Habitable Planets: 2
Estimating f_s

Stellar Requirements (f_s)

- We assume that our planet needs to orbit a star
  - Leaves out planets around brown dwarfs
  - Leaves out “nomad planets” (may be many)
  - About 6% of stars are white dwarfs (after all red giant phases). May be OK
- We will consider 5 sub-factors for f_s

1. Sufficient Heavy Elements

- Need for Terrestrial planets, bioelements
- 1st generation stars - No heavy elements: ruled out
- Next several generations, Population II – Few heavy elements: Probably ruled out
  - But NOTE: planets found around very old star (11×10^9 yr) with very few heavy elements!
- Few Stars are Population II

Do We Need A Lot of Heavy Elements?

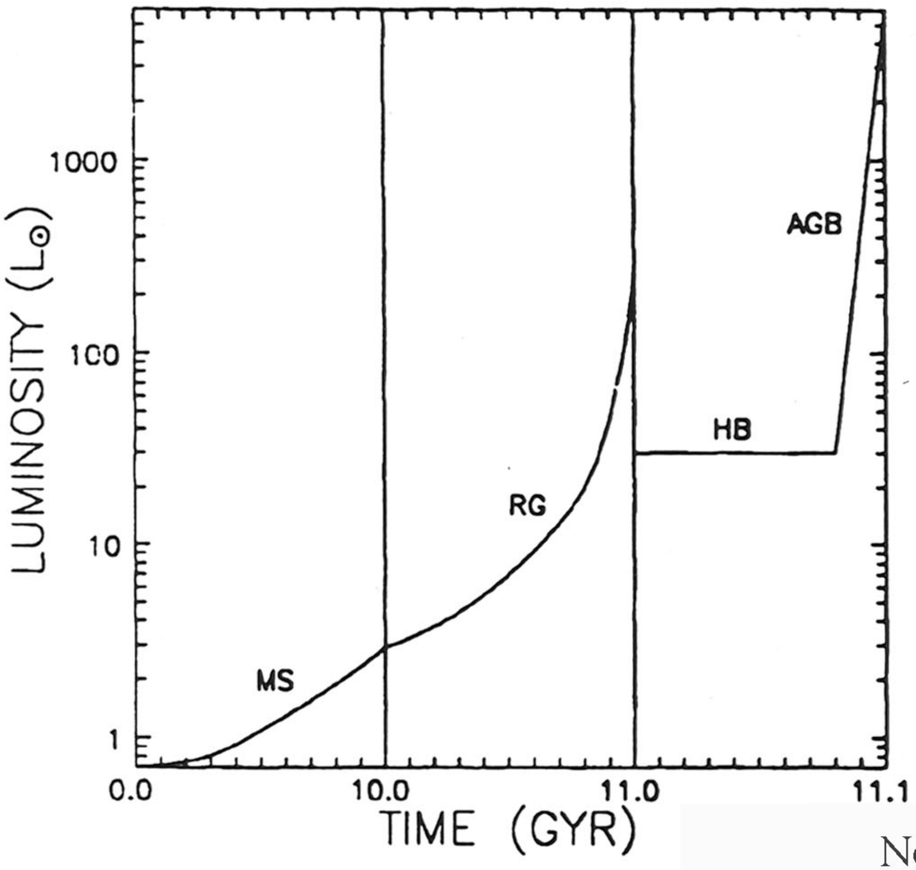
Massive, close-in planets are found more commonly around stars with more heavy elements than Sun

Does not seem to apply for lower mass planets.

Can probably assume 1.0 for this fraction.

2. On the Main Sequence

- Means stable hydrogen fusion
  - Stable Luminosity, stable planet temperature
- Red giants, later stages ruled out
- Except White dwarfs (end state)
  - 0.99 OK if include WDs
  - 0.94 OK if exclude WDs



Note Changing Scale

FIG. 1. *Luminosity evolution of a 1 $M_\odot$ star of solar composition. Note that the scale is broken at 10 and 11 Gyr. The discontinuity at 11 Gyr is real and is due to the helium flash. The phases are: MS = main sequence, RG = red giant, HB = horizontal branch, and AGB = asymptotic giant branch. The final white dwarf phase is not illustrated. Details of the evolution during the HB and AGB phases are omitted.*

$$r_2 = \sqrt{\frac{L(t)}{S_2(T)}}$$

What about White Dwarfs?

- Once they cool below 6000K,
  - planet orbiting at 0.01 AU
  - Orbital period around 12 hours!
  - in CHZ for 8×10^9 years
- How did planet get there?
  - Survive red giant phase?
  - Form again from debris?

3. Long Enough MS Lifetimes

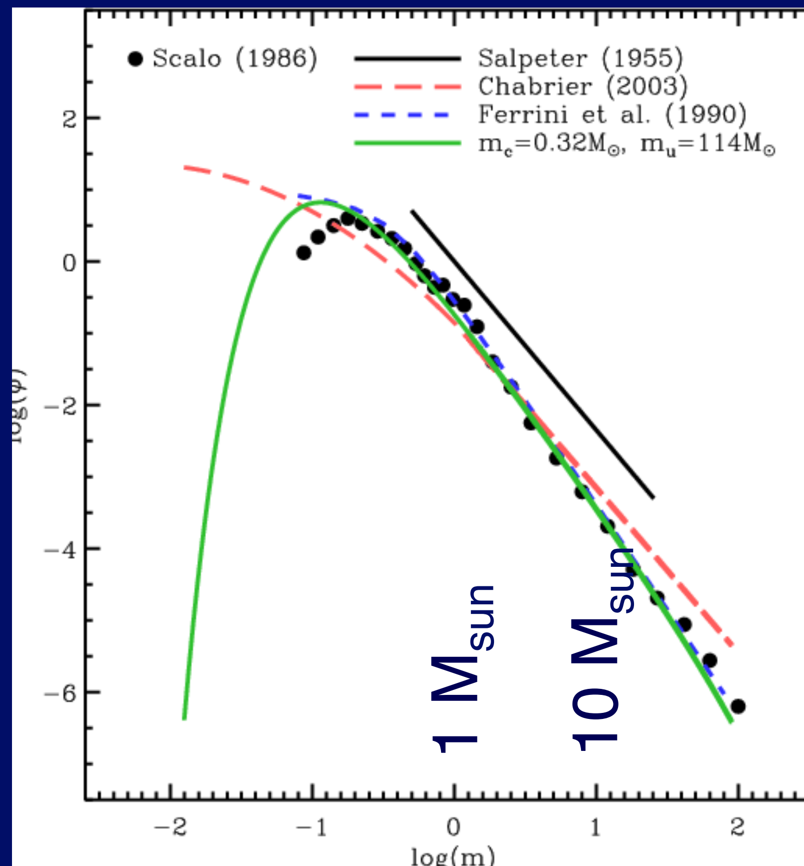
- Main Sequence Lifetime long enough for intelligent life to evolve (5 x10^9 yr)
- Roughly speaking $L \propto M^4$
- Fuel $\propto M$
- Lifetime $\propto M/L \propto 1/M^3$
- Big stars live fast, die young

Stellar Lifetimes

M ($M_\odot$)	Lifetime (yrs)
30	2×10^6
10	3×10^7
3	6×10^8
1	1×10^{10}
1/3	2×10^{11}
1/10	3×10^{12}

Most Stars are Low Mass

- If we require at least 5×10^9 yr on MS
- $M < 1.25\ M_{sun}$
- 90% OK
- So this factor is 0.9



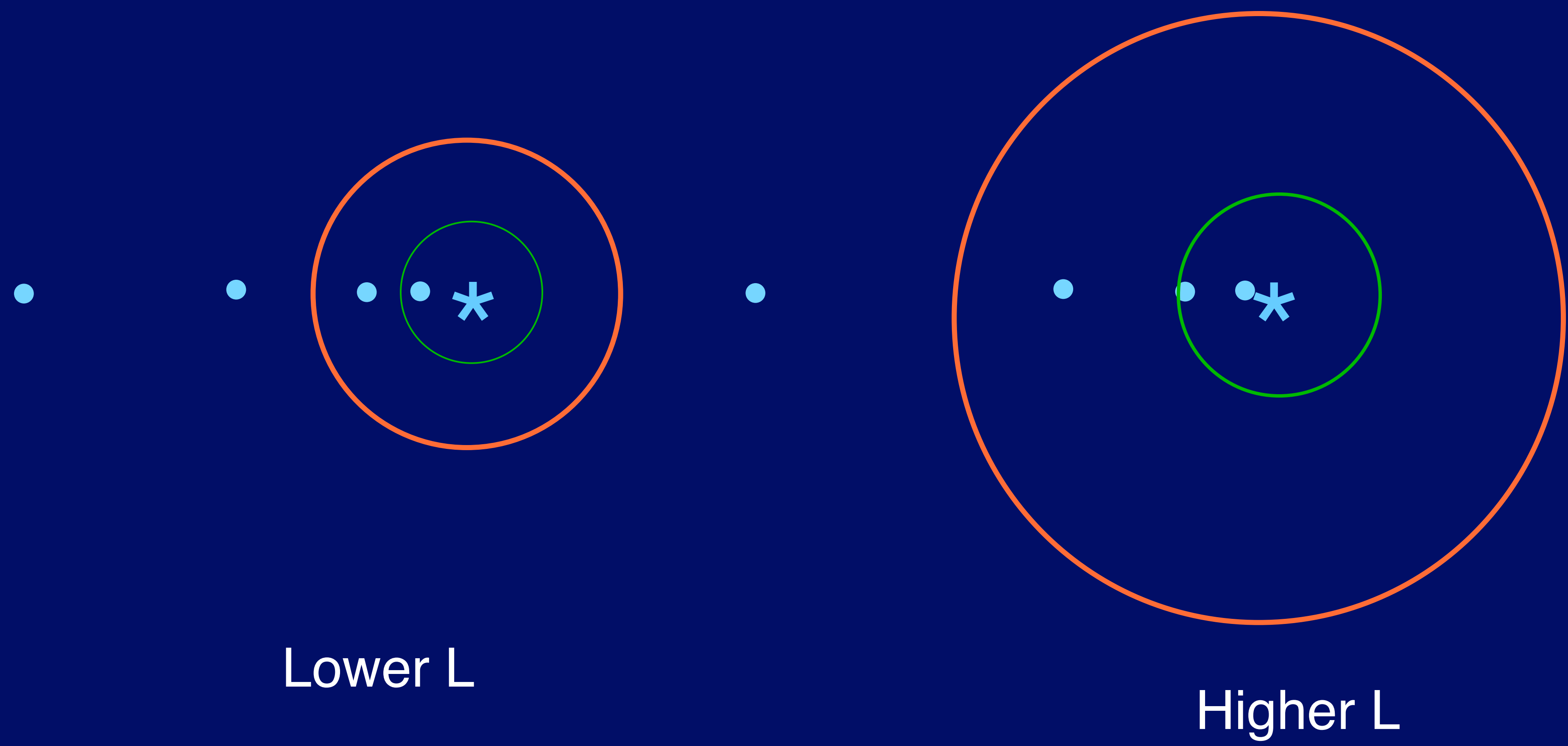
Fraction

Log M in units of M_{Sun}

4. Stellar Mass Not too Low?

- Do terrestrial planets form around low mass stars (M dwarfs)?
  - Latest evidence suggests yes
- HZ is much closer in
  - Planets in HZ much easier to find
  - Recent estimate: 0.3 to 0.5 planets in HZ per M dwarf, depending on definition of HZ

For Logarithmic Spacing, n_p independent of size



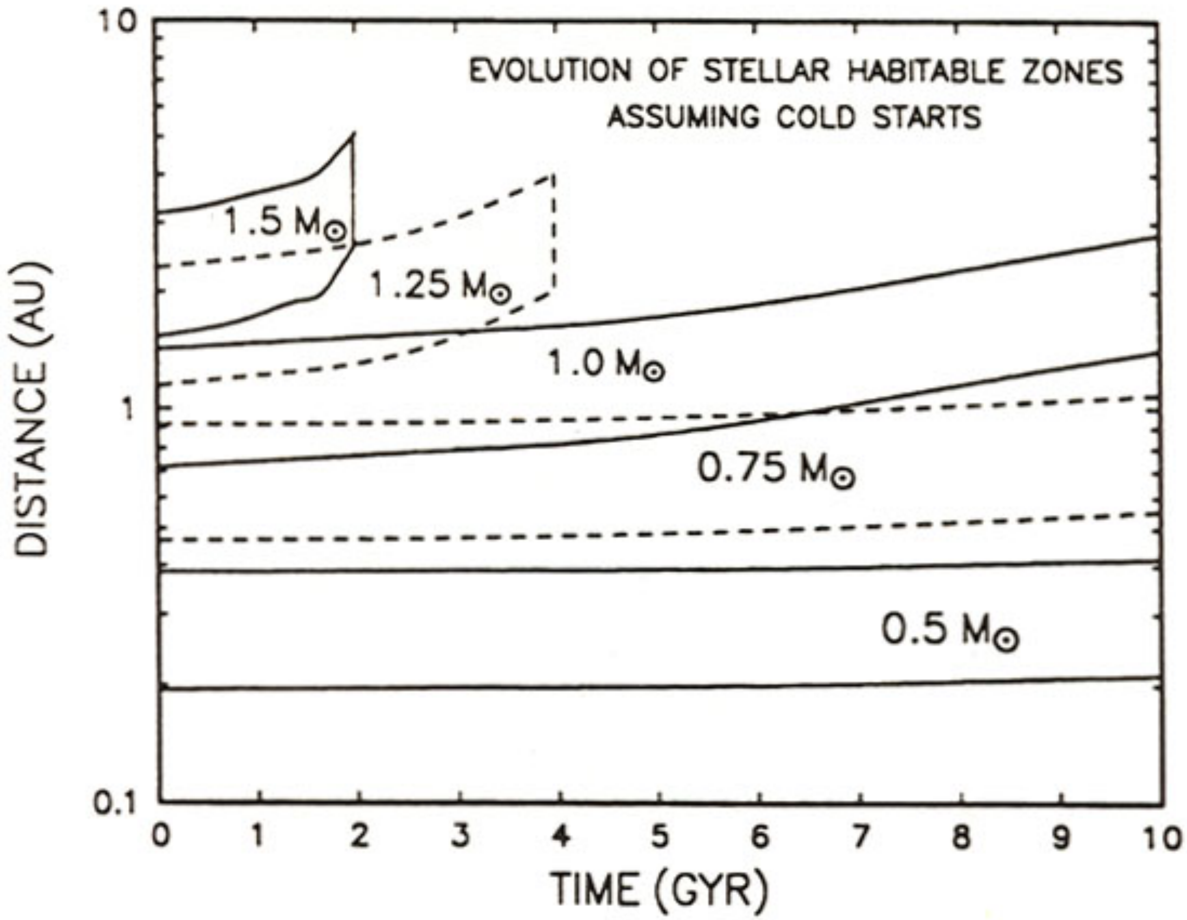


FIG. 5. *Evolution of the H around stars of different masses assuming that co starts are possible. Case critical fluxes were usea and the evolution was truncated at the end of tl main sequence phase.*

Advantage: Very Long time in CHZ for low mass stars

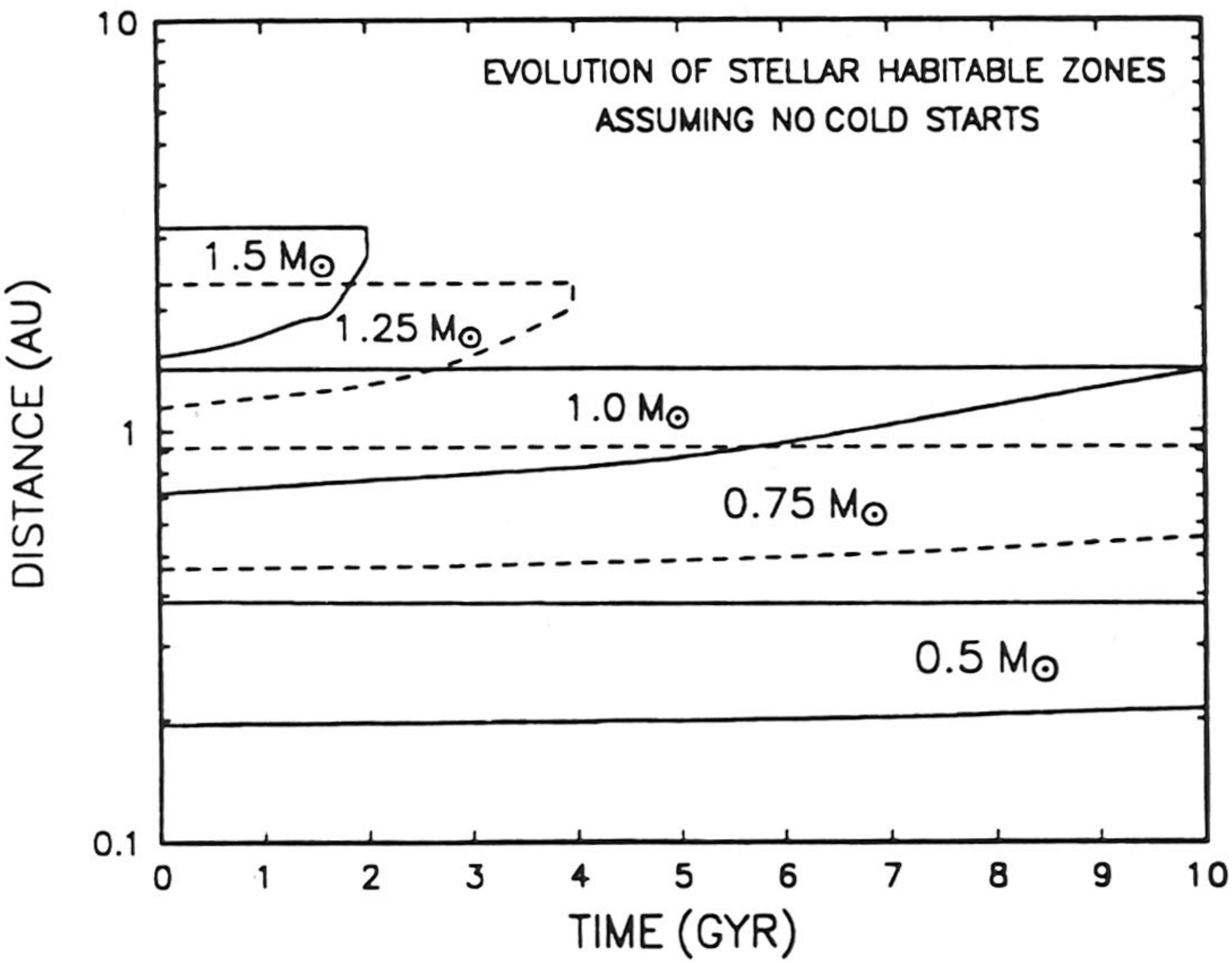


FIG. 6. *Evolution of the HZ around stars of different masses assuming that cold starts are not possible. Case 2 critical fluxes were used and the evolution was truncated at the end of the main sequence phase.*

Problem for Lowest Mass Stars

- VERY low mass stars (say $M < 0.3\ M_{sun}$)
  - Take 1 Gyr (1×10^9 yr) before nuclear reactions start
  - Luminosity decreases slowly for 1 Gyr
  - HZ moves in
  - Planets in HZ for most of life may have lost their hydrogen, runaway greenhouse BEFORE steady luminosity phase
  - Flares, radiation stronger
  - Synchronous rotation likely

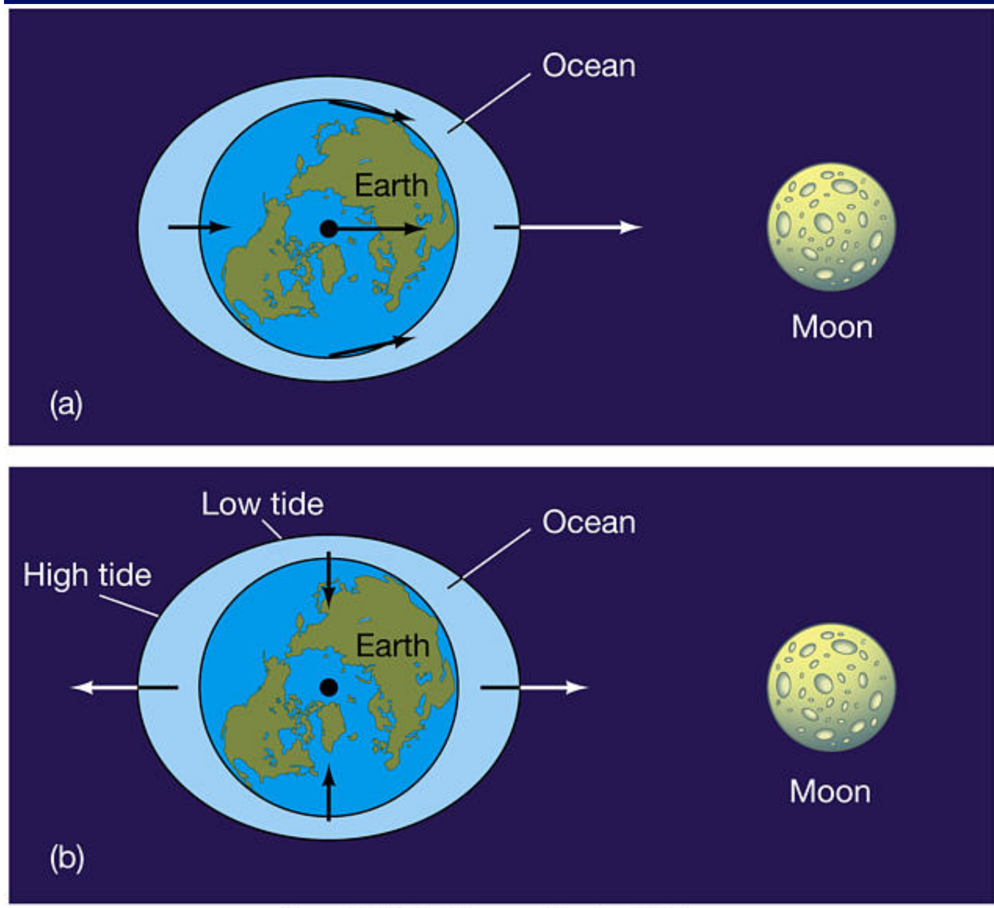
Synchronous Rotation
(Same side always faces star)

$$T \propto \left(\frac{L}{D^2}\right)^{1/4} \propto \frac{L^{1/4}}{D^{1/2}} \qquad \text{Tidal Forces} \propto \frac{1}{D^3}$$

$\Rightarrow$ As D decreases, Tidal forces become much more important

Cause synchronous rotation

Tidal Forces



Force greatest on side toward Moon, least on side away from Moon.

If rotation period not equal to orbital period, there is friction. That slows down rotation. Tides on Moon from Earth have made it rotate synchronously. Tides on Earth are slowing down rotation.

$\Rightarrow$ Atmosphere freeze-out?

May not happen if atmosphere thick enough

(0.1 Earth pressure)

$M > 0.5\ M_\odot \Rightarrow 0.25$ OK

$M < 0.5\ M_\odot$ - may be bad choices, but not sure

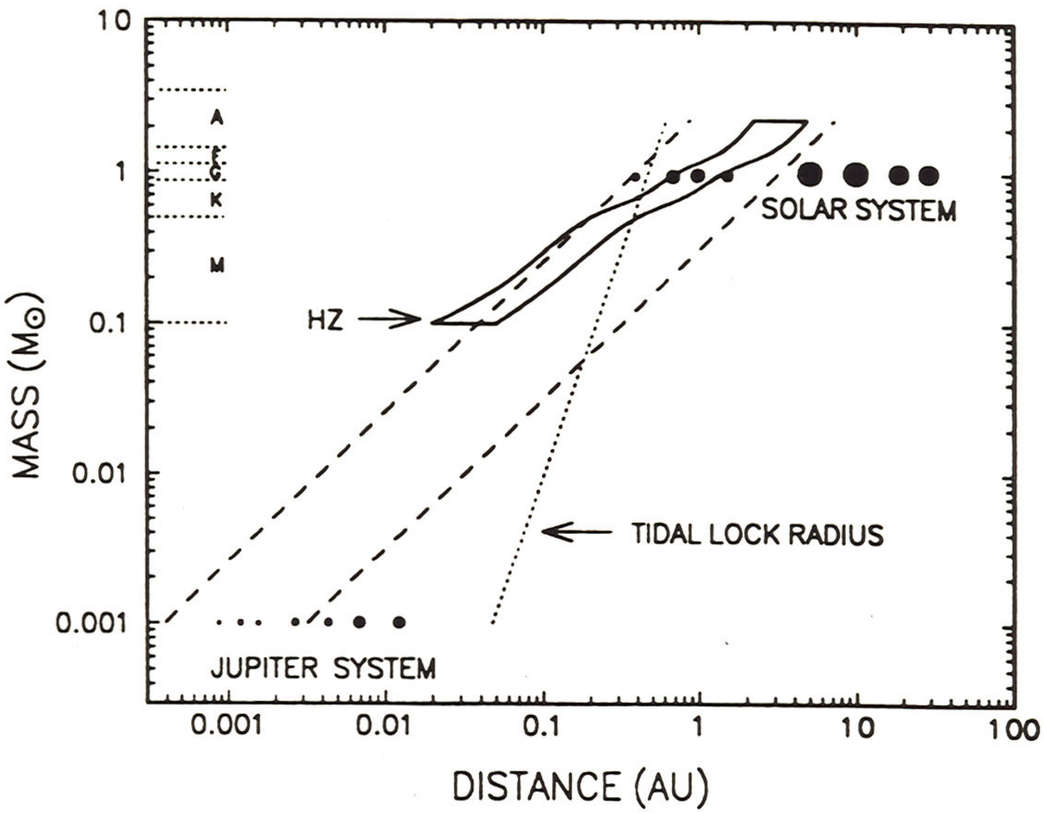


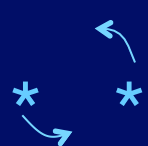
FIG. 8. *The ZAMS HZ (dark solid curve) as a function of stellar mass for Case 2 fluxes. The long-dash lines delineate the most probable terrestrial planet formation zone. The short-dash line is the radius for which an Earthlike planet in a circular orbit would be synchronously or slowly rotating as a result of tidal damping. Note that all such planets in the HZ around M stars are within this radius.*

5. Binary Stars

a) Unstable orbits

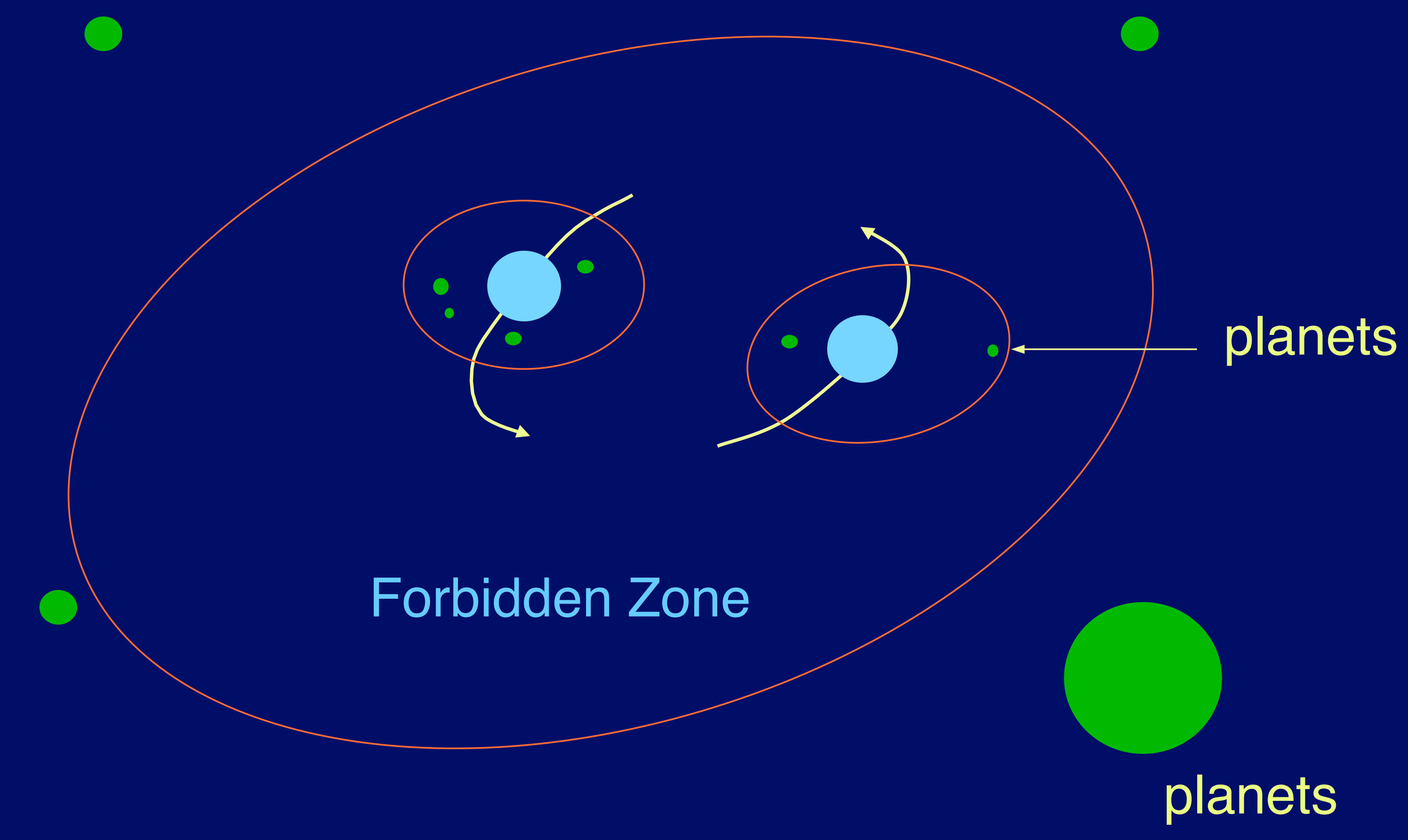
Unless two stars widely separated
or very close

Need $\dfrac{\text{Distance to Second Star}}{\text{Distance to Planet}} > \dfrac{7}{1}$ or $< \dfrac{1}{7}$



or

* (more likely)



Stable orbits around a Binary Star

b) Varying temperature in orbit
also need $\sim 7:1$

c) Both stars on main sequence,
$M < 1.25\ M_{\odot}$, …

2/3 of all stars are binaries
2/3 ~ "wide enough"

Binaries ruled out? $f_s < 1/3$ (if you kept them for f_p)
Not > 7 : 1 ruled out? $f_s < 1/2$

Summary of factors

Stellar Requirement	**Mass limit**	**Fraction OK**	**Cumulative Fraction**
Heavy Elements	…	1.0	1.0
Possibly Stable Temperature	…	0.99 0.94 w/o WDs	0.99 0.94 w/o WDs
Main Sequence Lifetime	($M<1.25\ M_\odot$)	0.90	0.89 0.85 w/o WDs
Not Synchronous Rotation	($M>0.5\ M_\odot$)	0.25	0.22 0.21 w/o WDs
Not a binary	…	0.30	0.07 0.06 w/o WDs
Wide separation binary	…	0.50	0.11 0.11 w/o WDs

Bottom Line

- Points 1 to 3 are pretty clear
  - But don't matter much…
- Points 4 and 5 are less established
  - And could matter a lot…
- Room for different estimates for f_s
  - Range 0.06 to 0.89 OK
- Then final step:
  - $n_e = n_p f_s$

What are we Learning from Kepler?

- In addition to f_p, Kepler getting information about planetary systems
- More and more low mass planets are seen in larger orbits
- Kepler was just getting to Earth-size planets in Earth-like orbits
- Pointing system failed
- Need to extrapolate from what we see so far

Information on Exoplanets

- Repeated Detections: Period of orbit
  - Radius of orbit (Kepler's 3rd law)
- Transits: size
- Spectroscopic: mass (or lower limit)
- Both: Density = Mass/Volume
  - Composition: gas giant, water world, terrestrial

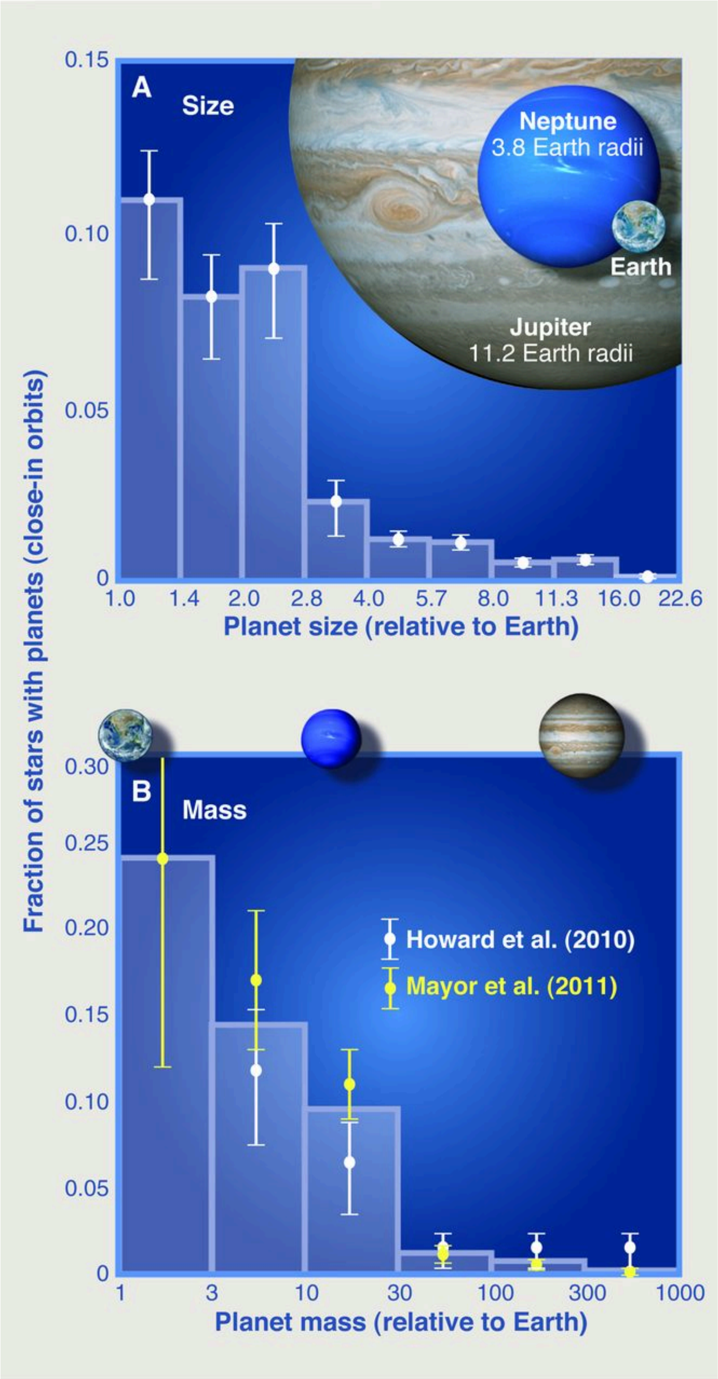


Fig. 2 The (A) size and (B) mass distributions of planets orbiting close to G- and K-type stars.The distributions rise substantially with decreasing size and mass, indicating that small planets are more common than large ones.

A W Howard Science 2013;340:572-576

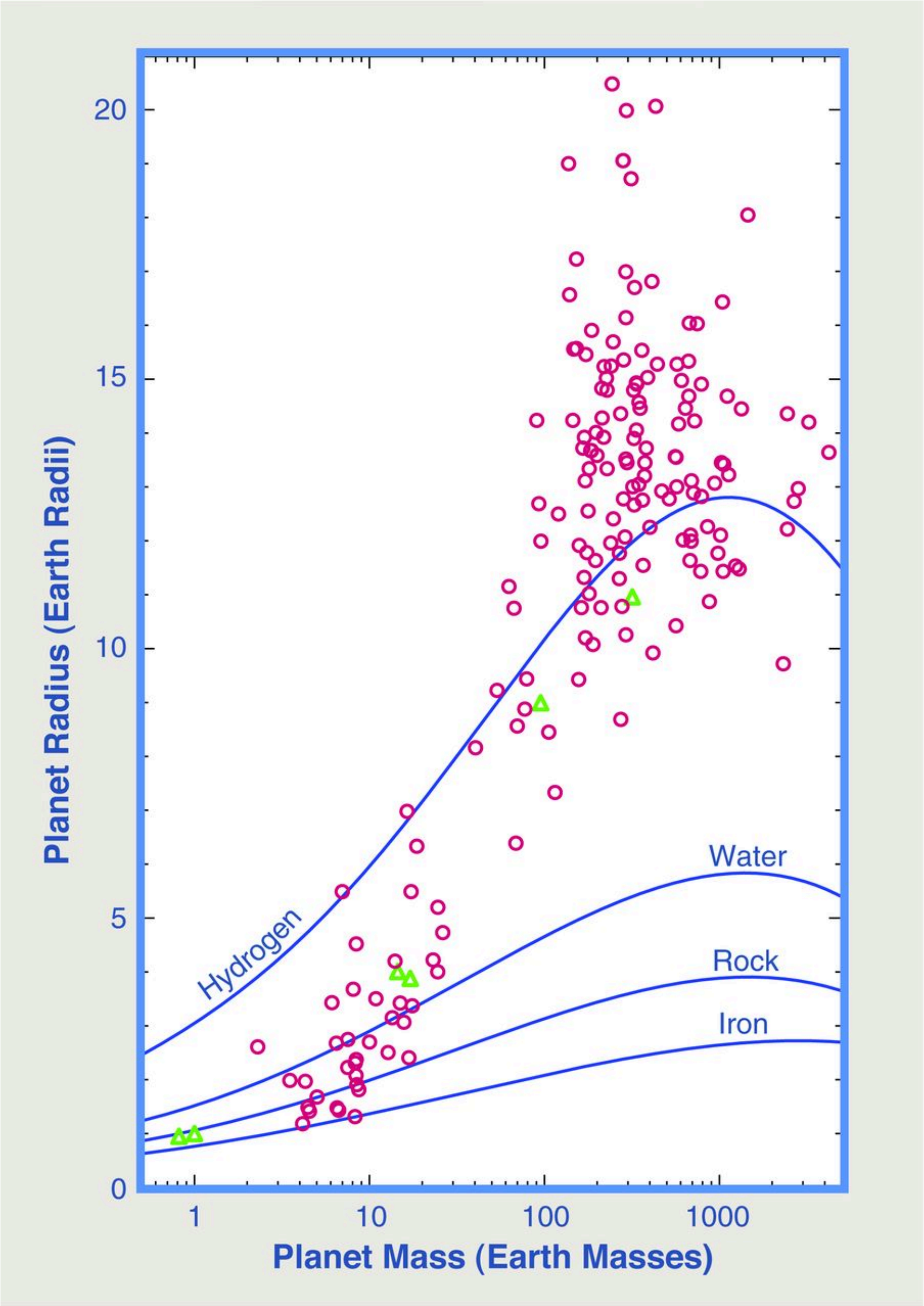


Fig. 3 Masses and sizes of well-characterized planets.Extrasolar planets (1, 58, 60) are shown as open red circles, whereas solar system planets are designated by open green triangles.

A W Howard Science 2013;340:572-576

Published by AAAS

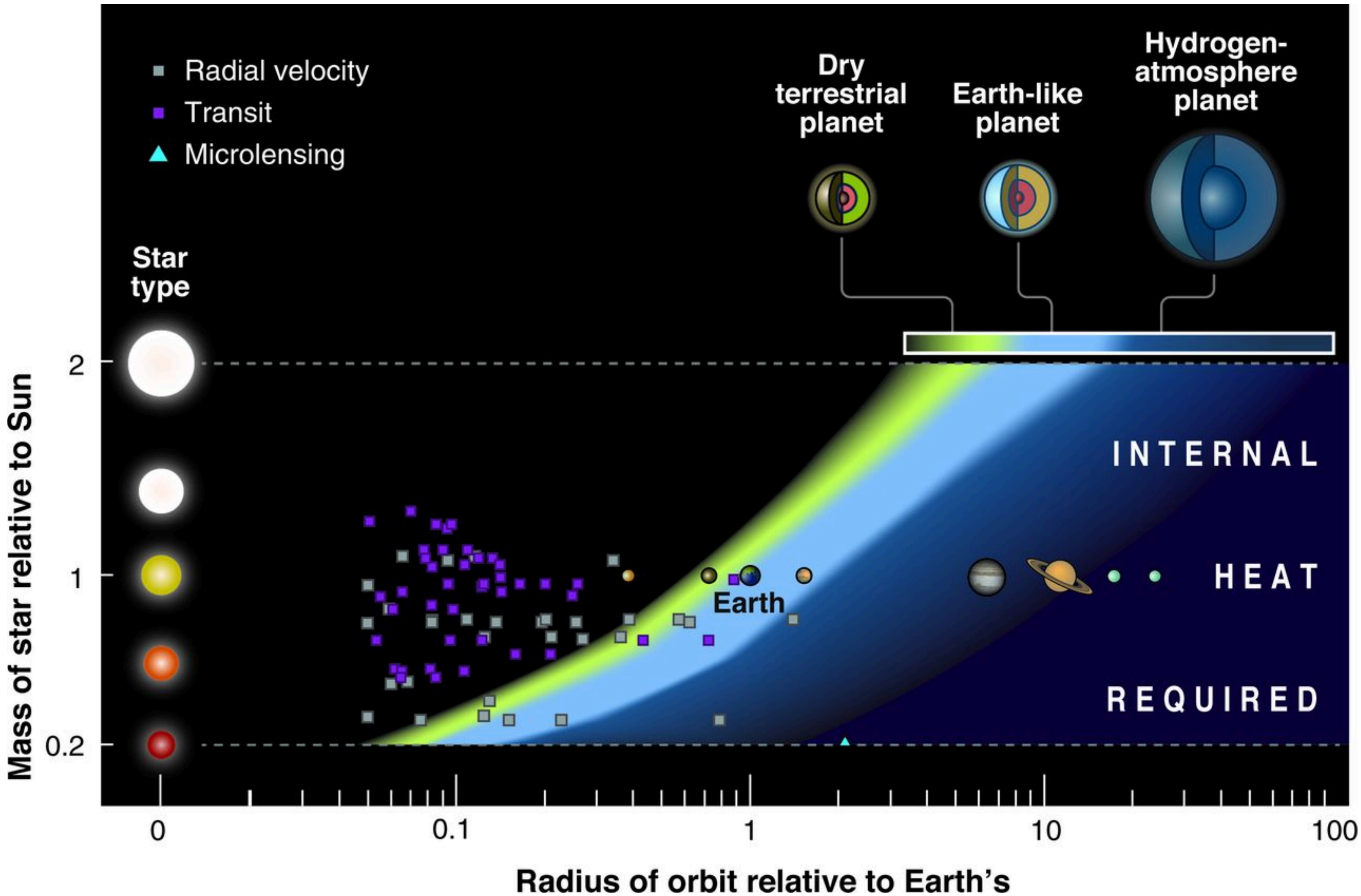
Current Status

- There are many planets with masses between Earth and Neptune.
  - Called “super-Earths”
  - Some may be “water worlds”
- Many planetary systems have planets much closer to their star than in solar system
- Earth-size planets in HZ: Recent estimate is 1 out of 5, or $n_e = 0.20$
  - Warning: BIG extrapolation!

Habitability Reconsidered

- S. Seager: Science 340, 577 (2013)
  - The diversity of exoplanets challenges traditional view of habitable zones.
  - Different locations, densities, atmospheres suggest wider range of orbits for liquid water.
  - Especially hydrogen atmospheres have strong greenhouse effect
    - Extends HZ farther out, even to “rogue” planets

Fig. 2 The habitable zone.The light blue region depicts the "conventional" habitable zone for planets with N2-CO2-H2O atmospheres (9, 10).



S Seager Science 2013;340:577-581

Better than Earth?

- Paper by Heller and Armstrong
  - Astrobiology 14, pg 50 (2014)
- What could be “super-habitable”?
  - Slightly smaller, older star
    - Longer stable temperature, time for life
  - Slightly larger, slightly drier planet
    - More “coastline” (deep oceans, continental interiors less hospitable)
    - Drier planet makes wider HZ

Summary

- Factor f_s:
  - heavy elements
  - main sequence
  - Mass not too high
  - Mass not too low (?)
  - Not binary? (or wide enough binary?)
- Exoplanets show diversity
  - Super-Earths, water worlds, …
  - Superhabitable planets?