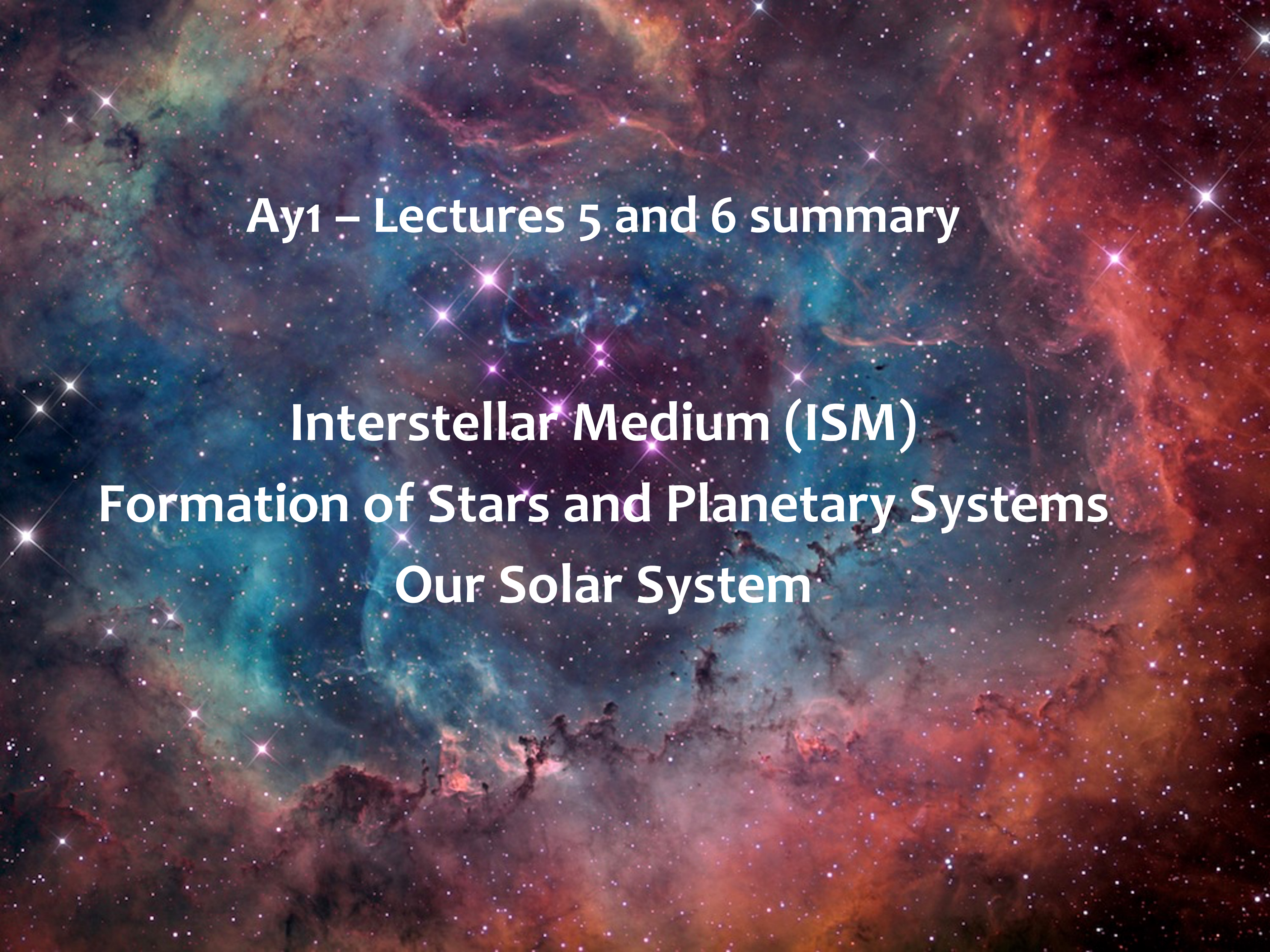


Ay1 – Lectures 5 and 6 summary

Interstellar Medium (ISM)

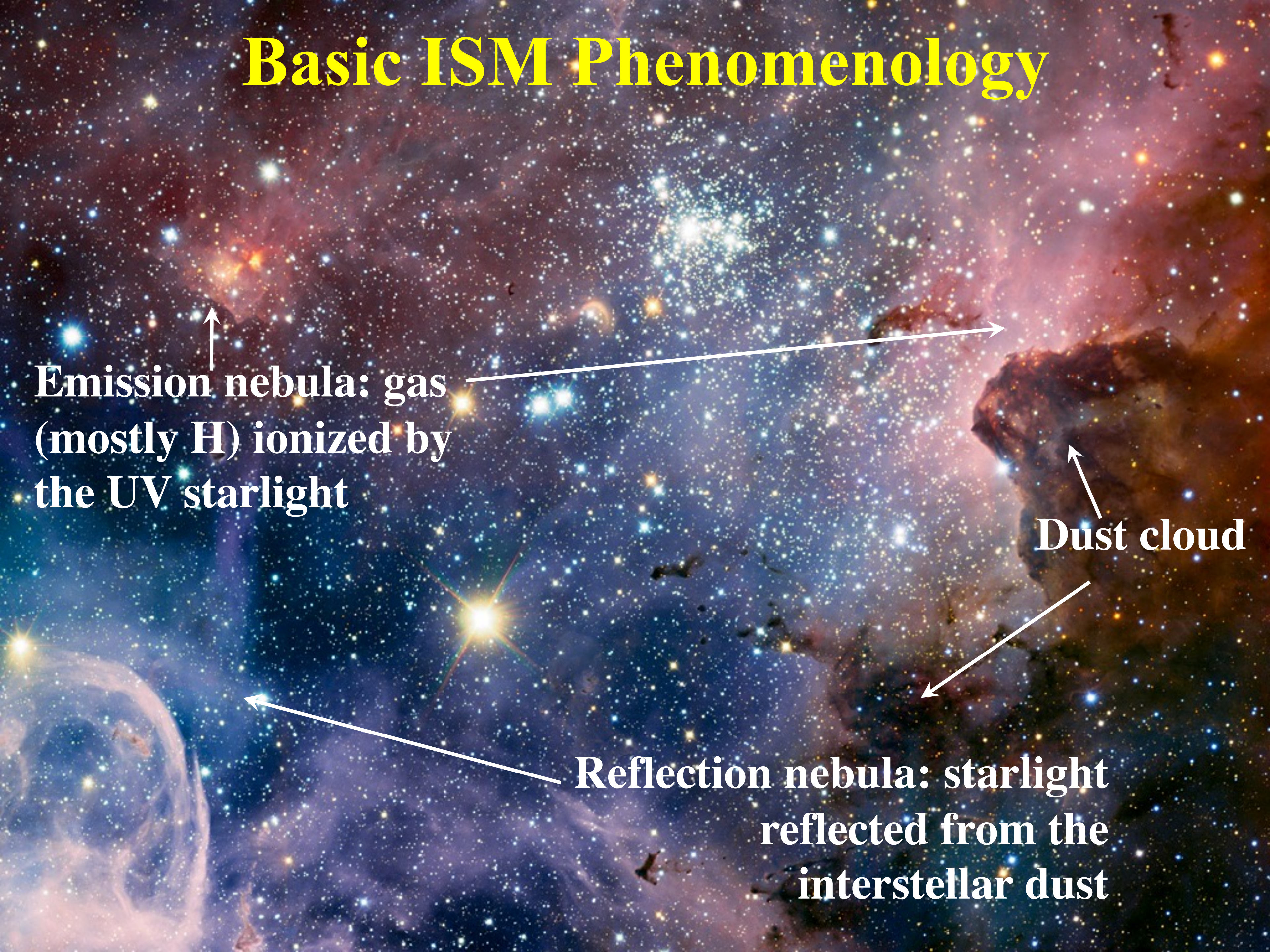
Formation of Stars and Planetary Systems

Our Solar System

Interstellar Medium (ISM): A Global Picture

- “The stuff between the stars”: gas and dust
- Generally concentrated in the Galactic disk
- Initially all of the baryonic content of the universe is a gas; and the baryonic dark matter probably still is
- Stars are formed out of the ISM, and return enriched gas to it via stellar winds, planetary nebulae, Supernovae - a cosmic ecology
- A complex physical system with many components and structures

Basic ISM Phenomenology



Emission nebula: gas (mostly H) ionized by the UV starlight

Dust cloud

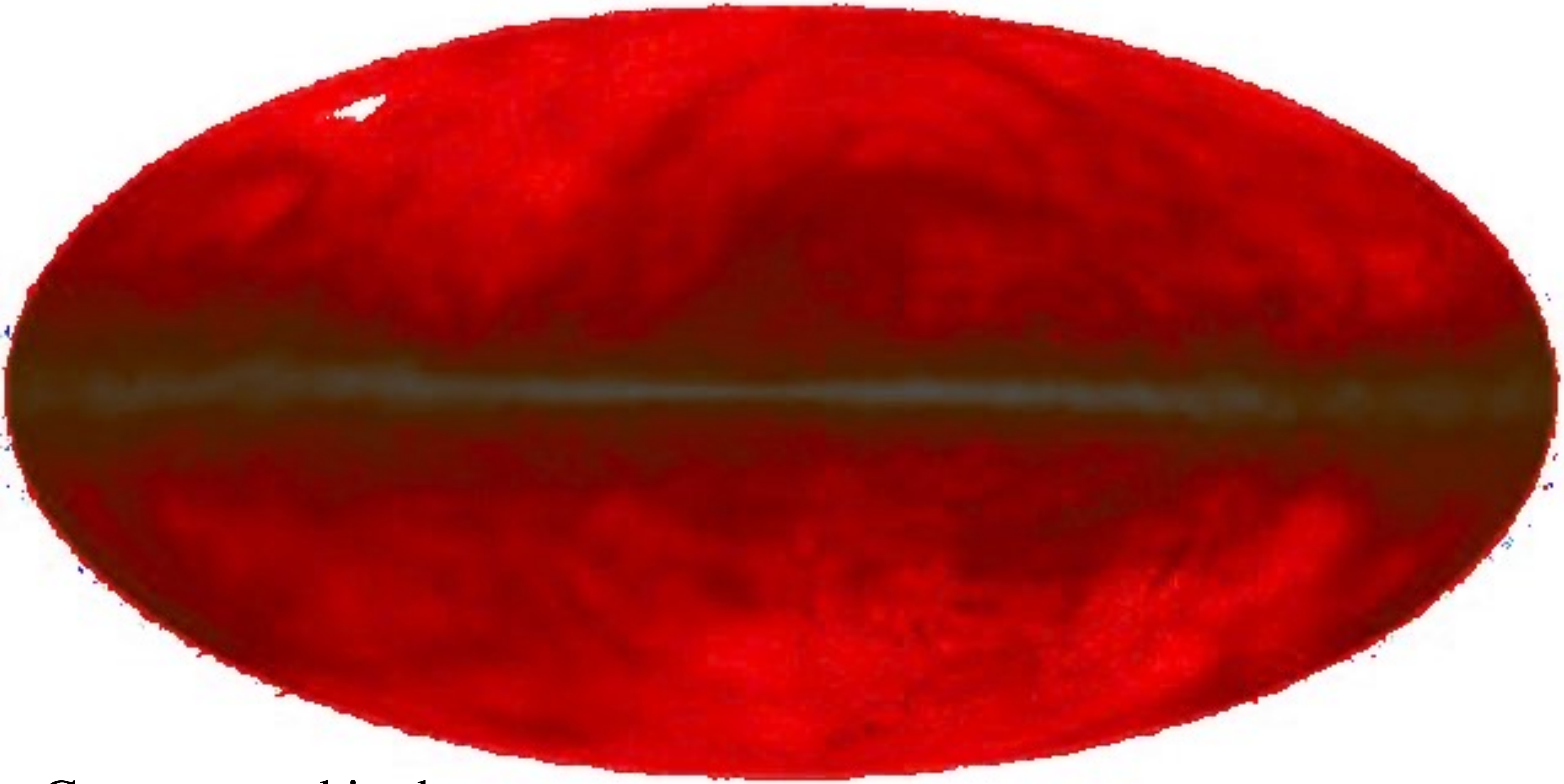
Reflection nebula: starlight reflected from the interstellar dust

Multi-Phase ISM

The ISM has a complex structure with 3 major components:

1. **Cold** ($T \sim 30 - 100$ K), dense ($n_{\mathrm{H\,I}} > 10$ cm^{-3}) atomic (H I) and molecular (H_2, CO, …) gas and dust clouds
   - ☆ Only ~ 1 - 5 % of the total volume, but most of the mass
   - ☆ Confined to the thin disk
   - ☆ Low ionization fraction ($x_{\mathrm{H\,II}} < 10^{-3}$)
   - ☆ Stars are born in cold, dense clouds
2. **Warm** ($T \sim 10^3 - 10^4$ K) neutral & ionized gas, $n \sim 1$ cm^{-3}
   - ☆ Energized mainly by UV starlight
   - ☆ Most of the total ISM volume in the disk
3. **Hot** ($T \sim 10^5 - 10^6$ K), low density ($n \sim 10^{-3}$ cm^{-3}) gas
   - ☆ Galactic corona
   - ☆ Almost fully ionized, energized mainly by SN shocks

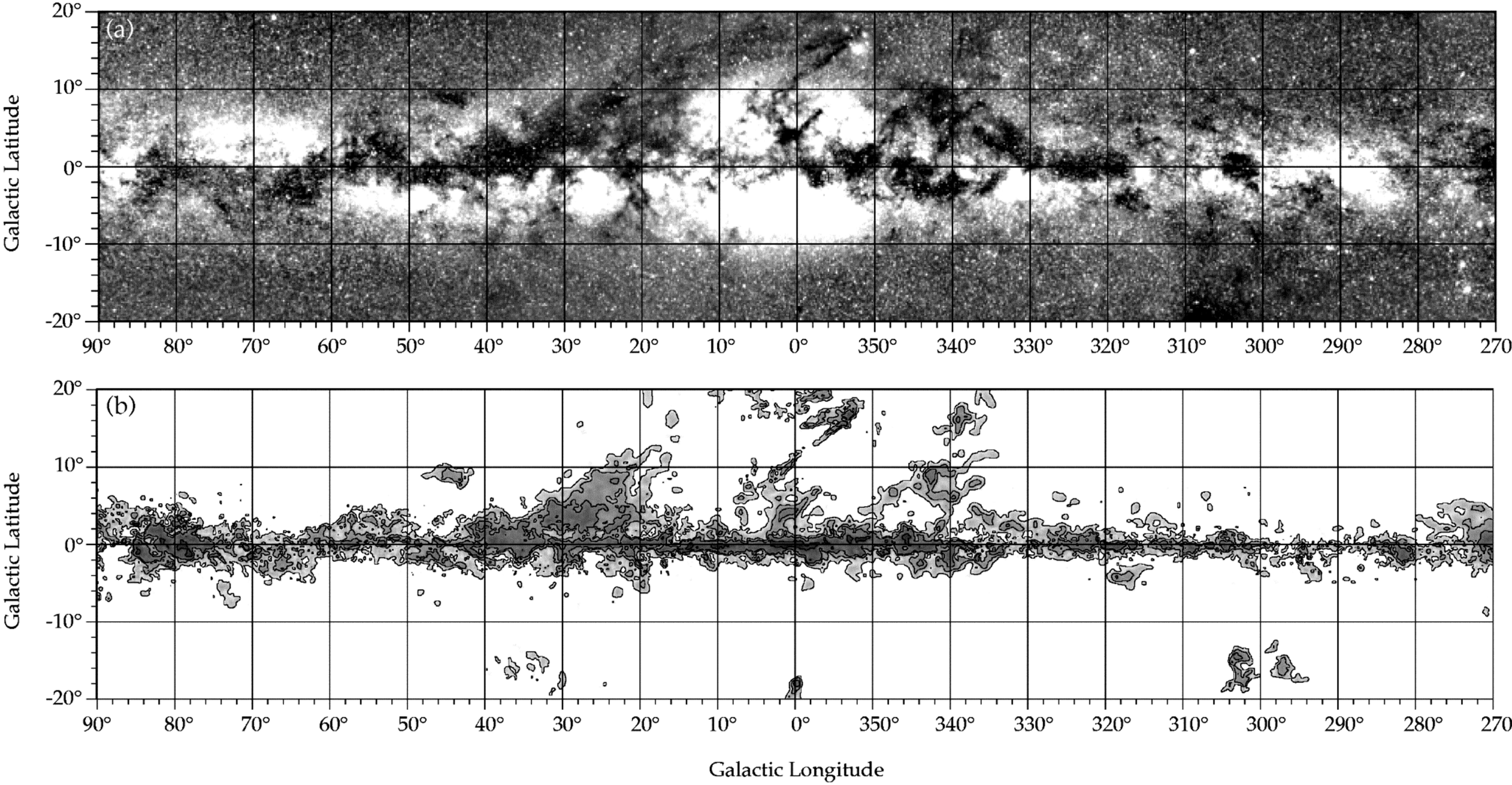
Global Distribution of H I in the Milky Way



Concentrated in the
Galactic Plane, but high-latitude features exist. These are believed to be remnants of SN and star formation driven shells and bubbles.

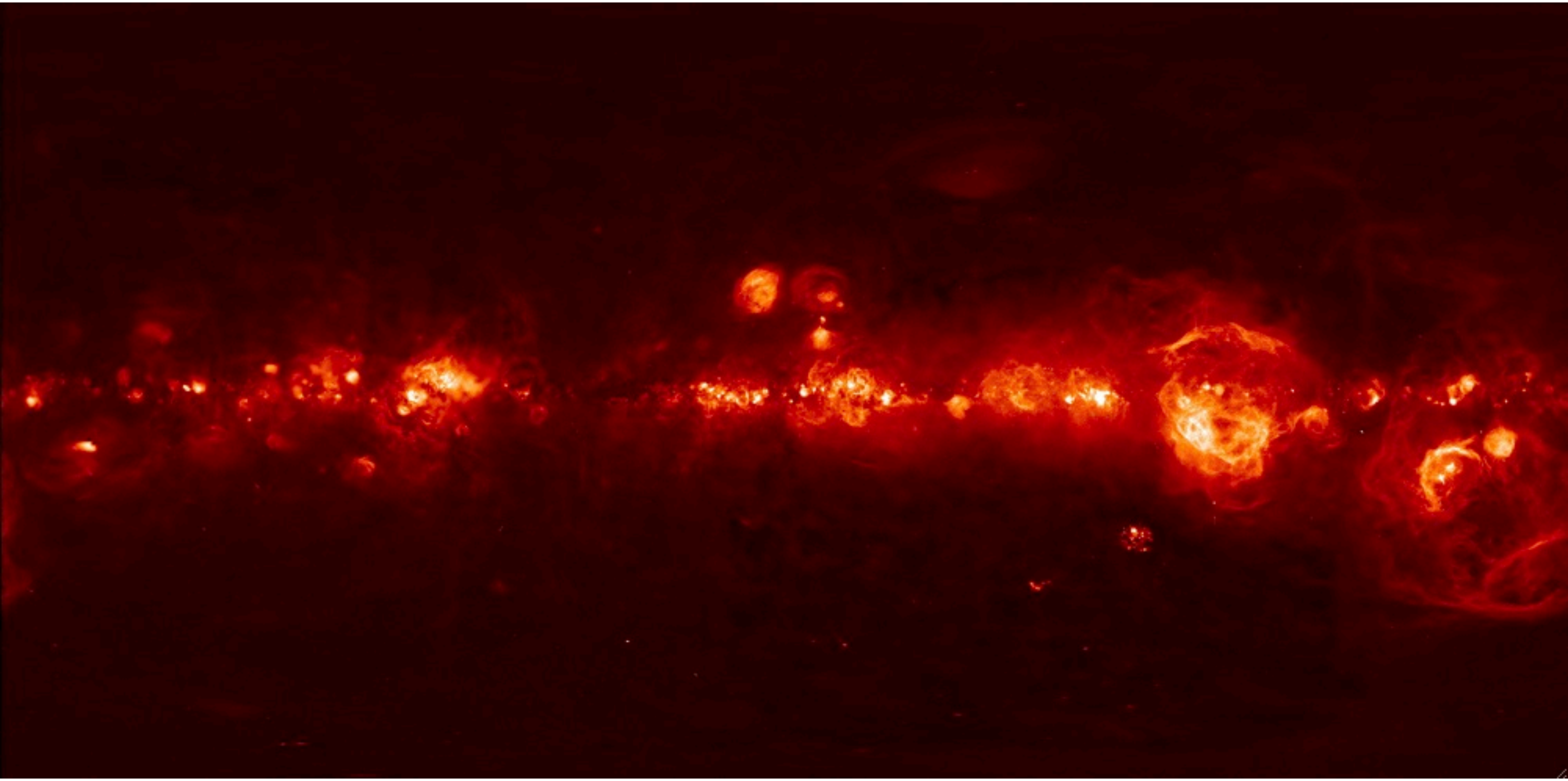
Milky Way:

Visible Light (with obscuration from dust lanes)



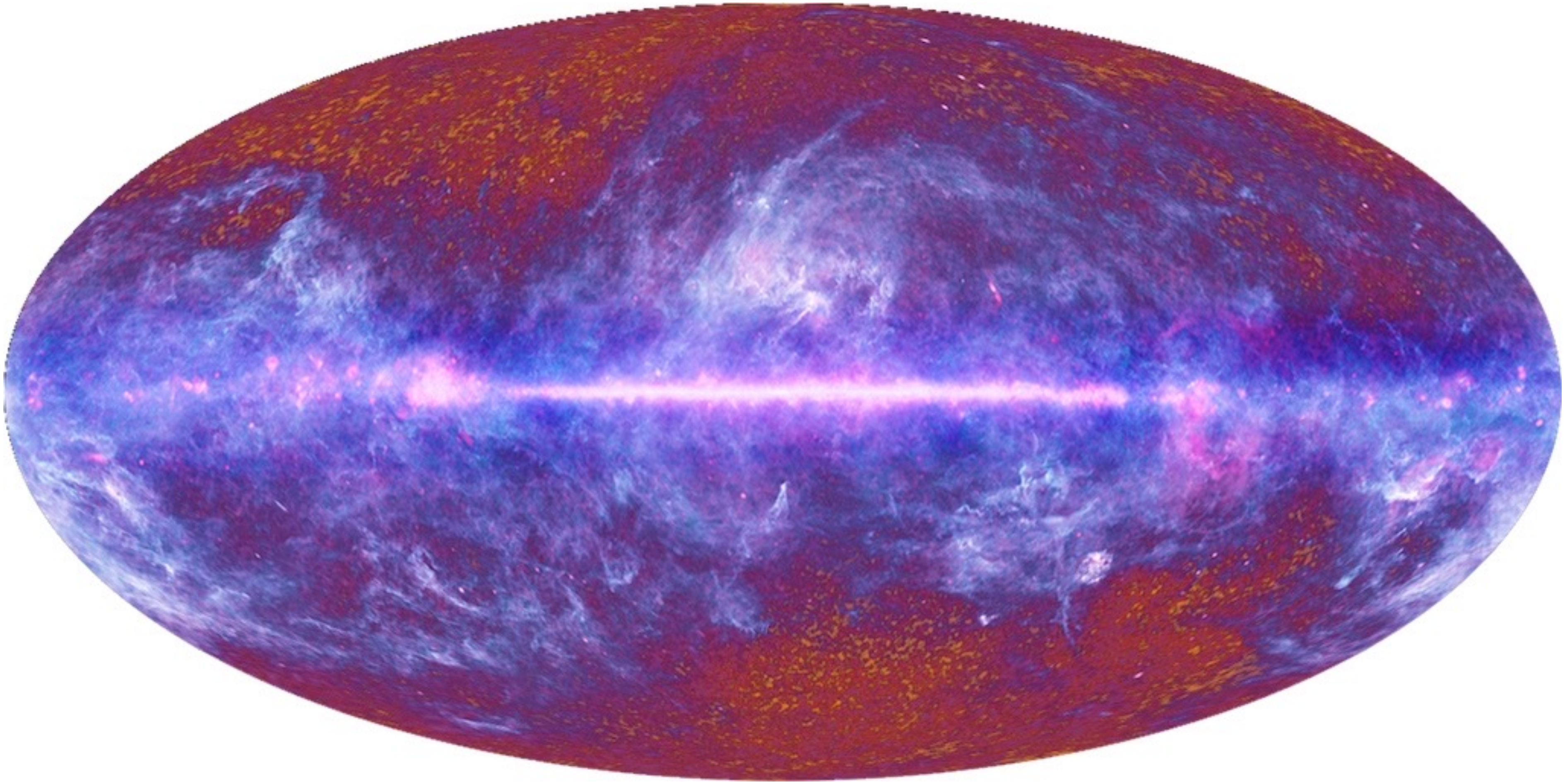
Molecular Gas (CO) - note correspondence with the dust lanes

Composite Hα Image of the Galaxy (Warm/Ionized ISM)



(From D. Finkbeiner)

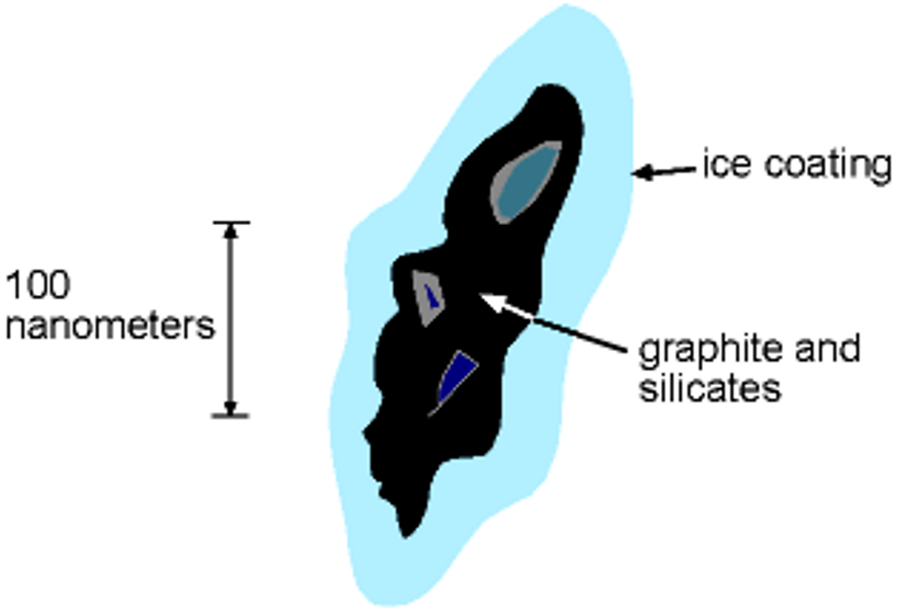
Galactic Dust Emission Map



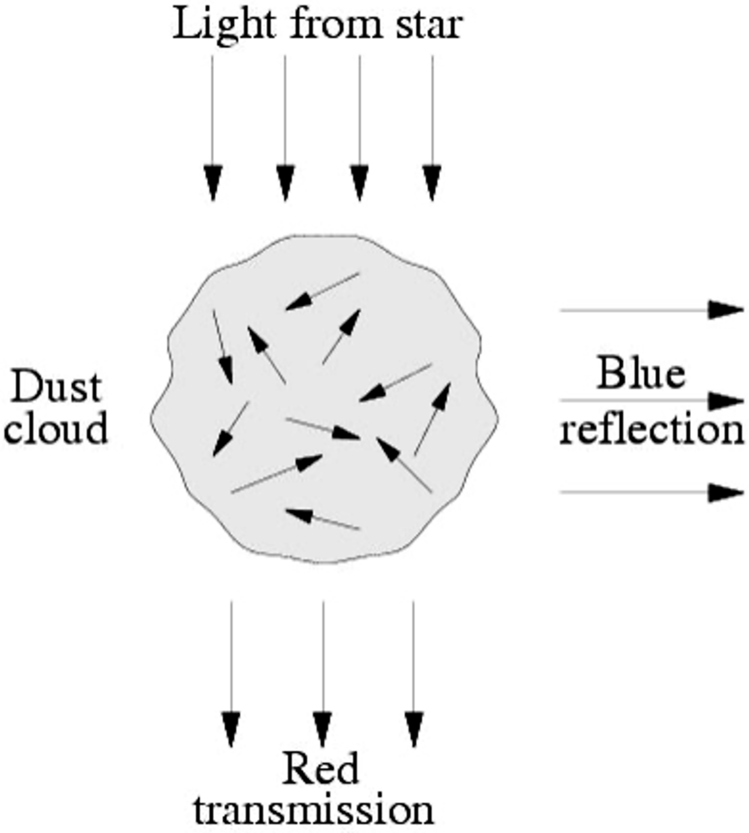
Planck

Interstellar Dust Grains

Probability of interaction with a photon increases for photons whose wavelength is comparable to or smaller than the grain size; longer wavelength photons pass through. Thus interstellar extinction = $f(\lambda)$. (Note: this breaks down for high-energy photons)

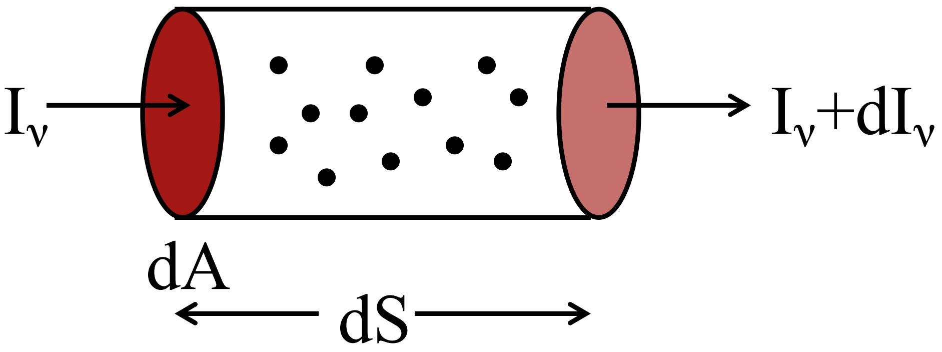


A typical dust grain (note the tiny scale!).



Absorption of Light

If the radiation travels through a medium which absorbs (or scatters) radiation, the energy in the beam will be reduced:



Number density of absorbers (particles per unit volume) = n
Each absorber has cross-sectional area = σ_ν (units cm^2)

If beam travels through dS, total area of absorbers is:

$$\text{number of absorbers} \times \text{cross-section} = n \times dA \times dS \times \sigma_\nu$$

Absorption of Light

Fraction of radiation absorbed = fraction of area blocked:

$$\frac{dI_\nu}{I_\nu} = -\frac{n\,dA\,ds\,\sigma_\nu}{dA} = -n\sigma_\nu ds$$

$$dI_\nu = -n\sigma_\nu I_\nu ds \equiv -\underset{\uparrow}{\alpha_\nu} I_\nu ds$$

absorption coefficient (units cm^{-1})

The solution of this differential equation is:

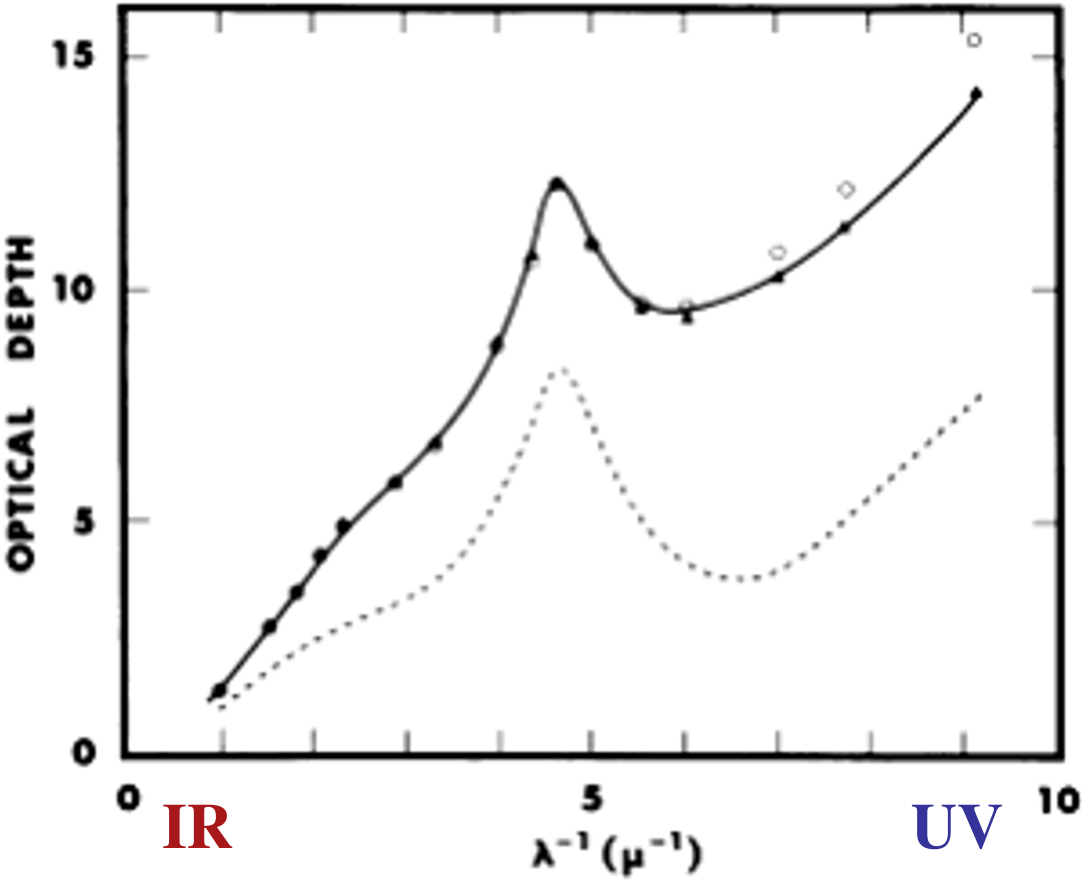
$$\int dI_\nu / I_\nu = \ln I_\nu = \int -\alpha\, dS = -\alpha\, S$$

$$I_\nu(S) / I_\nu(0) = \exp(-\alpha\, S)$$

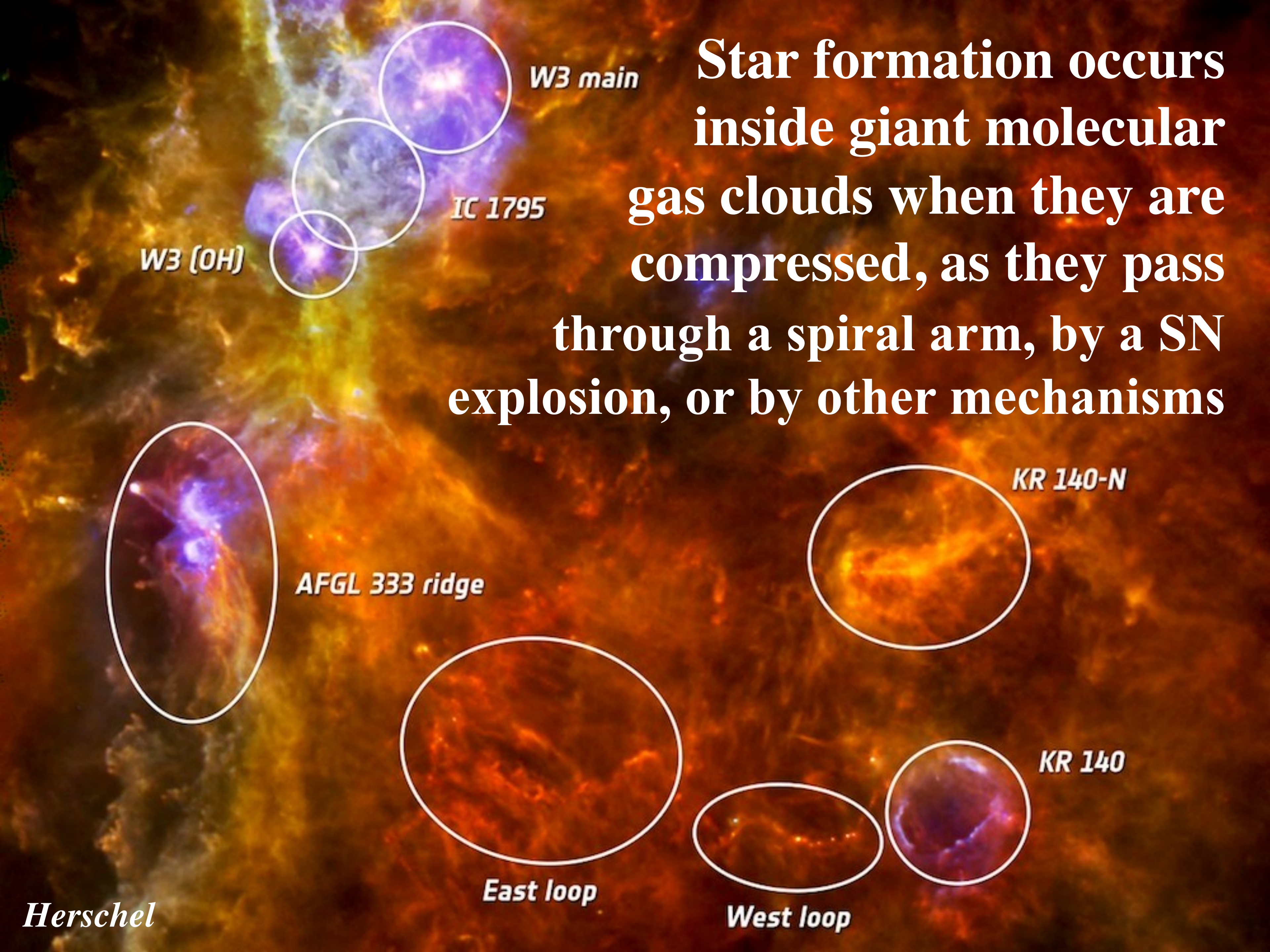
Extinction is an exponential process

Interstellar Extinction Curve

Note: this is a log of the decrement! (i.e., just like magnitudes)



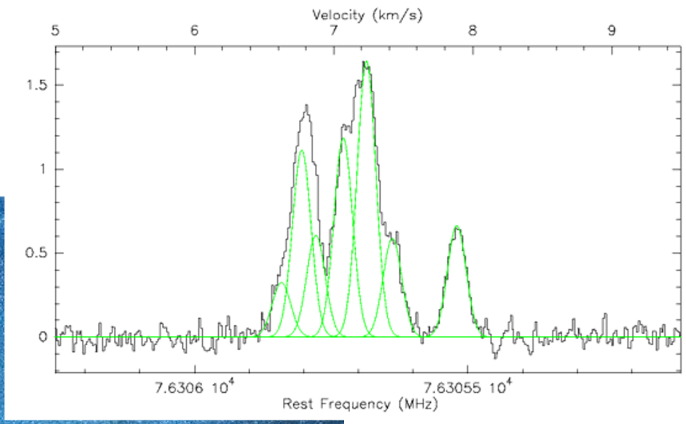
The bump at λ ~ 2200 Å is due to silicates in dust grains. This is true for most Milky Way lines of sight, but not so in some other galaxies, e.g., the SMC.

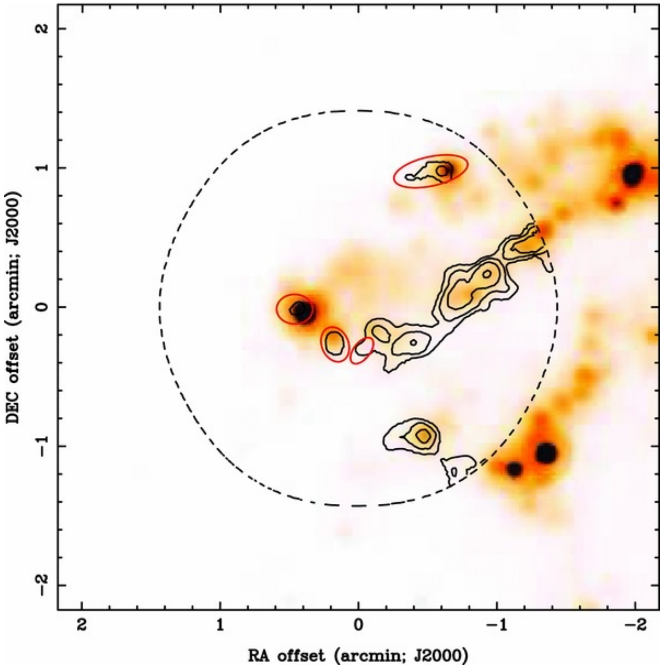


Star formation occurs inside giant molecular gas clouds when they are compressed, as they pass through a spiral arm, by a SN explosion, or by other mechanisms

Herschel

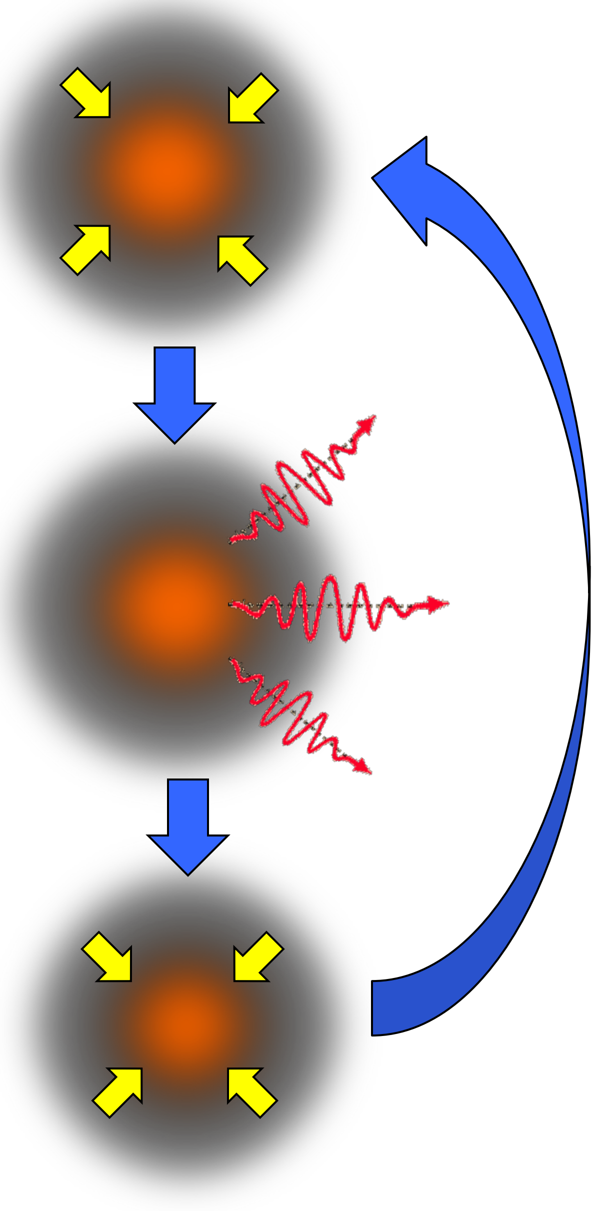
Molecular Clouds are Typically Studied With the mm Interferometers, like ALMA





Some commonly found interstellar molecules: H_2, CO, NH_3, … some very complex organic molecules…

Why Protostellar Clouds Collapse



Thermal pressure in the core balances the gravitational pressure

Heat escapes from the core, and the cloud shrinks a little as the kinetic energy is removed

The core heats up so that the thermal pressure balances the gravitational pressure

Basic Physics of Star Formation

Consider the forces acting on a protostellar cloud within a molecular cloud or its core:

- Gravity - acts to collapse the cloud
- Pressure
- Magnetic fields
- Bulk motions

} sources of support against collapse to form a star

If somehow we form a core in which gravity dominates over all other forces, collapse will occur on the dynamical or ***free-fall time***:

$$v_{esc} = \sqrt{\frac{2GM}{R}} \qquad \tau_{dyn} = \frac{R}{v_{esc}} = \sqrt{\frac{R^3}{2GM}} \sim \frac{1}{\sqrt{G\bar{\rho}}}$$

…for a cloud of mass M, radius R, and mean density ρ

The Jeans Mass

The *Jeans mass* is the minimum mass a cloud must have if gravity is to overwhelm pressure and initiate collapse:

$$M_J = \left(\frac{R_g}{\mu G}\right)^{3/2} \left(\frac{3}{4\pi}\right)^{1/2} T^{3/2} \rho^{-1/2}$$

R_g = Gas constant, *not* radius! μ = mean molecular weight

Typical values for the molecular gas:

- $\varrho \sim 10^{-19}$ g cm^{-3}
- T ~ 10 K

Use these numbers in the Jeans mass formula, and take μ = 2 for molecular hydrogen:

$$M_J = 7.6 \times 10^{32} \text{ g} \approx 0.4 M_{sun}$$

The Jeans Mass

Can likewise define a characteristic length scale (the Jeans length), by eliminating mass rather than radius from the previous expression:

$$\frac{4}{3}\pi R^3 \rho = \frac{R_g}{\mu G} T R$$

$$R_J = \left(\frac{R_g}{\mu G}\right)^{1/2} \left(\frac{3}{4\pi}\right)^{1/2} T^{1/2} \rho^{-1/2}$$

For the same density / temperature as before, $R_J = 10^4$ AU

Free-fall timescale for a cloud of this density is:

$$\tau_{dyn} \approx \frac{1}{\sqrt{G\rho}} = 10^{13} \text{ s} = 4 \times 10^5 \text{ yr}$$

This is just barely shorter than the lifetimes of most massive stars

Most stars form in clusters or groups

Young stars ionize the gas and evaporate the dust

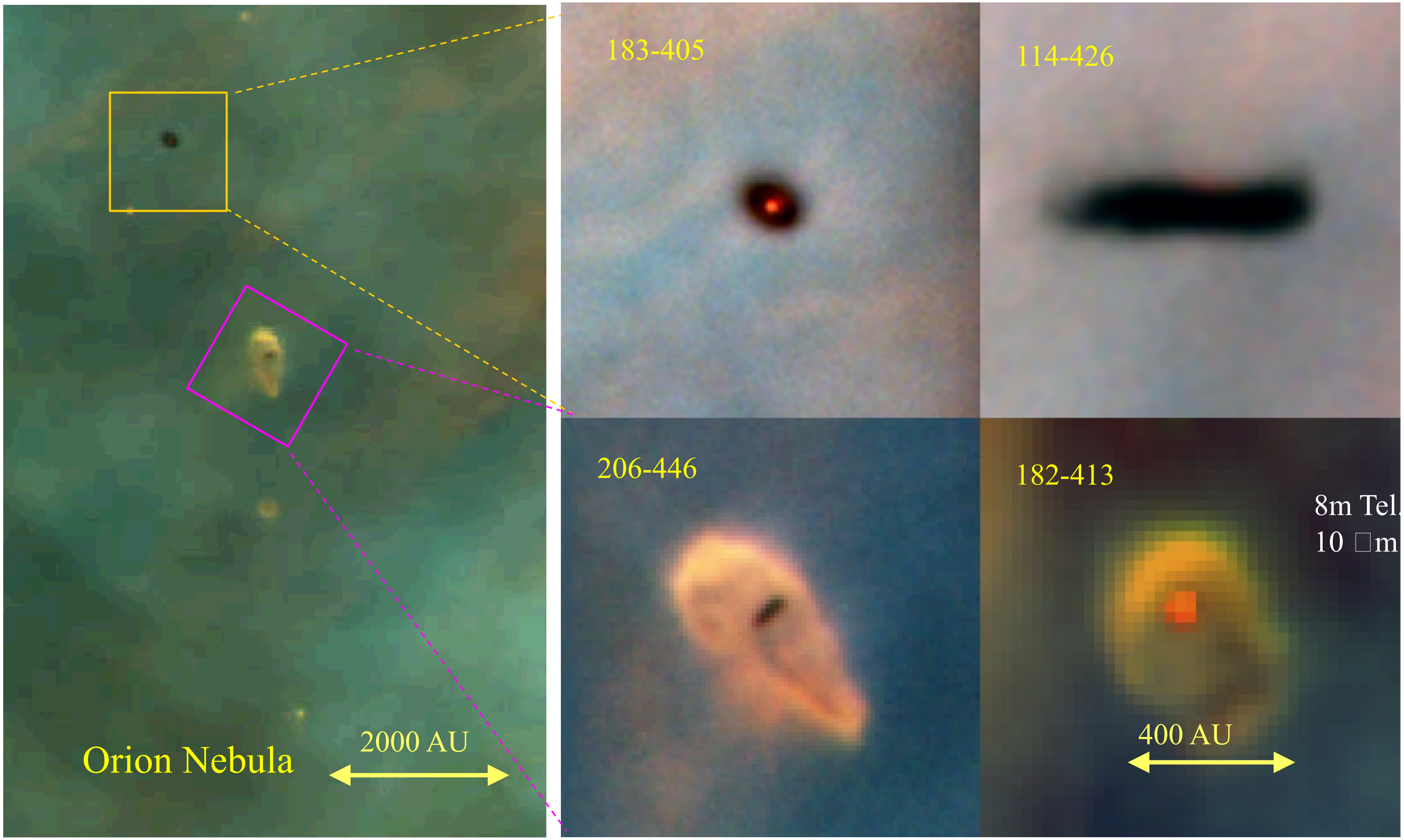
Supernovae are even more effective
in clearing out the gas and dust

This stops the
star formation

NGC 602 (HST)

A protostellar cloud core forms a star, and material with an excess angular momentum forms a protostellar disk

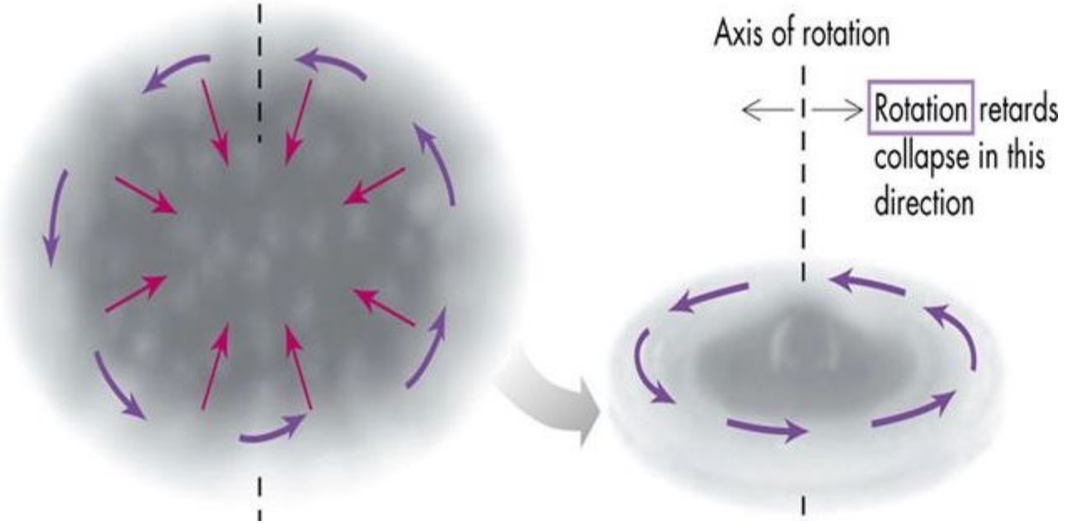
Direct Images of Circumstellar Disks



From HST. O’Dell & Wen 1992, McCaughrean & O’Dell 1996

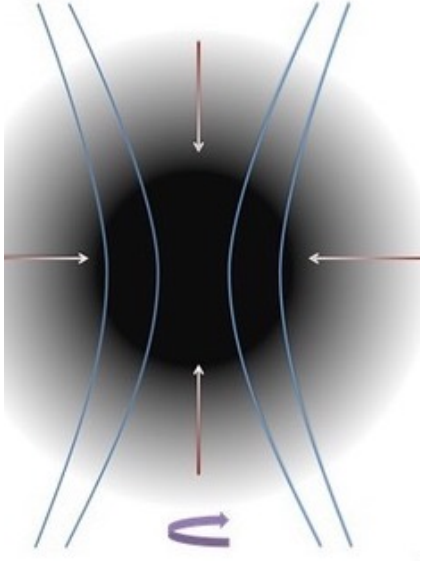
Why Disks?

Because you can dissipate the energy, but cannot dissipate the angular momentum

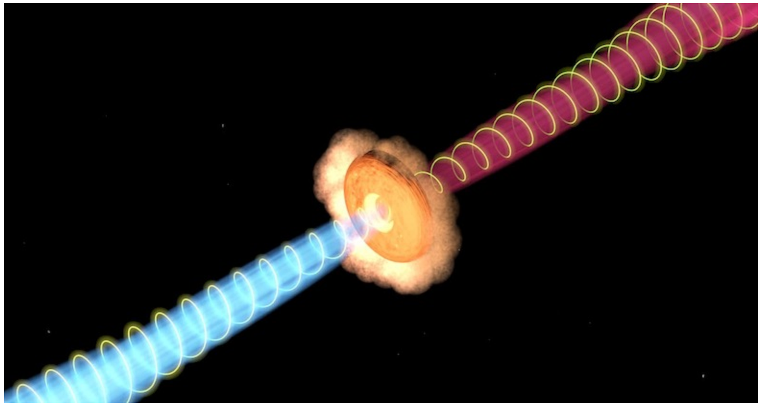


The material with the excess angular momentum settles into a disk – the lowest energy configuration for a given angular momentum

Why Jets?

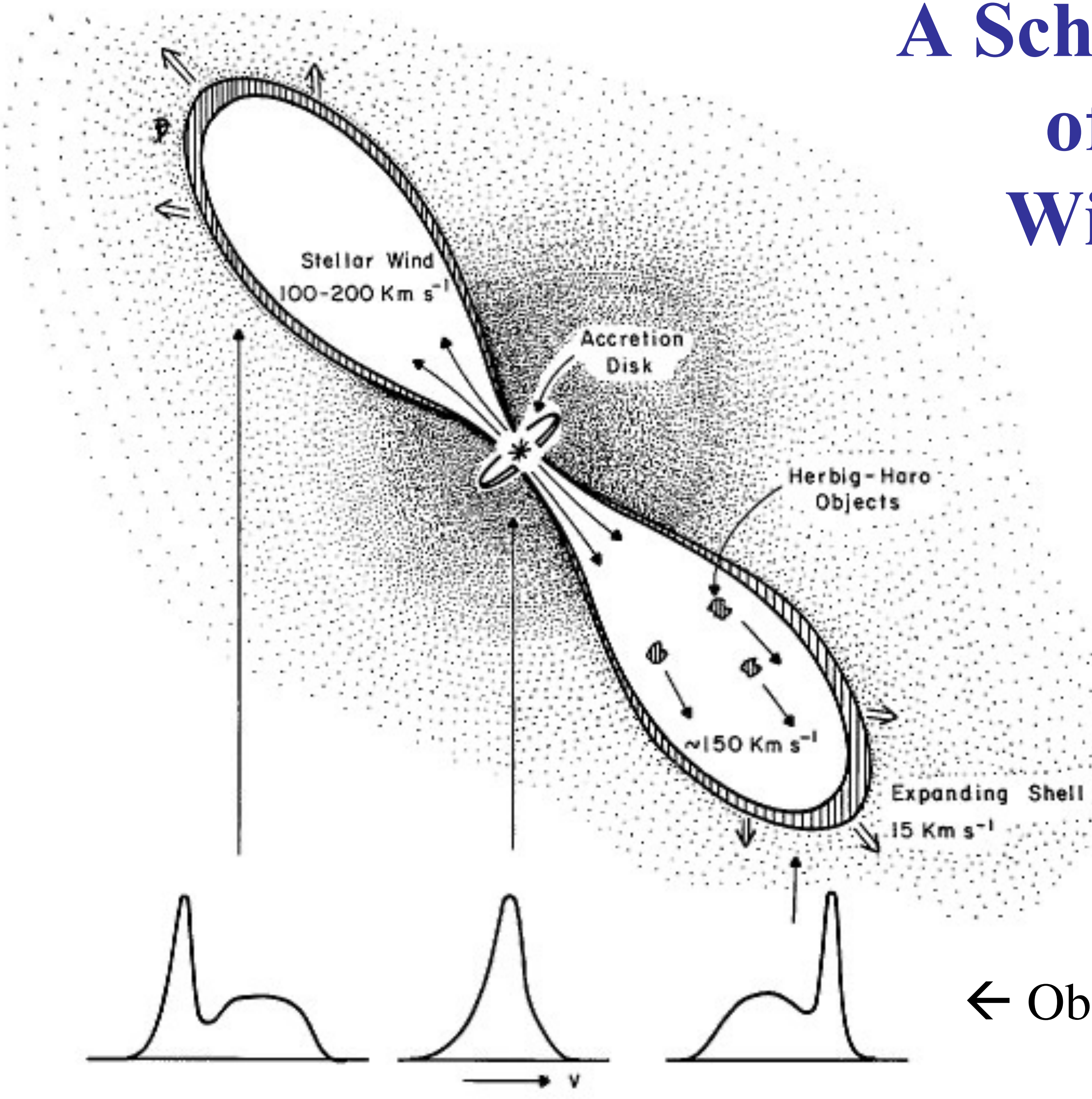


Magnetic fields are trapped in the collapsing cloud and the disk



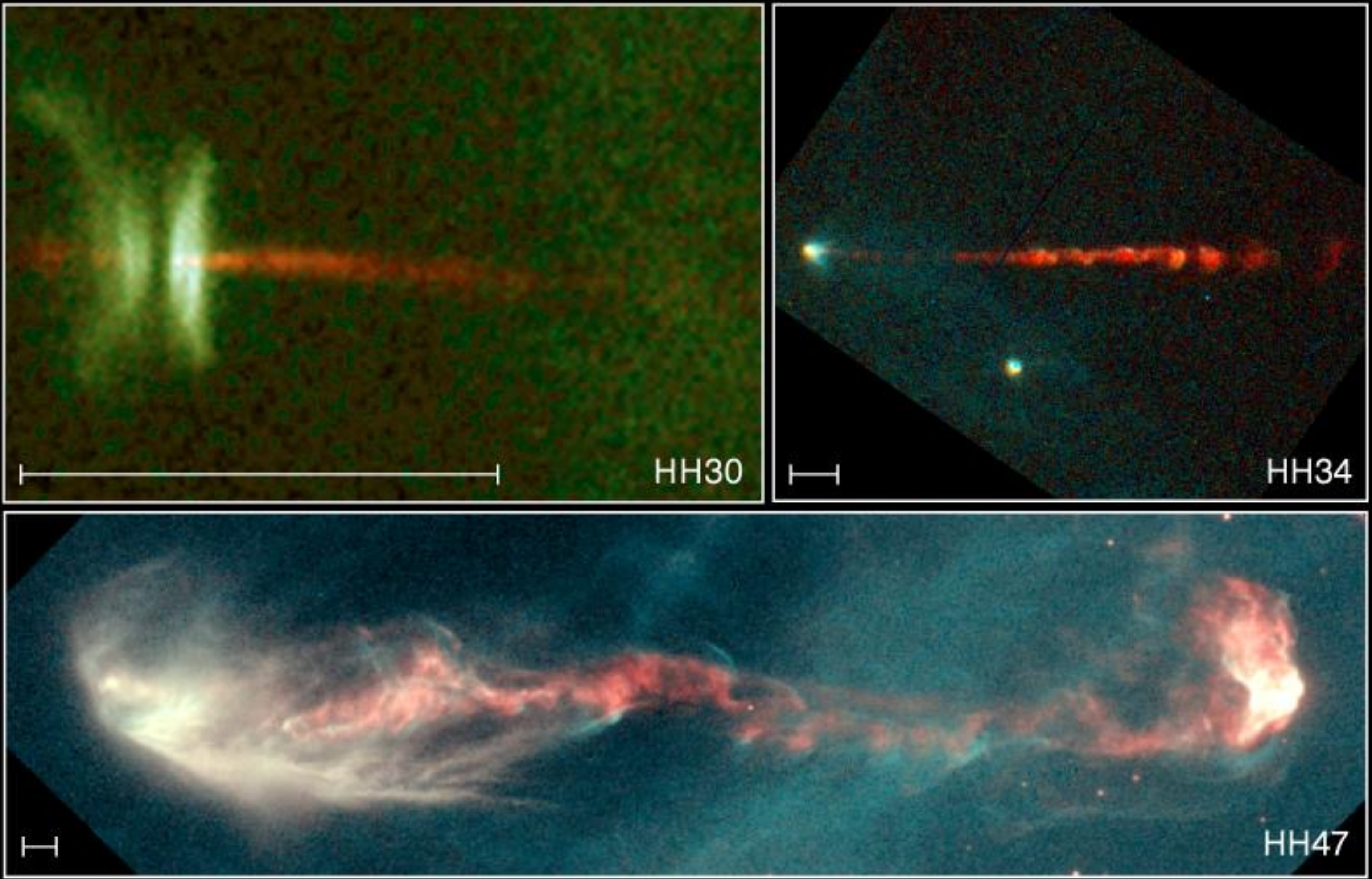
Disk rotation then winds up the field, making it even stronger – it then accelerates charged particles along the rotation axis

A Schematic View of a Protostar With a Bipolar Outflow



The outflows are due to the magnetic field that is threaded through the disk

← Observed line profiles



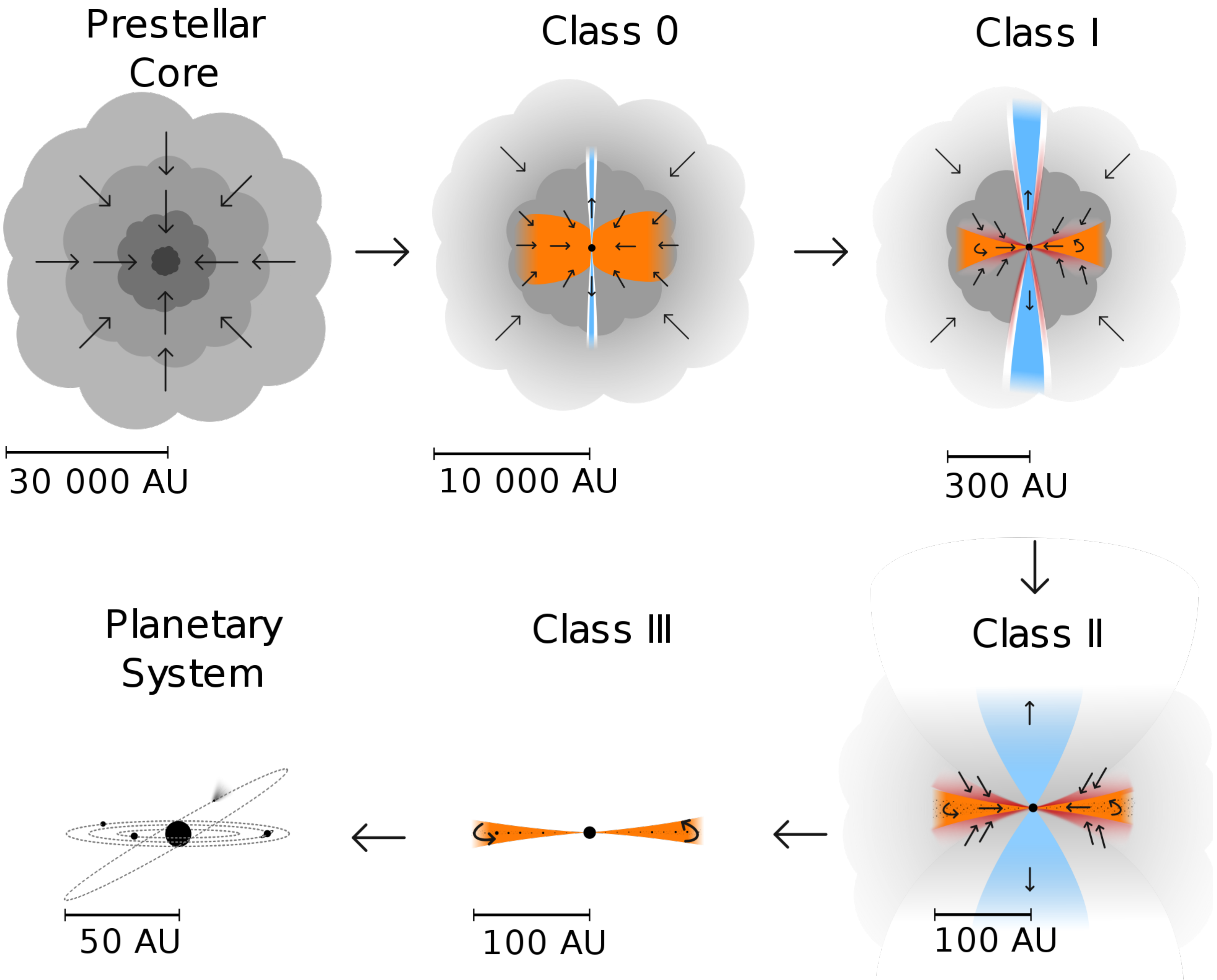
Jets from Young Stars

HST · WFPC2

PRC95-24a · ST ScI OPO · June 6, 1995

C. Burrows (ST ScI), J. Hester (AZ State U.), J. Morse (ST ScI), NASA

Protostellar Evolution



Prestellar Core

30 000 AU

Class 0

10 000 AU

Class I

300 AU

Class II

100 AU

Class III

100 AU

Planetary System

50 AU

Formation of Planetary Systems

Protoplanetary disks contain dust - micron sized solid particles formed for example in the stellar winds of some stars.

Initially the dust is uniformly mixed with the gas in the disk, but over time it will settle under gravity toward the midplane of the gas disk.

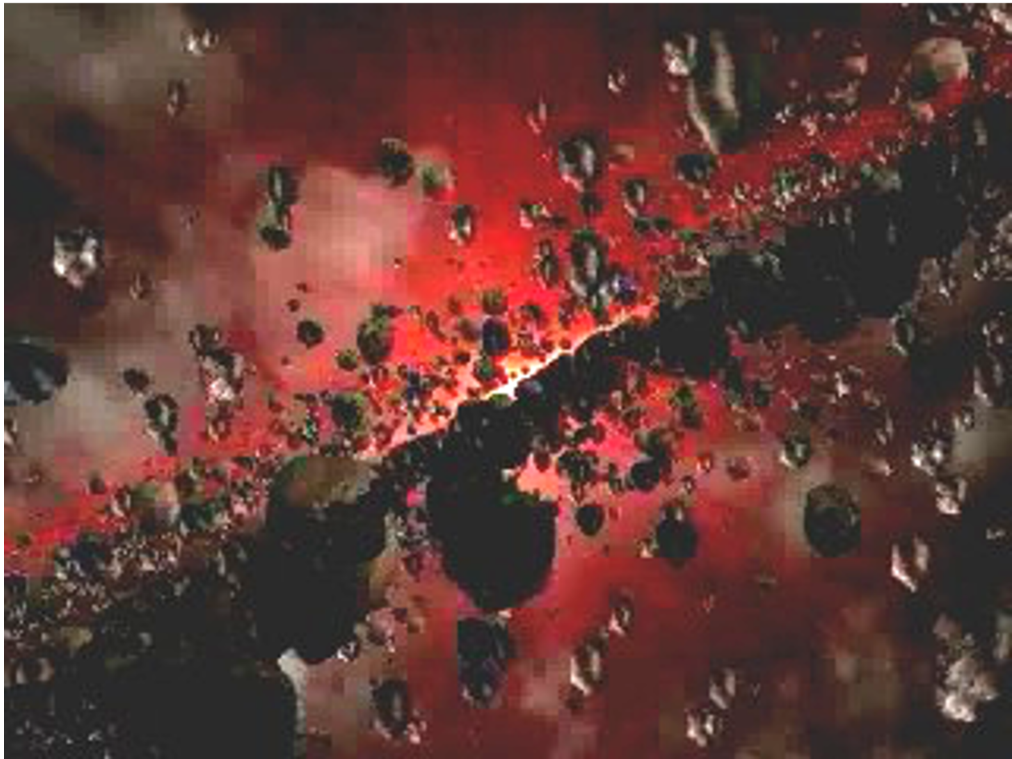
Collisions between particles lead to growth:

- Initially because particles are “sticky” - dissipate energy of relative velocity on impact
- Eventually because bodies become large enough that their own gravity attracts other bodies

Dust	→	**Pebbles / rocks**	→	**Planetesimals**	→	**Planets**
microns		cm - m		km		10^3 km

Planet Building

- Jovian planets began as aggregating bits of rock and ice that reached 15 Earth masses and began to capture large amounts of He & H
- Terrestrial planets have very little H & He because their low masses can't keep these gases from evaporating
- The comets are just remains of the icy planetesimals that Jupiter threw out far into the Solar system. They are fossils of the early Solar system

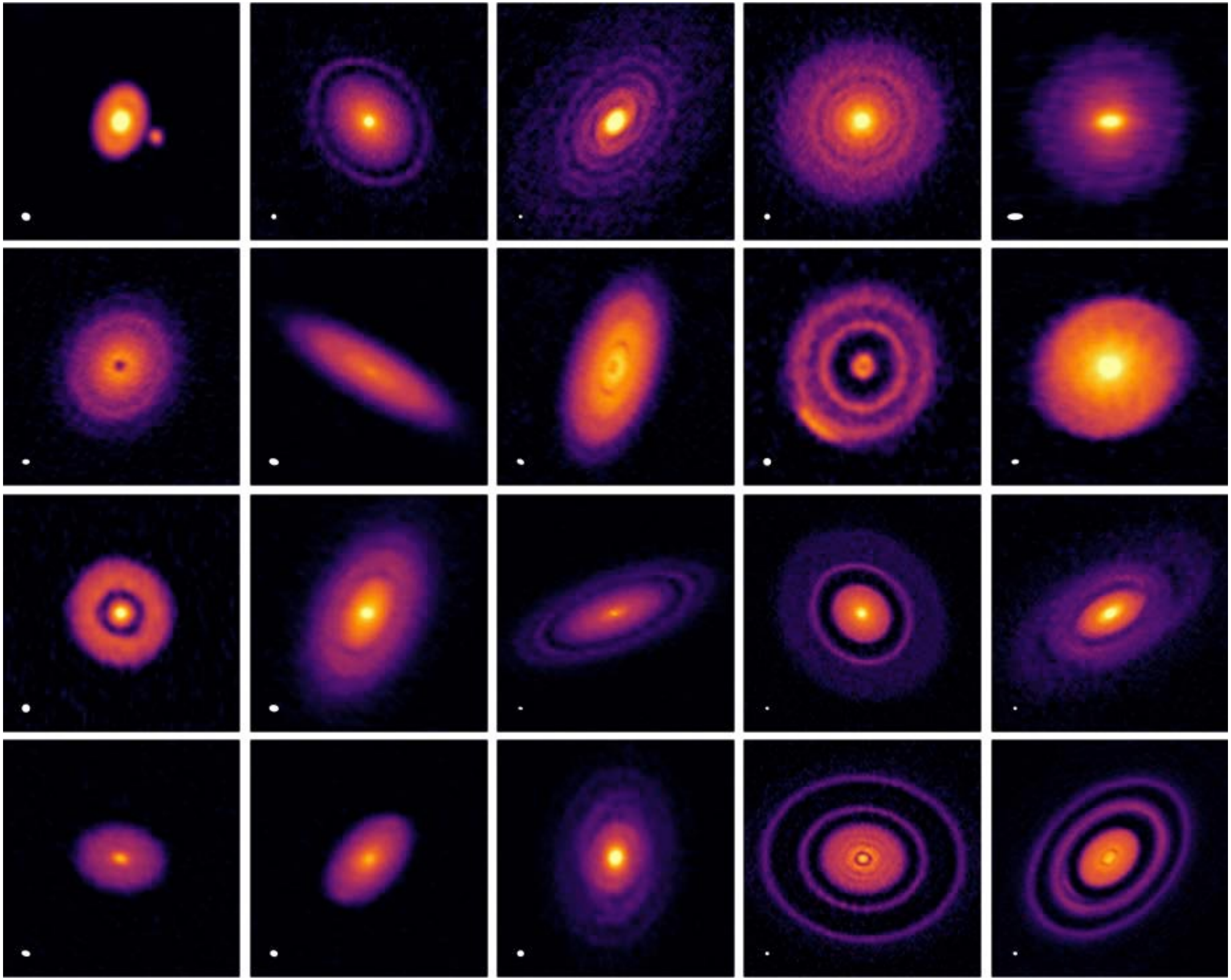


Clearing the Protosolar Nebula

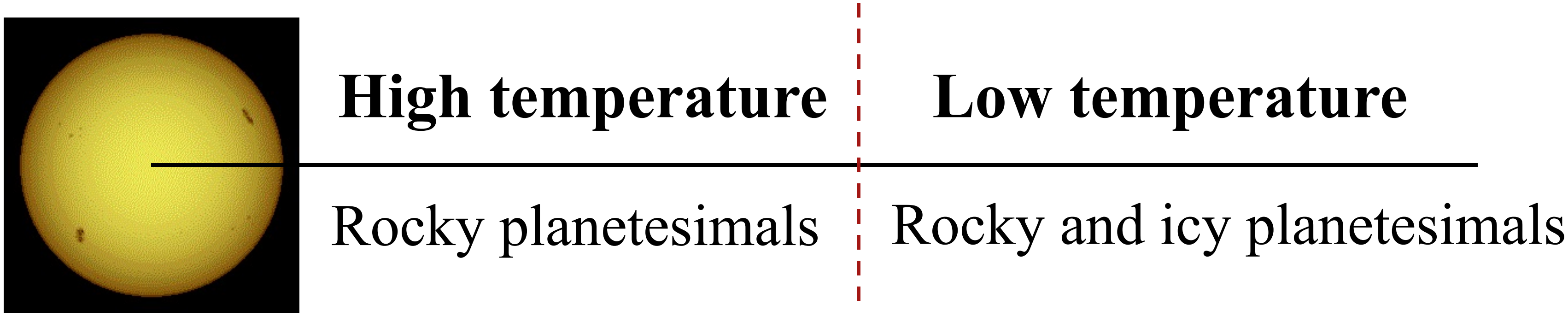
Four effects cleared the nebula:

1. **Radiation pressure**-light streaming from the sun pushed against the particles of the solar nebula.
2. **The solar wind**—flow of ionized H helped push dust and gas out of the nebula.
3. **Sweeping of space debris by the planets**—the moons and planets are constantly getting bombarded by meteorites. **Heavy bombardment**—was a period when the craters were formed roughly 4 billion years ago.
4. **Ejection of material from the solar system by close encounters with planets**

Protoplanetary Disks Observed by ALMA



Traditionally, understood this as resulting from a temperature gradient in the protoplanetary disk:

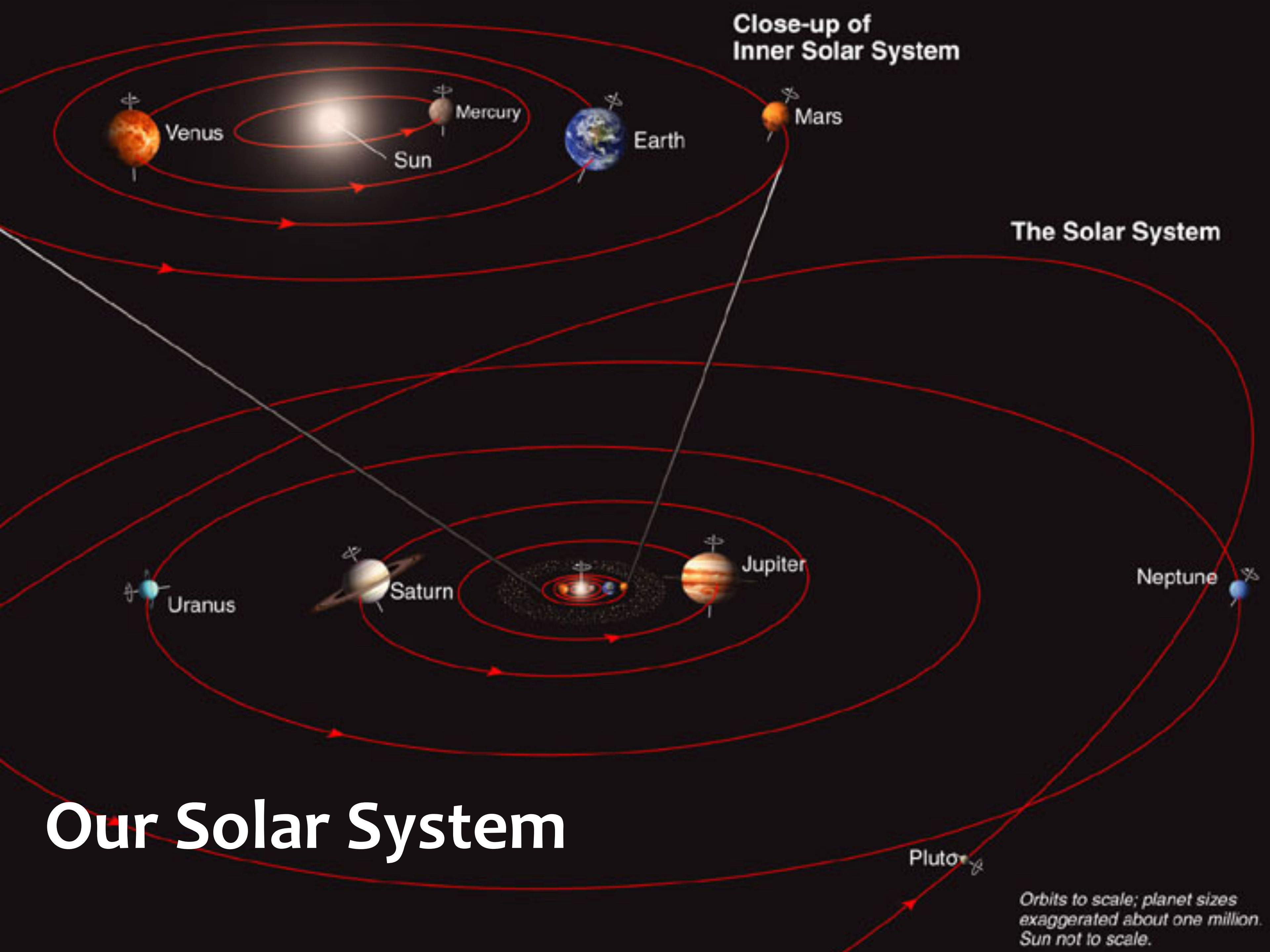


High temperature	Low temperature
Rocky planetesimals	Rocky and icy planetesimals

Snow (frost) line at r ~ 3 au

- Surface density of planetesimals is larger beyond the snow line, in parts of the disk cool enough for ice to be present
- Higher surface density → more rapid formation of planets
- In the outer Solar System, planets grew to ~20 M_{Earth} while gas was still present, captured gas to form gas giants
- In inner Solar System, no gas was captured
- All circular orbits as formed from a circular disk

Our Solar System



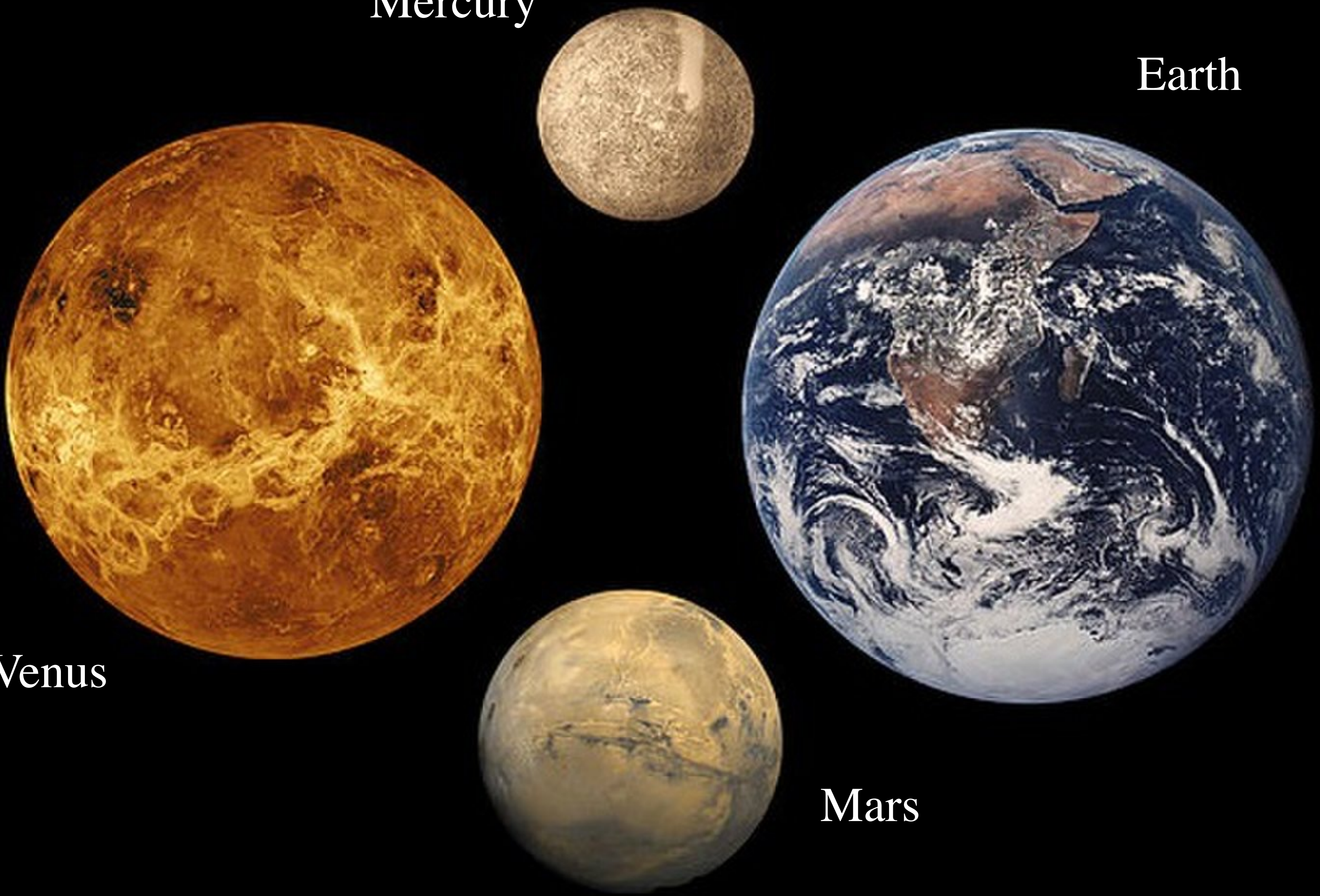
Three Kinds of Planets

- Rocky: inner Solar system, smaller, high density, composed of heavier elements
  - Mercury, Venus, Earth, Mars

- Gas giants: Outer Solar system, large, massive, lower densities, lighter elements are abundant
  - Jupiter, Saturn, Uranus, Neptune

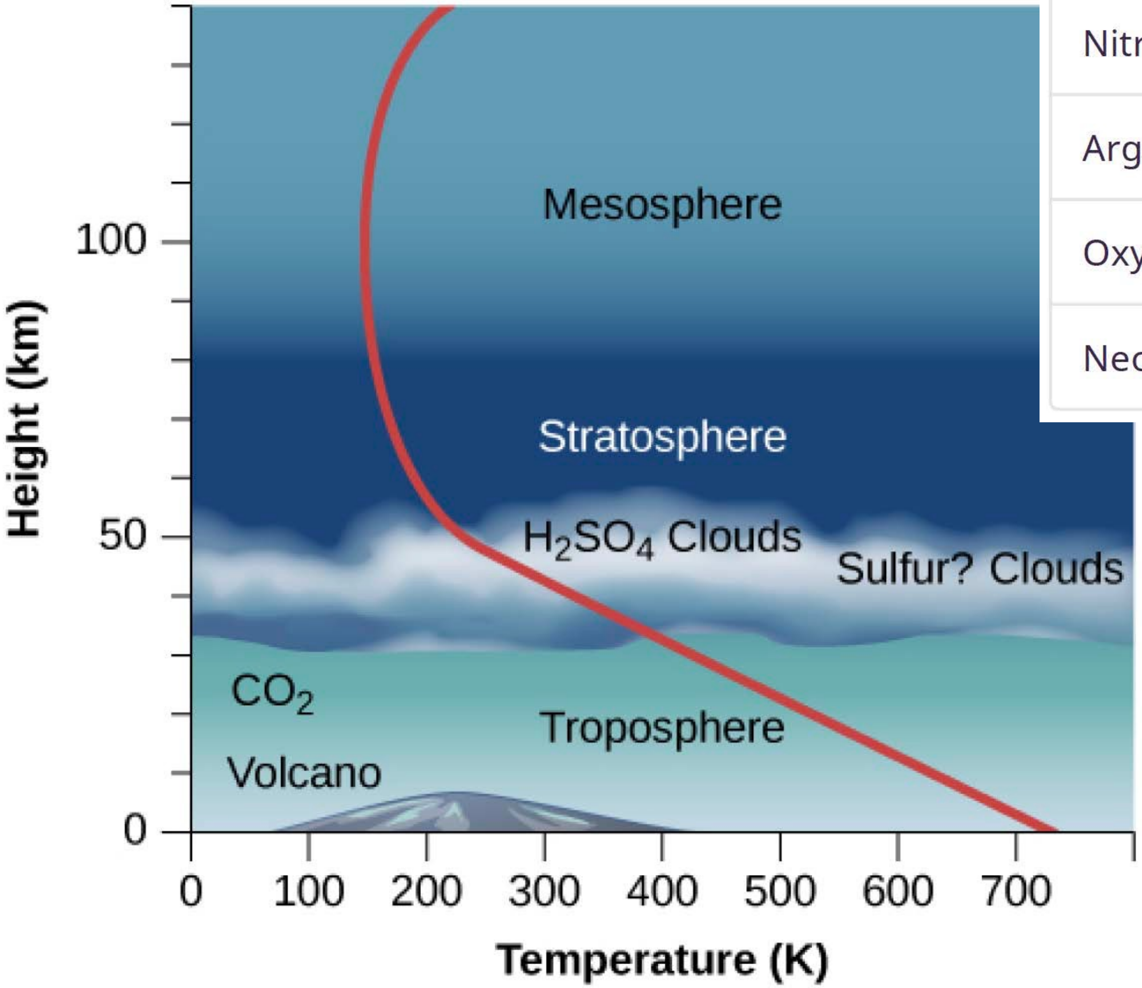
- Dwarf planets: Very Outer Solar system, low mass, small, icy
  - Pluto, Sedna, Eris, Makemake, Ceres, etc.

Inner Solar System (Rocky) Planets



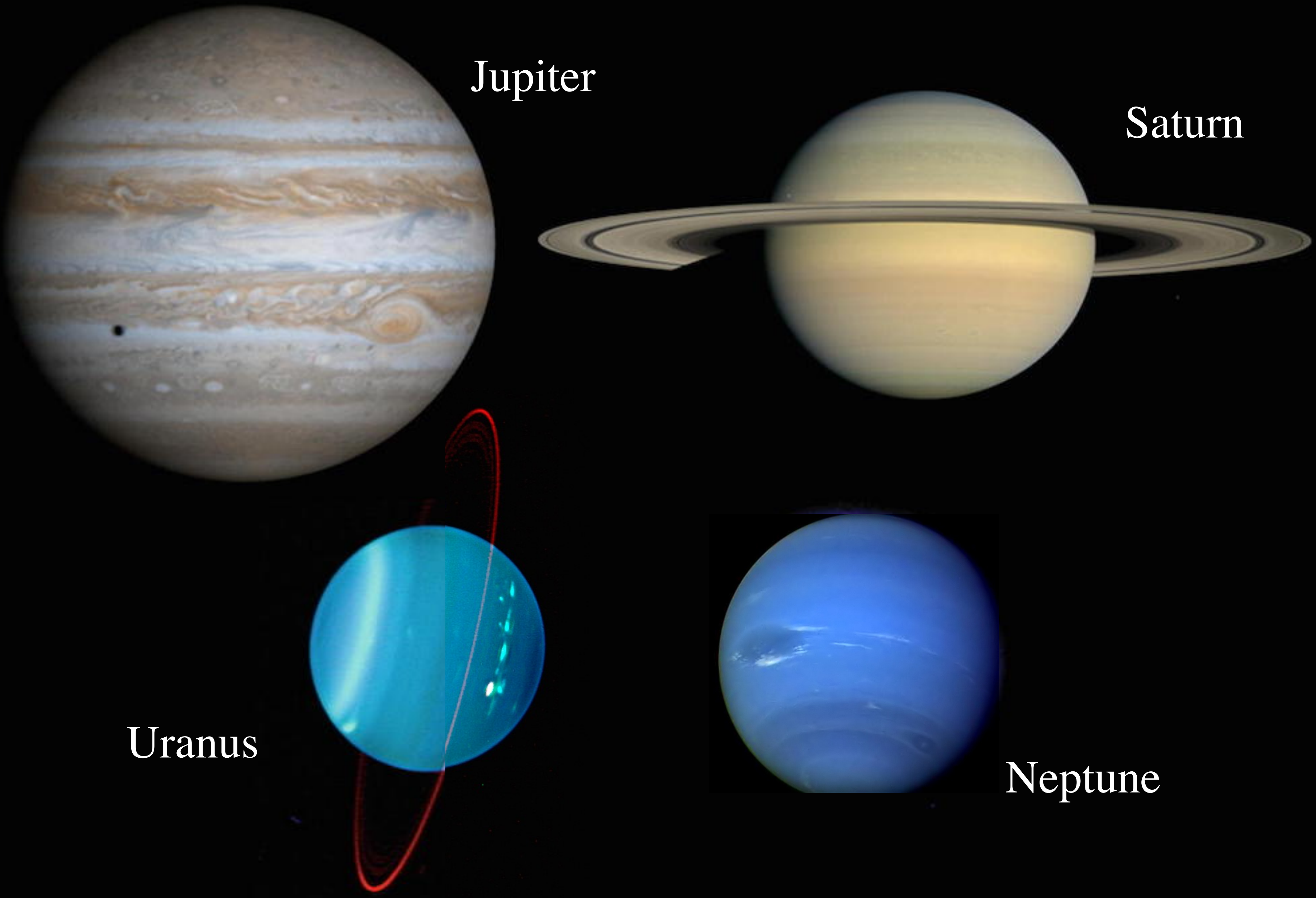
Runaway Greenhouse Effect on Venus

Gas	Earth	Venus
Carbon dioxide (CO_2)	0.03%	96%
Nitrogen (N_2)	78.1%	3.5%
Argon (Ar)	0.93%	0.006%
Oxygen (O_2)	21.0%	0.003%
Neon (Ne)	0.002%	0.001%

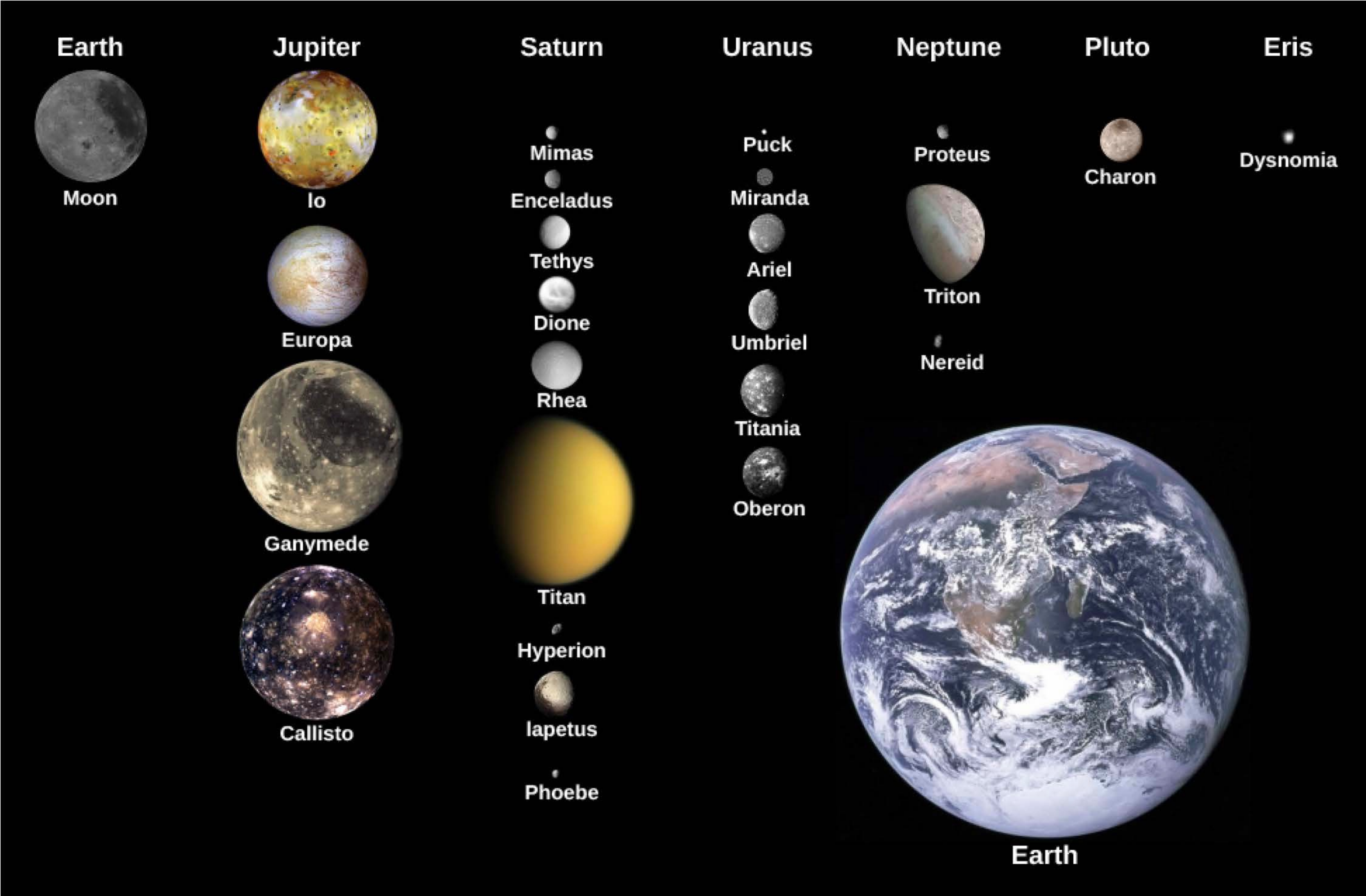


Water on Mars

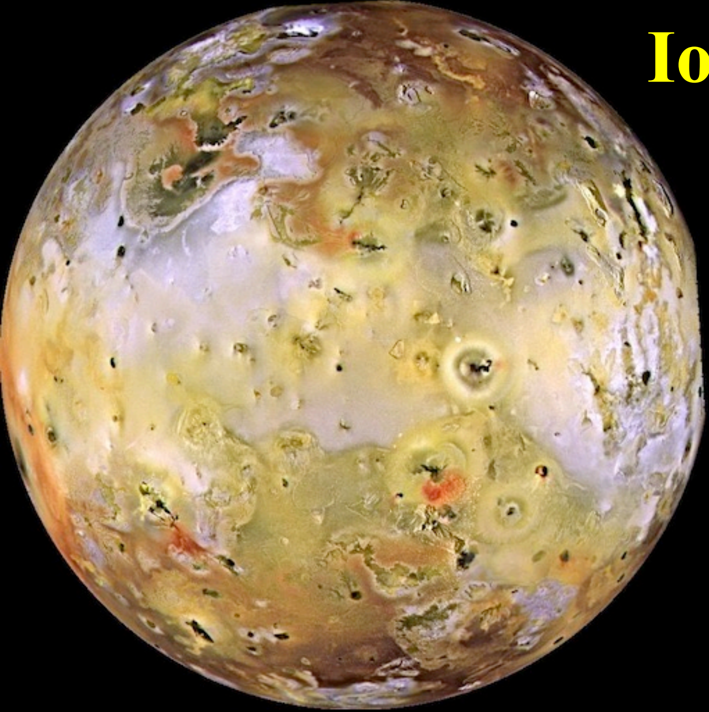
Solar System: Gas Giants



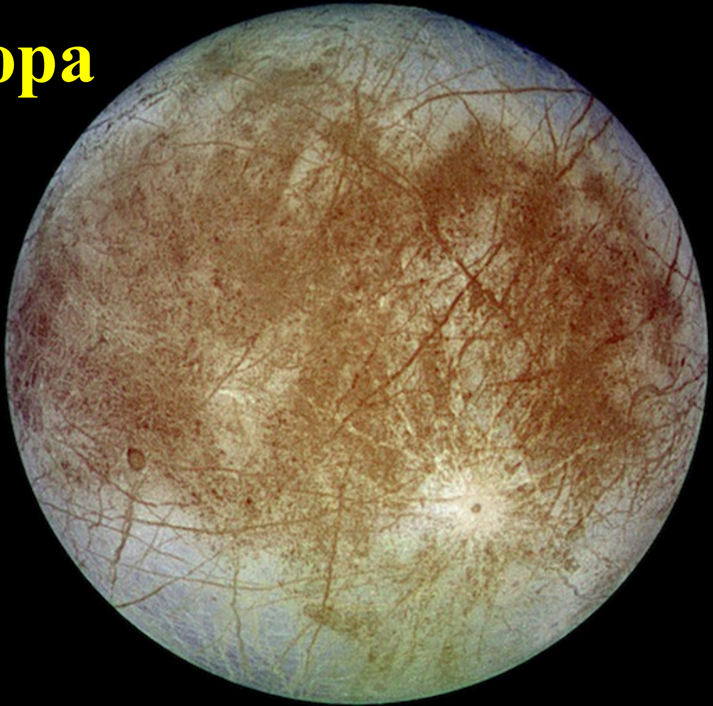
Larger Moons in the Solar System



Jupiter’s Moons



Io



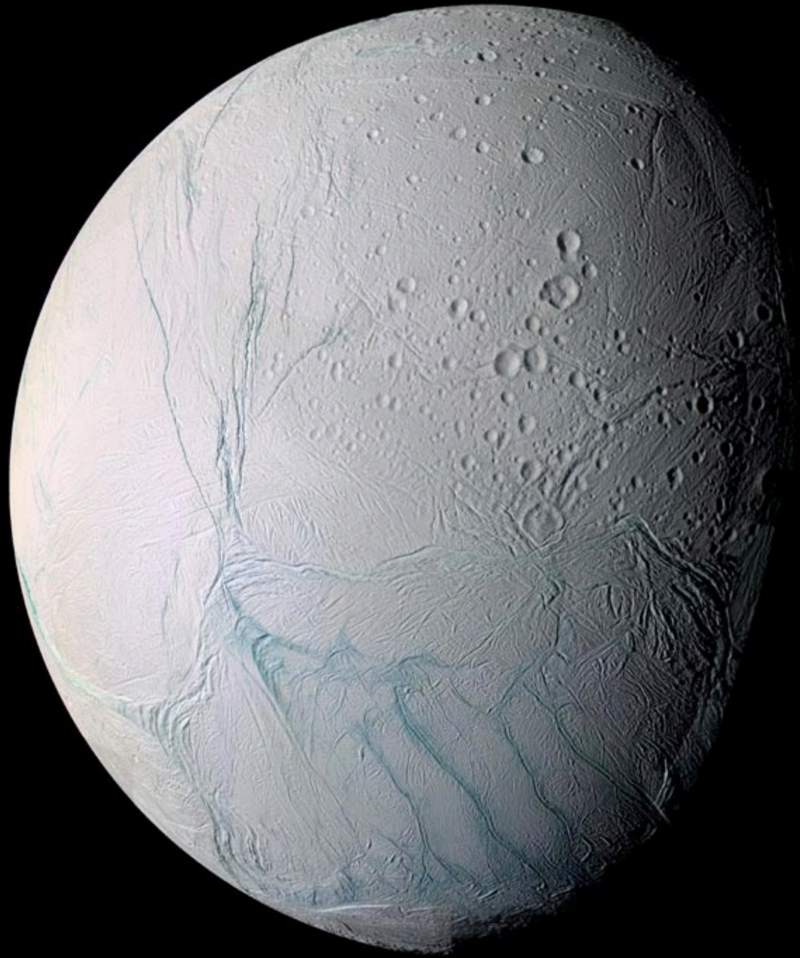
Europa

Ganymede

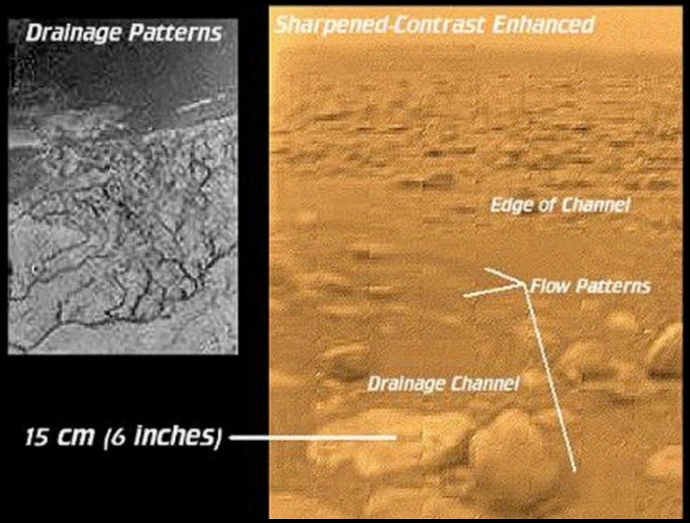
Calisto

Saturn’s Moons

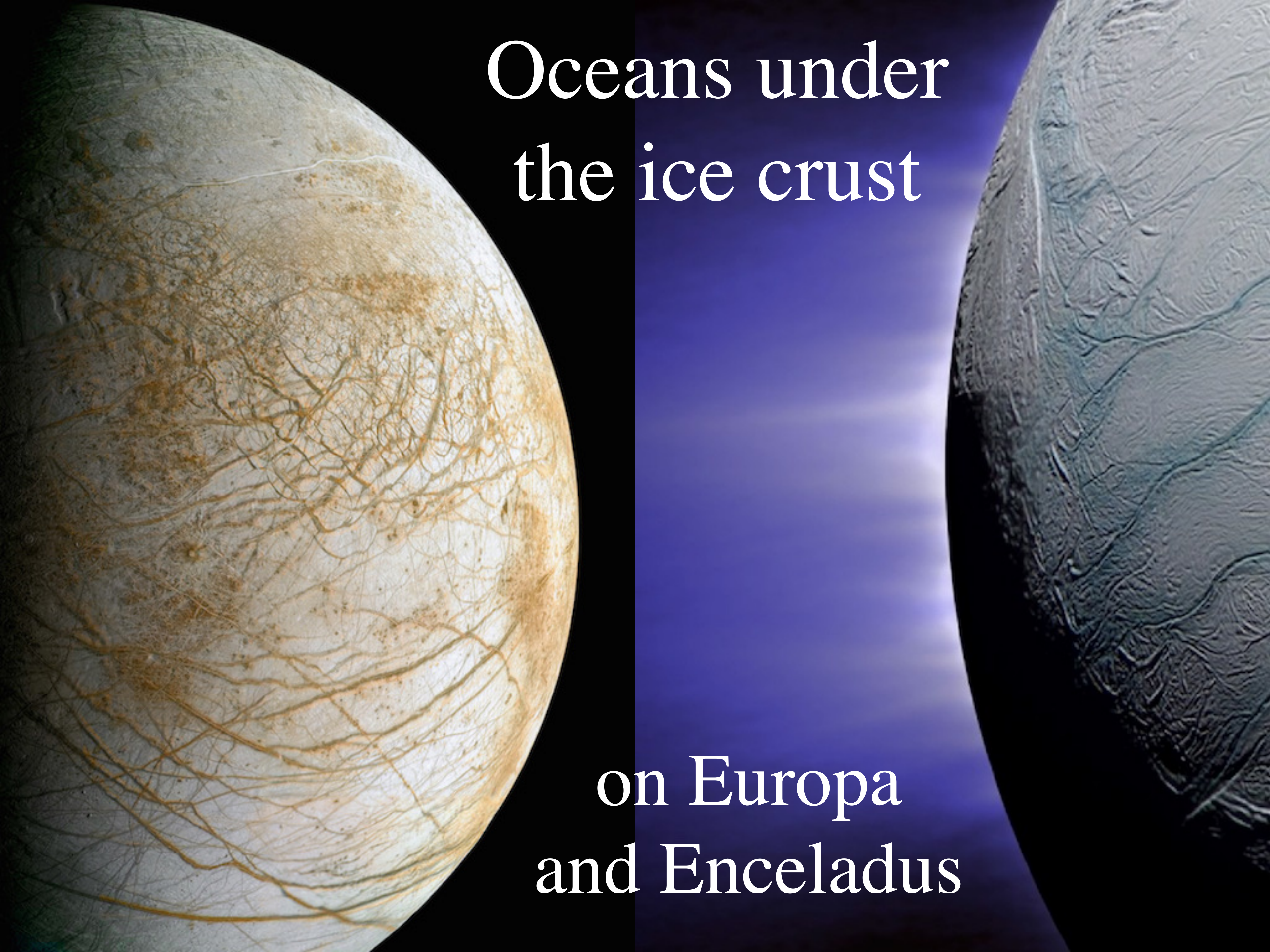
Enceladus



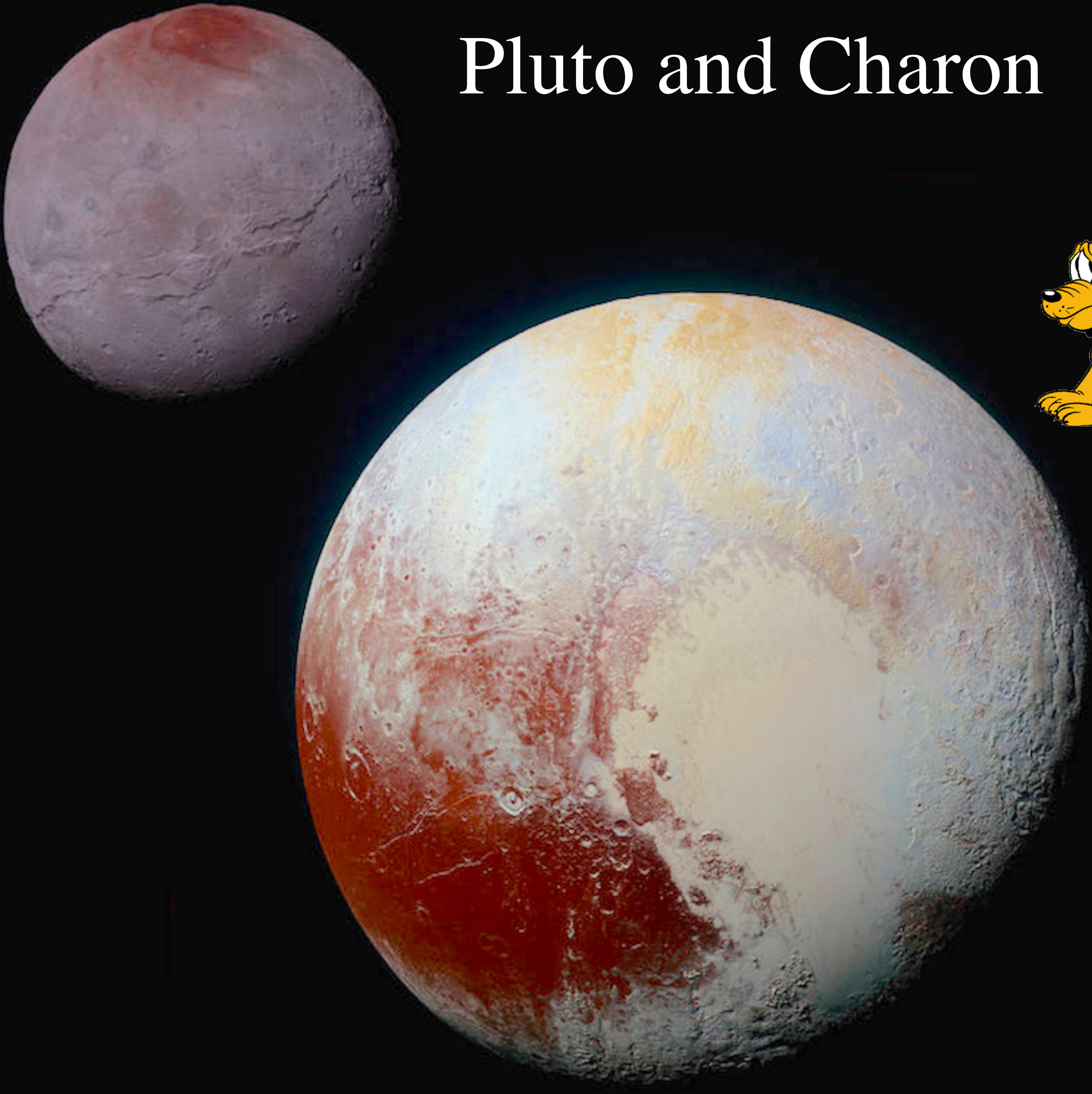
Titan



Oceans under the ice crust on Europa and Enceladus



Pluto and Charon



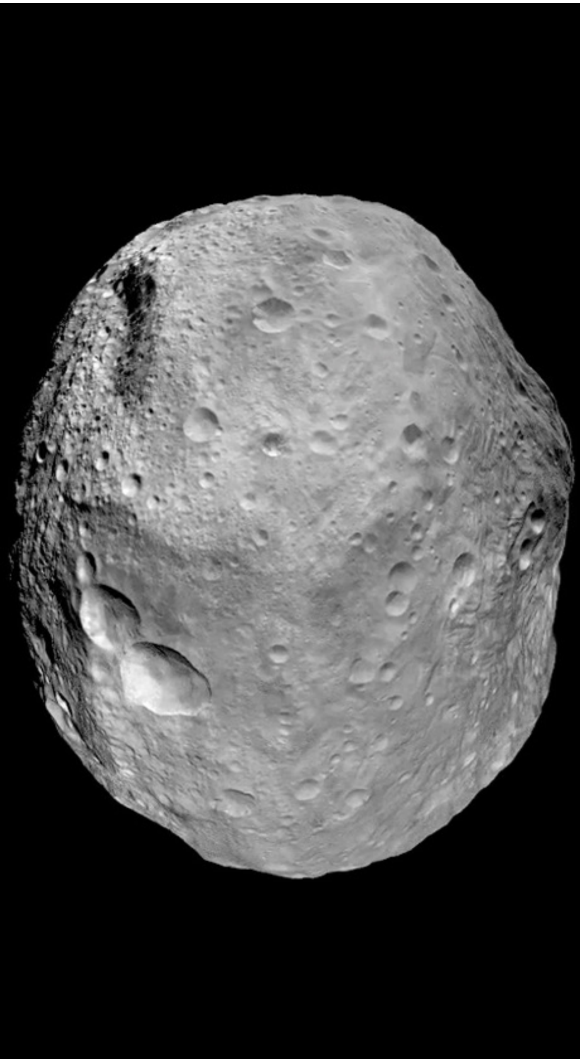
Pluto Killer
(Mike Brown)

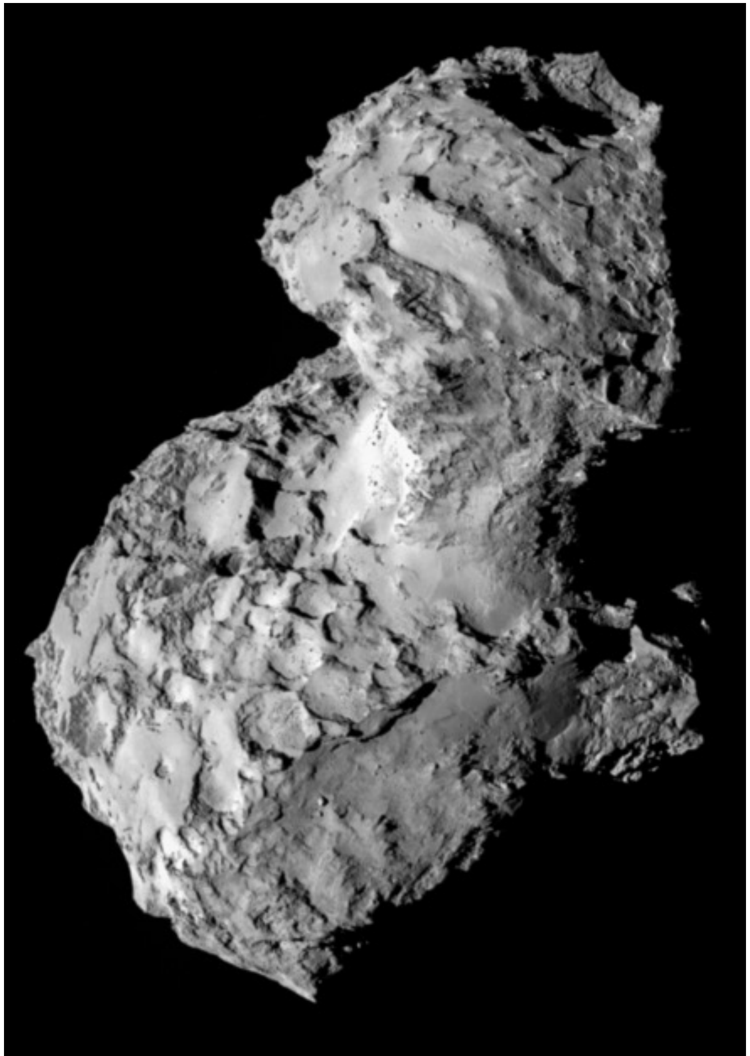
Planet 9?

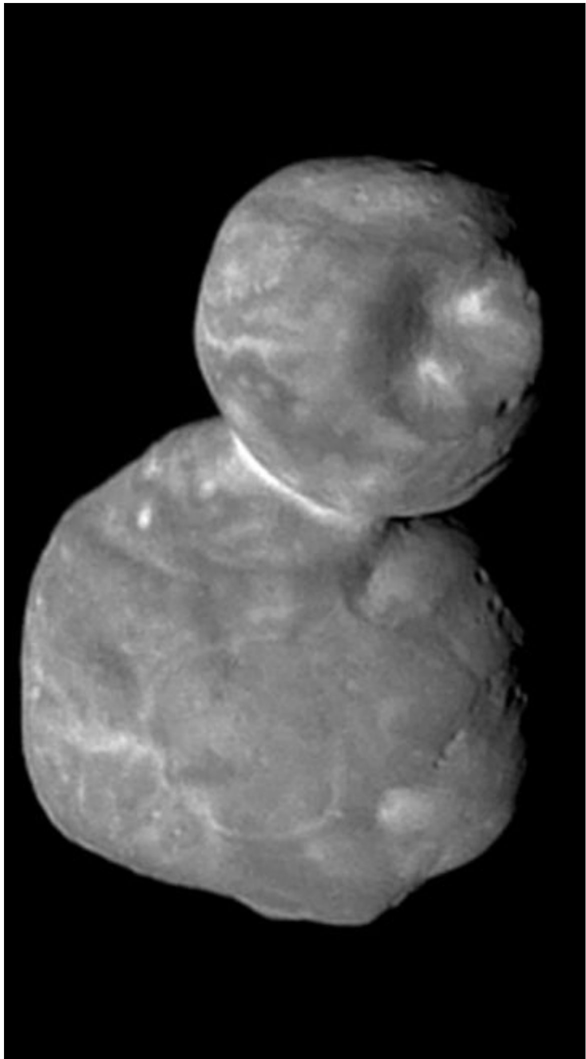
(M. Brown and
K. Batygin)

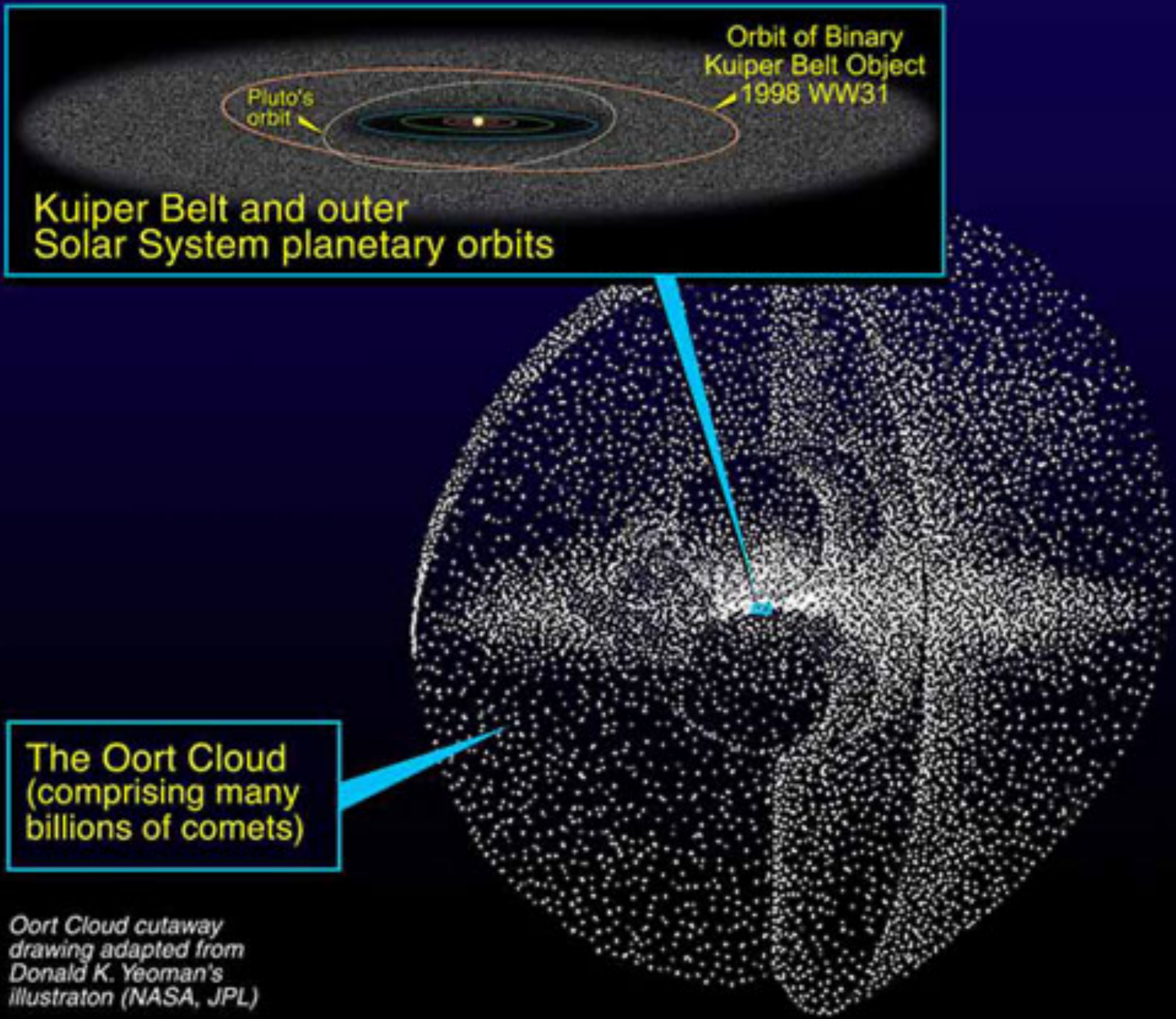
Largest known trans-Neptunian objects (TNOs)

Asteroids and Comets: Leftover Planetesimals


Asteroid Vesta
Dawn mission, NASA


Comet 67P/Churyumov–Gerasimenko
Rosetta mission, ESA


KBO Ultima Thule
New Horizons, NASA



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

Zodiacal Dust: Leftover Protoplanetary Disk Dust

The Idea of Planetesimals and the Origin of the Solar System

Everywhere in the solar nebula, tiny pieces of matter started condensing from the gas

At different places in the solar nebula, these "little bits of grit" were different compounds

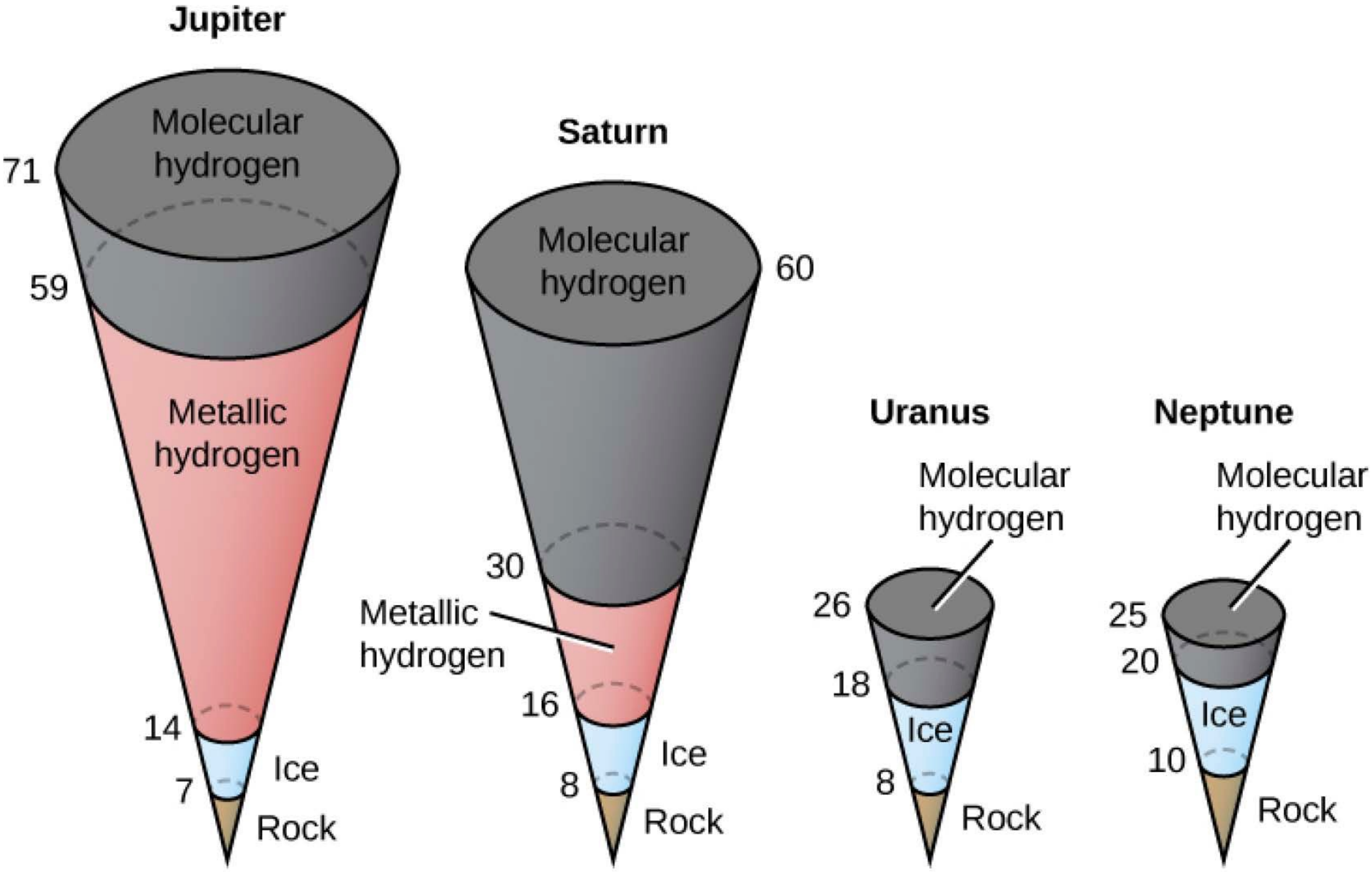
These small pieces of matter stuck to others, making larger sized blocks (the **planetesimals**)

Eventually, these planetesimals collected into objects the size of planets. Gravity got into the act when the planetesimals got big

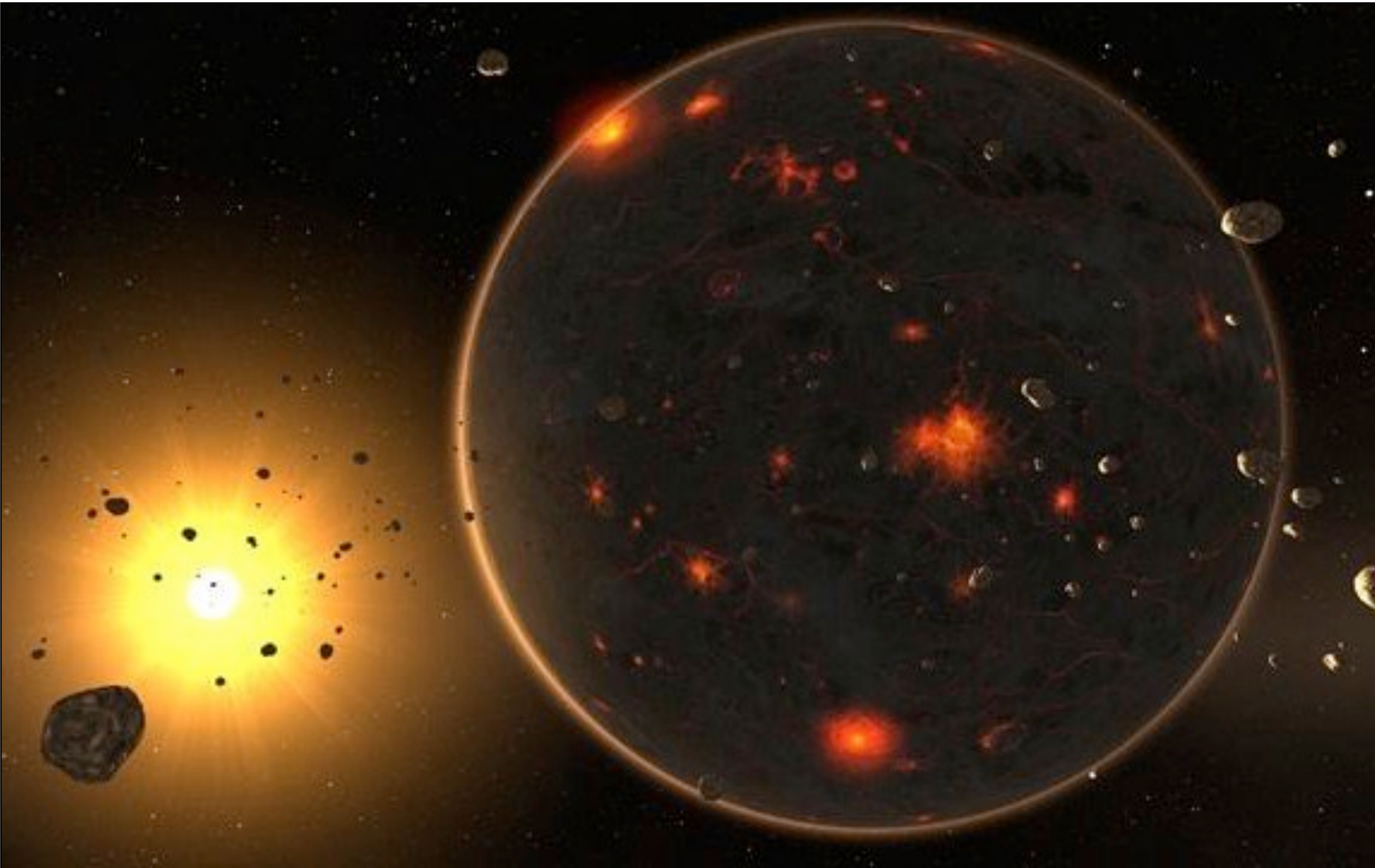
Masses and Compositions of the Major Planets

- At the location of the terrestrial planets, there was not much mass in the planetesimals, since they were formed of heavier, non-abundant elements
- In the outer solar system, there was more mass in the planetesimals, since they were formed of abundant, hydrogen-bearing compounds. Apparently, they produced more massive planetesimals that incorporated the hydrogen and helium gas that makes up most of Jupiter and Saturn
- At the position of the Earth, only silicates and other more "refractory" substances would have precipitated from the vapor state. At Jupiter and beyond, ices of water, ammonia, methane, would have condensed

Composition of the Gas Giant Planets



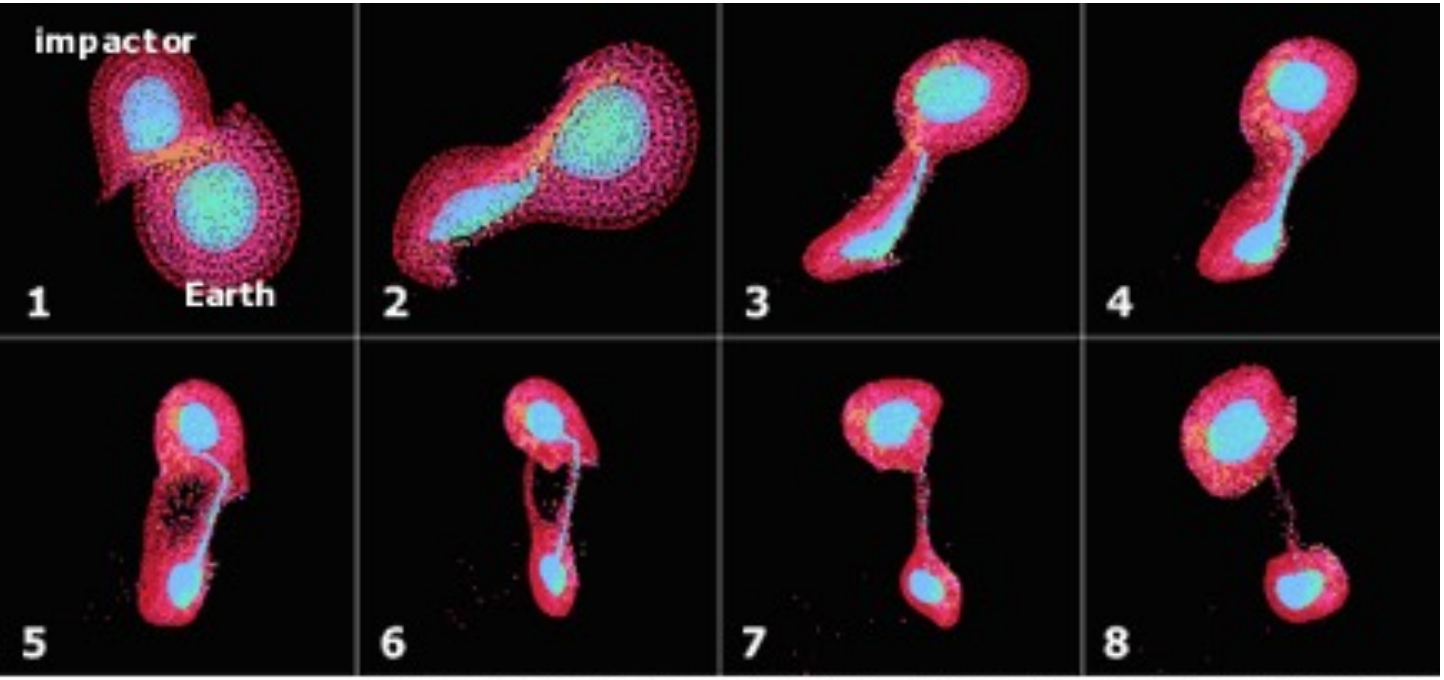
Late Heavy Bombardment



The Origin of the Moon

A Mars-sized protoplanet colliding with the proto-Earth

Moon condenses from the debris



(Courtesy of A. G. W. Cameron, Harvard College Observatory.)

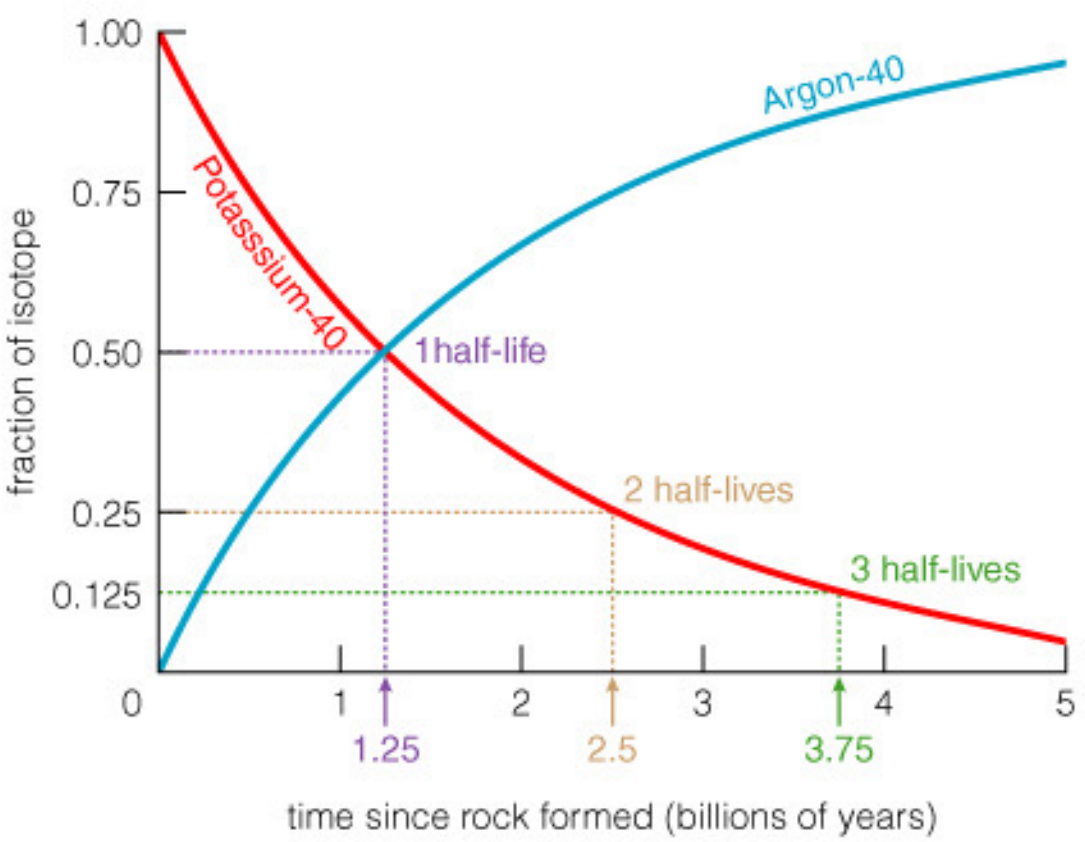
Explains:
- Lunar composition
- Tilt of the Earth's axis

The Impacts Continue

Tunguska >

Large meteor crater, Arizona

When Did the Planets Form?



- Some isotopes decay into other nuclei
- A **half-life** is the time for half the nuclei in a substance to decay
- Relative abundances of these isotopes then give us the age

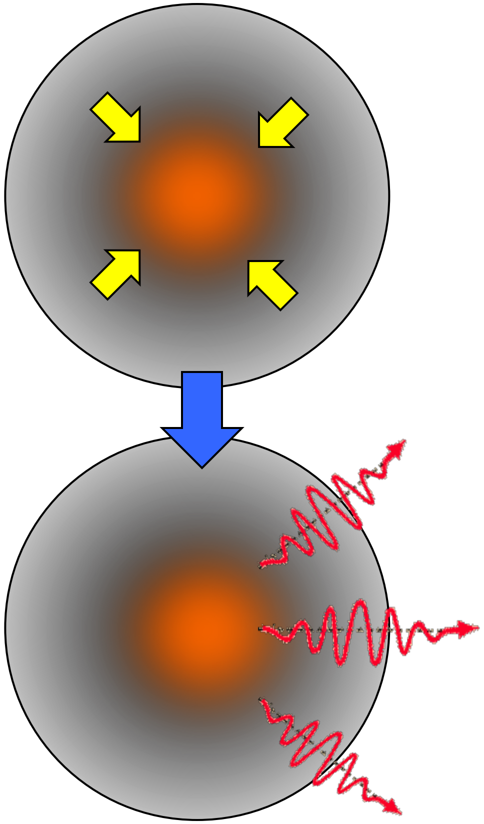
- Radiometric dating tells us that oldest moon rocks are 4.4 billion years old
- Oldest meteorites are 4.55 billion years old
- Planets probably formed ~ 4.6 billion years ago

Brown Dwarfs: Between Stars and Planets

Insufficiently massive to ignite nuclear reactions in the core

$M_{bd} < 0.085\ M_{\odot}$

The Kelvin-Helmholtz Mechanism



As a planet cools, it shrinks

The release of the binding energy produces heat, that radiates away

For example, Jupiter, and all brown dwarfs

Total binding energy available divided by the luminosity gives the *Kelvin-Helmholtz time scale*

For Sun, that is ~ 18 million years

How do you obtain an atmosphere?

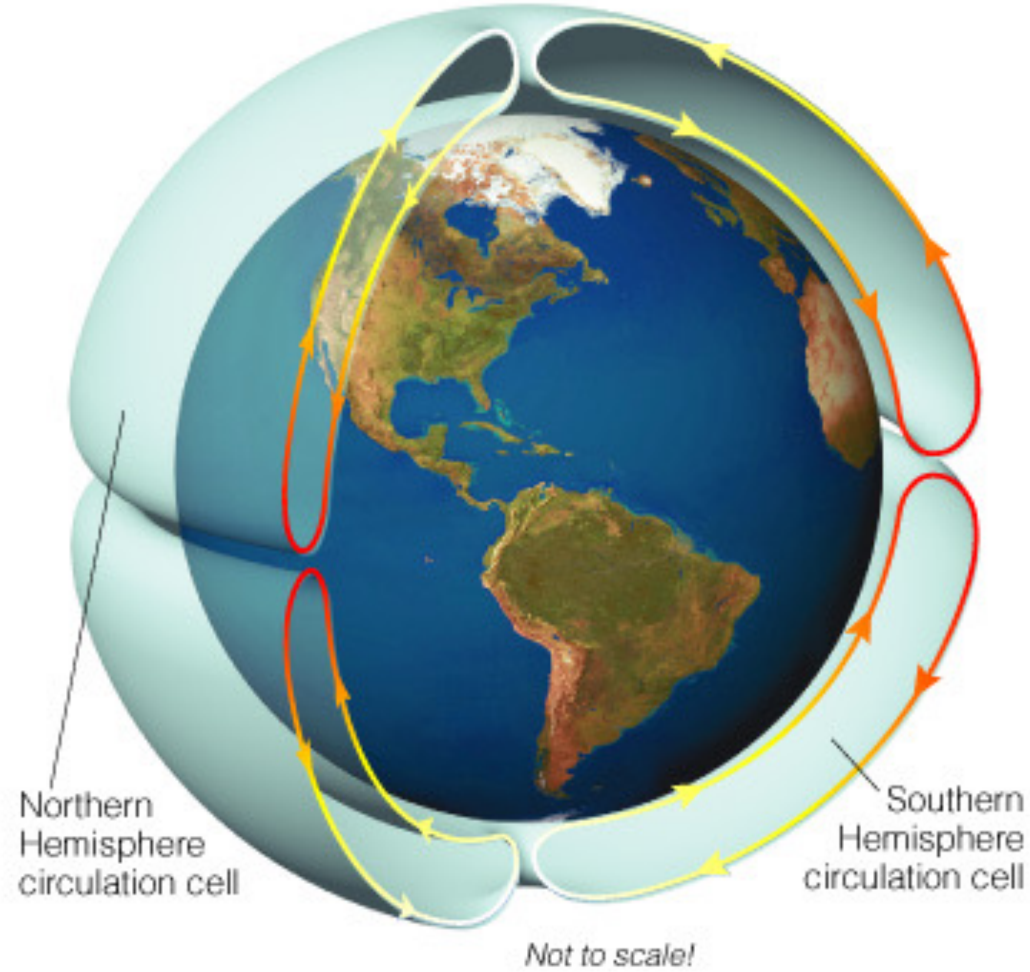
- Gain volatiles by comet impacts
- Outgassing during differentiation
- Ongoing outgassing by volcanoes

Keeping an Atmosphere

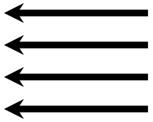
Atmosphere is *kept* by the world' s gravity

- Low mass worlds = low gravity = almost no atmosphere
- High mass worlds = high gravity = thick atmosphere

Why are the winds blowing? The answer, my friends, is…



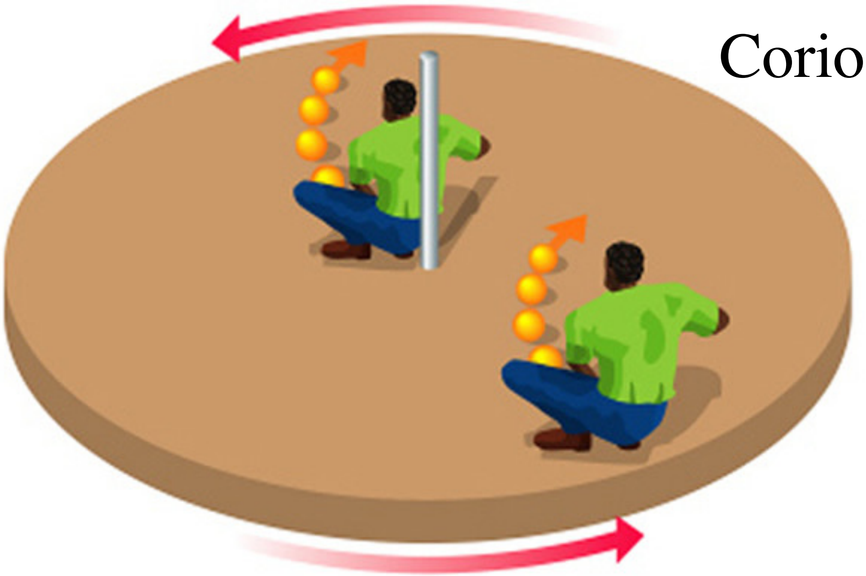
- Heated air rises at equator



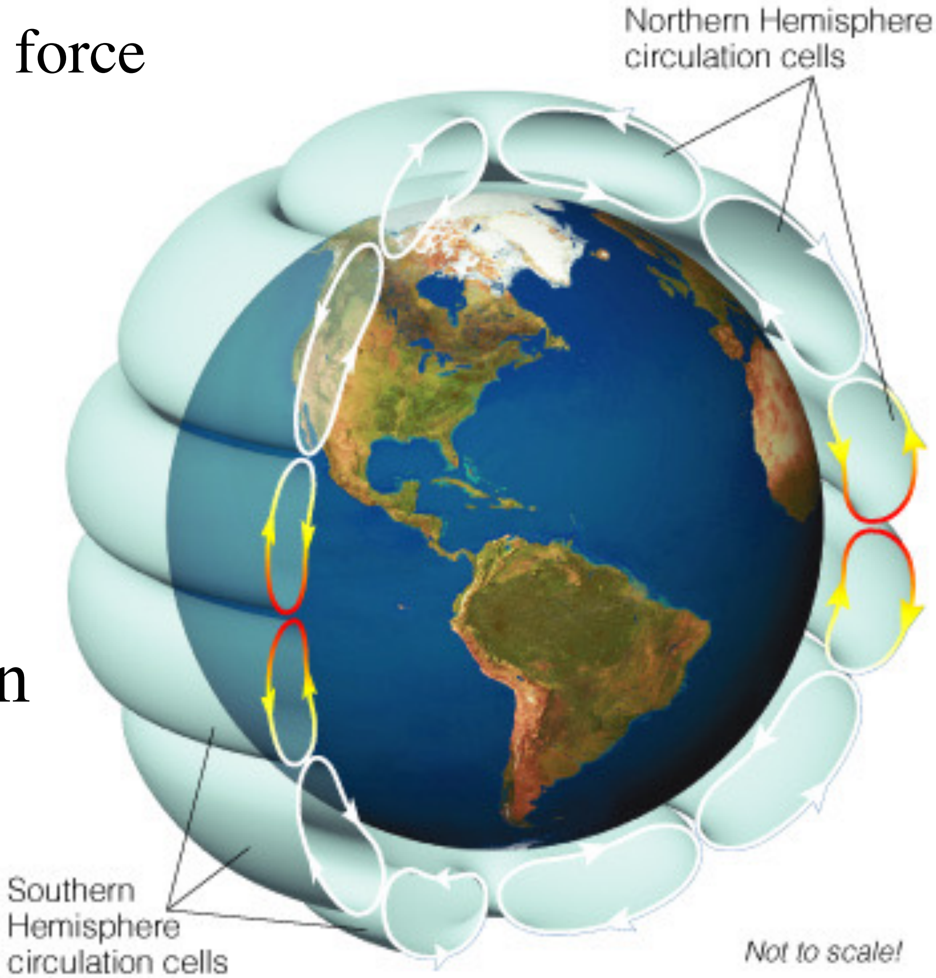
Maximum
Sun warming

- Cooler air descends at poles

The planetary rotation also plays a role:



Coriolis force



- On Earth the large circulation cell breaks up into 3 smaller ones, moving diagonally
- Other worlds have more or fewer circulation cells depending on their rotation rate