Today's Topics

Friday, April 4, 2025 (Week 9, Lecture 25) – Chapter 7, 14.3-4.

A. Formation of the Solar System

B. Examples of Protoplanetary systems

C. Exoplanets

Problem Set #8 is due on ExpertTA on Friday, April 11, 2025, by 9:00 AM

Midterm #2 will be on Monday, April 7, 2025.

Composition of Planets

water/ice H_2O = 1 g/cm^3
liquid hydrogen = 0.07 g/cm^3
liquid helium = 0.1 g/cm^3
liquid nitrogen = 0.8 g/cm^3
liquid methane = 0.4 g/cm^3
solid CO_2 = 1.6 g/cm^3

limestone ~ 2.6 g/cm^3
granite ~ 2.7 g/cm^3
basalt ~ 3.0 g/cm^3
rock

iron ~ 9 g/cm^3
nickel ~ 9 g/cm^3
uranium ~ 19 g/cm^3
iridium ~ 22.7 g/cm^3

Name	Distance from Sun (AU)[2]	Revolution Period (y)	Diameter (km)	Mass (10^{23} kg)	Density (g/cm^3)[3]
Mercury	0.39	0.24	4,878	3.3	5.4
Venus	0.72	0.62	12,120	48.7	5.2
Earth	1.00	1.00	12,756	59.8	5.5
Mars	1.52	1.88	6,787	6.4	3.9
Jupiter	5.20	11.86	142,984	18,991	1.3
Saturn	9.54	29.46	120,536	5686	0.7
Uranus	19.18	84.07	51,118	866	1.3
Neptune	30.06	164.82	49,660	1030	1.6

rocks + metals (Mercury, Venus, Earth, Mars)

icy (Jupiter, Saturn, Uranus, Neptune)

[OpenStax: Astronomy]

Differentiation: structure of solar system

Solar Nebula

This artist's conception shows the flattened cloud of gas and dust from which the Solar System formed [OpenStax: Astronomy].

- Icy and rocky planetesimals (precursors of the planets) can be seen in the foreground.
- The bright center is where the Sun is forming.

[William K. Hartmann, Planetary Science Institute]

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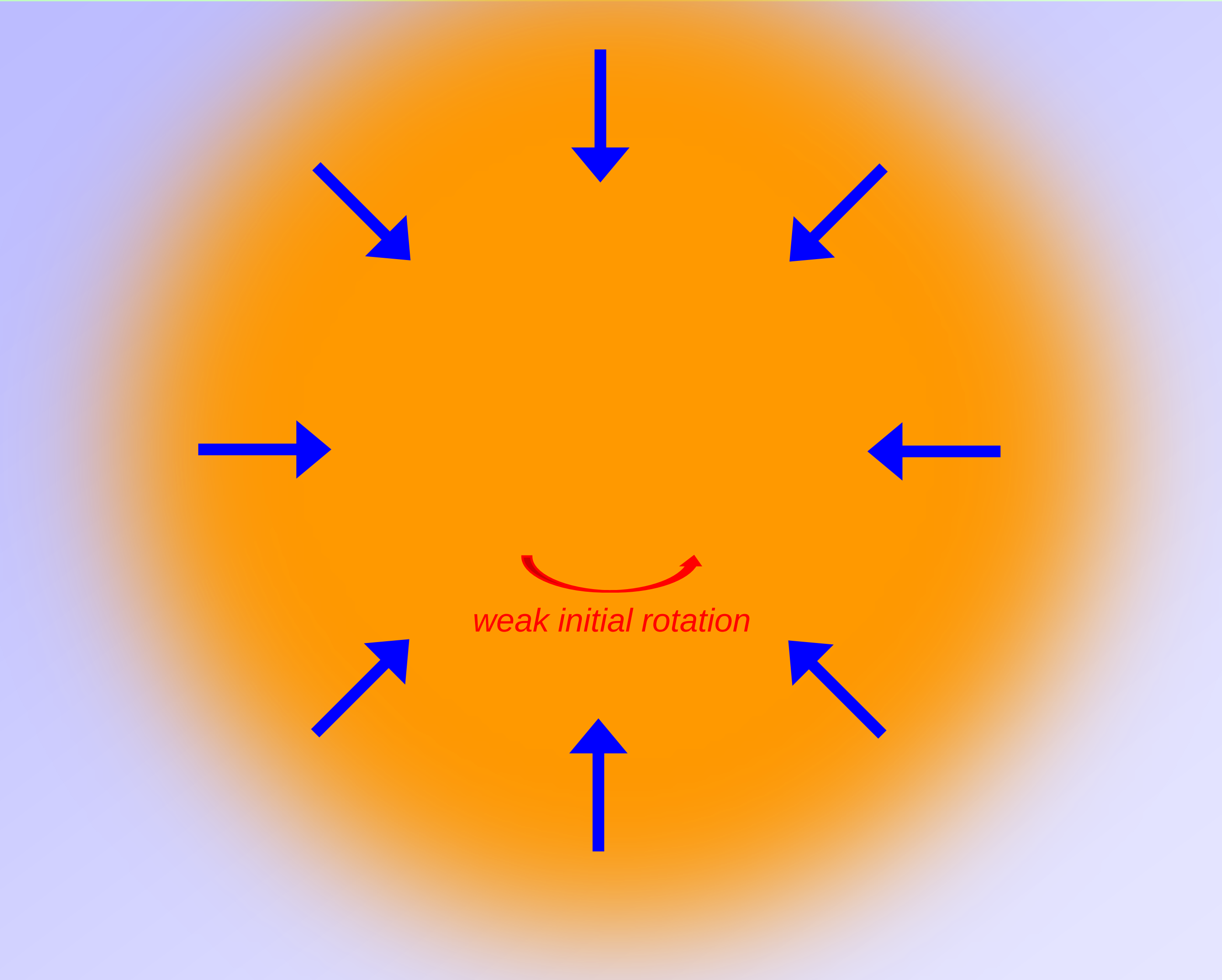
[William K. Hartmann, Planetary Science Institute]

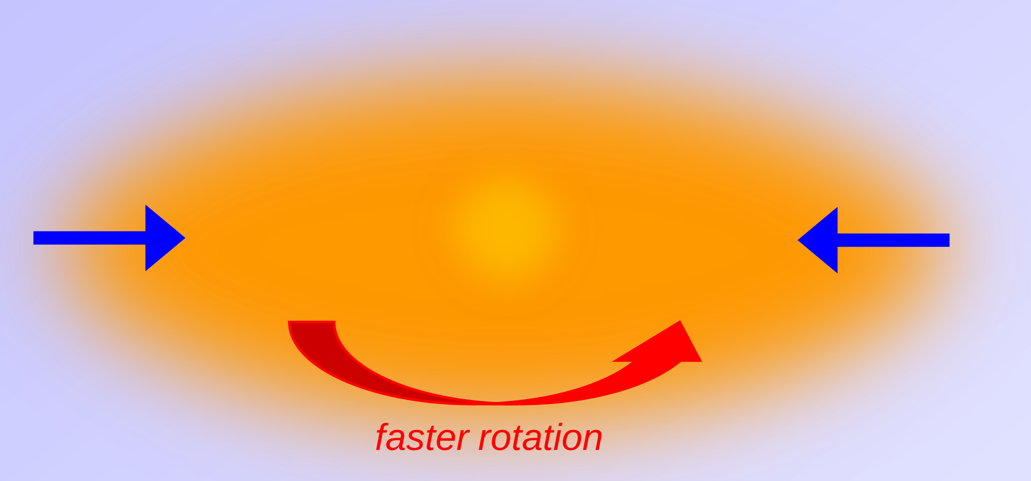
- **Mutual gravity** pulls dust, particles, material, and gas inwards.
- **Contraction:** As the solar nebula contracts it **heats up** (energy conservation), <u>spins faster</u> (angular momentum conservation), and flattens out.
- **Condensation:** As the nebula cools (blackbody radiation) heavy element gases condense around dust particles. Hydrogen and helium do not condense.
- **Accretion of planetesimals:** Solid particles collide and stick together to progressively start planets. The central region gets dense enough to **ignite fusion**.
- **Differentiation:** Hydrogen based molecules can condense far from the center (where it is colder), but not near the center where it is hotter. Heavier elements can condense closer to the Sun where it is hotter.

Step 0: large cloud of gas & dust



Mutual gravity pulls gas, dust, particles, and material inwards.

Step 1: Contraction



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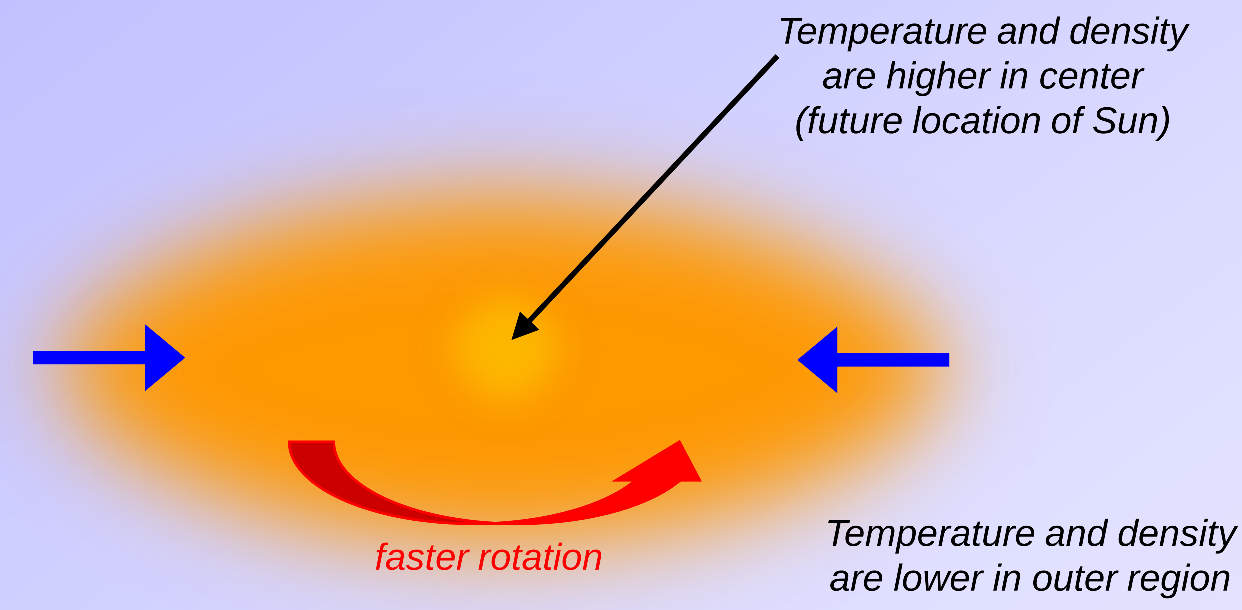
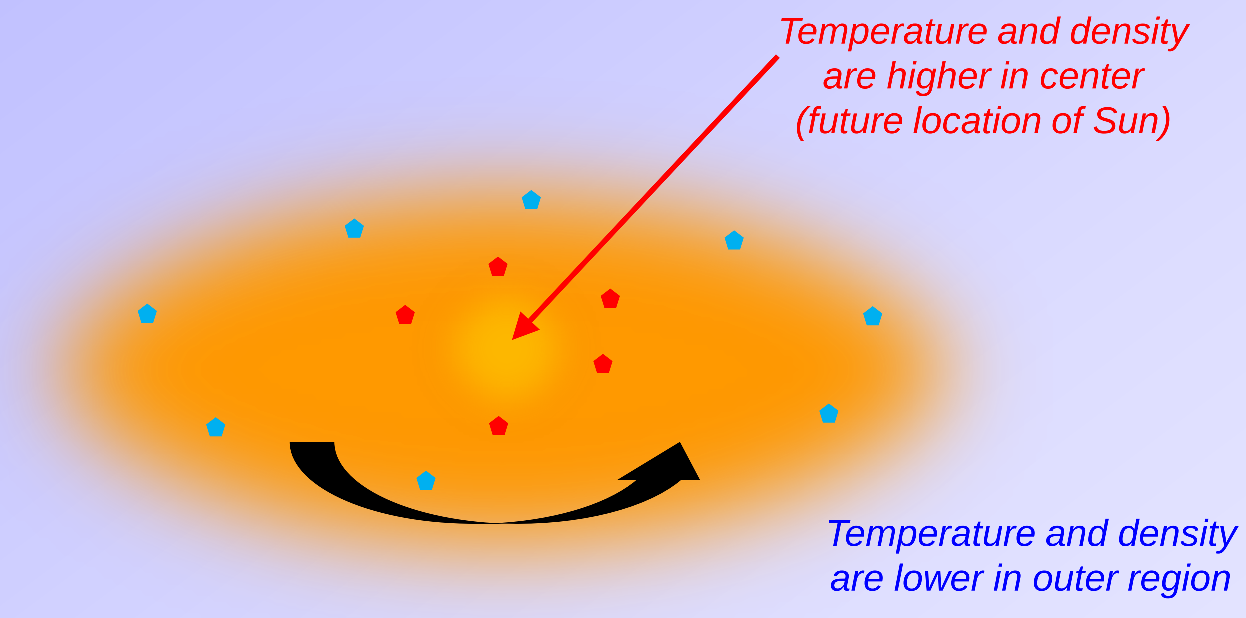
Step 1: Contraction



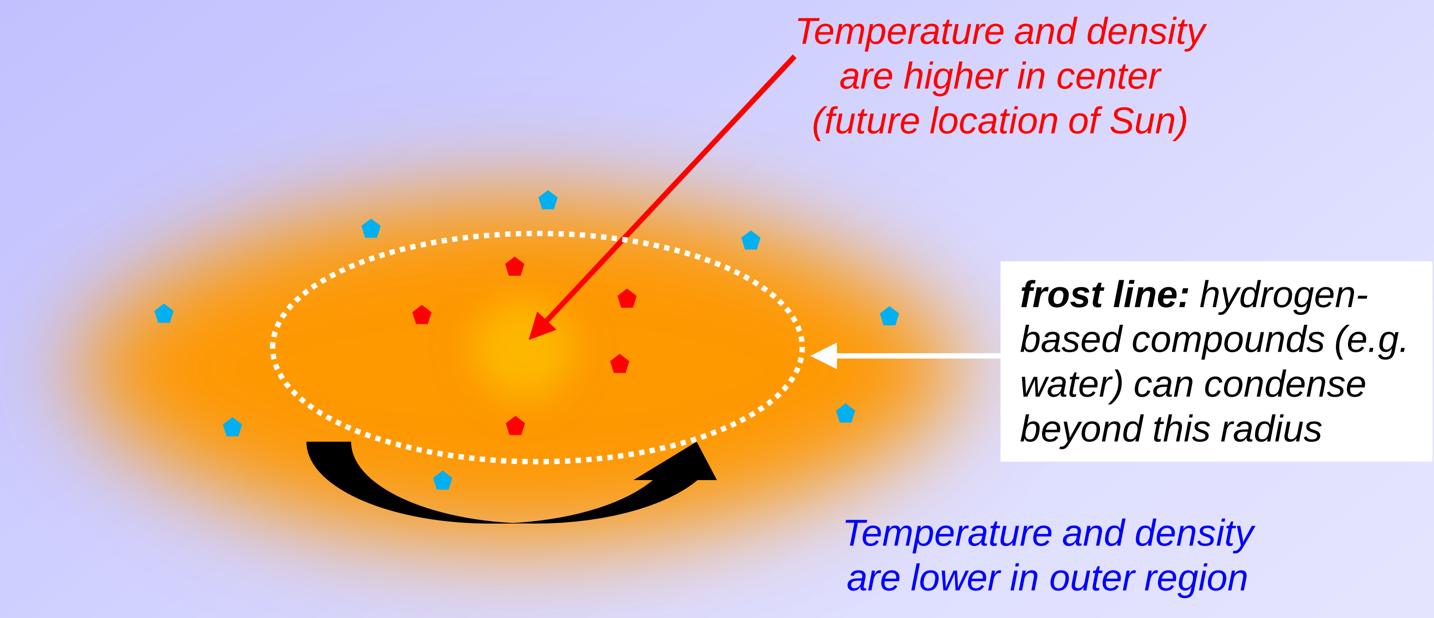
As the solar nebula contracts it **heats up** (energy conservation), spins faster (angular momentum conservation), and flattens out.

Step 2: Condensation



As the nebula cools (blackbody radiation) heavy element gases condense around dust particles. Hydrogen and helium do not condense, but hydrogen-based molecules can in the cooler outer parts.

Step 2: Condensation – “frost line”



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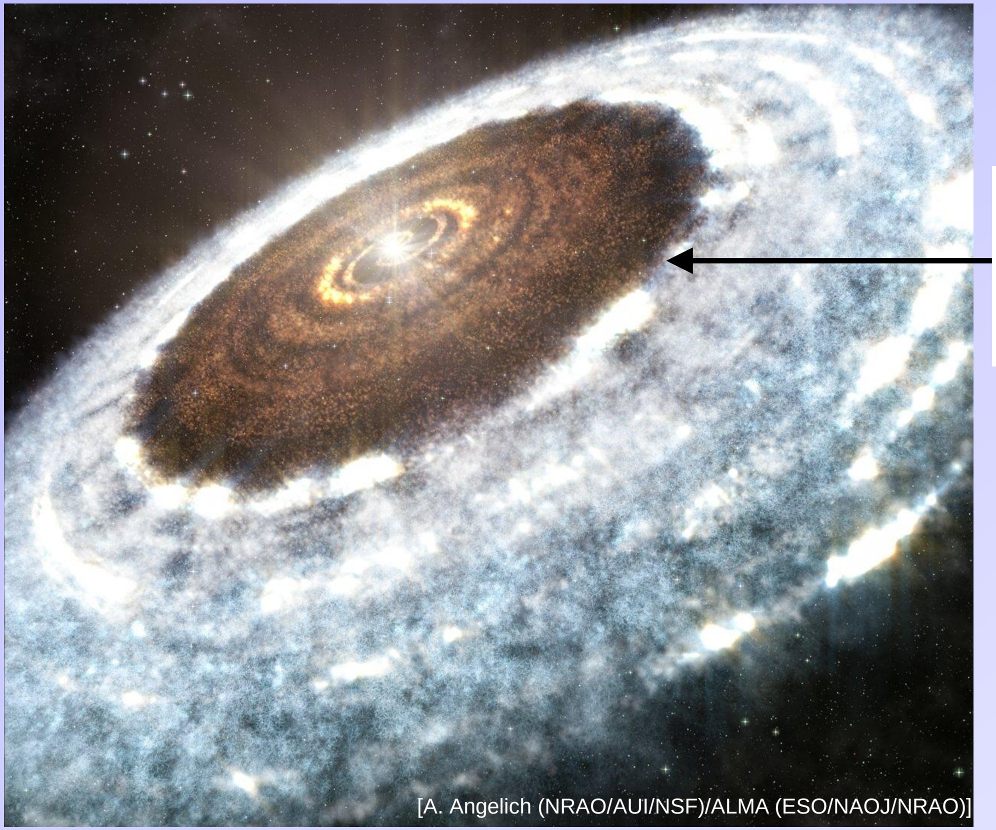
Step 2: Condensation – "frost line"

Artist's impression of the water snowline around the star V883 Orionis [Wikipedia].



***frost line:** hydrogen-based compounds (e.g. water) can condense beyond this radius*

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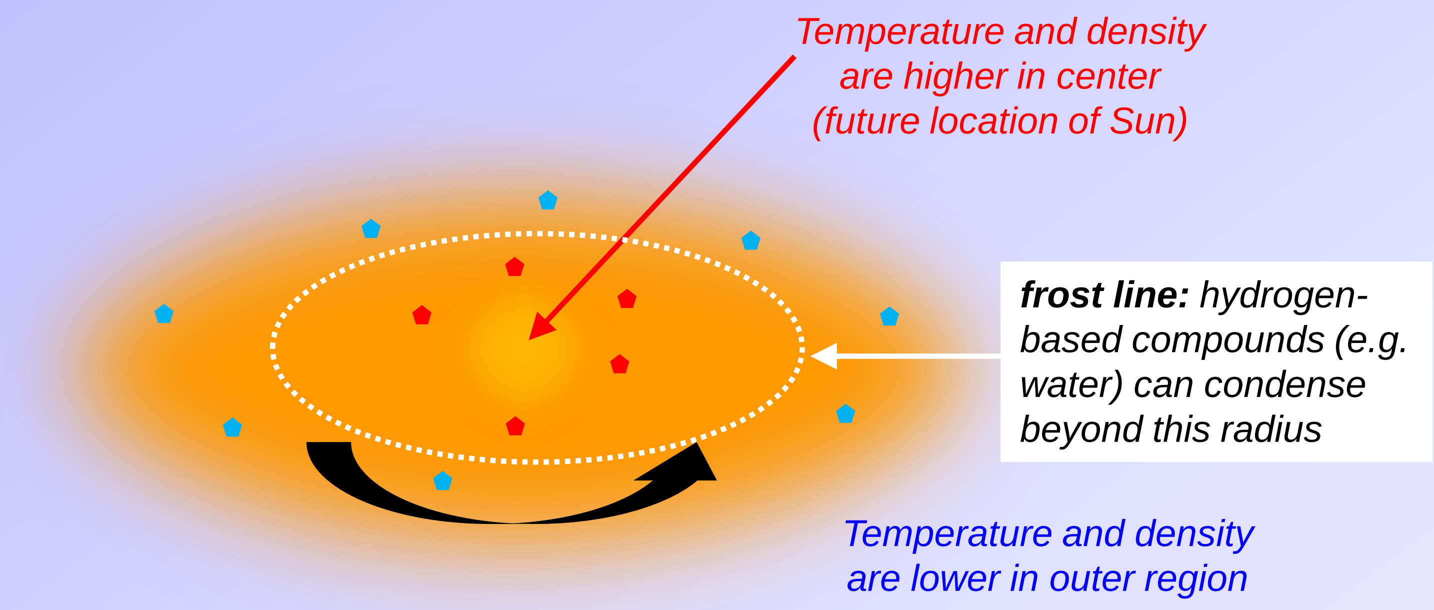
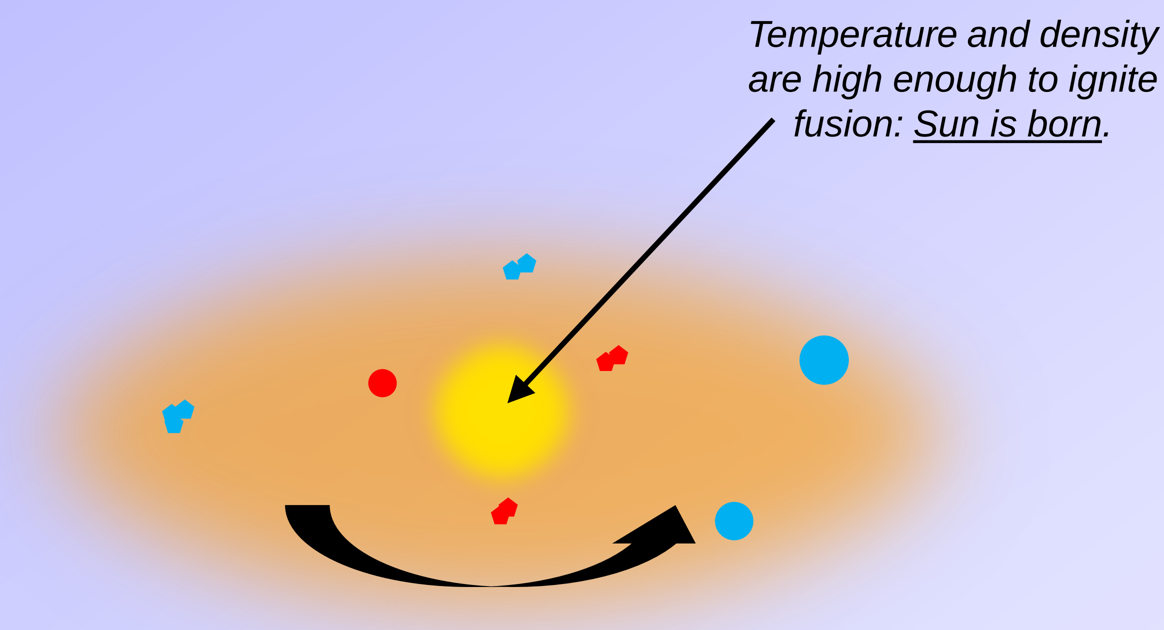


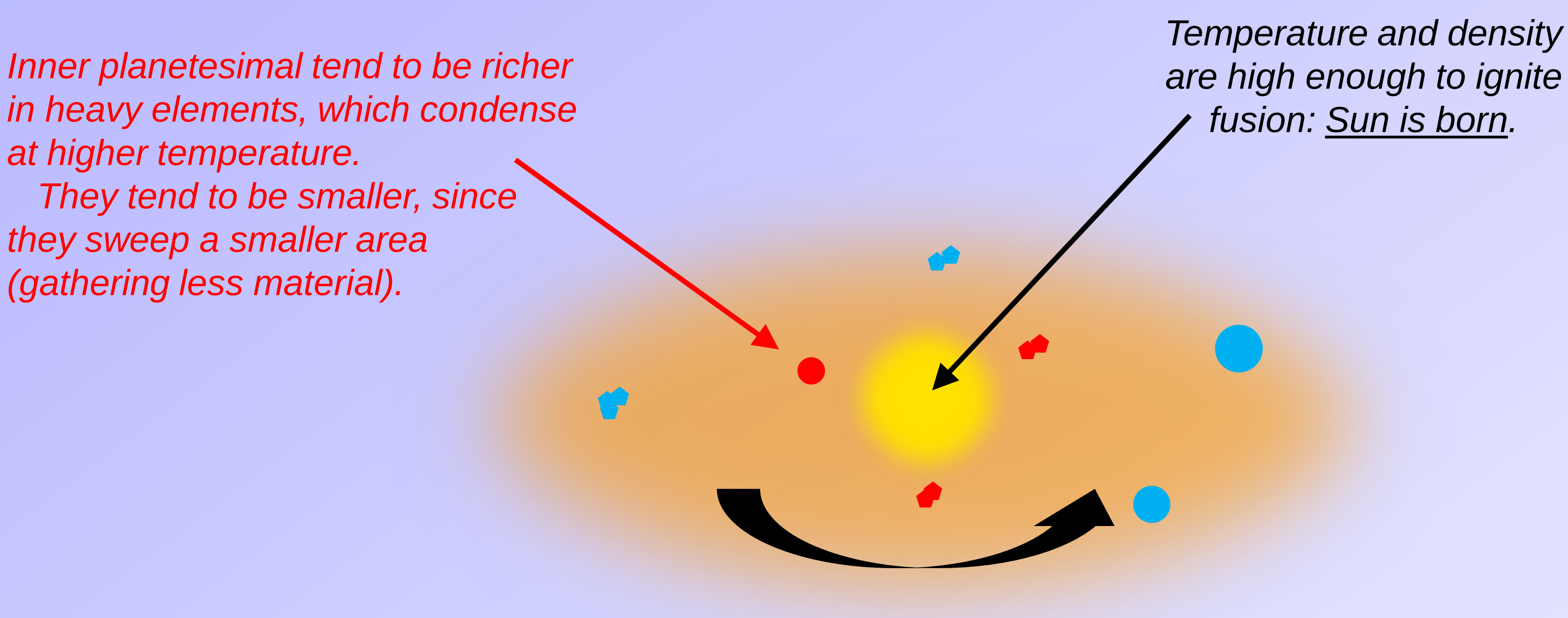
As the nebula cools (blackbody radiation) heavy element gases condense around dust particles. Hydrogen and helium do not condense, but hydrogen-based molecules can in the cooler outer parts.

Step 3: Accretion of Planetesimals



- **Accretion of planetesimals:** Solid particles collide and stick together to progressively start planets. Their gravity becomes strong enough to collect gases.
- **Star ignition:** The central region gets dense enough to **ignite fusion**.

Step 3: Accretion of Planetesimals



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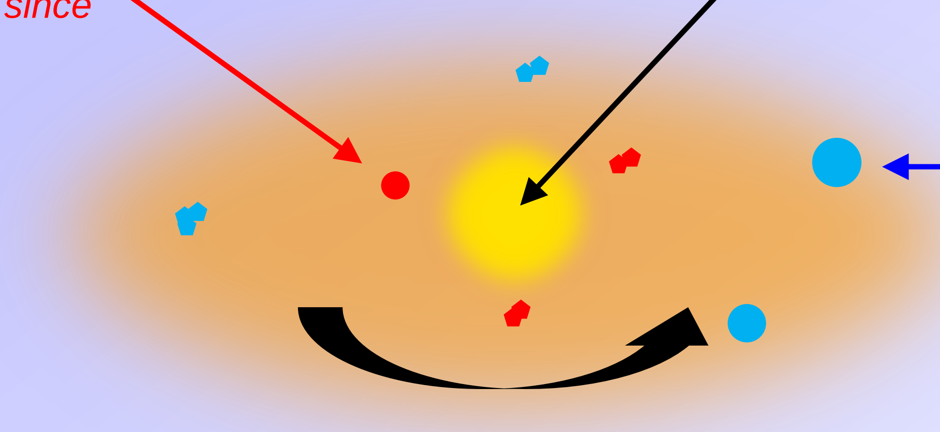
Step 3: Accretion of Planetesimals

Inner planetesimal tend to be richer in heavy elements, which condense at higher temperature.
They tend to be smaller, since they sweep a smaller area (gathering less material).

Temperature and density are high enough to ignite fusion: Sun is born.



Outer planetesimals tend to be more icy and hydrogen rich.
They tend to be bigger because they sweep out a larger region, so they can gather more material.

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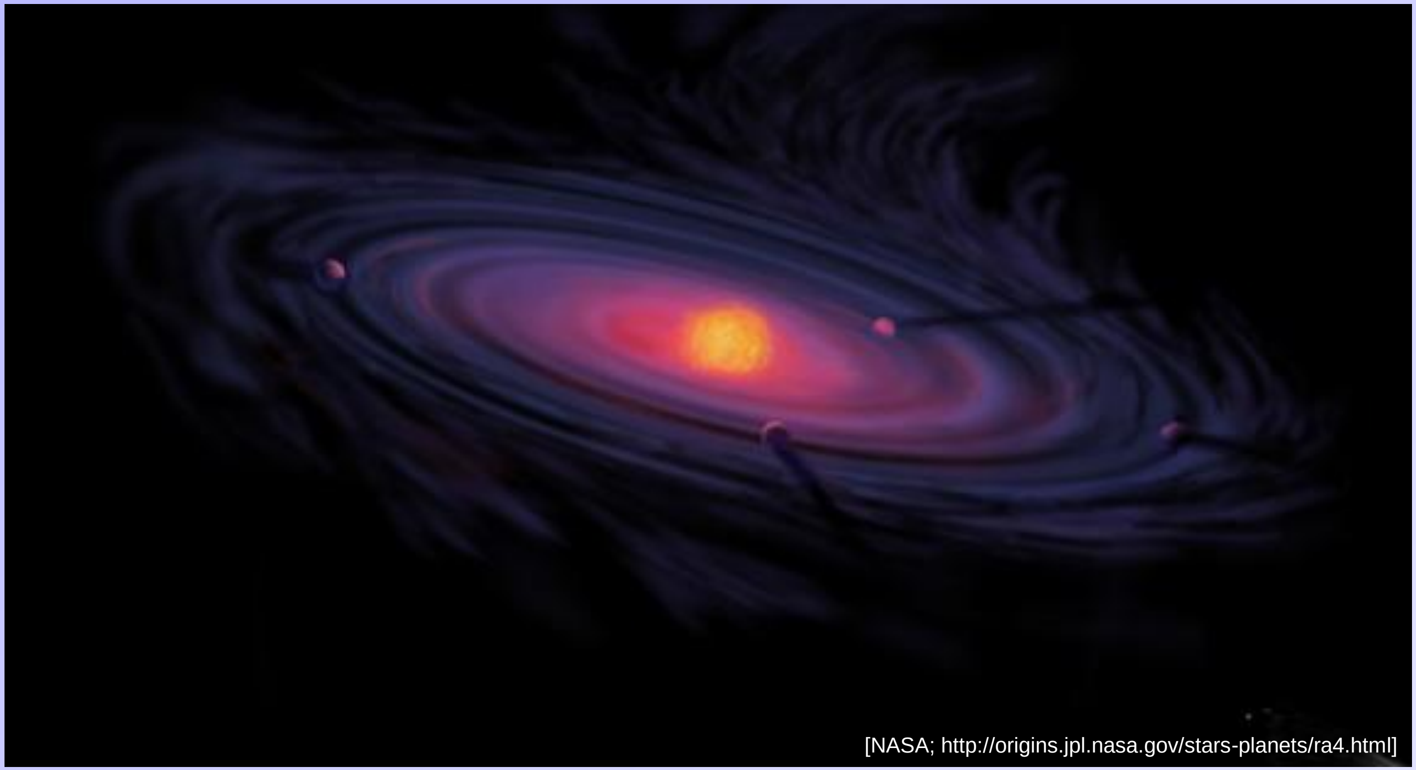
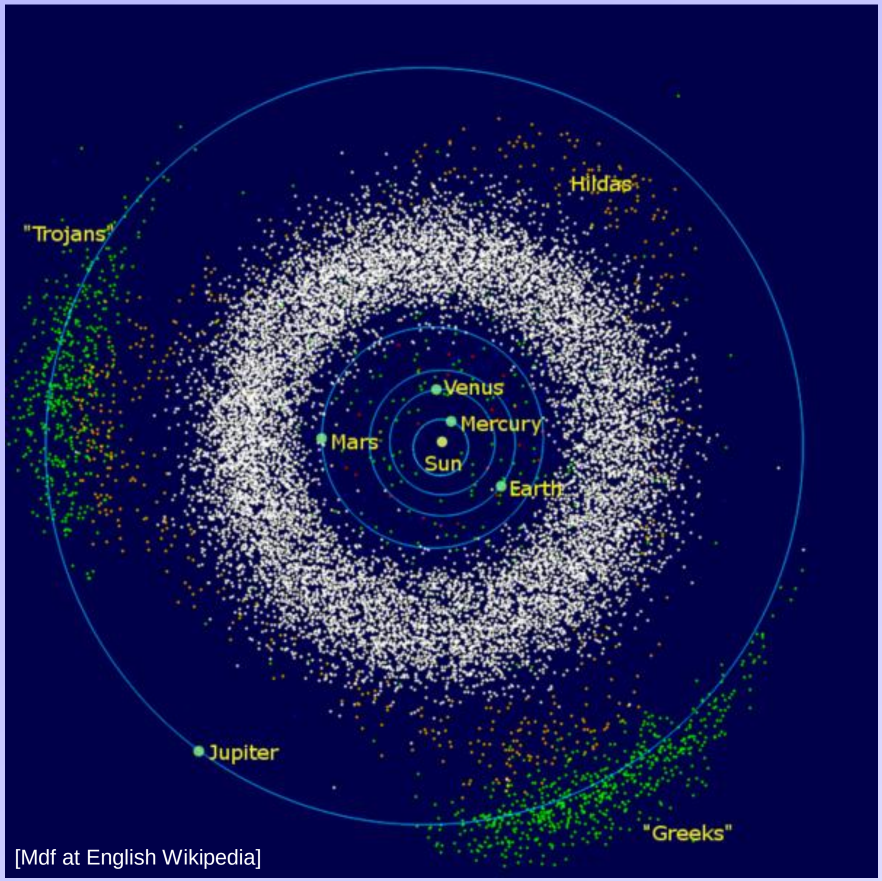
Step 3: Planetesimals to Planets


[NASA; http://origins.jpl.nasa.gov/stars-planets/ra4.html]

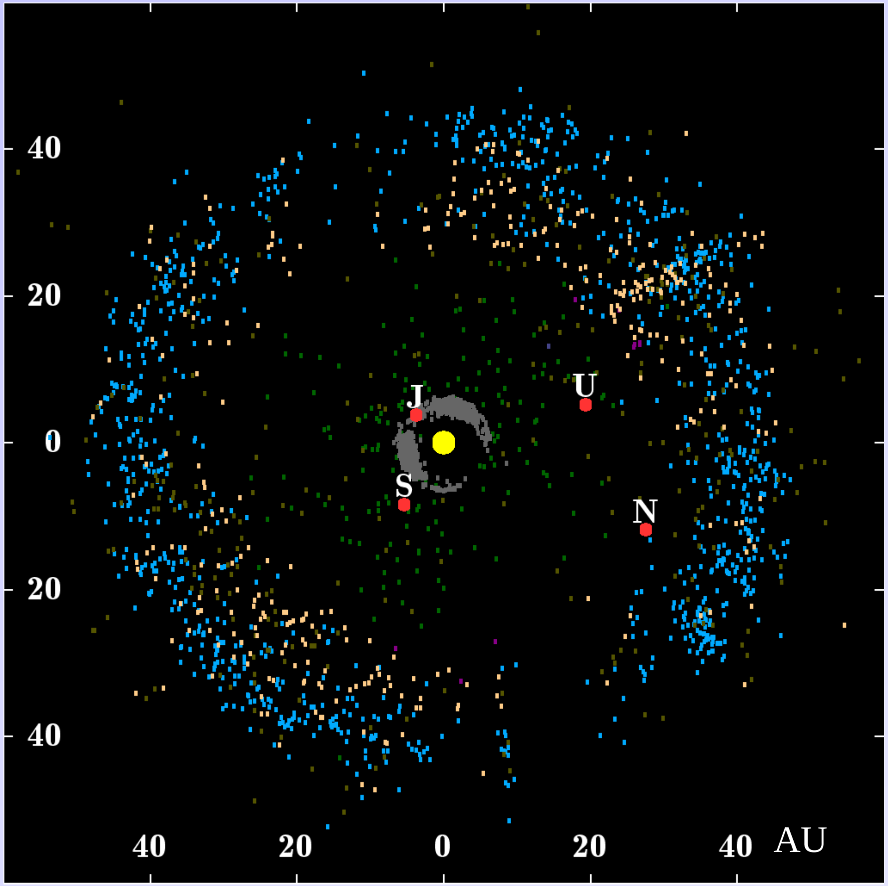
- As the planetesimal collide and stick together, they become bigger and evolve into planets. In doing so, they clear out their orbits.
- Near circular orbits are more stable, since more eccentric elliptical ones can lead to collisions between planetesimals/planets.

Solar System Planets + Planetismals

Inner Solar System + Jupiter



Outer Solar System with Gas Giants



[By WilyD at English Wikipedia, CC BY-SA 3.0]

Asteroid (white, green, brown) are left over planetesimals.

Kuiper belt objects (blue, beige, green) are icy left over planetesimals in the region of the gas giants and beyond.

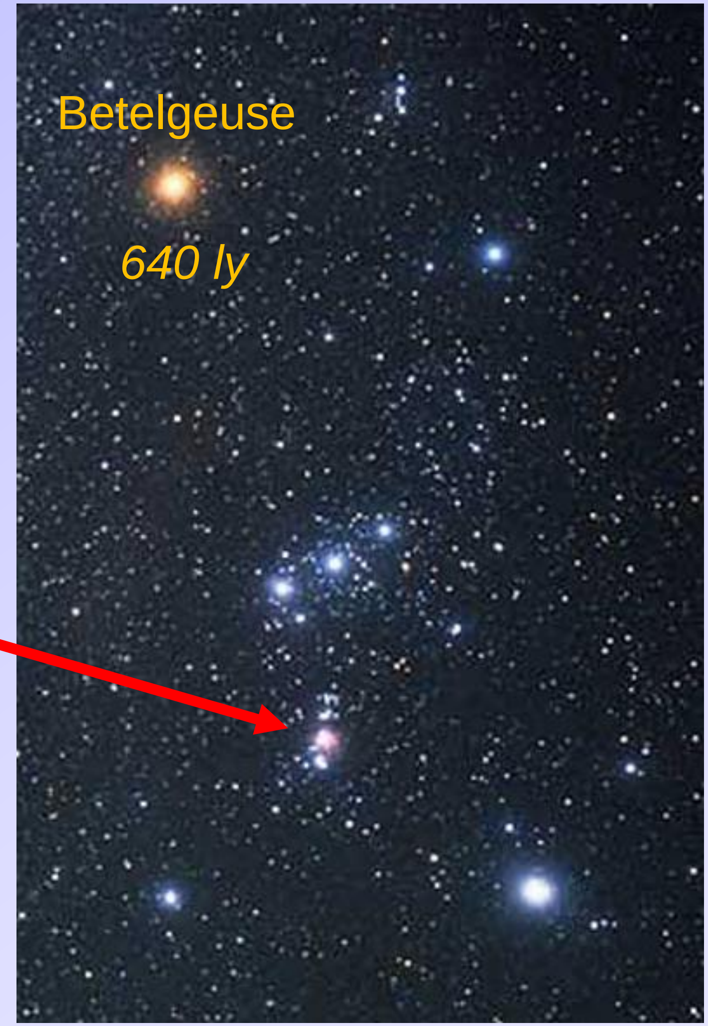
PollEv Quiz: PollEv.com/sethaubin

Nascent Protoplanetary Systems

Constellation: **Orion**

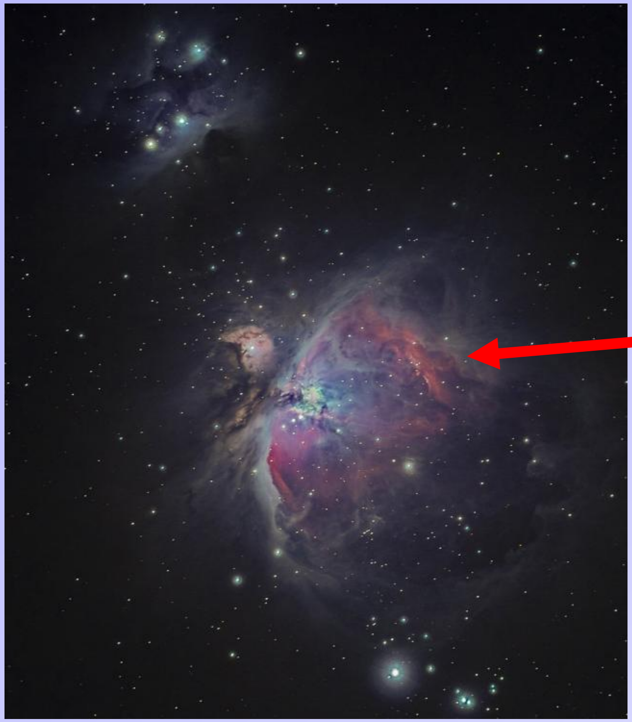
Nascent Protoplanetary Systems

Orion Nebula



Constellation: **Orion**

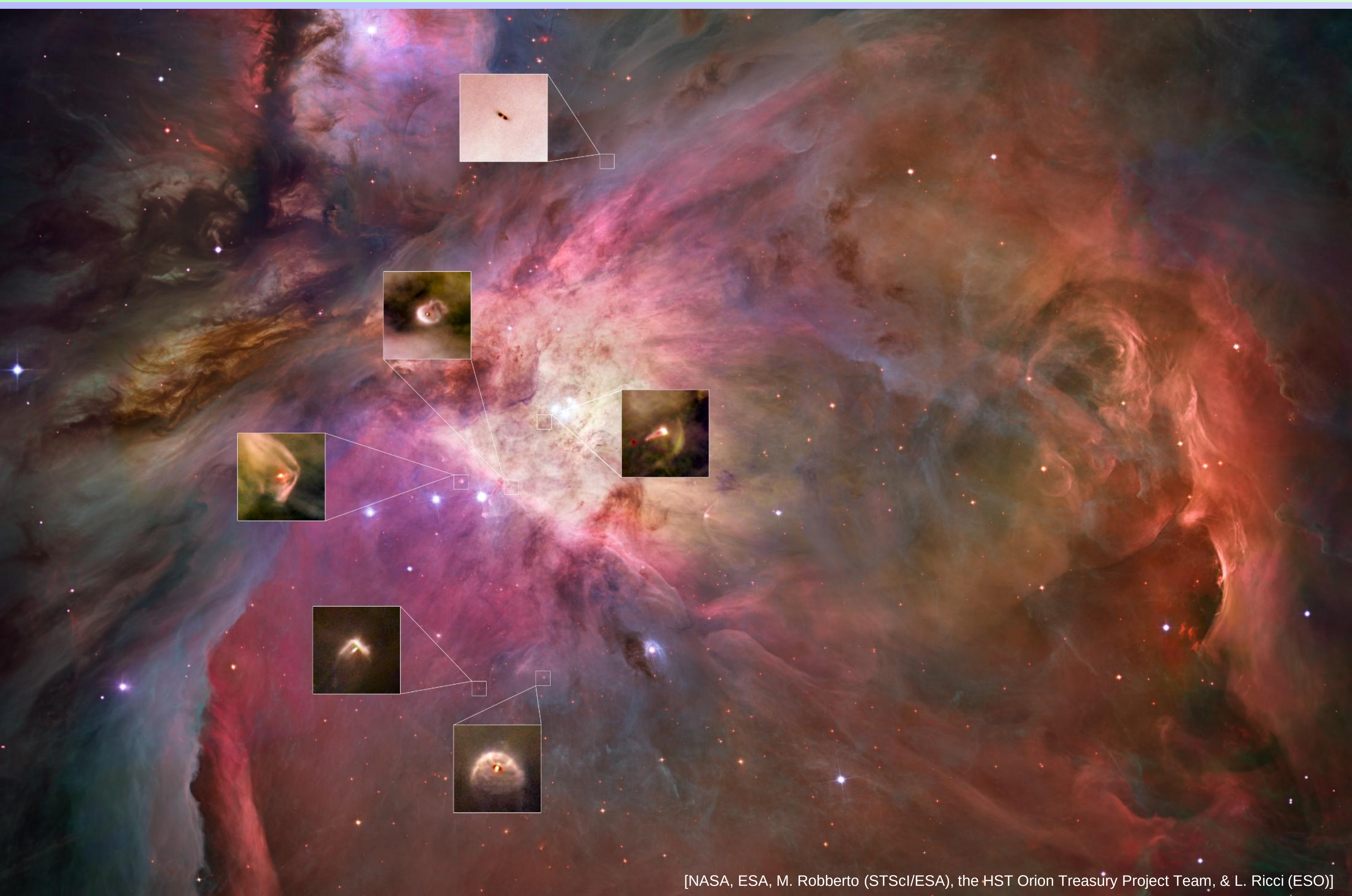
Nascent Protoplanetary Systems



Orion Nebula

[NASA, ESA, M. Robberto (Space Telescope Science Institute/ESA) and the Hubble Space Telescope Orion Treasury Project Team]

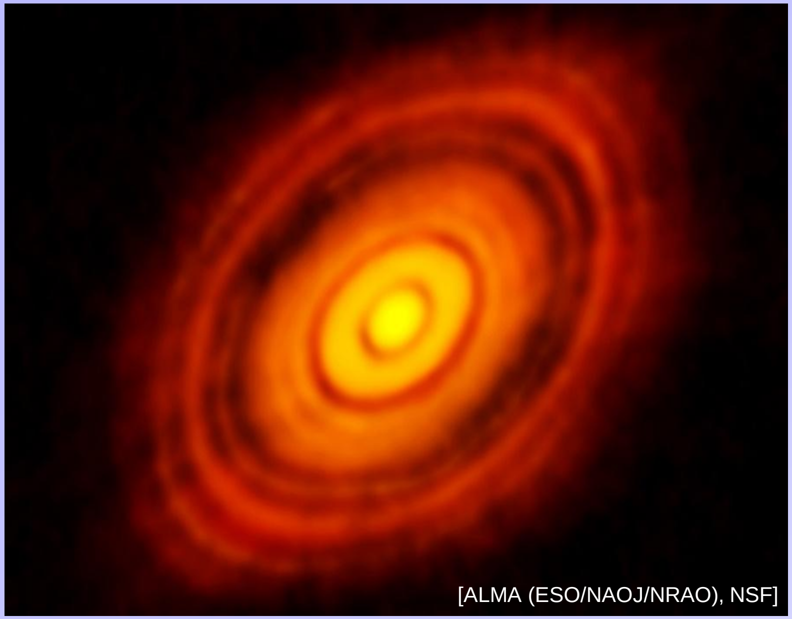
Nascent Protoplanetary Systems



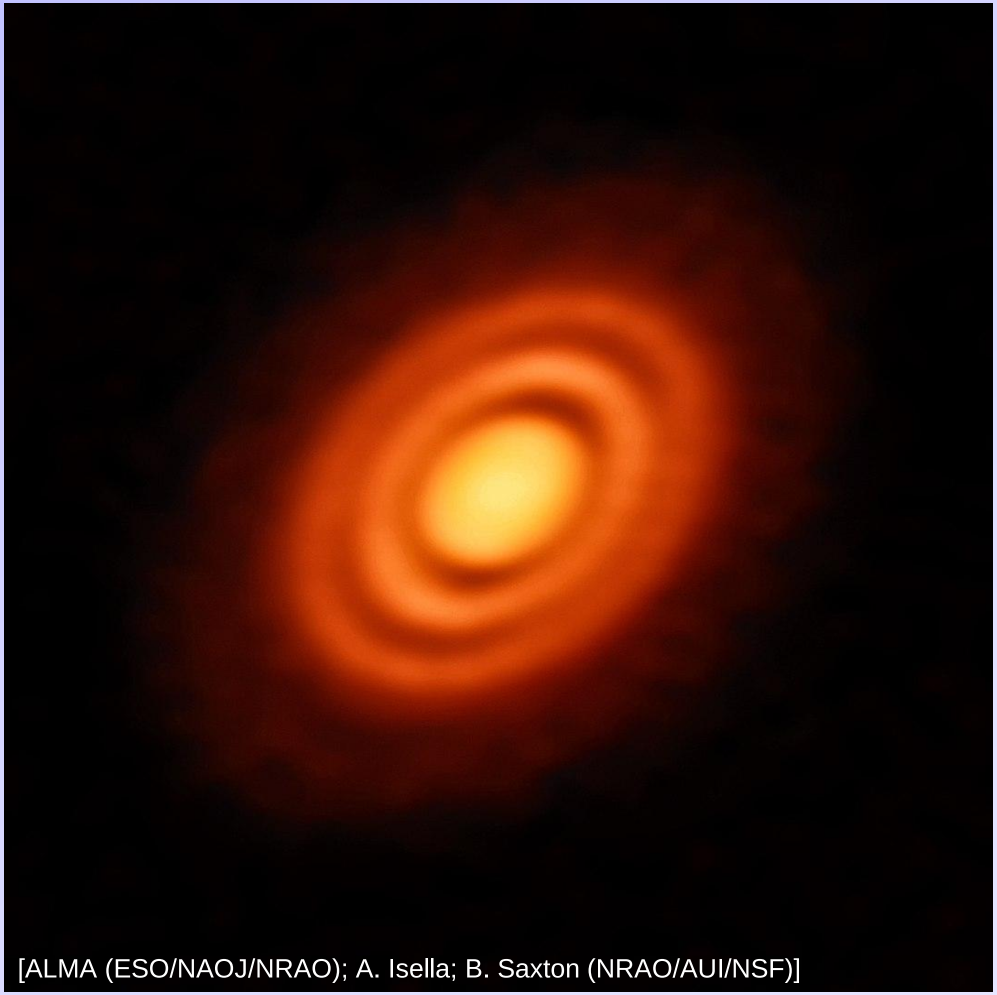
[NASA, ESA, M. Robberto (STScI/ESA), the HST Orion Treasury Project Team, & L. Ricci (ESO)]

Nascent Protoplanetary Systems

Protoplanetary Disks – mm wave

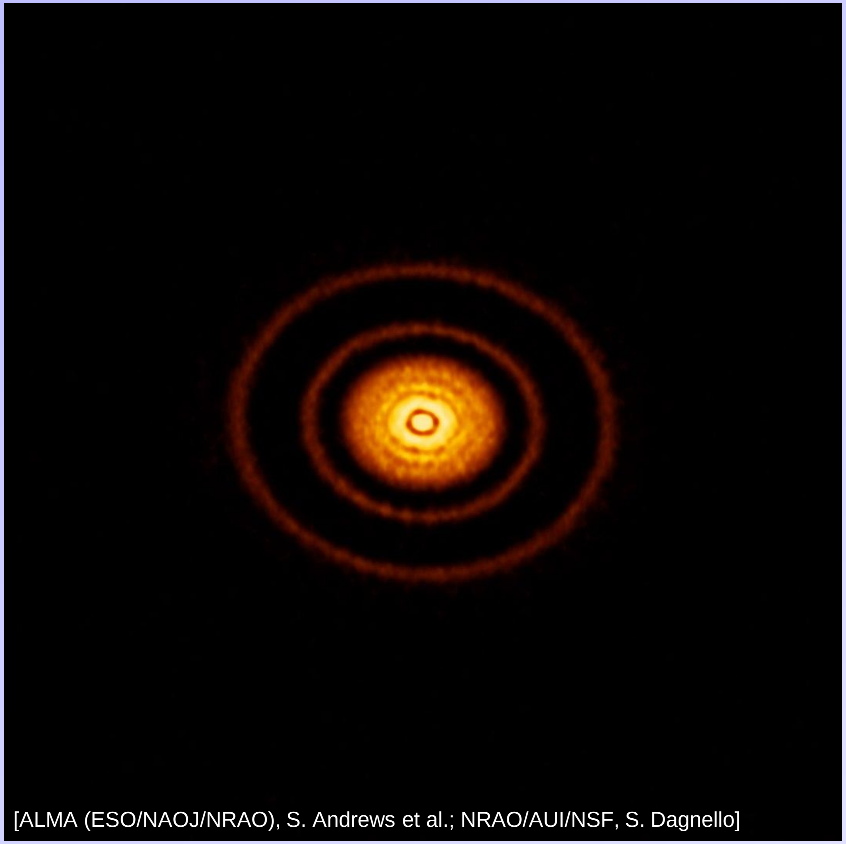


The Protoplanetary Disk of the young star HL Tauri
(in Milky Way galaxy, Taurus constellation)



Cloud of gas and dust surrounding the young star HD 163296.
(in Milky Way galaxy, Sagittarius constellation)

Protoplanetary Disks – mm wave



Protoplanetary disk around the young star AS 209.

(in Milky Way galaxy, Ophiuchus constellation)

Exoplanets

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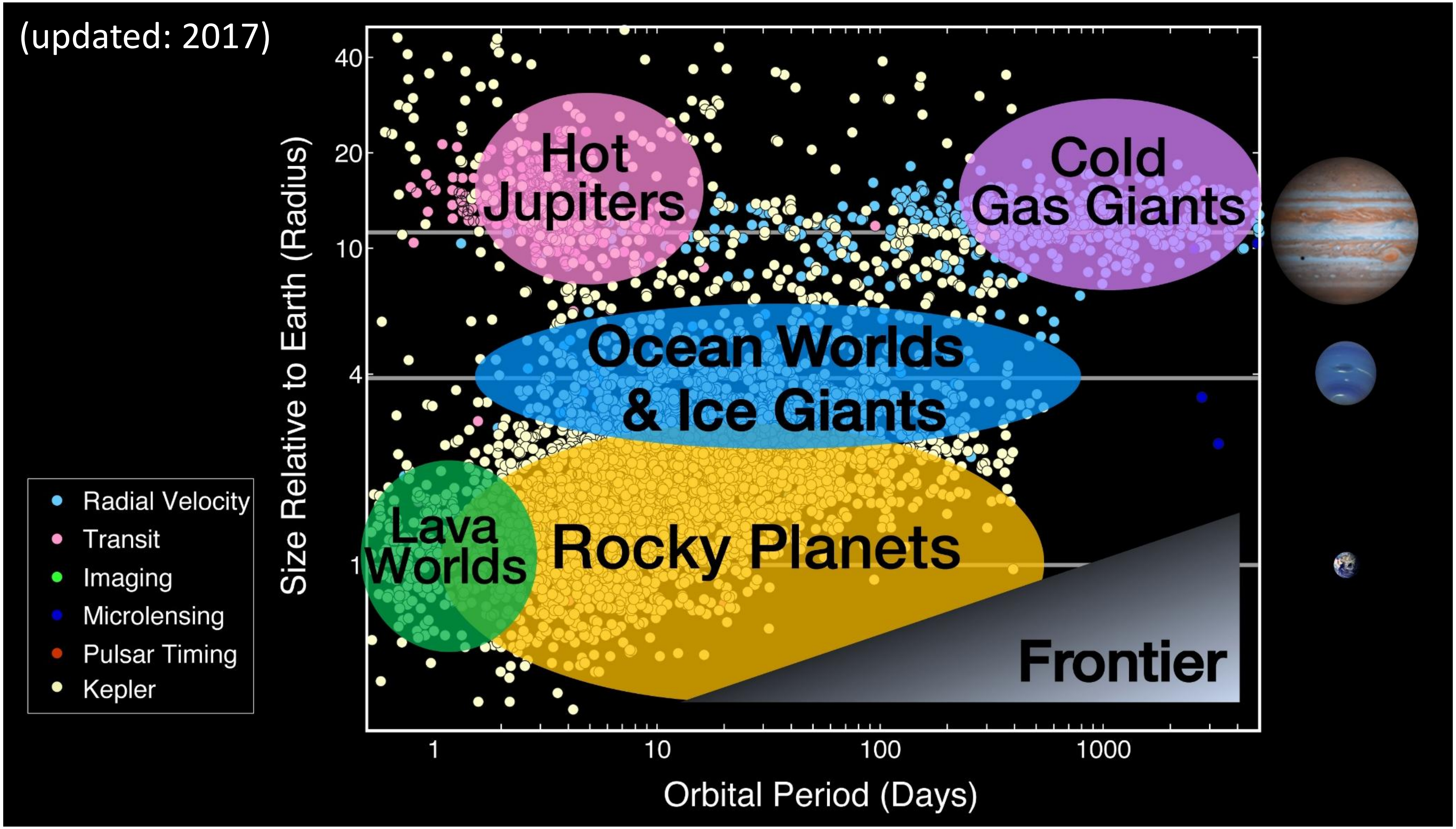
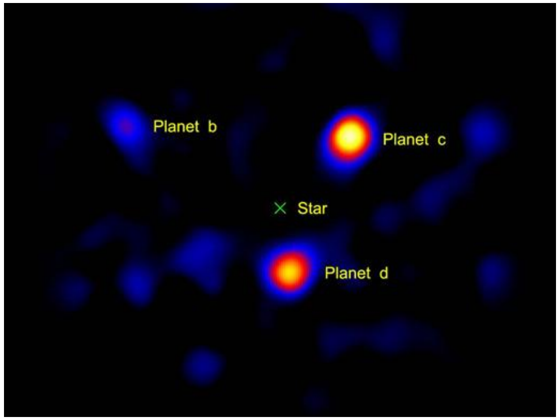


[https://www.nasa.gov/image-feature/ames/kepler/exoplanet-populations]

Exoplanets

What we know so far

➢ **Most stars (possibly all) have planets.**



3 planets around star HR8799 (120 ly)
Orbits: 24 AU, 38 AU, 68 AU.
[Hale telescope, 2010]

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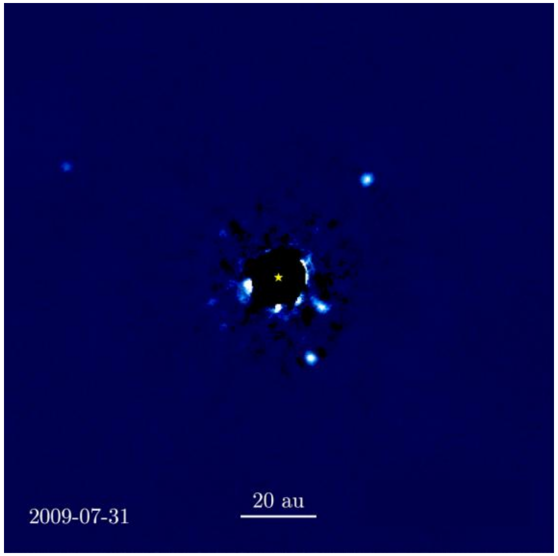
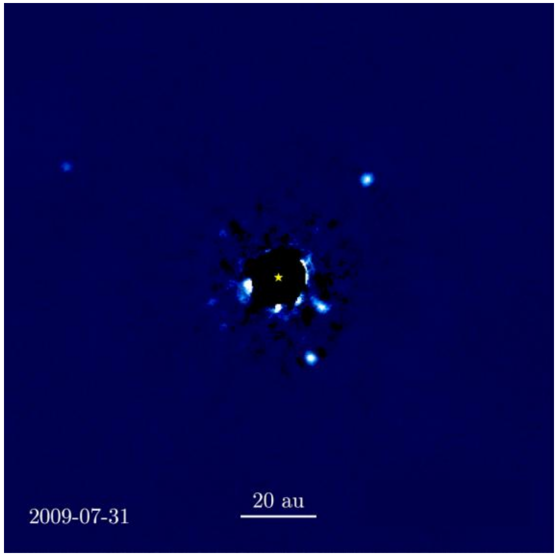


4 planets around star HR8799 (120 ly) [Keck telescope, 2009-2016, J. Wang, C. Marois]

Exoplanets
What we know so far

- **Most stars (possibly all) have planets.**
- We see many **gas giants** <u>inside the frost line</u>.

  Models of evolution for solar systems show that planets often perturb the orbits of other planets and **move them towards the star** (or shoot them out).



4 planets around star HR8799 (120 ly) [Keck telescope, 2009-2016, J. Wang, C. Marois]

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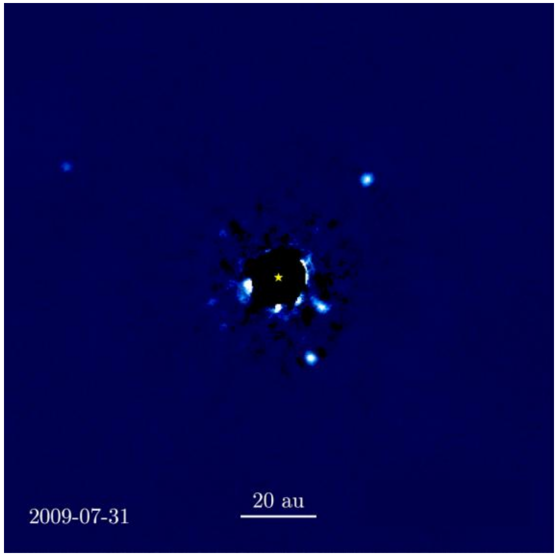

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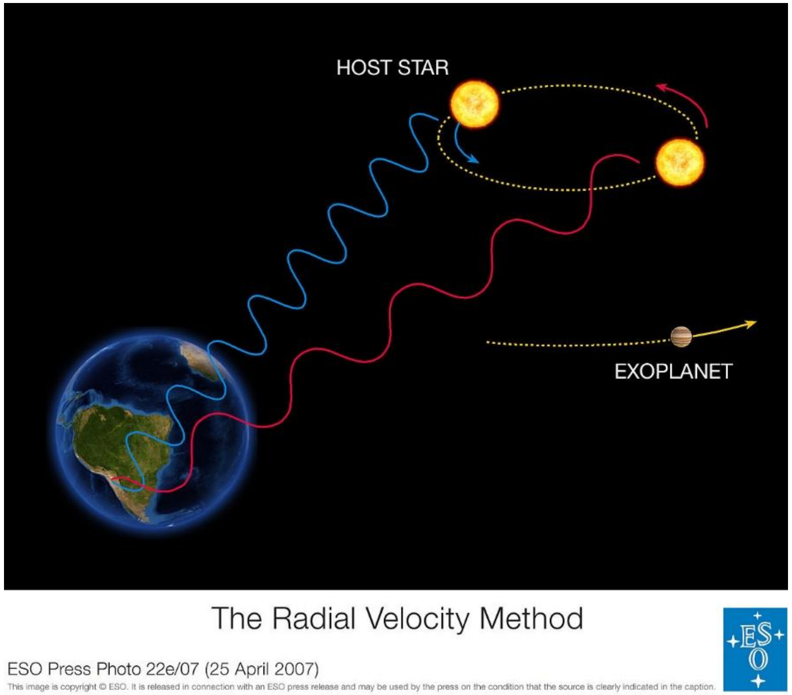
- Roughly 40% of Sun-like stars have terrestrial planets in the **"goldilocks"** region.

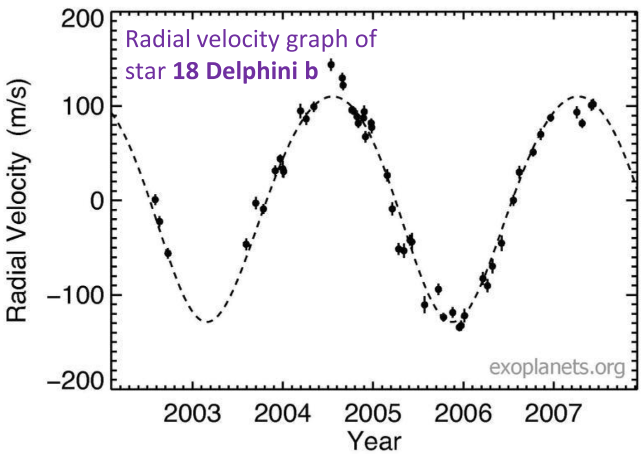
  → Above freezing and below boiling for water.

- **Earth-like** planets are very common

  They are harder to detect than larger ones, so we have not seen very many yet.

Main Detection Methods





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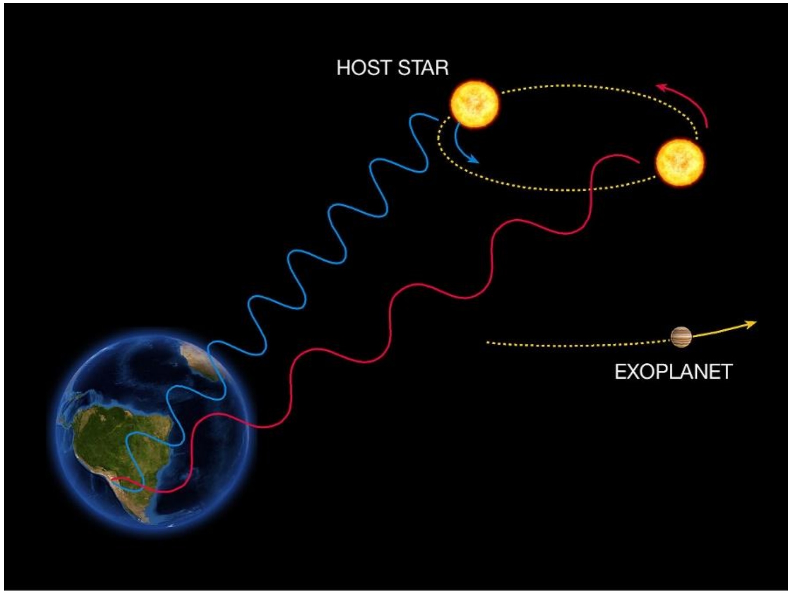
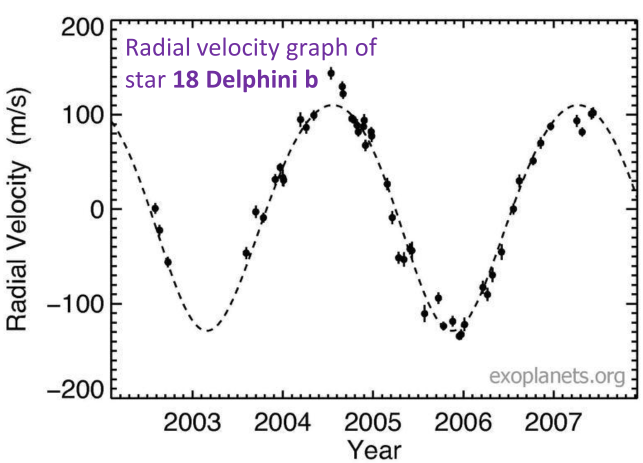
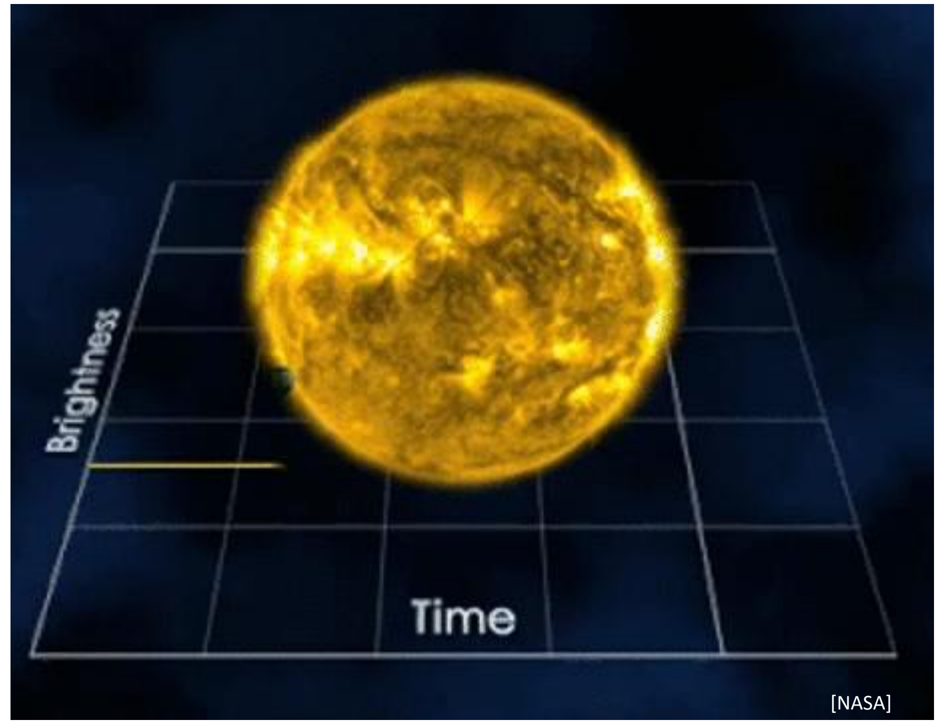


The Radial Velocity Method

ESO Press Photo 22e/07 (25 April 2007)



Transit Photometry



Signal is typically 1 part per 10,000 dimming.