An introduction to

Planet Formation

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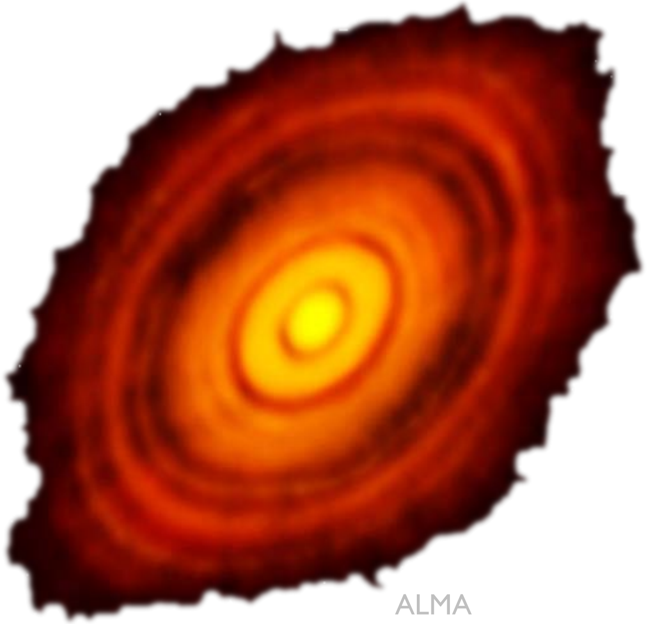
Formation process

- Young stars are surrounded by a disk (see Intro to Star Formation), which slowly cools
- Molecules begin to be able to stick together to form dust (~μm-size)
- Dust grains collide and electrostatically attract to form larger chunks of dust, that you would at some point call a rock
- Rocks collide and can stick together
- Once an object is ~1km wide, gravity is the main thing holding it together and it is a **planetesimal**
- Planetesimals undergo further collisions, ultimately growing into **protoplanets**. These are ~moon-sized objects that are large enough that internal radioactivity and gravitational pressure has melted the interior, causing heavy elements to sink
- Protoplanets further collide to form planets, formally defined in the Intro to Star Formation lecture
- Large planets can capture gas atmospheres

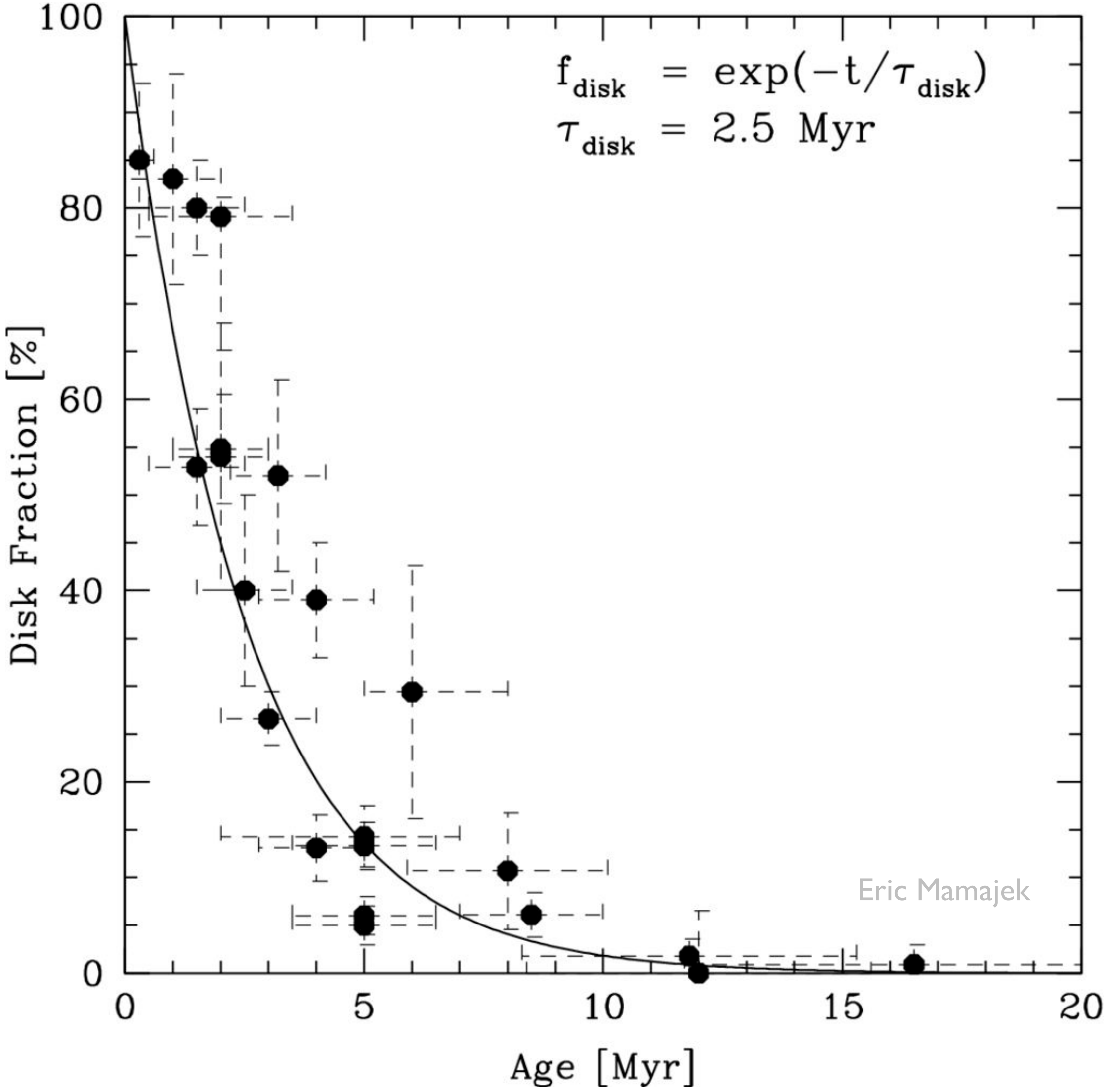


ALMA

NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute/Roman Tkachenko

Formation timescale

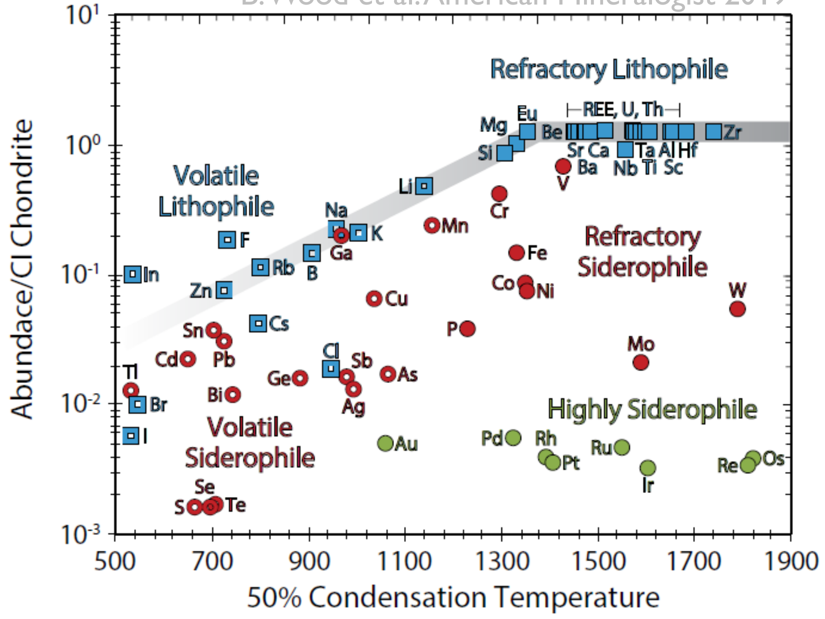
- Planet formation is super-hard to see, so we mostly rely on looking for the presence of disks around young stars
- From a star's position on the HR diagram, we can roughly determine the age
- Then we look for disks and count the fraction that have a disk
- This sets the planet formation time to be on the order of millions of years.
    - This also makes planet formation difficult to study, since planets spend roughly no time in this phase



Formation location

- Material condensing to form planets needs to be cool enough that the condensation is possible.
- But condensation temperature depends on the elements involved!
- Metals condense at much higher temperature than easy to vaporize molecules (e.g. water, methane, CO_2)
- So, rocky planets (e.g. Earth) can form close to the host star, but stars with large gaseous envelopes (e.g. Jupiter) can only form far away from the host star and stars with highly volatile atmospheres (e.g. methane) need to form even further out (e.g. Neptune)
- The boundary between the rocky and gaseous planets is referred to as the **frost line** or **snow line**

B. Wood et al. American Mineralogist 2019



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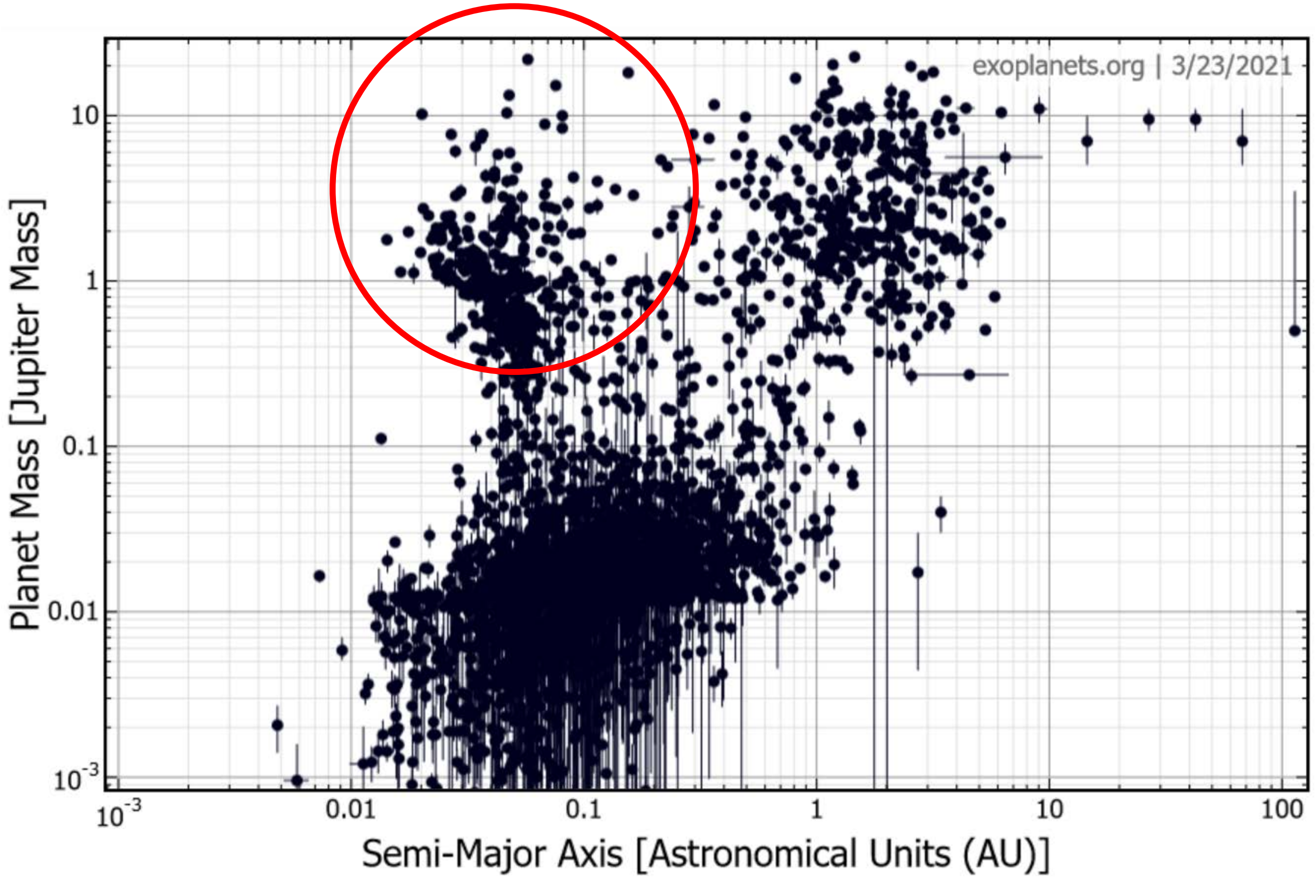
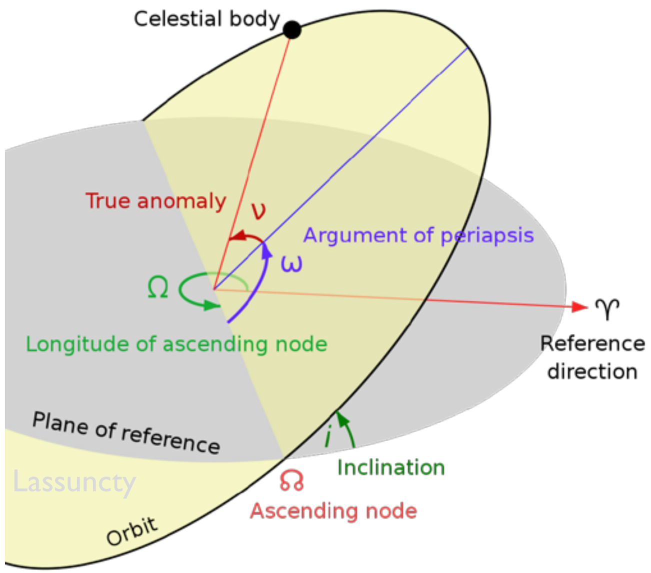
Problem: *Hot Jupiters*

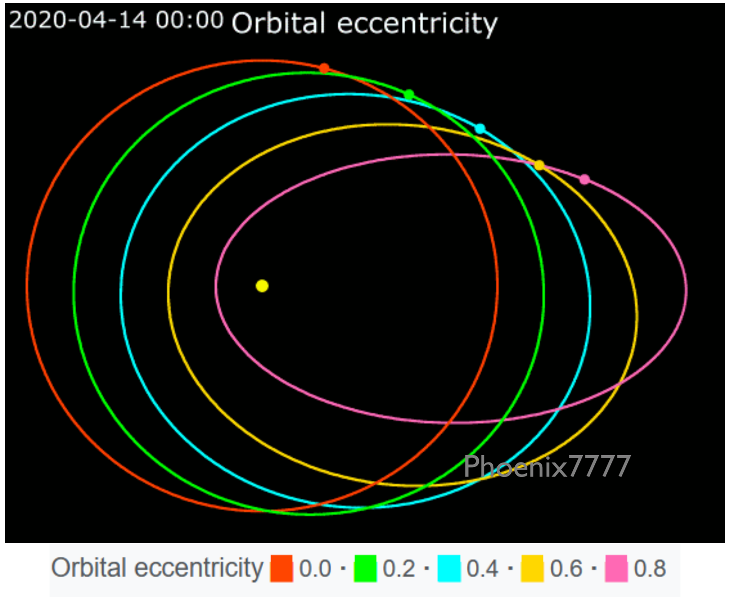
- One big problem that early extra-solar planet (exoplanet) observations discovered was the phenomenon of "hot Jupiters"
- These are gas giants located at much less than an earth-sun distance
- One issue is that early planet detection methods were biased towards finding these objects
- But nonetheless, they existed and had to get that way somehow

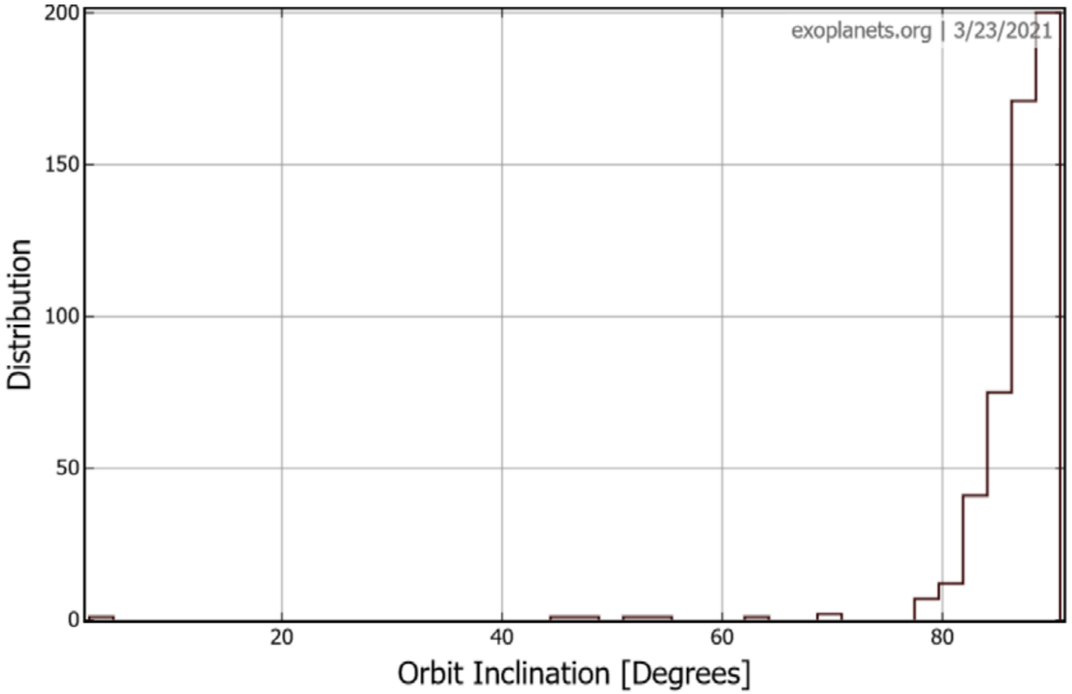


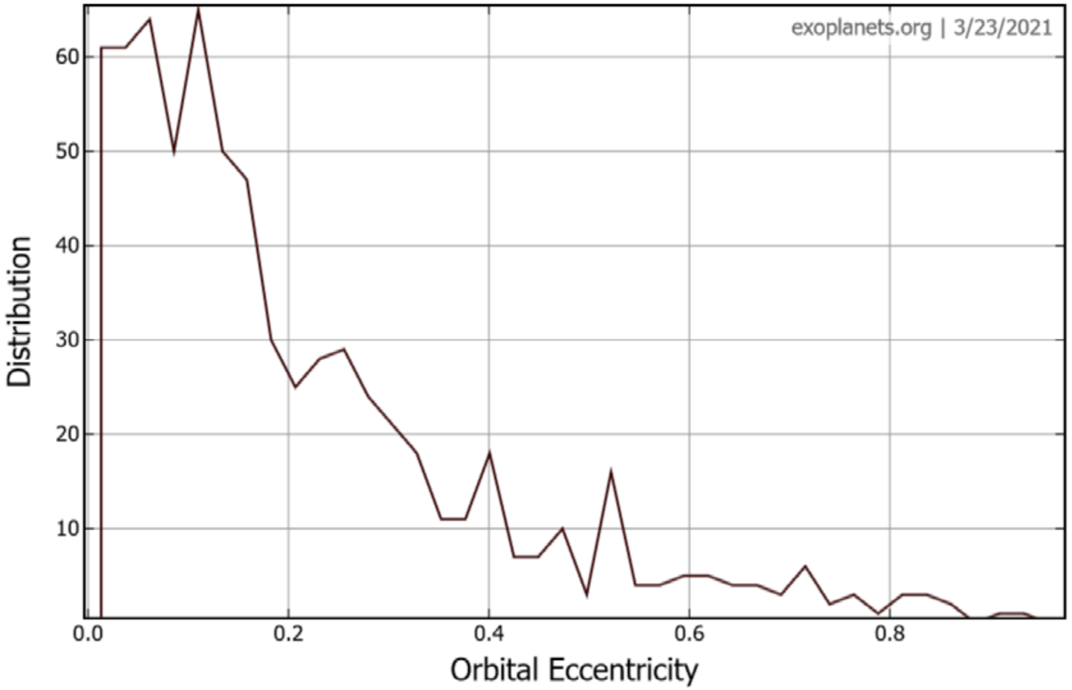
Problem: *Odd orbits*

Looking beyond our solar system, there are planets with orbits that don't fit the simple planet formation picture









Solution: *Gravitational interactions between planets*

Simulations, benchmarked by observations in our solar system, show that (1) drag-like effects of the early gas-disk and (2) complicated gravitational interactions between planets cause **planetary migration**