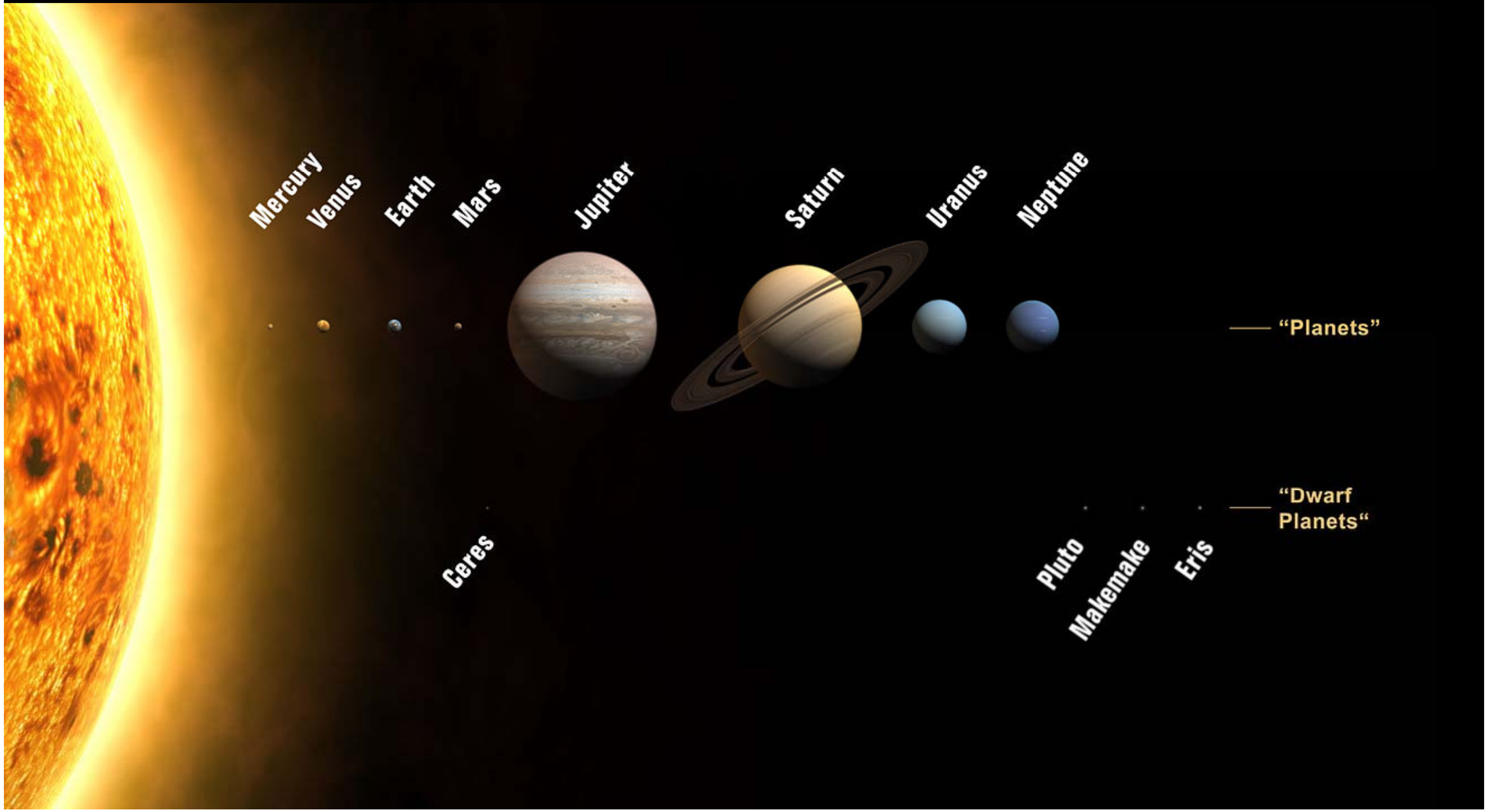
The Formation of Solar System

IST Summer 2008

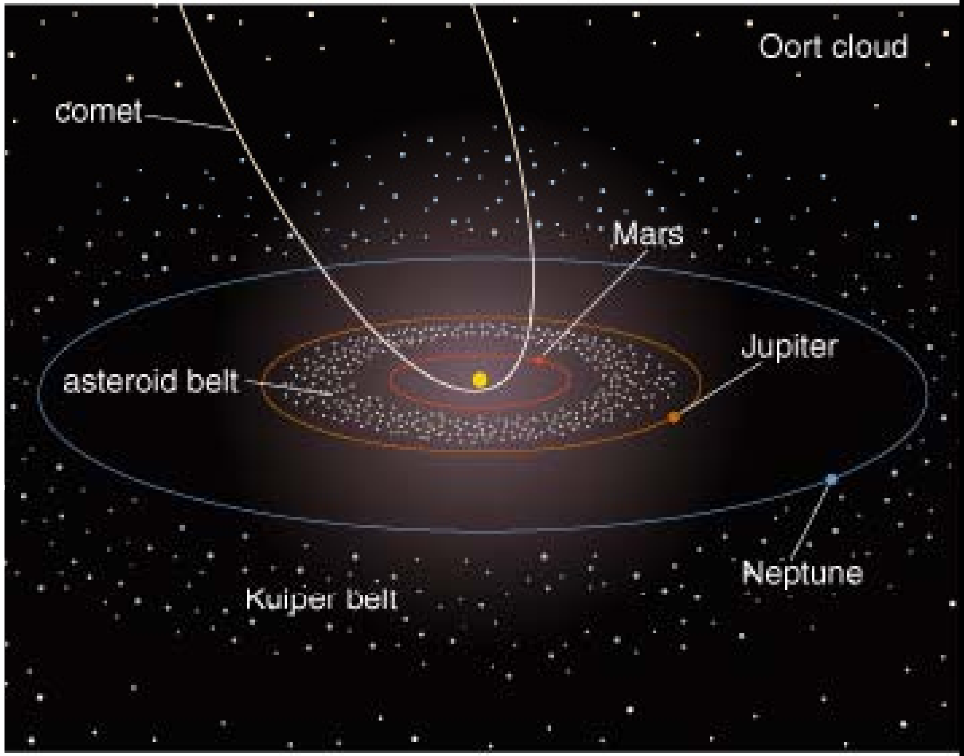
Dynamics of the Solar System

- Sun, containing 99.9% of mass
- 8 planets
- 15 moons over 1000 km in diameter
- ~ 200 smaller moons
- ~100,000 asteroids
- billions of potential comets
- billions of meteorites, meteoroids and debris
- solar wind
- magnetic field

Characteristics of the Solar System



Swarms of Smaller Bodies



LEFTOVERS

- **Asteroids mostly orbit between Mars and Jupiter**
- **Comets usually come from far outside Neptune's orbit**

Minor Bodies (The Leftovers)

- Asteroids (Asteroid Belt):
  - Range from 500km to large boulders
  - Made of rock (density 2-3 g/cc)
- Comets (Oort Cloud & Kuiper Belt):
  - Composite rock & ice “dirty snowballs”
  - Longs tails of gas & dust are swept off them when they pass near the Sun.

Asteroids

951 Gaspra

253 Mathilde

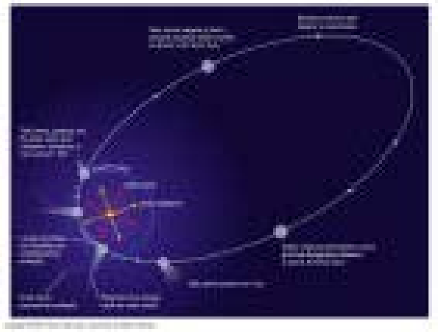
243 Ida

COMETS

Comets are sometimes called dirty snowballs or "icy mudballs".
They are a mixture of ices (both water and frozen gases) and dust that for
some reason didn't get incorporated into planets when the solar system was formed.
This makes them very interesting as samples of the early history of the solar system.

Comets have elliptical orbits.

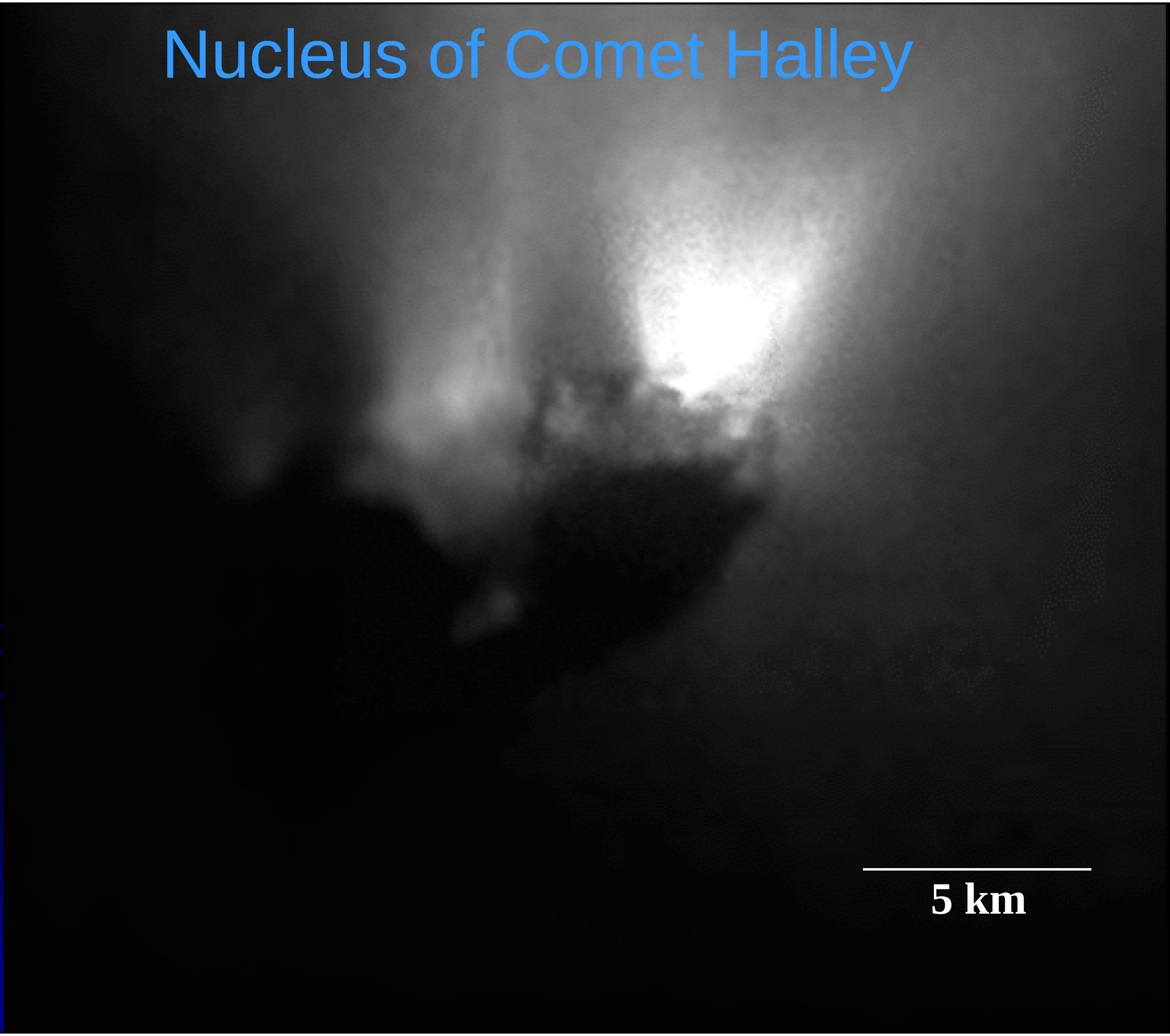
Comet Halley in 1910



When we see a comet, we are seeing the tail of the co
as comes close to the Sun.

Comet Hale-Bopp

Nucleus of Comet Halley



The Kuiper Belt and the Oort Cloud

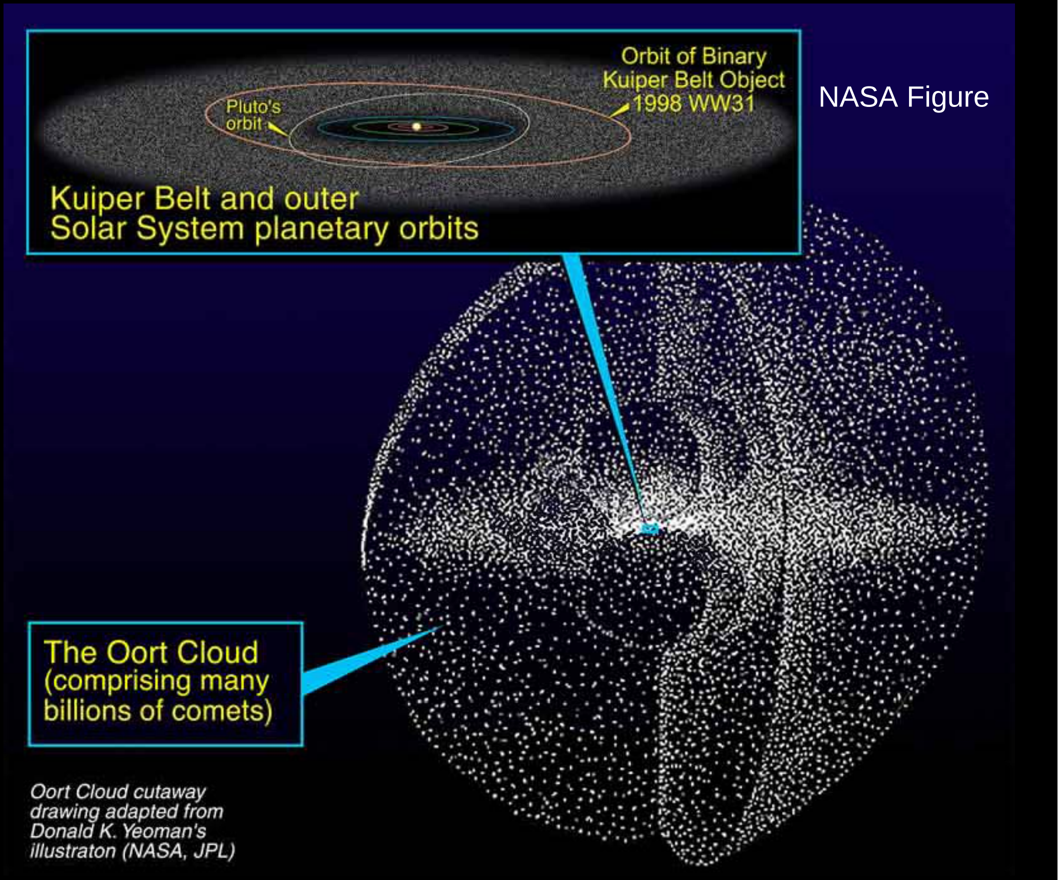
Kuiper Belt

A large body of small objects orbiting (the short period comets) the Sun in a radial zone extending outward from the orbit of Neptune (30 AU) to about 50 AU. Pluto maybe the biggest of the Kuiper Belt object.

Oort Cloud

Long Period Comets (period > 200 years) seems to come mostly from a spherical region at about 50,000 AU from the Sun.

Astronomical Unit (AU)
=149,597,870.7 km



Oort Cloud cutaway drawing adapted from Donald K. Yeoman's illustraton (NASA, JPL)

NASA Figure

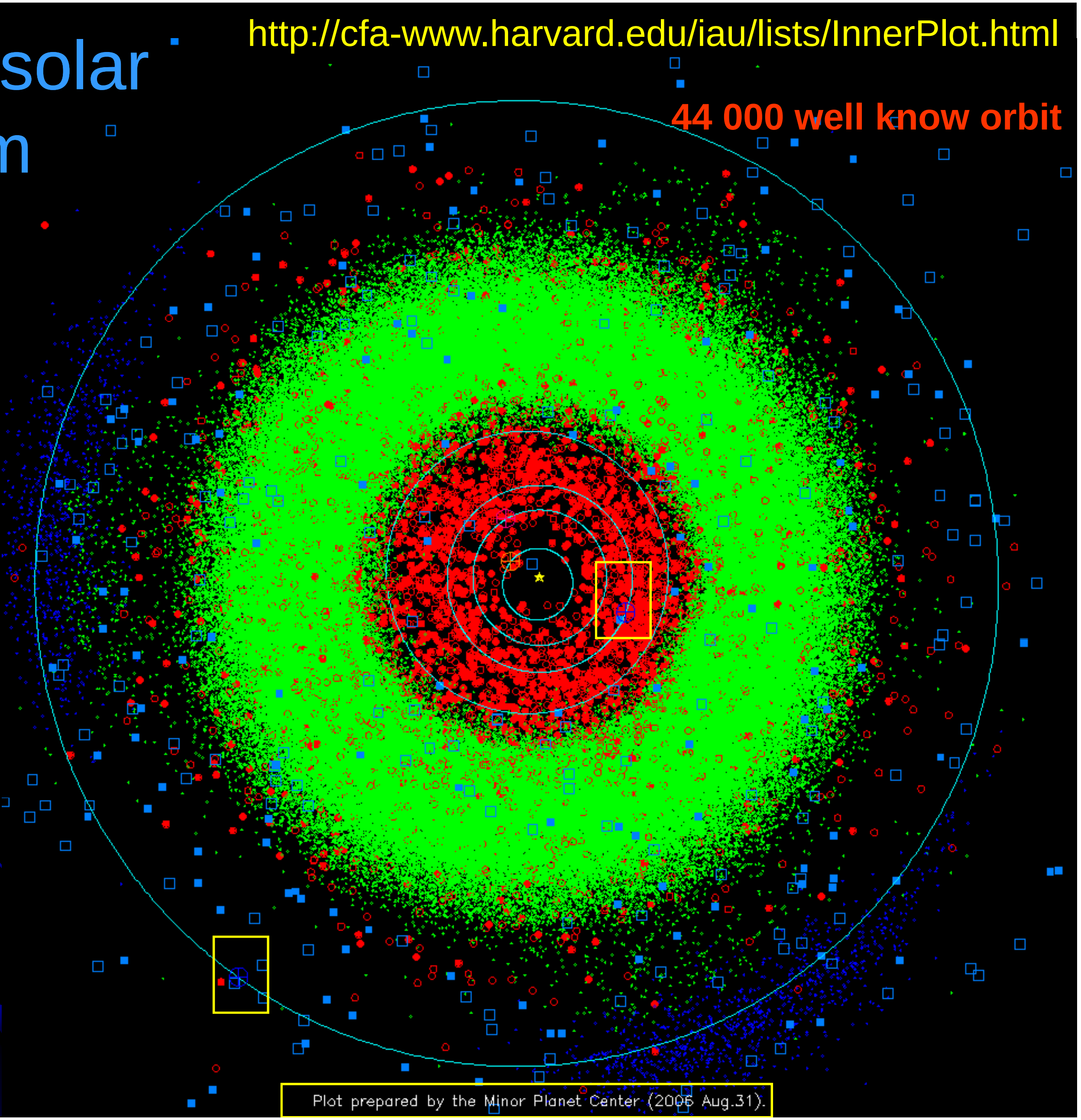
The Inner solar System

http://cfa-www.harvard.edu/iau/lists/InnerPlot.html

44 000 well know orbit

Location of the minor planets that are in the inner region of the solar system.

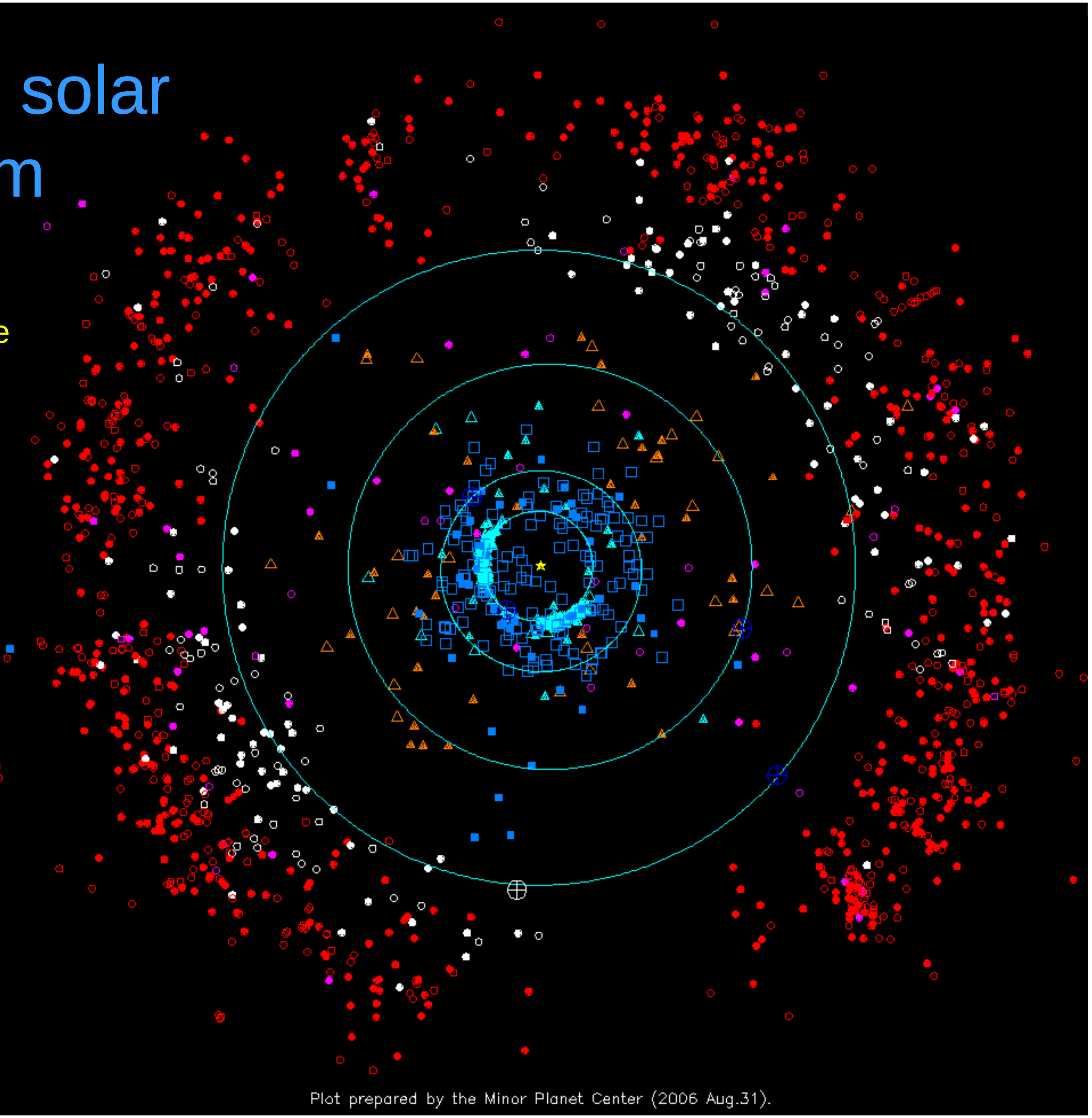
- Unnumbered objects: green circles.
- Objects with perihelia within 1.3 AU: red circles.
- Jupiter Trojans: deep blue - two "clouds" at 60° ahead and behind Jupiter (and at or near Jupiter's distance from the sun).
- Numbered periodic comets: filled light-blue squares.
- Other comets: unfilled light-blue squares.



Plot prepared by the Minor Planet Center (2006 Aug.31).

The Outer solar System

- The current location of the minor bodies:
- Unusual high-e objects: cyan triangles
- Centaur objects: orange triangles,
- Plutinos (resonance with Neptune): white circles
- Pluto: large white
- scattered-disk objects: magenta circles
- "classical" or "main-belt" objects: red circles.
- Numbered periodic comets: filled light-blue squares.
- Other comets: unfilled light-blue squares.



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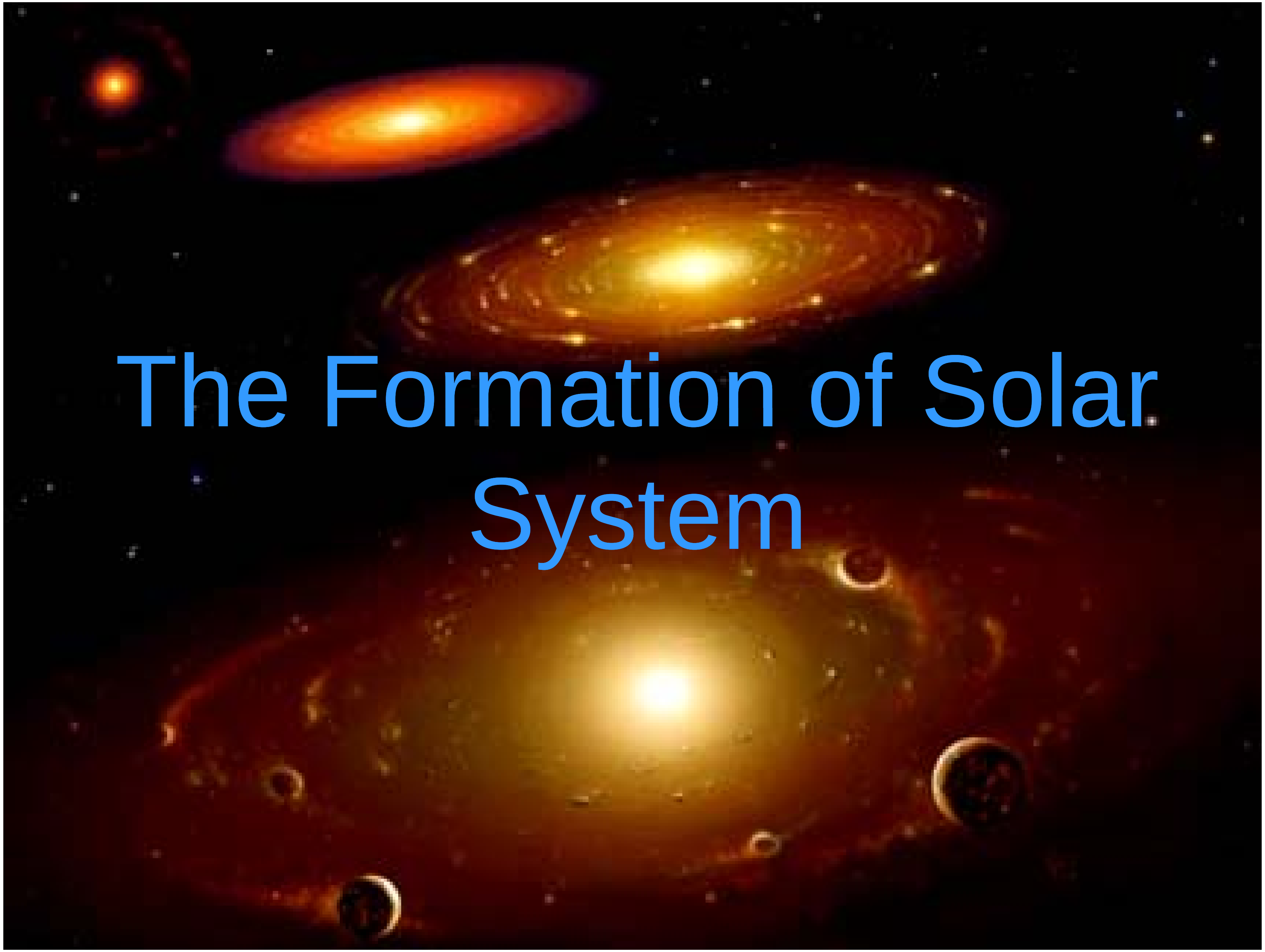


The Formation of Solar System

The Origin of the Solar System

Four Challenges

- **a) Patterns of Motion**
  - Planets orbit in the same direction...
  - ...in nearly the same plane...
  - ...in nearly circular orbits.
  - Most planets rotate in the same direction.
  - Most moons orbit in the same direction.

The Origin of the Solar System

Four Challenges

- **b) Categorizing Planets**
  - Planets are either rocky or gas-rich.

The Origin of the Solar System

Four Challenges

- **c) Asteroids and Comets**
  - Most asteroids are found between Mars and Jupiter.
  - Most comets have highly elliptical orbits.

The Origin of the Solar System

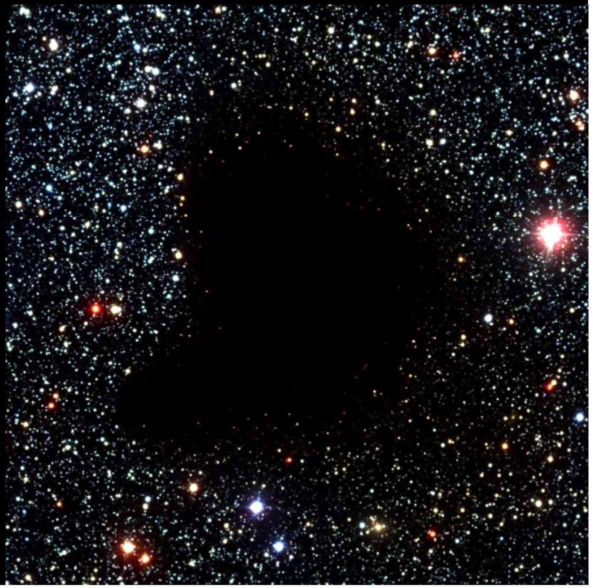
Four Challenges

- **d) Exceptions to the Rules**
  - What about Pluto’s elliptical orbit and composition?
  - What about the odd rotation of Venus and Uranus?

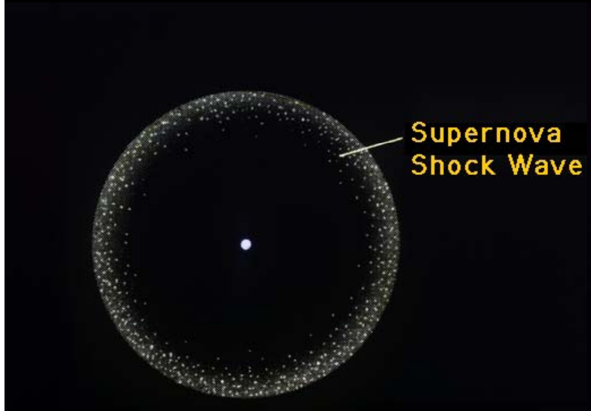
Primordial Solar Nebula

- The rotating solar nebula is composed of
  - ~75% Hydrogen & 25% Helium
  - Traces of metals and dust grains
- Starts out at ~2000 K, then cools:
  - As it cools, various elements condense out of the gas into solid form as grains or ices.
  - Which elements condense out when depends on their “condensation temperature”.

Cold Interstellar H_2 Cloud



Supernova Shock Wave



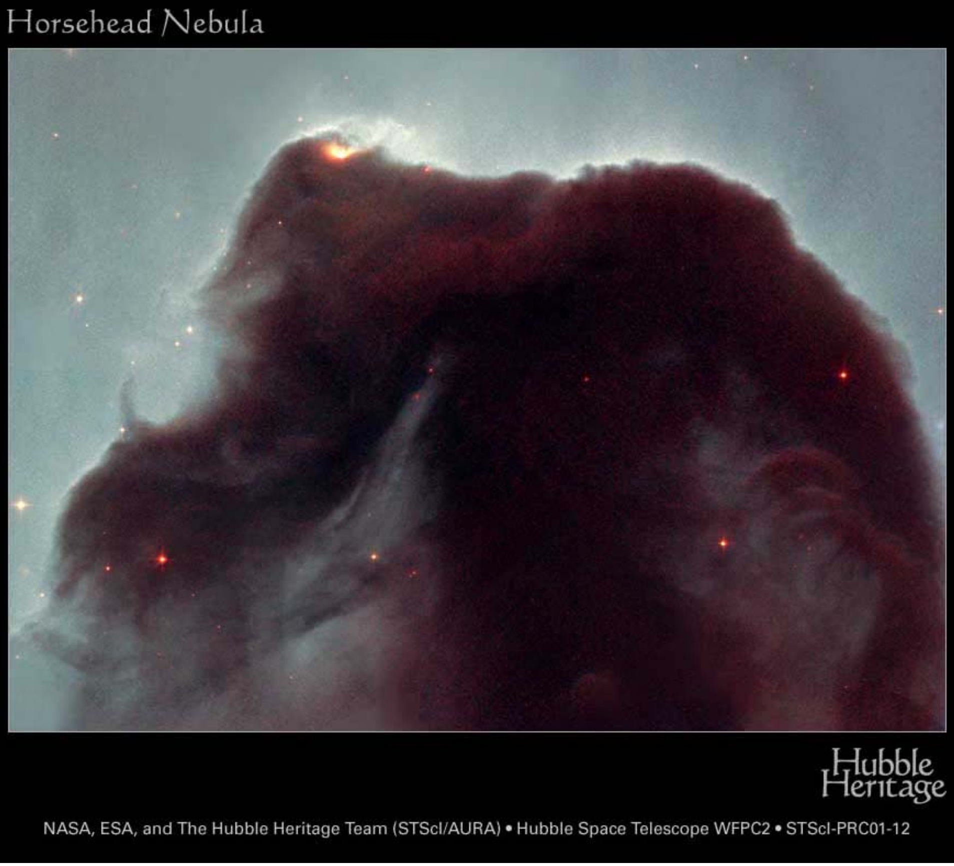
Shell of gases ejected from a supernova as a shock wave.

Interaction of shock wave front with nebula causes contraction

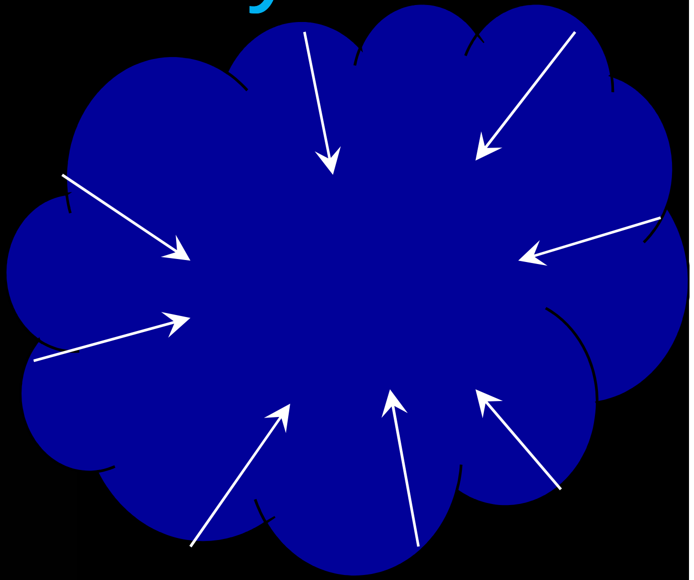
Shock wave passes leaving proto-planetary system

Formation of the Solar System

Gravity causes collapse of part of a gas cloud:

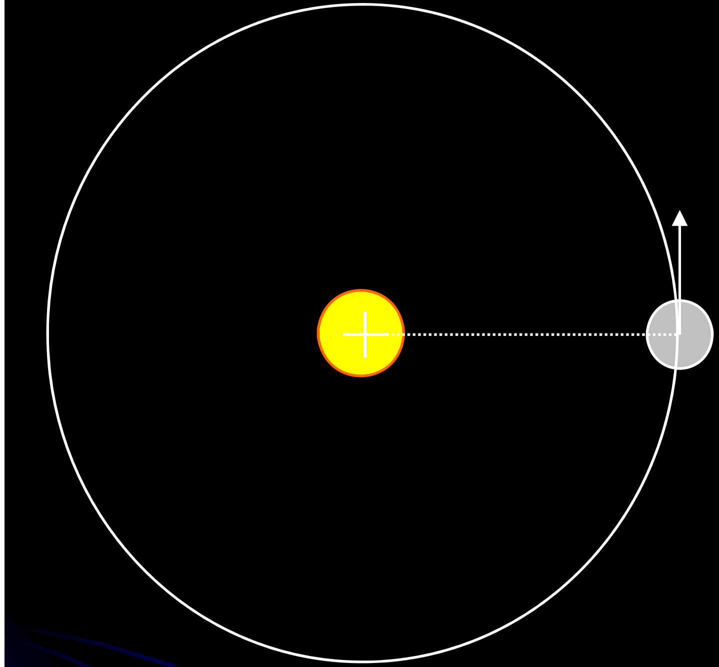


NASA, ESA, and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope WFPC2 • STScI-PRC01-12



clouds are *mostly* hydrogen and helium

Conservation of Angular Momentum



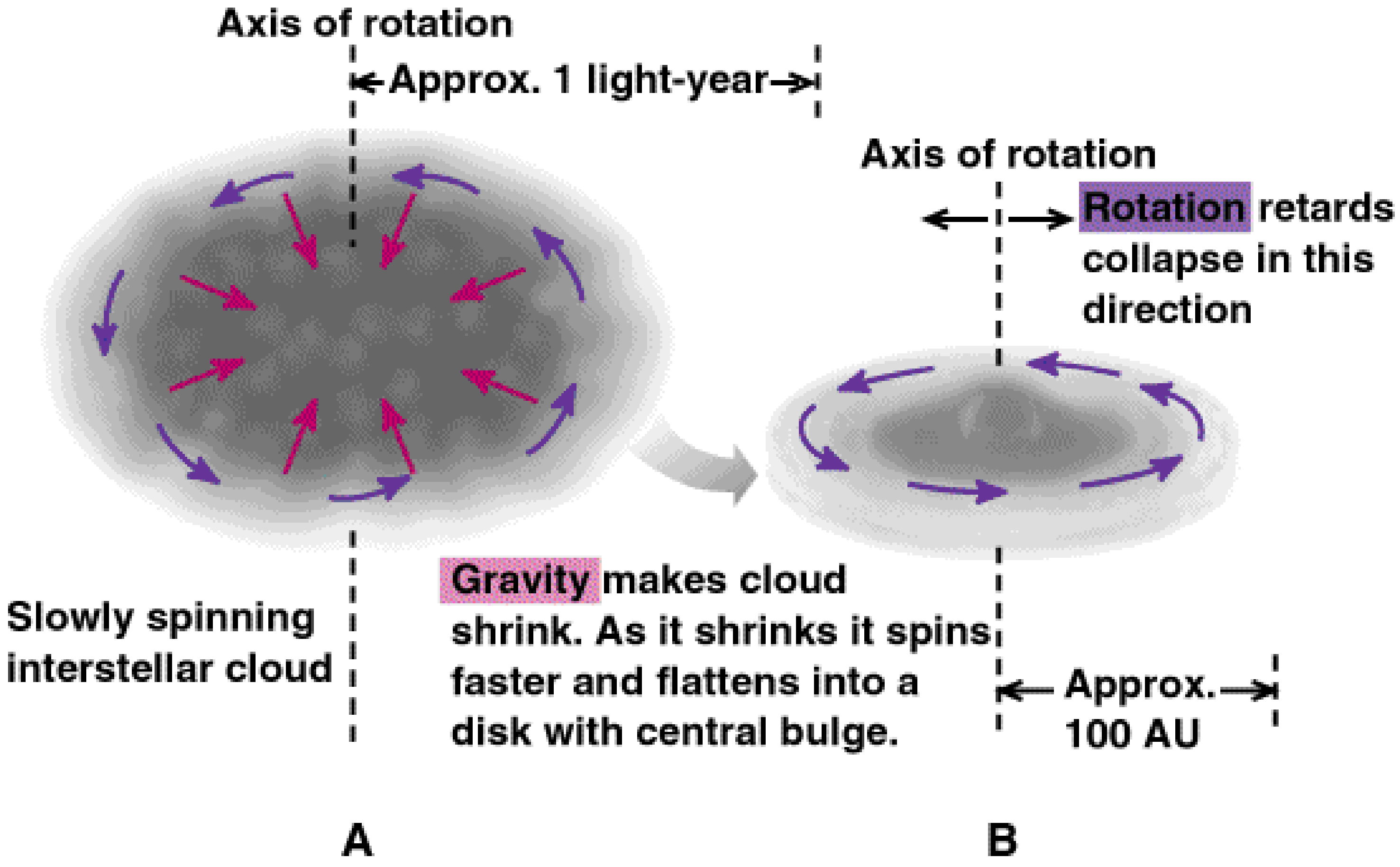
Angular momentum depends on:

- **mass of object**
- **speed**
- **distance from center**

$$\boxed{l = mvr}$$

Rotating objects have "momentum" that they keep

Collapse and Flattening of an Interstellar Cloud to Form Solar Nebula



Slowly spinning interstellar cloud

Rotation retards collapse in this direction

Gravity makes cloud shrink. As it shrinks it spins faster and flattens into a disk with central bulge.

Collapse of the Solar Nebula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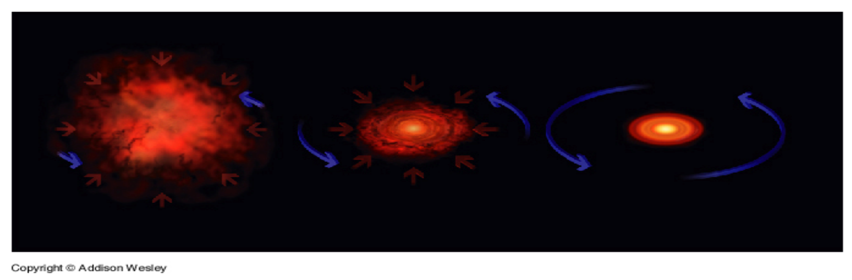
Gravitational Collapse →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Denser region in a interstellar cloud, maybe caused by the shock wave from a exploding supernova, triggers the gravitational collapse.

1. **Heating** ⇒ Prototsun ⇒ Sun
   In-falling materials loses gravitational potential energy, which were converted into kinetic energy. The materials collides with each other, causing the gas to heat up. Once the temperature gets high enough for nuclear fusion to start, a star is born.
2. **Spinning** ⇒ Smoothing of the random motions
   Conservation of angular momentum causes the in-falling material to spin faster and faster as they get closer to the center of the collapsing cloud.
3. **Flattening** ⇒ Protoplanetary disk
   The solar nebular flattened into a flat disk. Collision between clumps of material turns the random, chaotic motion into a orderly rotating disk.

This process can explains the orderly motion of most of the solar system objects!

Angular Momentum problem

The Angular Momentum Problem

As it collapsed, the nebula had to conserve its angular momentum

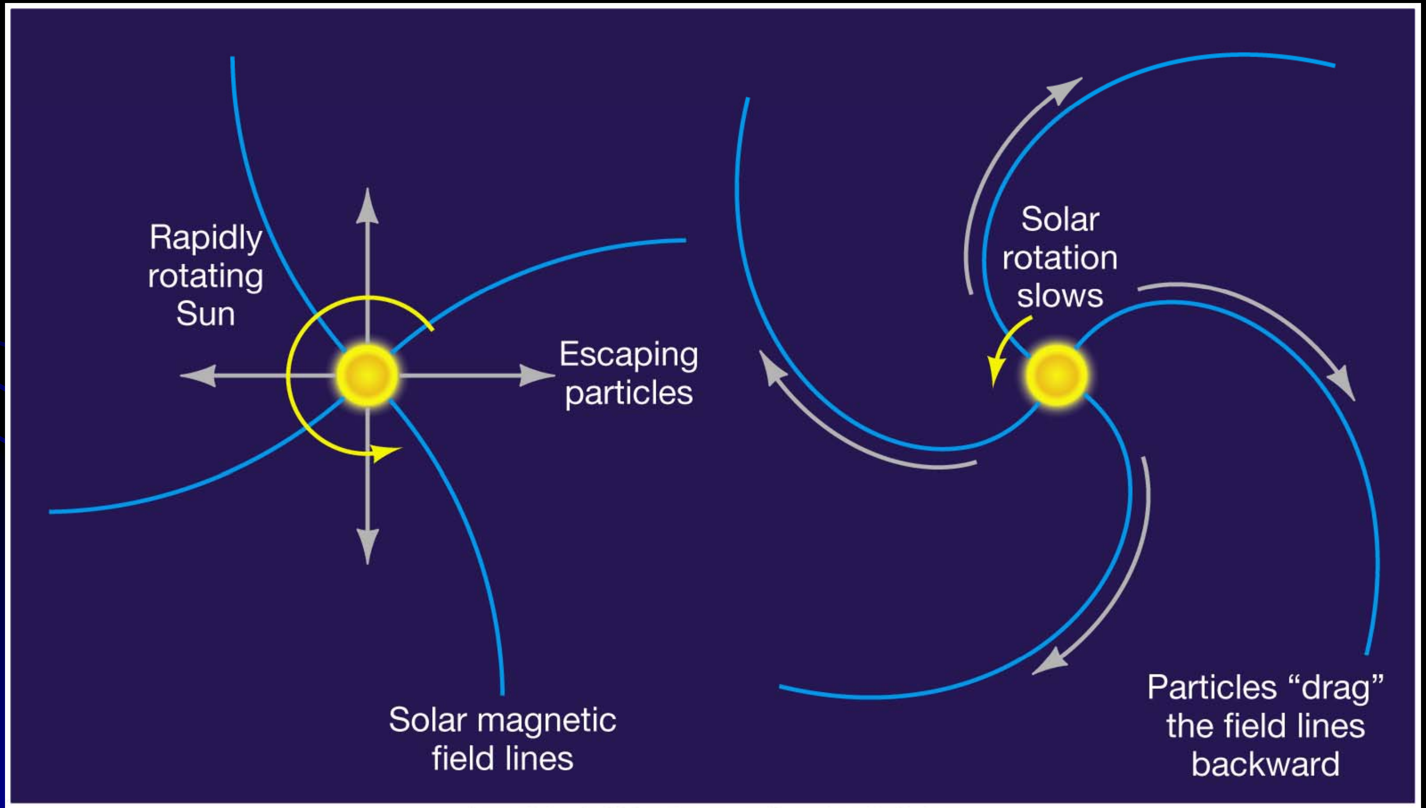
However, at the present day, the Sun has almost none of the solar system’s angular momentum

- **Jupiter alone accounts for 60%**
- **Four jovian planets account for more than 99%**

Angular Momentum problem

The Angular Momentum Problem

Theory: The Sun transferred most of its angular momentum to outer planets through friction



Three stages in the Planet formation

1) Condensation nuclei formed the first clumps of matter

2) Accretion Grow by sticking and collisions with other clumps

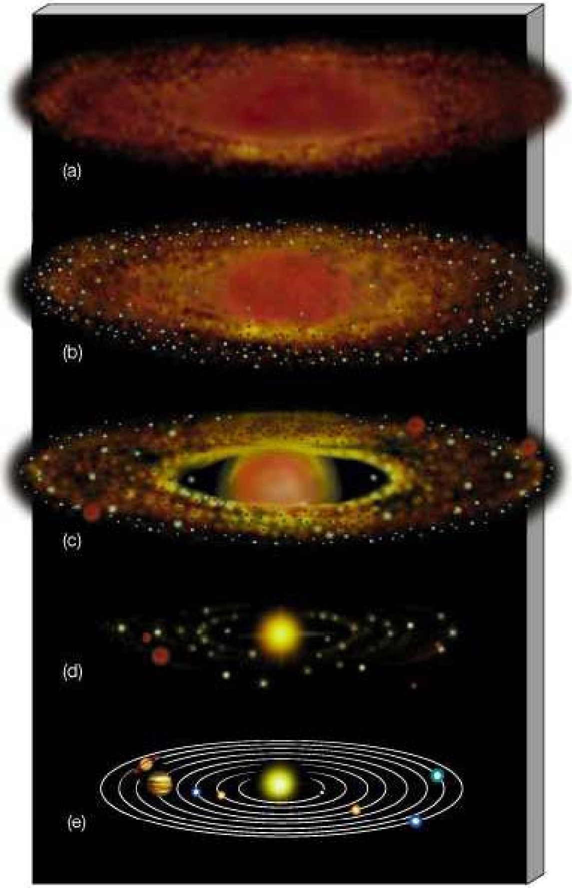
⇒ Surface area increase, increasing rate increase exponentially.

3) Formation of planetesimals with a strong gravitation field which becomes dominant

Number of bodies decreased, orbits become more circular and spaced

Collisions lead to fragmentation

⇒ fragments collides with protoplanets (craterization) or are swept away from the Solar system.

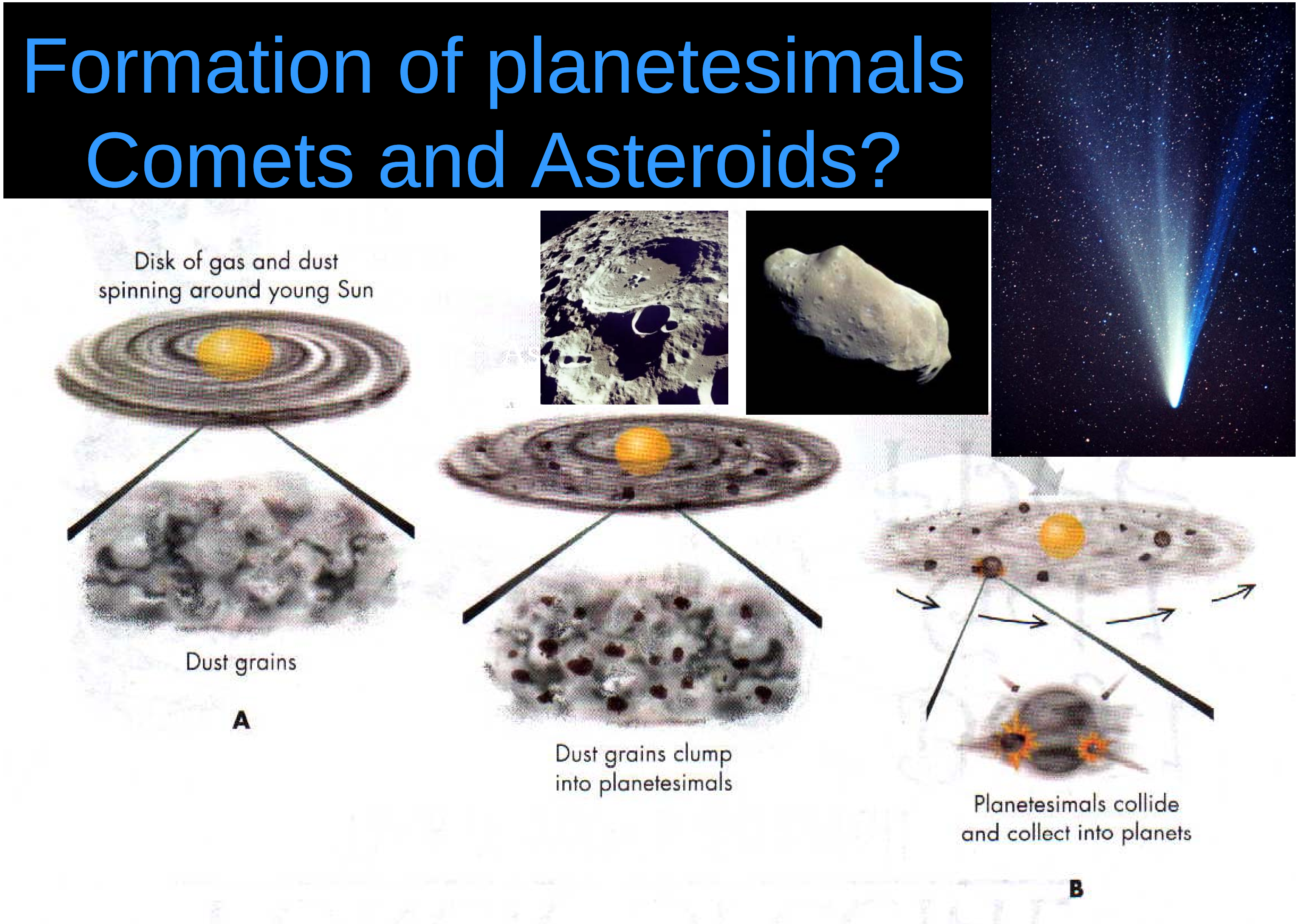


Dust grains act as condensation nuclei

Gas expelled by strong solar wind. Accretion creates planetesimals

Gravitational interaction between planetesimals

Formation of planetesimals
Comets and Asteroids?



Condensation of the Solar Nebula

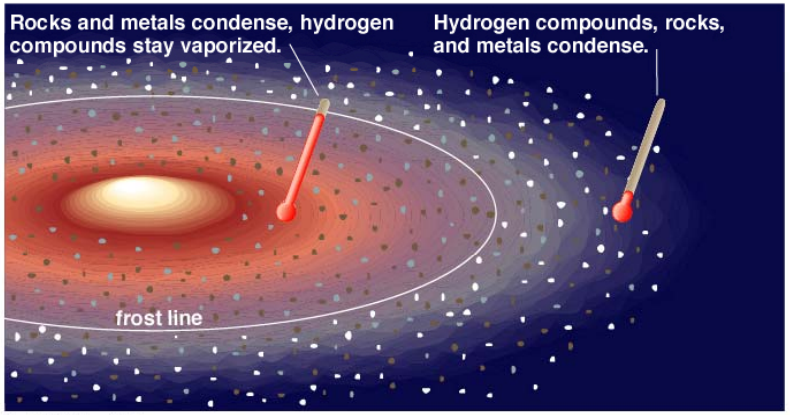
Composition of the Solar Nebula

As the protoplanetary disk cools, materials in the disk condensate into planetesimals

- Local thermal environment (Temperature) determines what kind of material condensates.
- The solar nebular contains 98% Hydrogen and Helium, 2% everything else (fusion products).
- Frost line lies between the orbit of Mars and Jupiter.

Condensation Temperatures =>

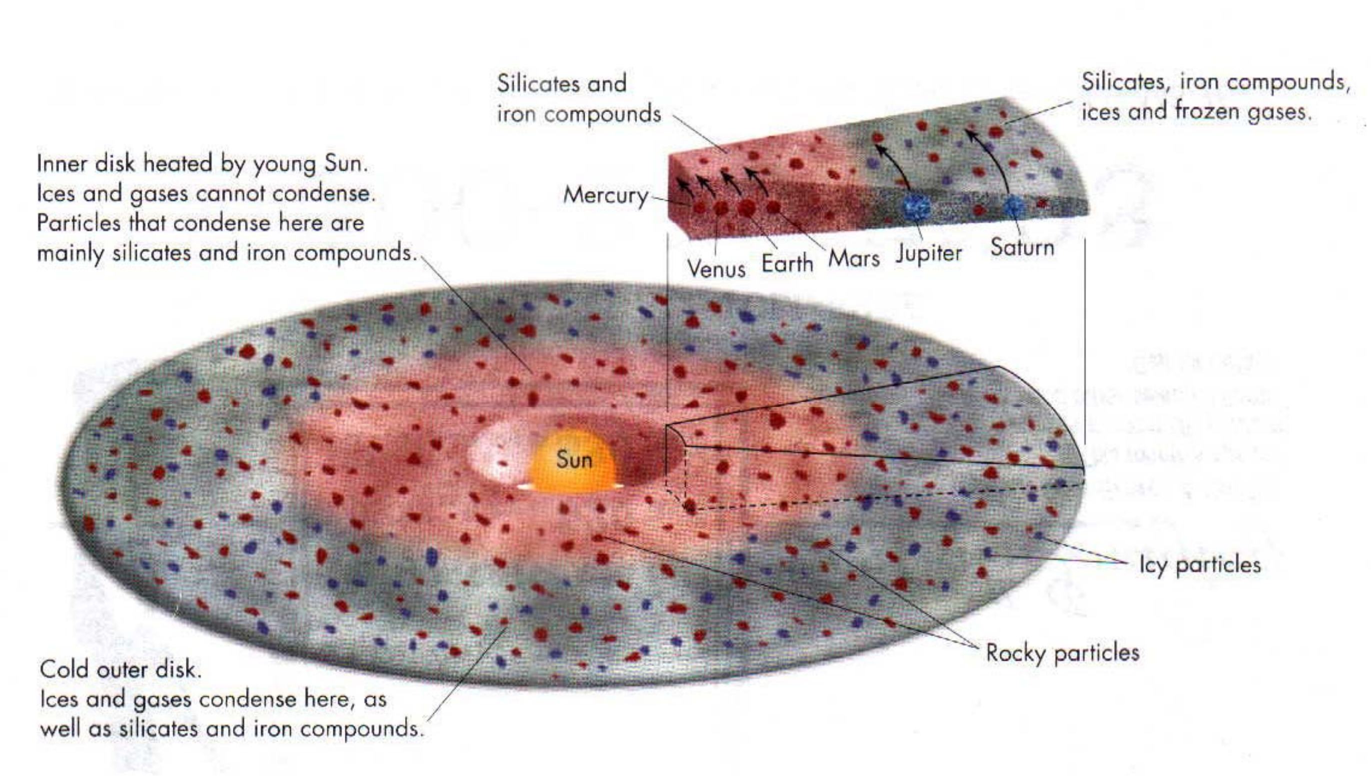
Temp (K)	Elements	Condensate
>2000 K	all are gaseous	
1600 K	Al, Ti, Ca	Mineral oxides
1400 K	Iron & Nickel	Metal Grains
1300 K	Silicon	Silicate grains
300 K	Carbon	Carbonaceous Grains
300-100 K	H, N	Ices (H_2O, CO_2, NH_3, CH_4)



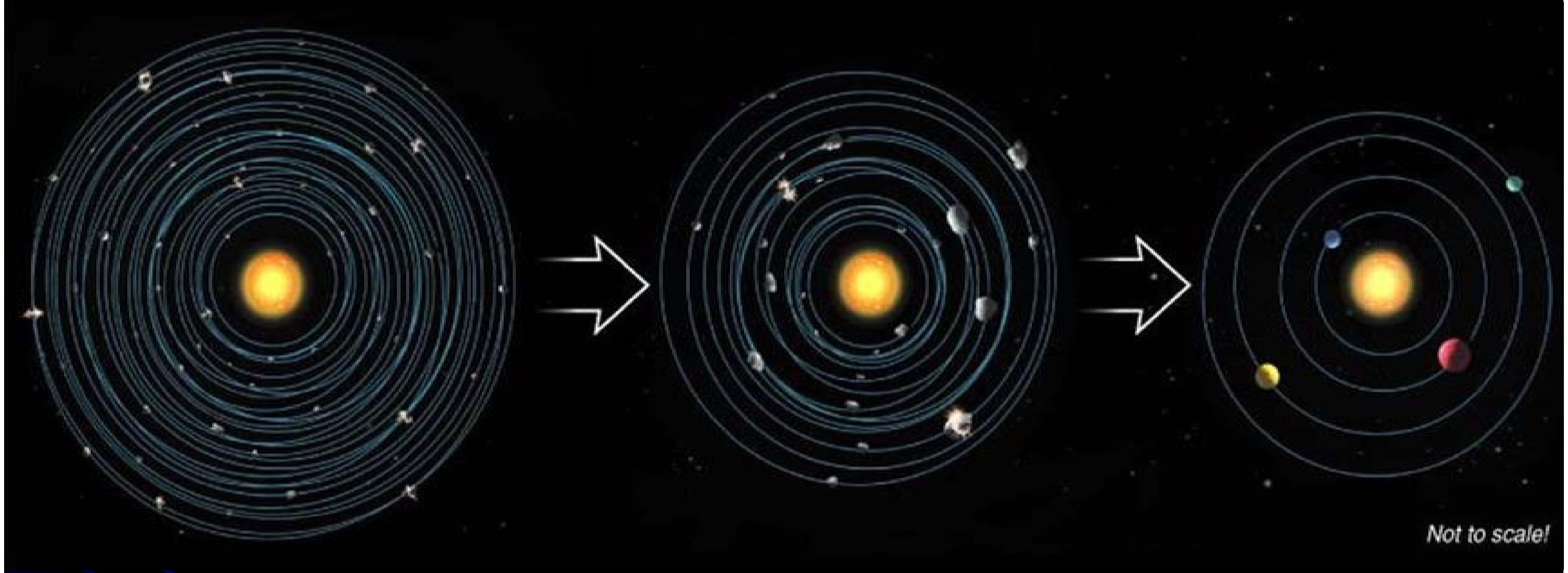
Differentiation in the proto-disk

The composition of the disk around the Sun depends on distance from it, through temperature (can you have ice or not). After H and He, C- N- O are the most common chemical compounds

Formation of Icy and Rocky Planetesimals

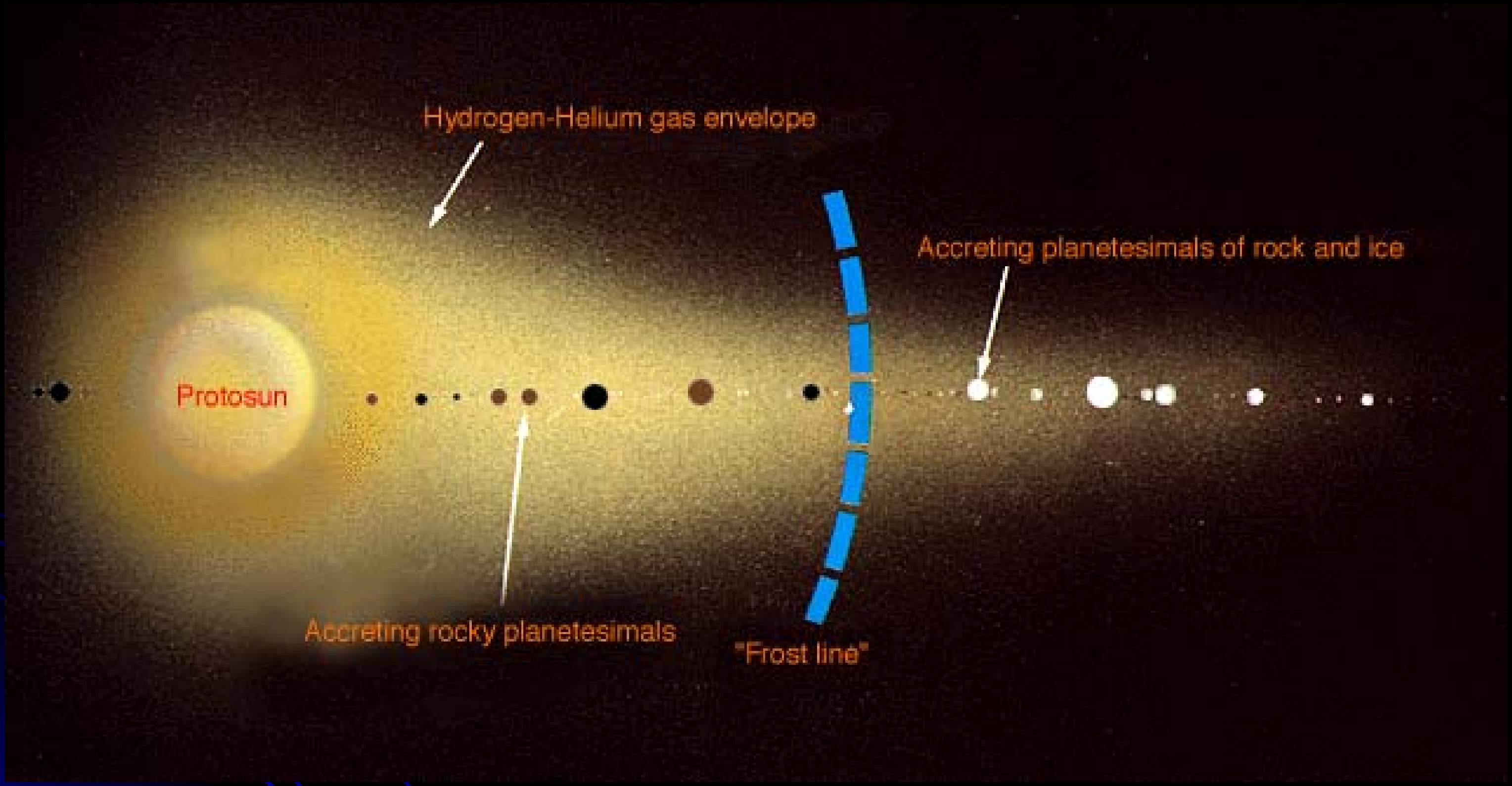


Accretion



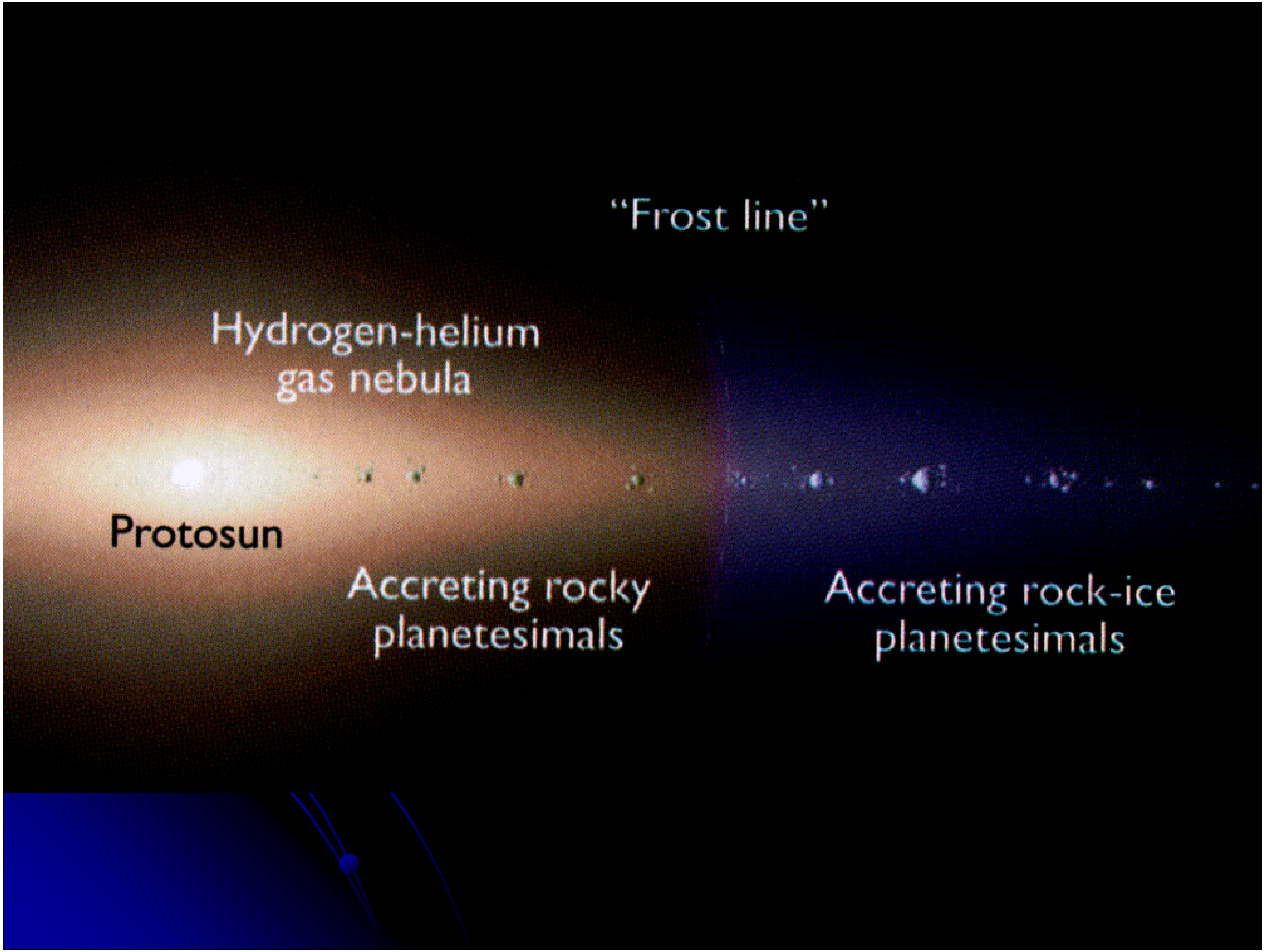
- **many small objects collected into just a few large ones**
- **collisions become less frequent**

Segregation of Inner and Outer Solar System



The “Frost Line”

- Rock & Metals form anywhere the gas cooler than 1300 K.
- Carbon grains & ices only form when the gas is cooler than 300 K.
- Inner Solar System:
  - Too hot for ices & carbon grains.
- Outer Solar System:
  - Carbon grains & ices form beyond the “frost line”.


"Frost line"
Hydrogen-helium gas nebula
Protosun
Accreting rocky planetesimals
Accreting rock-ice planetesimals

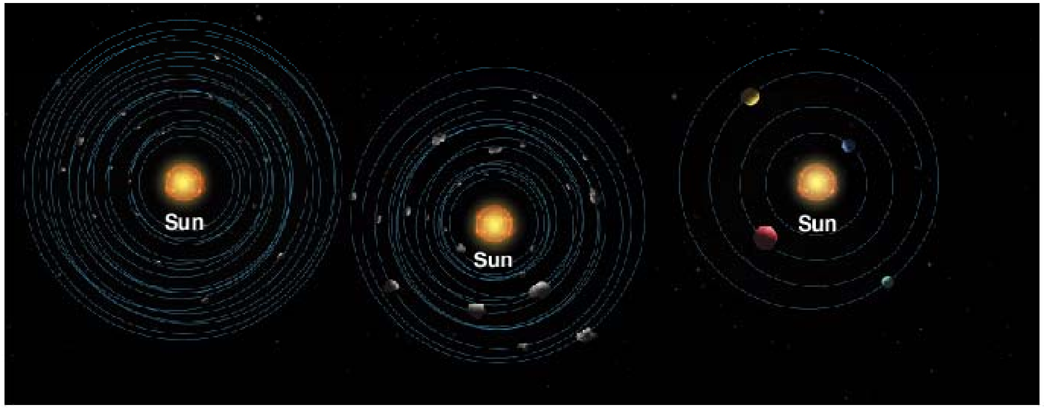
From Grains to Planetesimals

- Grains that have low-velocity collisions can stick together, forming bigger grains.
  - Beyond the “frost line”, get additional growth by condensing ices onto the grains.
- Grow until their mutual gravitation assists in aggregation, accelerating the growth rate:
  - Form km-sized *planetesimals* after few 1000 years of initial growth.

Inner Solar System :**Formation of the Terrestrial Planets (Accretion)**

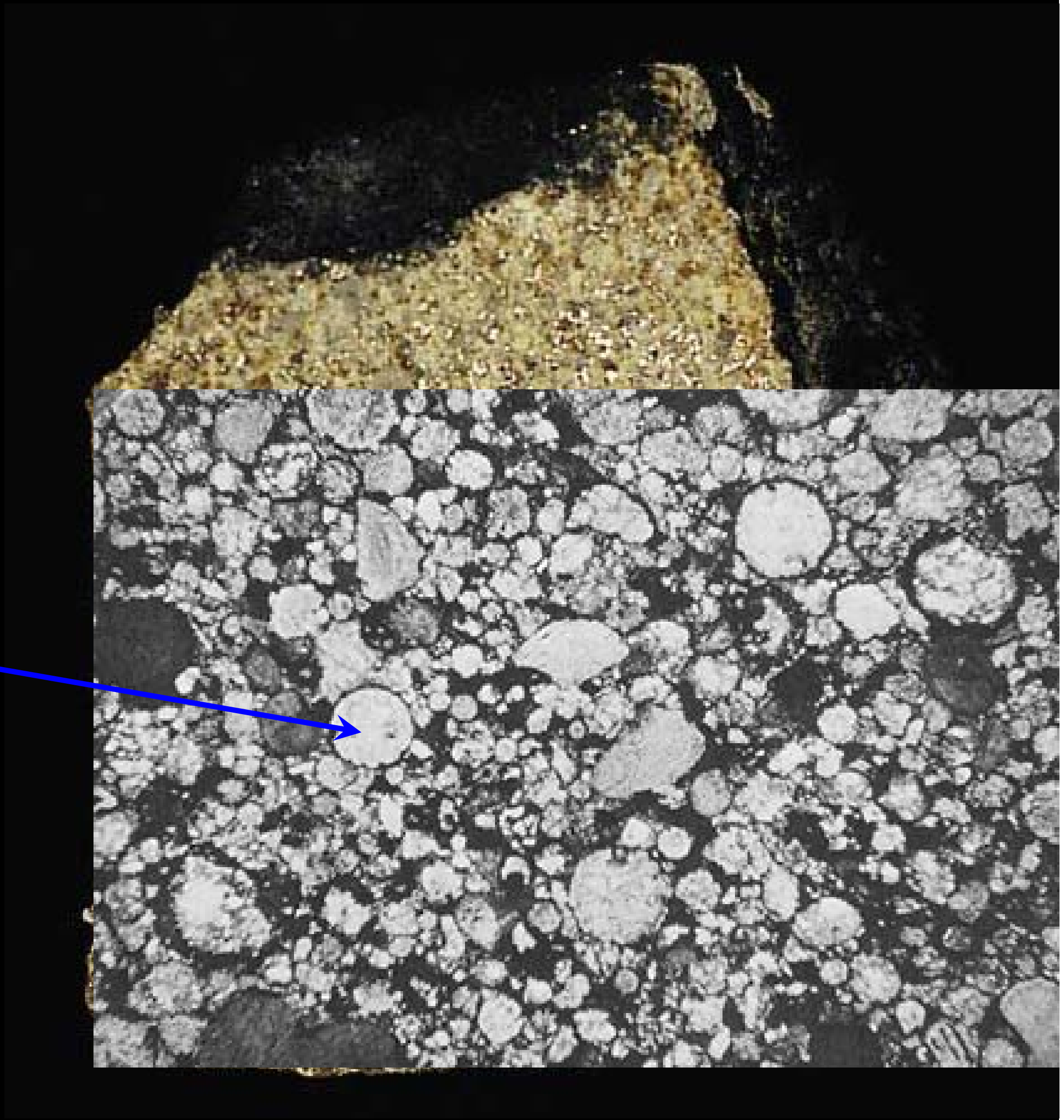
Accretion the process by which small 'seeds' grew into planets.

- Near the Sun, where temperature is high, only metals and rocks can condense. The small pieces of metals and rocks (the *planetesimals*) collide and stick together to form larger piece of planetesimals.
- Small pieces of planetesimals can have any kind of shape.
- Larger pieces of planetesimals are spherical due to gravity.
- Only small planets can be formed due to limited supply of material (~0.6% of the total materials in the solar nebula).
- Gravity of the small terrestrial planets is too weak to capture large amount of gas.
- The gas near the Sun were blown away by *solar wind*.



Condensation

Inner solar system:



★ rocky, metallic dust condensed together into small objects

mete

Condensation

ASTEROID:

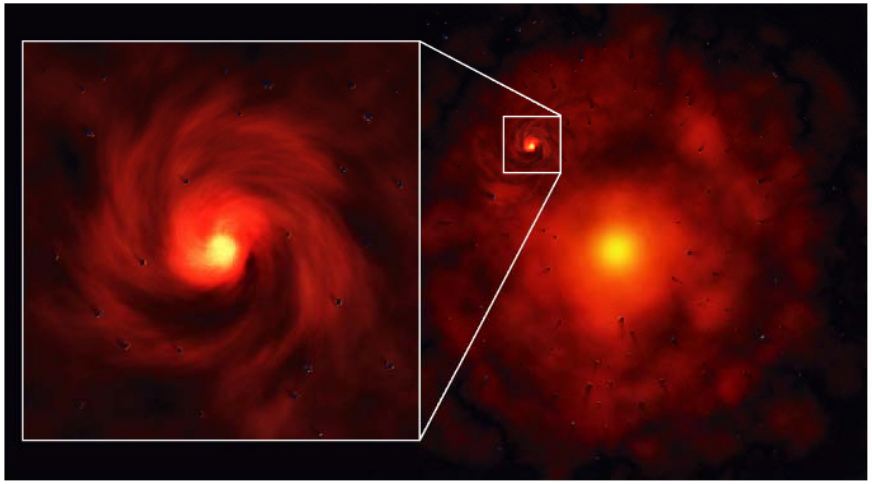
Inner solar system:

- **high temperatures**
- **only dust can condense**

★ Rocky and metallic dust particles are raw material for terrestrial planets

Outer Solar System: **Formation of the Jovian Planets (Nebula Capture)**

- In the regions beyond the frost line, there are abundant supply of solid materials (ice), which quickly grow in size by accretion.
- The large planetesimals attract materials around them gravitationally, forming the jovian planets in a process similar to the gravitational collapse of the solar nebula (heating, spinning, flattening) to form a small accretion disk.
- Abundant supply of gases allows for the creation of large planets.
- *However, the jovian planets were not massive enough to trigger nuclear fusion at their core.*

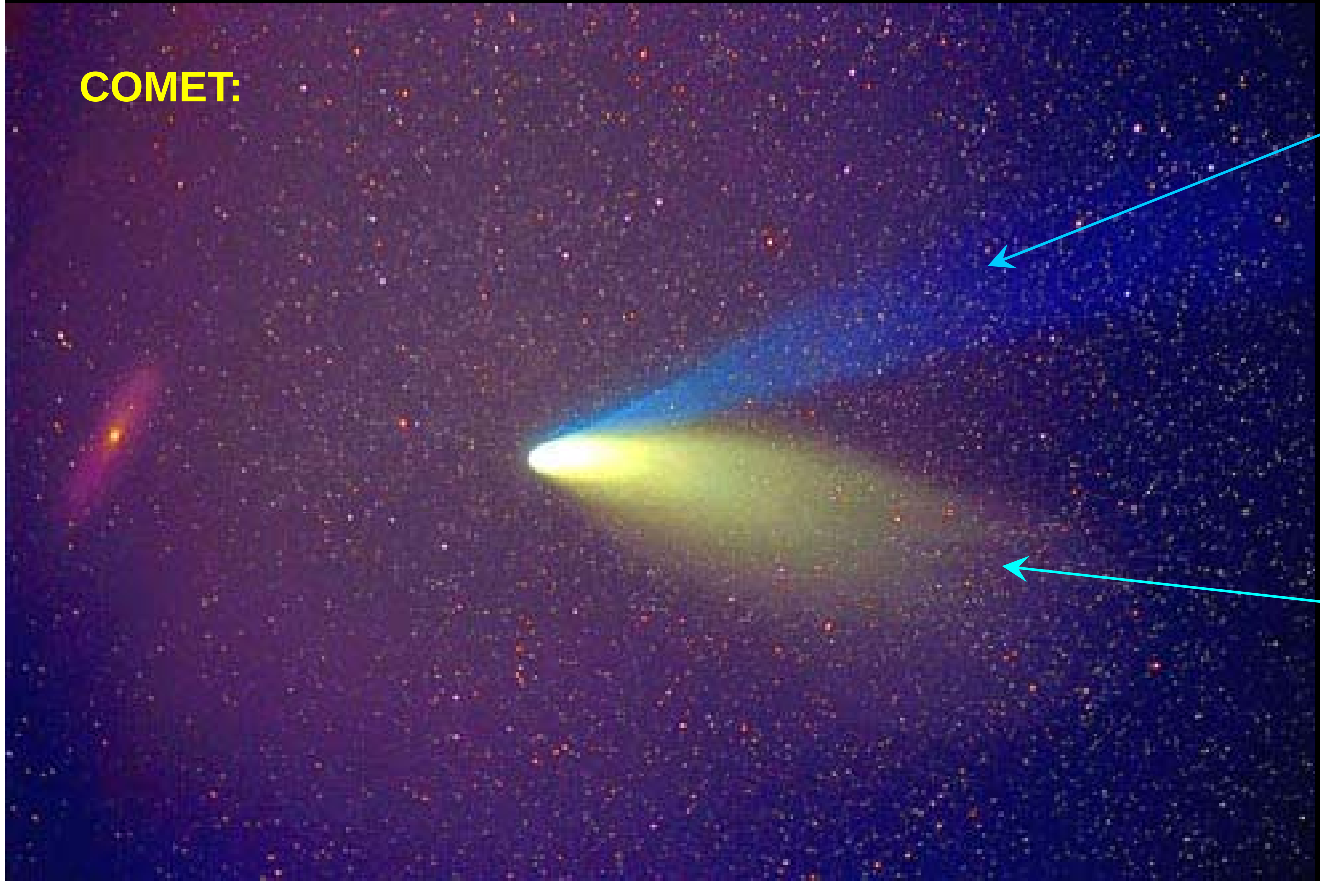


Condensation

<u>Outer solar system</u>:

- **low temperatures**
- **dust *<u>and</u>* ices can condense**

★jovian planets became larger than terrestrial planets because <u>more raw materials were available</u>



ion tail (from ices)

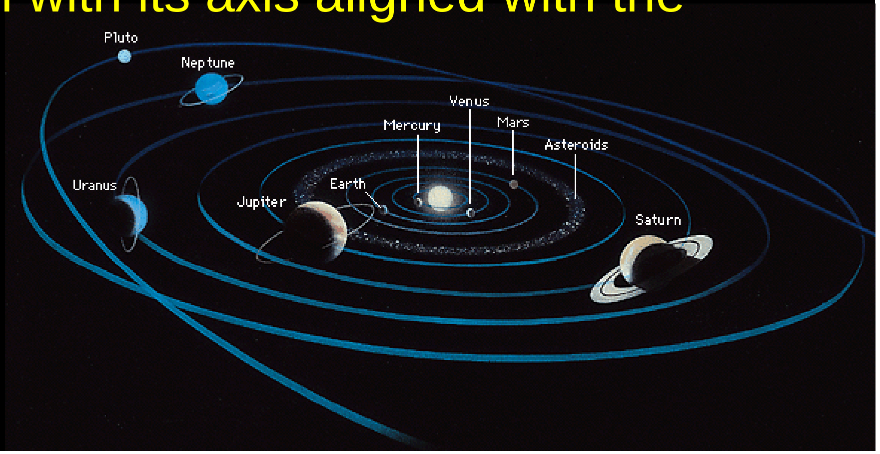
dust tail

End of Planetary System Formation

- The proto-planetary system assembly process took about 100 Million years.
- Followed by ~1 Billion years of heavy bombardment of the planets by the remaining rocky & icy pieces.
- Sunlight dispersed the remaining gas in the Solar Nebula gas into the interstellar medium.

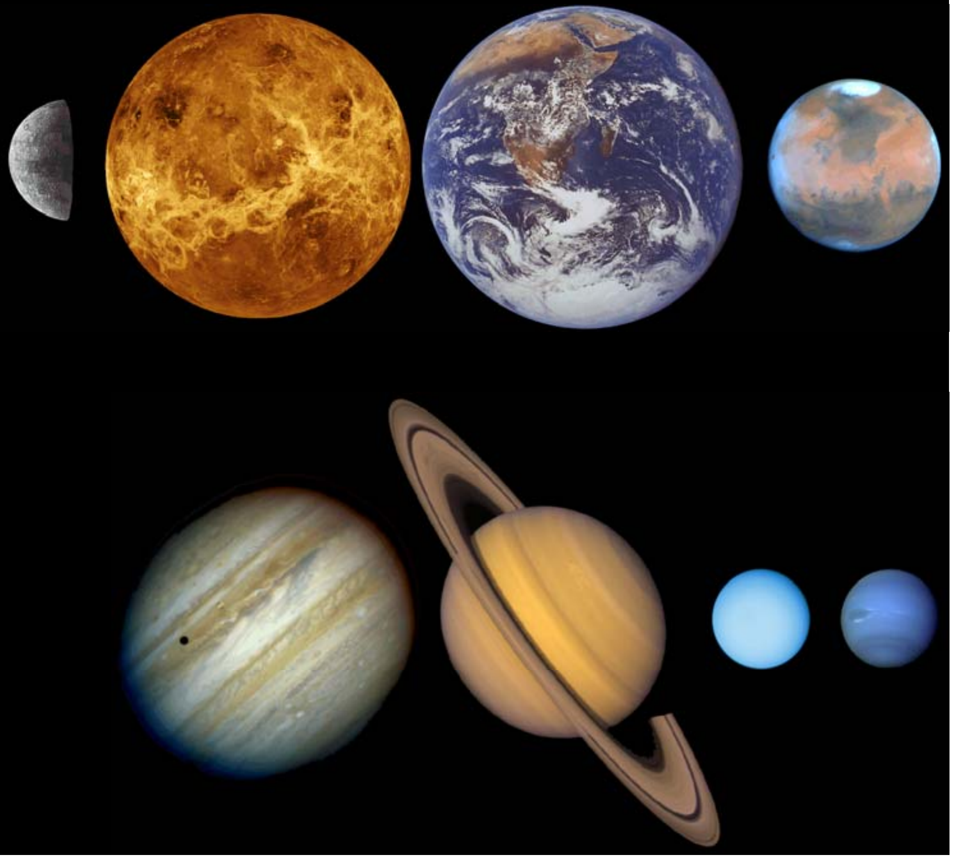
Planetary motions reflect the history of their formation.

- Planets formed from a thin rotating gas disk:
  - The disk’s rotation was imprinted on the orbits of the planets.
  - Planets share the same sense of rotation, but were perturbed from perfect alignment by strong collisions during formation.
- The Sun “remembers” this original rotation:
  - Rotates in the same direction with its axis aligned with the plane of the Solar System.



Planetary compositions reflect the different environments of formation.

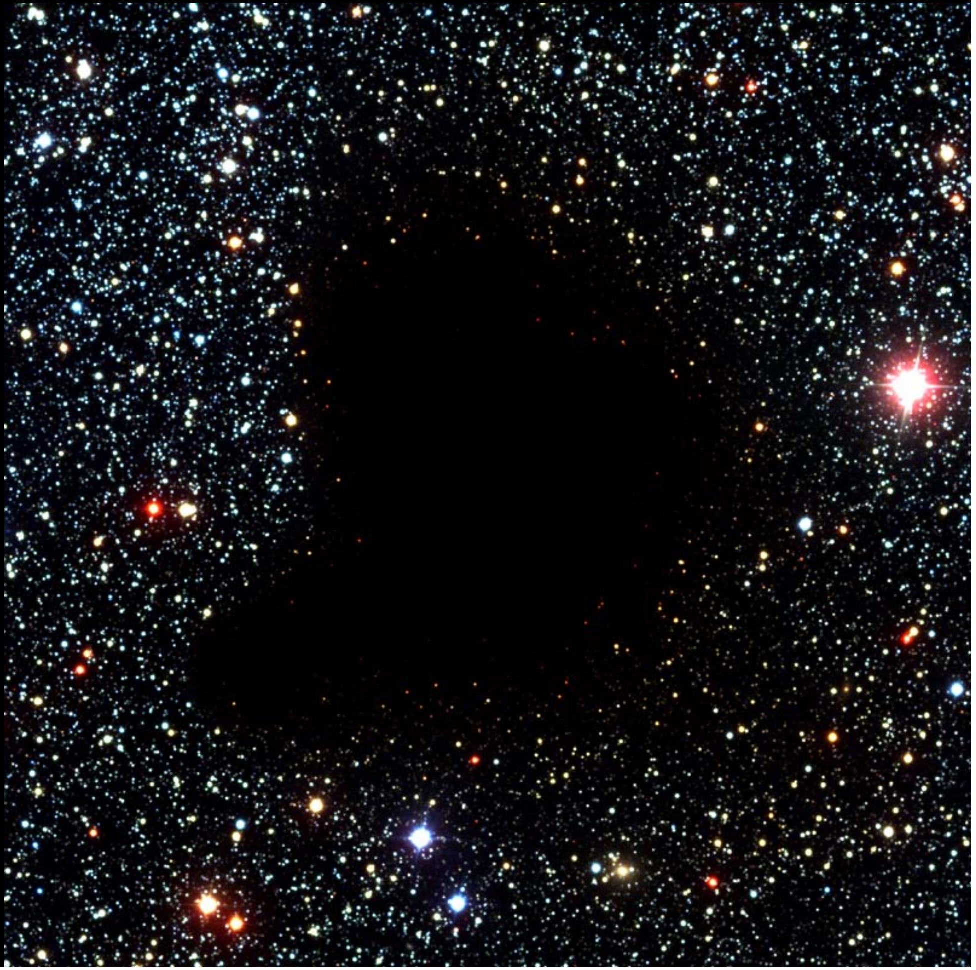
- Terrestrial planets are rock & metal:
  - Formed in the hot inner Solar Nebula.
  - Too hot to capture and retain Hydrogen & Helium.
- Jovian planets contain ices, H, & He:
  - Formed in the cool outer Solar Nebula
  - Grew large enough to accrete lots of H & He.



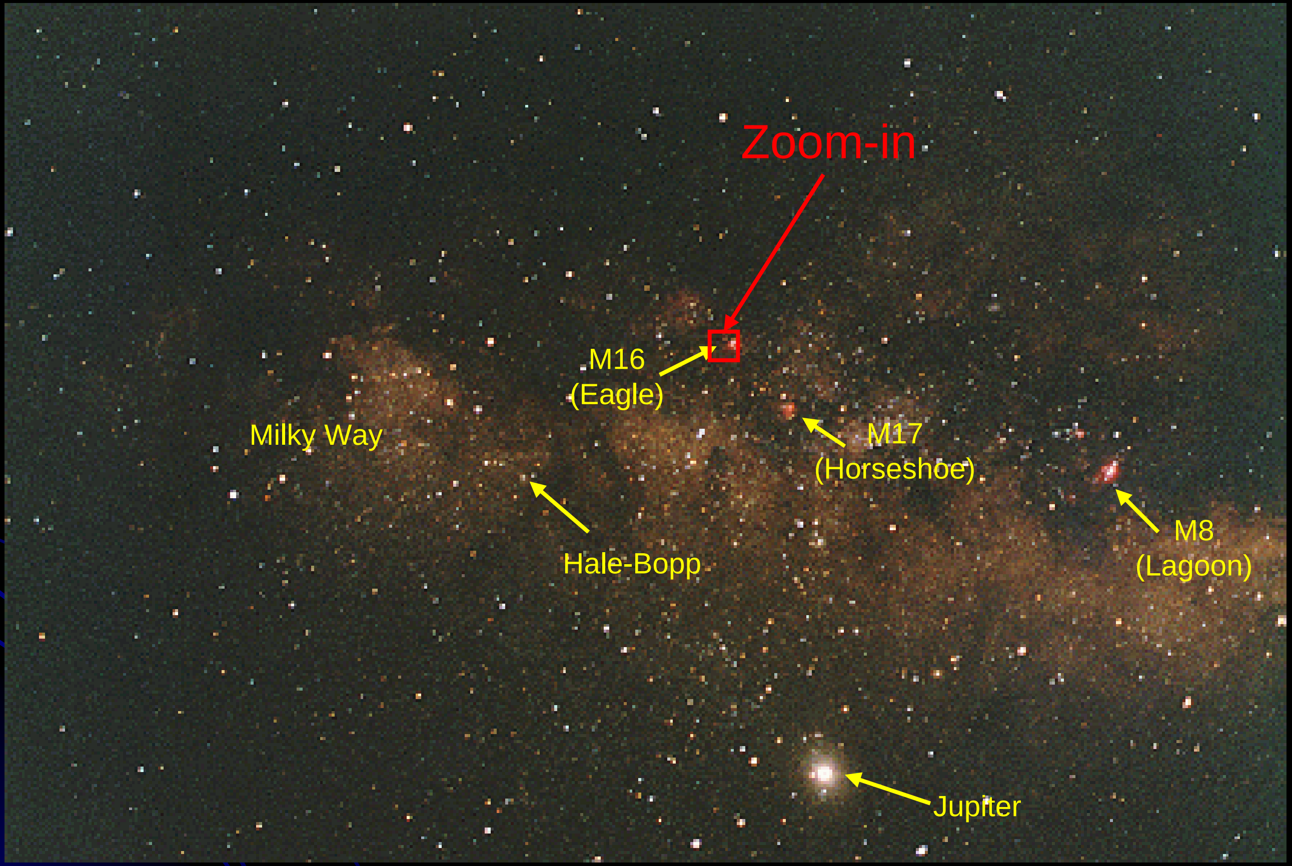
The Formation of the Solar System

Formation of the Solar System - Observation

Cold Interstellar H_2 *Cloud*



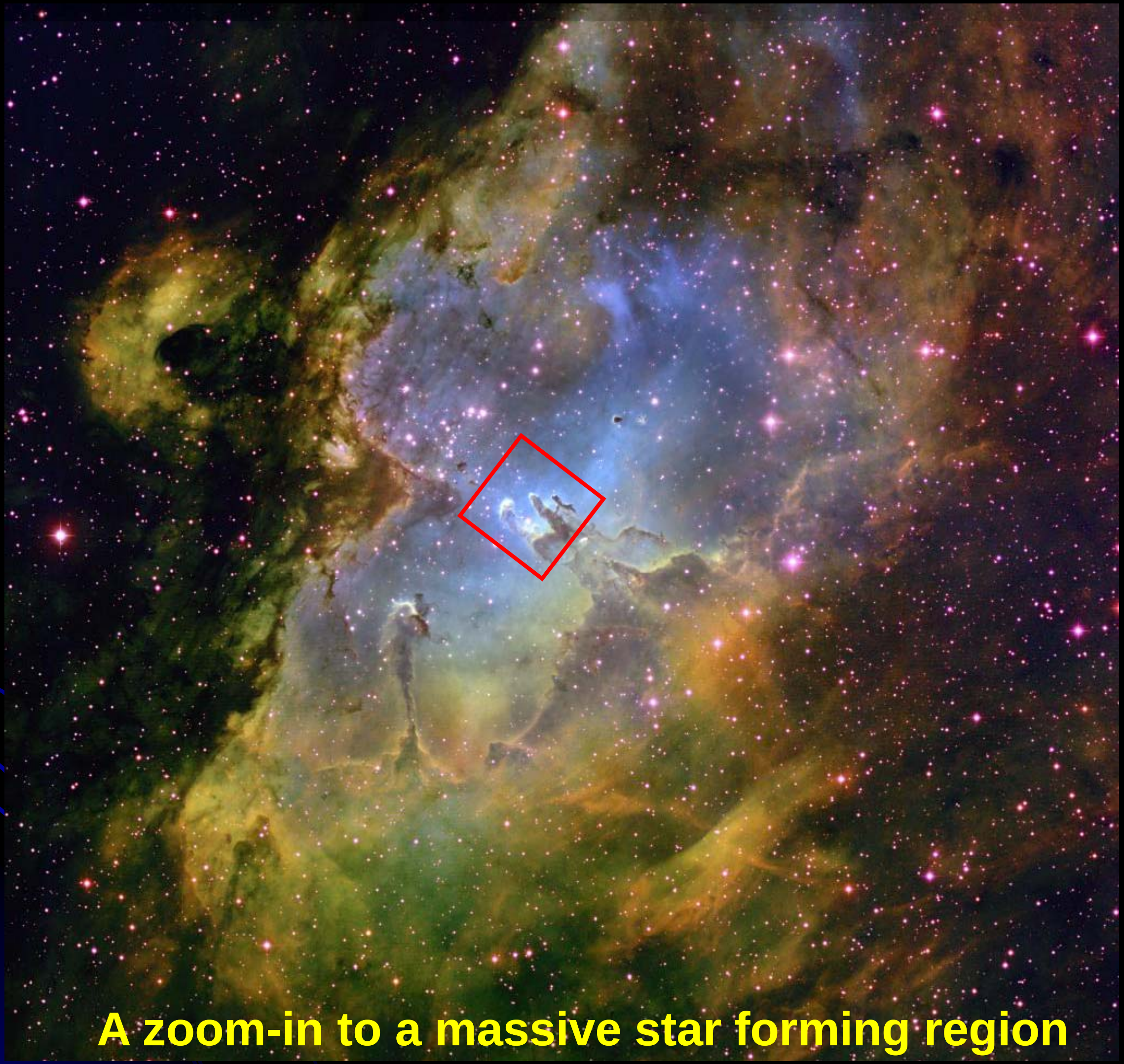
Formation of the Solar System - Observation



A zoom-in to a massive star forming region

Picture credit: W. Keel

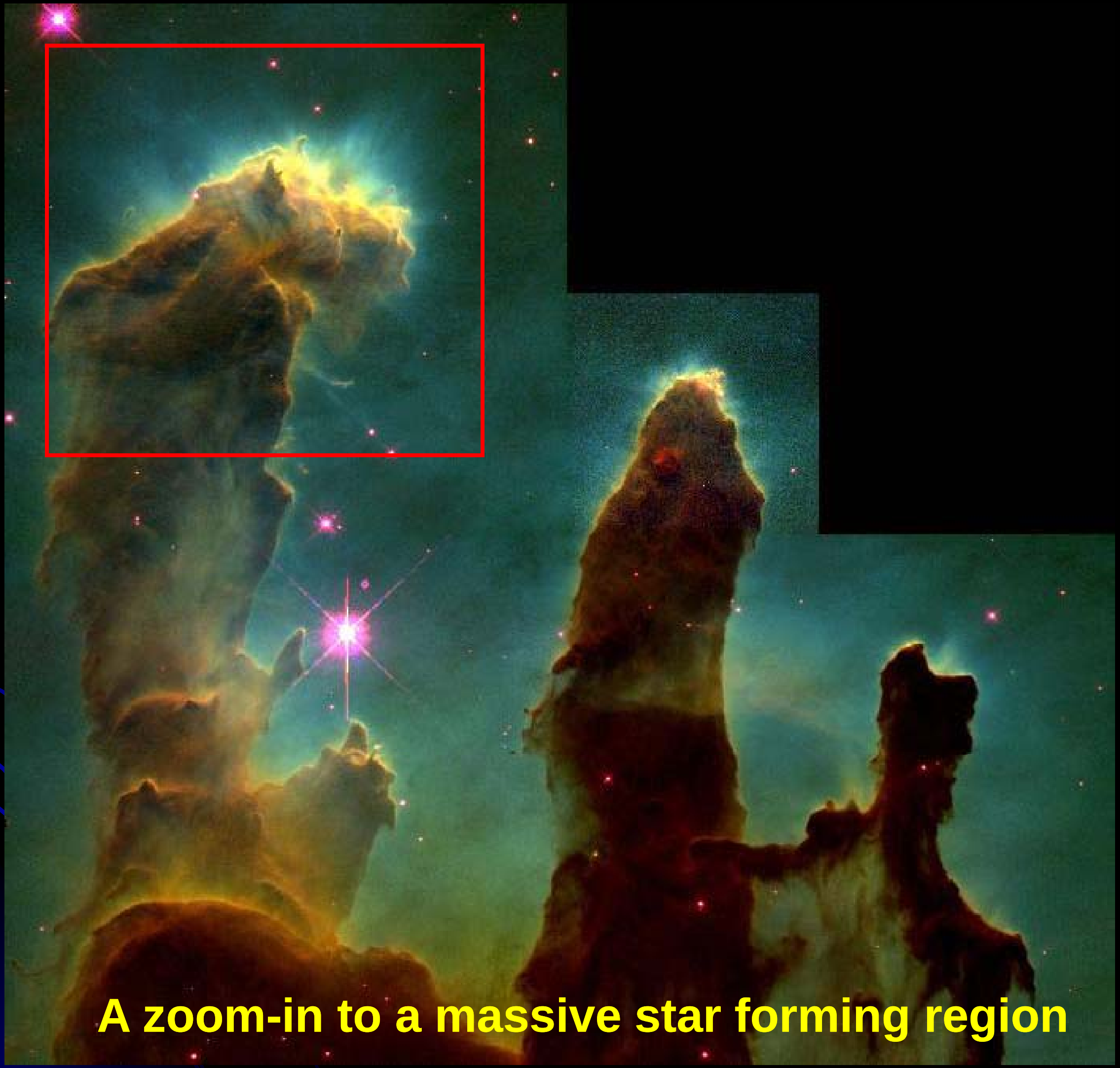
Formation of the Solar System - Observation



Eagle
Nebula
(M16)

Picture credit: T.A. Rector & B.A. Wolpa

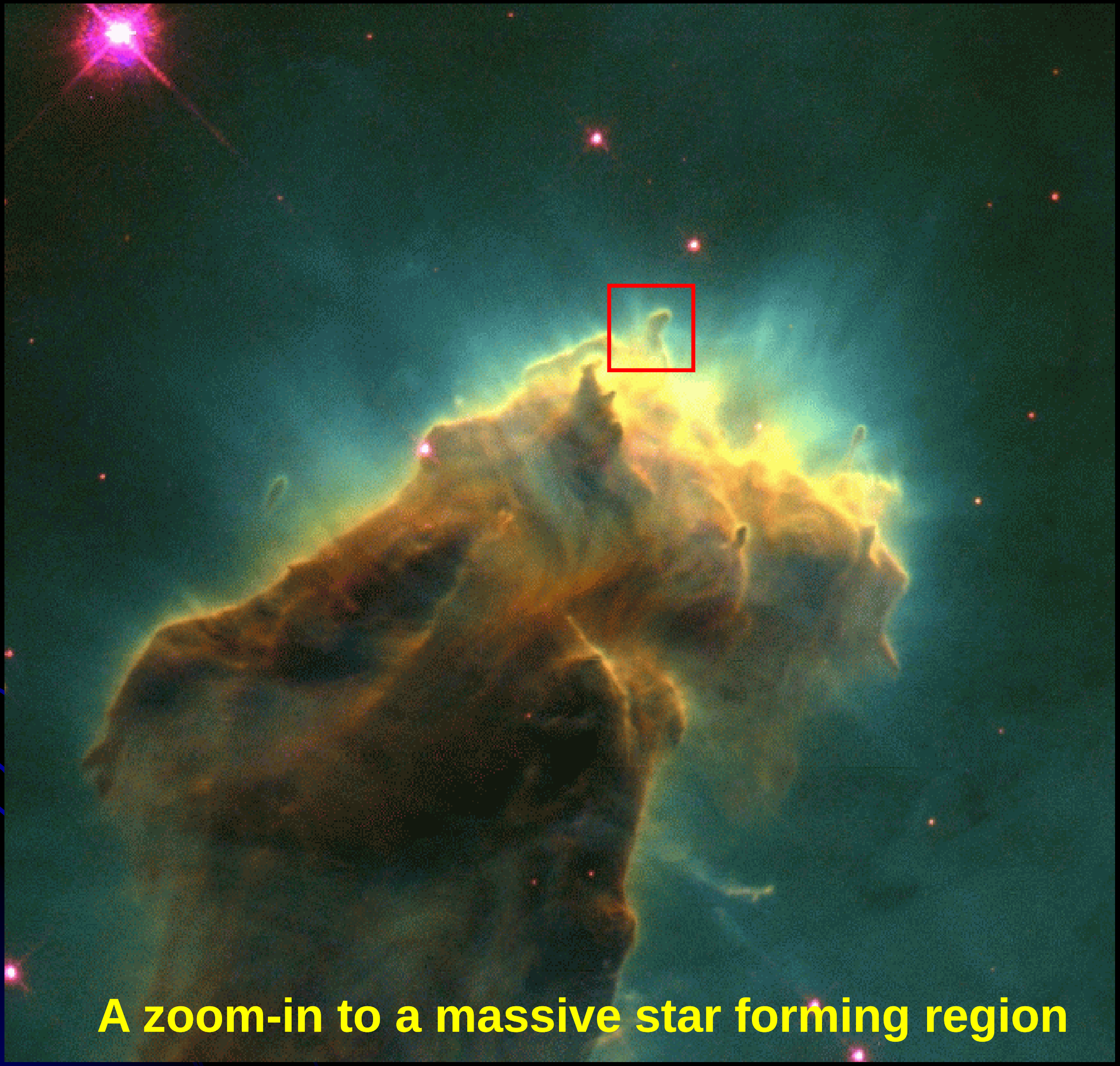
Formation of the Solar System - Observation


A zoom-in to a massive star forming region

Eagle
Nebula
(M16)

Picture Credit: J. Hester & P. Scowen

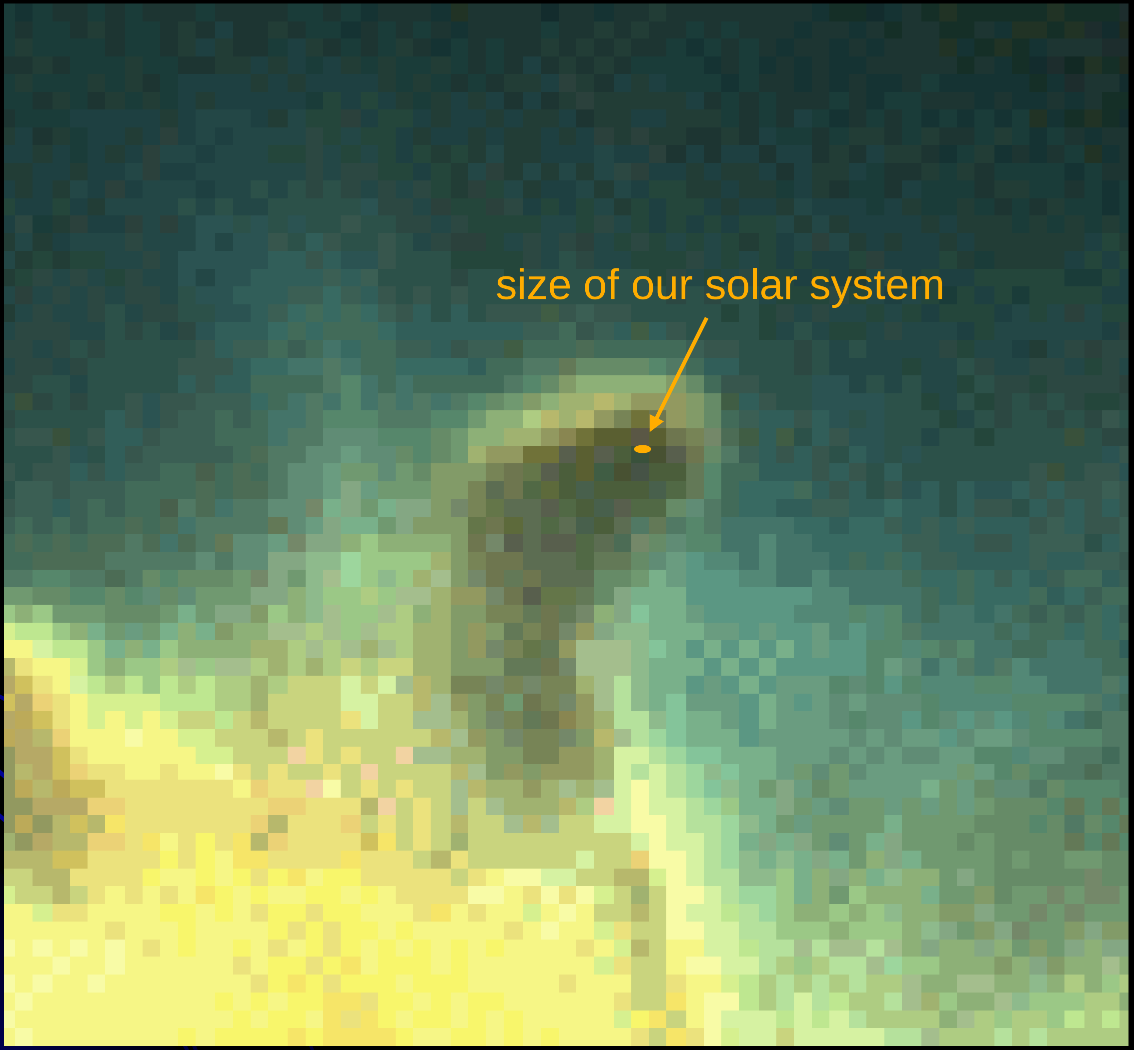
Formation of the Solar System - Observation



Eagle
Nebula
(M16)

Picture Credit: J. Hester & P. Scowen

Formation of the Solar System - Observation



Stellar-
mass
fragment

Eagle
Nebula
(M16)

A zoom-in to a massive star forming region

Picture Credit: J. Hester & P. Scowen

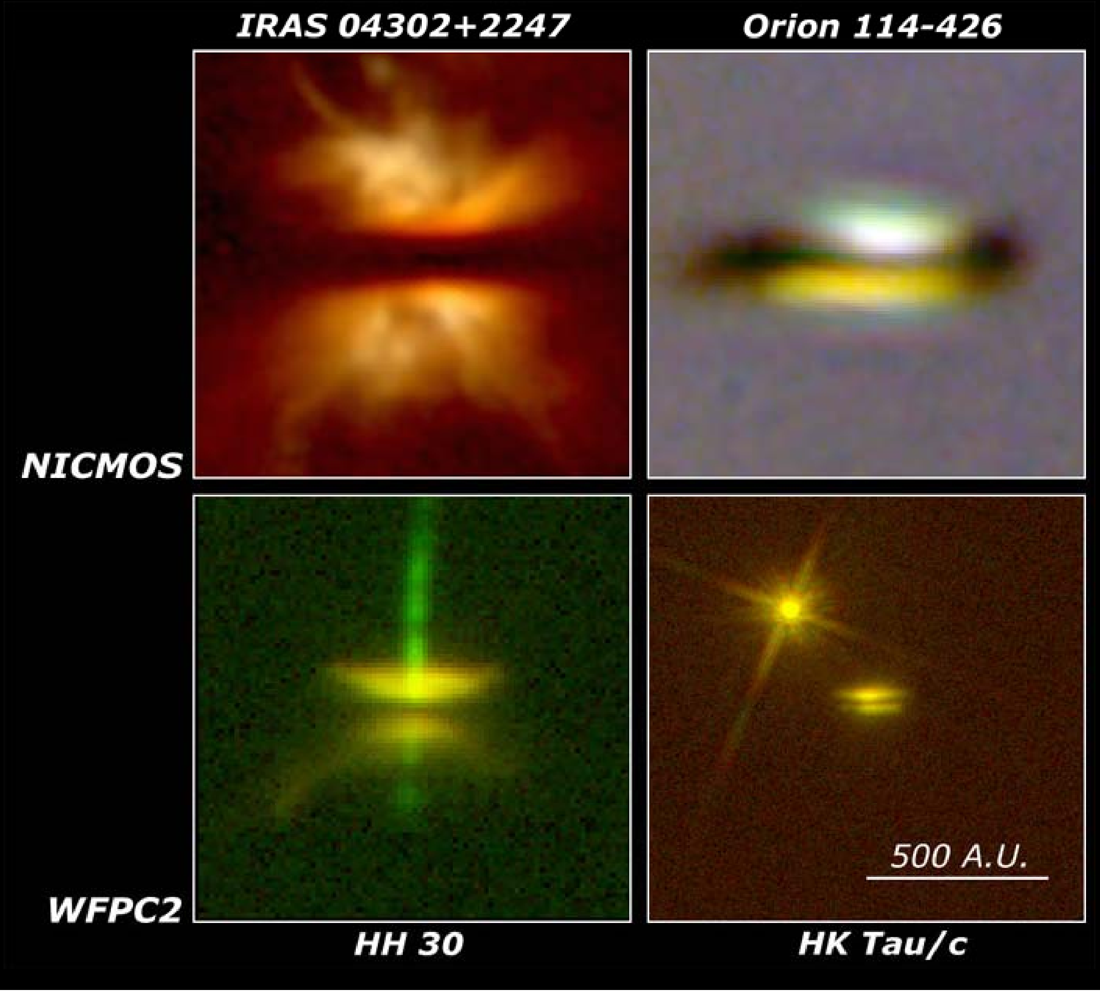
Formation of the Solar System - Observation

Clearing of the remnant birth cloud

Formation of the Solar System - Observation

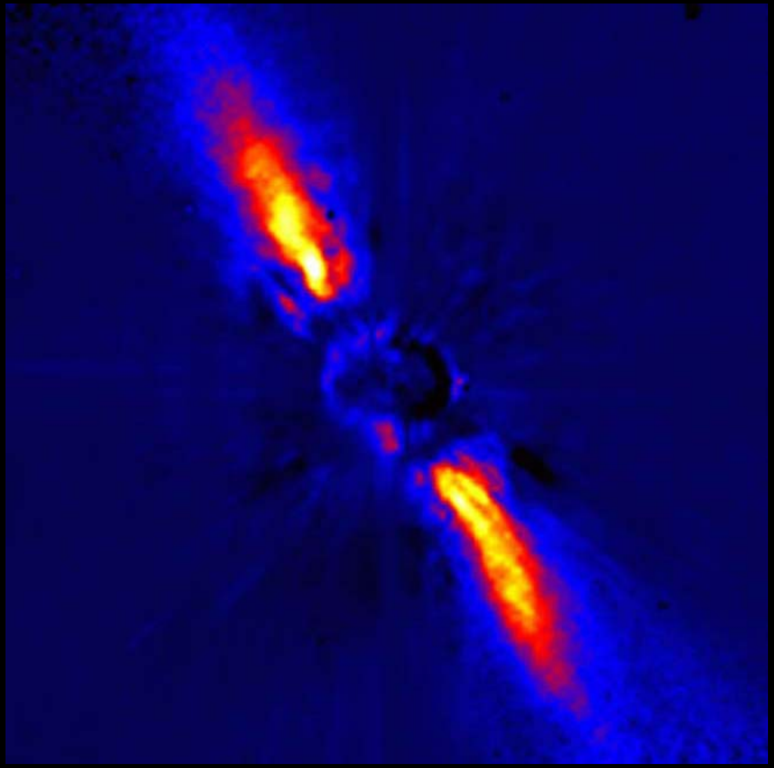
A star+disk appears...

Gas & dust disks observed around young stars

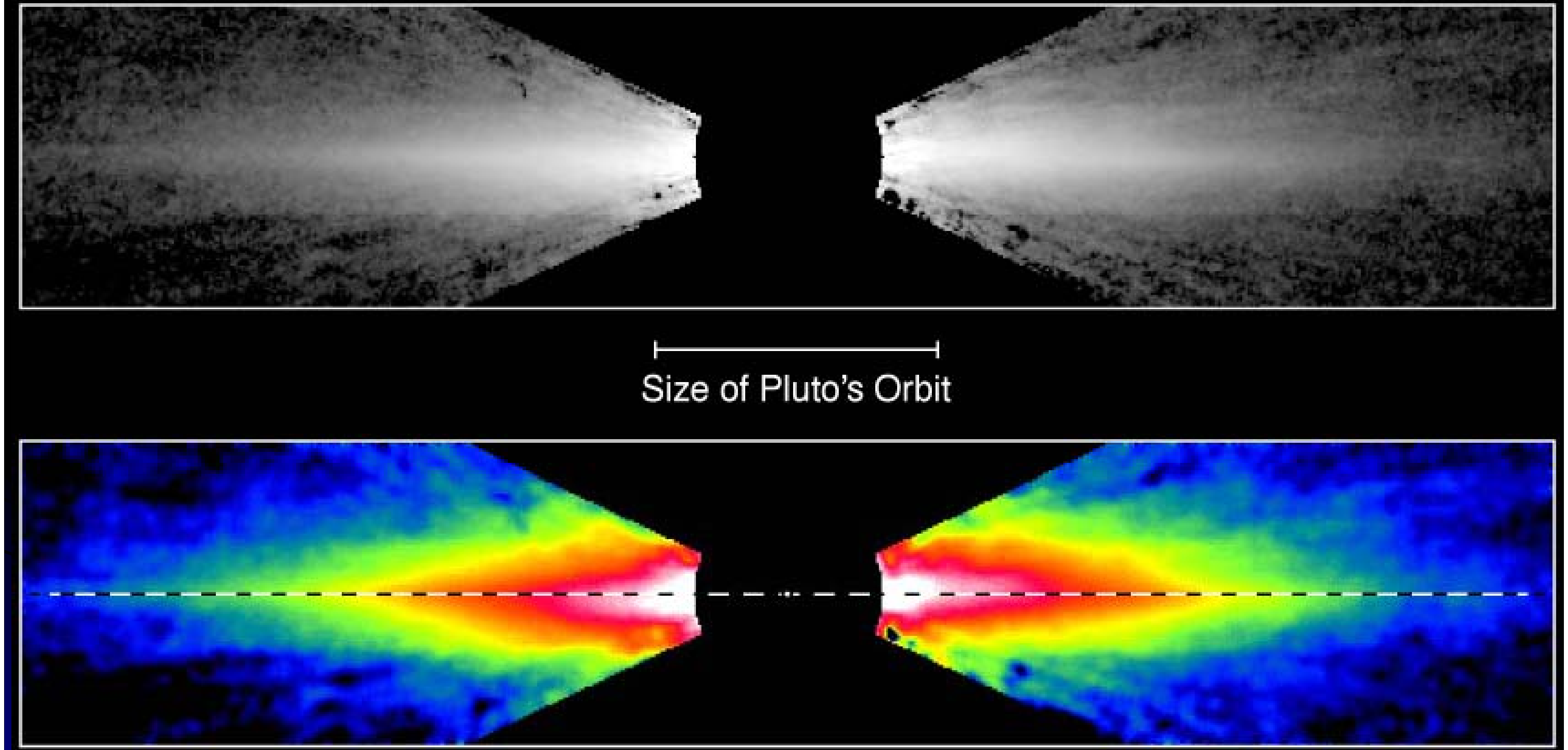


Formation of the Solar System -Observation

- We see evidence of accretion disk around other stars.
- For example, β Pictoris.



Formation of the Solar System -Observation



Warped Disk · Beta Pictoris HST · WFPC2

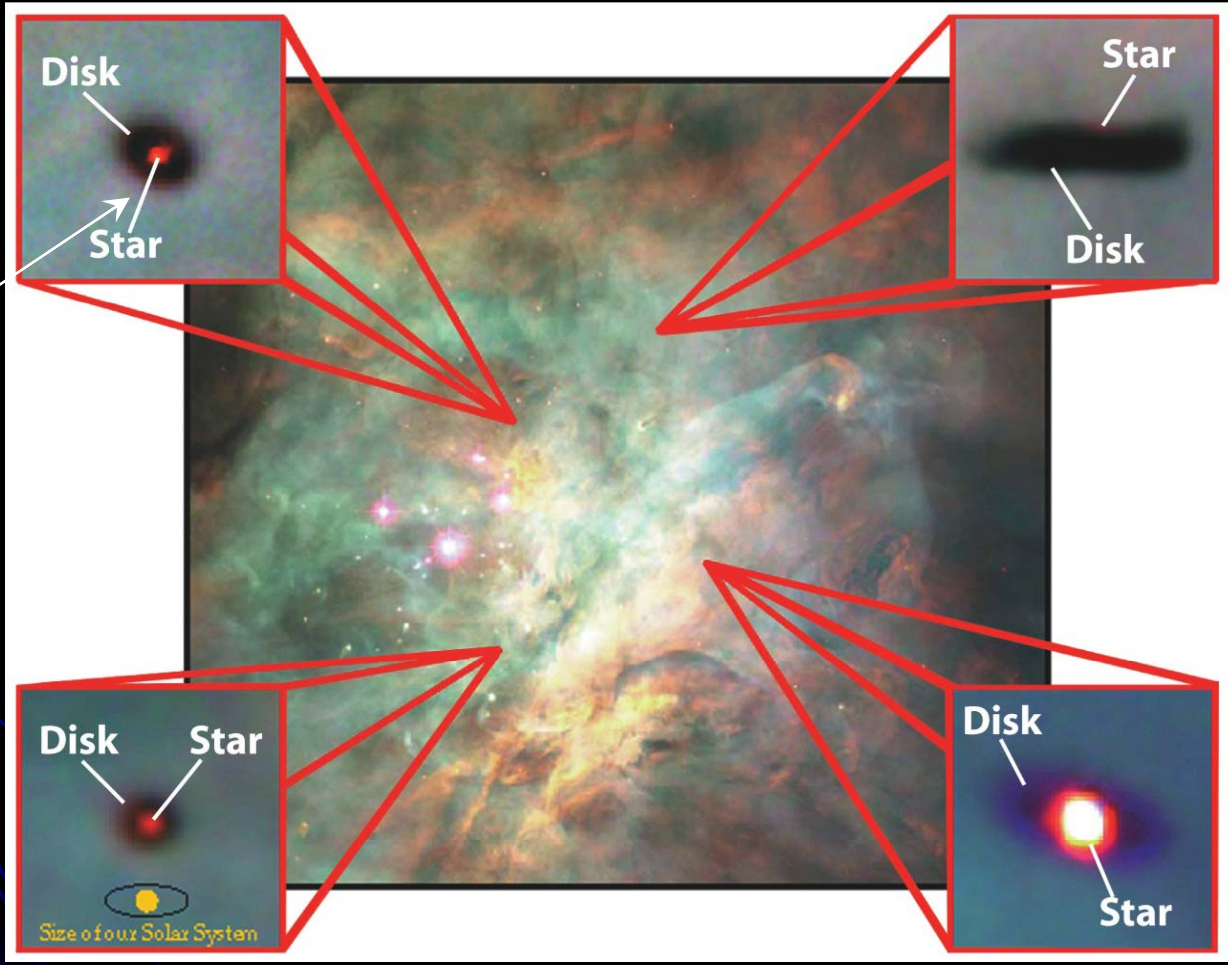
PRC96-02 · ST ScI OPO · January 17, 1995 · C. Burrows and J. Krist (ST ScI), WFPC2 IDT, NASA

The Rotating Disk

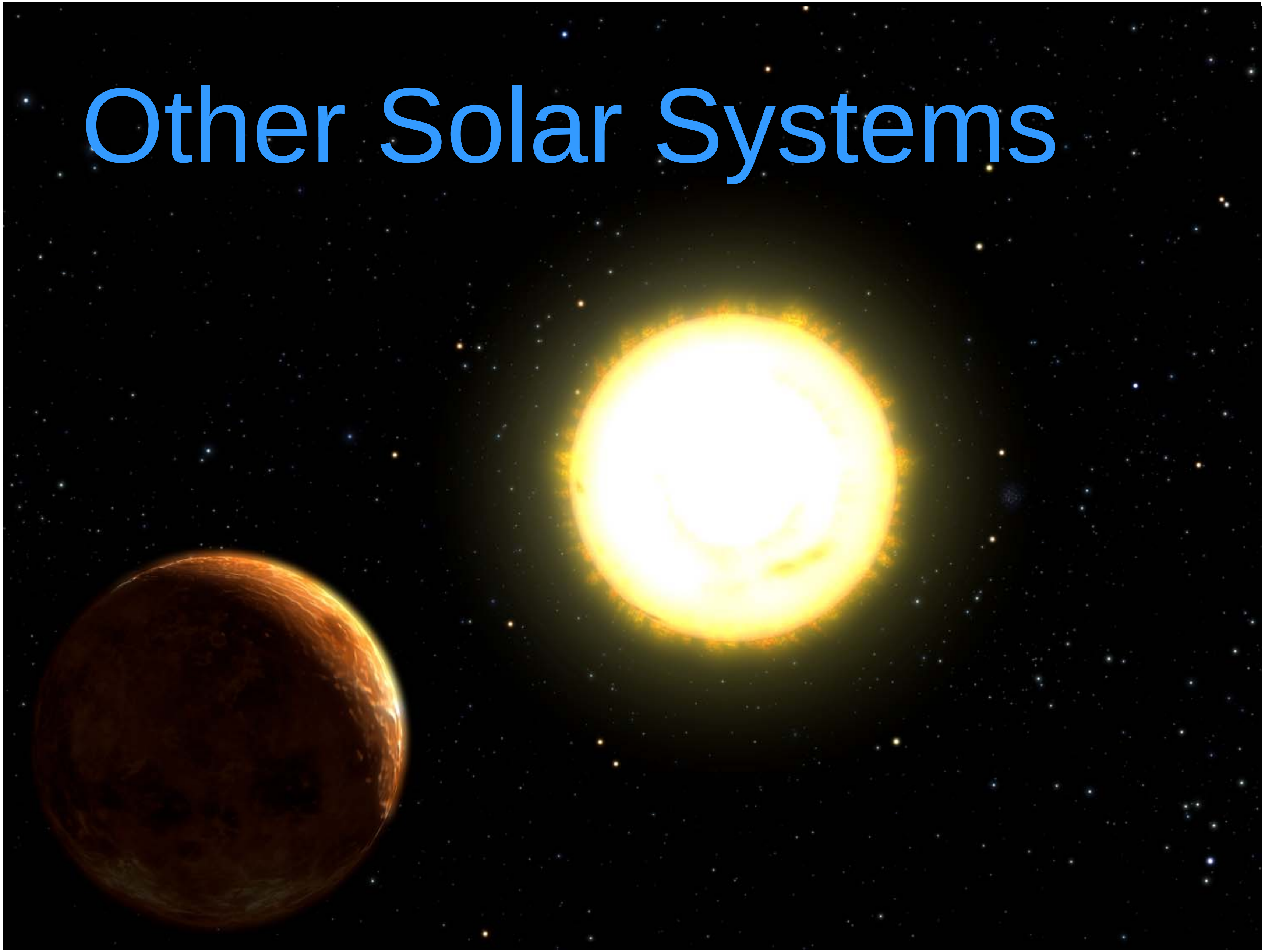
Part of cloud becomes flattened disk

→ seen around other stars

★Planets will orbit in direction disk rotates

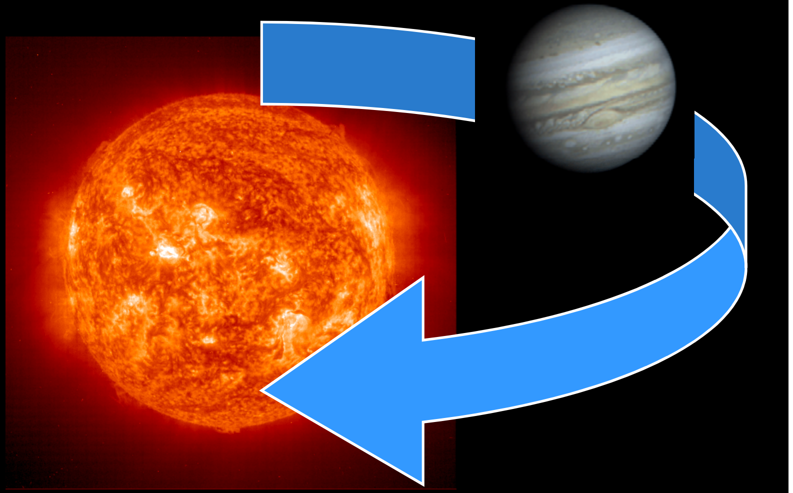


Other Solar Systems



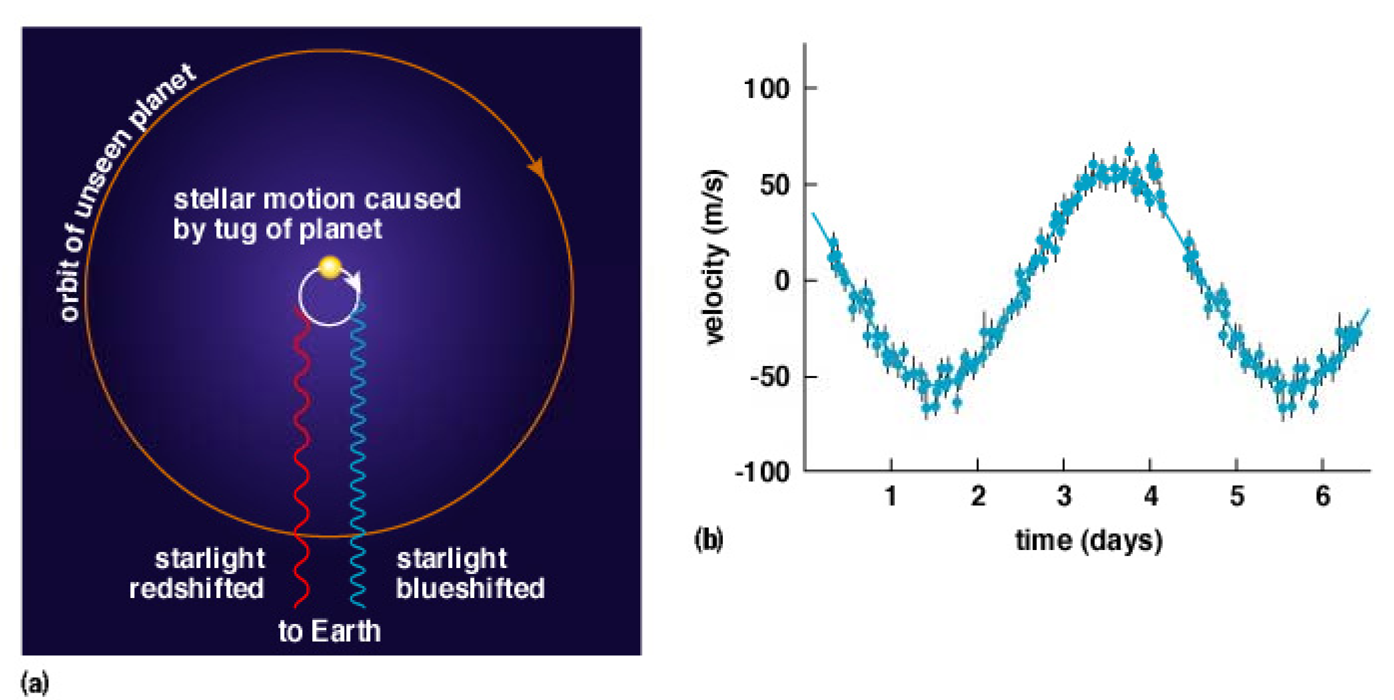
Finding Planets Indirectly

- Gravitational Effects on Parent Star
  - Radial Velocity Changes
  - Positional Wobble (Astrometry)
- Effect of Planet on Star's Brightness
  - Transits of edge-on systems
  - Gravitational micro-Lensing



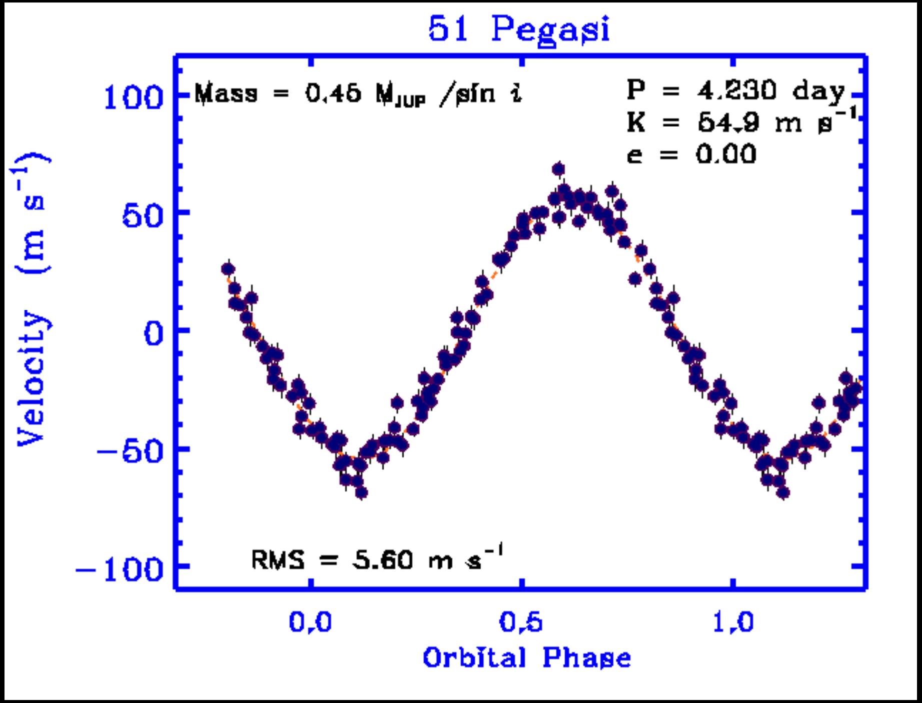
Other Solar Systems:
Radial Velocity Changes

- Planets outside of our solar system have been found recently using Doppler shifts in the spectra of some stars.



First Doppler Wobble Planet : 51 Peg (1995)

P = 4.2 days (!)
a = 0.05 AU
T ~2000K



New type of Planet:
“Hot Jupiter”

Other Solar Systems:
Transit Light-curves

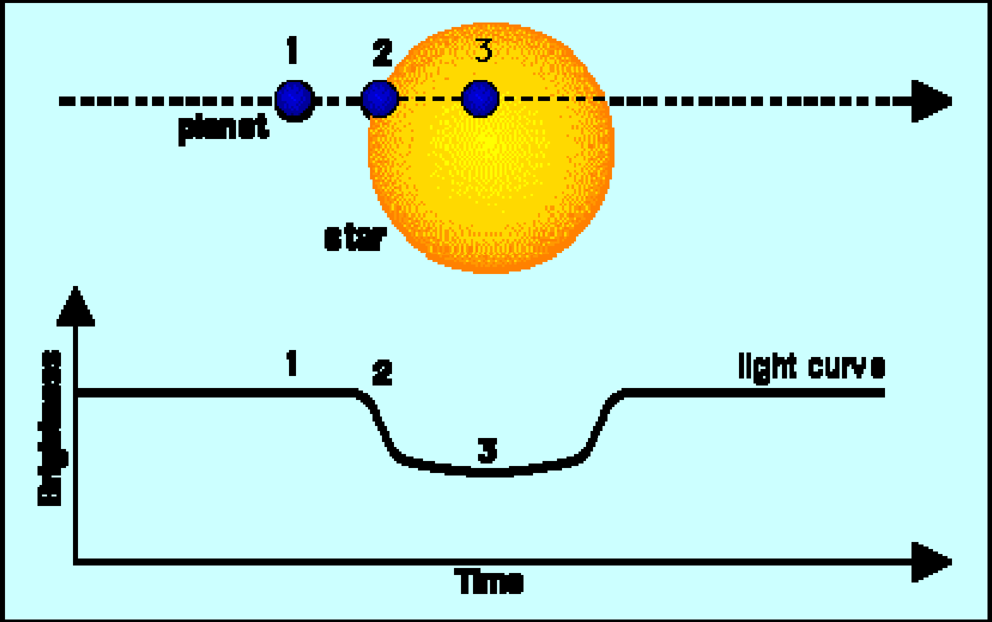
$r_{Jup} \approx 0.1 R_{Sun}$

Depth:

$$\frac{\Delta f}{f} \approx 1\% \left(\frac{r_p}{r_{Jup}}\right)^2 \left(\frac{R_*}{R_{Sun}}\right)^{-2}$$

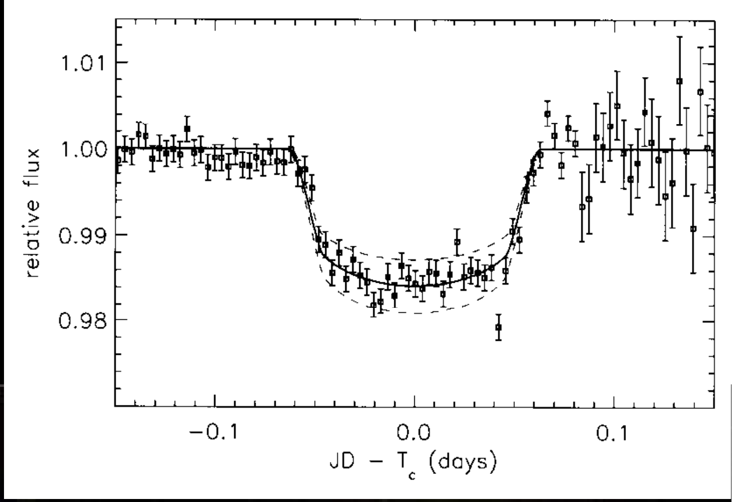
Duration:

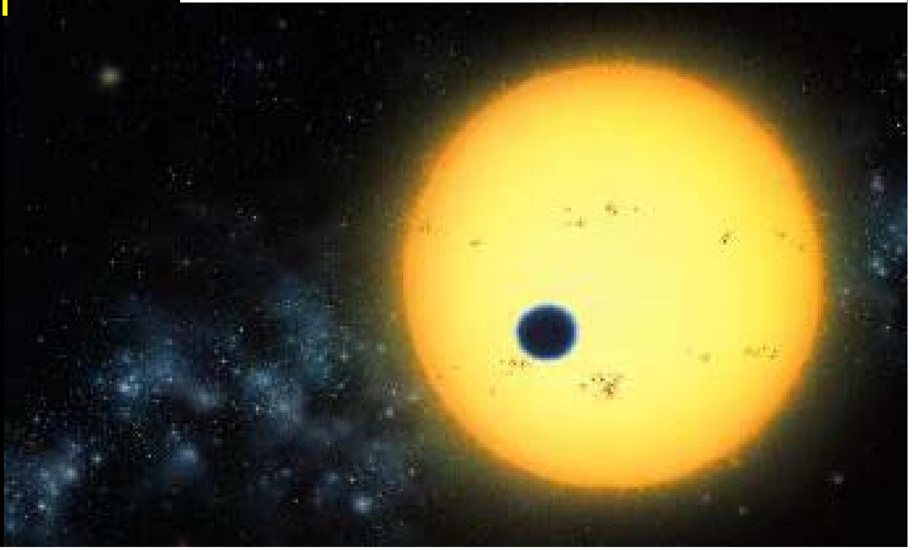
$$\Delta t \approx 3h \left(\frac{M_*}{M_{Sun}}\right)^{2/3} \left(\frac{P}{4d}\right)^{1/3}$$



Transit of HD 209458

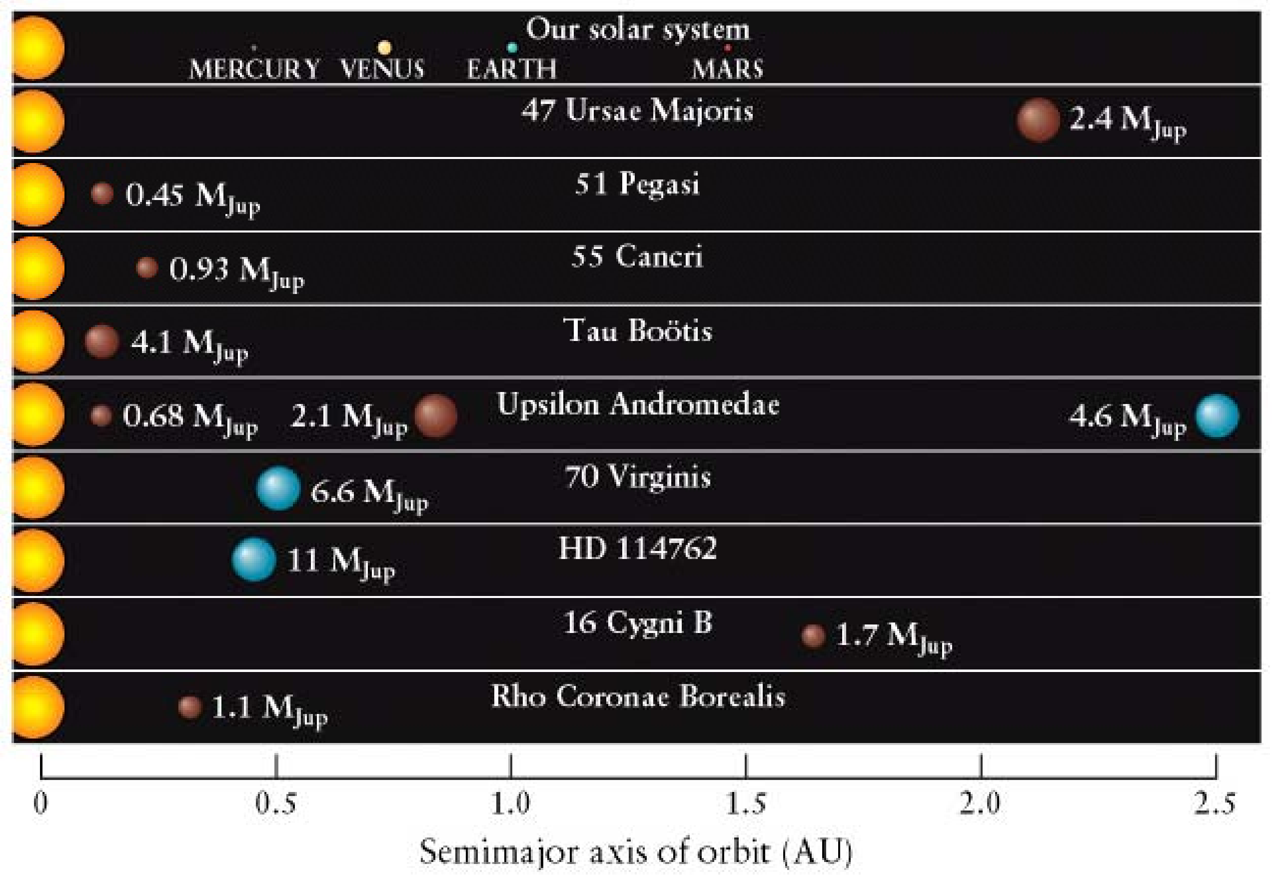
- Transits of HD 209458 determine properties of another Solar System
  - Mass= 0.69 ± 0.07 M_{jup}
  - Radius =1.35 ± 0.06 R_{jup}
  - Density= 0.35 g/cc <Saturn





Other Solar Systems
hot Jupiter

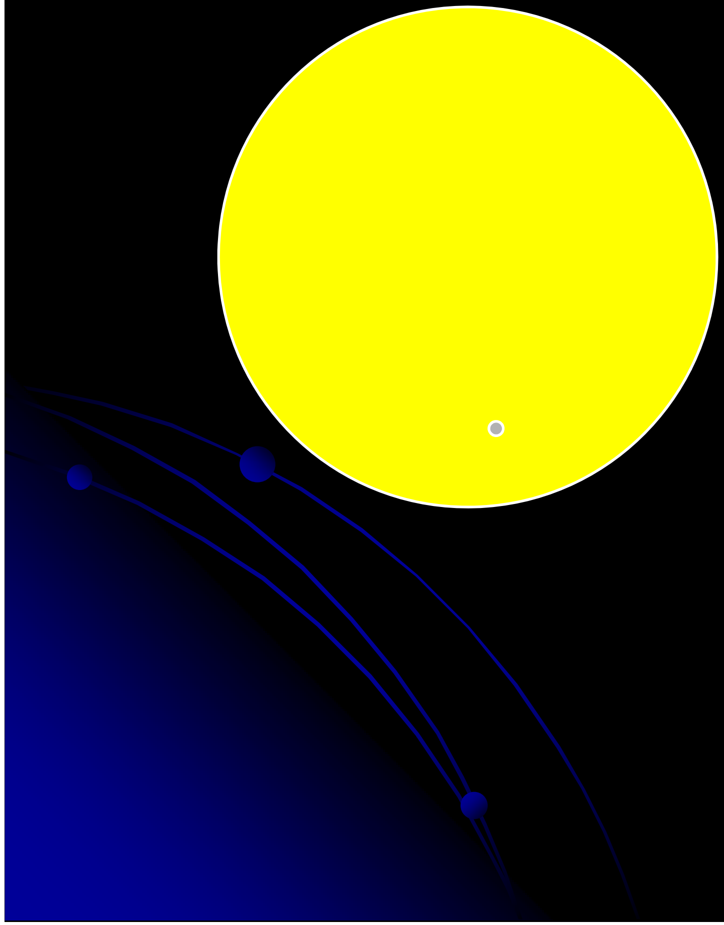
130+ planetary systems discovered / 150+ total planets



Space Transit Missions

Other Earths

$$r \sim r_{\oplus} \sim 0.01\, R_{sun}$$



$$T \approx 300\,\mathrm{K}$$

$$P \sim 1\ \mathrm{yr}$$

$$a \sim 1\ \mathrm{au}$$

$$\Delta t \sim 13\ \mathrm{h}$$

$$\Delta f / f \sim 10^{-4}$$

Mercury transiting the Sun 1999 Nov

© Rick Scott & Joe Orman

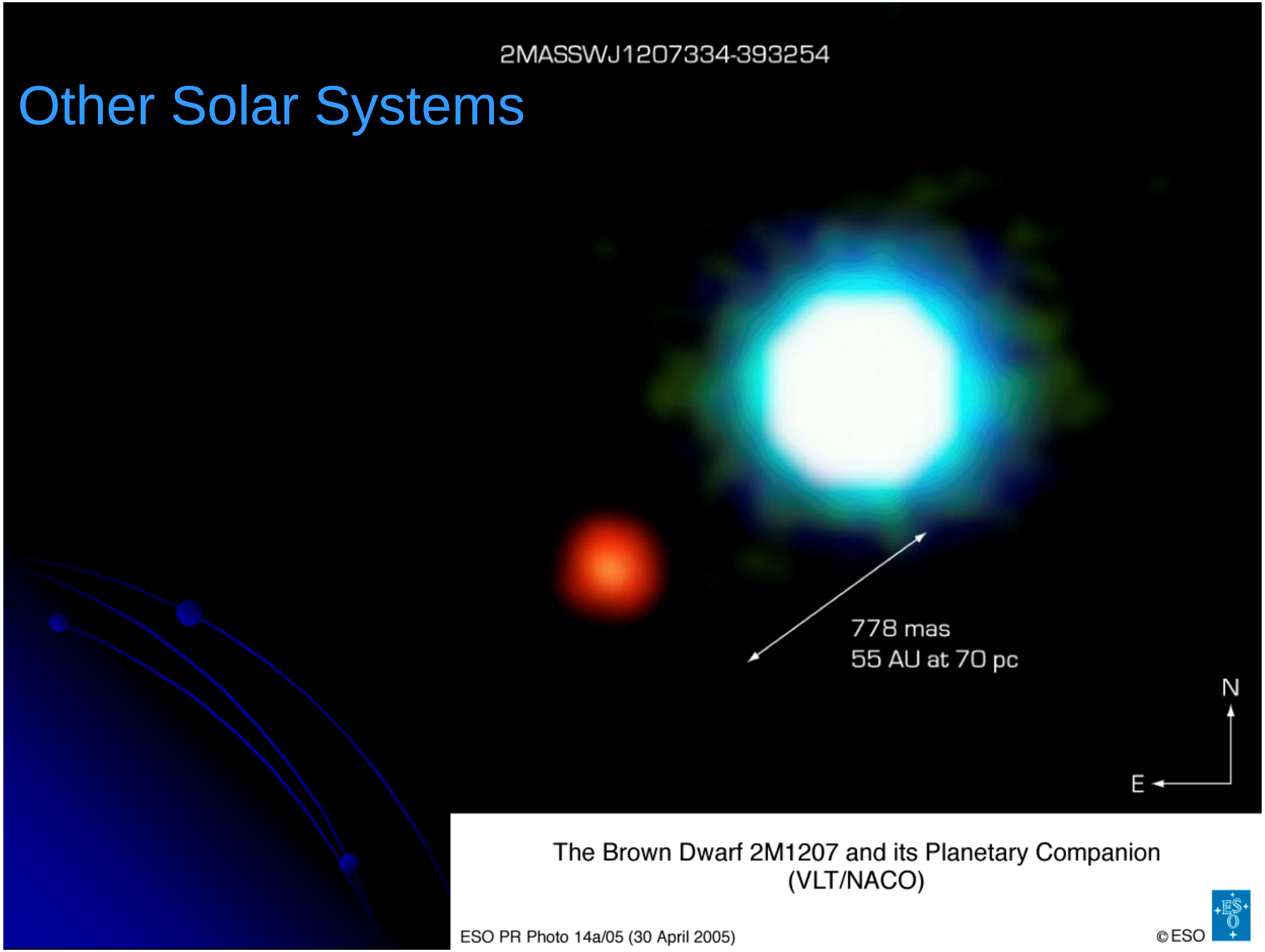
Mercury transits:

2003 May 07
2006 Nov 08

Earth transits:

$$\frac{\Delta f}{f} \sim 10^{-4}$$

Other Solar Systems



The Brown Dwarf 2M1207 and its Planetary Companion (VLT/NACO)

ESO PR Photo 14a/05 (30 April 2005)

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END