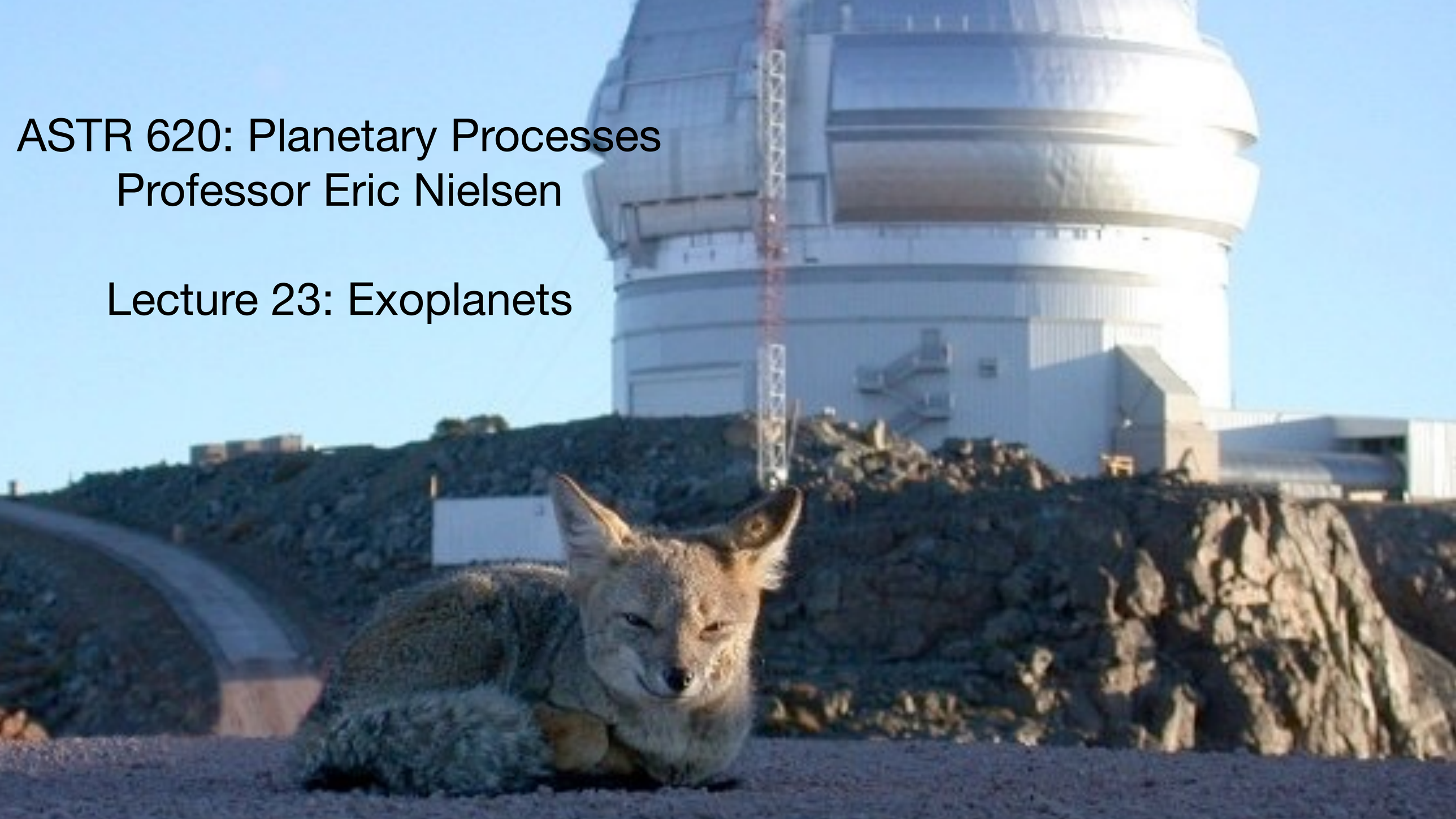


ASTR 620: Planetary Processes

Professor Eric Nielsen

Lecture 23: Exoplanets

Logistics

- Masks are encouraged
- No laptops, phones, or other electronic devices during class (I'll let you know in advance if we'll need laptops for an activity) **You may use a tablet to take notes if prefer, but please only use it for note-taking.**
- Remember to bring you response card to class
- Order of Magnitude project written assignment due Monday, November 14 at the start of class

STUDENT:	First Question	Second Question	Presentation slot
Asif Abbas	19	24	Wednesday 1
Erick Aguirre	7	25	Monday 5
Neha Babbar	10	12	Wednesday 5
Kevin Brooks	5	9	Monday 3
Sarah Chinski	18	27	Monday 7
Anna Conly	15	23	Wednesday 7
Victoria De Cun	16	28	Monday 6
Dylan Gatlin	3	13	Monday 2
Daniel Godines Alcantara	1	17	Monday 1
Ezra Huscher	21	26	Wednesday 6
Khagendra Katuwal	4	22	Monday 4
Jessica Klusmeyer	14	20	Wednesday 2
Julio Morales	2	8	Wednesday 4
Annie Peck	6	11	Wednesday 3

Review of the last class

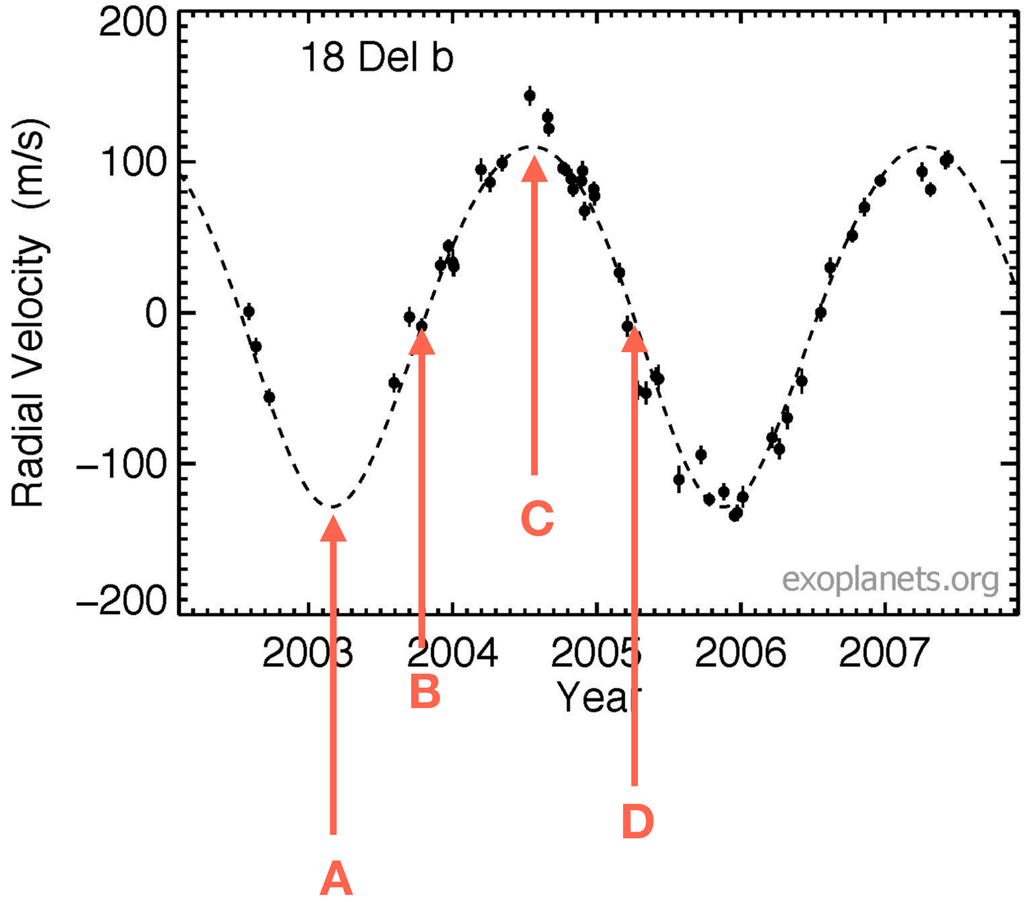
- An alien astronomer is trying to detect Jupiter and Earth via the transit method. What are the chances that each planet will transit, and if they do transit (with i=90.0 degrees), how long do the two transits last?
  - (A) — Earth is more likely to transit than Jupiter, and Earth's transit will last longer
  - (B) — Earth is less likely to transit than Jupiter, and Earth's transit will last longer
  - (C) — Earth is more likely to transit than Jupiter, and Jupiter's transit will last longer
  - (D) — Earth is less likely to transit than Jupiter, and Jupiter's transit will last longer
  - (E) — Both planets have an equal chance of transiting, and the transits would last the same length of time

Review of the last class

- The transit method allows us to measure:
  - (A) — size of the planet (if we know size of the star), mass of the planet (if we know the mass of the star), inclination angle, and semi-major axis
  - (B) — size of the planet (if we know size of the star), mass of the planet (if we know the mass of the star), inclination angle, and period
  - (C) — size of the planet (if we know size of the star), inclination angle, and semi-major axis
  - (D) — size of the planet (if we know size of the star), inclination angle, and period
  - (E) — size of the planet (if we know size of the star) and period

Review of the last class

- If 18 Del b had a 90 degree inclination angle (it doesn't, sadly), when would we expect secondary eclipse to happen?
  - (A) — 2003.2
  - (B) — 2003.8
  - (C) — 2004.5
  - (D) — 2005.3
  - (E) — There's not enough information to narrow it down to one of these options

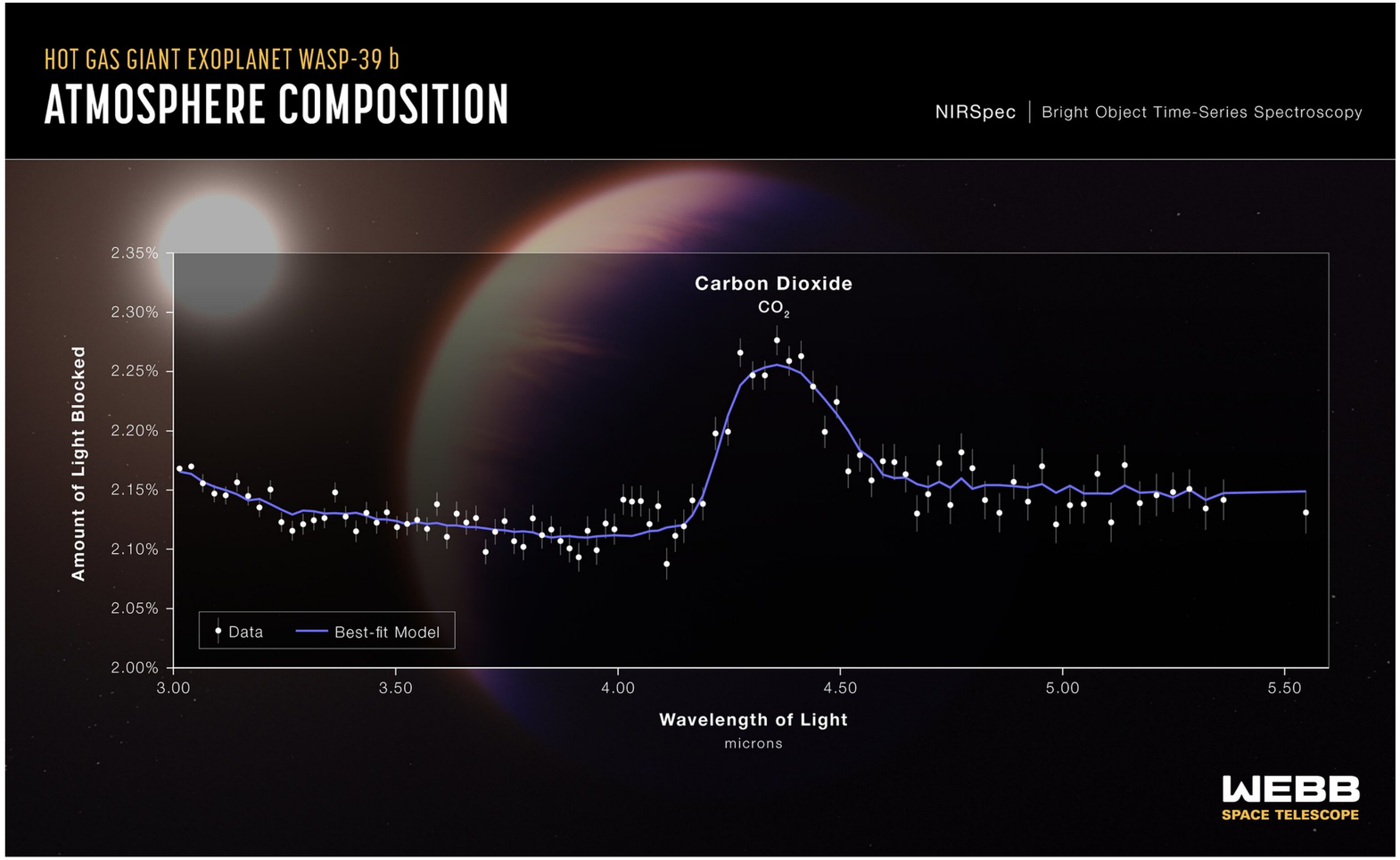


Review of the last class

- If (when observing from outside our Solar System) Earth transits the Sun, how much fainter does the Sun get?
  - (A) — 10% fainter
  - (B) — 1% fainter
  - (C) — 0.1% fainter
  - (D) — 0.01% fainter
  - (E) — 0.001% fainter

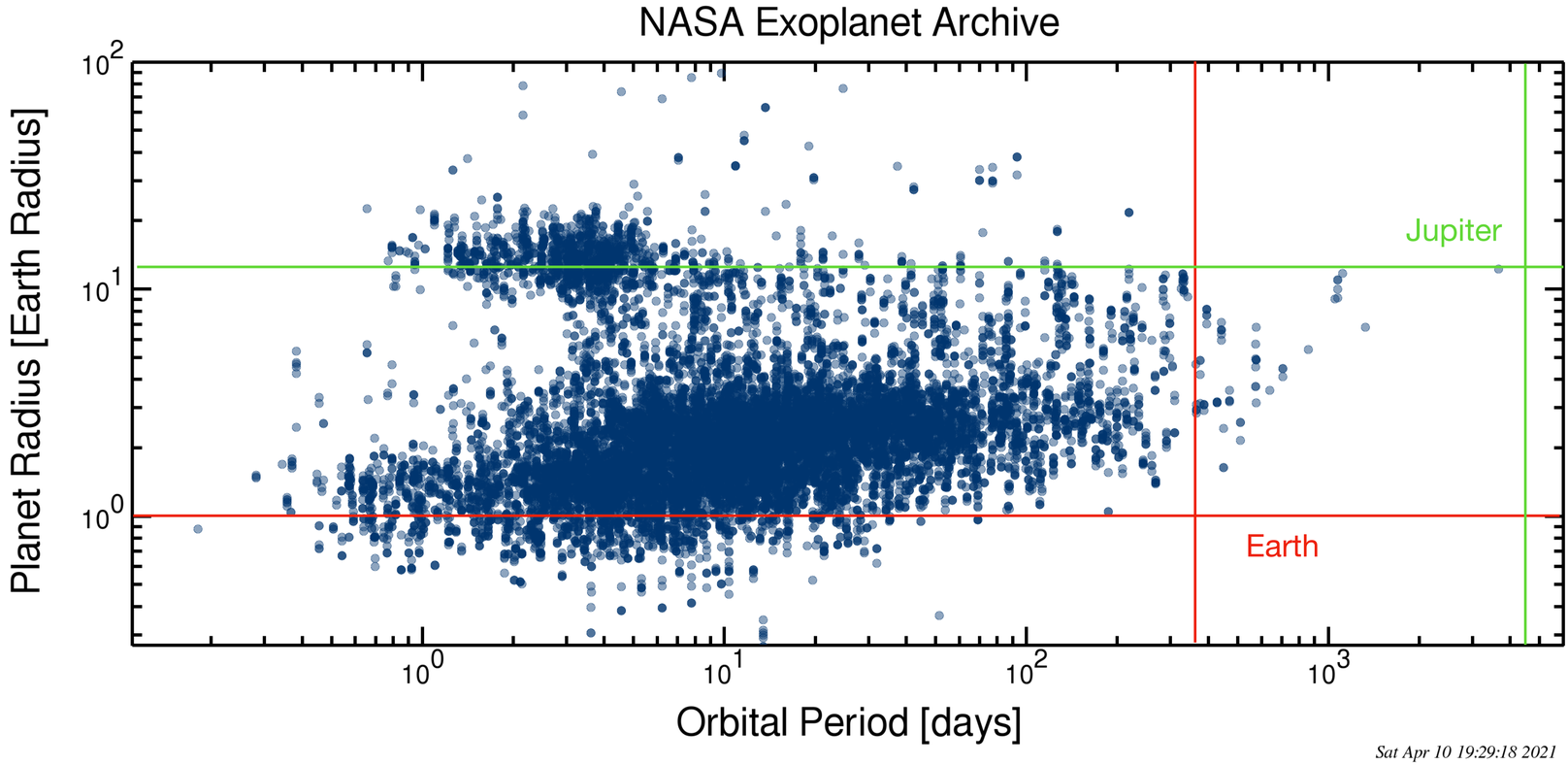
Review of the last class

- This plot shows amount of light blocked vs. wavelength. Is the carbon dioxide feature at 4.4 microns an absorption feature or an emission feature?
  - (A) — Absorption
  - (B) — Emission
  - (C) — There's no way to tell



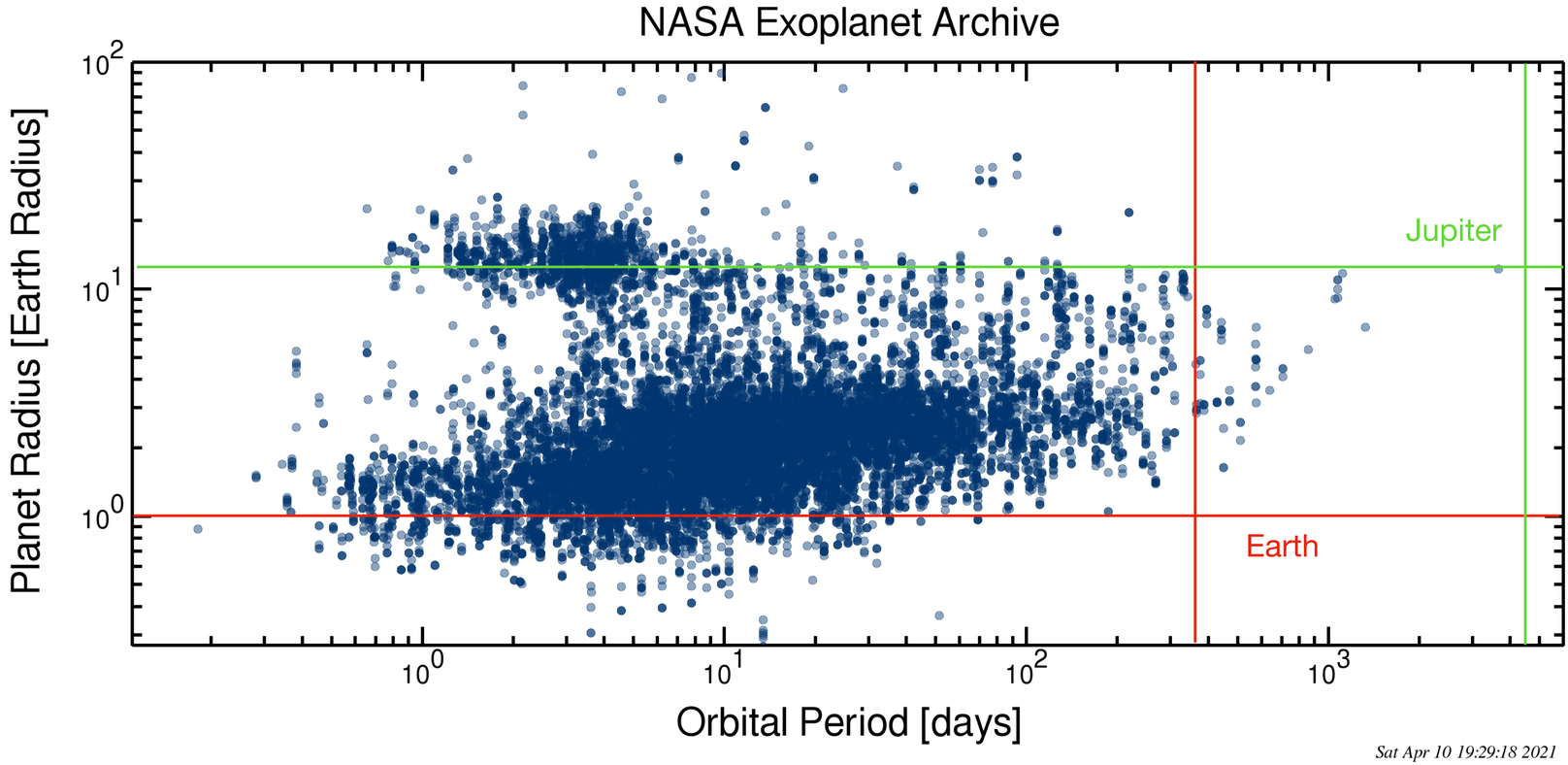
The Transit Method

- Can measure:
  - orbital period and inclination angle
  - planet size
  - spectra of atmosphere (for the best cases)



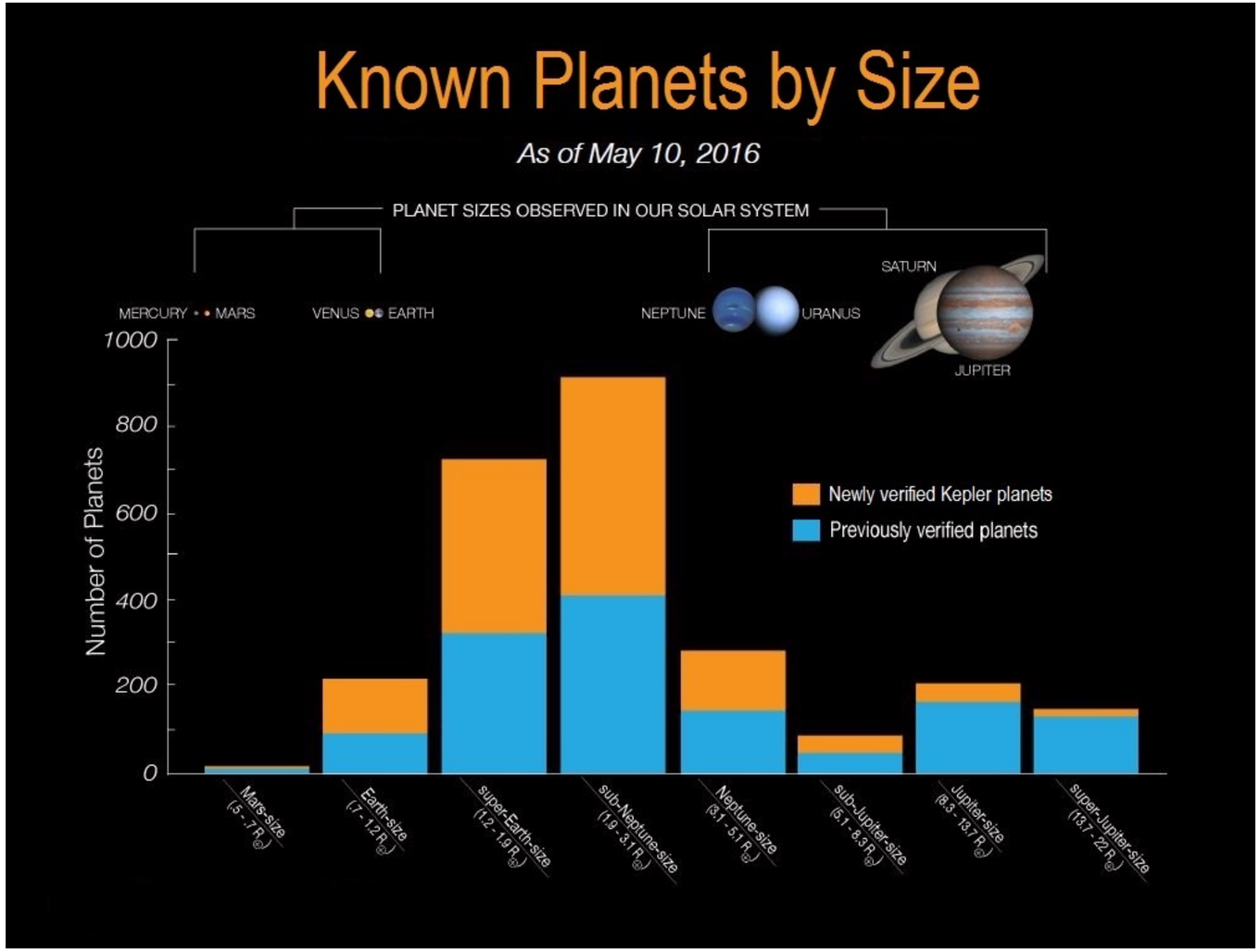
The Transit Method

- Biases:
  - Close-in planets are most likely to transit, and are easier to detect (more transits during your observing window)
  - Larger planets are much easier to detect (block out more light)
  - Planets are easier to detect around smaller stars
  - Non-transiting planets (inclination not near 90 degrees) can't be detected



Two new types of Planets

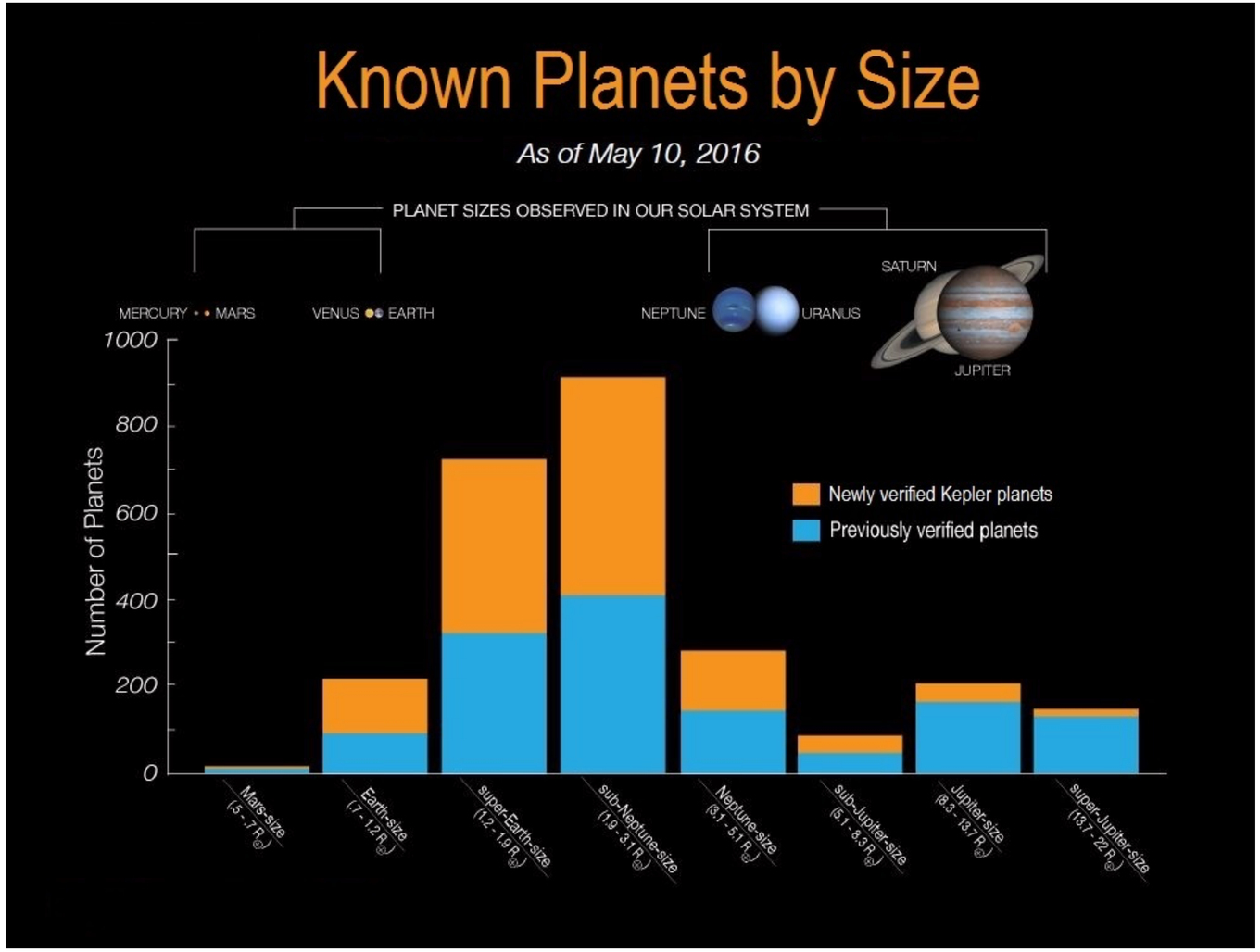
- Important caveat: almost all Kepler exoplanets orbit closer to their star than Mercury orbits the Sun
- Also: numbers are very incomplete for Earth-sized planets and smaller
- In terms of planet size, most planets found by Kepler are between the size of Earth, and the size of Neptune



NASA/Kepler

Two new types of Planets

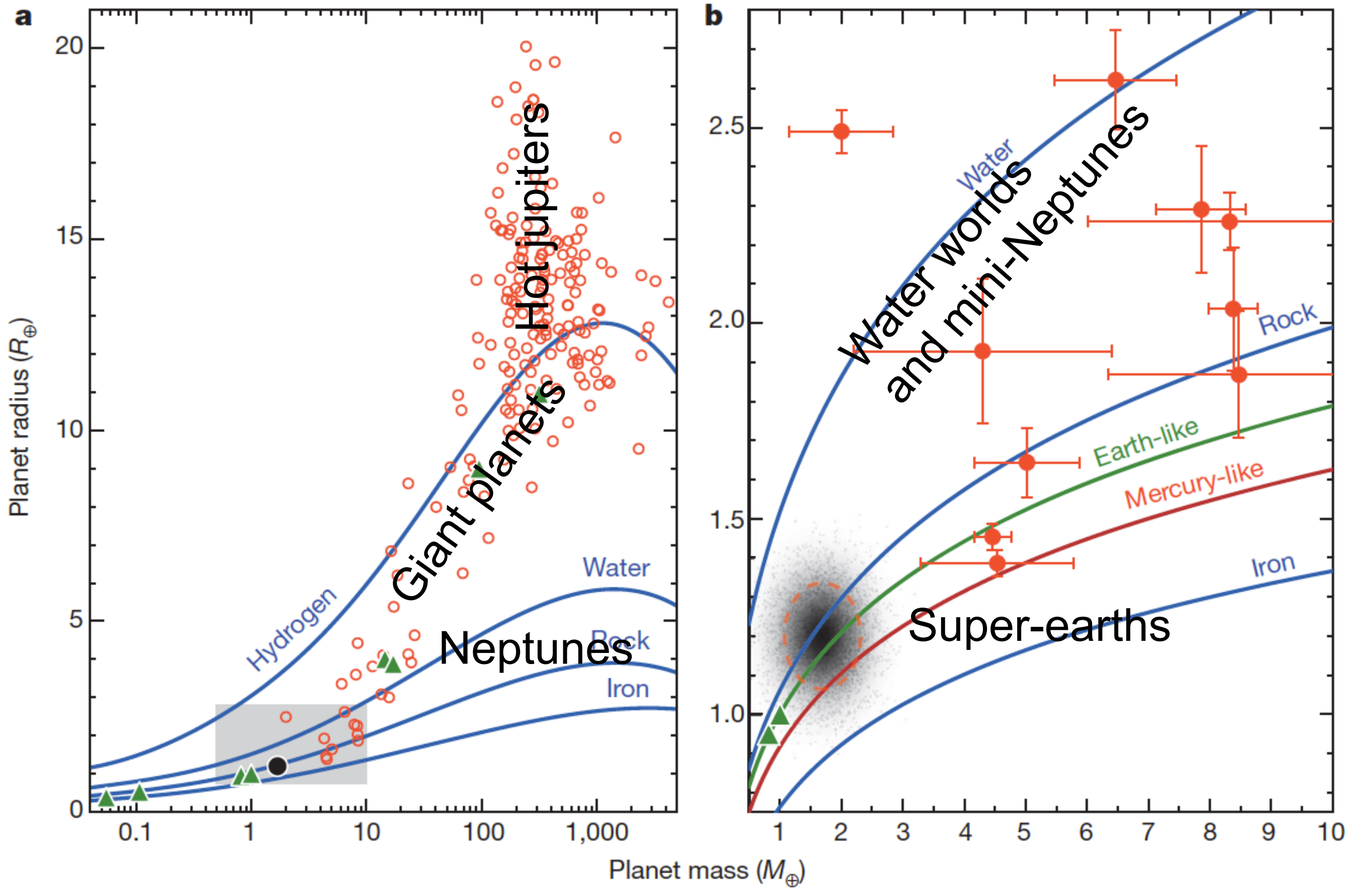
- “Mini Neptunes” look to be ice giants, but smaller than Neptune
- “super Earths” look to be rocky planets, but larger than Earth
- We have no analog for planets that size in our own Solar System
- Ongoing question how important proximity to the host star is: did these exoplanets lose most of their atmosphere from photoevaporation and stellar wind stripping?



NASA/Kepler

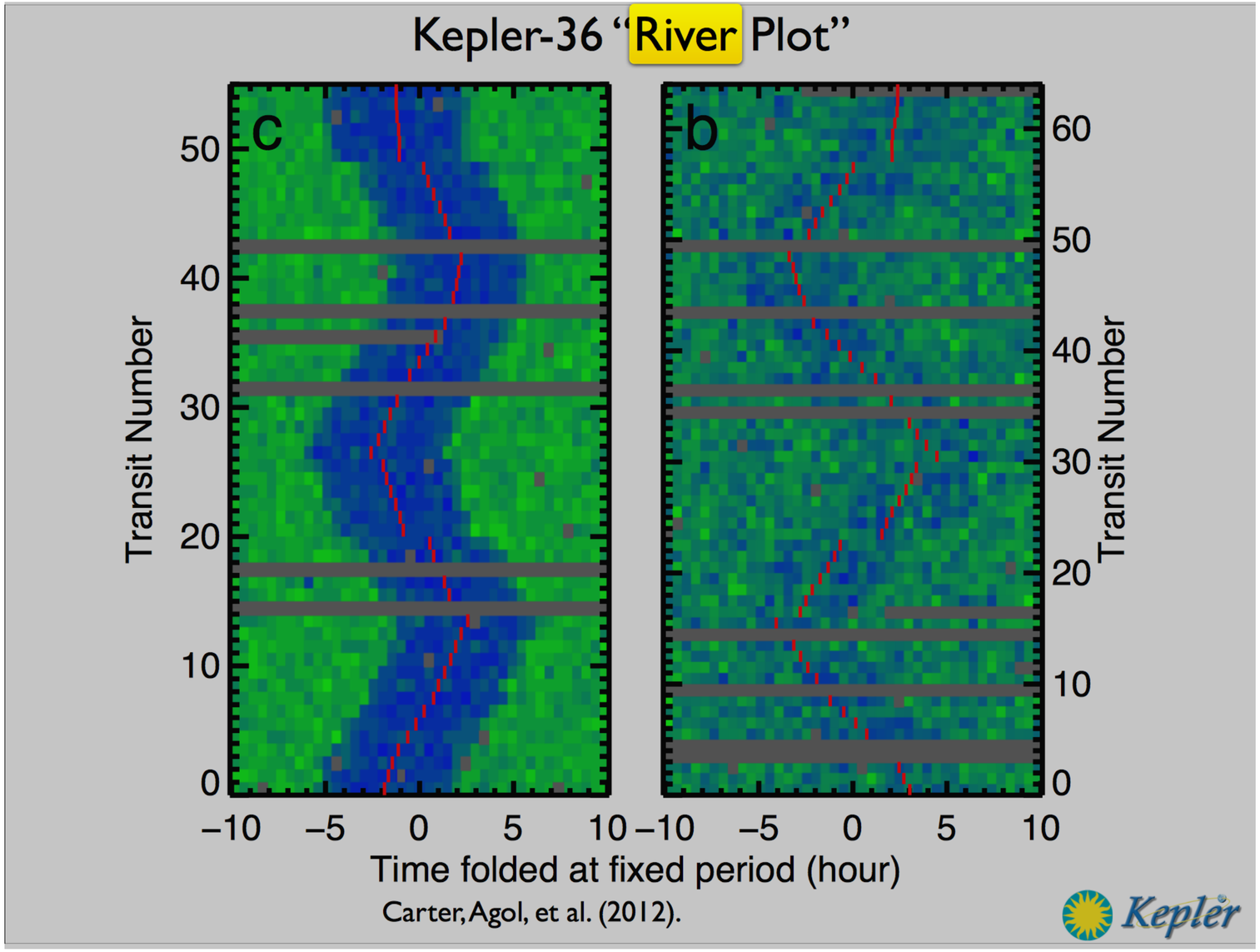
Planet Density

- By observing the same planet with radial velocity and transits, we can measure the density of the planet:
  - Radial velocity gives us mass * sin(i)
  - Transits give us planet size (radius), and inclination angle (almost all transits are within a few degrees of edge on)
  - Density = mass / volume
- Can infer composition from the bulk density of exoplanets

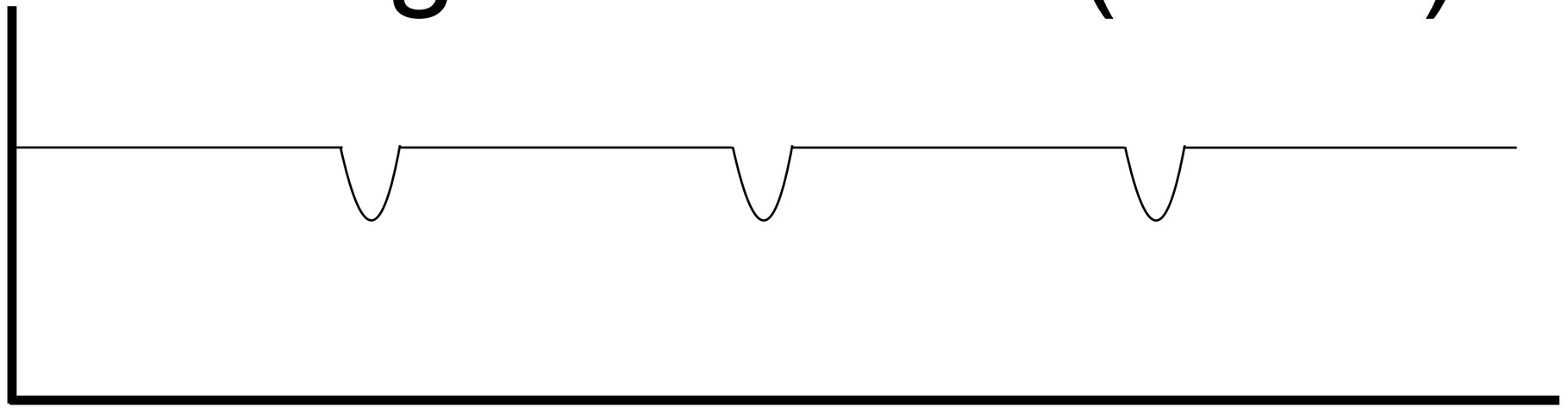


Howard et al. 2014

Transit Timing Variations (TTVs)



Transit Timing Variations (TTVs)



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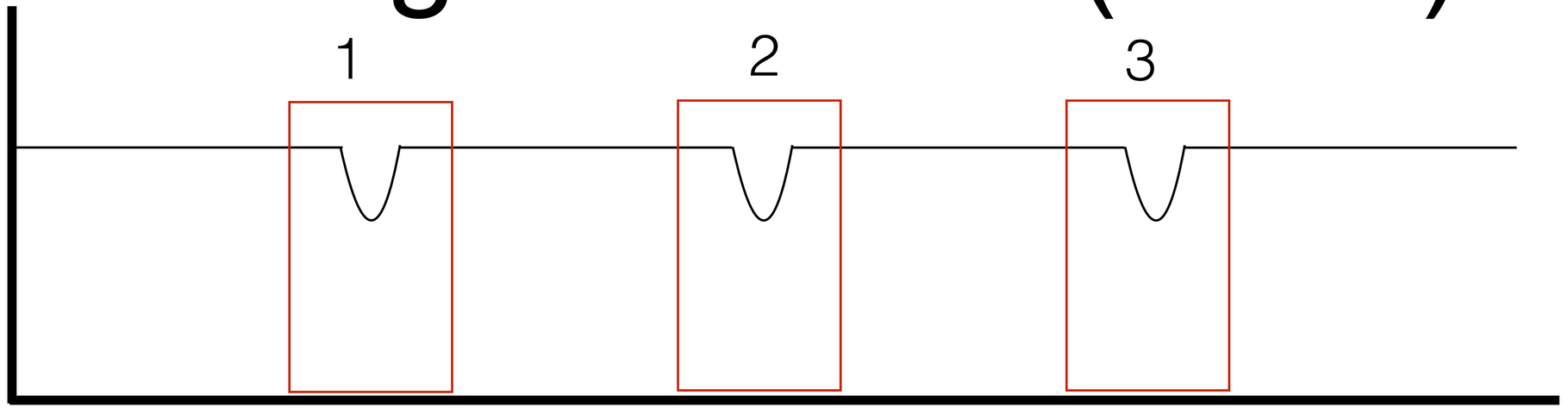
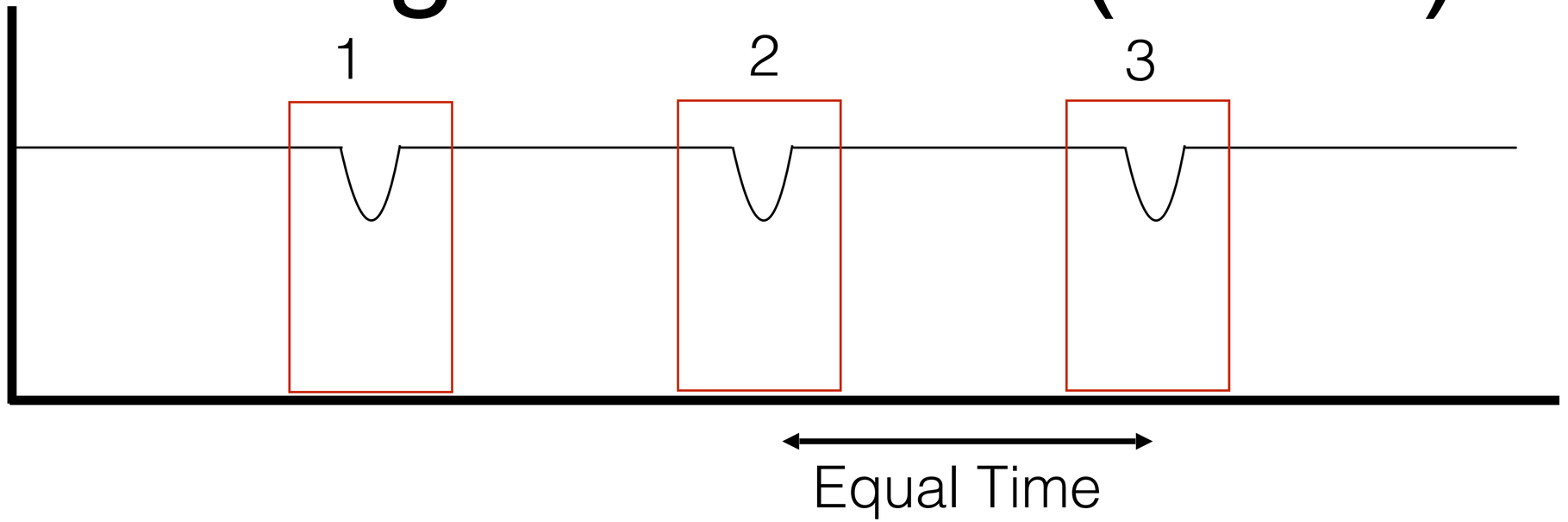


Transit Timing Variations (TTVs)



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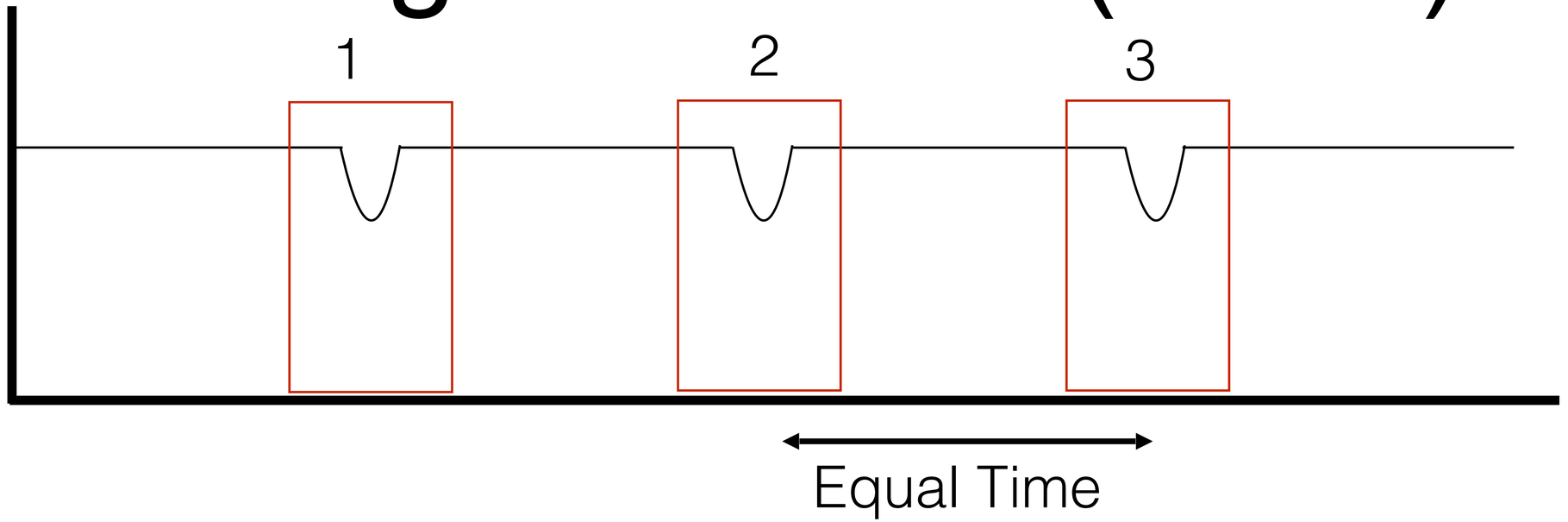

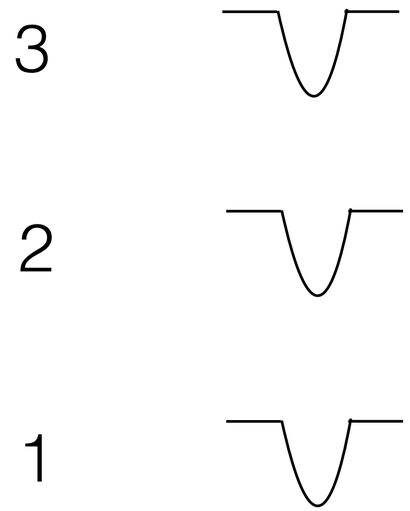

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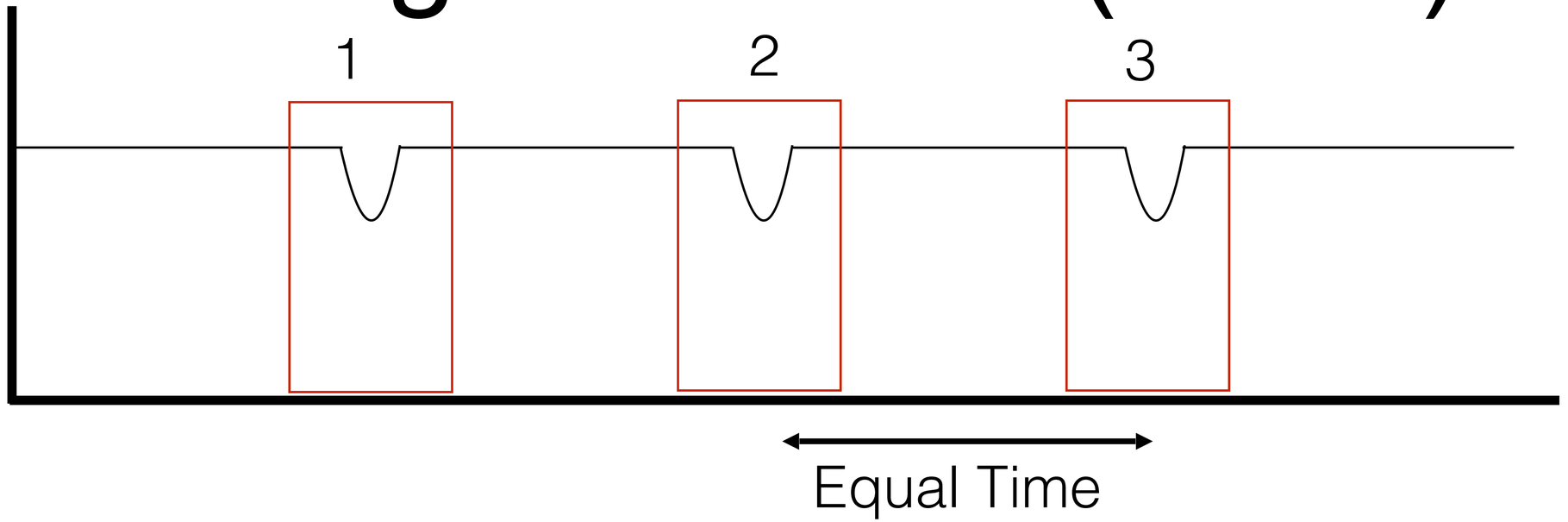

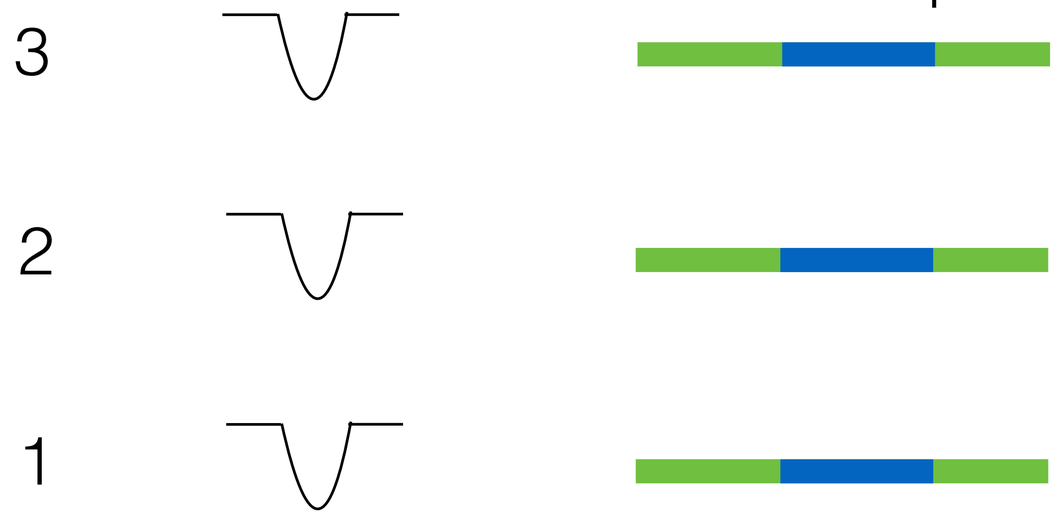

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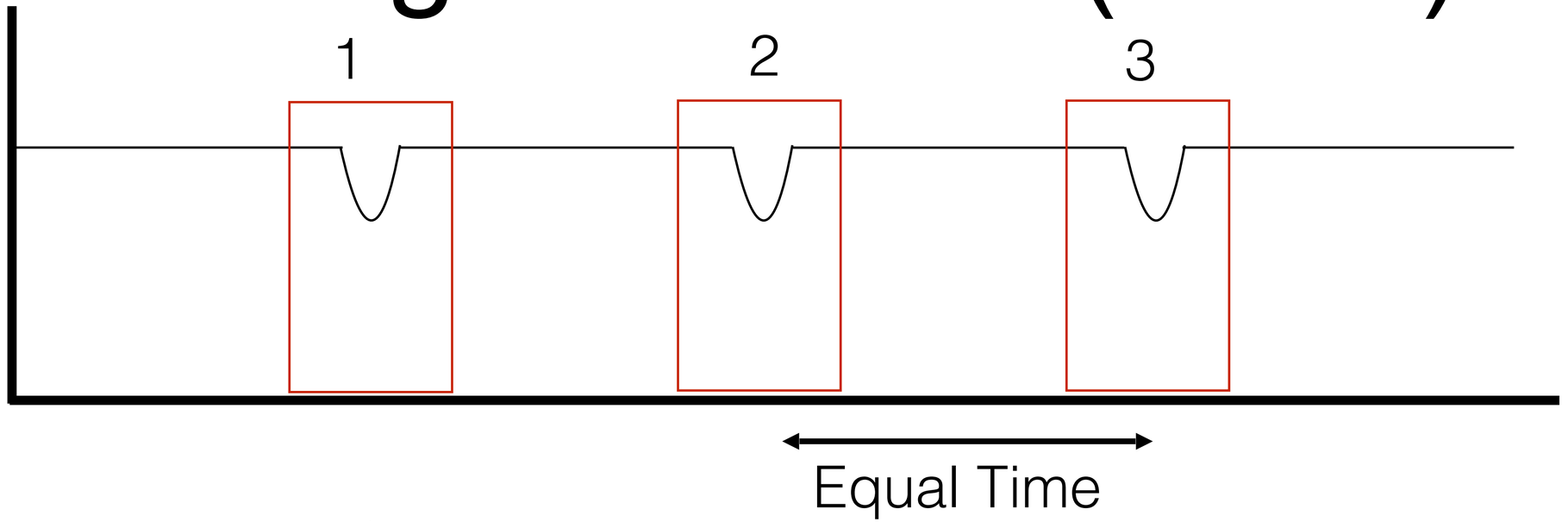

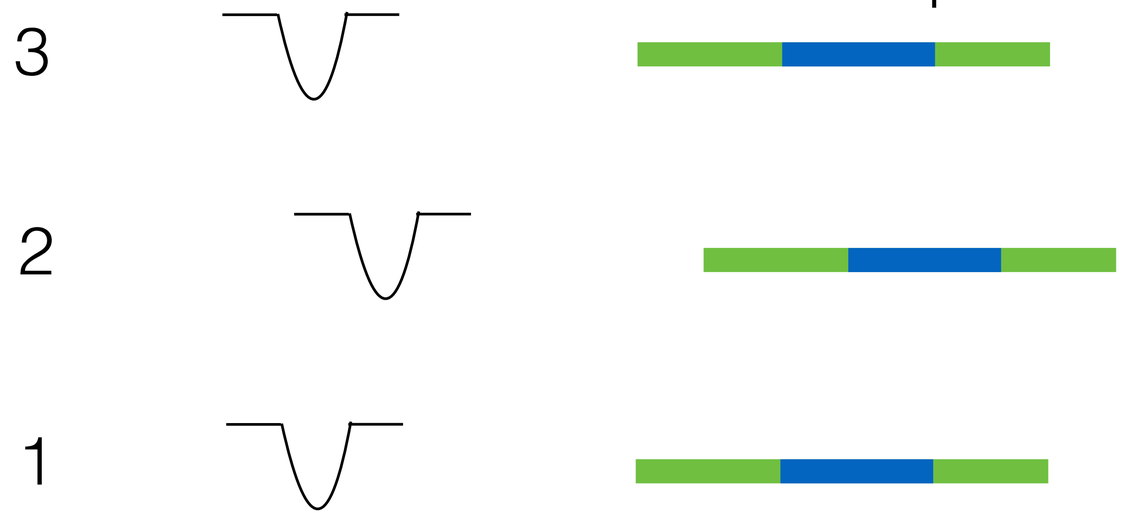

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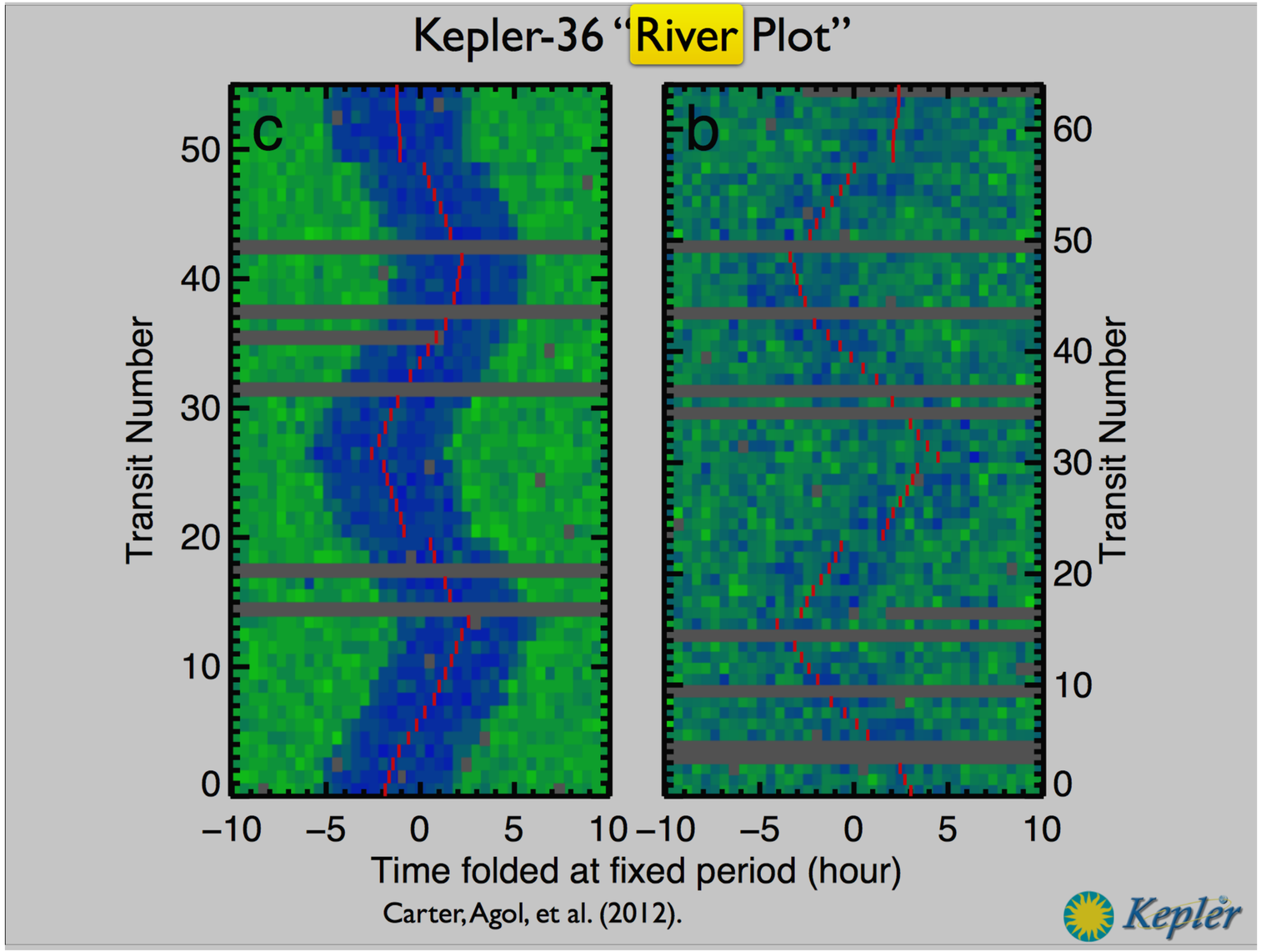
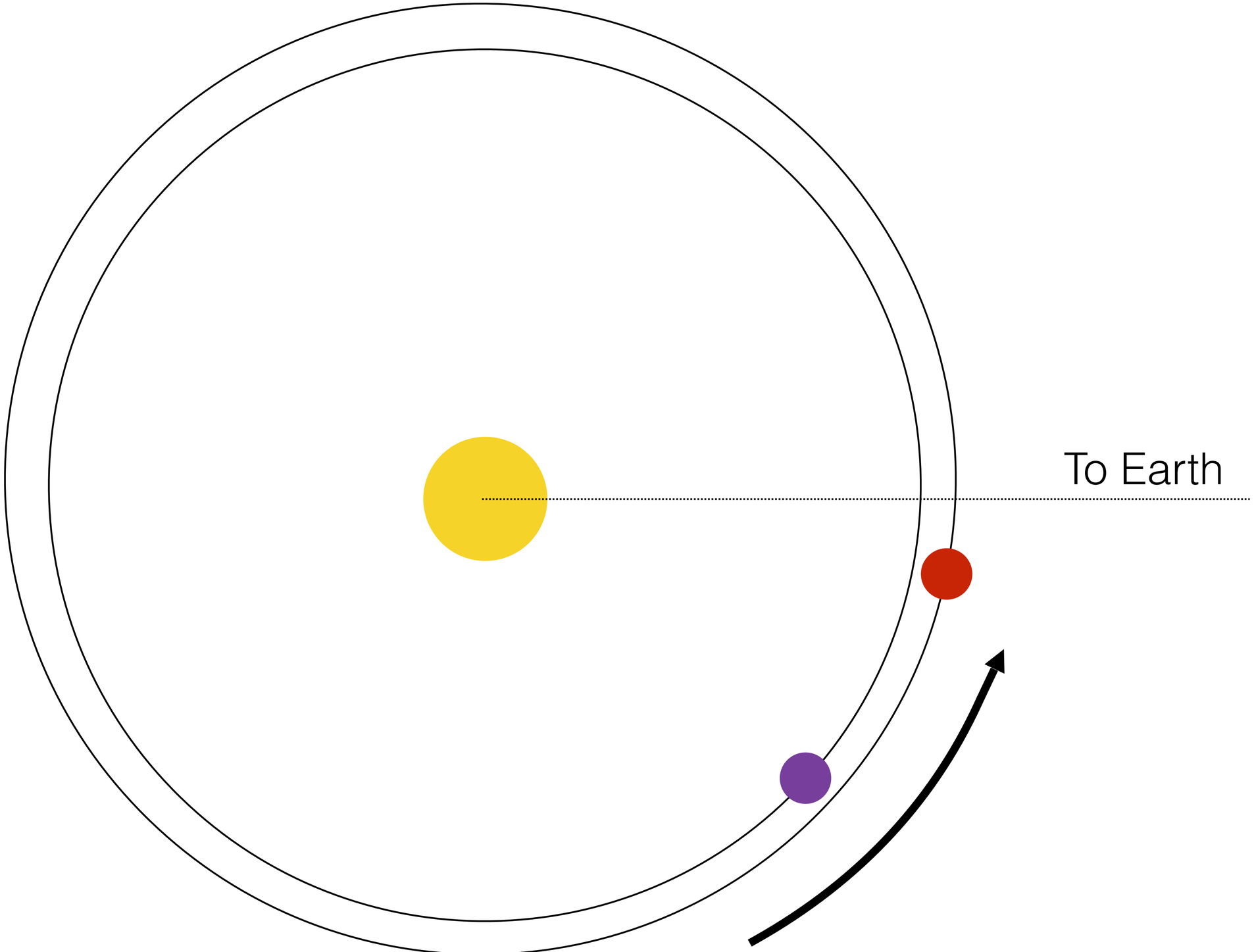
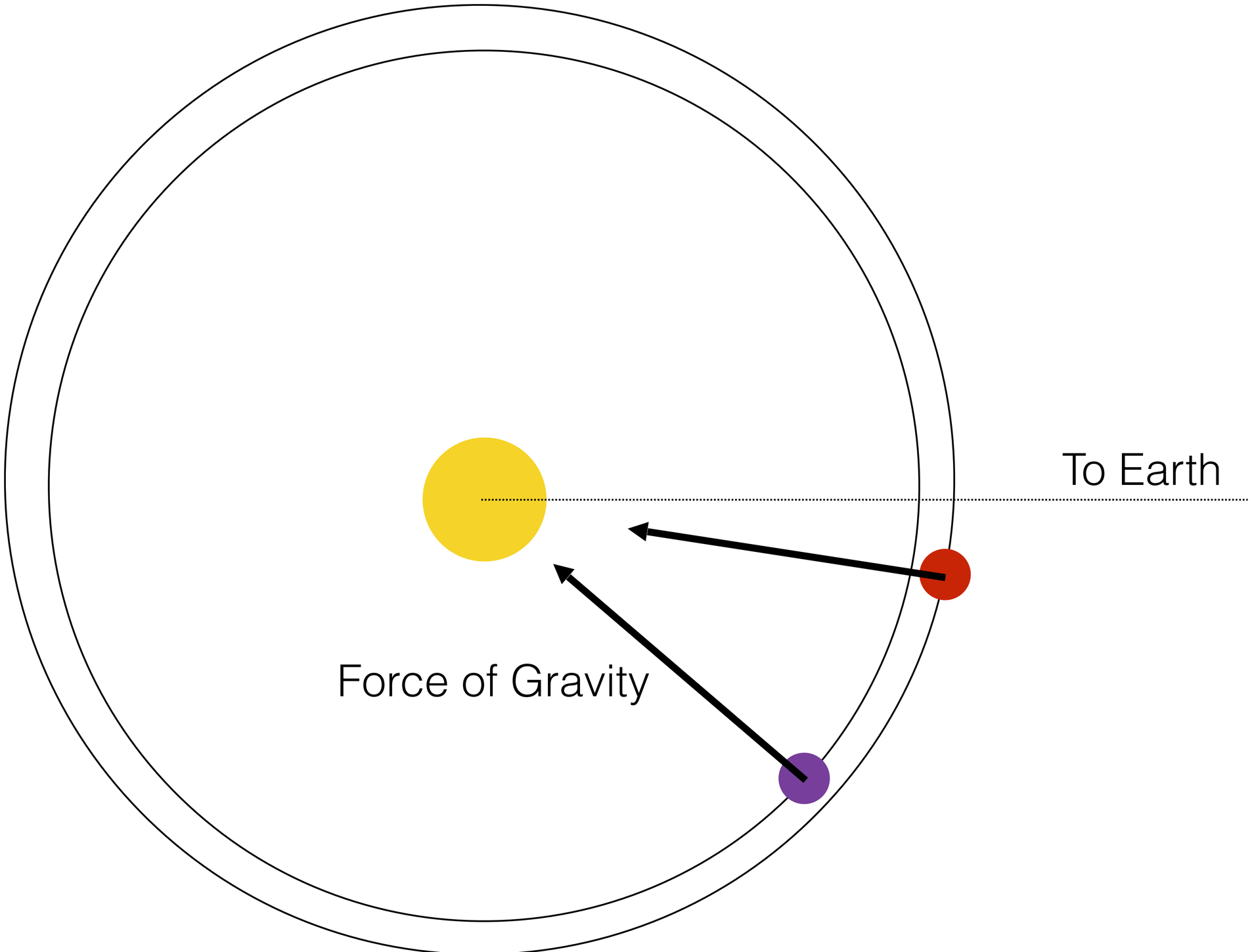
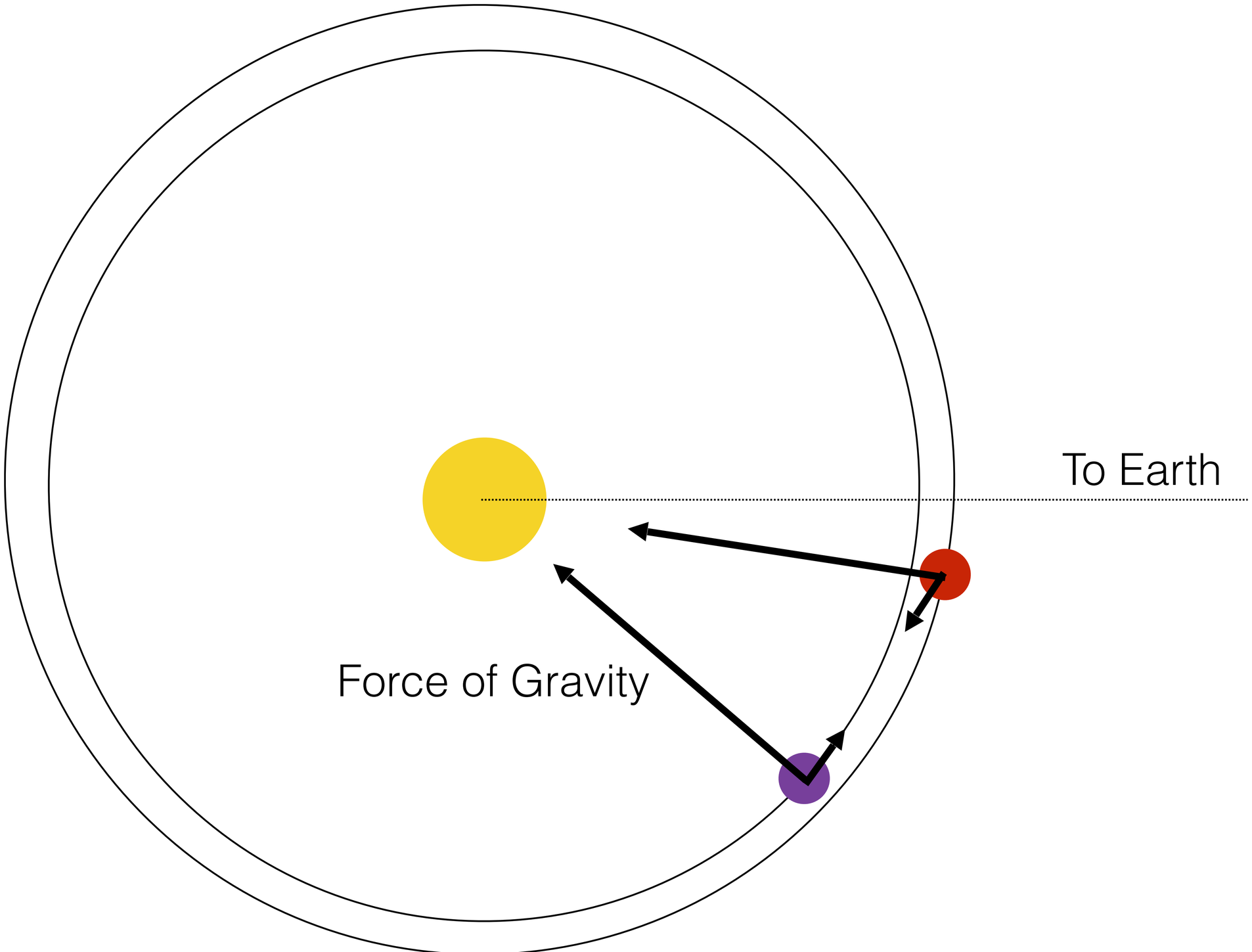
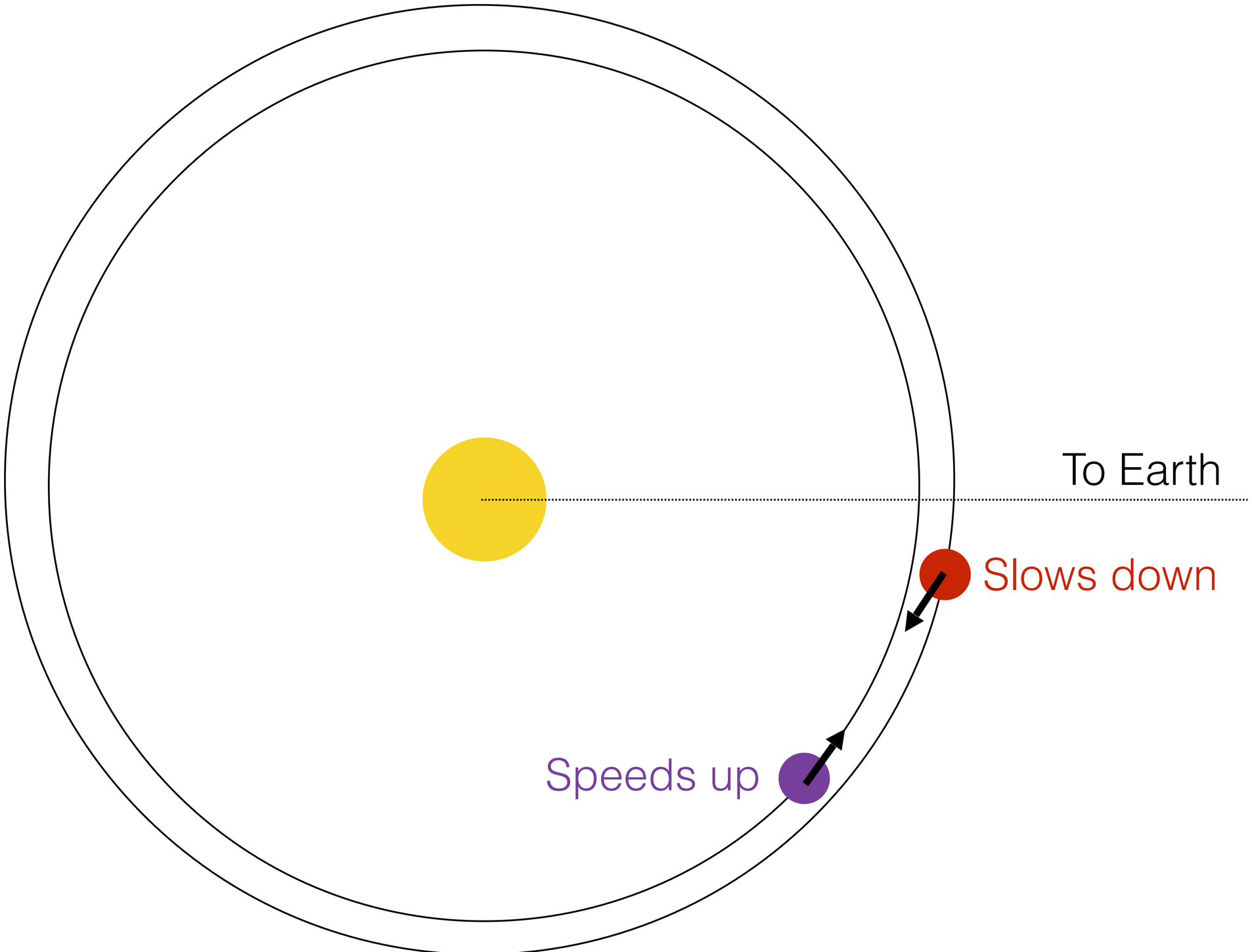
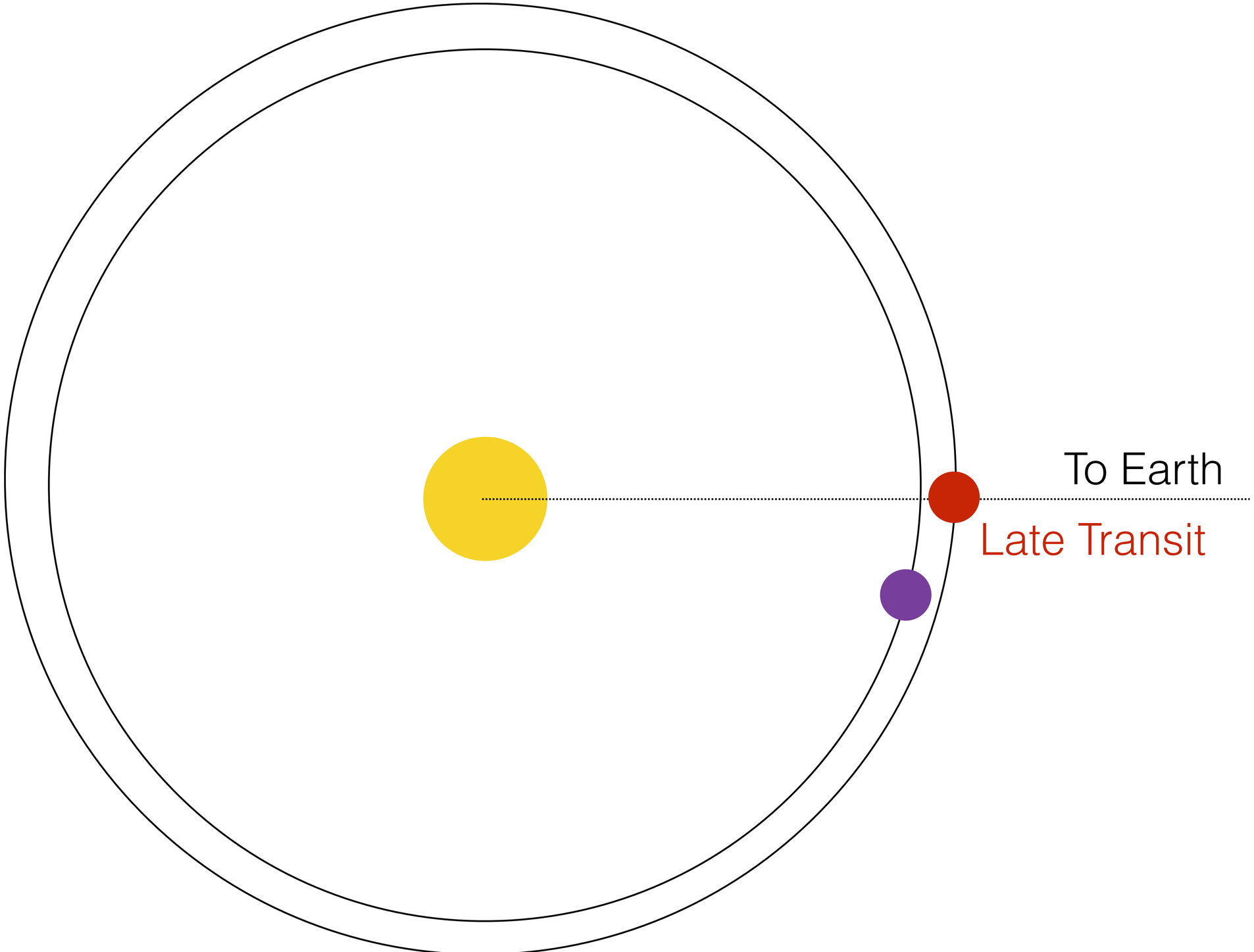


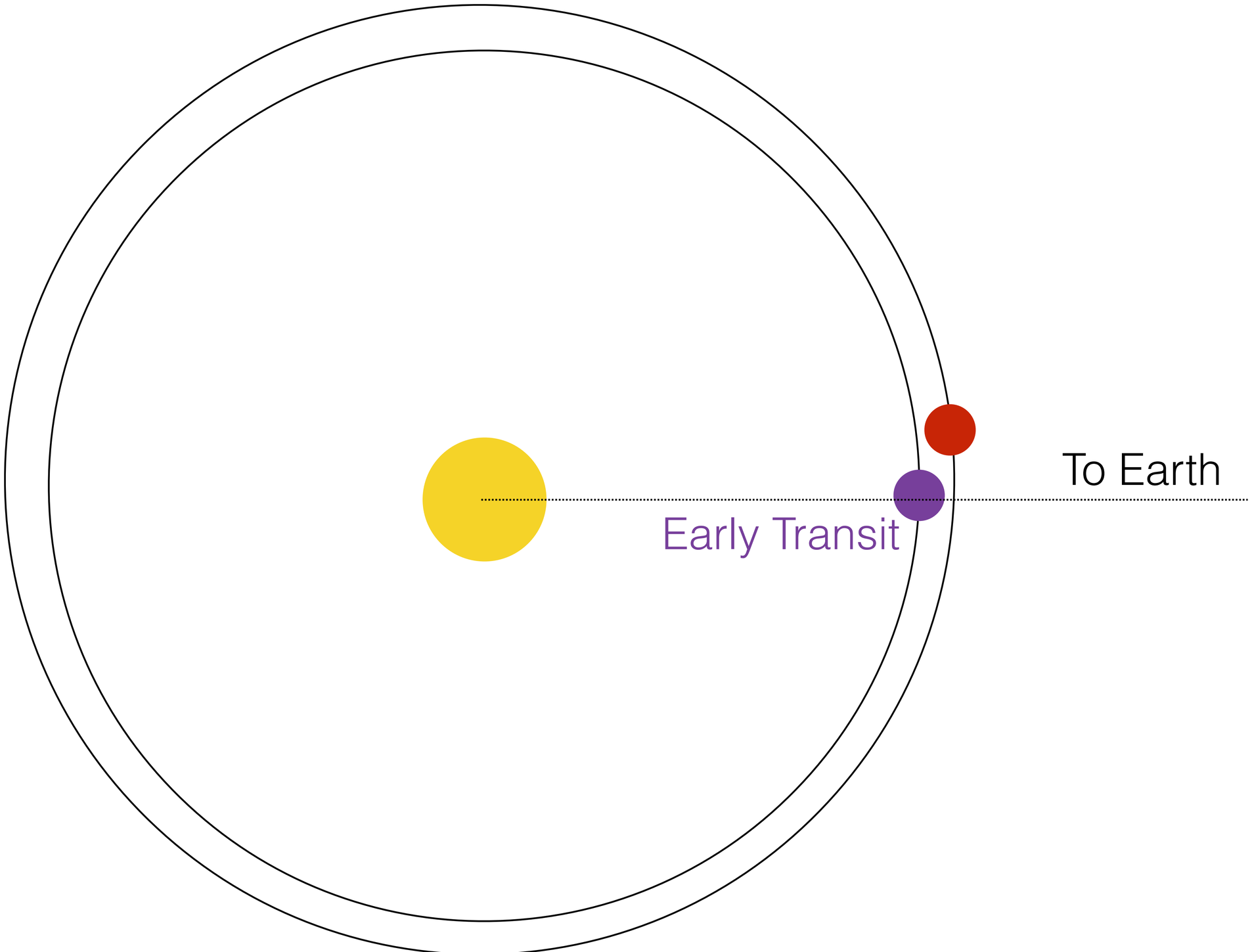

To Earth

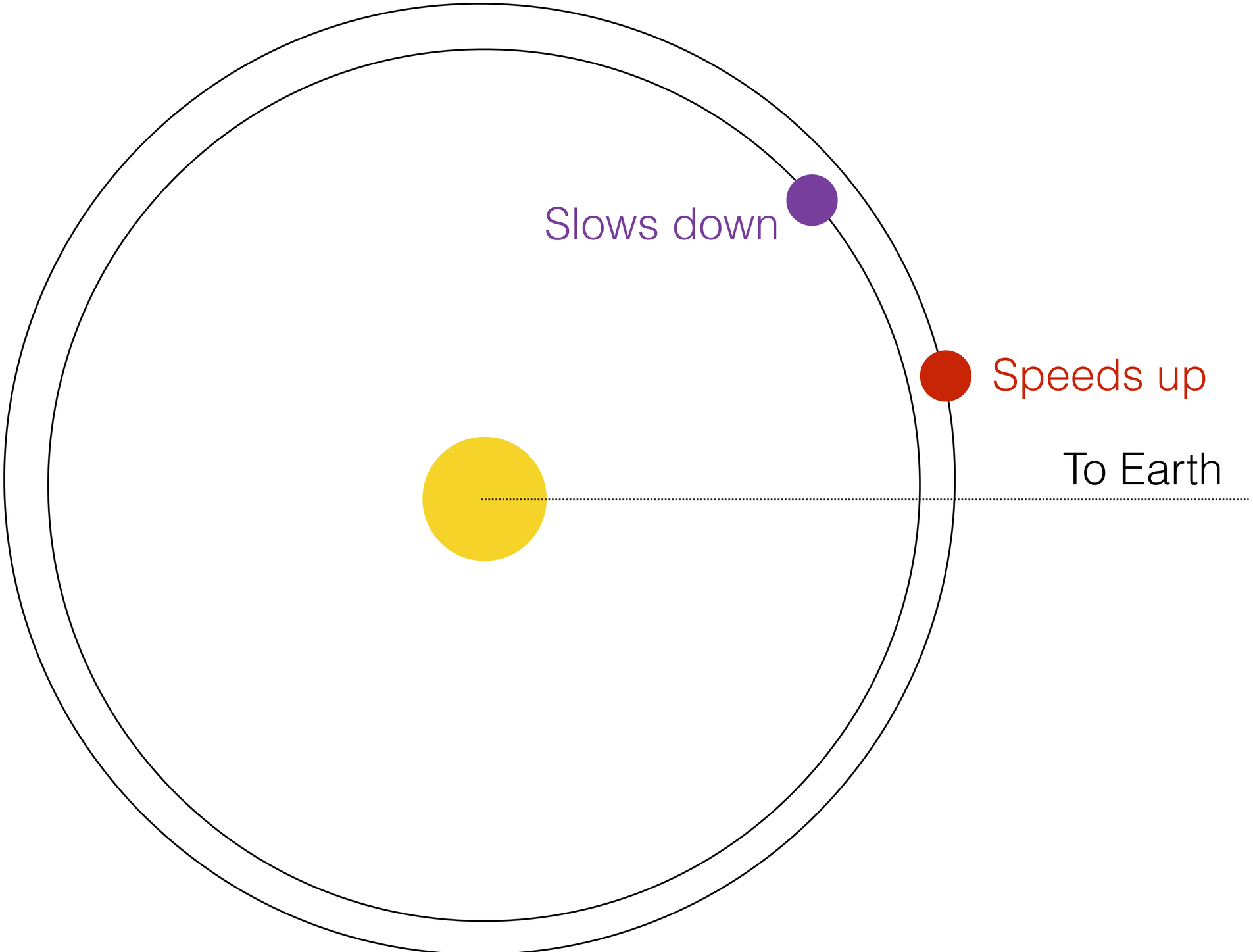

To Earth
Force of Gravity


To Earth
Force of Gravity


To Earth
Slows down
Speeds up

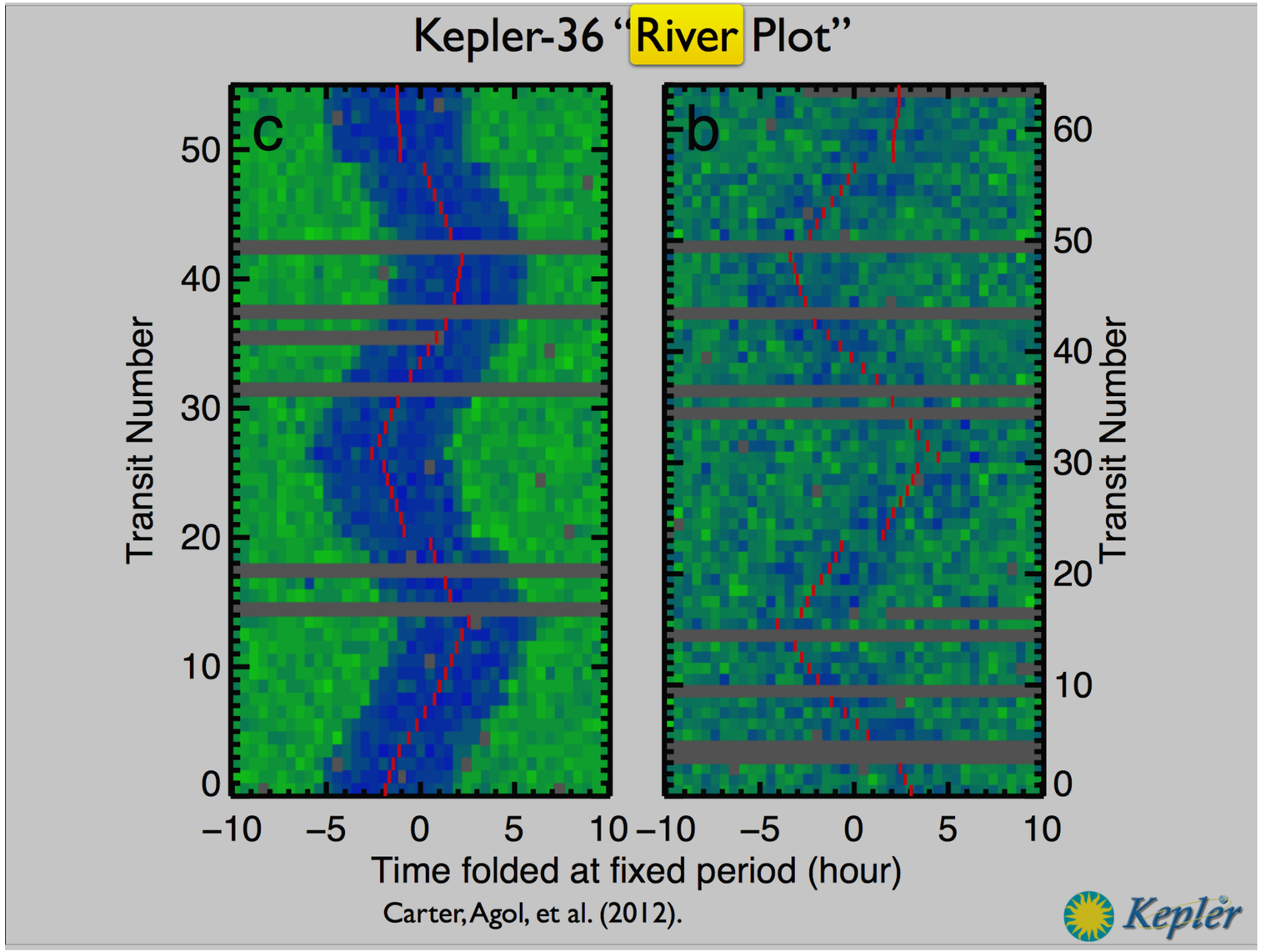

To Earth
Late Transit


To Earth
Early Transit


Slows down
Speeds up
To Earth

Transit Timing Variations (TTVs)

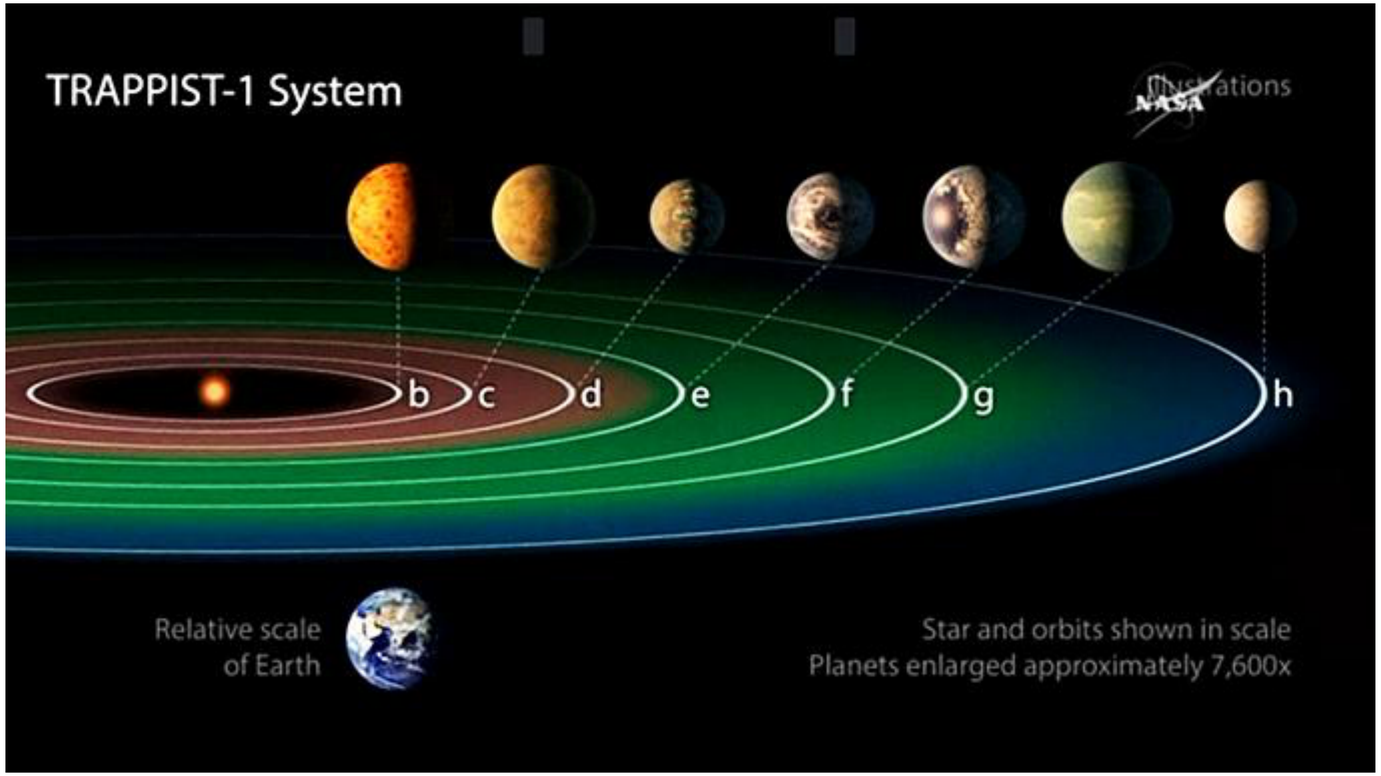
- Even without RV, can measure masses of planets in multi-planet systems
- If planets feel significant gravity from each other, they'll arrive early or late for their transits
    - TTVs are strongest for planets in orbital resonances
- Modeling that variation can give planet masses



Break

TRAPPIST-1

- In 2015, 7 planets were found to be transiting the very low-mass star TRAPPIST-1
- TRAPPIST-1 is an M8 star, and is just barely above the mass required to fuse hydrogen
- Planet masses were found using TTVs



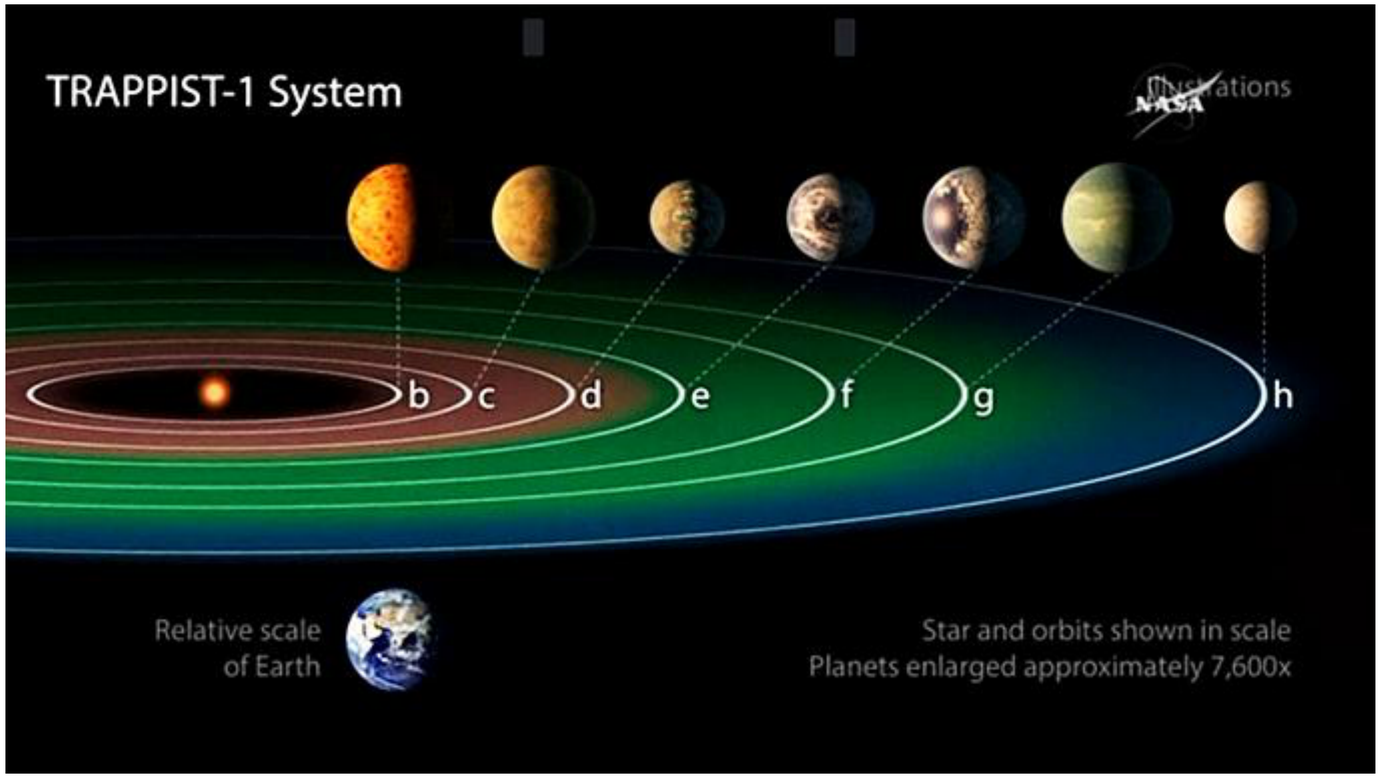
NASA

TRAPPIST-1

- $$T_{eq} = \left(\frac{L_{\odot}(1 - A_b)}{16\pi\sigma\epsilon d^2} \right)^{\frac{1}{4}}$$

- A planet can have the same equilibrium temperature as the Earth if it's much closer to its low-luminosity host star than Earth is to the Sun

- "Habitable zone": the range of distance from a star such that an Earth-like planet with an Earth-like atmosphere would have a surface temperature such that water would be in liquid form at the surface (0-100 C)

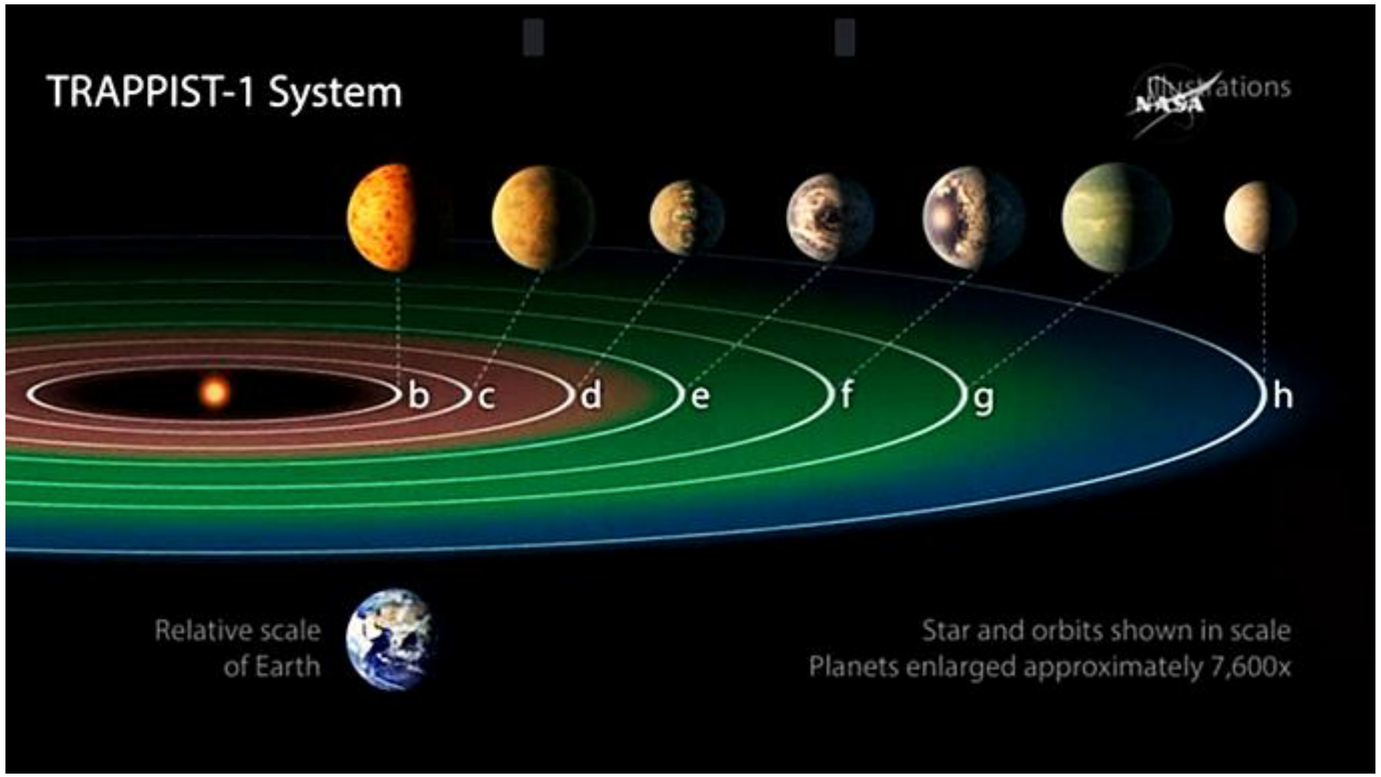


NASA

TRAPPIST-1

- $T_{eq} = \left(\frac{L_{\odot}(1 - A_b)}{16\pi\sigma\epsilon d^2} \right)^{\frac{1}{4}}$

- Calling a planet a “habitable zone planet” tells us the predicted surface temperature of that planet (if it has an Earth-like atmosphere) is between 0 and 100 C
    - And nothing else



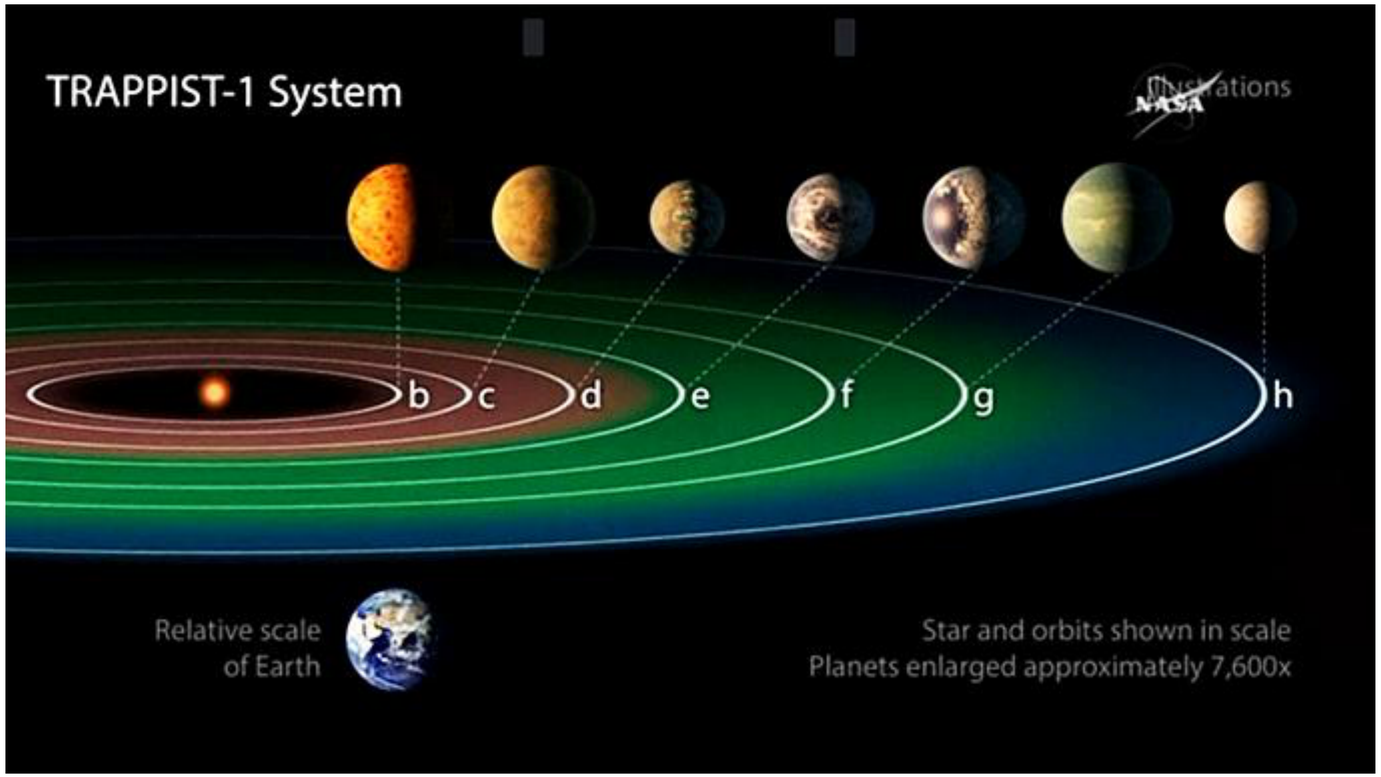
NASA

Order of Magnitude

- TRAPPIST-1 has a luminosity of 1/1000 solar luminosities, and mass of 80 M_{Jup}. Suppose there's a planet orbiting TRAPPIST-1 with the same surface temperature (and atmospheric properties) as the Earth.

$$T_{eq} = \left(\frac{L_{\odot}(1 - A_b)}{16\pi\sigma\epsilon d^2} \right)^{\frac{1}{4}}$$

- (1) What is this planet's semi-major axis (in AU)?
- (2) What is this planet's orbital period (in days)?



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$$T_{eq} = \left(\frac{L_{\odot}(1 - A_b)}{16\pi\sigma\epsilon d^2} \right)^{\frac{1}{4}}$$

- (1) What is this planet's semi-major axis (in AU)?

- Ok, if equilibrium temperature is a constant, and the atmospheres are the same (identical albedo, emissivity, constants), then the only two things changing are luminosity and distance, and luminosity divided by distance squared has to stay the same:

- $$\frac{L_{\odot}}{d_E^2} = \frac{L_T}{d_T^2}$$

Order of Magnitude

- Then, solving for distance (semi-major axis):

$$d_T = d_E\sqrt{\frac{L_T}{L_\odot}} = (1AU)\sqrt{\frac{10^{-3}L_\odot}{L_\odot}} = \frac{1AU}{30} = 0.03AU$$

- (2) What is this planet's orbital period (in days)?
- Kepler's third law to the rescue. The mass of the star is 80 Jupiter masses, or 0.08 solar masses:
- $$P^2 = \frac{a^3}{M}$$
- $$P = \sqrt{\frac{a^3}{M}} = \sqrt{\frac{(3x10^{-2})^3}{0.08}} = \sqrt{\frac{27x10^{-6}}{8x10^{-2}}} = \sqrt{3x10^{-4}} = 2x10^{-2}yr$$

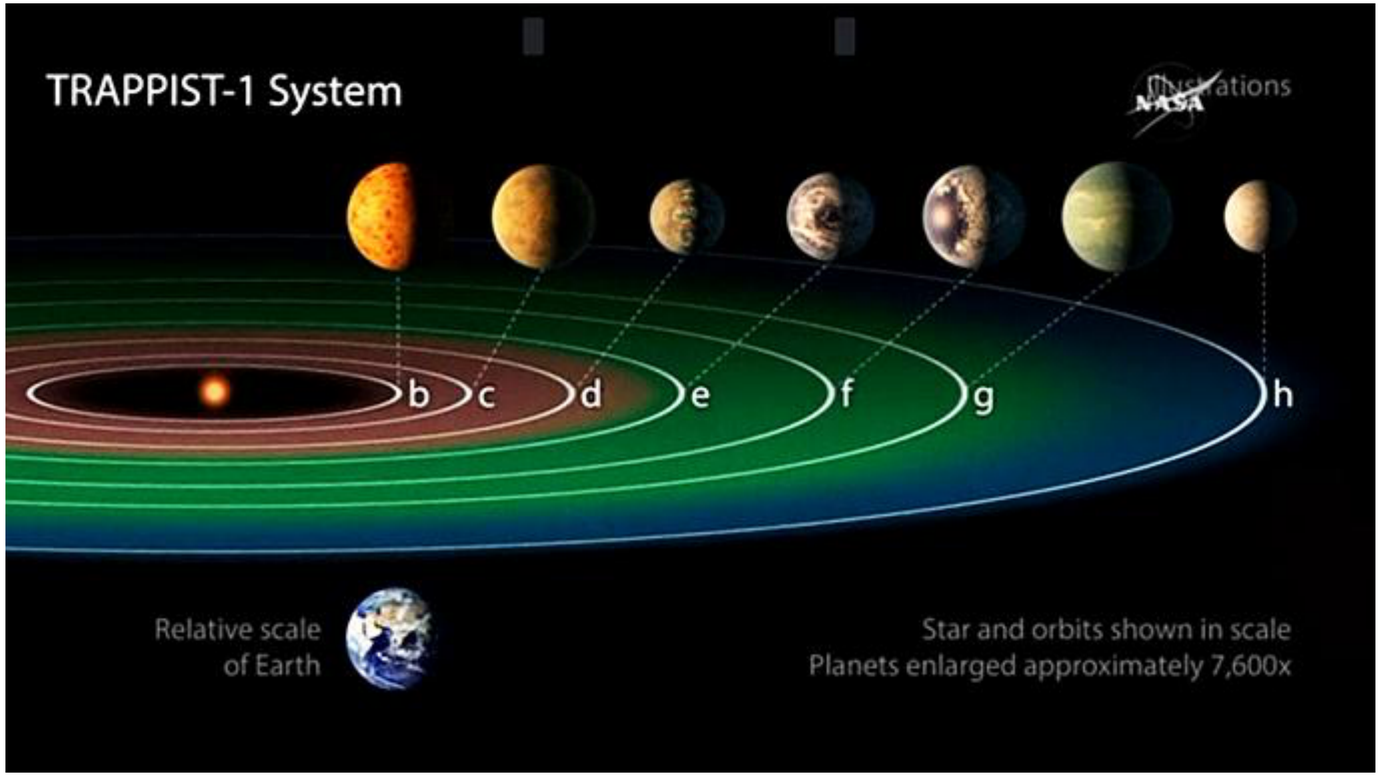
Order of Magnitude

- Finally, converting to days:

$$P = 2x10^{-2}yr\frac{365days}{1yr} = 7days$$

TRAPPIST-1

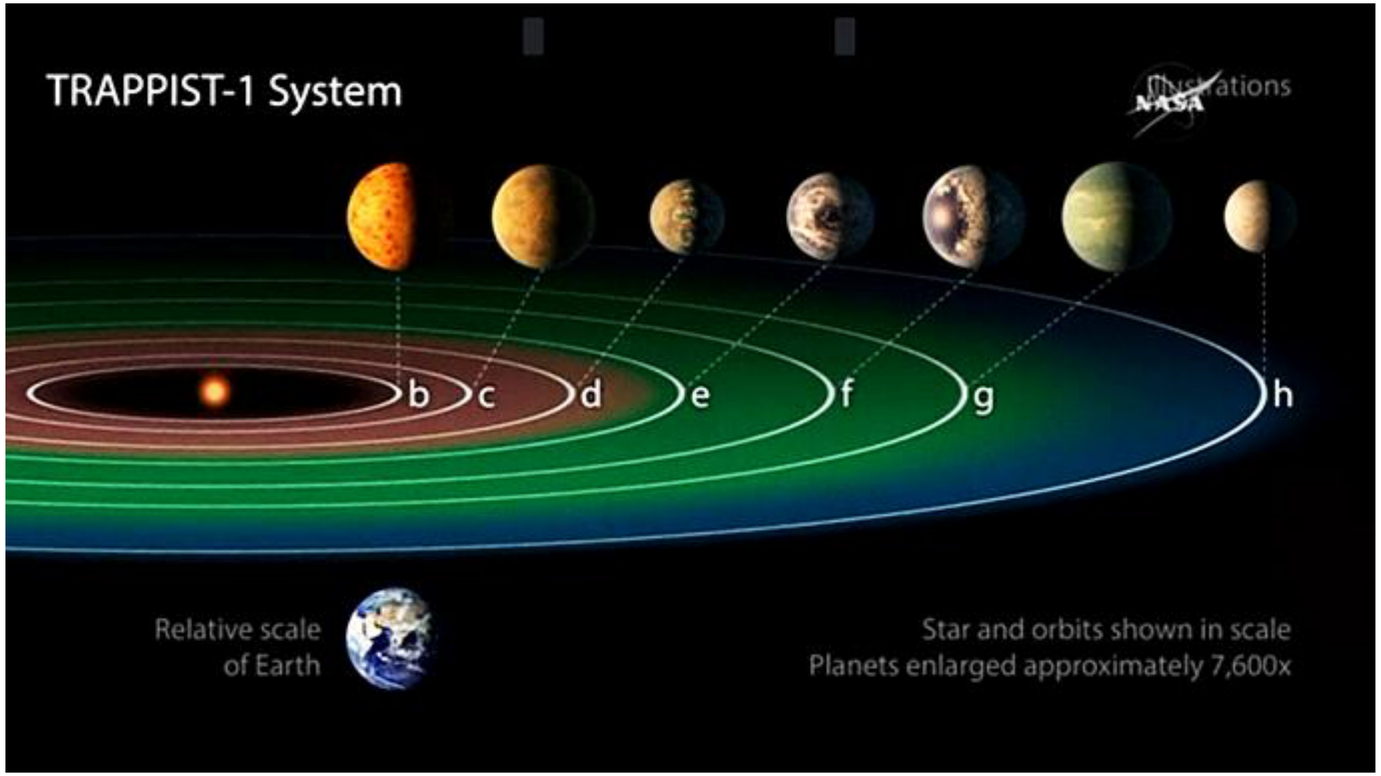
- The semi-major axis of the outermost planet is only 0.06 AU
- Planets are about the same size, mass and density as the Earth
- Three planets (TRAPPIST-1e, TRAPPIST-1f, and TRAPPIST-1g) are within the star's habitable zone



NASA

TRAPPIST-1

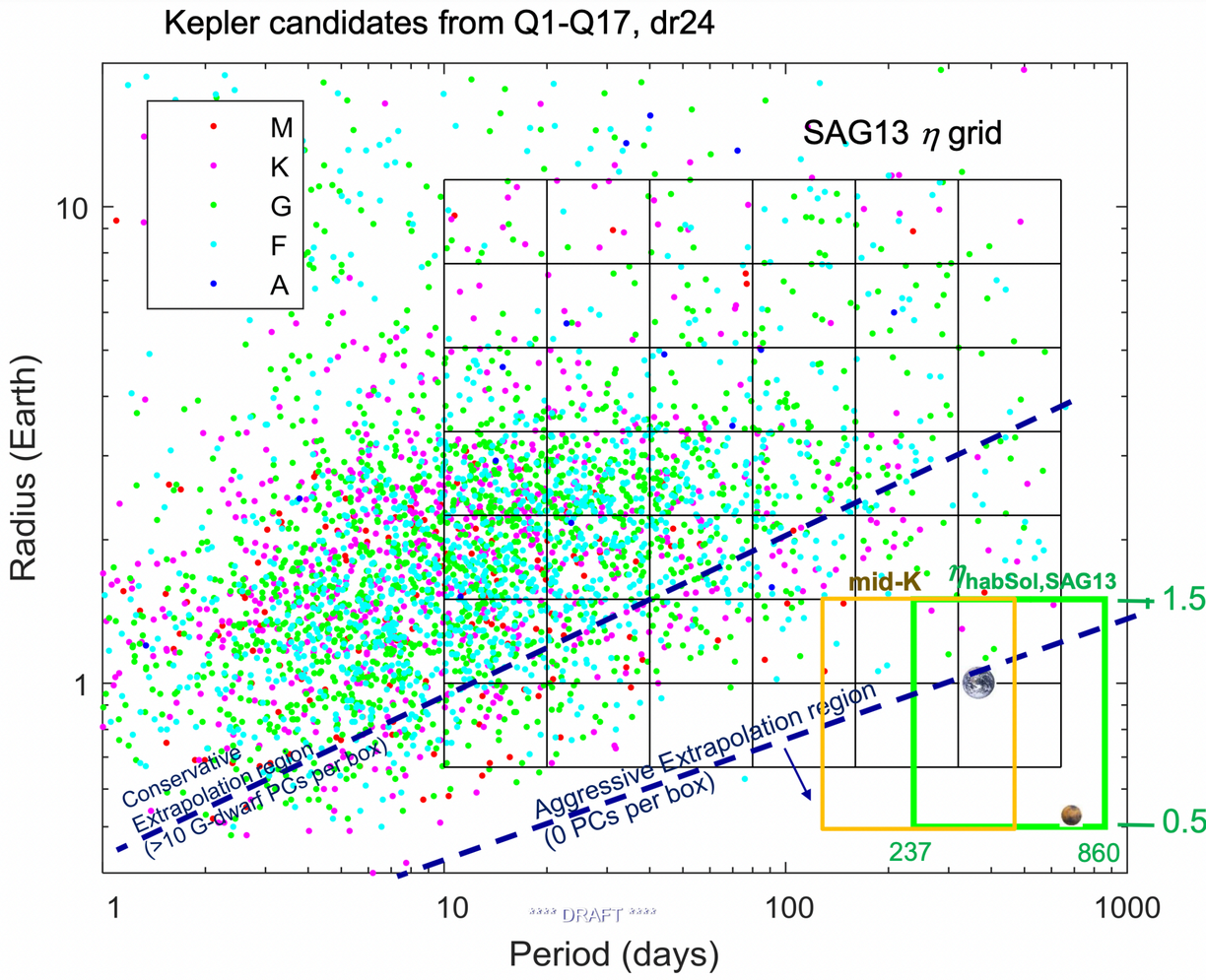
- M stars are much more active than Sun-like stars: these planets likely have to contend with much higher stellar winds compared to the Earth
    - Planets are also much closer to their star than Earth is to the Sun
    - These could strip off a planet's atmosphere
- Planets would also be tidally locked
    - Slower rotation means less magnetic field, less protection from stellar wind stripping



NASA

Short-period exoplanet Demographics

- Thanks to Kepler, can make very granular occurrence rate estimates as a function of planet radius and orbital period
    - Generally for radii above 2-3 Earth, period less than 100 days
- Extrapolation required to get to Earth analogs



NASA/SAG13

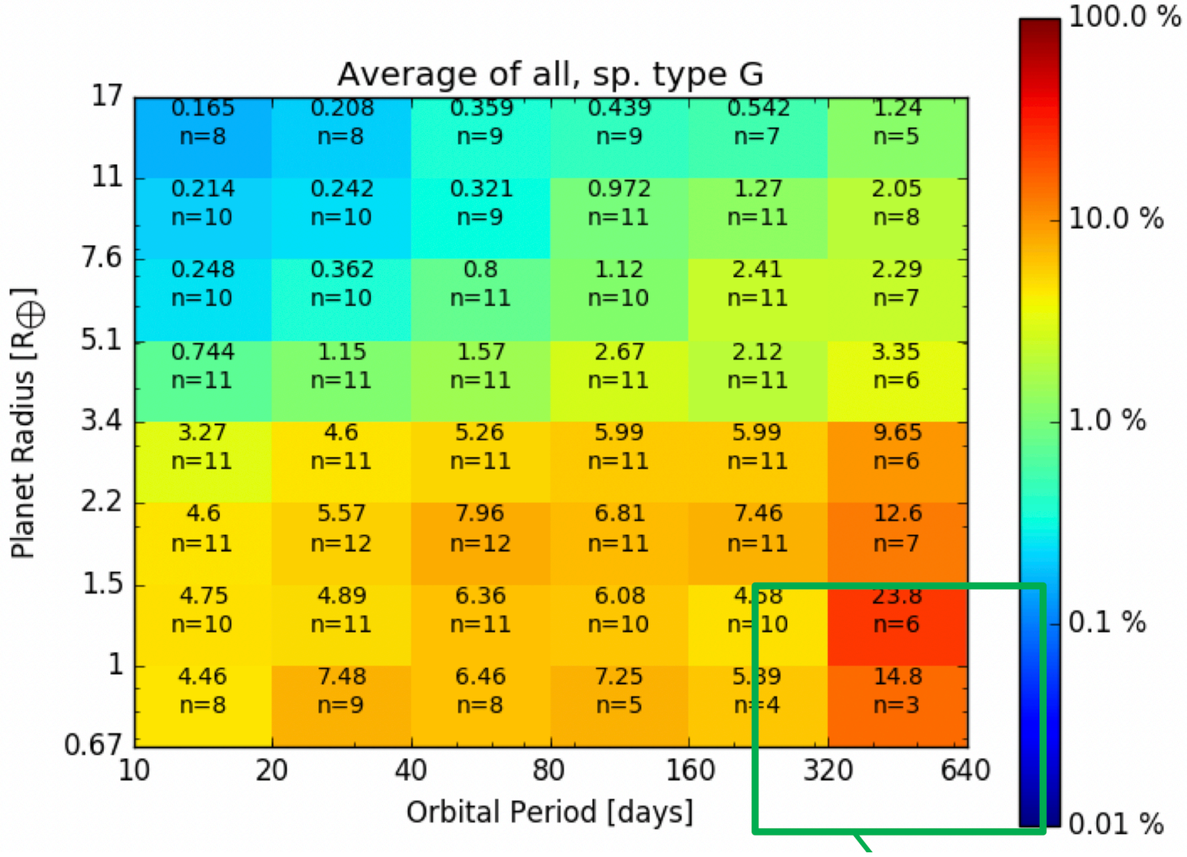
Short-period exoplanet Demographics

- Thanks to Kepler, have very granular occurrence rate estimates as a function of planet radius and orbital period

- Restricting ourselves to periods less than 160 days:

  - 19% of sun-like stars have a planet between 2.2 and 3.4 Earth radii

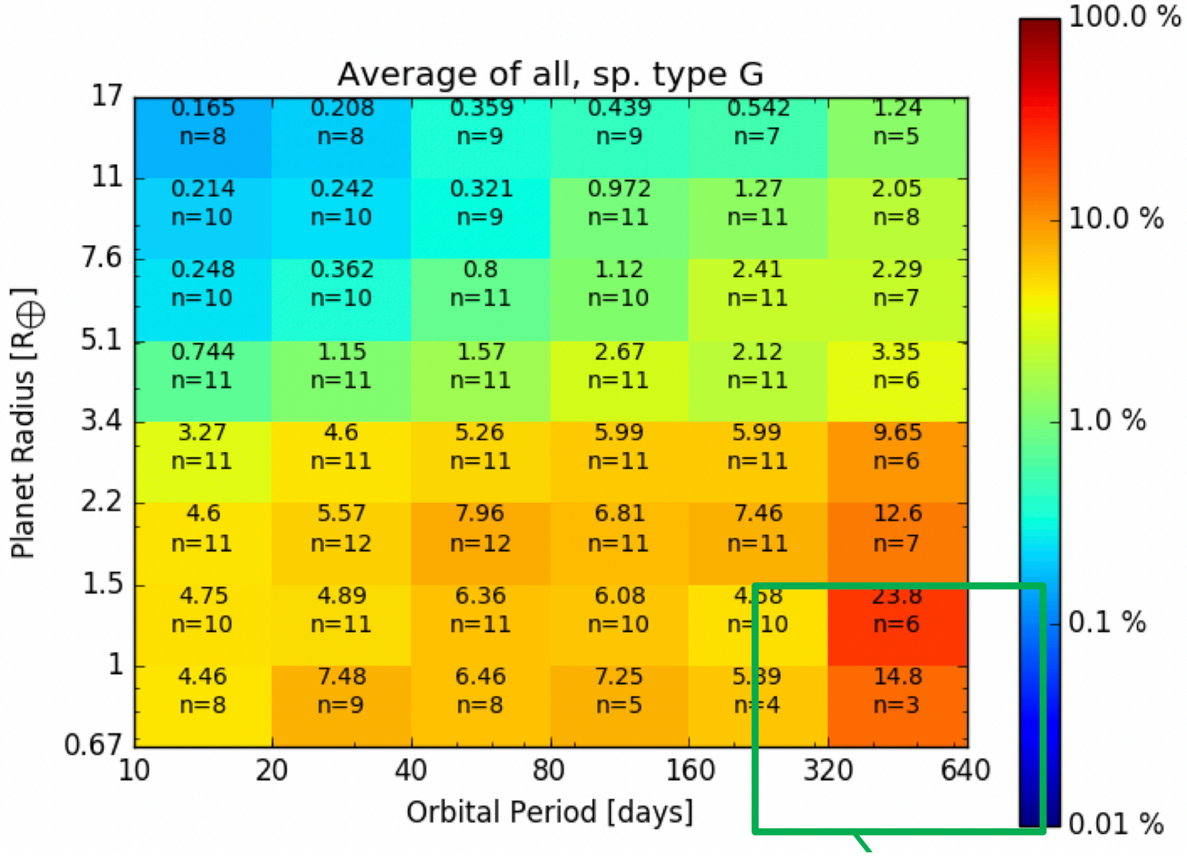
  - 25% of sun-like stars have a planet between 1.5 and 2.2 Earth radii



NASA/SAG13

Short-period exoplanet Demographics

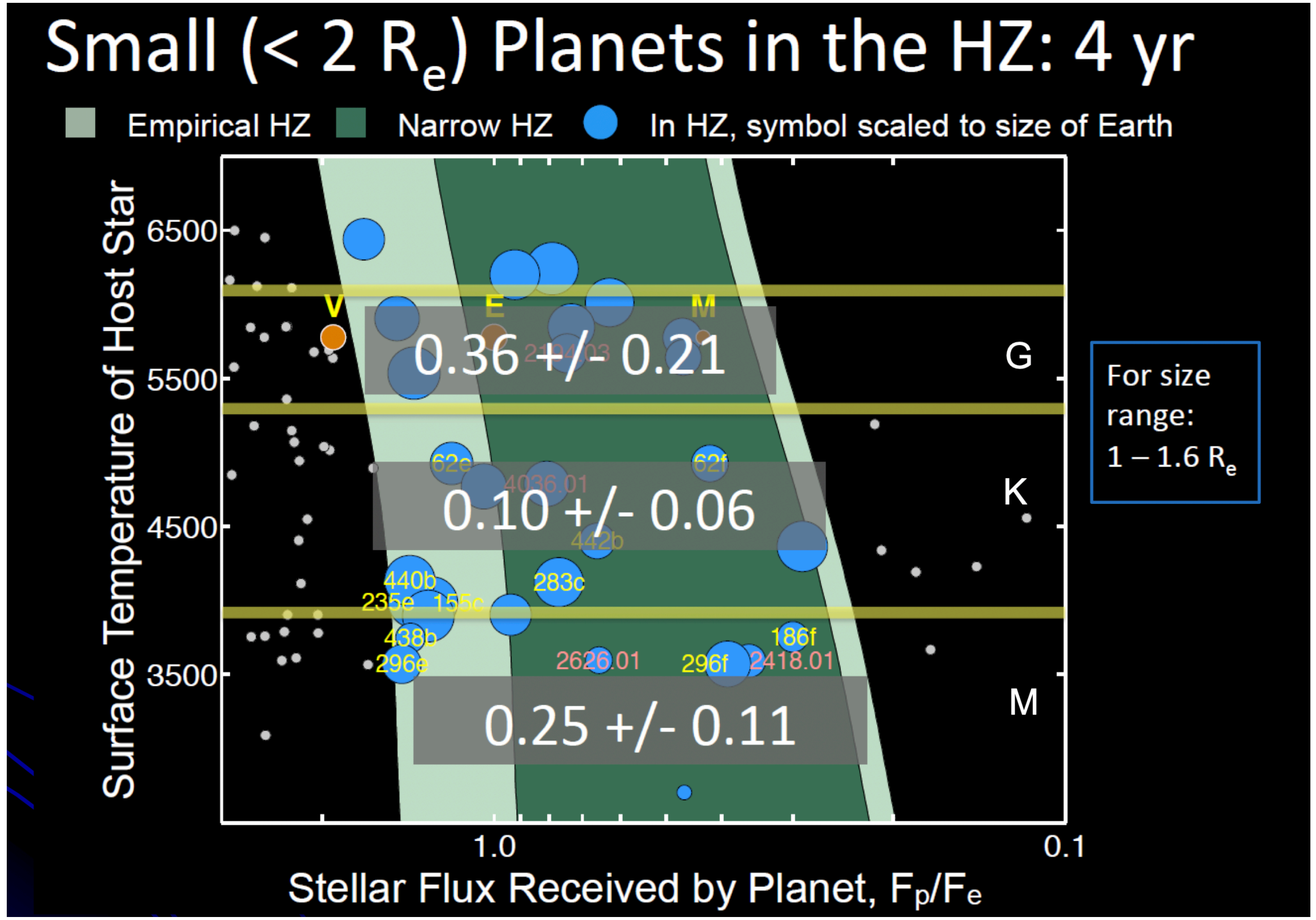
- More small planets than big planets at short periods around Sun-like stars
- Not easy to tell (with current data) if trend continues to Earth-sized planets and Earth-like periods.



NASA/SAG13

Short-period exoplanet Demographics

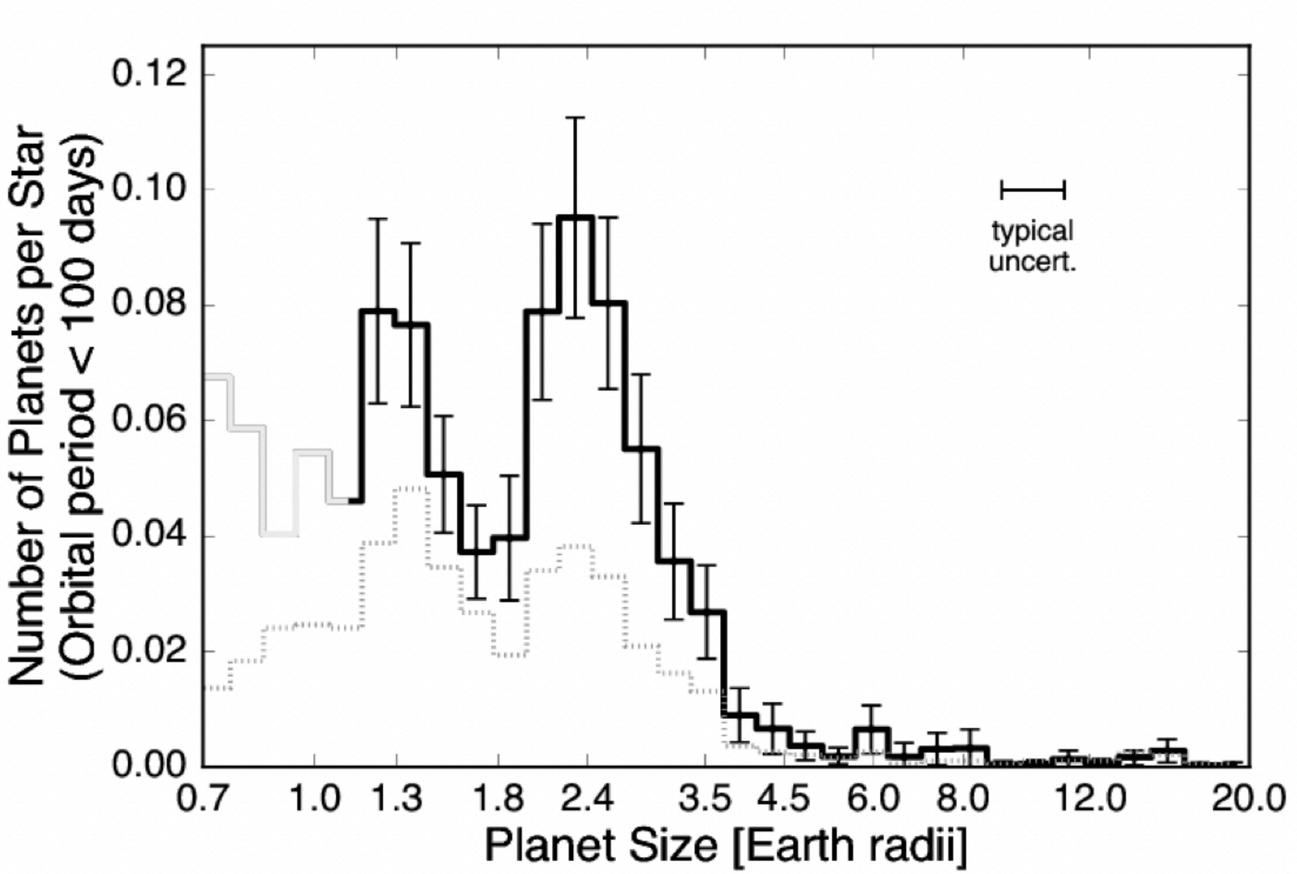
- Kepler is more complete to habitable zone planets around M stars
  - have much smaller orbital periods
  - have stronger transit signals
- 25% of M stars could have ~1 Earth radius planets in the habitable zone
  - 90% of stars are M stars
  - Remember caveats for “habitable zone”



NASA/SAG13

Fulton Gap

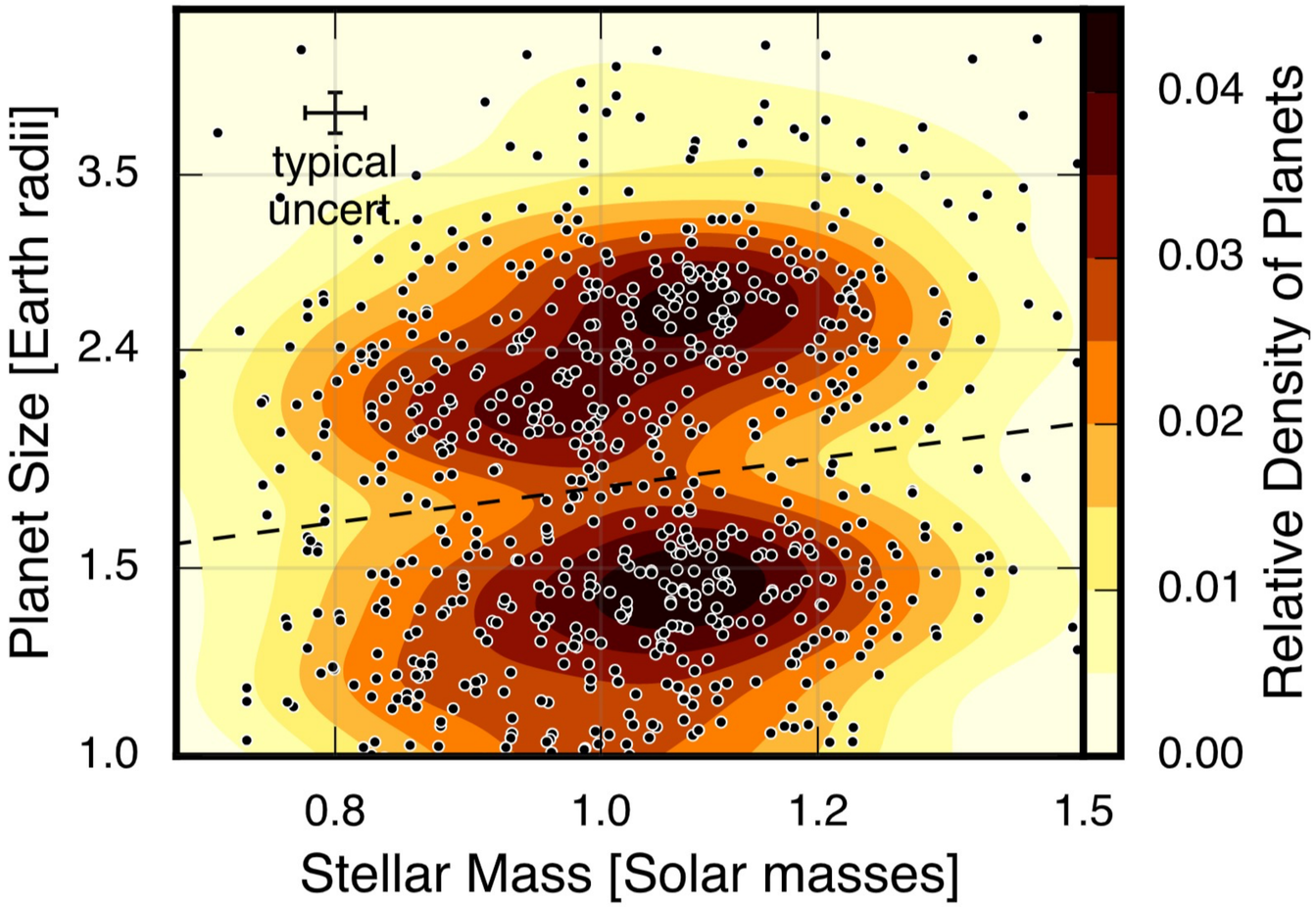
- Based on RV mass measurements of Kepler planets
  - Both select for close-in planets, <100 day periods
- Gap in the occurrence rate at ~1.8 Earth radii



Fulton et al. 2017

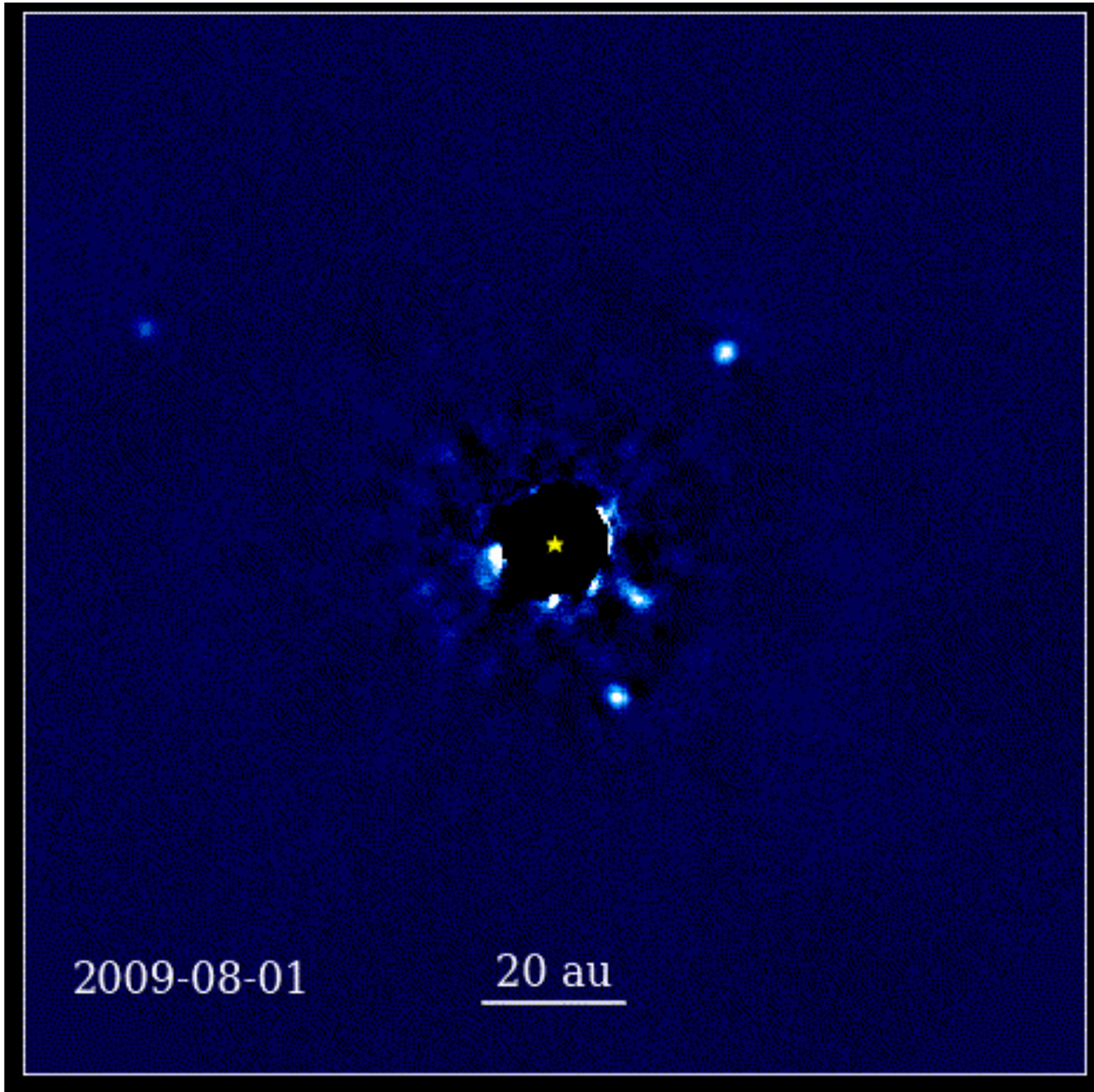
Fulton Gap

- Trend with stellar mass in the Fulton gap
- Likely this is due to photoevaporation of planet's atmosphere
  - Larger planets have enough mass to hold onto their atmosphere above their rocky core
  - Smaller planets lose their atmosphere and we just see the rocky core
- Need to be careful extrapolating to larger separations based on data on planets with periods smaller than 100 days



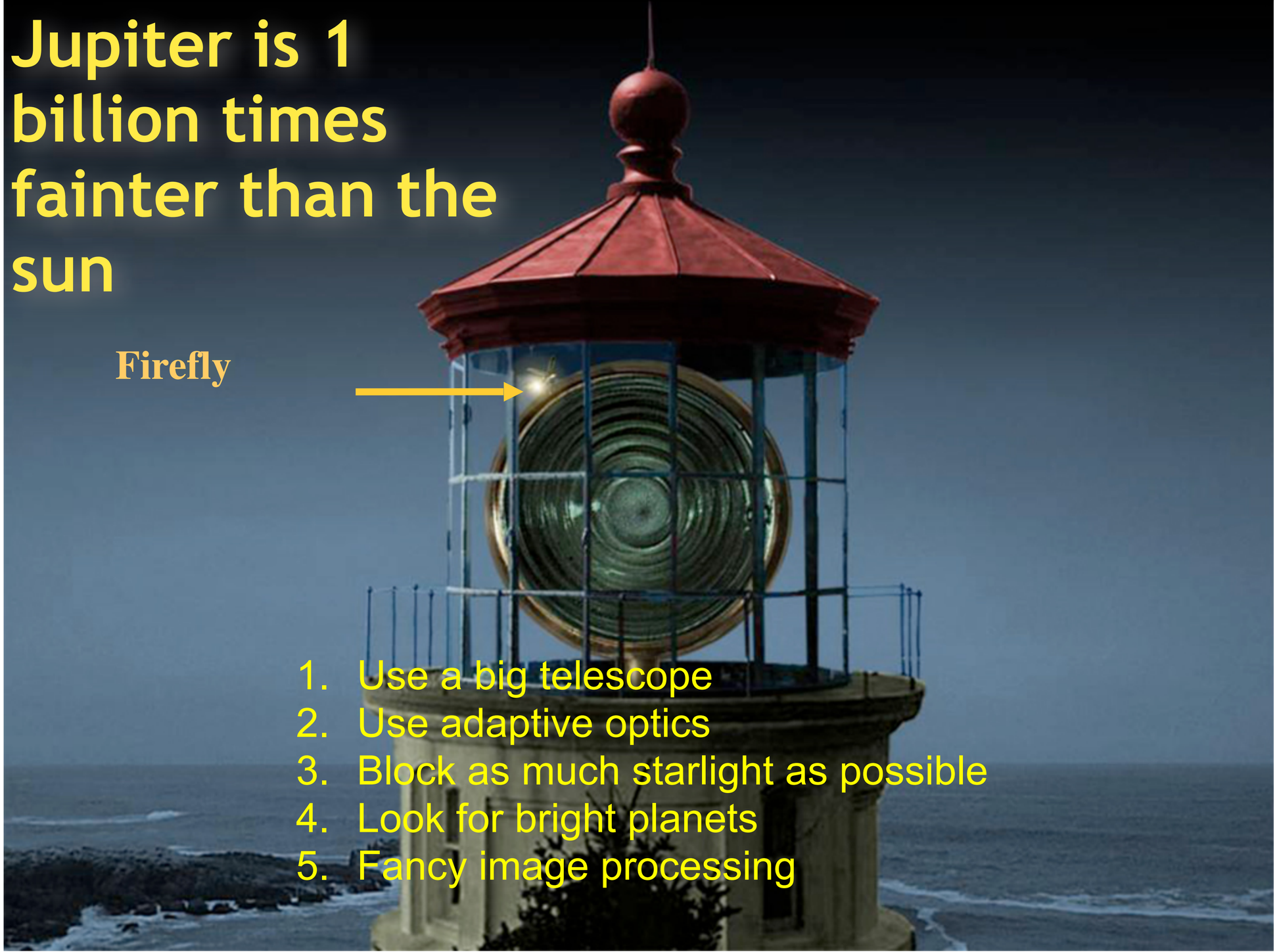
Fulton & Petigura 2018

Direct Imaging



Movie from Jason Wang and Christian Marois

Directly
imaging
exoplanets


Jupiter is 1 billion times fainter than the sun
Firefly
1. Use a big telescope
2. Use adaptive optics
3. Block as much starlight as possible
4. Look for bright planets
5. Fancy image processing

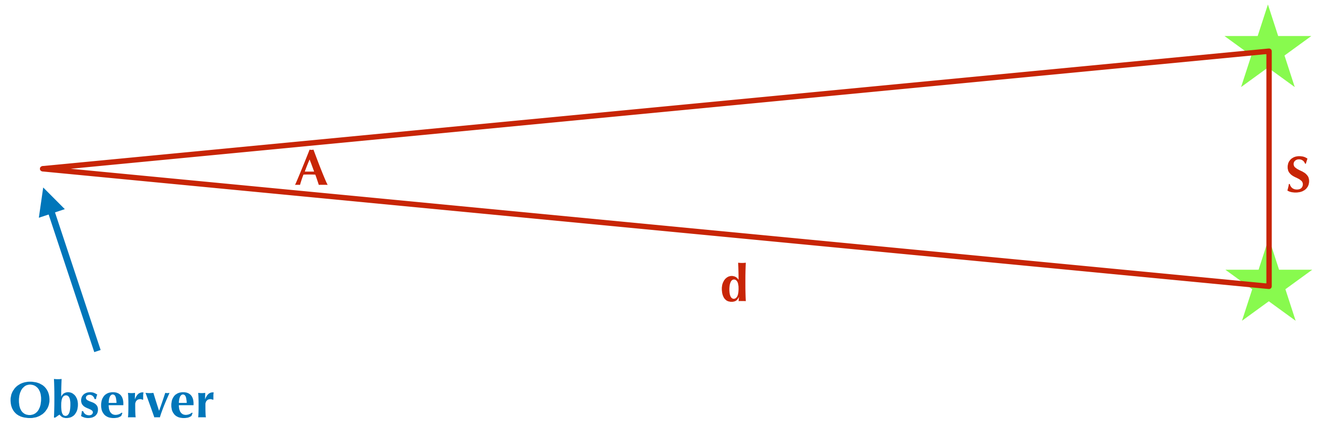
Angular Size

- When taking an image of something, a telescope measures separations in angular distance: the angle between two point source
    - For example, two stars in a binary system
- If the angular size is very small (and it almost always in astronomy), can treat triangle as a right triangle:

$$\sin A = \frac{S}{d}$$

- And if the angle A is in radians, and very small, we can use the approximation:

$$A_{radians} \approx \frac{S}{d}$$

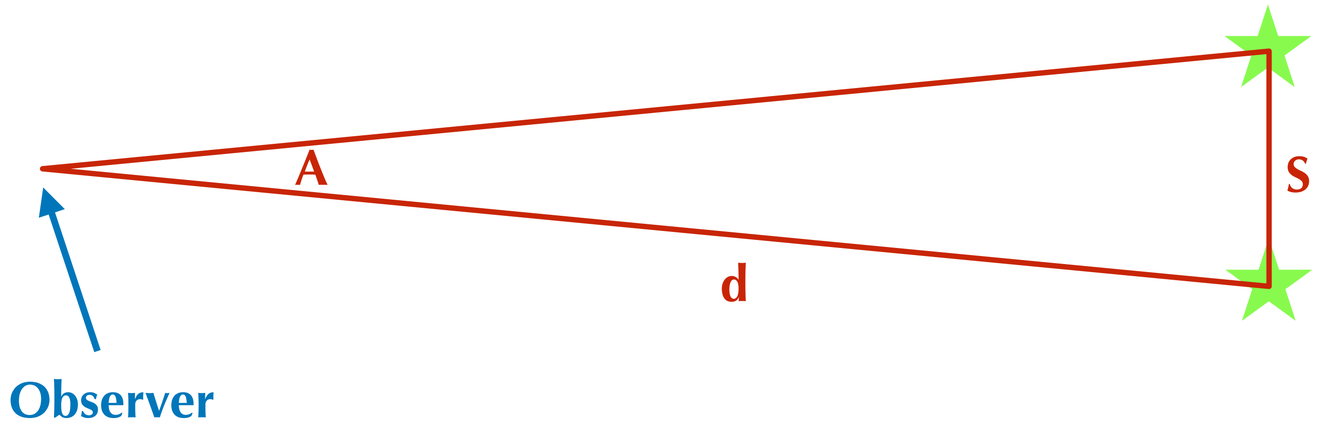


Angular Size

- $A_{radians} \approx \frac{S}{d}$
- We prefer to work in arcseconds, and there are 206265 arcseconds in a radian

$$\frac{A_{arcseconds}}{206265} \approx \frac{S}{d}$$

- Distance to stars is usually given in parsecs, and physical sizes for exoplanetary systems is usually given in AU
    - There are 206265 AU in a pc (not a coincidence)
- $\frac{A_{arcseconds}}{206265} \approx \frac{S_{AU}}{2026265 d_{pc}}$
- $A_{arcseconds} \approx \frac{S_{AU}}{d_{pc}}$



Response Card Question

- An exoplanet orbits a star 10 pc away, with a semi-major axis of 1 AU, in a circular orbit. What is the maximum angular separation between star and exoplanet?
  - (A) — 100”
  - (B) — 10”
  - (C) — 1”
  - (D) — 0.1”
  - (E) — 0.01”

$$A_{arcseconds} \approx \frac{S_{AU}}{d_{pc}}$$

For next time

- Order of Magnitude project, written assignment due Monday, November 14 at start of class