Two stars have the same apparent brightness and temperature, but different distances. The star that is closer to the Sun has a

a) lower luminosity.
b) higher luminosity.
c) larger radius.
d) bluer color.
e) higher apparent brightness.

$L = 4\text{pi}\ R^2\ \sigma T^4$

Star and Planet Formation

Picture of nebula in Orion

Astronomy 1101

Key Ideas:

Star Formation Stages:

- Giant Molecular Cloud
- Cloud Collapse and Fragmentation into clumps
- Protostar formation
- Onset of Hydrostatic Equ (Kelvin-Helmholtz time)
- Ignition of core Hydrogen burning & onset of Thermal Equilibrium

Planet Formation:

Collapse to disk. Hotter near star, cooler further away: condensation of dust, ices, growth of planetesimals. Frost/Ice line and the planet dichotomy.

The Sun is Old, & in Equilibrium:

Hydrostatic Equilibrium:

- Pressure = Gravity

Thermal Equilibrium:

- Energy produced = Energy radiated

Sun

But, how did the Sun form?

Star formation

Star birth is a 3-stage process:

1. Gravitational Collapse of gas blob.
2. Establish Hydrostatic Equilibrium
   - Proto-star Formation phase
3. Establish Thermal Equilibrium
   - Pre-Main Sequence phase

Land on Main Sequence.

Giant Molecular Clouds (GMCs)

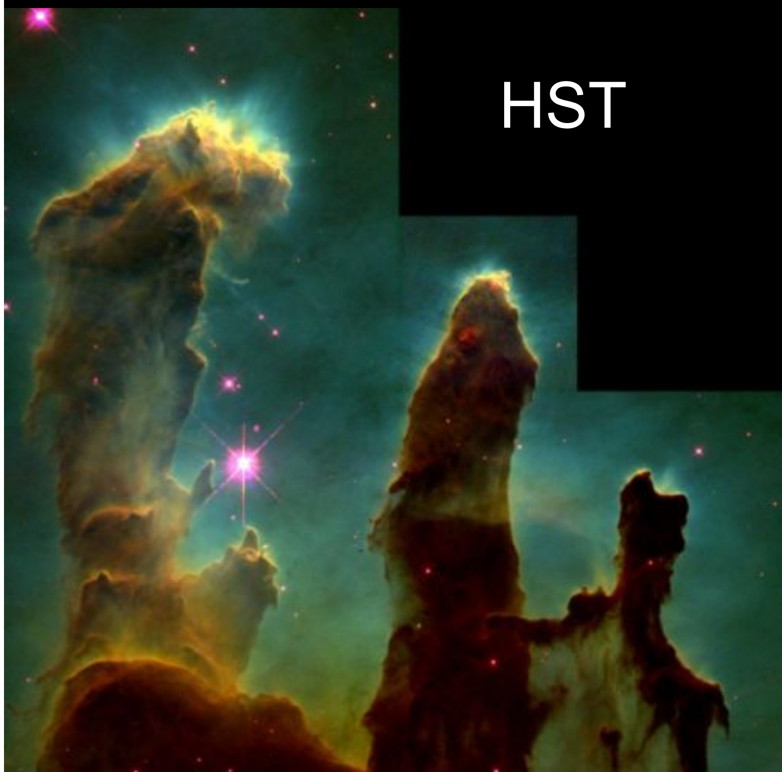
Clouds of Molecular Hydrogen (H_2)

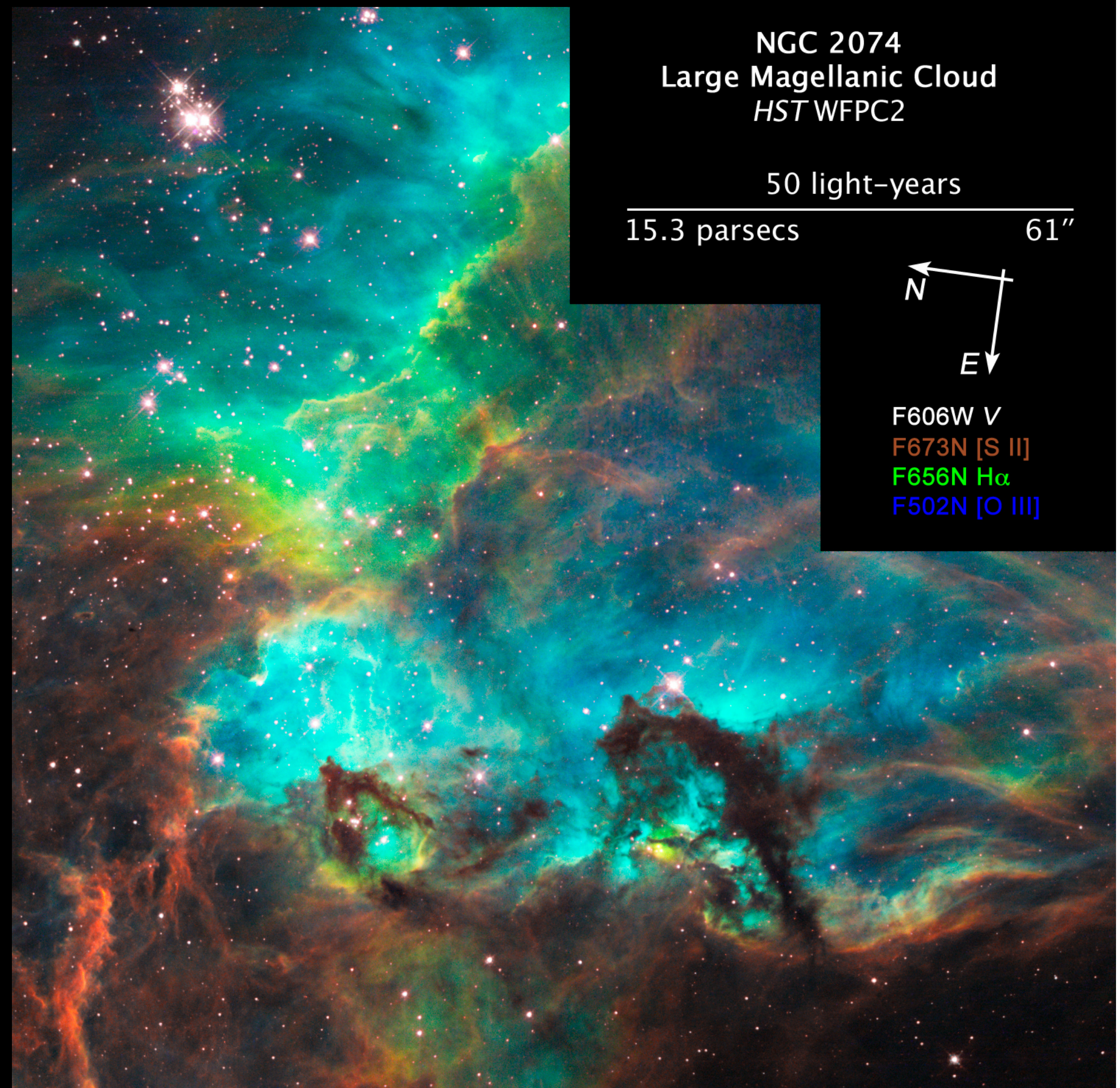
Properties:

- Sizes: ~10 – 50 parsecs
- Masses: $\sim 10^5\ M_{sun}$
- Temperatures: 10−30 K (cold!)
- Densities: 10^{5-6} atoms/cm^3

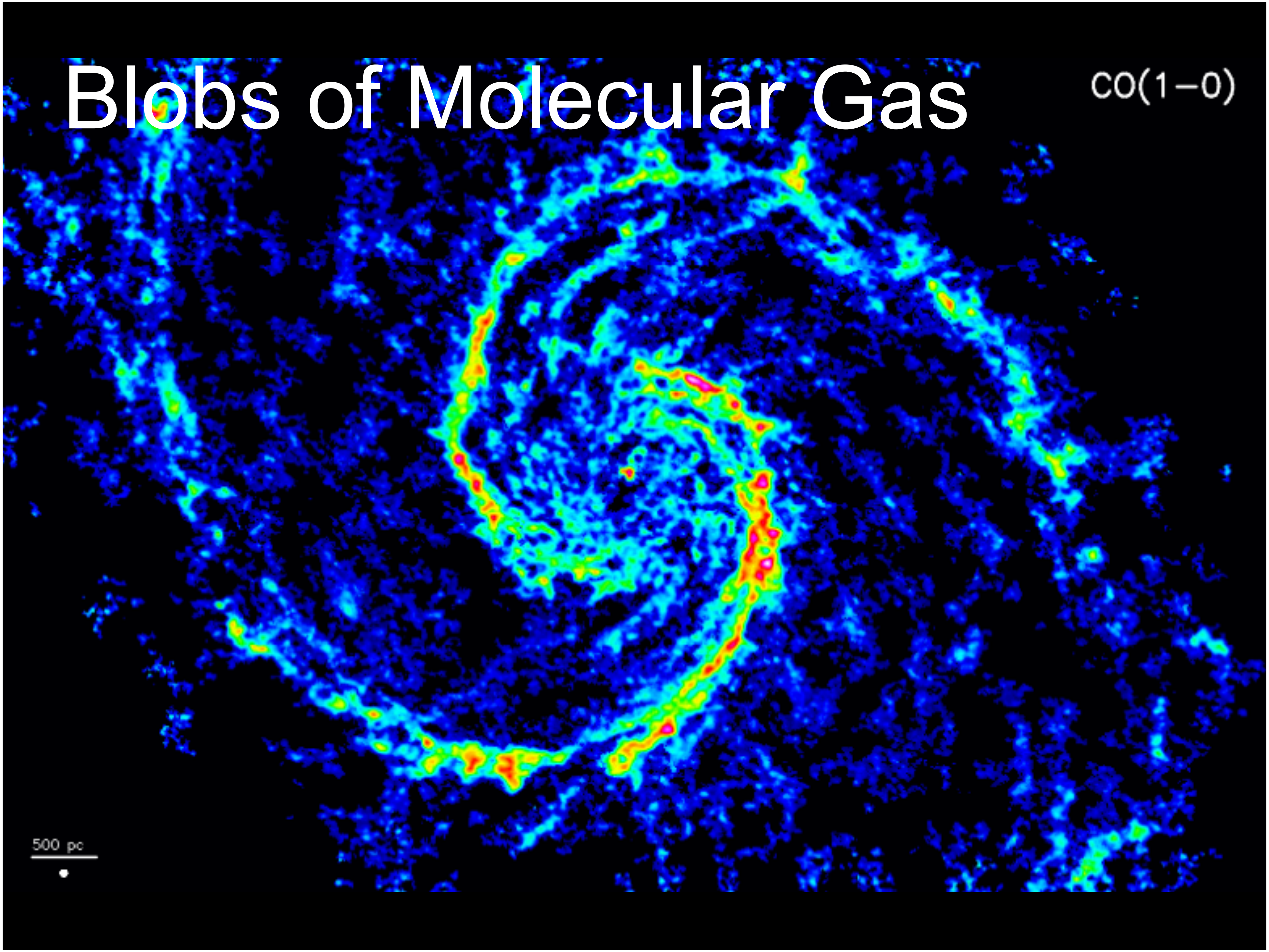
Raw materials from which new stars form

Giant Molecular Clouds (GMCs)





Blobs of Molecular Gas



GMCs Make Stars if Gravity > Pressure

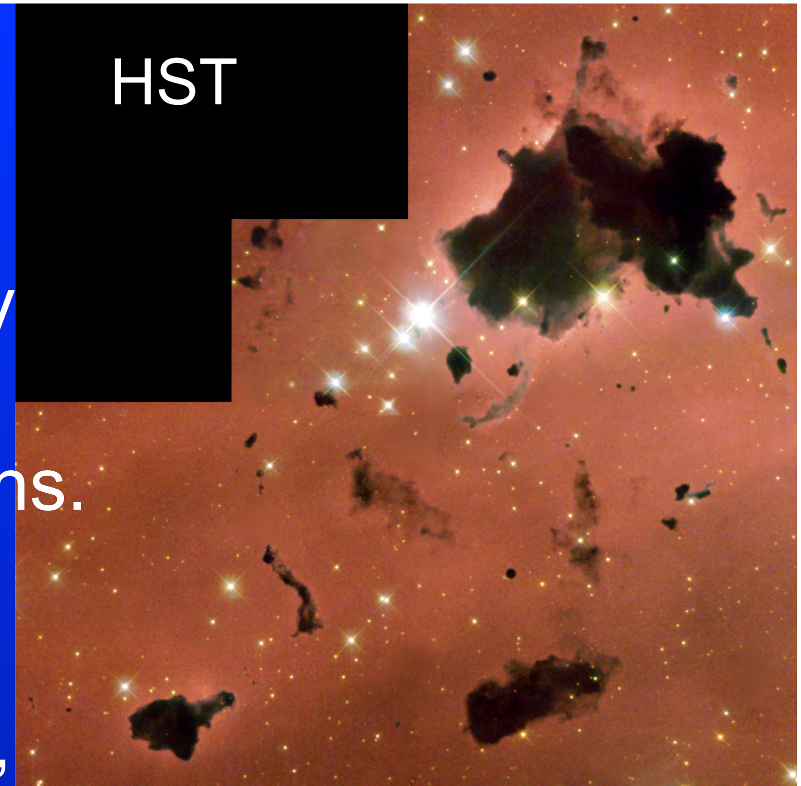
A GMC and the clumps within it can become unstable to collapse if

Gravity > Pressure

Ways to trigger a collapse:

- Cloud-Cloud/blob-blob collisions
- Passage through a spiral arm
- Supernova shockwave
- Gravitational Instability: Pressure < Gravity because the gas can radiate away its heat (it is transparent).

Clouds fragment.

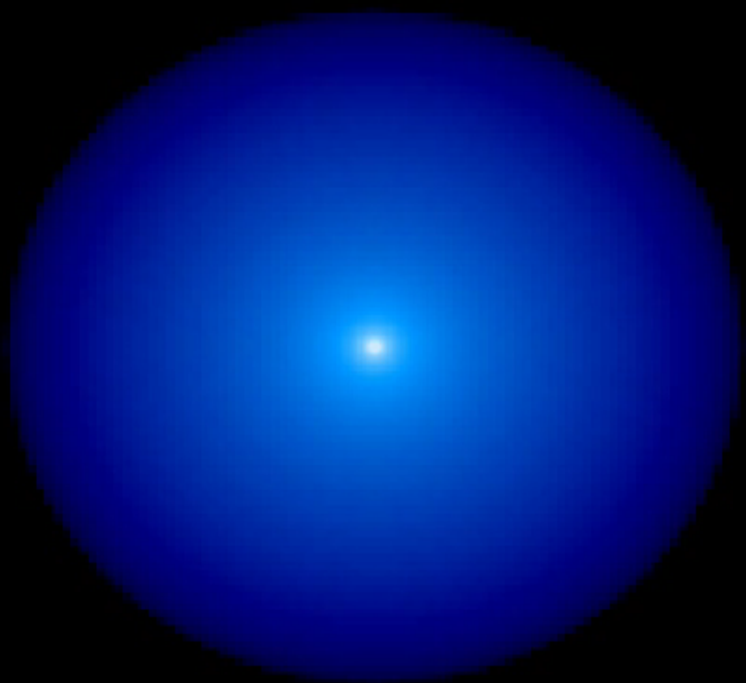


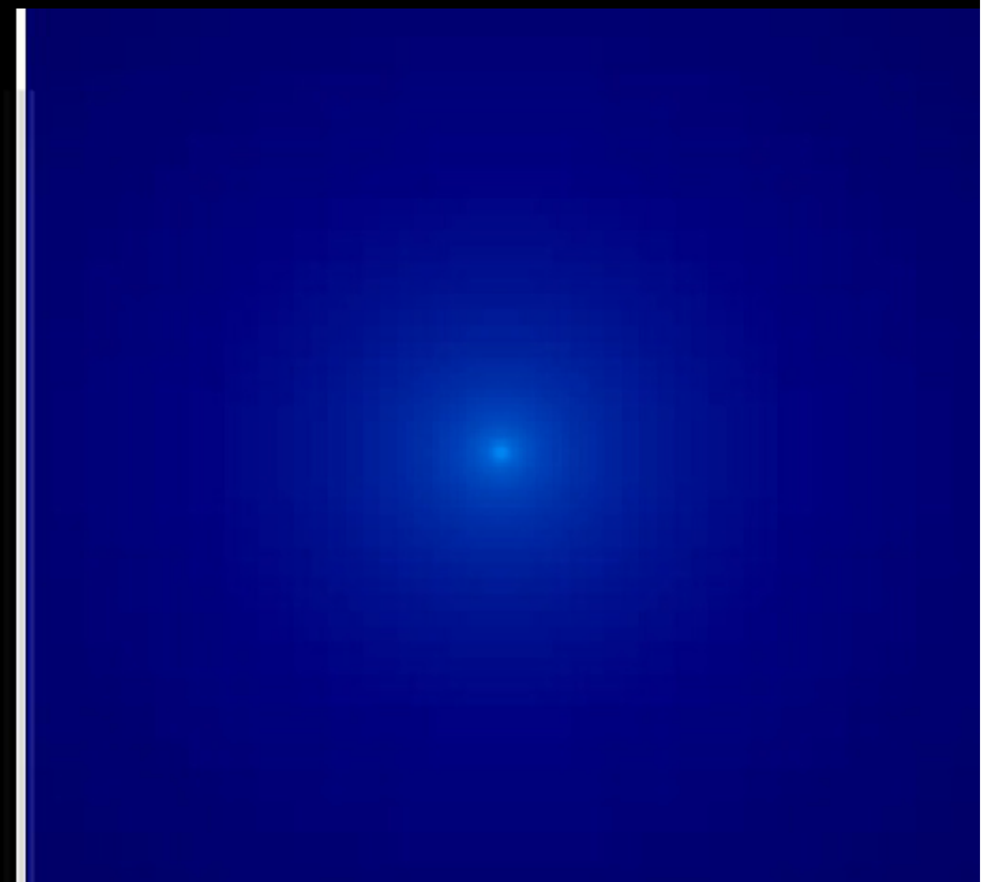
GMCs are clumpy. Higher density clumps are more gravitationally unstable than lower density regions.

Densest clumps collapse first & fastest: fragmentation into "cores" from which individual stars form.

Core density rises, pressure increases, $P = n\ k_B\ T$, hydrostatic equilibrium achieved. No fusion yet.

Formation of a massive star from clumps.





Krumholtz

Short protostar phase.

10^4 - 10^5 years

Proto-stars in this phase are:

- In Hydrostatic Equilibrium
- Deeply embedded in their parent gas & dust clouds
- *Not yet in Thermal Equilibrium*

"Short Lived" + "Hard to See" means very few protostars are observed. Like infants!

Protostar
Invisible in the Optical, but visible In the infrared.

Kelvin-Helmholz Mechanism Powers Protostars

Protostars shine.

- Need an energy source to stay hot, but central temperature is **too cool for nuclear fusion.**

Initial energy source: Gravitational Contraction

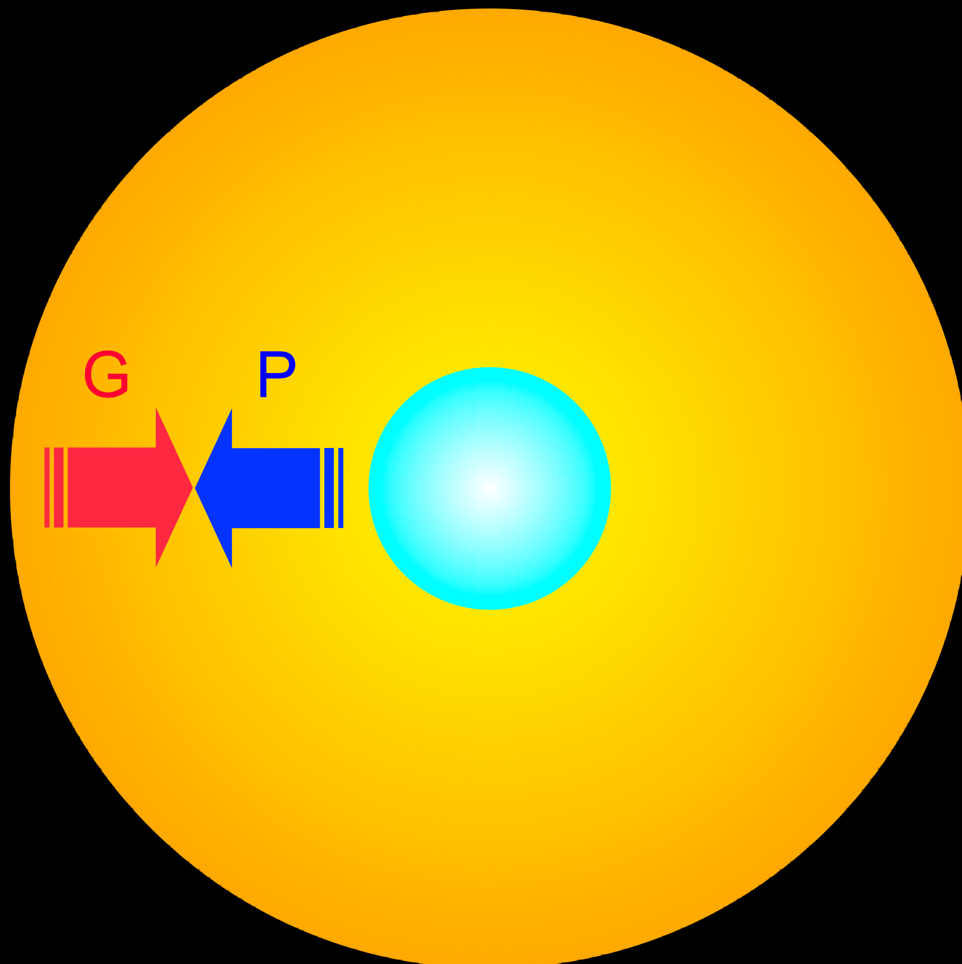
- Protostar shrinks, releasing gravitational energy
- Core gets hotter, but some energy radiated.
- The Kelvin-Helmholz Mechanism!

Timescale? $E_G = GM^2/R$ and L imply

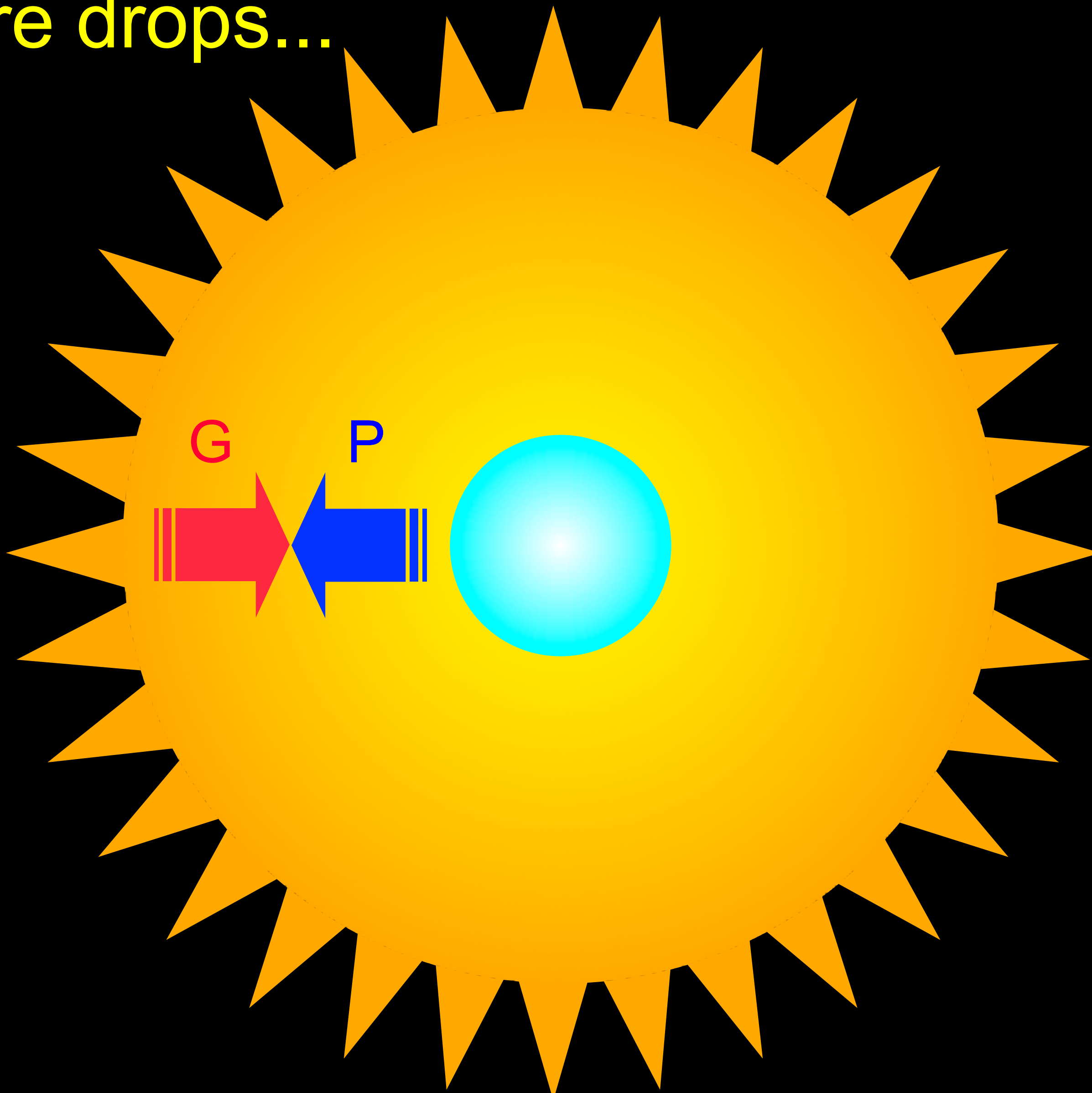
$$t_{KH} = E_G/L$$

30 Myr for the Sun. Faster for higher M stars, slower for lower mass stars.

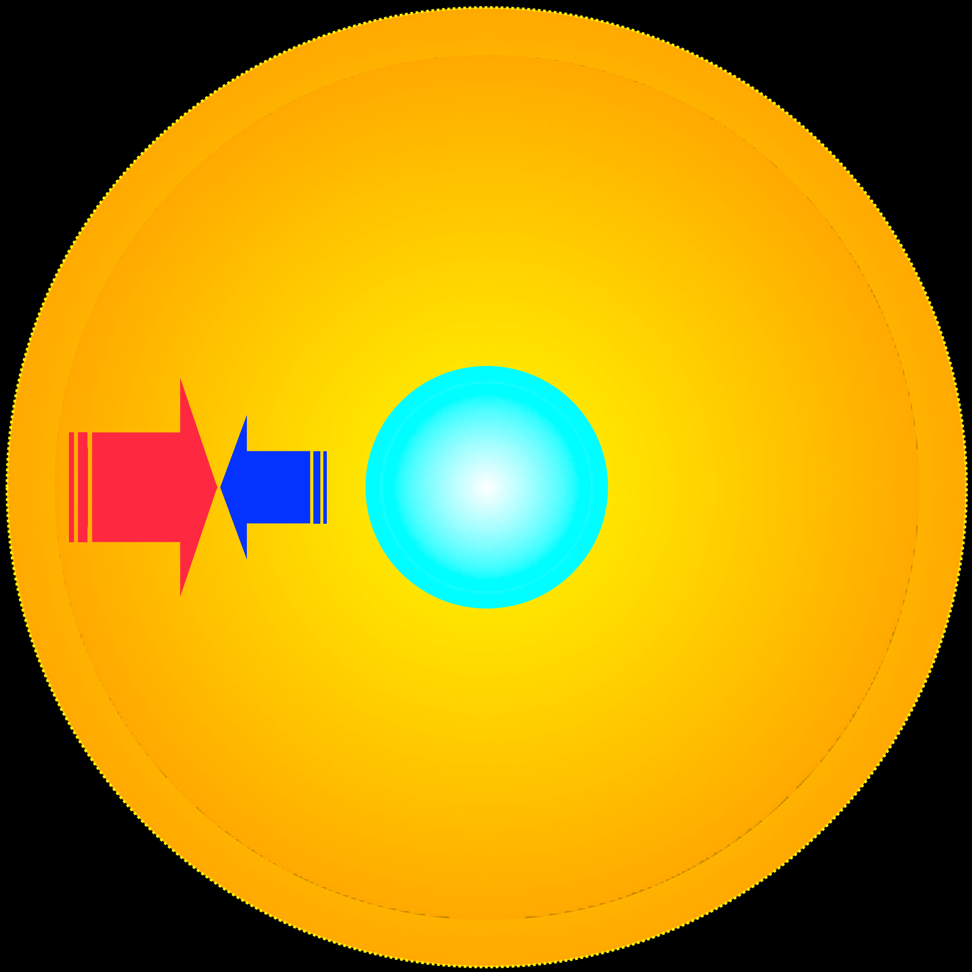
Hydrostatic Equilibrium: Pressure = Gravity



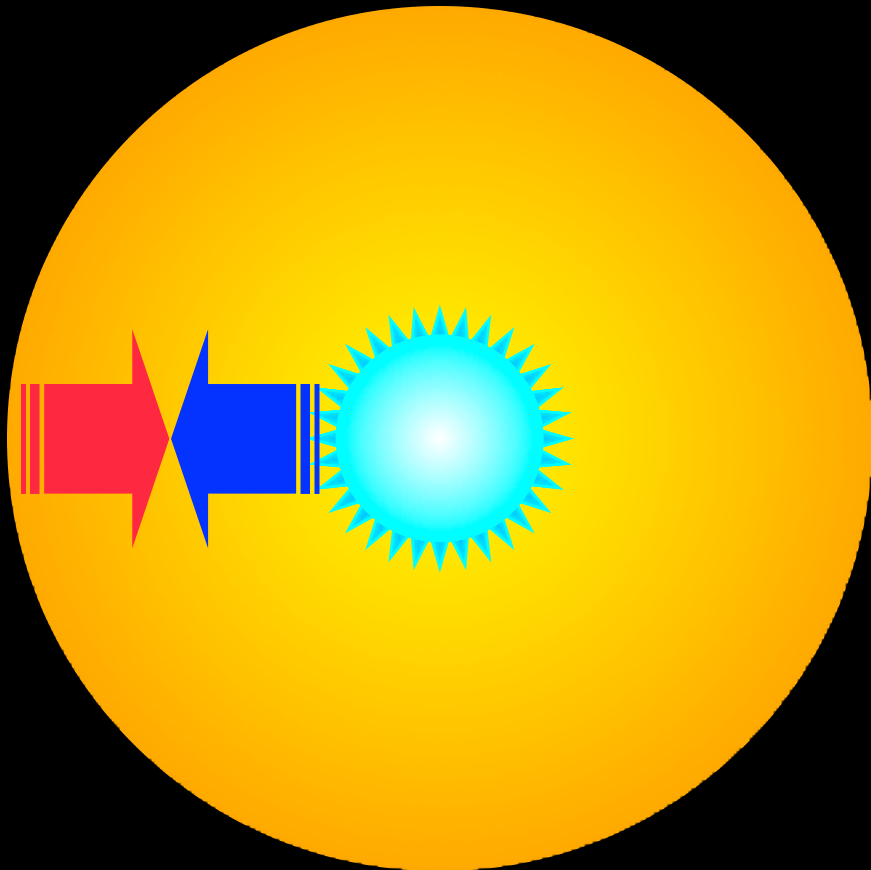
Luminosity radiates away heat, and the internal Pressure drops...



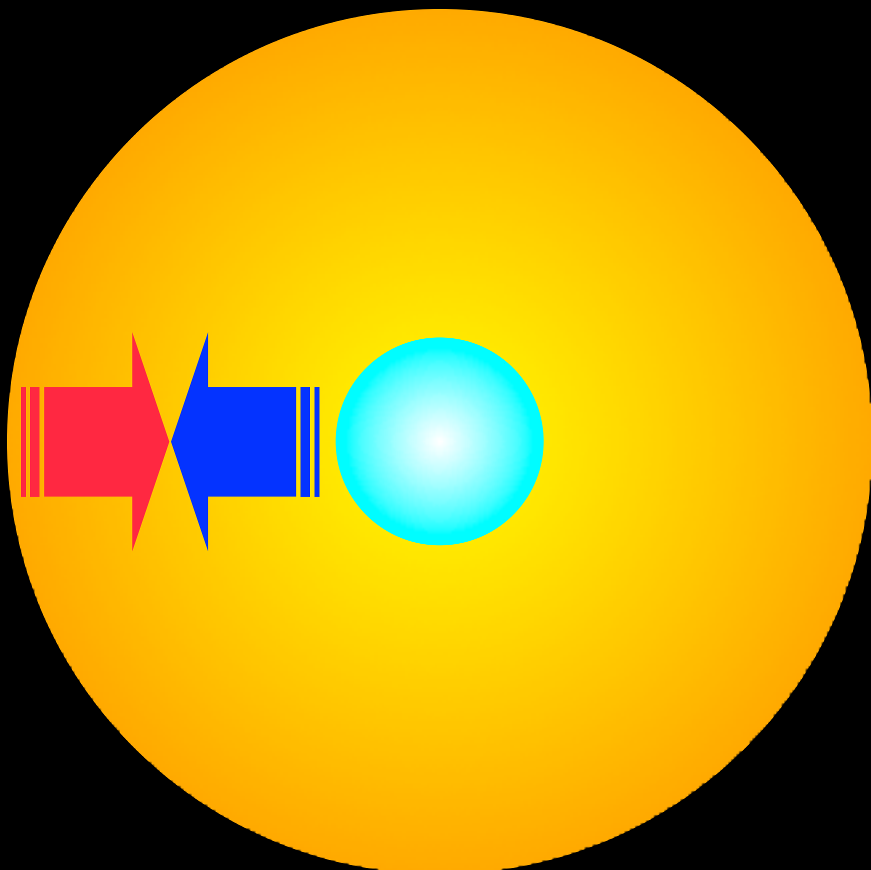
Balance tips in favor of gravity, so the Sun contracts, becoming more tightly bound...



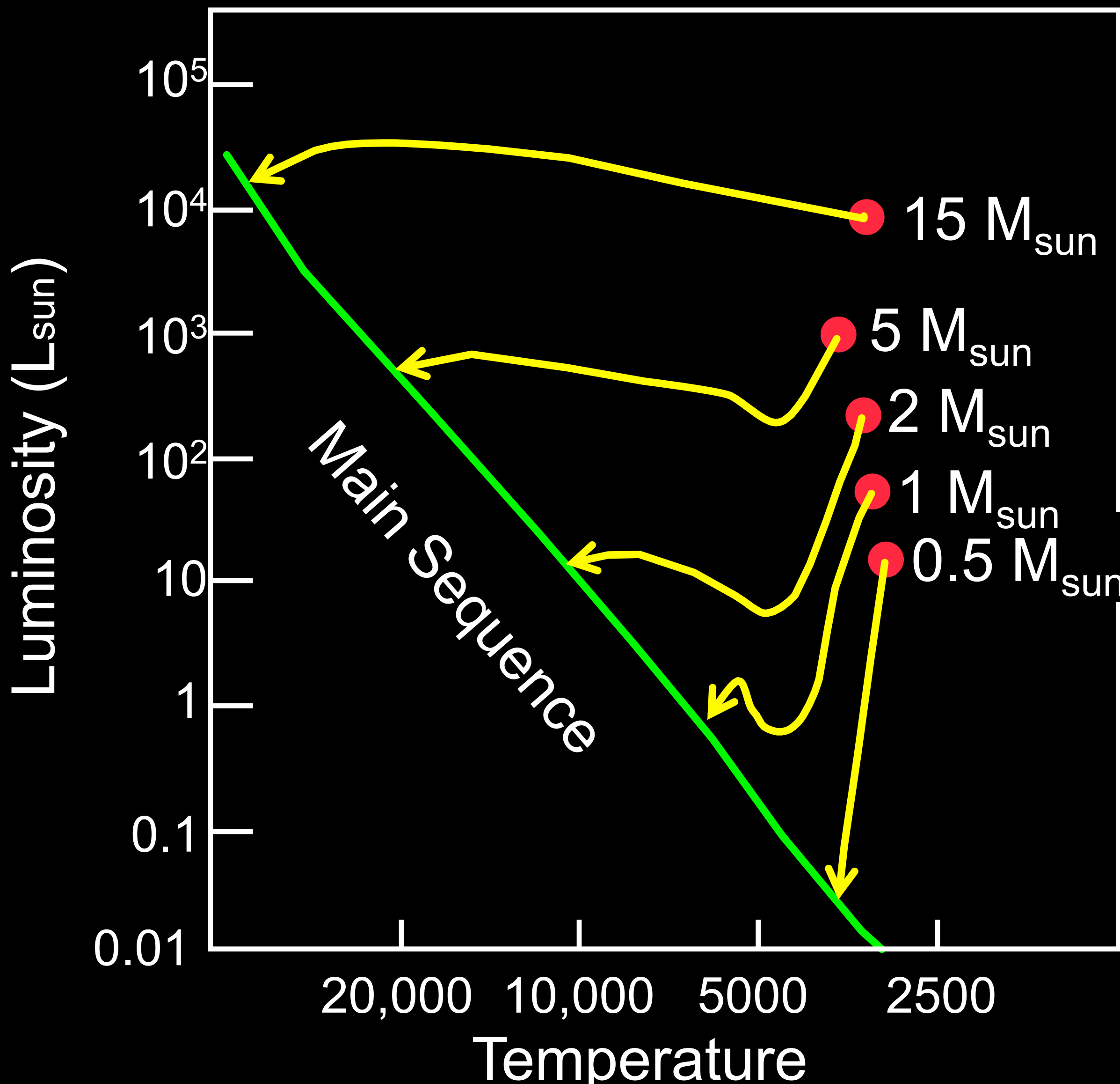
Contraction makes core heat up, increasing the internal Pressure.



Balance restored, but with higher gravity, pressure & temperature than before...



Starts the cycle all over again...



10^5
10^4
10^3
10^2
10
1
0.1
0.01
Luminosity (L_{sun})
20,000
10,000
5000
2500
Temperature
Main Sequence
15 M_{sun}
5 M_{sun}
2 M_{sun}
1 M_{sun}
0.5 M_{sun}

High-Mass Protostars

Gravitational Collapse is very fast:

- 30 M_{sun} Protostar collapses in 10,000 years

Core Temperature gets hotter than 10 Million K:

- Ignites CNO fusion in its core, establishes Thermal Equilibrium.

Quickly ionizes and blows away any remaining gas.

Low-Mass Protostars

Collapse is slower for low-mass protostars:

- 1 M_{sun} takes ~30 Myr
- 0.2 M_{sun} takes ~1 Gyr

Core Temperature gets >10 Million K:

- Ignite P-P chain fusion in the core

Settles slowly onto the Main Sequence, establishes Thermal Equilibrium

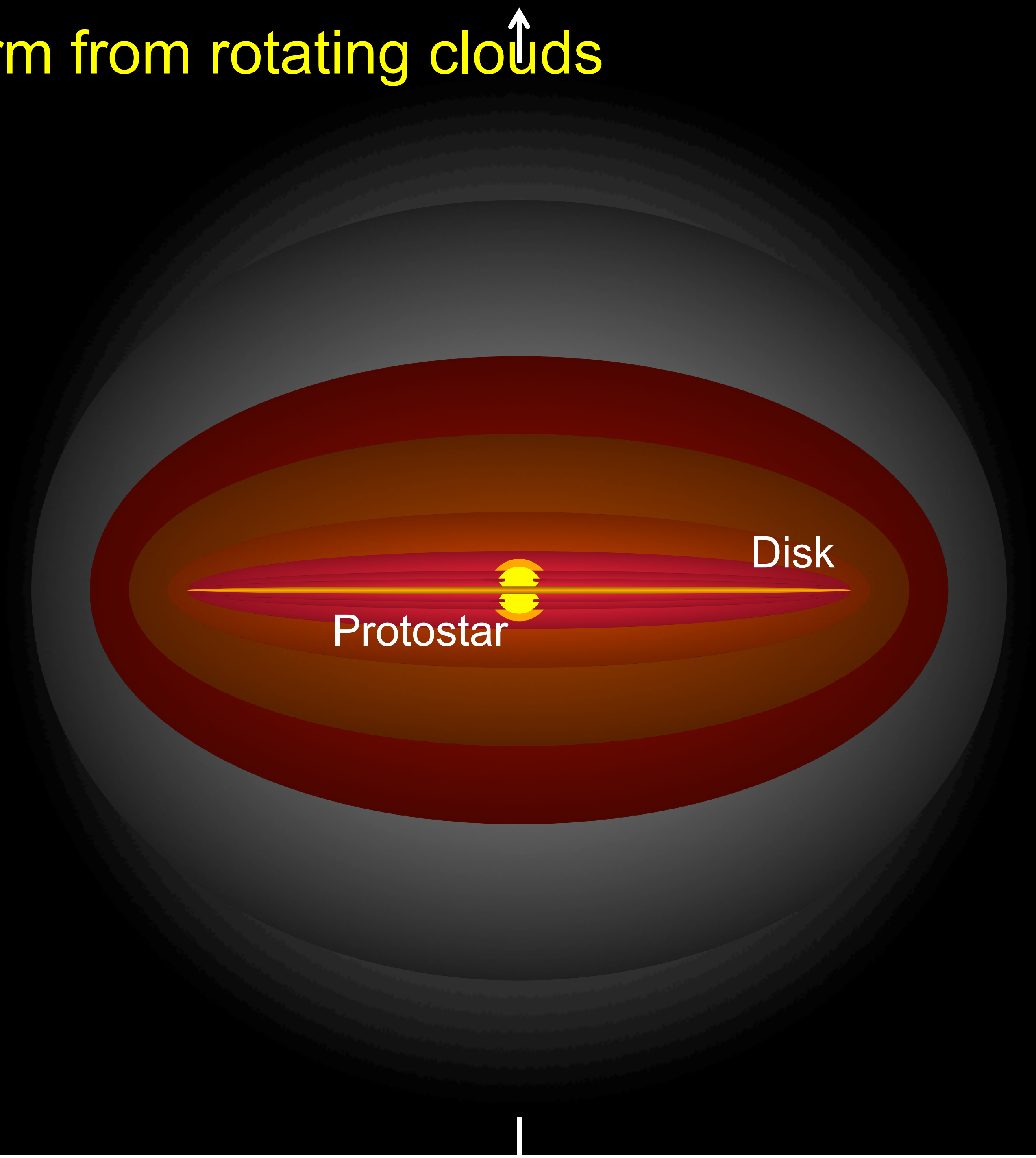
Protostars have disks, form planets. Short timescale: ~10 million years.

As matter rains onto a Protostar:

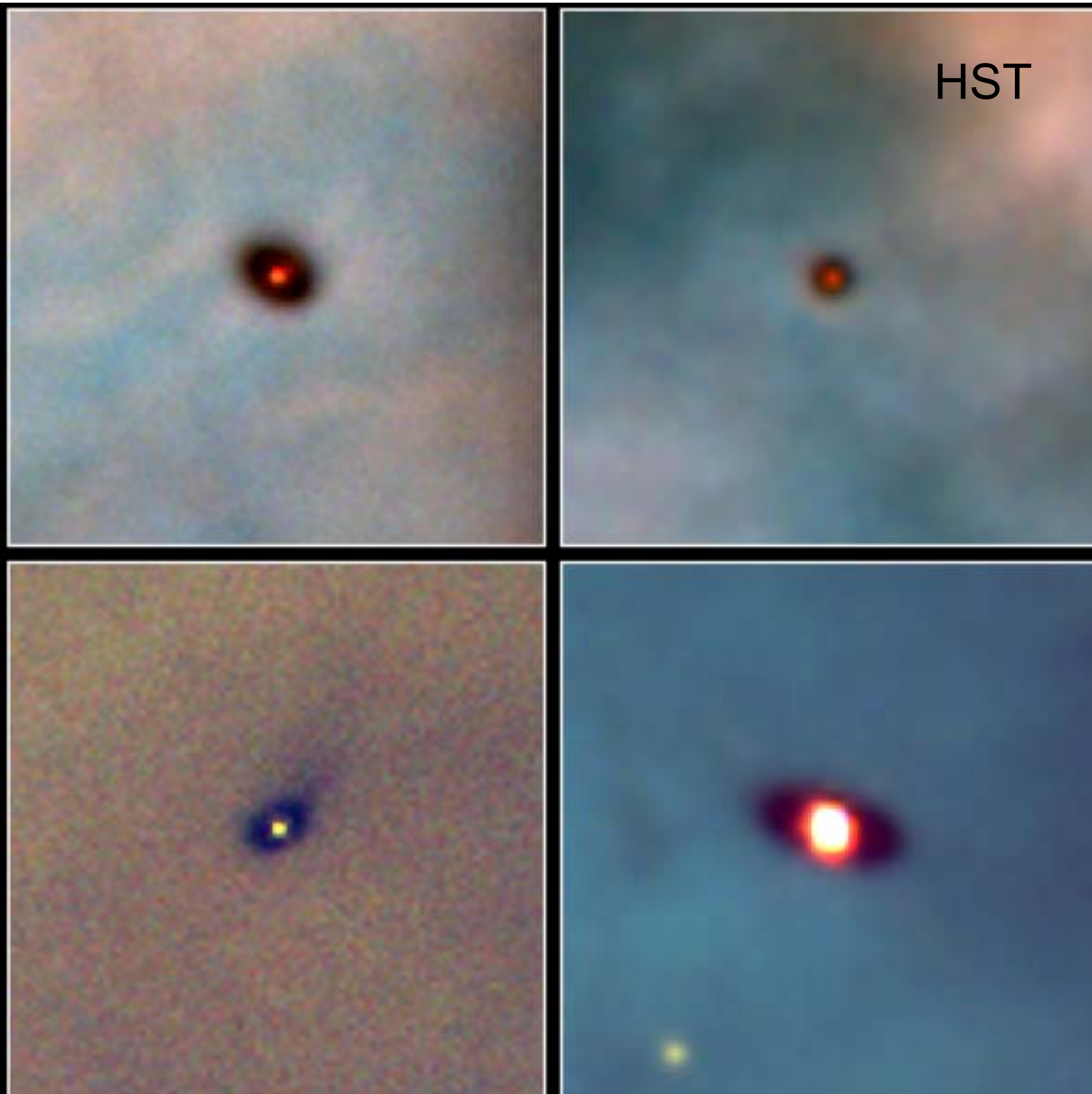
- Matter along the poles free-falls in rapidly
- Matter along the equator infalls more slowly (due to angular momentum conservation).

Result is a flat, rotating disk of gas & dust around the equator of the Protostar.

Stars form from rotating clouds



Gas & dust disks observed around young stars


HST

Primordial Solar Nebula

The rotating solar nebula is composed of

- ~75% Hydrogen & 25% Helium
- <1% Traces of metals

Starts out at several thousand K, then cools:

- Which elements condense out (gas → solid) when depends on their individual "*condensation temperatures*"

The “Frost Line” (Snow line)

Rock & Metals condense when gas is cooler than 1400-1300 K.

Ice condenses when the gas cools below 200 K.

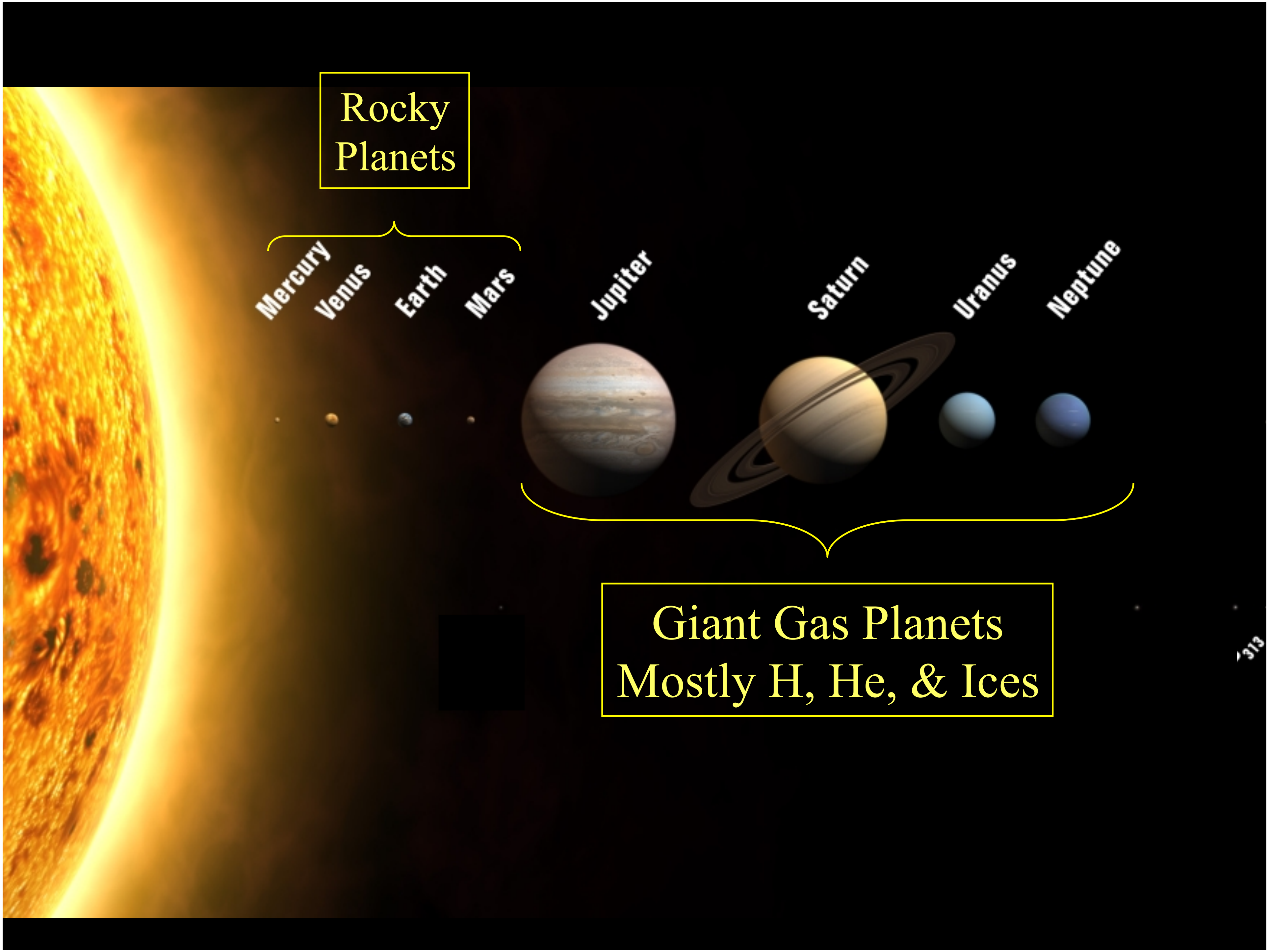
Inner Solar System:

- Too hot for ices & carbon grains

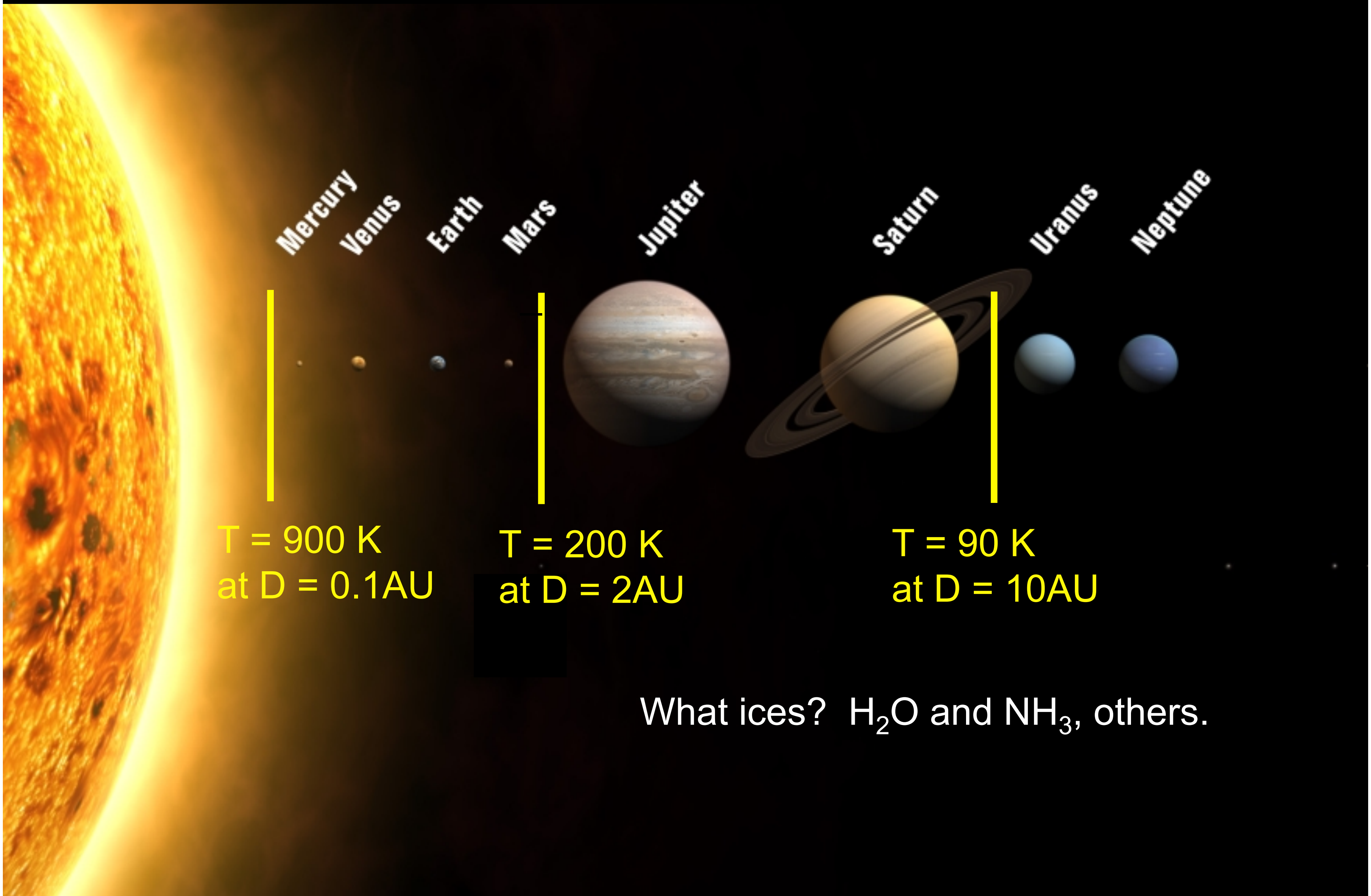
Outer Solar System:

- Carbon grains & ices form beyond the “frost line”

Temperature is determined predominantly by distance from the Sun!


Rocky Planets
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Giant Gas Planets
Mostly H, He, & Ices

Energy In = Energy Out implies that $T = 280\ K\ (AU/D)^{1/2}$

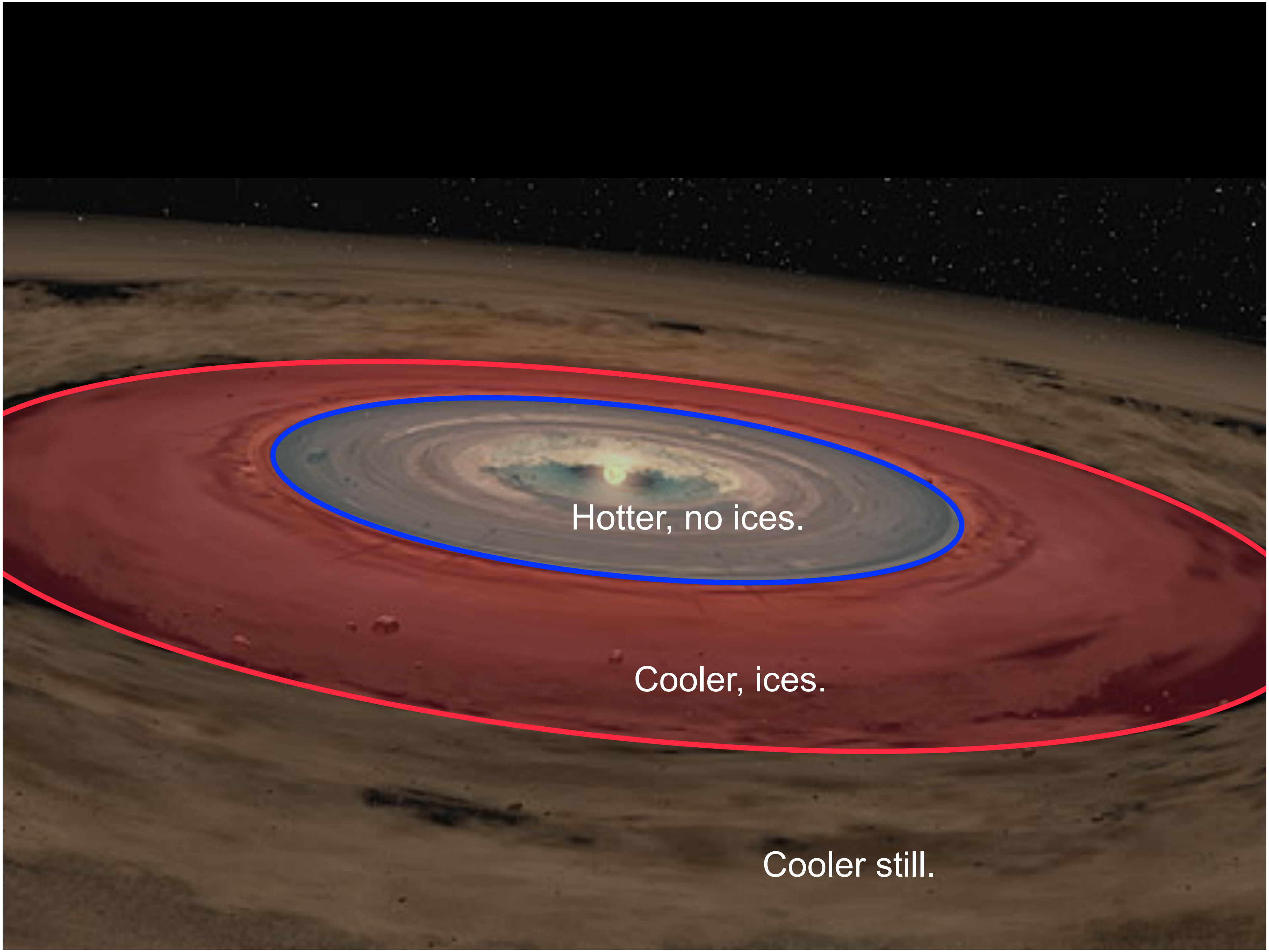


T = 900 K
at D = 0.1AU

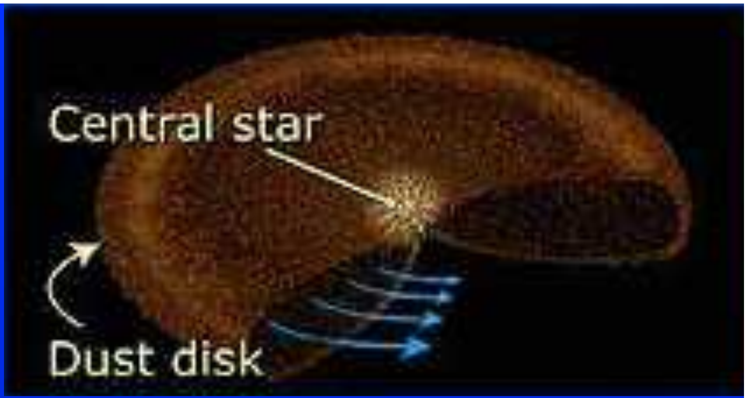
T = 200 K
at D = 2AU

T = 90 K
at D = 10AU

What ices? H_2O and NH_3, others.

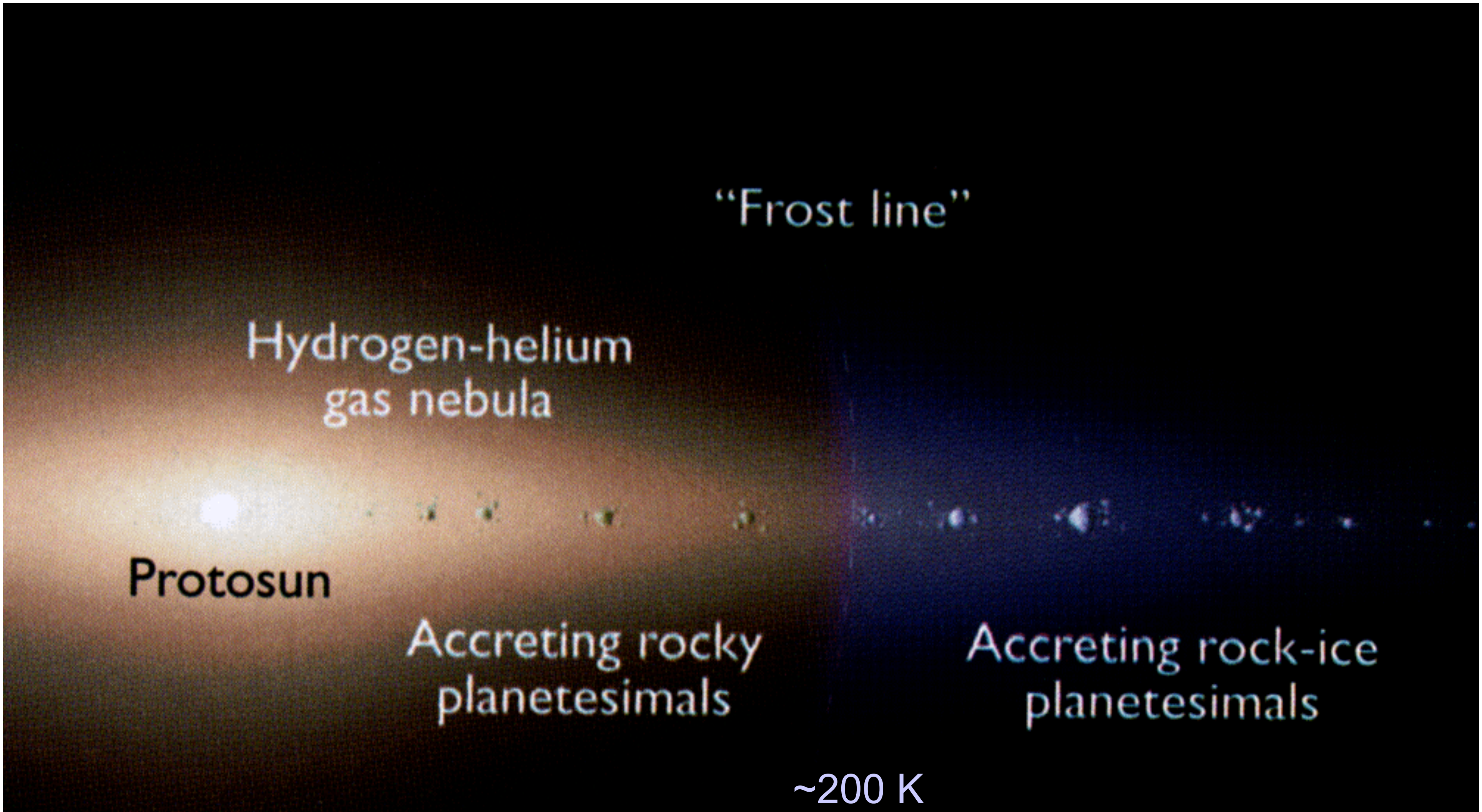

Hotter, no ices.
Cooler, ices.
Cooler still.

Dust grains form "planetesimals"



Grains have low-velocity collisions, stick, form bigger grains.

- Beyond the "frost line", get additional growth by condensing ices onto the grains. Lots of H!!!
- Grow into km-size *planetesimals* in few thousand years.
- Once km-sized, gravitation assists further aggregation: gravity attracts more material.
- Rapidly accelerated growth (runaway) into planets.
- Gather H and He if available. Dichotomy.



Hotter, no ices.
Less mass to collect.
Smaller, rocky, no ice or gas.
Terrestrial Planets

Cooler, ices.
More mass.
Collect more gas!
Gas and Ice Giants

Terrestrial Planets

Only rocky planetesimals inside the frost line.

It is Hotter closer to the Sun:

- Inner planets cannot capture H & He gas, and thus do not become gas giants.
- Solar wind disperses H & He.

Result:

- Form rocky terrestrial planets with few ices.

Jovian Planets

Ices augment the masses of planetesimals

These collide to form large rock & ice cores:

- Jupiter & Saturn: 10-15 M_{Earth} rock/ice cores.
- Uranus & Neptune: 1-2 M_{Earth} rock/ice cores.

Larger masses & colder temperatures:

- Accrete (gravitationally gather) H & He gas from the surrounding disk.
- Planets with the biggest cores grow most rapidly.

Largest gas giants scatter or accrete the remaining planetesimals & protoplanets (the big get bigger, the smaller get eaten, or ejected).