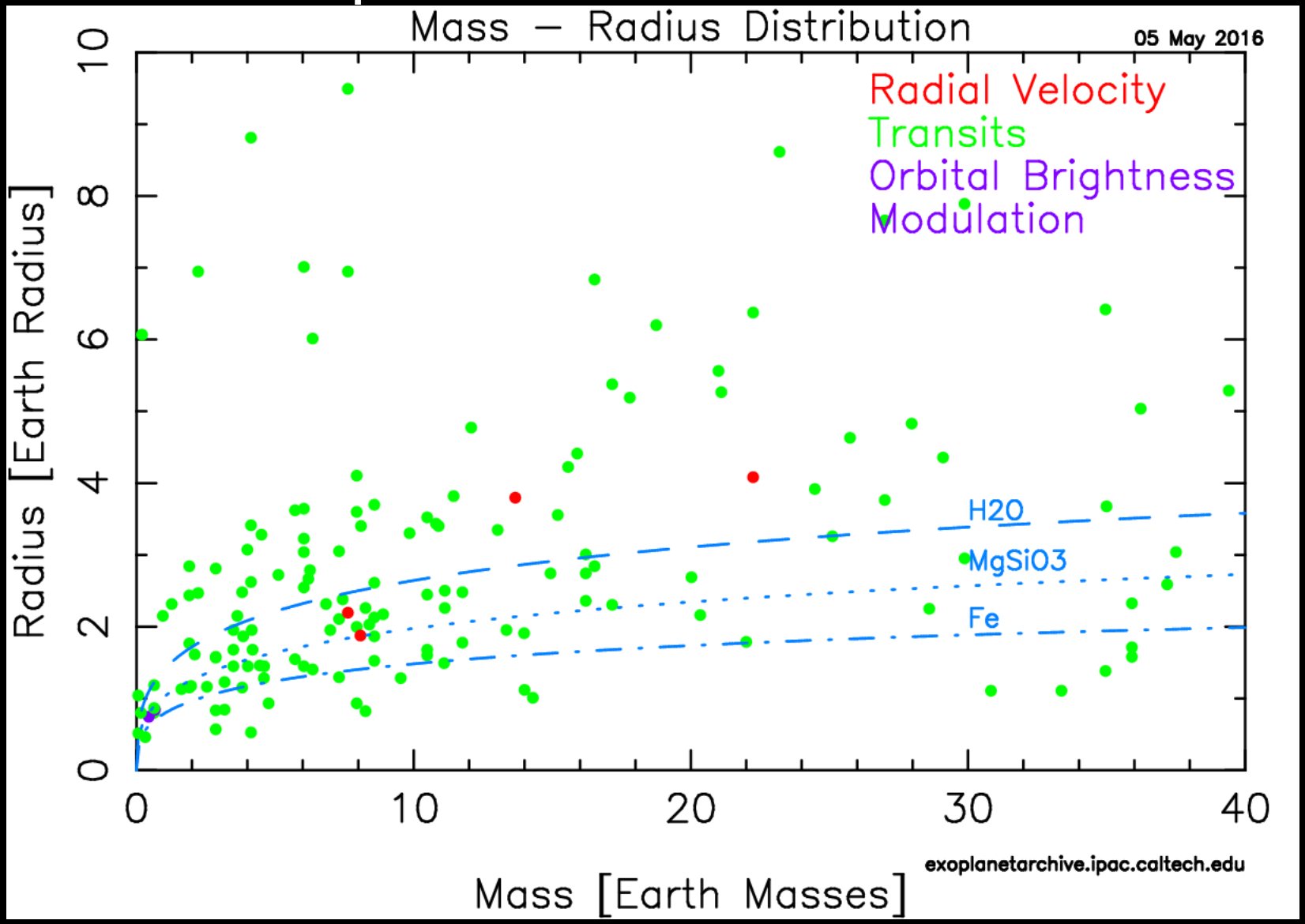
Kepler 22b, at 600 ly away, is in the habitable zone of its Sun-like star.

OGLE-2005-BLG-390Lb (Hoth), ~5.5 times mass of Earth, 20,000 ly away is NOT in the habitable zone. Hoth's orbit is about three times farther out than Earth.




HR 8799, at 130 ly away, has four large planets, each 2-3 times the mass of Jupiter.

# Kepler Mission: Results



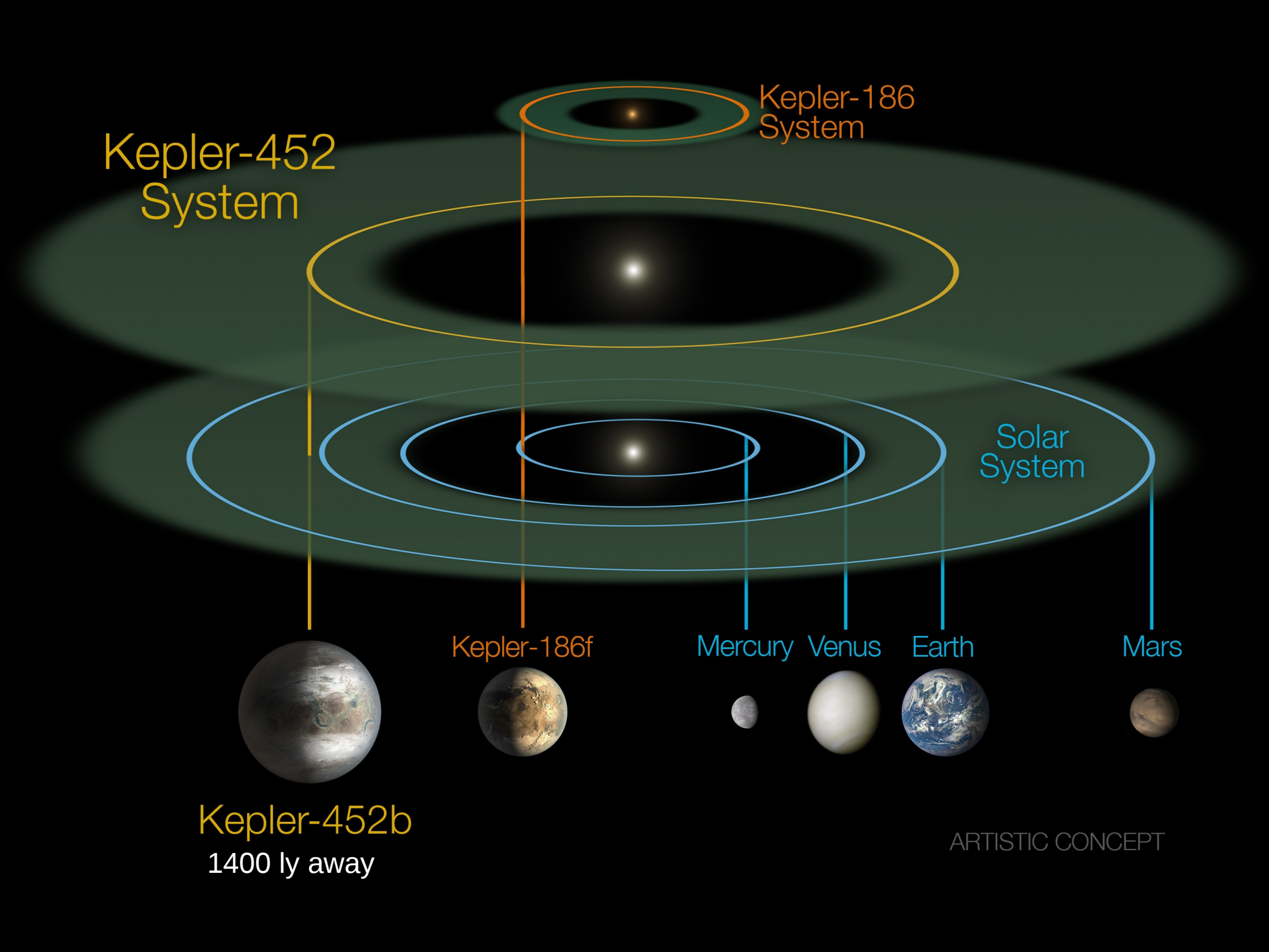

http://kepler.nasa.gov/Mission/discoveries/

1041 Confirmed Planets out of 4706 Candidates

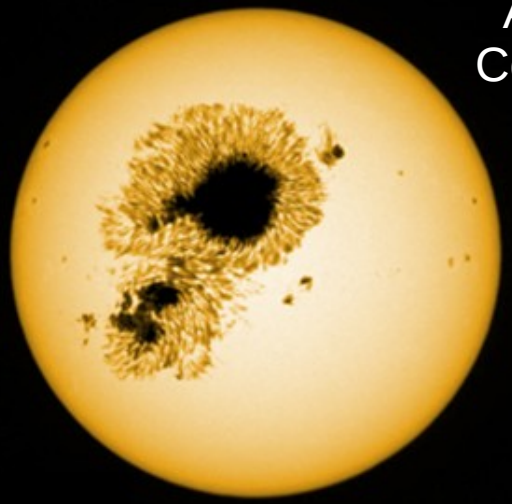
http://exoplanetarchive.ipac.caltech.edu/videos/koi-radiusvperiod-nexsci.mp4

http://exoplanetarchive.ipac.caltech.edu/videos/mass_period_movie_nexsci.mp4

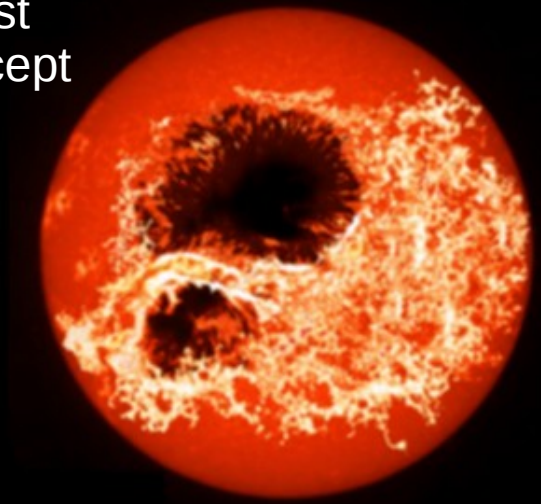
http://exoplanetarchive.ipac.caltech.edu/videos/exo_discovery_histogram.mp4

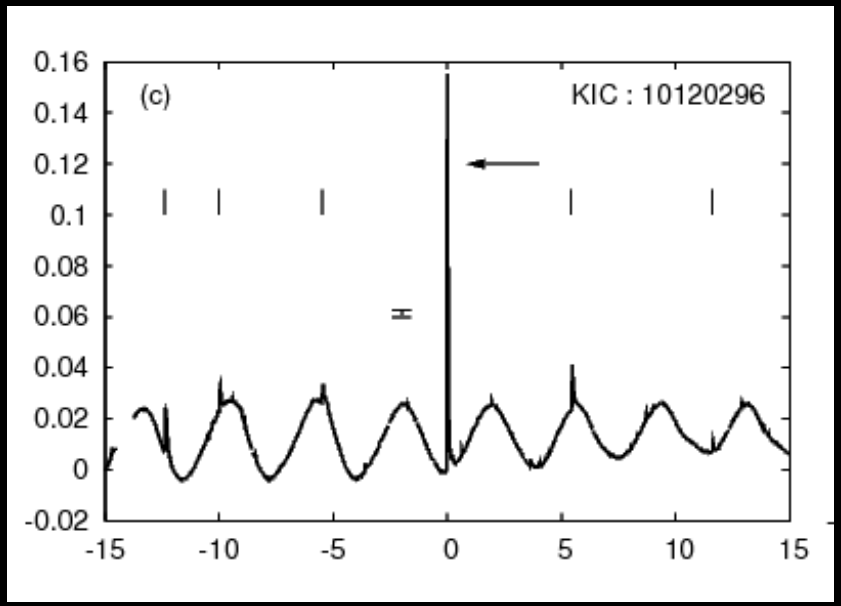

Kepler-452
System
Kepler-186
System
Solar
System
Kepler-186f
Mercury
Venus
Earth
Mars
Kepler-452b
1400 ly away
ARTISTIC CONCEPT

# Not Exoplanets -- Flare Stars



Artist Concept






In a 2013 study, of stars with spectral classes ranging from F8 to G8, 1547 superflares were found on 279 solar-type stars. The most intense events increased the brightness of the stars by 30% and had an energy of $10^{36}$ ergs. White-light flares on the Sun change the brightness by about 0.01%, and the strongest flares have a visible-light energy of about $10^{32}$ ergs.

*Superflares on solar-type stars,* Hiroyuki Maehara, et al., Nature, 2012

Flares common on all stars
Spots on flare stars are, in general, larger than on non-flare stars
Long flares from stars with low surface gravities
Flare energies correlated with stellar luminosity and radius

*Flare stars across the H–R diagram,* L.A. Balona, in MNRAS, 2015

# KIC 8462852: WTF object, Where's the Flux?

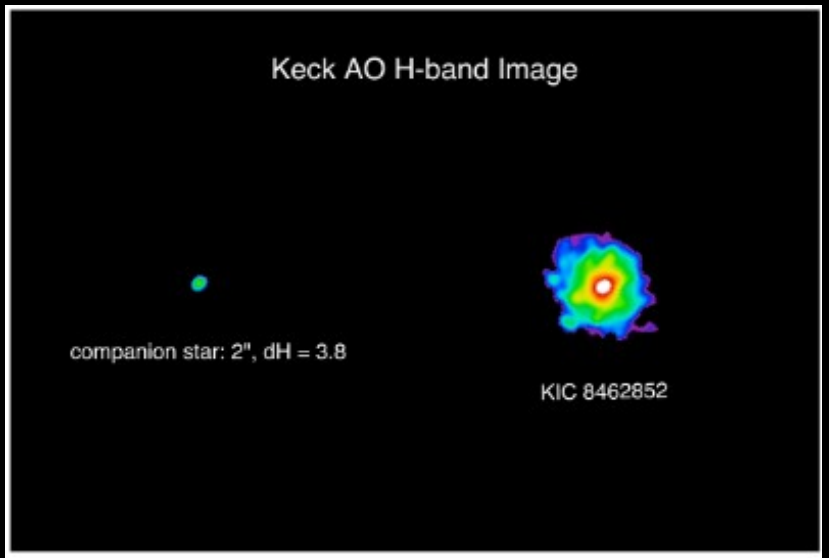



**Figure 7.** Keck AO $H$-band image for KIC 8462852 showing the companion was detected with a $2''$ separation and a magnitude difference $\Delta H = 3.8$. Refer to Section 2.3 for details.

Younger star with coalescing material around it

Planetary debris field

A cloud of disintegrating comets

A megastructure

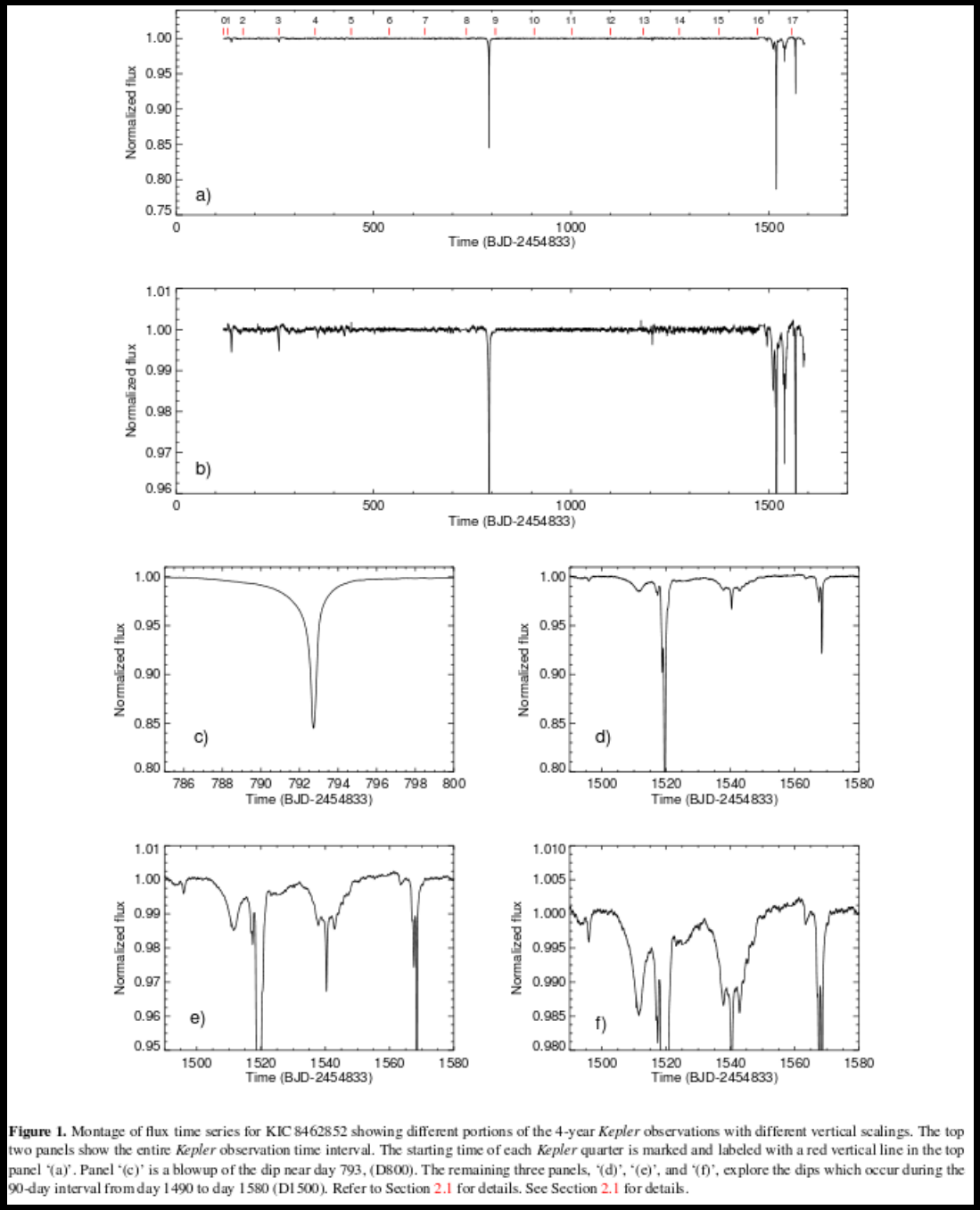
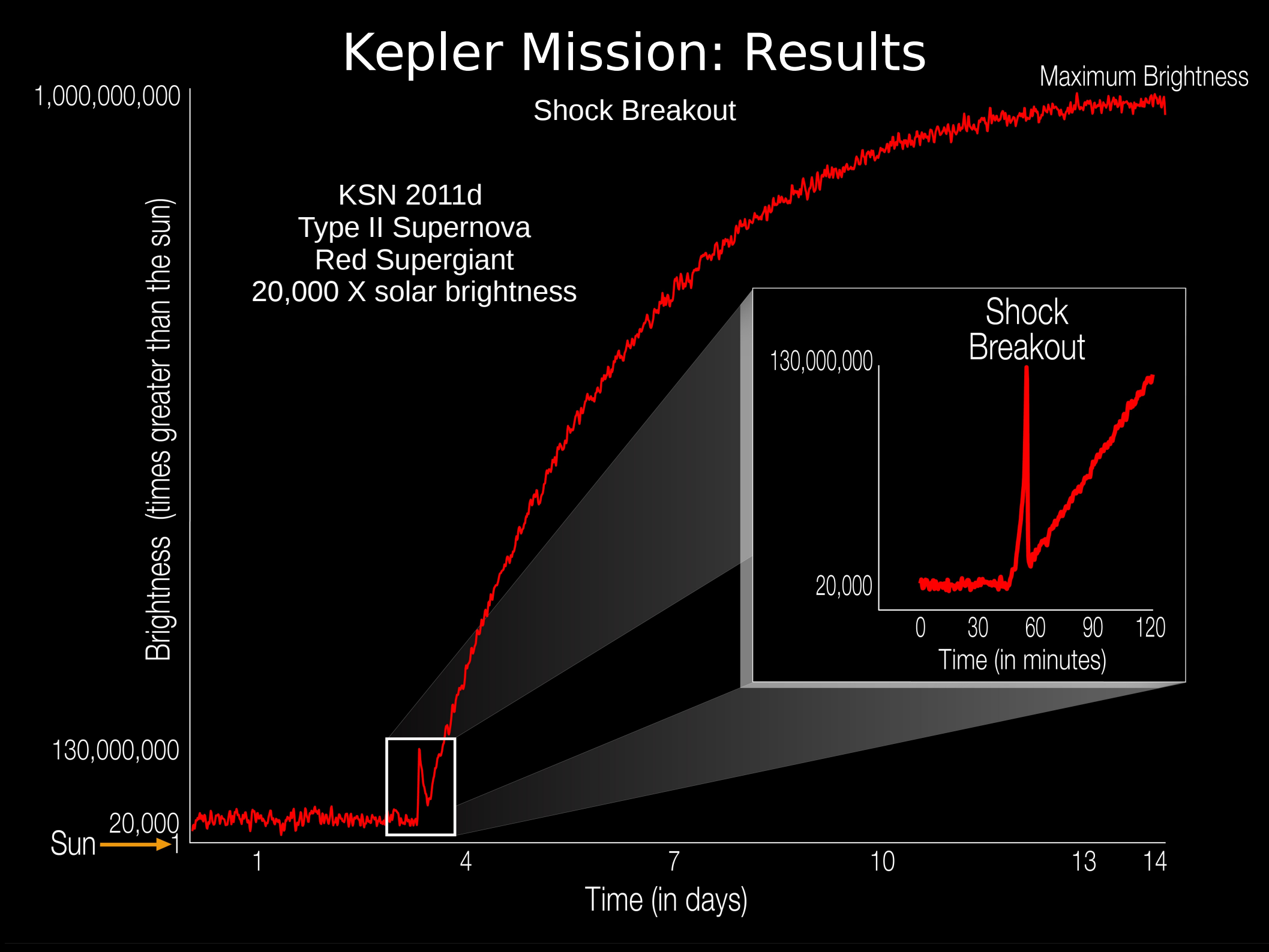


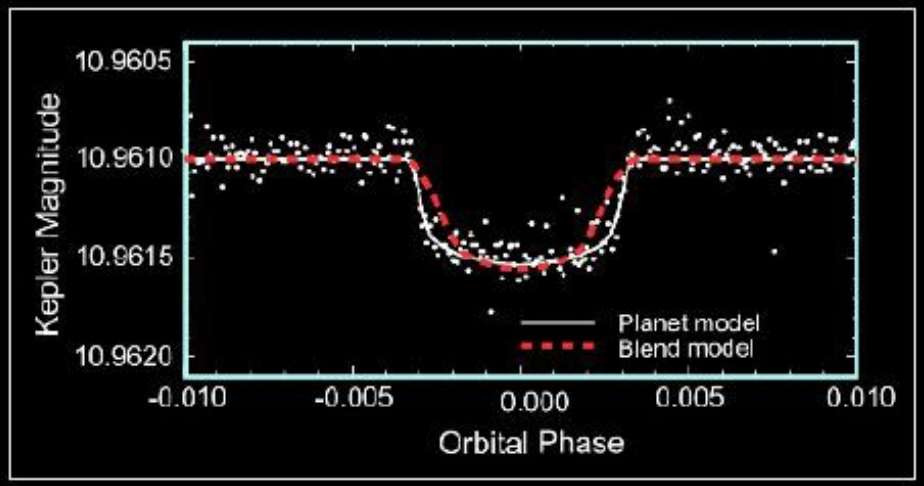

**Figure 1.** Montage of flux time series for KIC 8462852 showing different portions of the 4-year *Kepler* observations with different vertical scalings. The top two panels show the entire *Kepler* observation time interval. The starting time of each *Kepler* quarter is marked and labeled with a red vertical line in the top panel '(a)'. Panel '(c)' is a blowup of the dip near day 793, (D800). The remaining three panels, '(d)', '(e)', and '(f)', explore the dips which occur during the 90-day interval from day 1490 to day 1580 (D1500). Refer to Section 2.1 for details. See Section 2.1 for details.

# Kepler Mission: Results



# New Validation Method

Does the signal look like a planet?

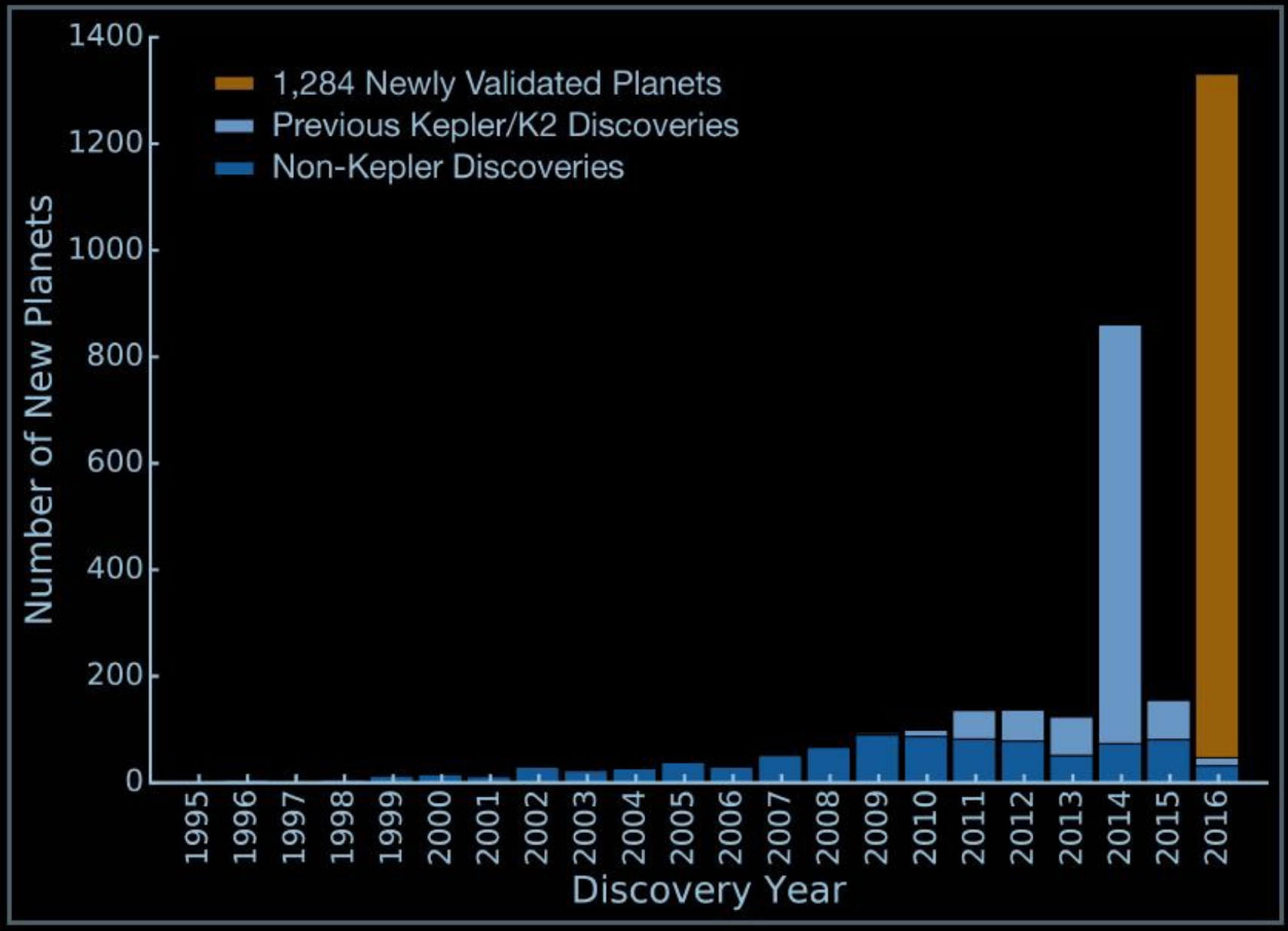



How common are imposters?

Results in ApJ paper: *FALSE POSITIVE PROBABILITIES FOR ALL KEPLER OBJECTS OF INTEREST: 1284 NEWLY VALIDATED PLANETS AND 428 LIKELY FALSE POSITIVES;* Timothy D. Morton, *et al.*
http://www.astro.princeton.edu/~tdm/koi-fpp/ms.pdf

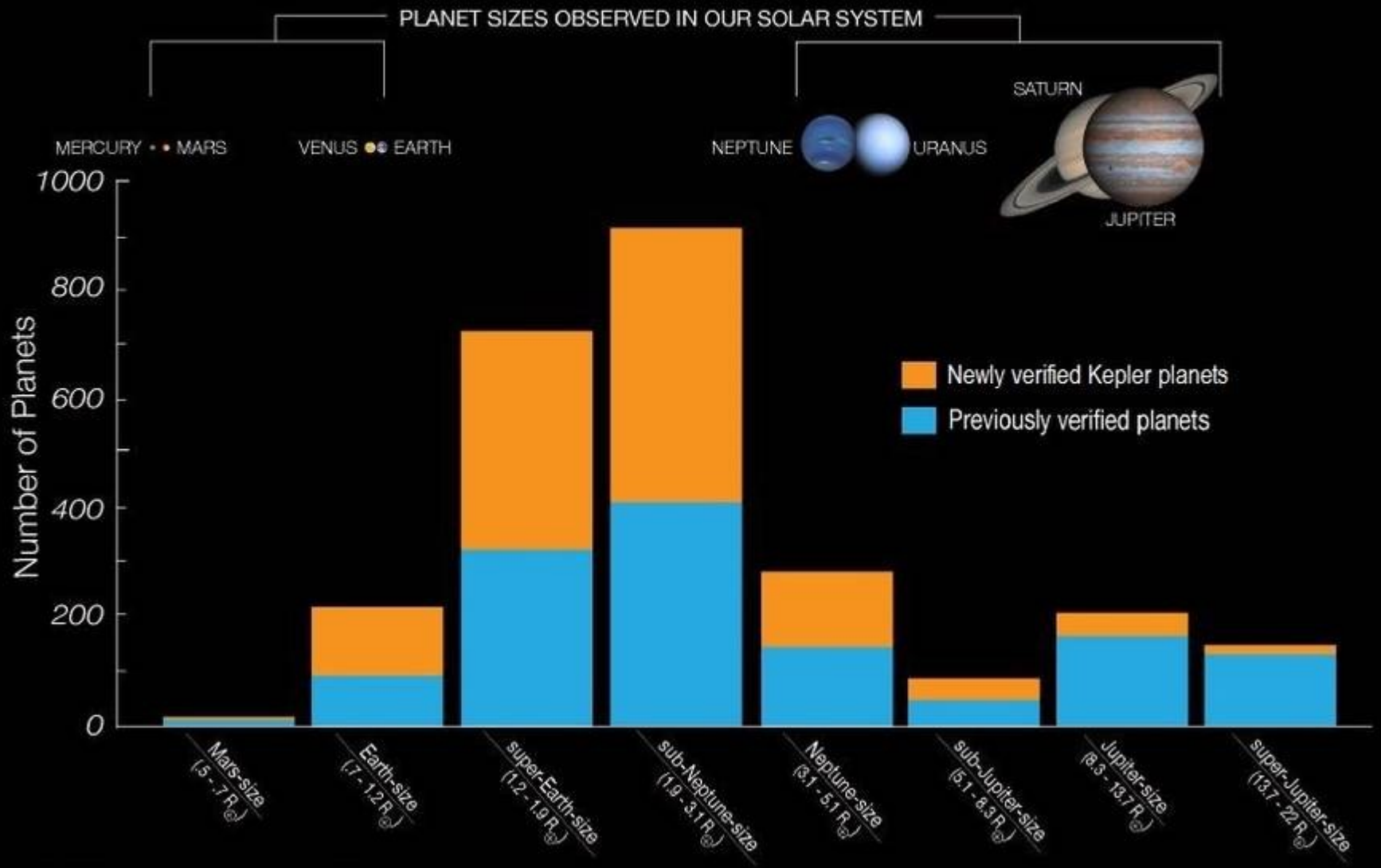
# Exoplanet Discoveries Through the Years

*As of May 10, 2016*



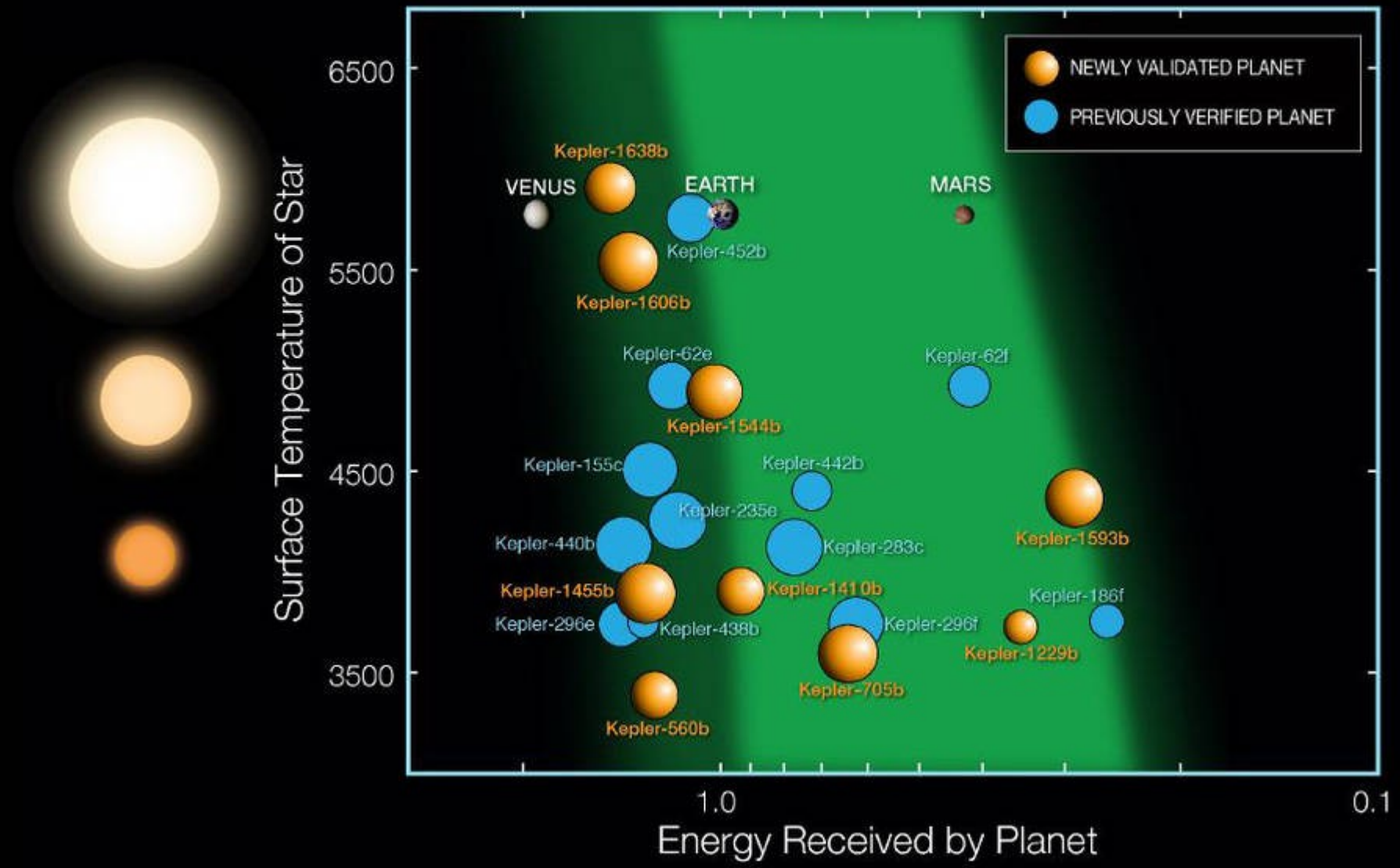
# Known Planets by Size

*As of May 10, 2016*



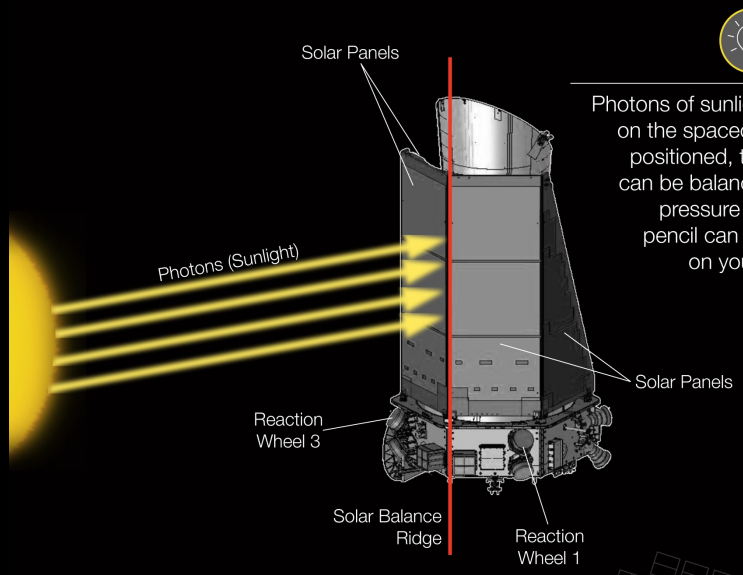
# Kepler's Small Habitable Zone Planets

*As of May 10, 2016*

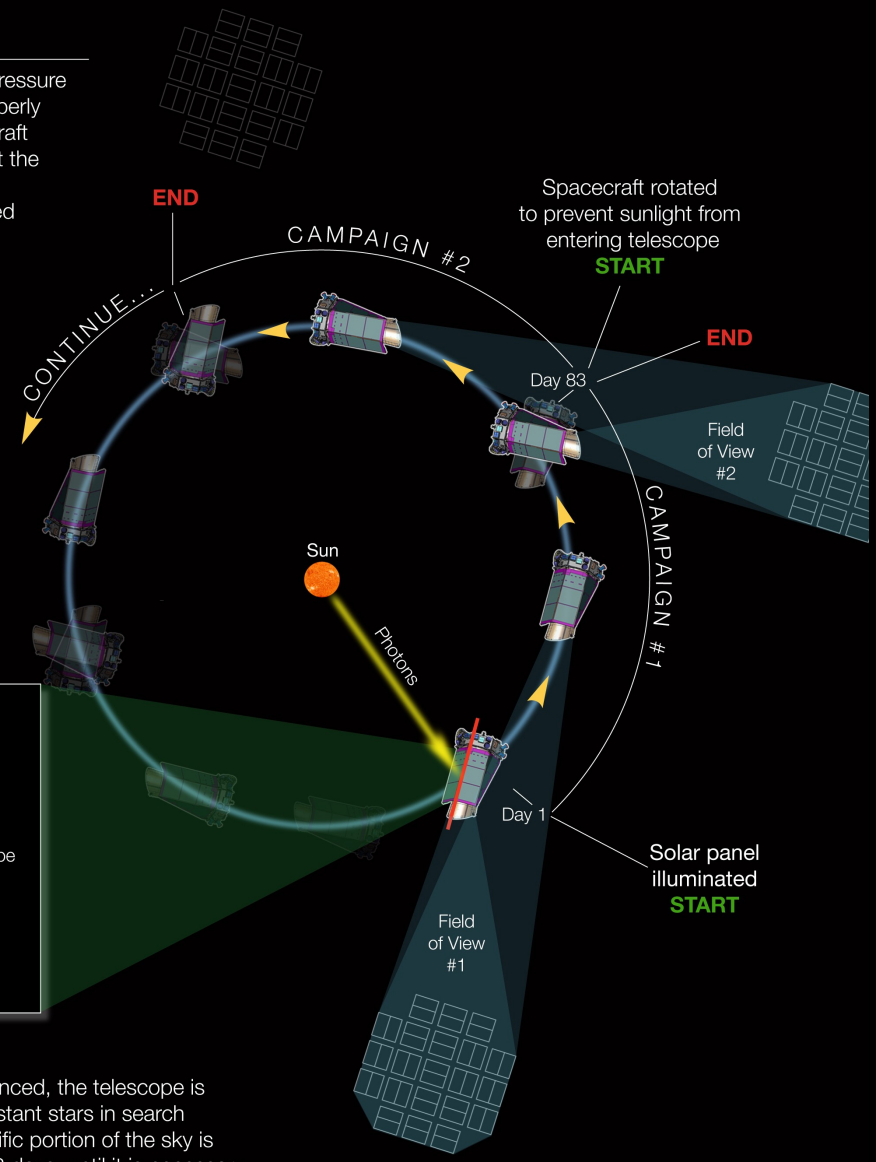



Closest Earth-like planet in habitable zone (statistically) at about 11 ly
(Natalie Batalha during press conference May 10, 2016)

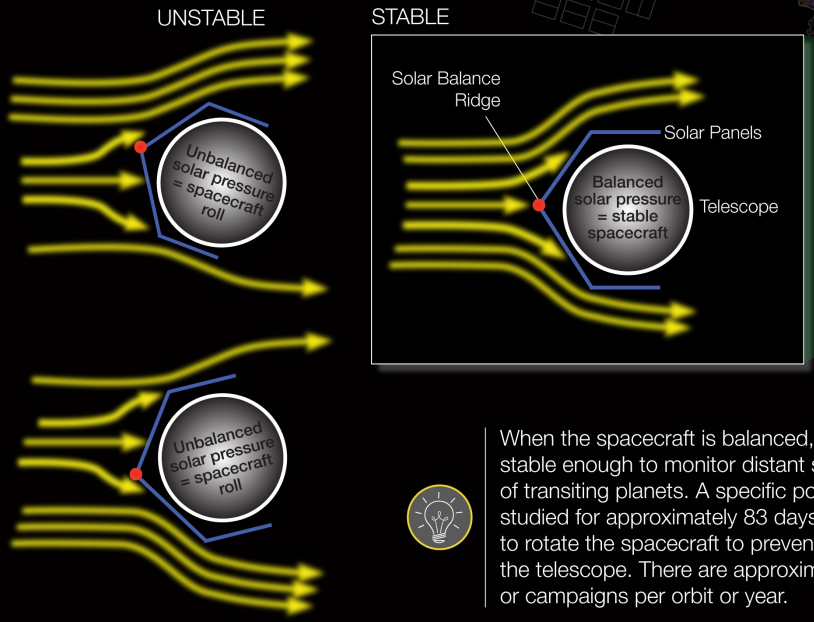
# Kepler's Second Light: How K2 Will Work




Photons of sunlight exert pressure on the spacecraft. If properly positioned, the spacecraft can be balanced against the pressure much as a pencil can be balanced on your finger.




TOP-DOWN VIEWS OF SPACECRAFT

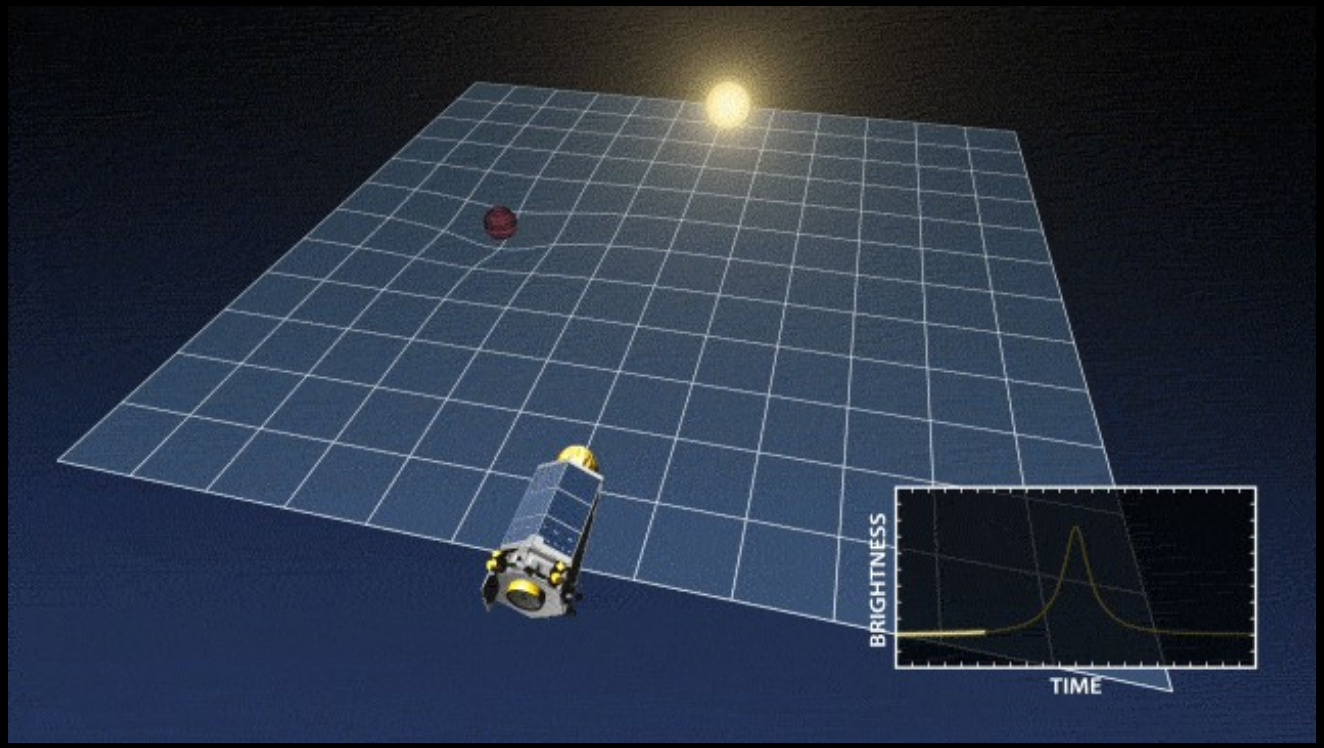



When the spacecraft is balanced, the telescope is stable enough to monitor distant stars in search of transiting planets. A specific portion of the sky is studied for approximately 83 days, until it is necessary to rotate the spacecraft to prevent sunlight from entering the telescope. There are approximately 4.5 viewing periods or campaigns per orbit or year.

CONCEPTUAL ILLUSTRATION OF SPACECRAFT SOLAR DISTURBANCE. THE ACTUAL DISTURBANCE IS DUE TO PHOTON PRESSURE, NOT SOLAR WIND.

# Kepler Mission: Reconfiguring for Gravitational Lensing

Along with ground-based observatories, *K2* will survey millions of stars in the direction of the center of the Milky Way for evidence of even more exoplanets.



# Exoplanet Missions

JWST

WFIRST

TESS

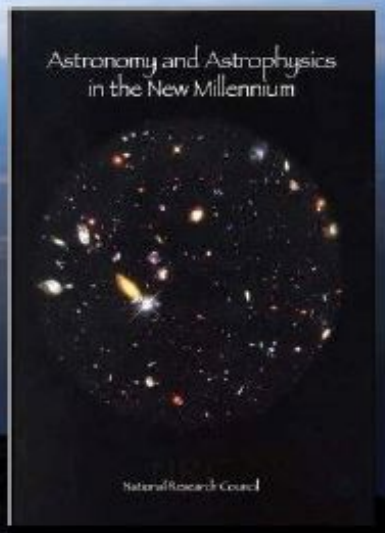
Kepler & K2

*New Worlds Telescope*

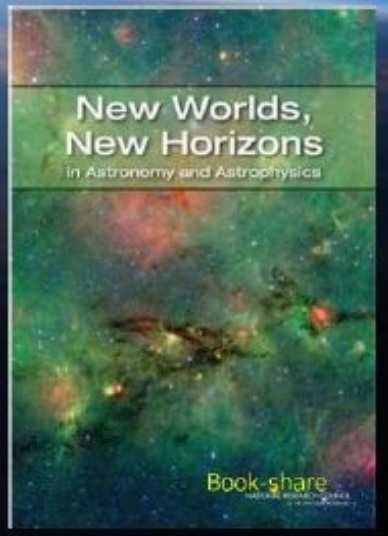
Spitzer

Hubble

Ground-based Observatories




**2001** Decadal Survey




**2010** Decadal Survey

# Mission Perspective

Kepler collected data for 4 years and produced a remarkable data set that will be used for decades.

Approximately 2 more years of fuel

The K2 mission is extending Kepler's legacy to new parts of the sky and new fields of study.

Together with other missions, Kepler and K2 are a part of this Arc of Discovery.

984 previously confirmed, 1284 newly validated

100,000,000 stars, 70% main sequence, 25% M stars...