An introduction to
Exoplanets

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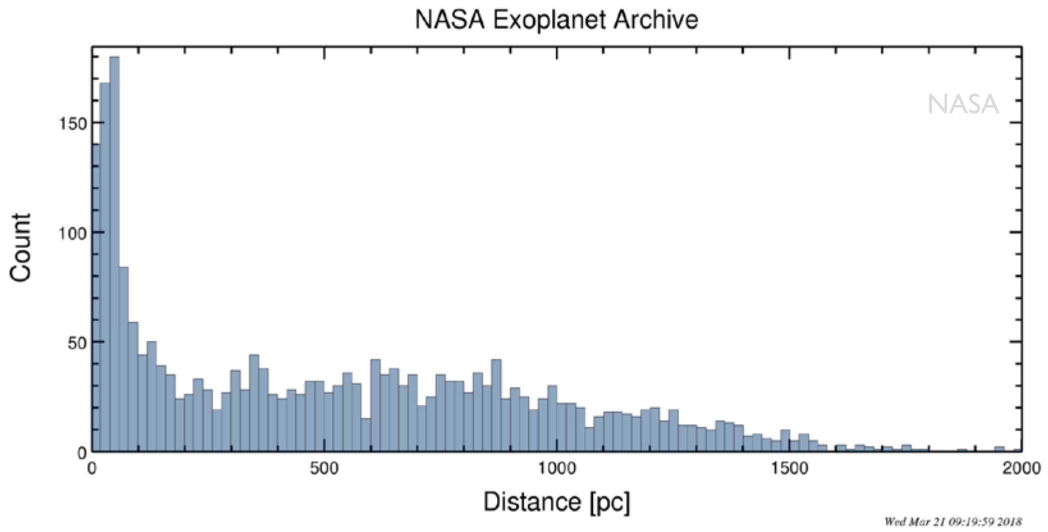
Exoplanet definition

- An exoplanet is a planet orbiting a star that isn't the sun
- The definition is pretty different than for solar system planets, because most of that criterion can't be assessed here
  - We don't know if it's spherical
  - We don't know if it's cleared its orbital path

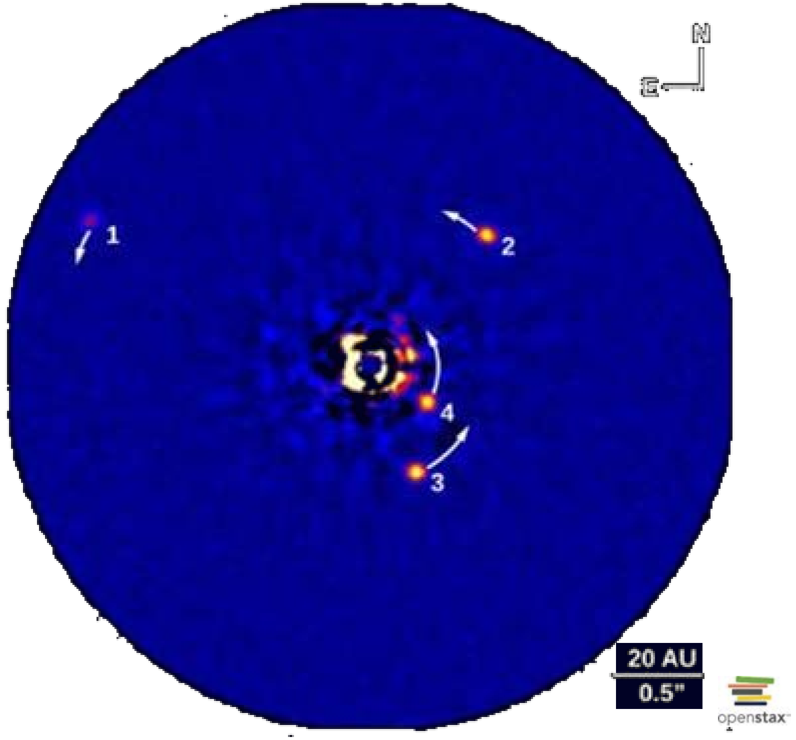
though practically we can't see objects that are small enough for these to not be true

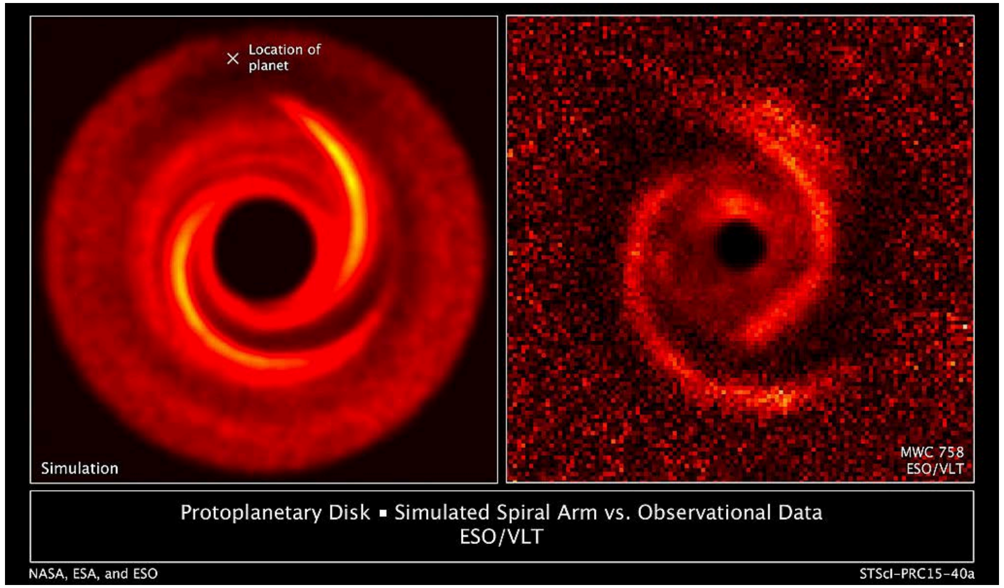
- Instead, we're concerned with the mass and formation
  - An exoplanet is not so massive that nuclear fusion (of deuterium) happens in the core. This limits them to ~13 Jupiter masses or less.
  - An exoplanet should form by accretion and not direct collapse
- As of Spring 2021, there are
  - ~4,600 confirmed exoplanets
  - + ~4,000 suspected exoplanets
  - which are located within a few-thousand light years (due to detection difficulties)
- Most stars have them



Exoplanet detection: *Direct Imaging*

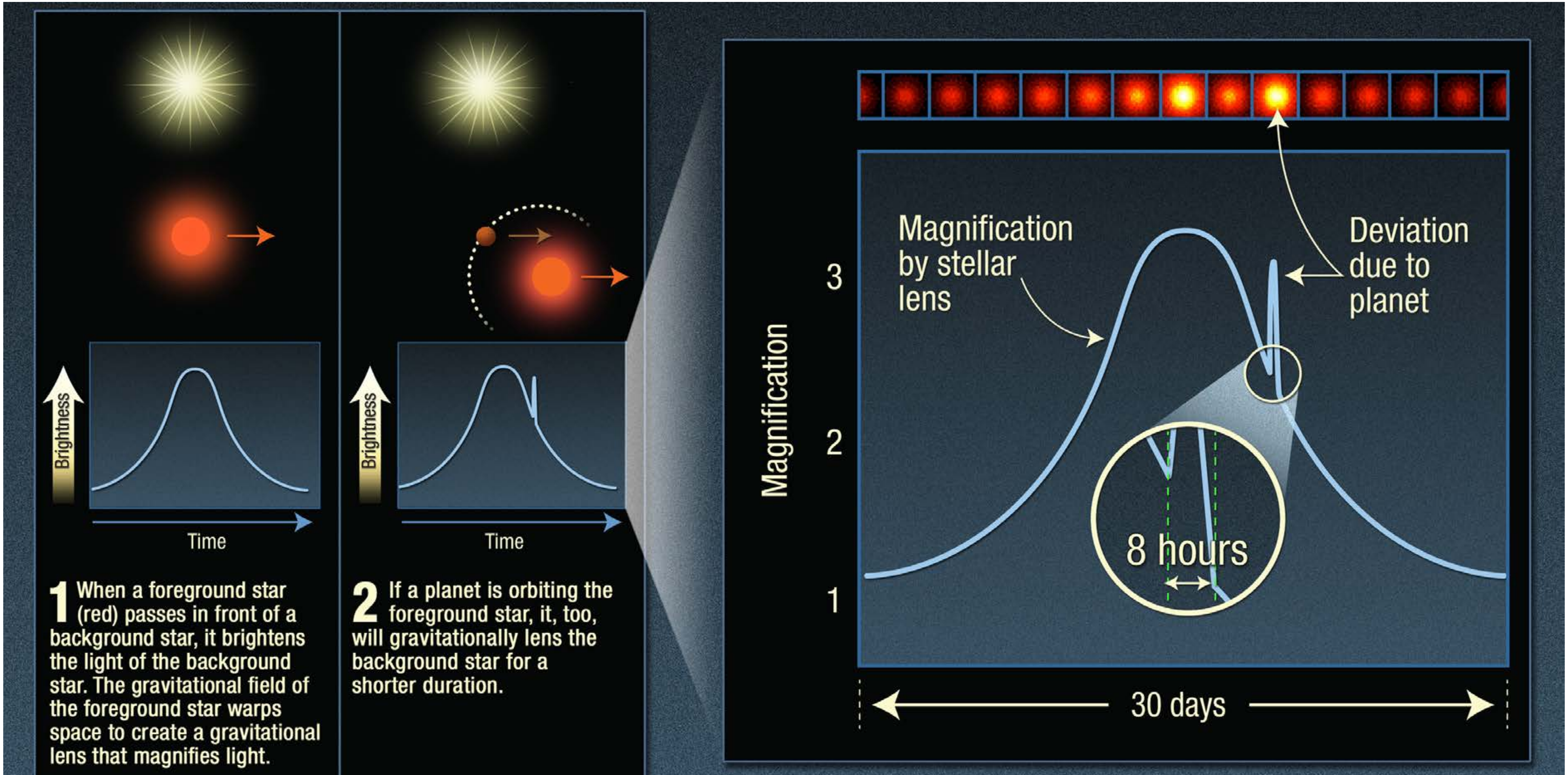
- Ideally, we would directly observe planets…but the problem is that they're very dim compared to the host star
- For a handful of cases, we can in fact do that, blocking-out the light of the host-star and imaging the reflection of that light off of the orbiting planets
- When we cannot image the planets directly, sometimes we can instead directly image the impact on the protoplanetary disk
  (see Intro to Star Formation)
  But this is only relevant for the first several million years when the protoplanetary disk





Exoplanet detection: *Microlensing*

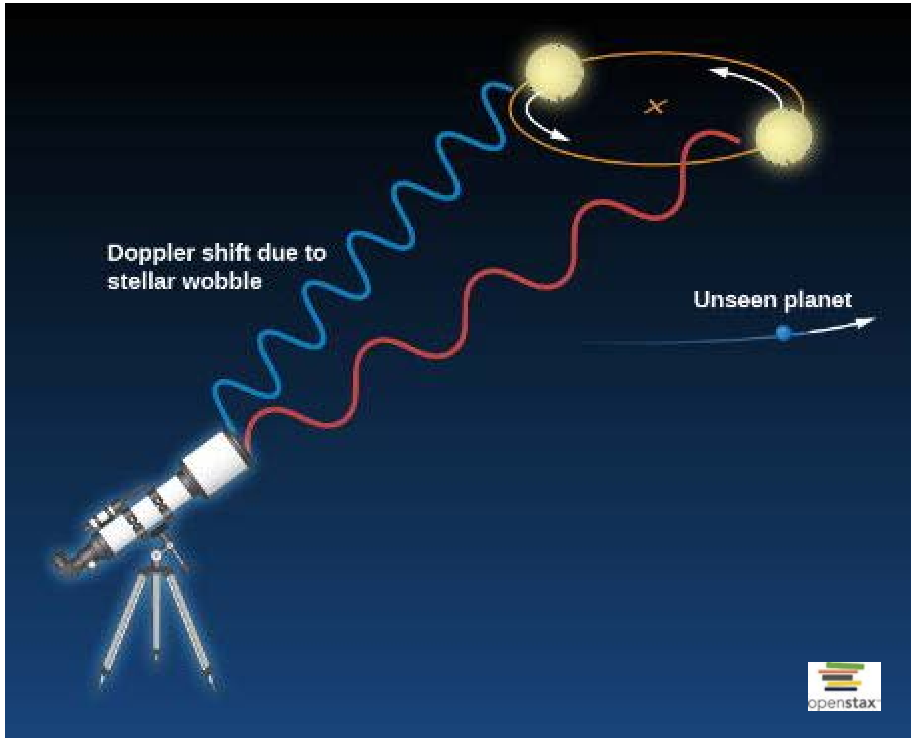
see Intro to Galaxies and Dark Matter

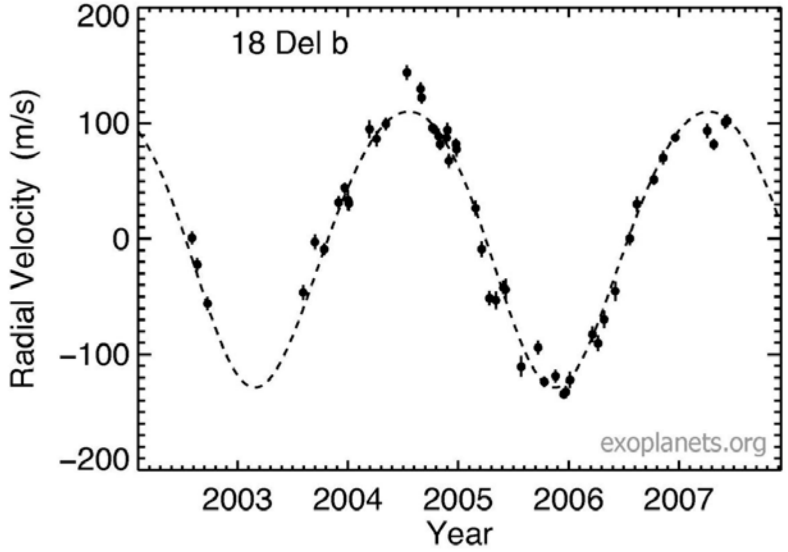


NASA, ESA, and K. Sahu (STScI)

Exoplanet detection: *Radial velocity*

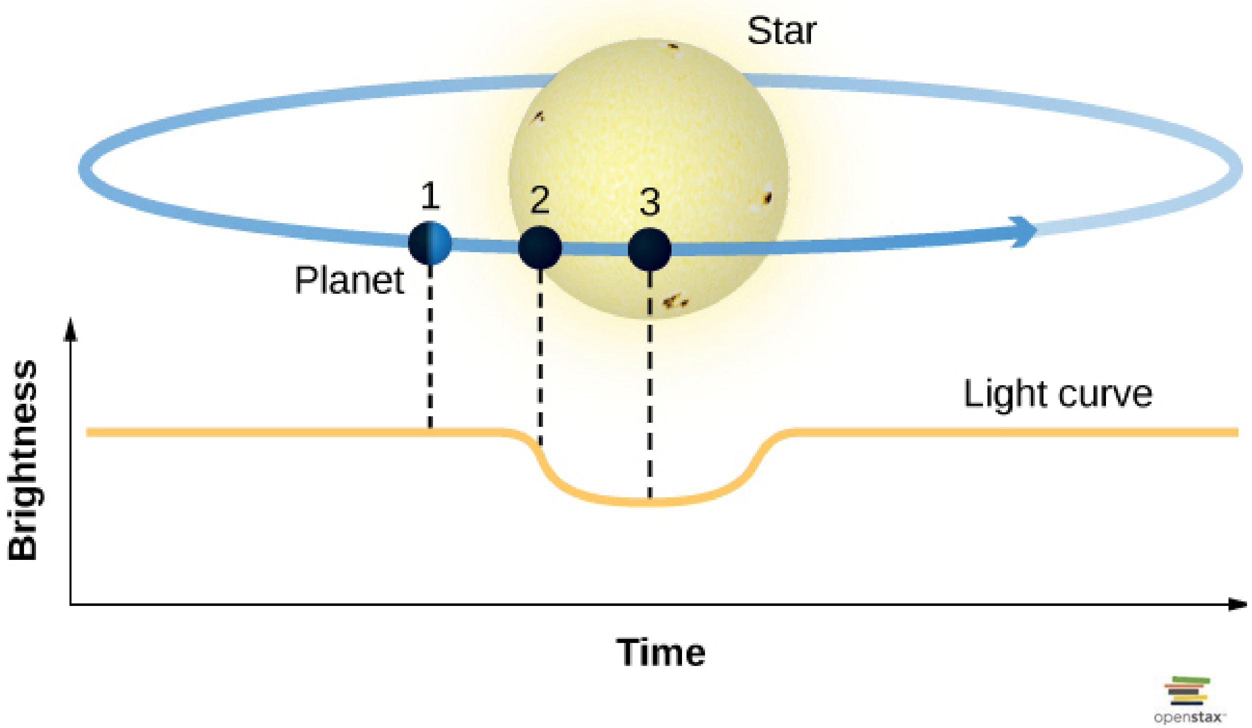
- This is the same as the spectral method used to determine stellar masses for binary star systems (See Intro to the HR Diagram)
- From Kepler's 3rd law $a^3 = (M_{star} + M_{planet})T^2$ — a in Astronomical Units, M in solar masses, T in years
- …but! $M_{star} + M_{planet} \approx M_{star}$, which we can get from the location on the HR diagram (See Intro to the HR Diagram), so we can solve for a
- The velocity of the planet is $v_{planet} = \sqrt{\frac{GM_{star}}{a}}$, from Newton's law of gravity
- From momentum conservation, $m_{planet}v_{planet} = M_{star}v_{star}$, where v_{star} is from the radial velocity measured using the spectrum
- This is a lower-limit on mass, since we only measure motion in the line-of-sight

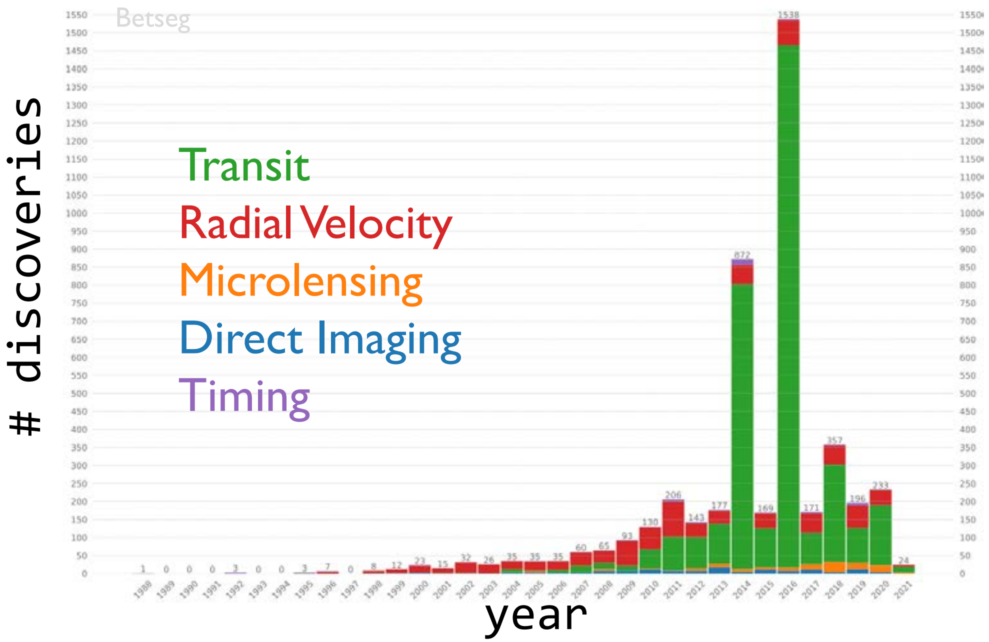




Exoplanet detection: *Transit*

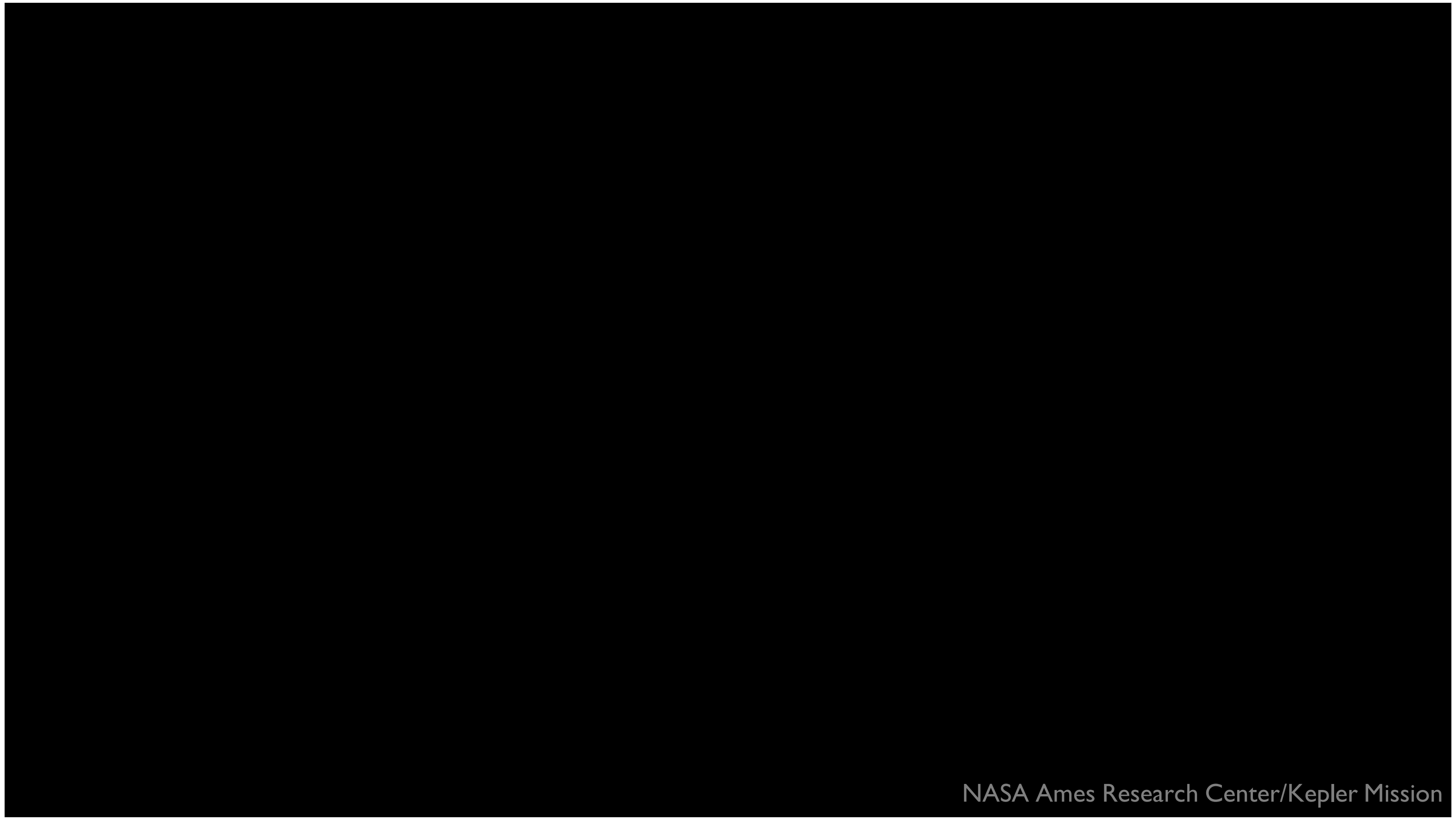
- This is the same as the transit process used to determine stellar masses and radii for binary star systems
  (See Intro to the HR Diagram)
- As with the radial velocity method, the period from Kepler's laws and star mass from the HR diagram gives the planet-star separation distance
- The mass can be determined in a similar way as for the spectral method,
  but we can also get the radius based on the amount of light blocked
- Transit depth = $\frac{A_{planet}}{A_{star}} = \frac{\pi R^2_{planet}}{\pi R^2_{star}}$
- We can determine R_{star} from the location on the HR diagram, giving us R_{planet}





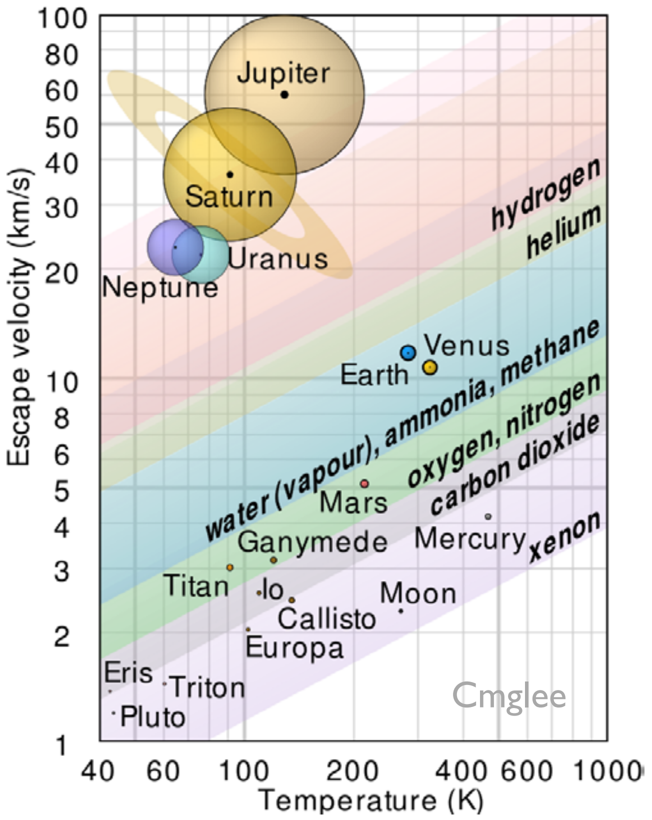
Exoplanet detection: *Transit timing*

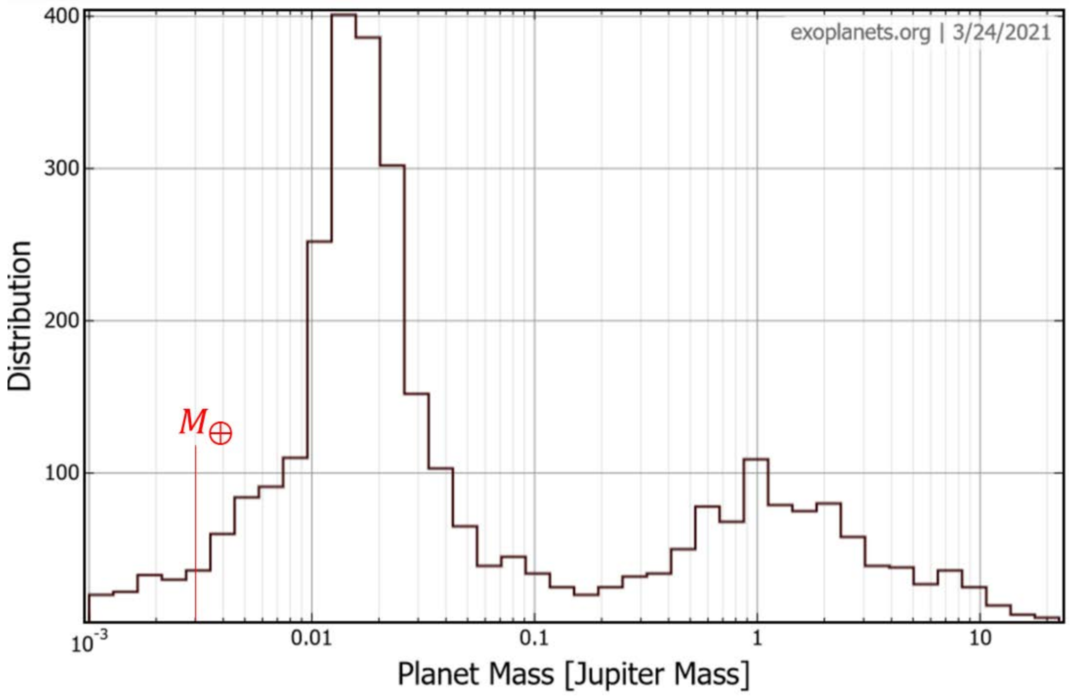
- For systems with multiple exoplanets, some may be too small to directly observe a transit for
- However, we can observe perturbations to the transit time of a larger planet, allowing us to infer the presence of other, smaller planets

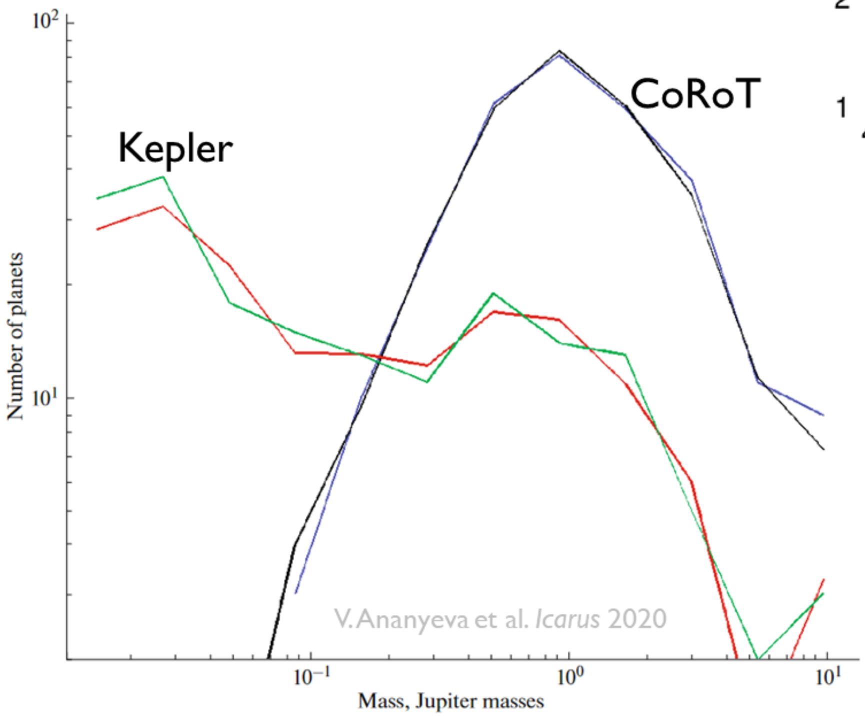


Exoplanet masses

- Most planets appear to be either small & rocky or large and gaseous
- This could be because once you have enough mass to capture an atmosphere of hydrogen, there is a lot of hydrogen to capture, and so a planet is very large
- However, we have to be careful, since there are huge selection effects

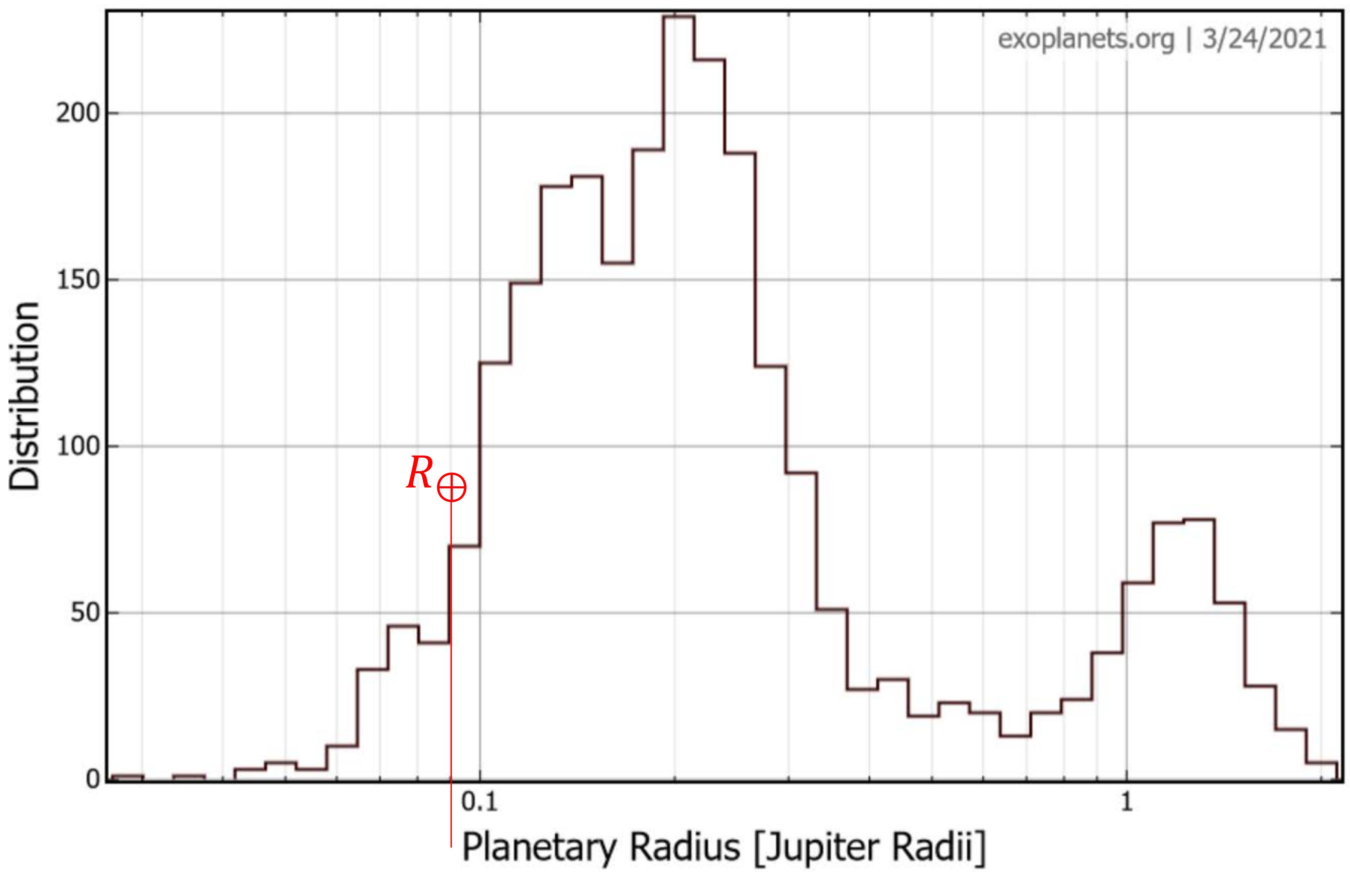






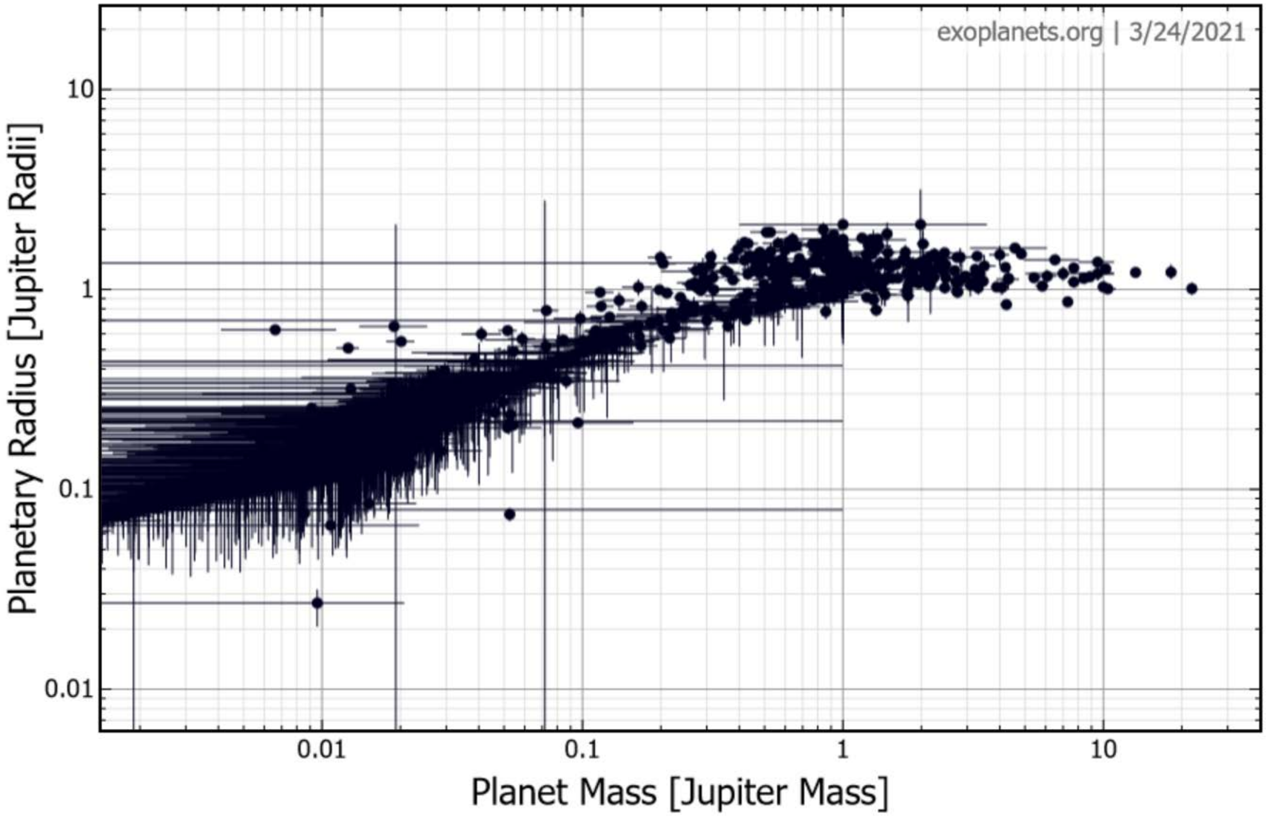
Exoplanet radii

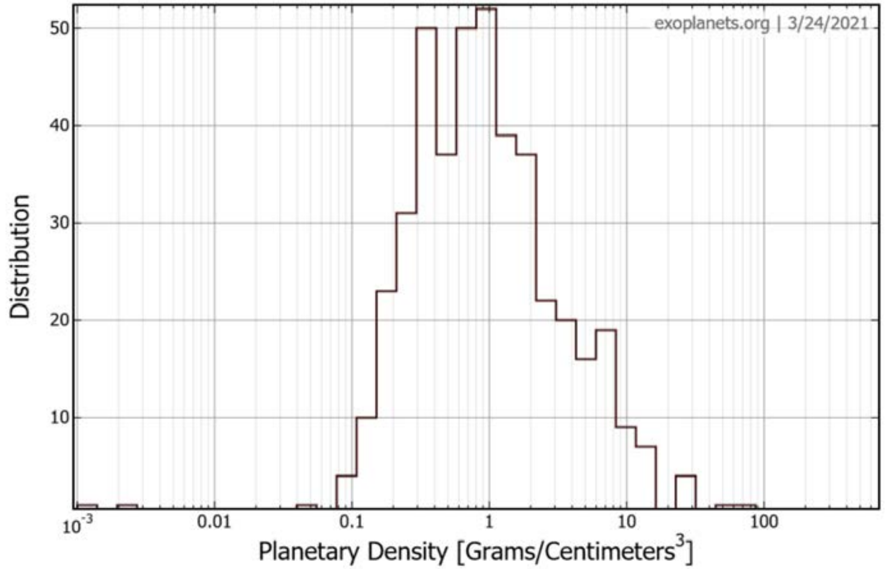
- Exoplanet radii are similarly bimodal and the same explanation & caveats apply here



Exoplanet masses vs radii

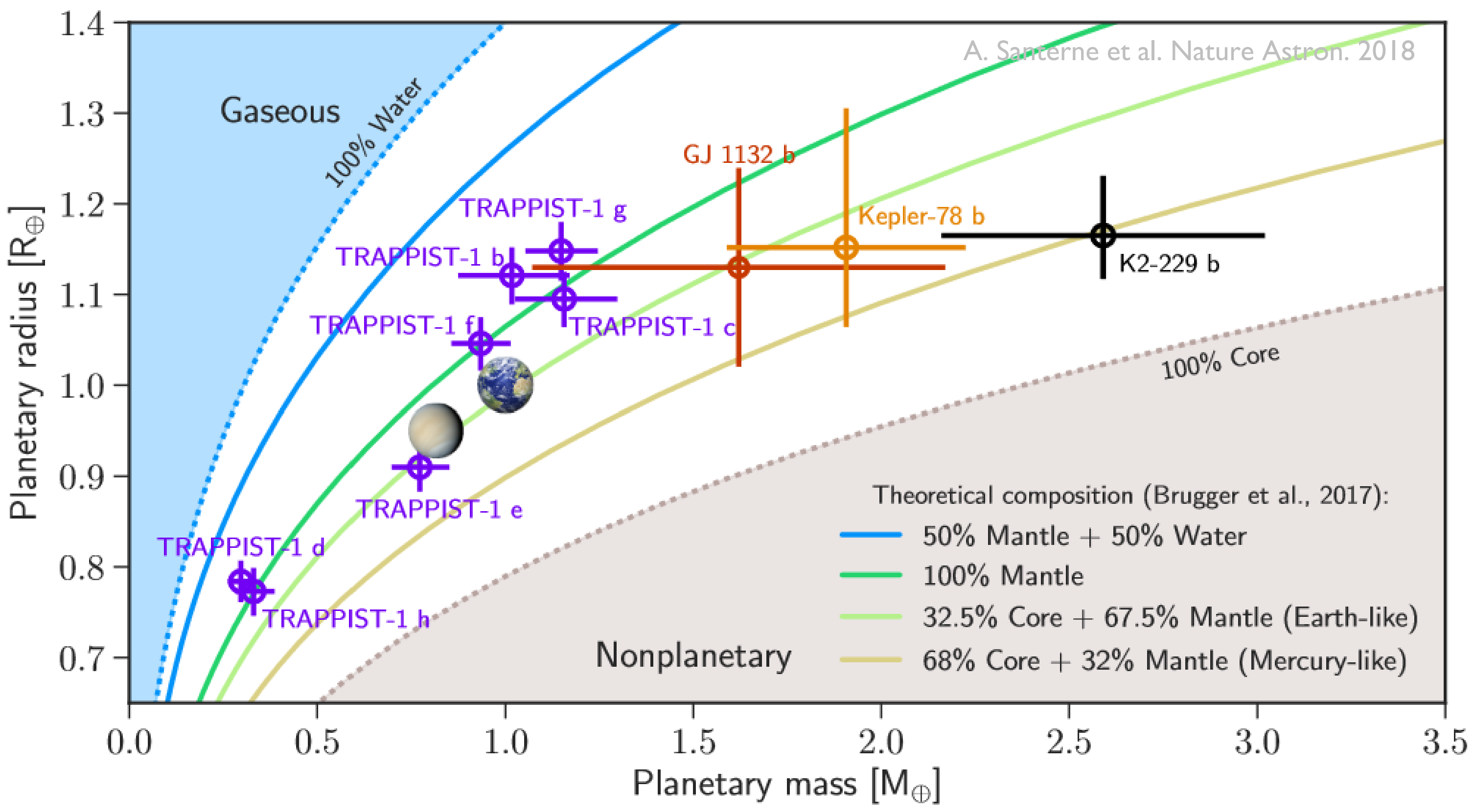
- For planets up to ~Jupiter-size, $R \propto \sqrt{M}$
- For larger planets, $R \propto M^{-1/3}$
- To calculate these, take ASTR 4201
- The average densities $\left(\frac{M}{\frac{4}{3}\pi R^3}\right)$ are (unsurprisingly) in the same range as most solids & liquids

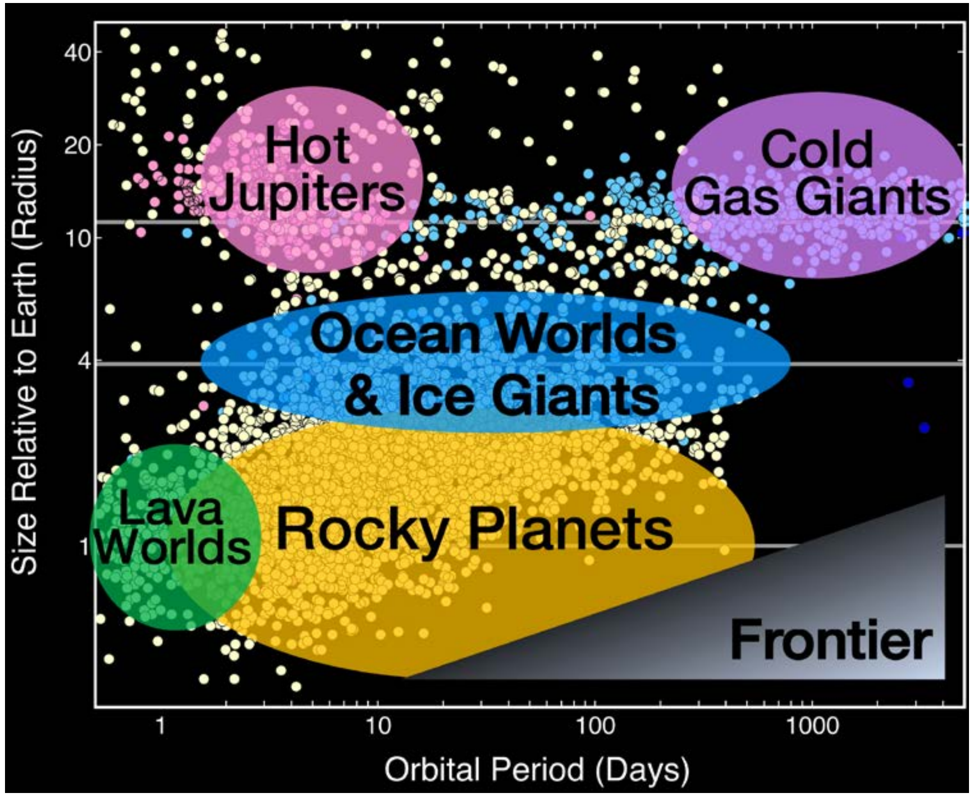




Exoplanet compositions

- The mass & radius of a planet give clues as to its composition:
    - If we assume a planet's density is set by inter-atomic spacing, this sets M vs R
    - For Jupiter-sized planets and above, electron-degeneracy pressure sets the density
- Other clues to composition: **albedo** (shiny-ness) for several wavelengths, **spectra** (comparing the stellar system spectrum during & not-during transit), & **distance** from the star





NASA/Ames Research Center/Natalie Batalha/Wendy Stenzel