Today's Topics

Friday, April 3, 2026 (Week 9, Lecture 26) – Chapter 7, 14.3-4.

… What happens when you fall into a Black hole?

A. Formation of the Solar System

B. Examples of Protoplanetary systems

C. Exoplanets

Problem Set #8 is due today on ExpertTA by 9:00 AM

Midterm #2 will be on Monday, April 6, 2026.

What happens if you fall into a Black Hole?

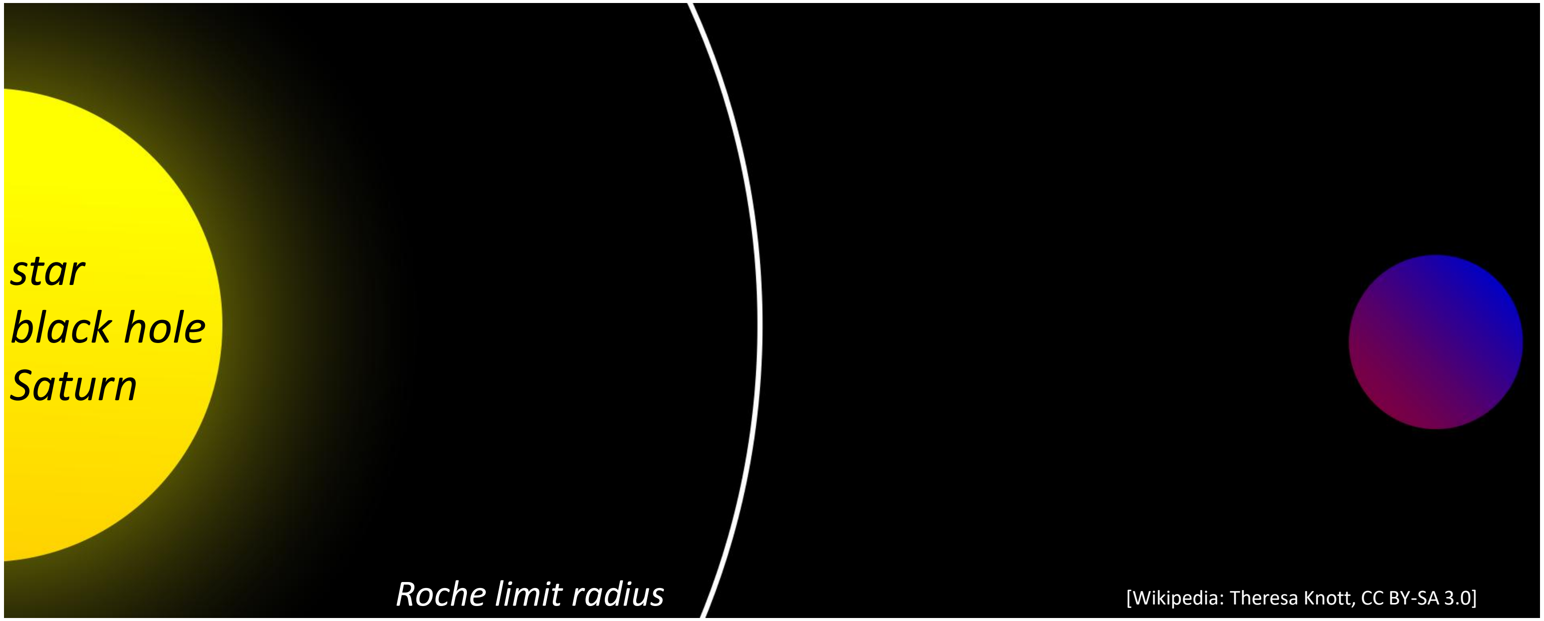
Stellar mass black hole

- The **Roche limit** is well outside of the event horizon.
- Any object falling towards the event horizon is **pulled apart** (spaghettified) by the strong **gravity gradient** (tidal force) of the black hole.

The Roche Limit

The Roche limit is the orbital radius at which a gravitational bound object will be **pulled apart** by the **tidal force** from the central mass (i.e. Sun, Saturn, black hole, etc).
(gravity gradient)

→ The Roche limit depends on nature of body (solid, fluid, density).
→ Proposed by Eduard Roche in 1848 (French astronomer).



[Wikipedia: Theresa Knott, CC BY-SA 3.0]

Far outside the Roche limit radius, the tidal force and deformation are **weak**.

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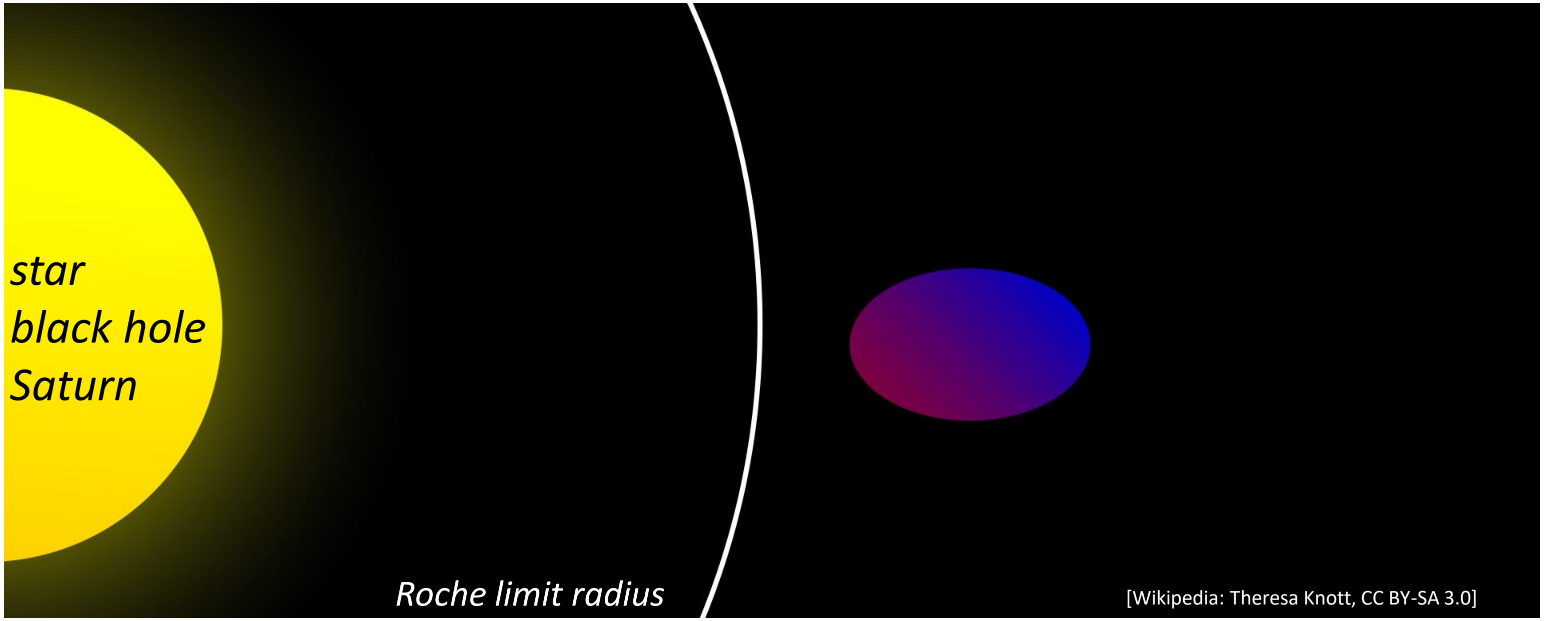

[Wikipedia: Theresa Knott, CC BY-SA 3.0]

Close to the Roche limit radius, the tidal force and deformation are **strong**.

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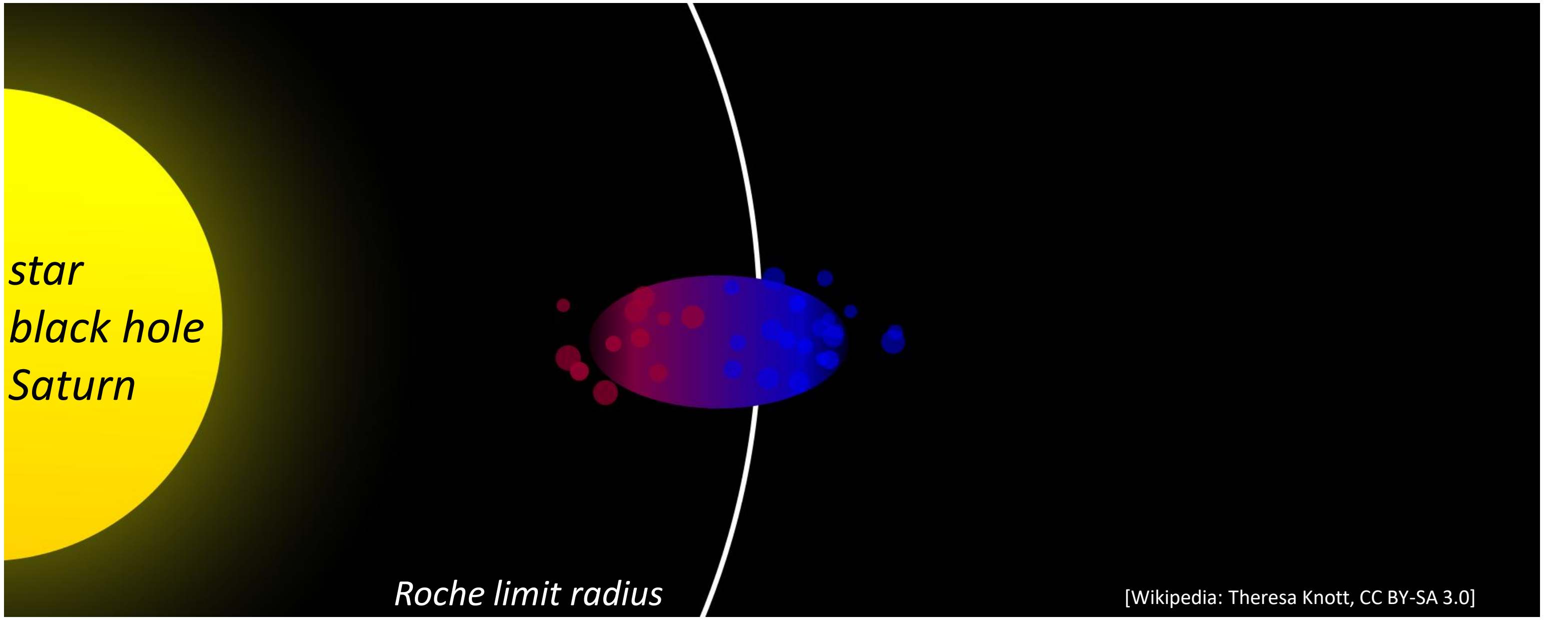

[Wikipedia: Theresa Knott, CC BY-SA 3.0]

At the Roche limit radius and within it, the tidal force and deformation **pull the planet/moon/star apart**.

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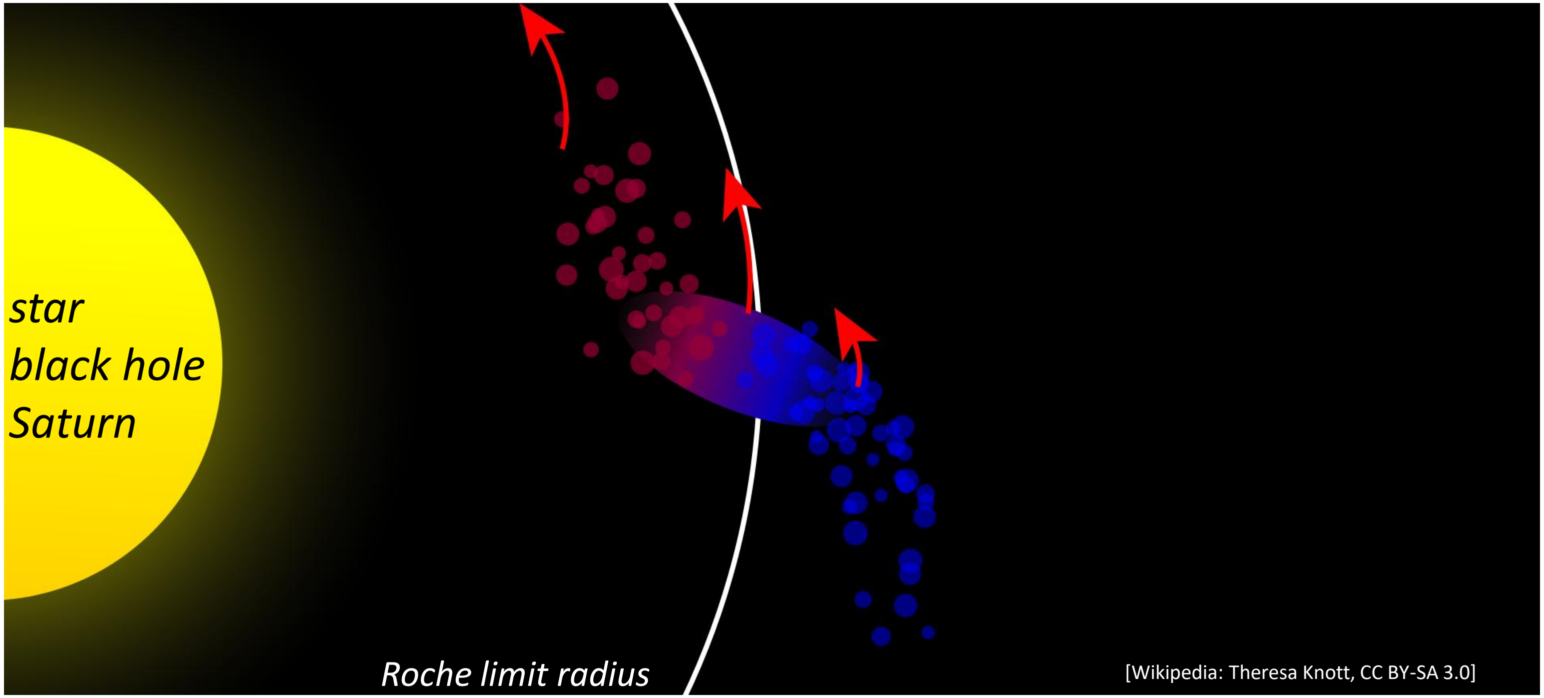

[Wikipedia: Theresa Knott, CC BY-SA 3.0]

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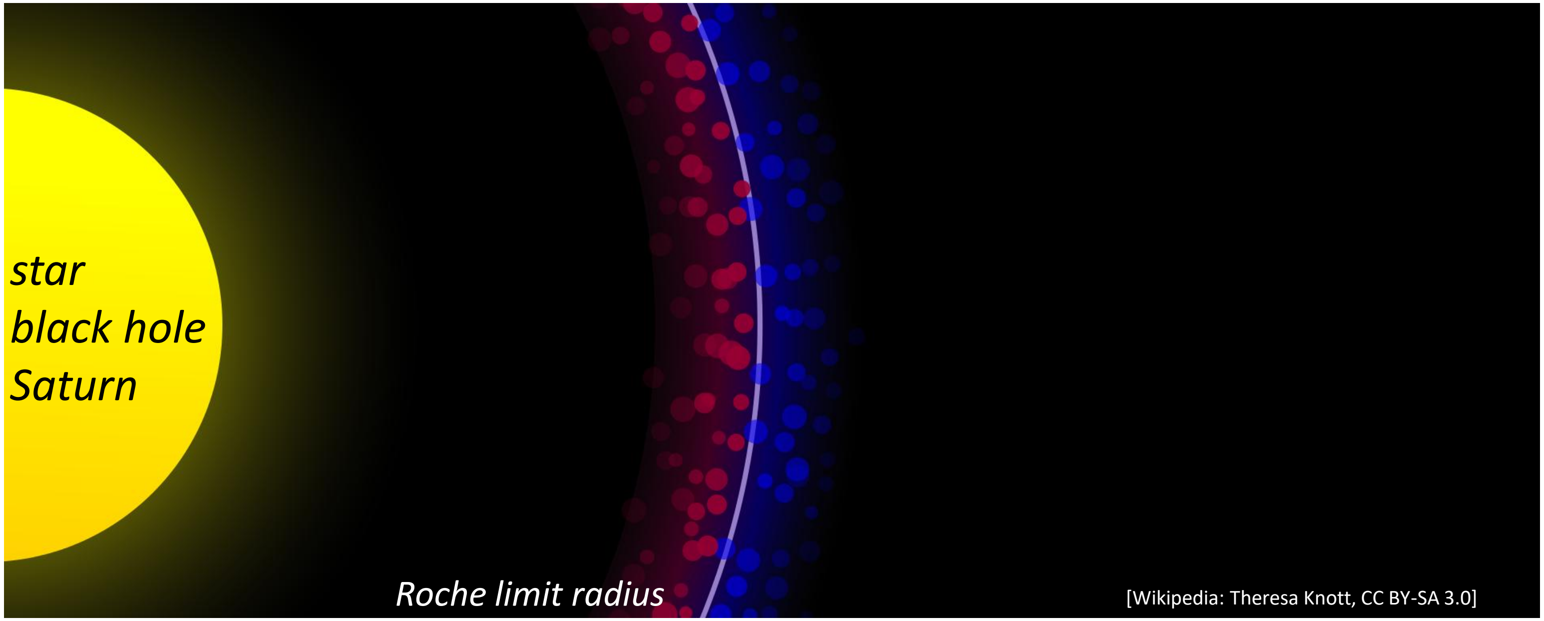

[Wikipedia: Theresa Knott, CC BY-SA 3.0]

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Gravitational time dilation: The object appears to slow down as it gets closer and closer to the event horizon.

→ Very close to the event horizon, the object becomes too redshifted to be well seen and also appears to come to a standstill.

(note: in frame of object, the object falls into black hole.)

Solar Systems & Exoplanets

Chapter 7, 14.3-4

A. Formation of the Solar System

B. Examples of Protoplanetary systems

C. Exoplanets

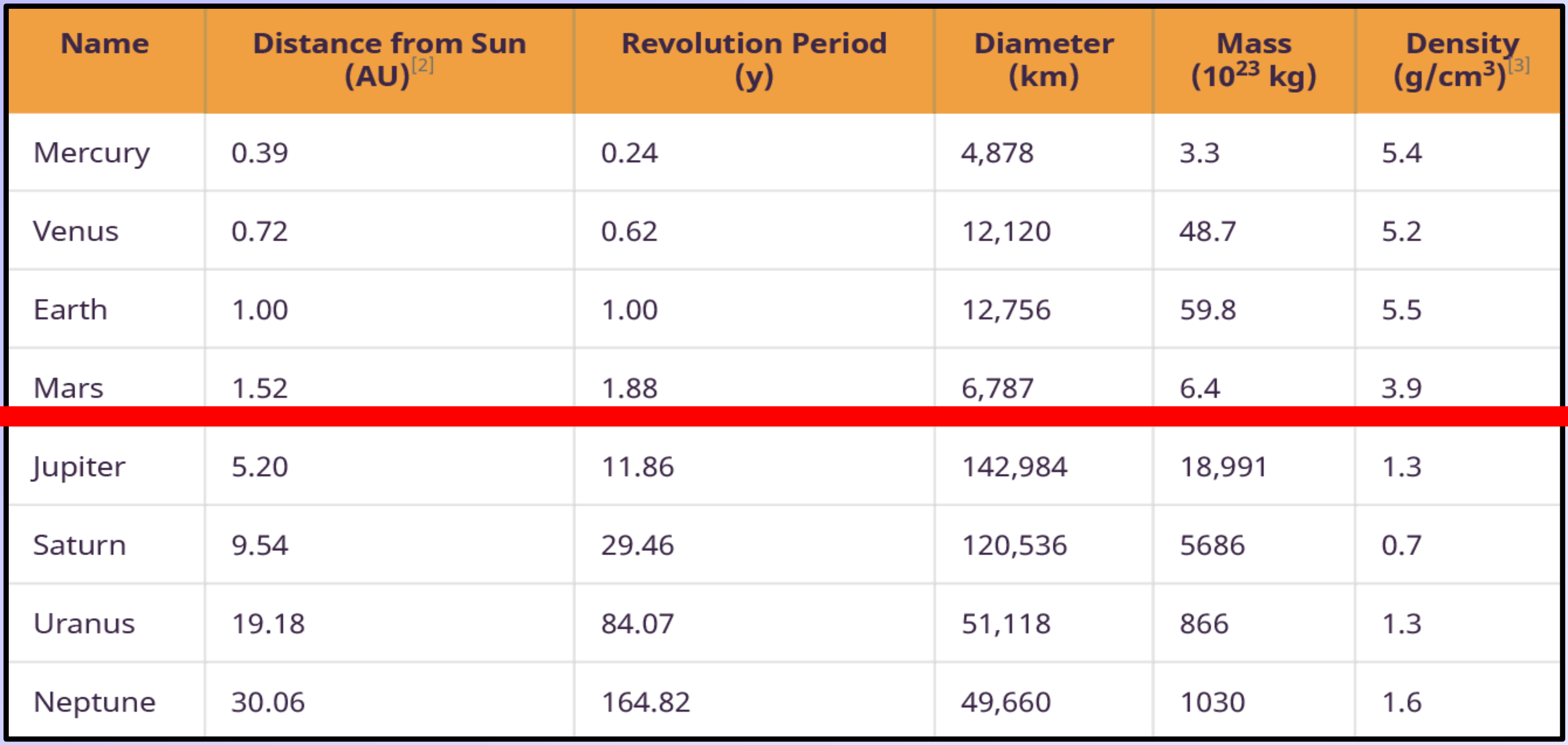
Composition of Planets

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

icy

[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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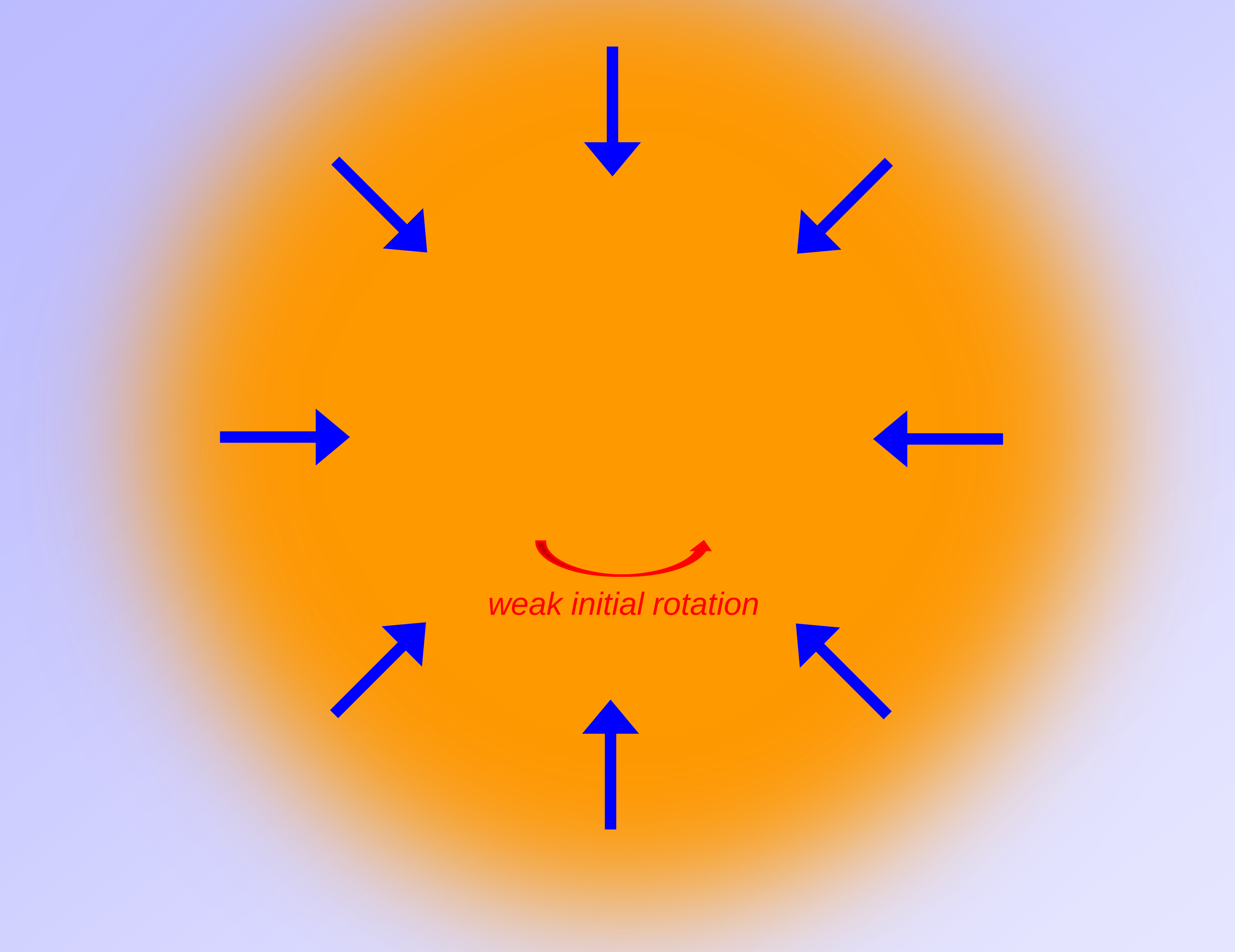
[William K. Hartmann, Planetary Science Institute]

- **Mutual gravity** pulls dust, particles, material, and gas inwards.
- **Contraction:** As the solar nebula contracts it **heats up** (energy conservation), spins faster (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



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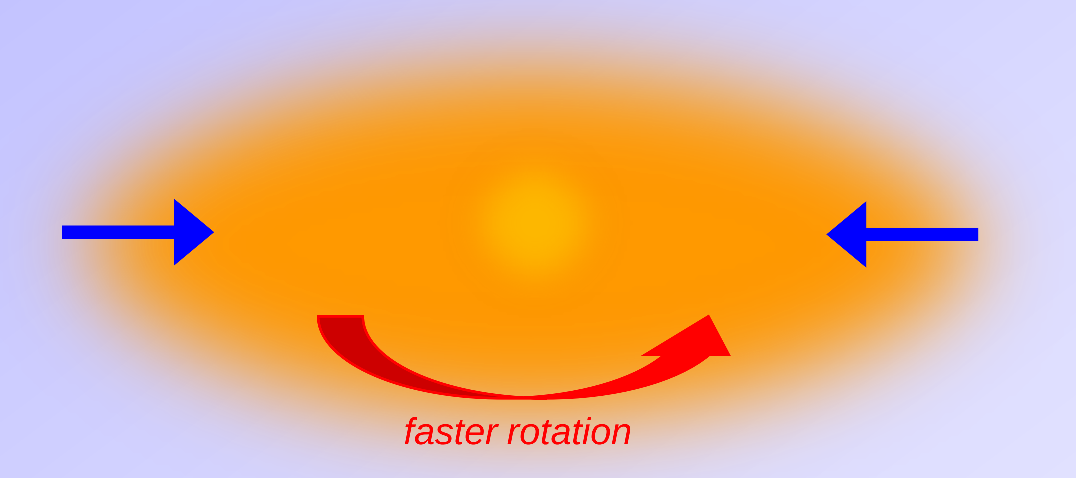
Step 1: Contraction



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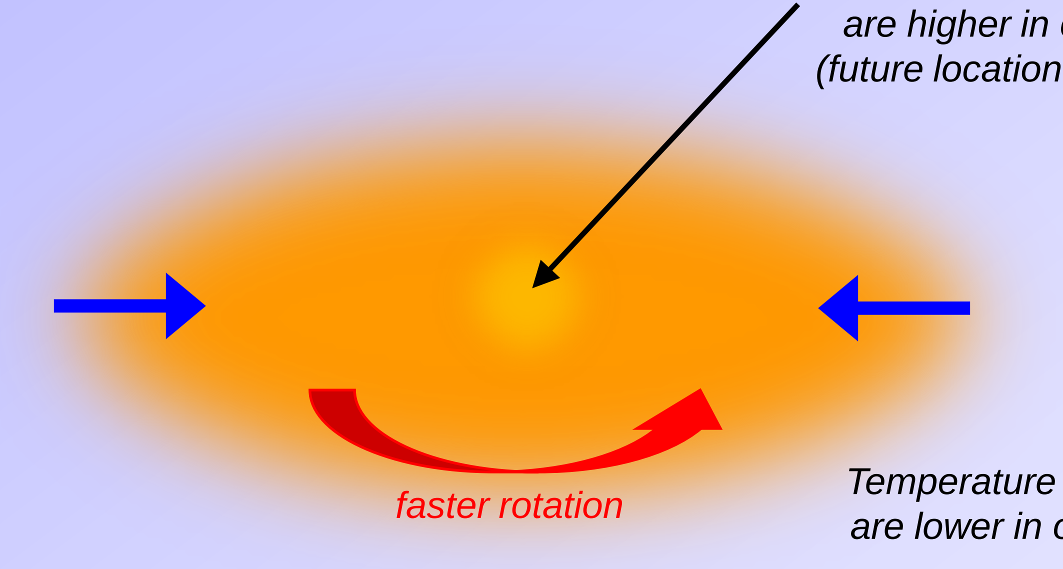

Temperature and density are higher in center (future location of Sun)

faster rotation

Temperature and density are lower in outer region

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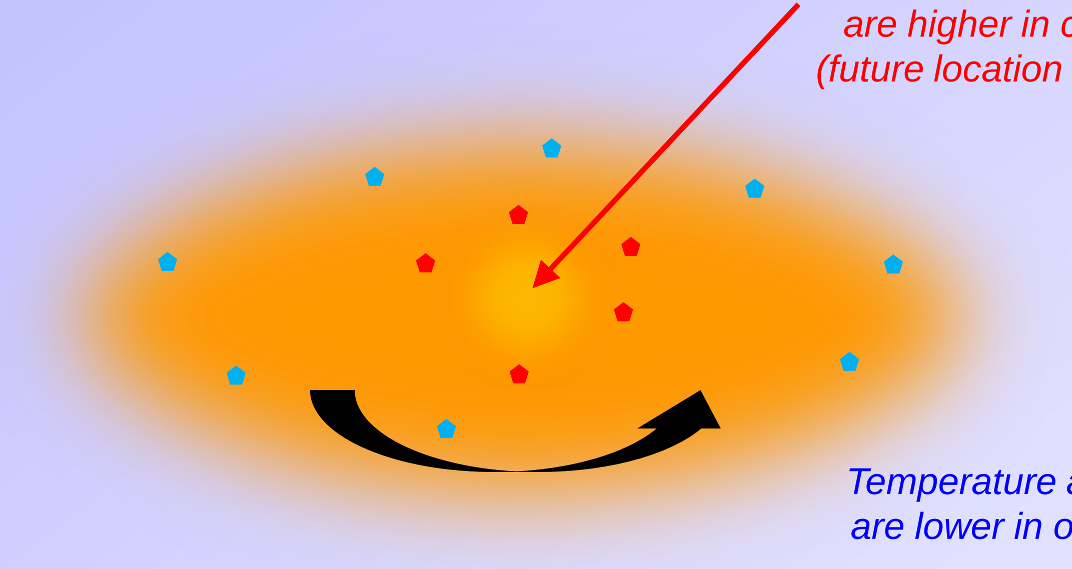
Step 2: Condensation

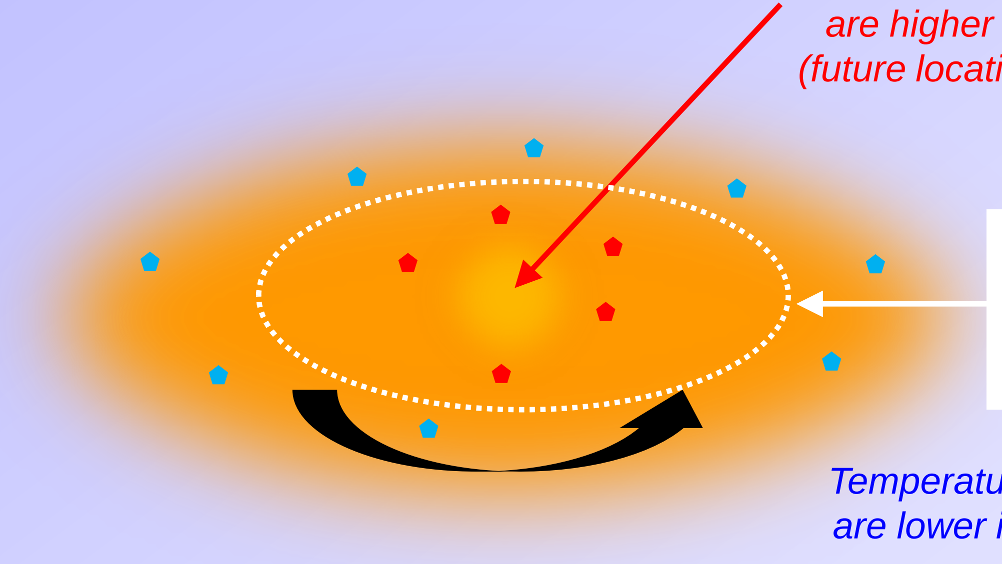


Temperature and density are higher in center (future location of Sun)

Temperature and density are lower in outer region

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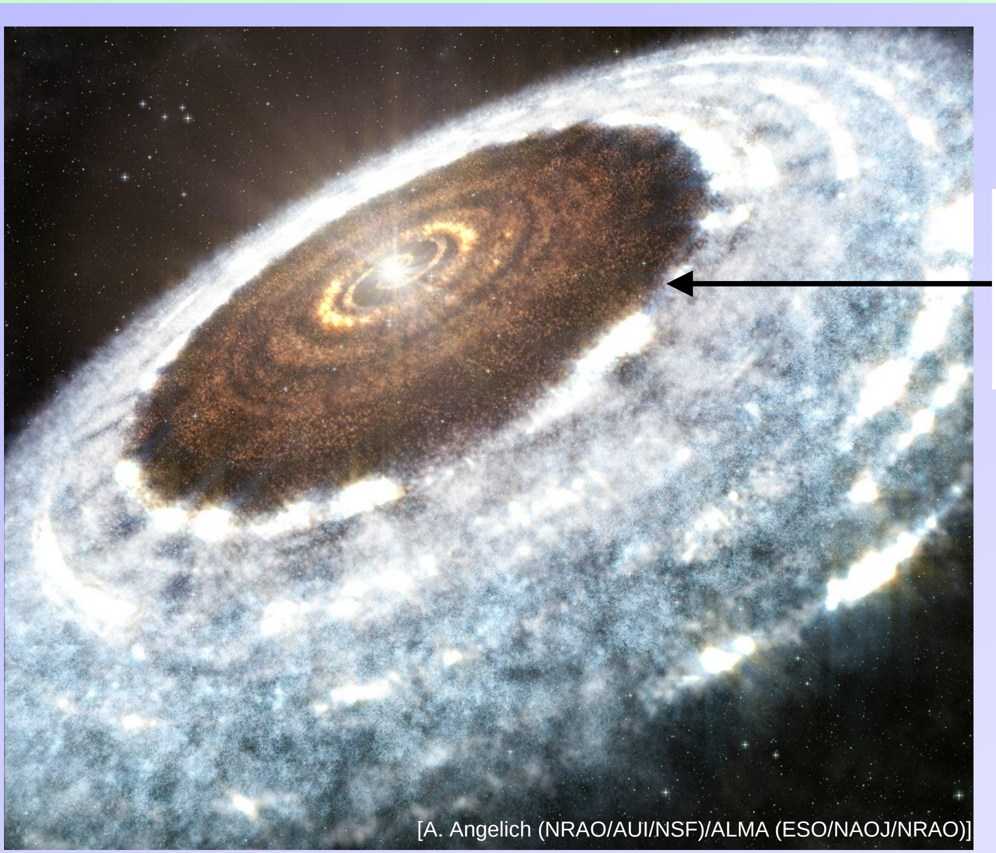
Artist's impression of the water snowline around the star V883 Orionis [Wikipedia].


[A. Angelich (NRAO/AUI/NSF)/ALMA (ESO/NAOJ/NRAO)]

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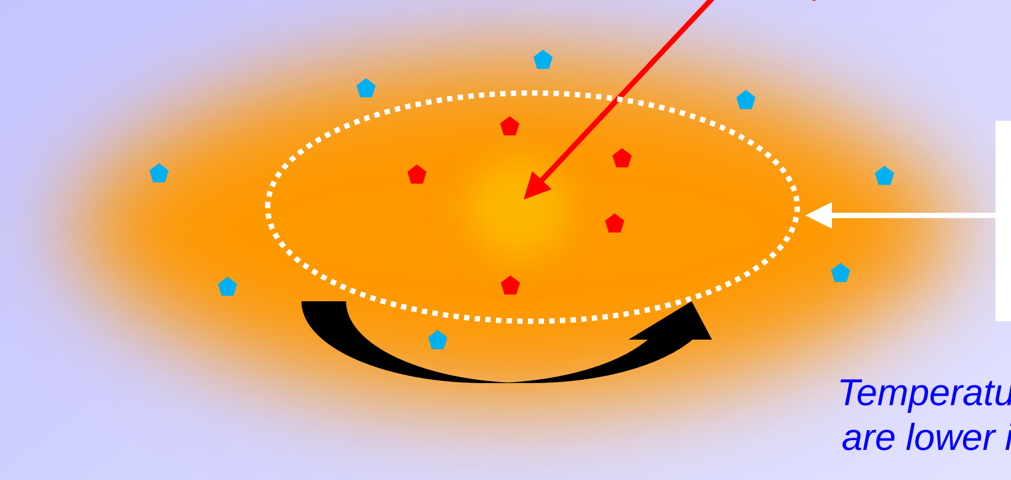

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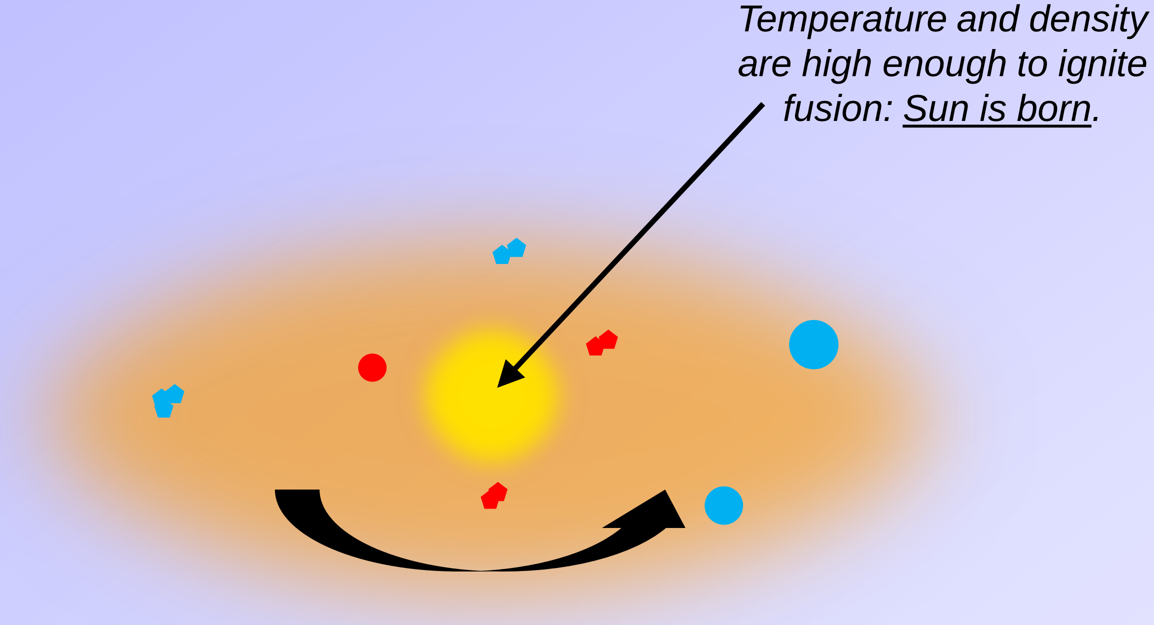
Step 3: Accretion of Planetesimals


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

- **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**.

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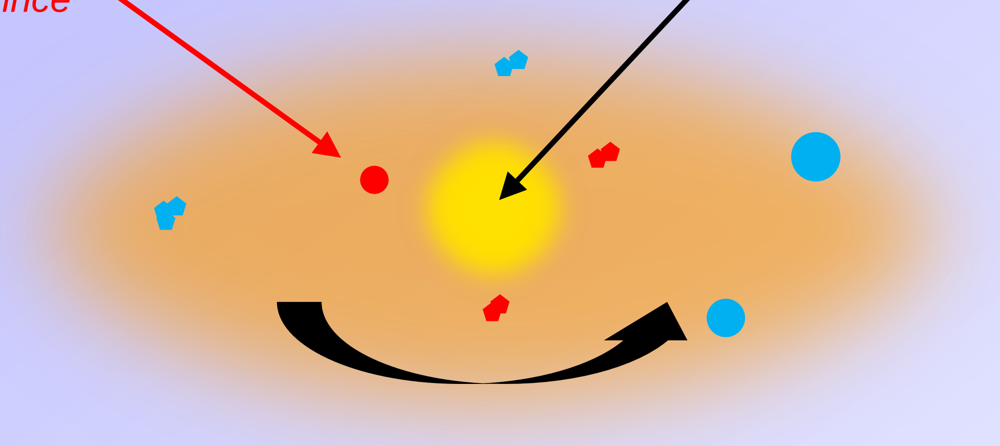

Inner planetesimal tend to be richer in heavy elements, which condense at higher temperature.

They tend to be smaller, since they sweep a smaller area (gathering less material).

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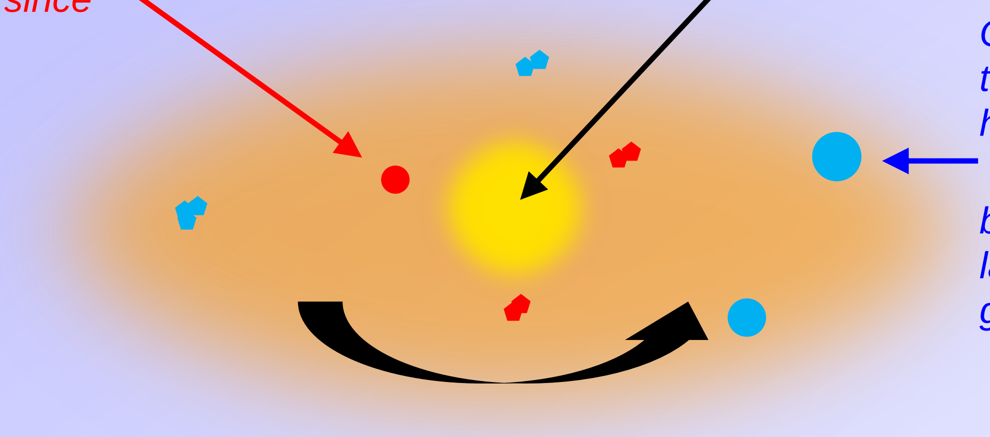

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Temperature and density are high enough to ignite fusion: Sun is born.

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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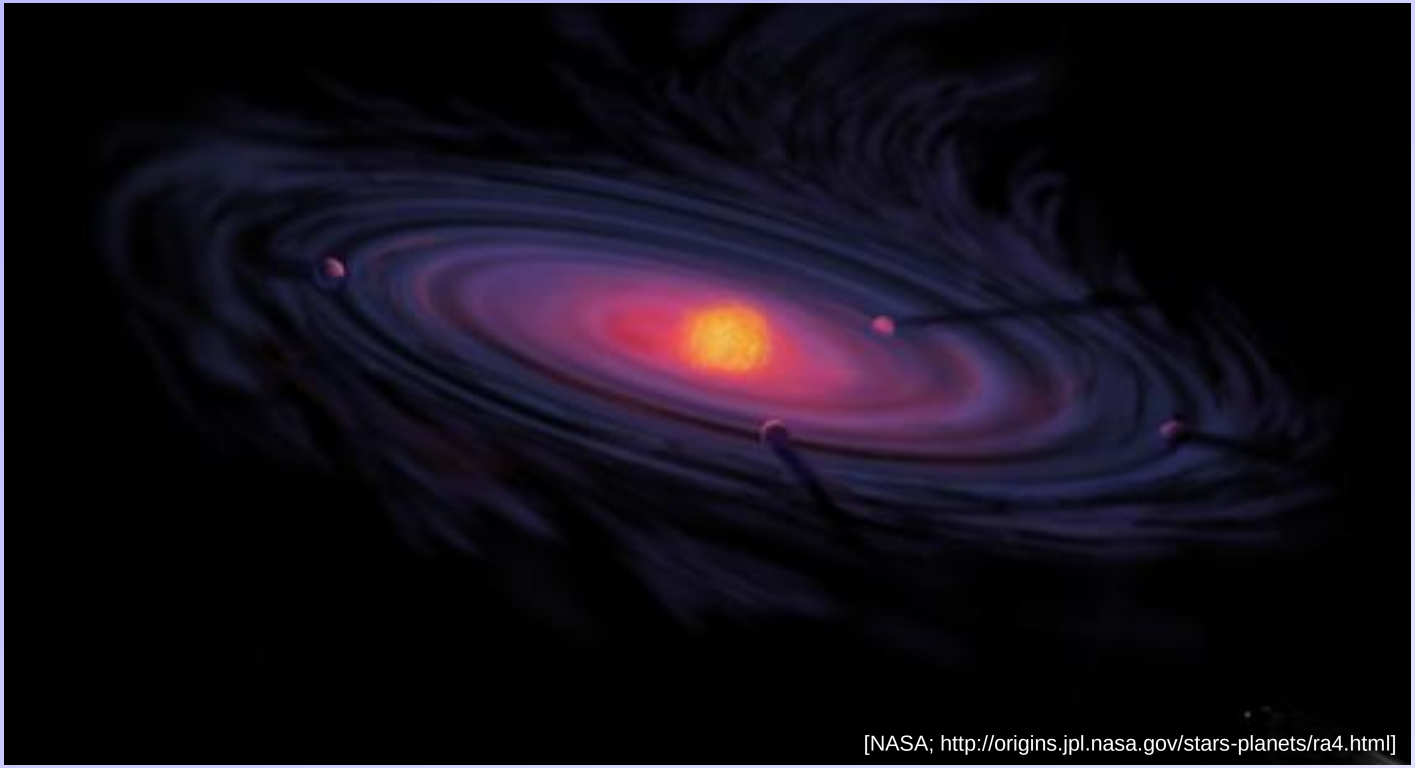
Step 3: Planetesimals to Planets

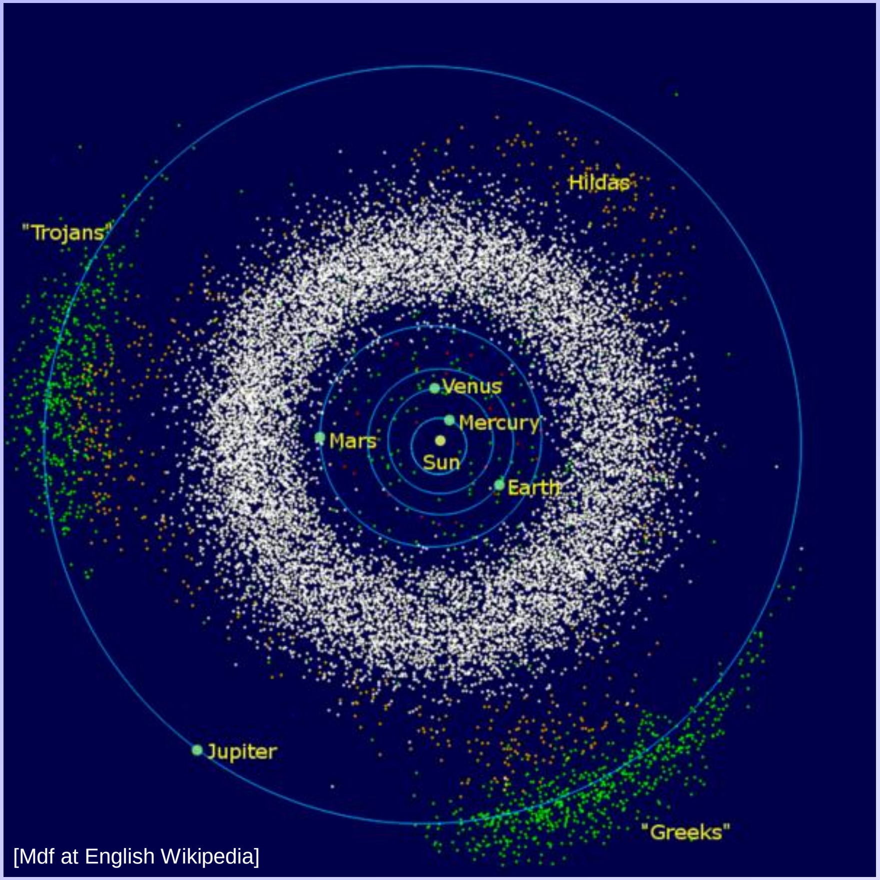


[NASA; http://origins.jpl.nasa.gov/stars-planets/ra4.html]

- 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

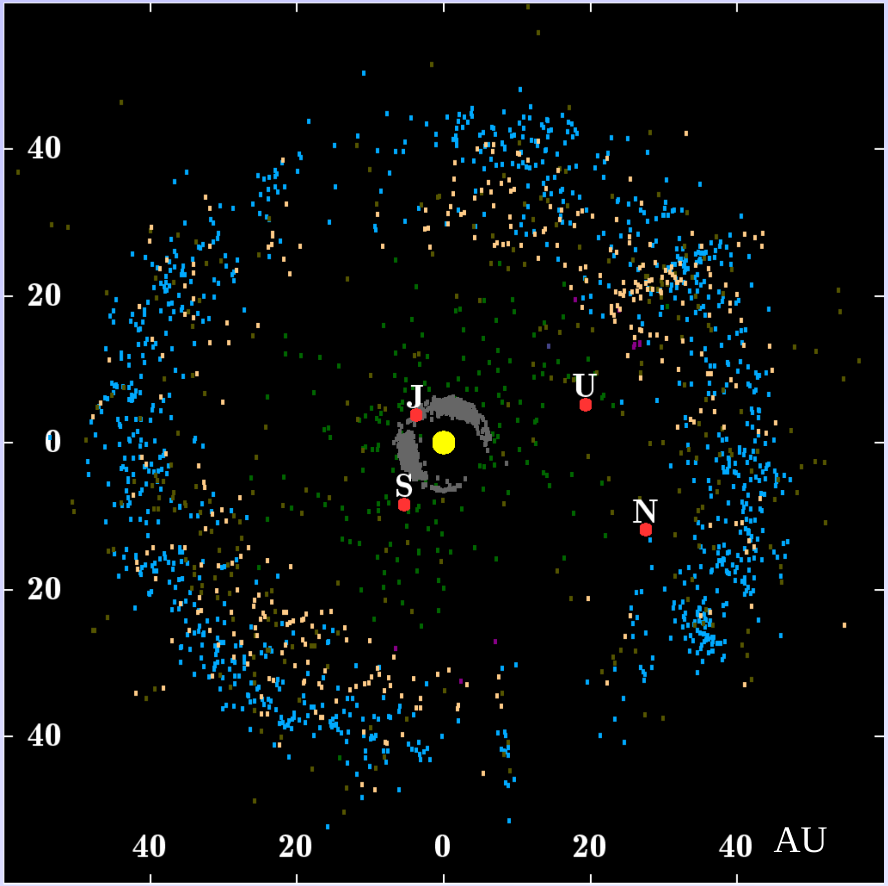
Inner Solar System + Jupiter



[Mdf at English Wikipedia]

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

Outer Solar System with Gas Giants



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

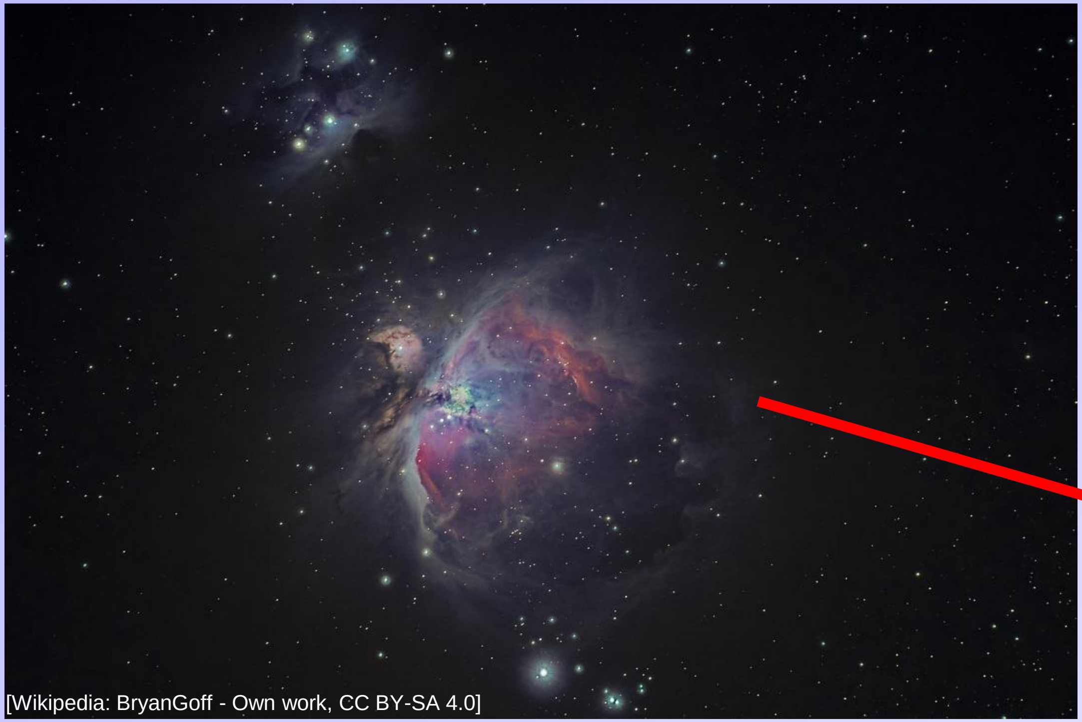
Kuiper belt objects (blue, beige, green) are icy left over planetesimals in the region of the gas giants and beyond.

PollEv Quiz: **PollEv.com/sethaubin**

Nascent Protoplanetary Systems

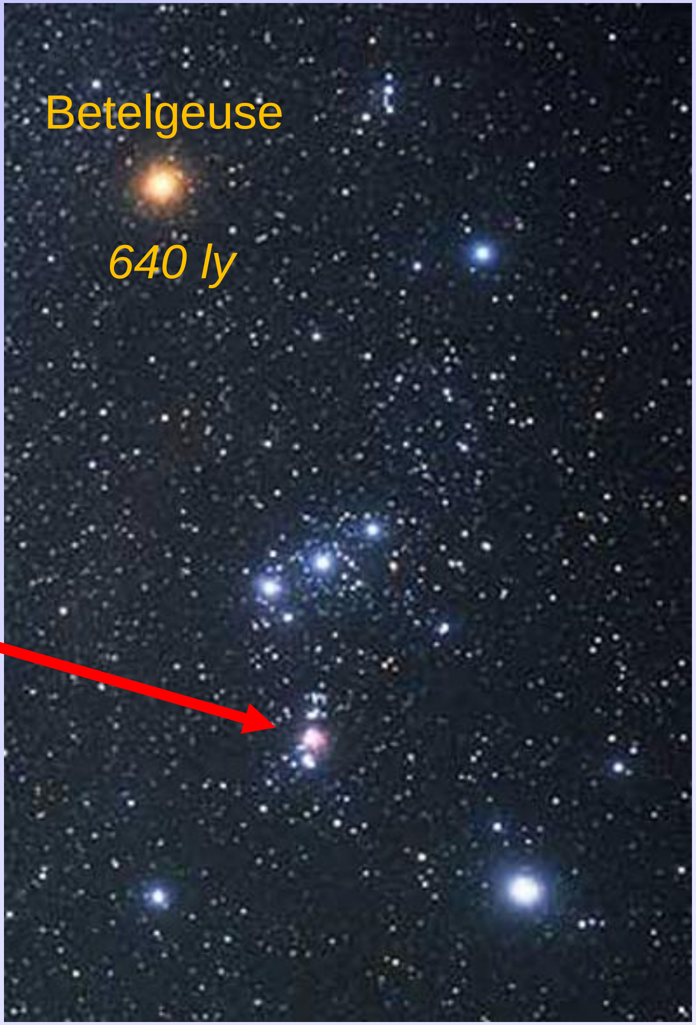
Constellation: **Orion**

Nascent Protoplanetary Systems



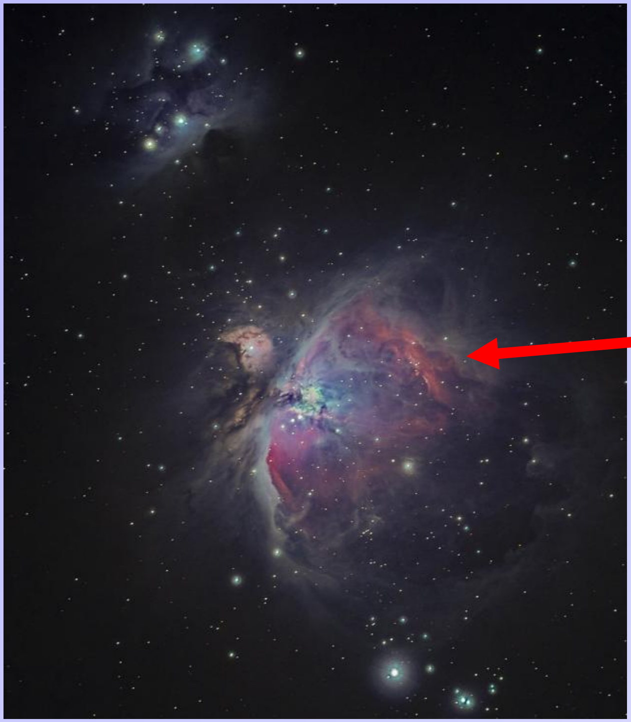
[Wikipedia: BryanGoff - Own work, CC BY-SA 4.0]

Orion Nebula



Constellation: **Orion**

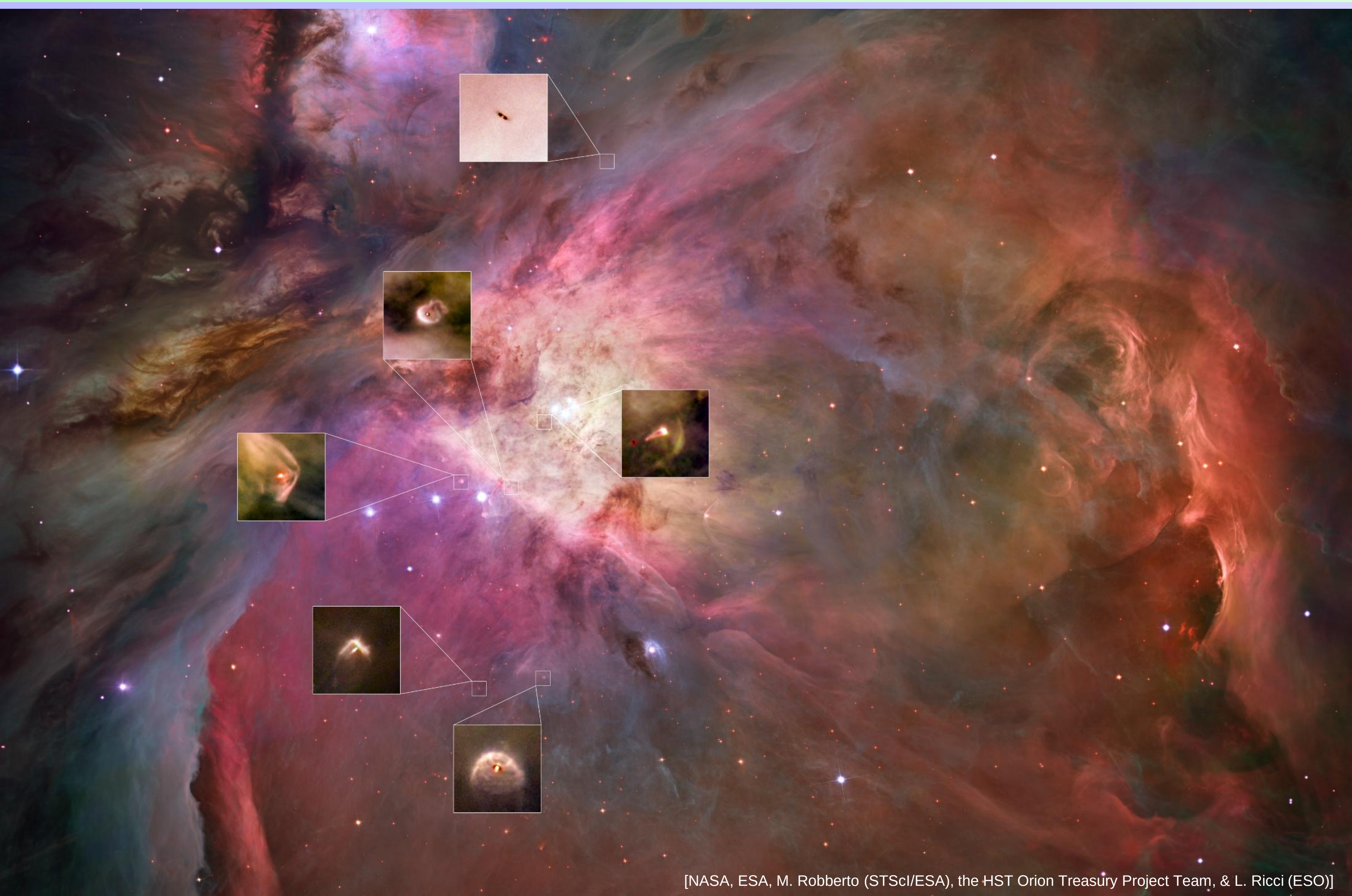
Nascent Protoplanetary Systems



Orion Nebula

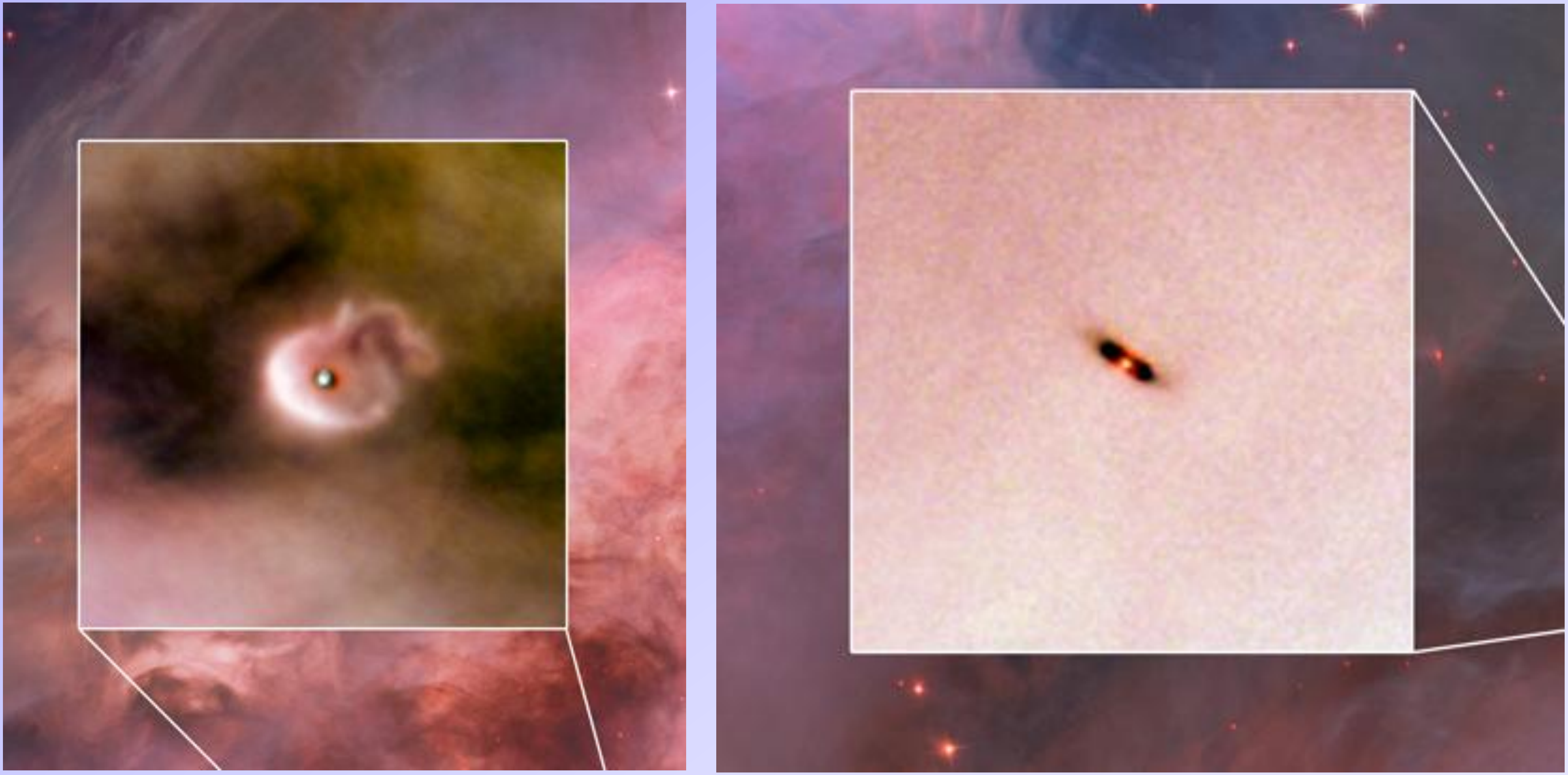
[NASA, ESA, M. Robberto (Space Telescope Science Institute/ESA) and the Hubble Space Telescope Orion Treasury Project Team]

Nascent Protoplanetary Systems

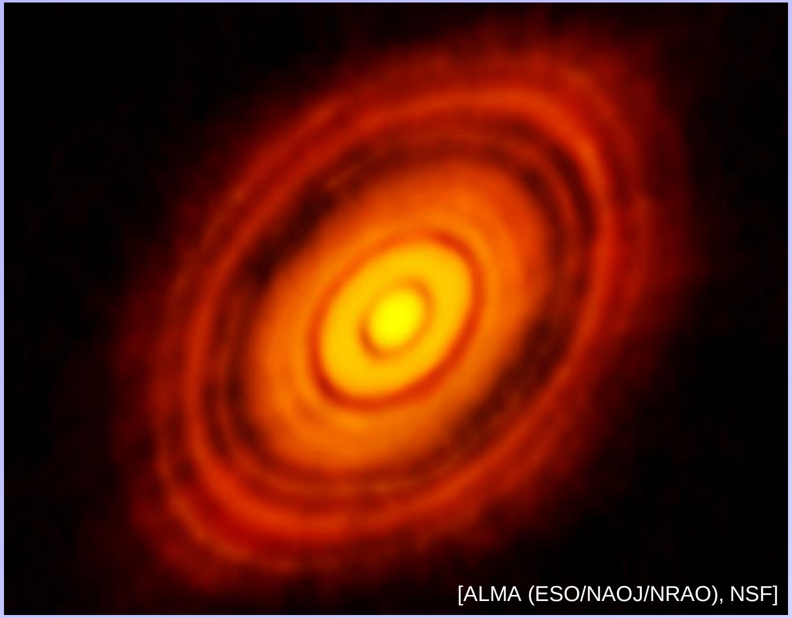


[NASA, ESA, M. Robberto (STScI/ESA), the HST Orion Treasury Project Team, & L. Ricci (ESO)]

Nascent Protoplanetary Systems



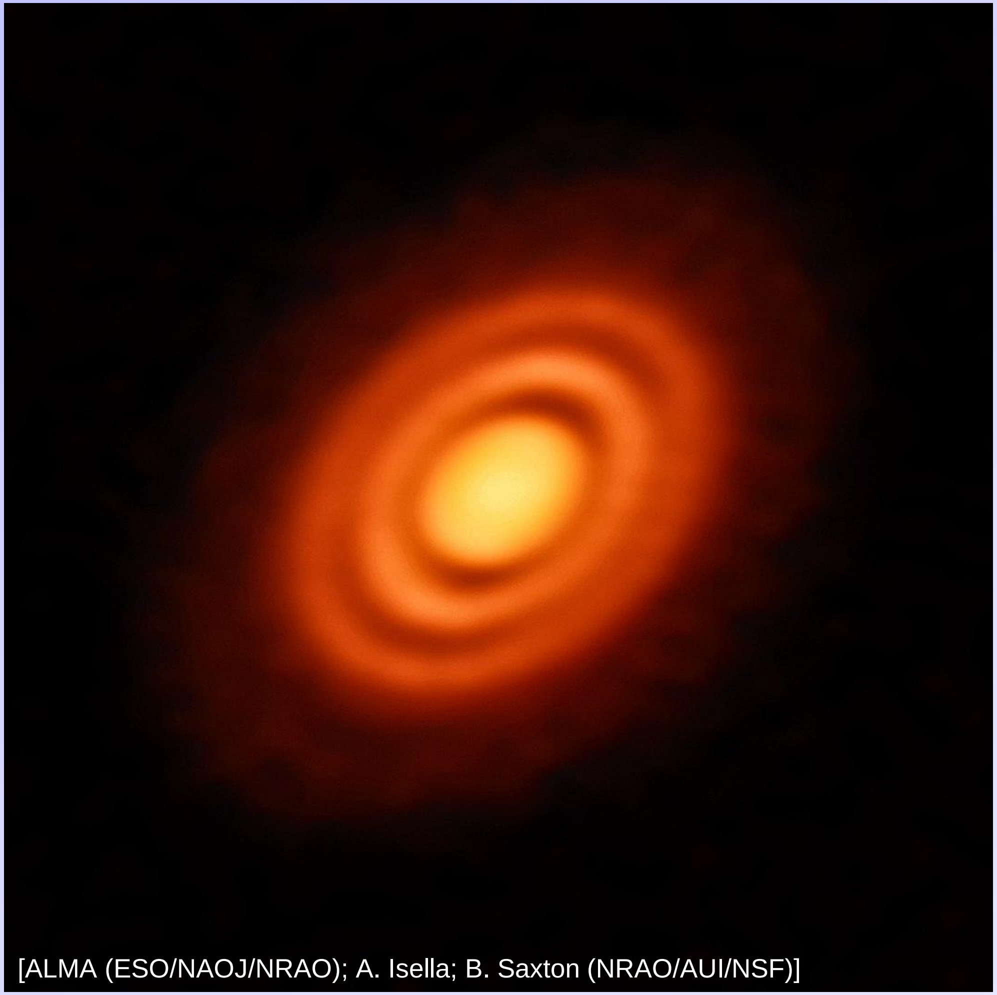
Protoplanetary Disks – mm wave



[ALMA (ESO/NAOJ/NRAO), NSF]

The Protoplanetary Disk of the young star HL Tauri

(in Milky Way galaxy, Taurus constellation)

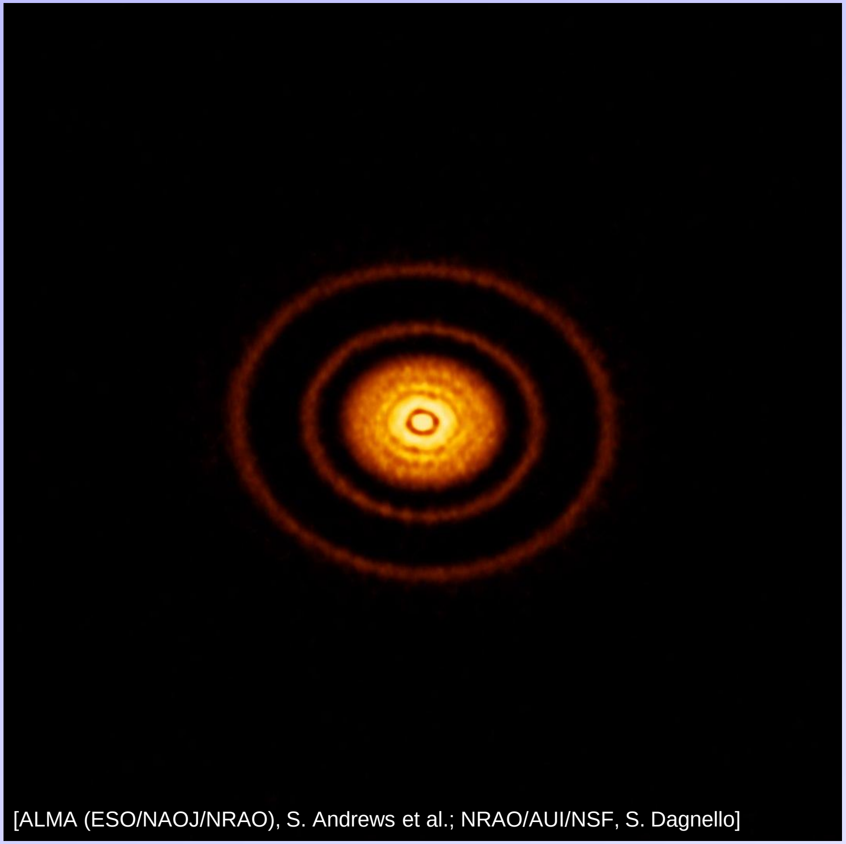


[ALMA (ESO/NAOJ/NRAO); A. Isella; B. Saxton (NRAO/AUI/NSF)]

Cloud of gas and dust surrounding the young star HD 163296.

(in Milky Way galaxy, Sagittarius constellation)

Protoplanetary Disks – mm wave



[ALMA (ESO/NAOJ/NRAO), S. Andrews et al.; NRAO/AUI/NSF, S. Dagnello]

Protoplanetary disk around the young star AS 209.

(in Milky Way galaxy, Ophiuchus constellation)

Exoplanets

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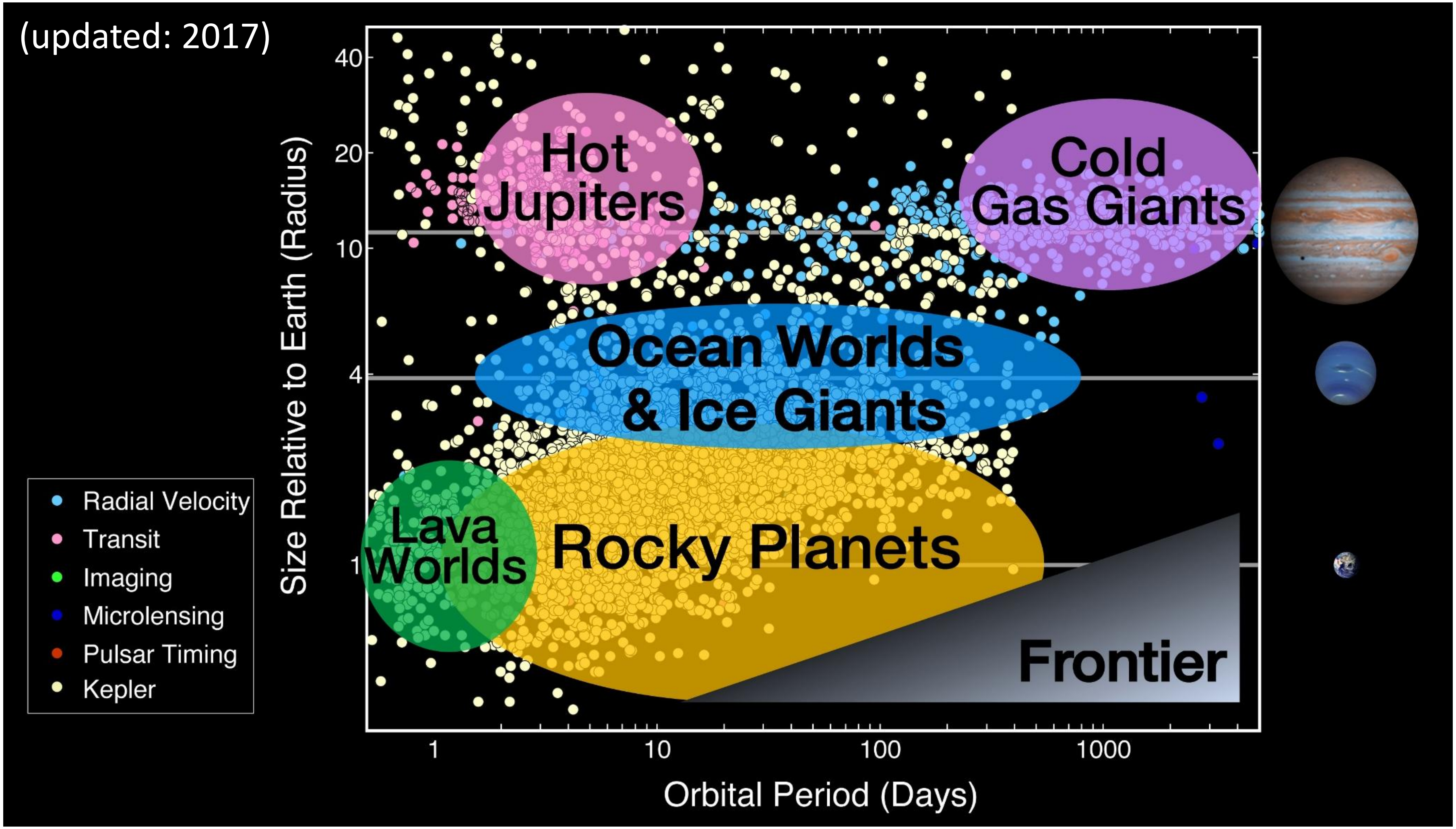
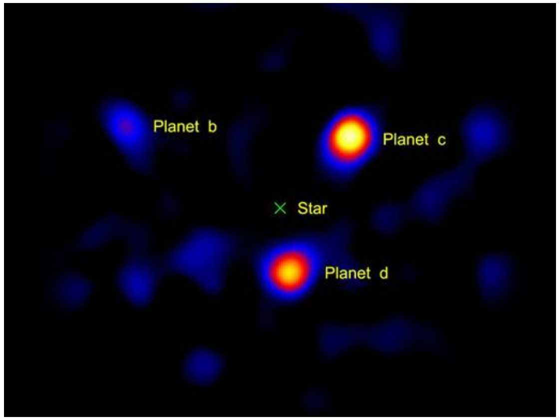


[https://www.nasa.gov/image-feature/ames/kepler/exoplanet-populations]

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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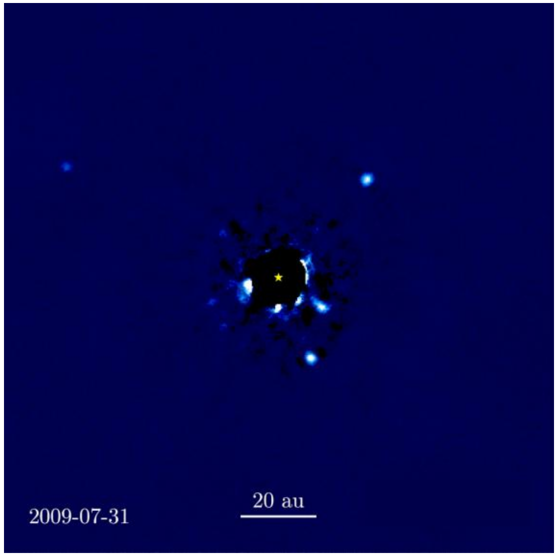

4 planets around star HR8799 (120 ly) [Keck telescope, 2009-2016, J. Wang, C. Marois]

Exoplanets

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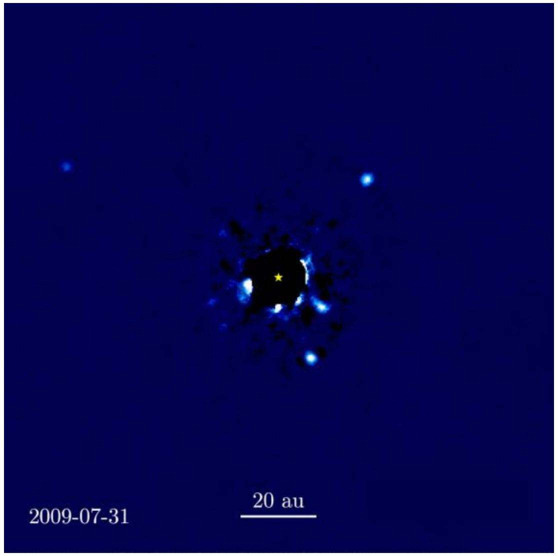
- We see many **gas giants** inside the frost line.

  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).



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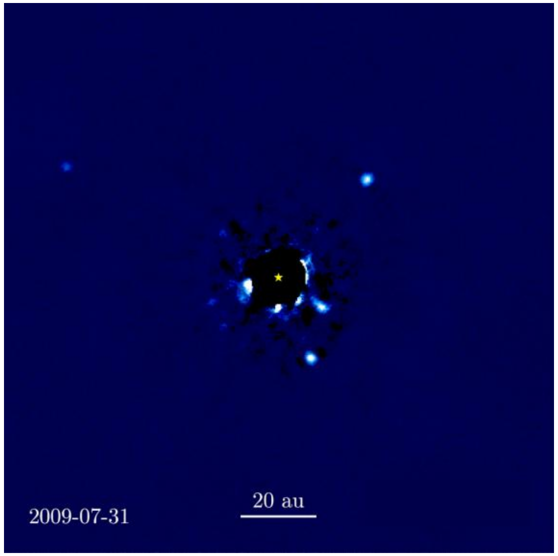
- Roughly 40% of Sun-like stars have terrestrial planets in the **“goldilocks”** region.

  → 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.



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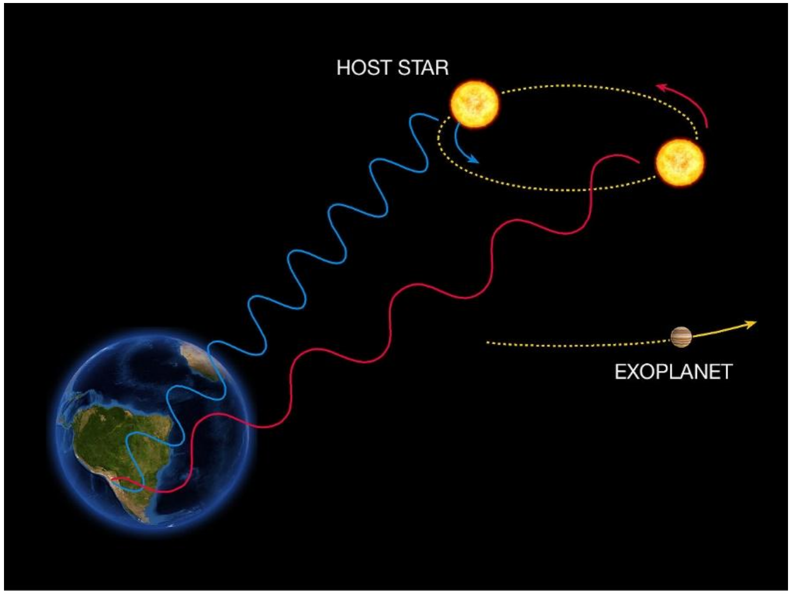
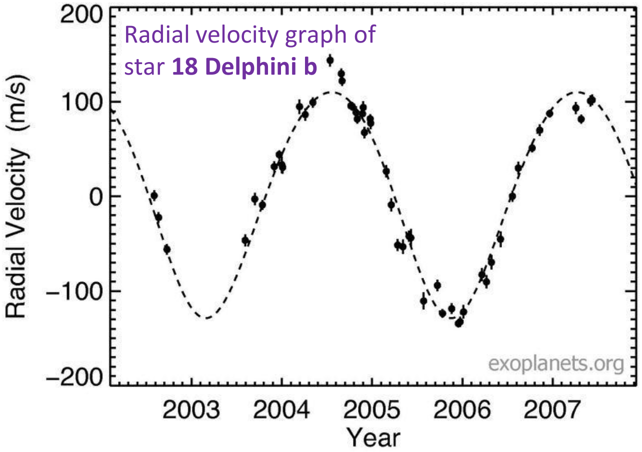
Main Detection Methods



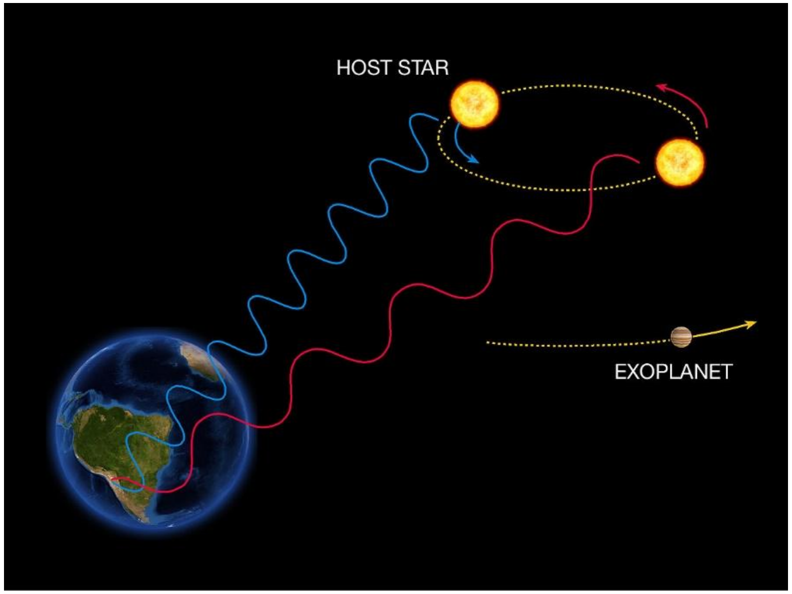
The Radial Velocity Method

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



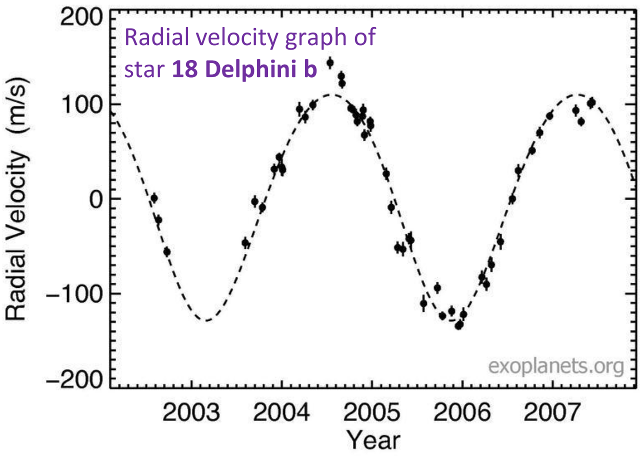
Radial velocity graph of star **18 Delphini b**

Main Detection Methods



The Radial Velocity Method

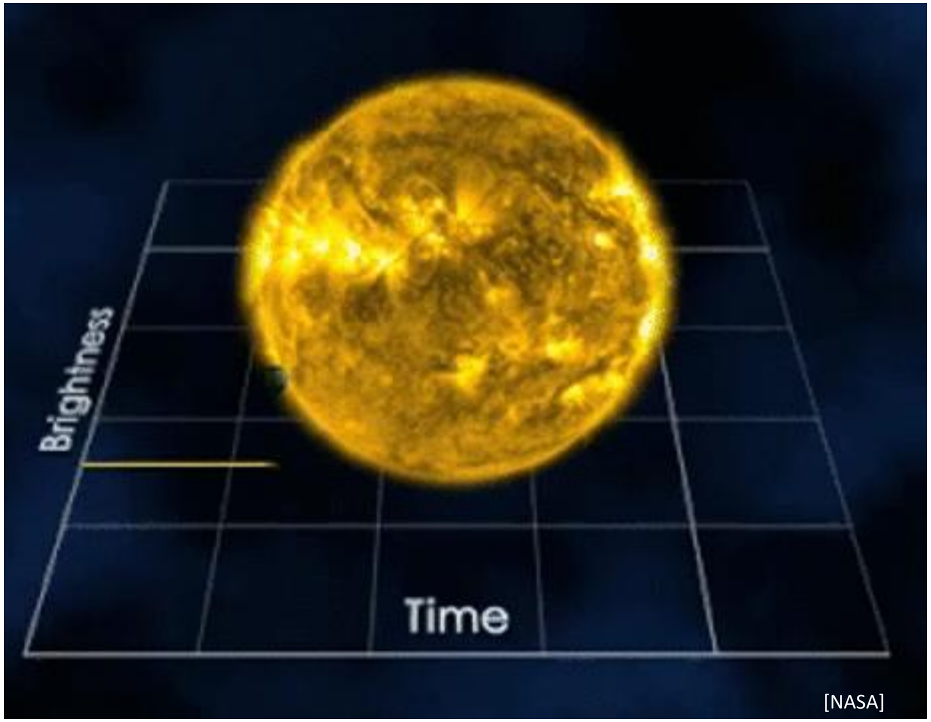
ESO Press Photo 22e/07 (25 April 2007)



Radial velocity graph of star **18 Delphini b**

exoplanets.org

Transit Photometry



[NASA]

Signal is typically 1 part per 10,000 dimming.