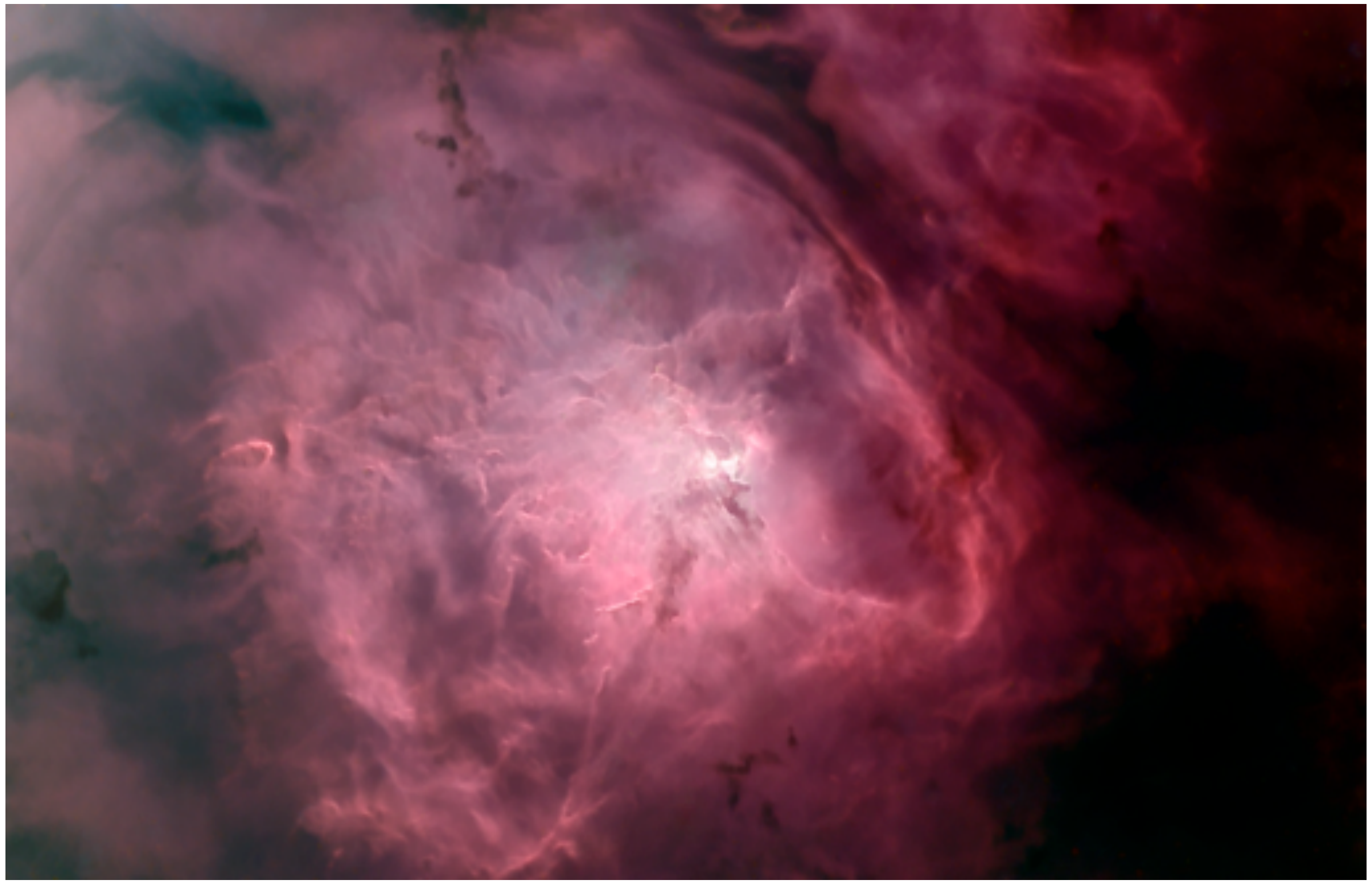
Astronomy 150: Killer Skies
Lecture 8, February 3

Last time: Pluto, Origin of the Solar System I

Today: Origin of the Solar System II

Assignments:

- HW 2 was due at start of class
- HW 3 posted today, due next Friday at start of class
- Planetarium shows this week and next; info and reservations on class website



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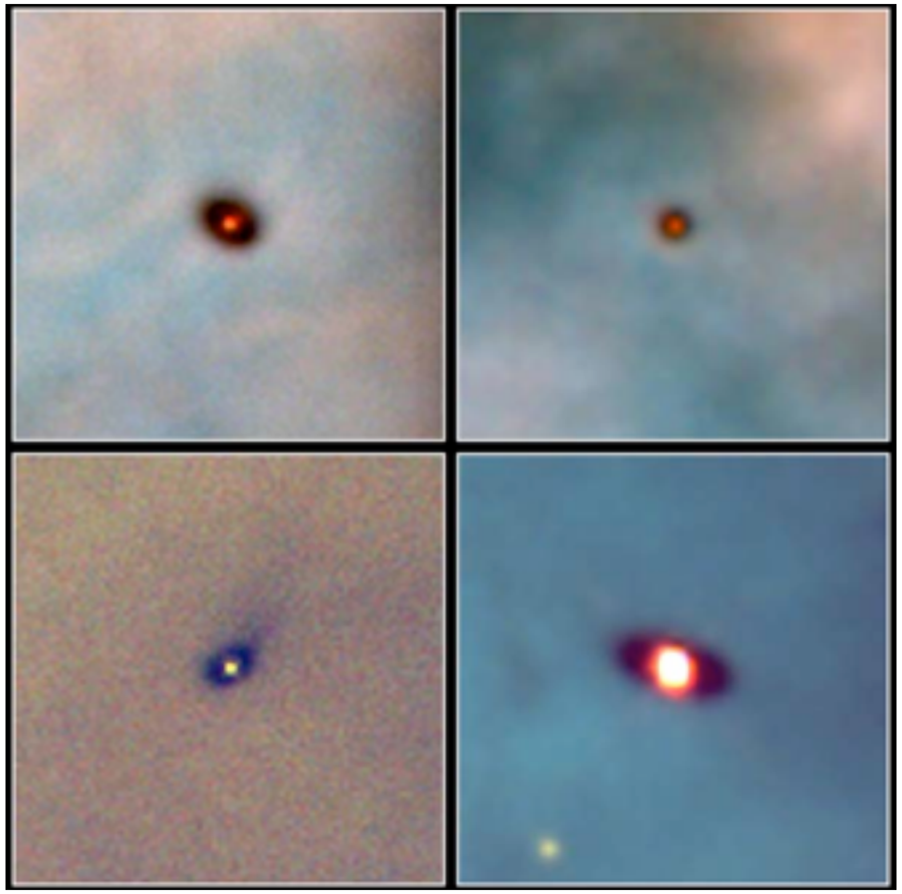

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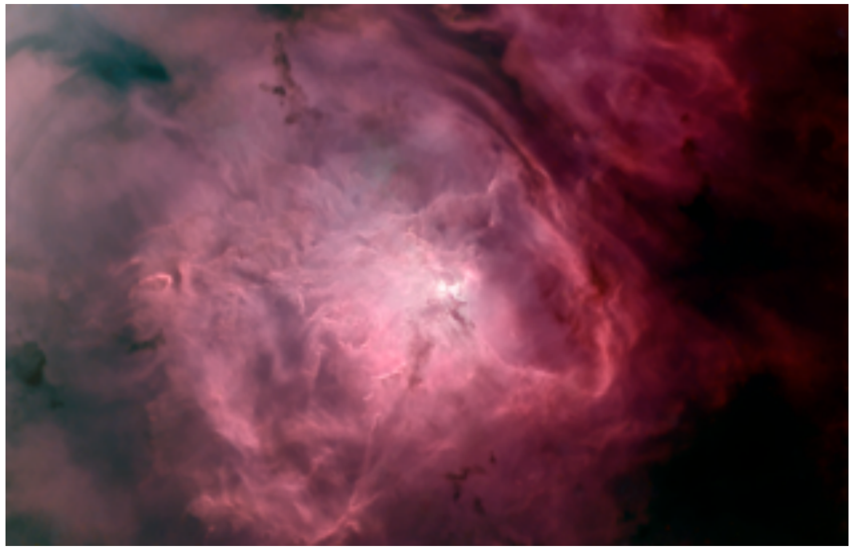
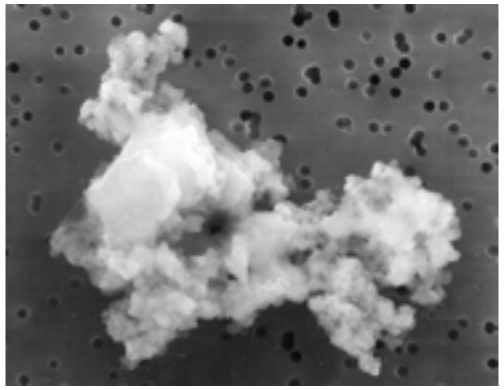
Recap: Solar Nebula Theory





Starting Point: Solar Nebula

Where: interstellar cloud = “nebula”

When: 4.6 billion years ago

Raw ingredients: a mix

- 98% of mass is gas mostly hydrogen and helium
- 2% of mass is “dust”

  microscopic solid clumps of heavy elements

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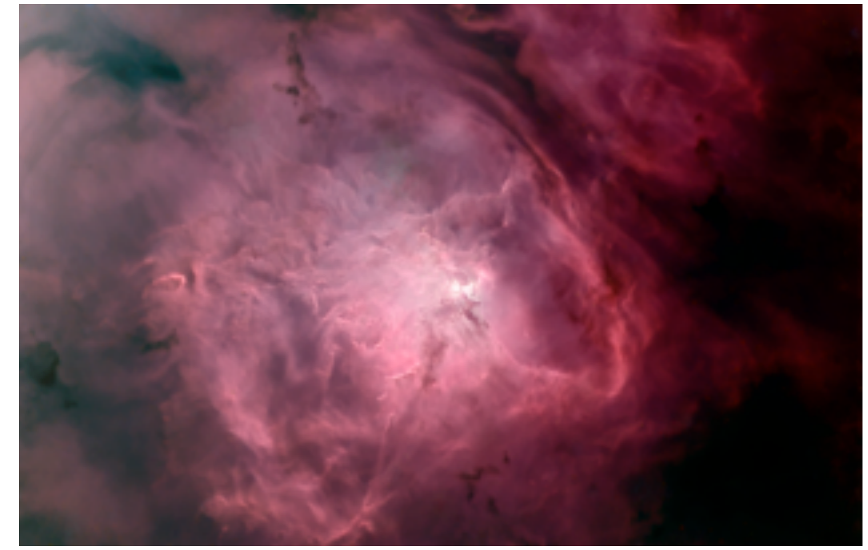

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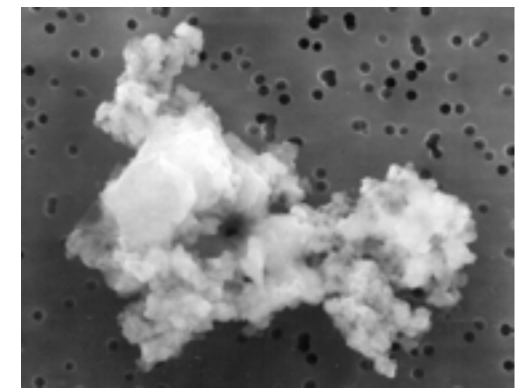


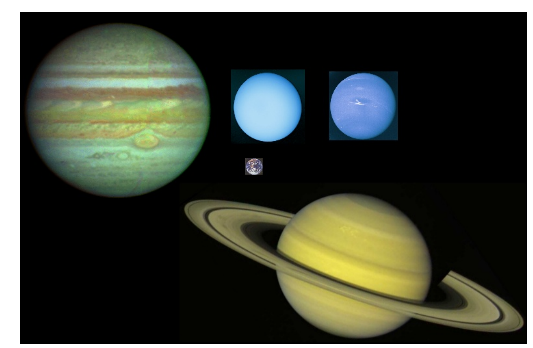
Ending Point: Solar System Today

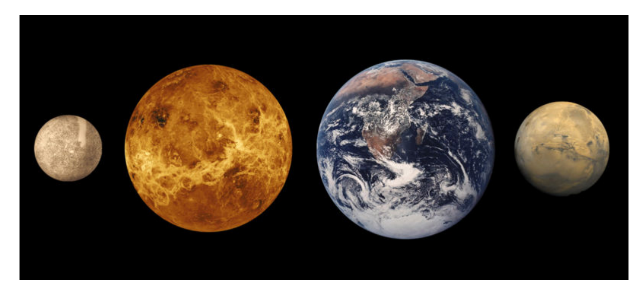
planet orbits nearly coplanar

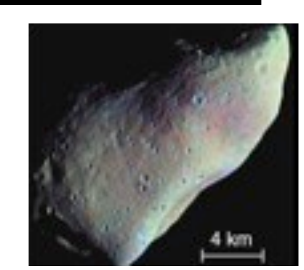
two planet classes:

- small, rocky terrestrial planets
- massive gas giants

debris: rocky (asteroids), icy (Kuiper belt, Oort cloud)







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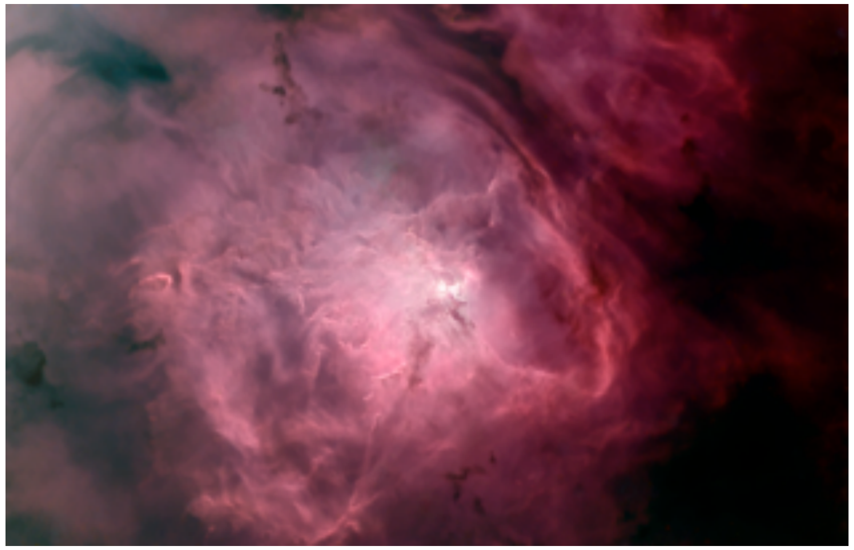

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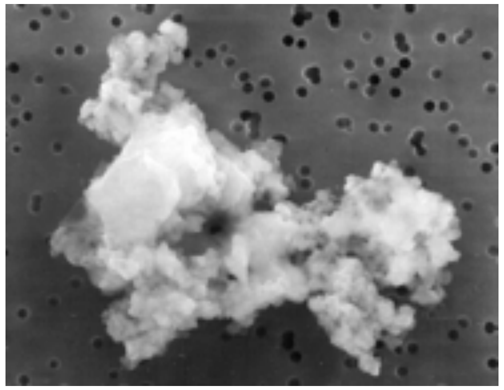

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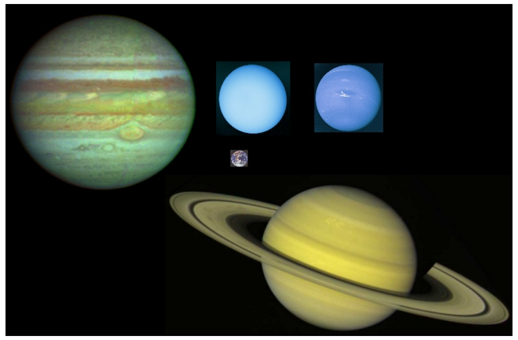

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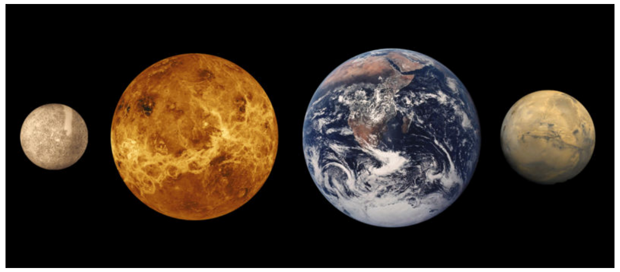

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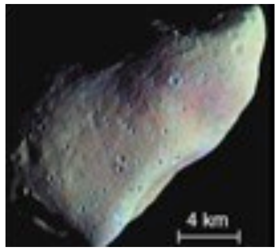

Solar Nebula Theory Goal

explain how to go between start and today

Gravitational Contraction

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- The gravity of the gas and dust clumps pushes the cloud together, but there is some resistance from pressure and magnetic fields to collapse.
- Probably as the cloud core collapses, it fragments into blobs that collapse into individual stars.
- Cloud becomes denser and denser until gravity wins, and the clumps collapse under their own mass– a protostar = "embryo" of Sun

But..

- Not all mass falls in directly (radially). Why?

- All gas has a small spin that preferentially causes the formation of a flattened structure
  - time for an interlude.

http://homepages.igrin.co.nz/moerewa/Pages/

Interlude: Angular Momentum

$$\text{ang. mom.} = \begin{pmatrix} \text{orbit} \\ \text{speed} \end{pmatrix} \times \begin{pmatrix} \text{distance} \\ \text{to orbit axis} \end{pmatrix}$$

Interlude: Angular Momentum

Spinning or orbiting objects in closed system have **angular momentum**.

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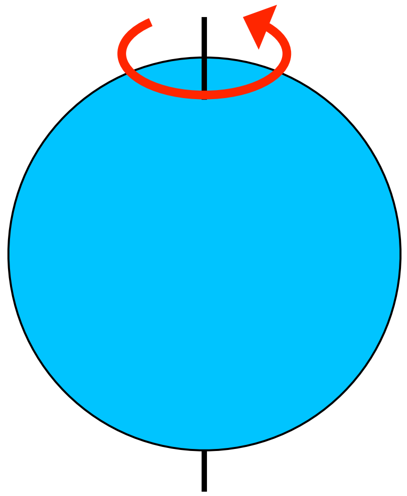
Keep same dist. to axis → speed same

Move closer to axis → speed up!

Taking The Solar System for a Spin

Solar nebula competition:
Gravity vs Angular Momentum



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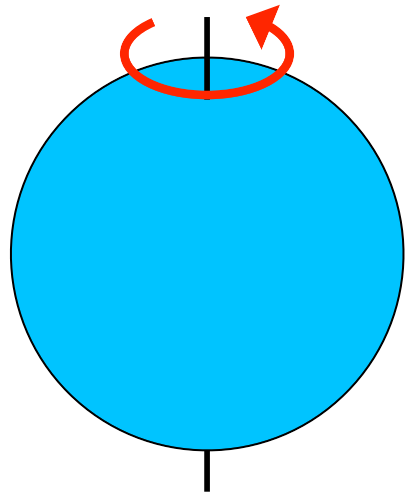

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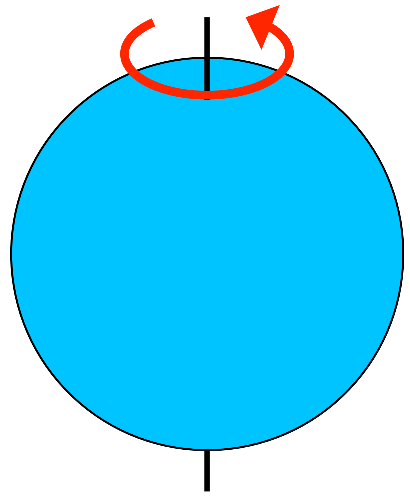

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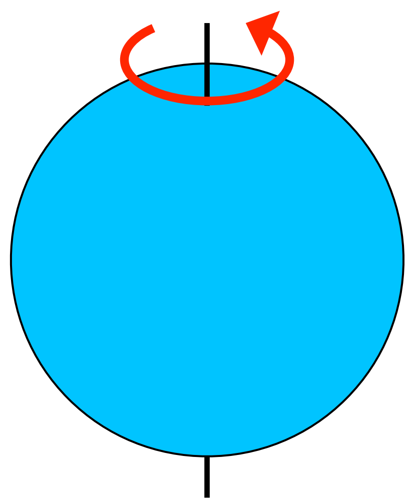

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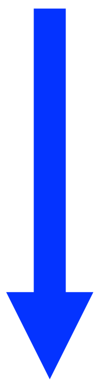
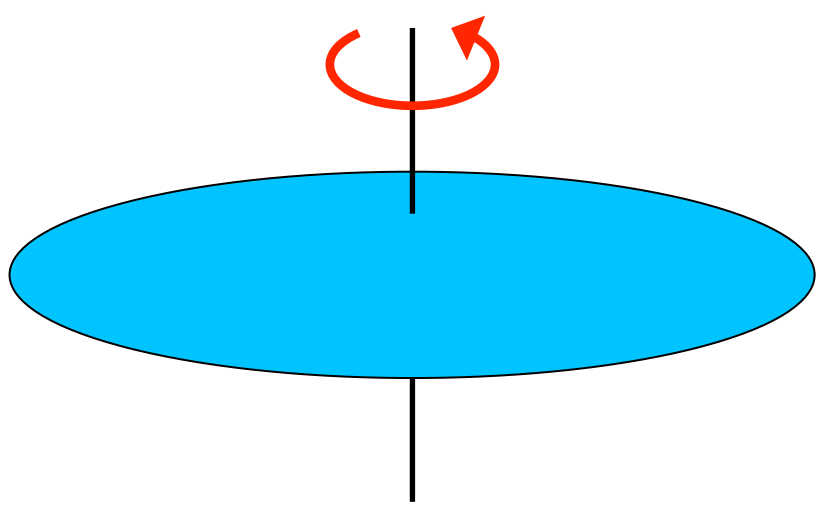


- If fall parallel to spin axis:
  same speed, so no resistance
  → forms protoplanetary disk
  swirling gas and dust
  raw material for planets



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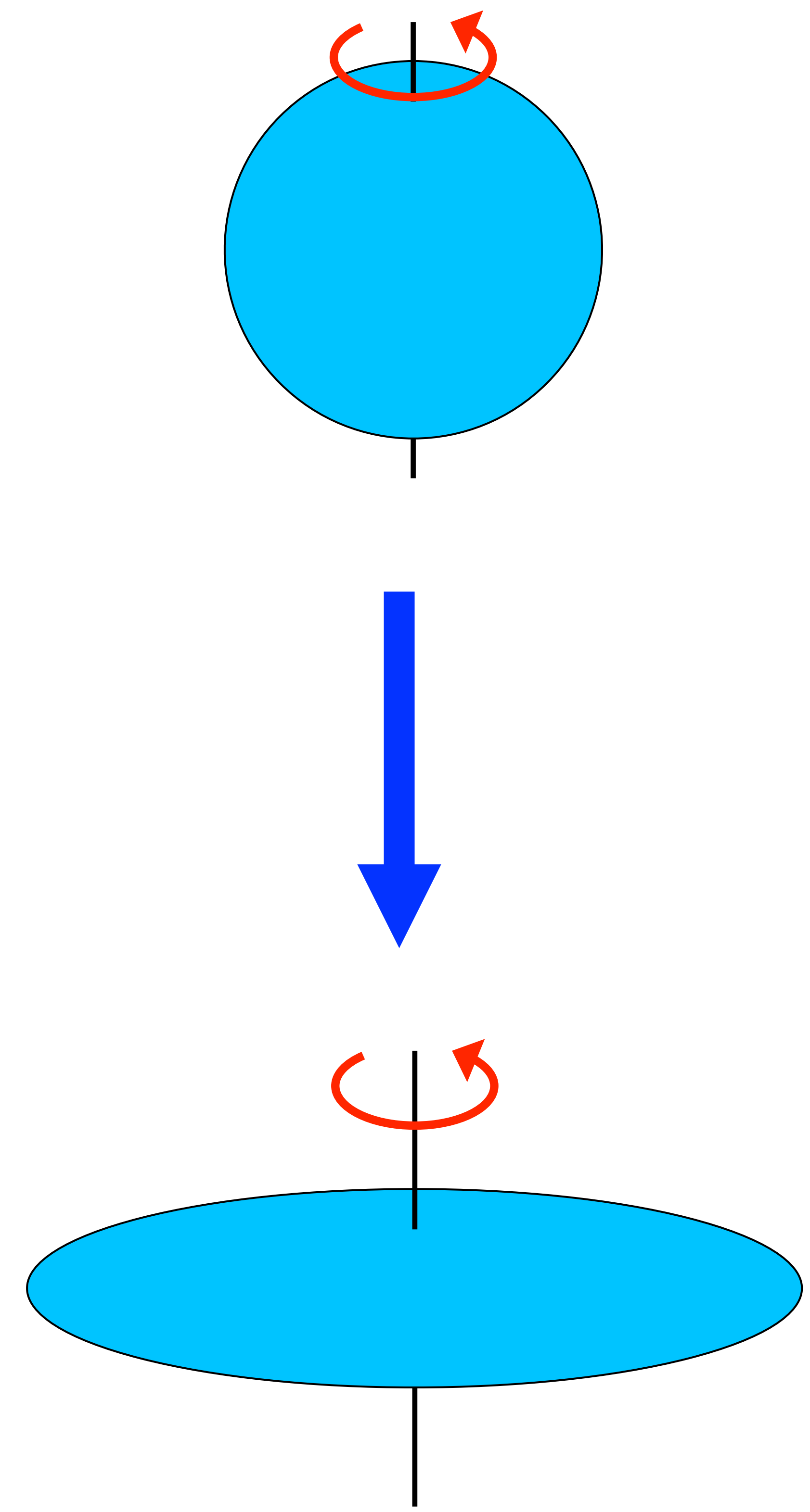

– **Origin of planet's orbits!**
– **Origin of Ecliptic plane**
– **Organizes spins along initial spin axis**

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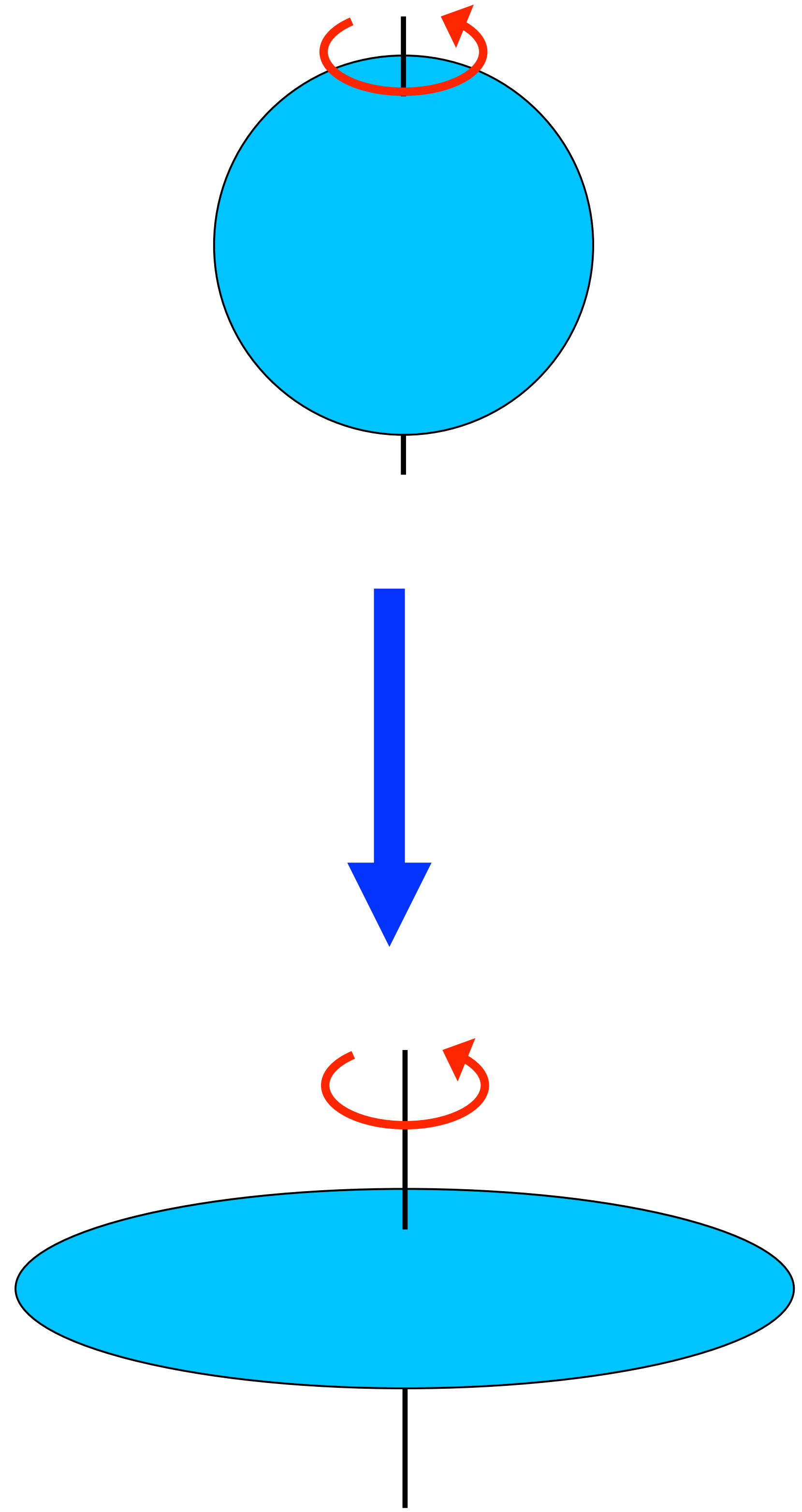

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Q: how can we test if these ideas are right?

Testing the Solar Nebula Theory: Searching for Disks

Solar nebula theory is based on

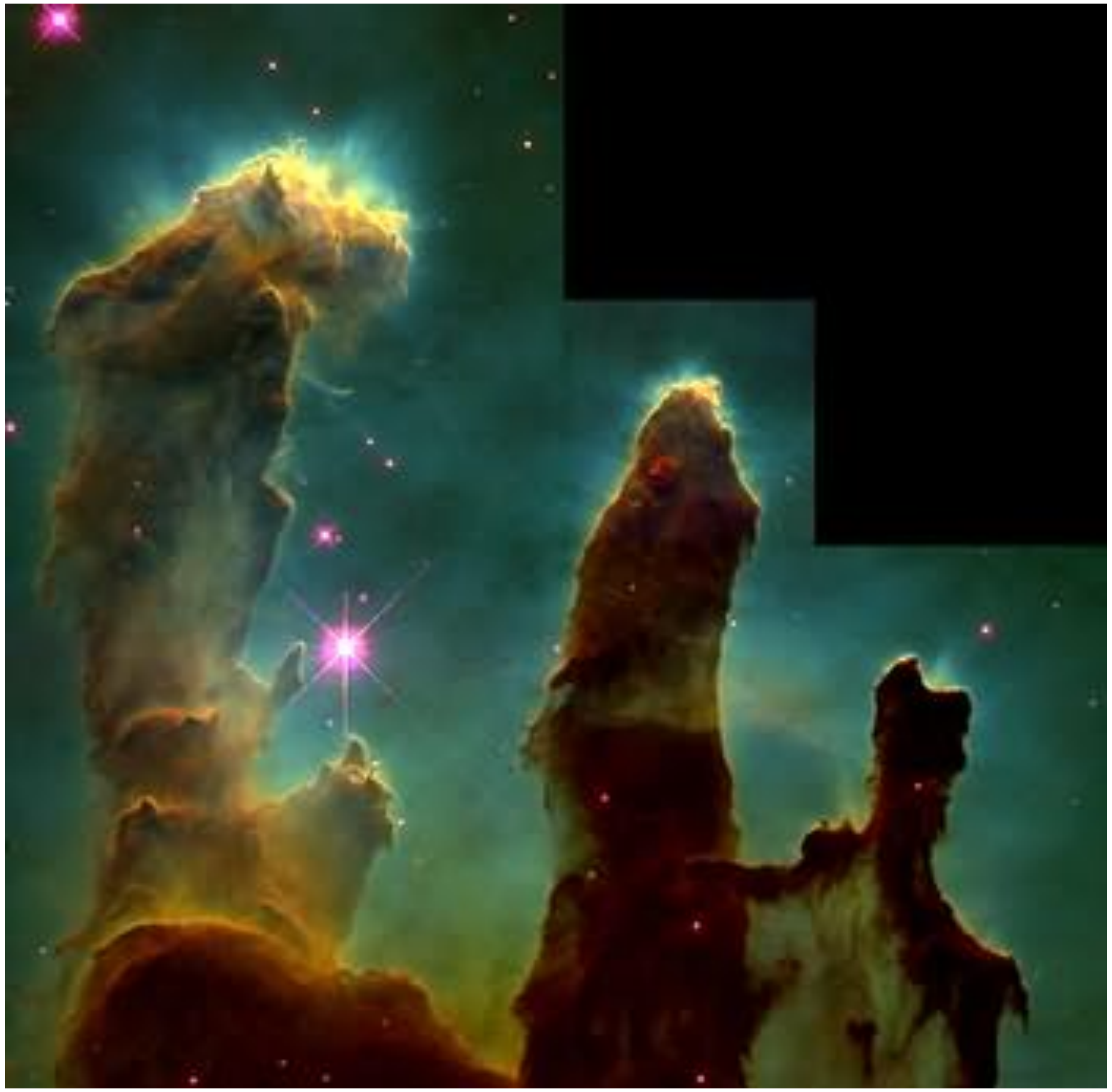
- patterns in Solar System today
- observations of present-day star-forming regions

But the main predictions of the theory are general

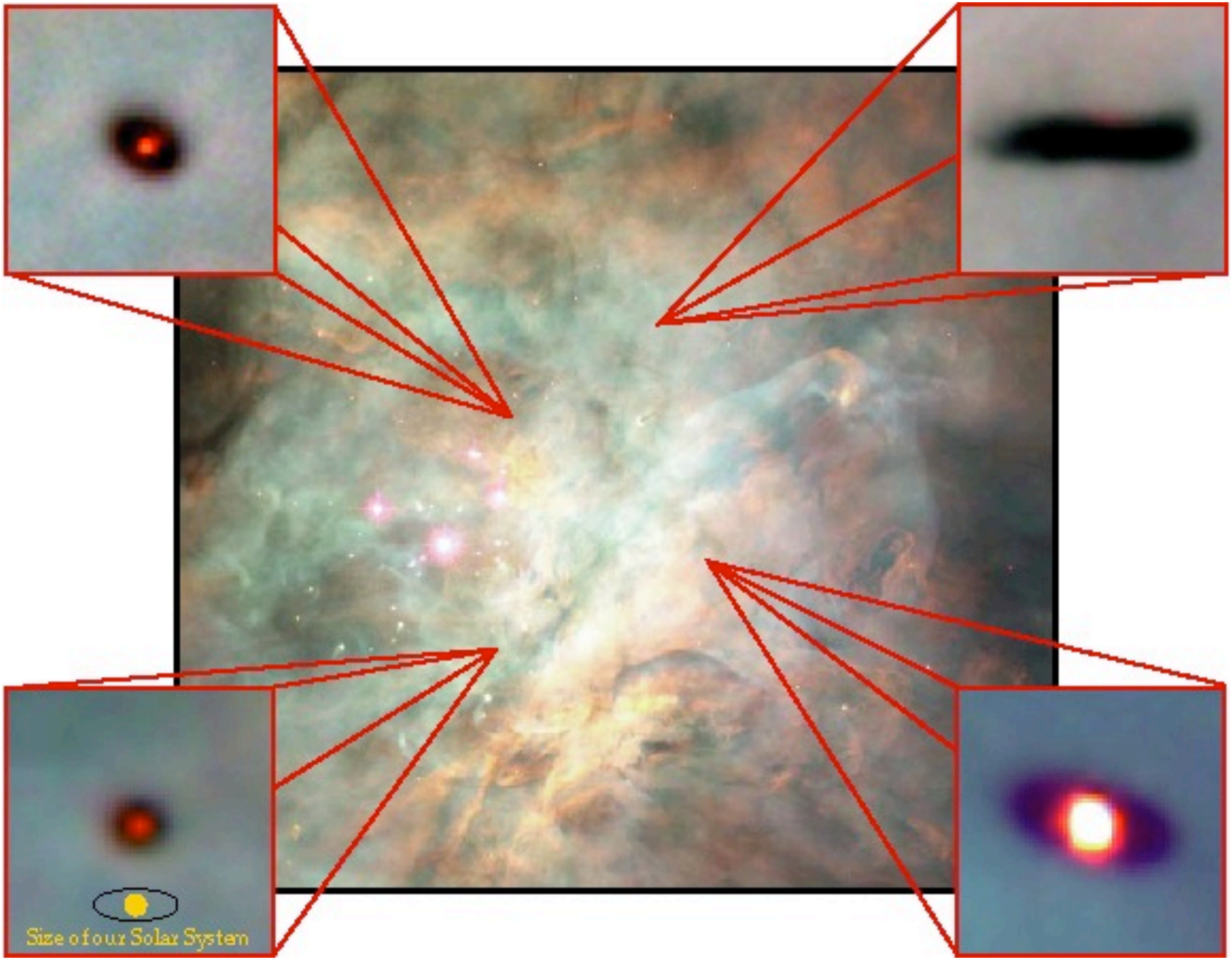
- example: gravity + angular momentum = disk
- predictions should apply to formation of stars and planets elsewhere

Test:

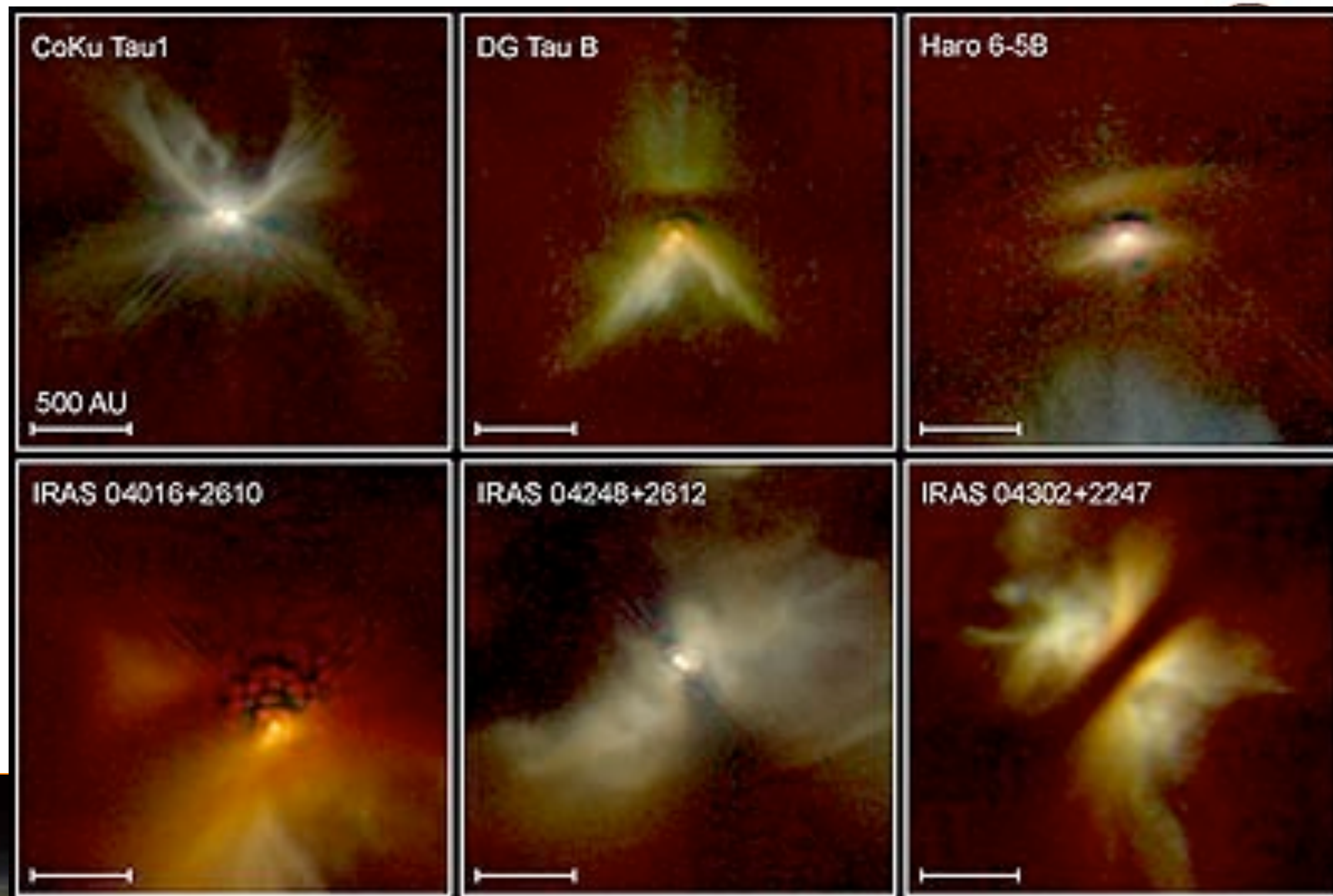
- do we see disks around young stars?



Disks around Young Stars are Common



Disks have been imaged with HST's infrared camera



Young stars are surrounded by dense disks of gas and dust

iClicker Poll:
What made what?

Solar nebula collapse leads to

- pre-Sun (“protostar”) forming in center
- surrounded by disk of gas and dust

which will lead to planets, comets, asteroids

What will make what?

A. Earth mostly made of disk dust, Jupiter mostly made of disk gas

B. Earth and Jupiter mostly made of disk gas

C. Earth and Jupiter mostly made of disk dust

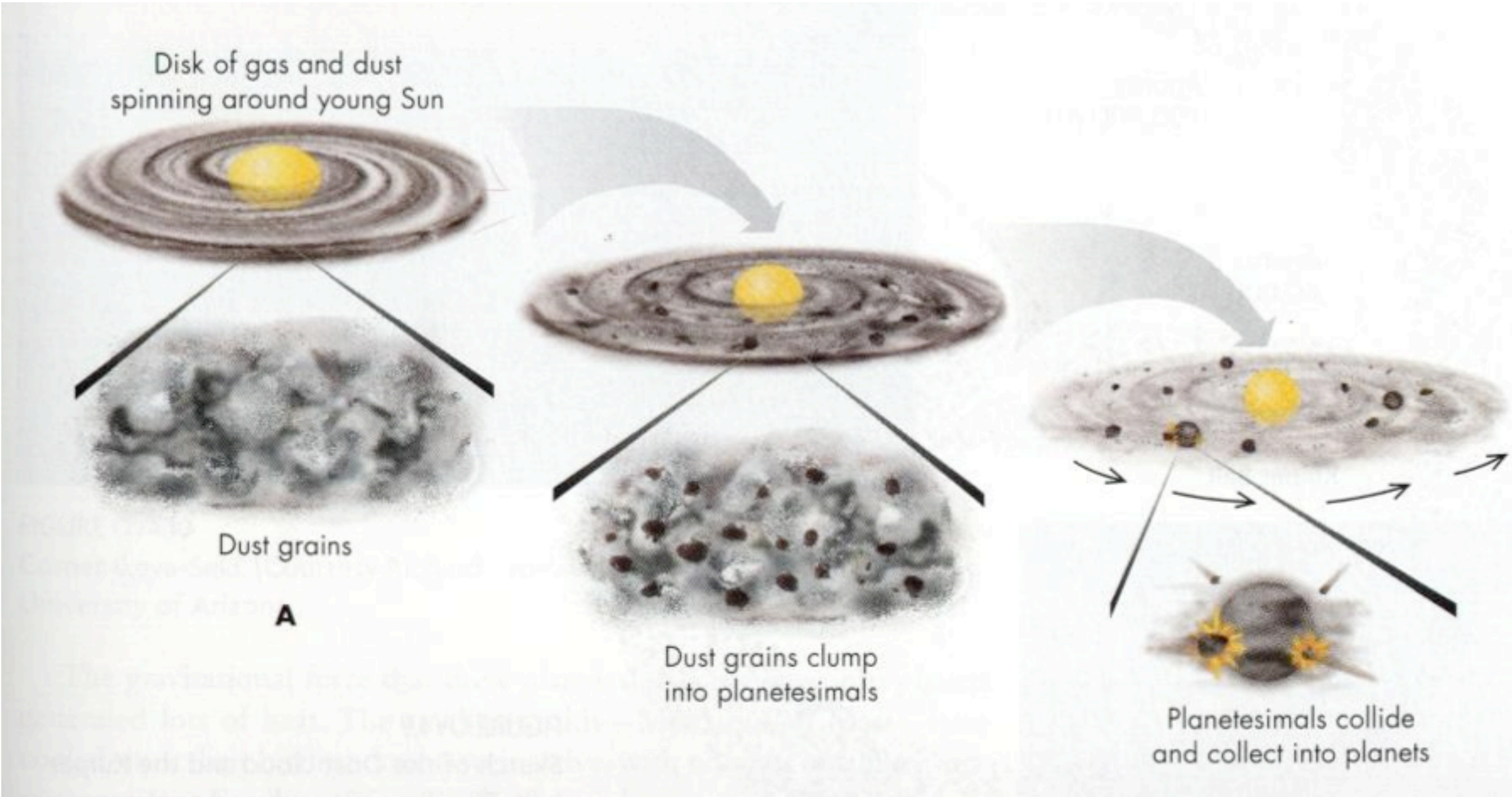
D. Earth mostly made of disk gas, Jupiter mostly made of disk dust

What are the ‘seeds’ made of?

- The ingredients of the solar nebula fell into four major categories
- Hydrogen/helium gas (98% of mass) do not condense to form solids or ices
- Other components can condense at the right temperature - i.e., planet seeds!

	Examples	*Typical Condensation Temperature*	*Relative Abundance (by mass)*
Hydrogen and Helium Gas 	hydrogen, helium	do not condense in nebula	98%
Hydrogen Compounds 	water (H_2O) methane (CH_4) ammonia (NH_3)	<150 K	1.4%
Rock 	various minerals	500–1,300 K	0.4%
Metals 	iron, nickel, aluminum	1,000–1,600 K	0.2%

From dust grains to planetesimals to planets



Dust grains are the 'seeds' of planet formation

http://www.metacafe.com/watch/111454/formation_of_the_solar_system_great_animation/

Planet Formation in the Disk

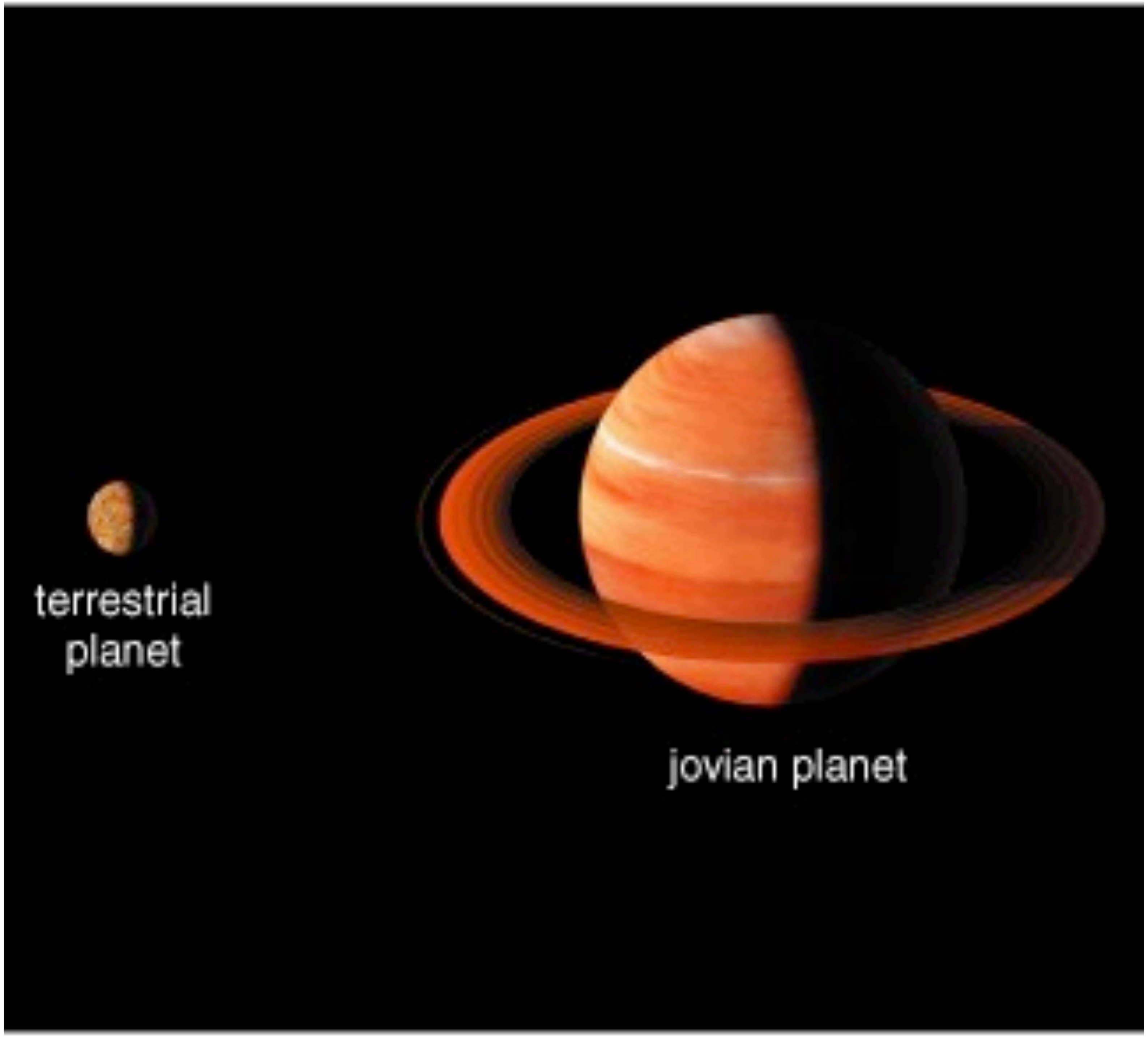
Heavy elements clump

1. Dust grains collide, stick, and form planetesimals– about 10^{12} of them, sort of like asteroids! All orbit in the same direction and in the same plane.

2. Gravity Effects: Big planetesimals attract the smaller planetesimals. So, fewer and fewer of large objects (100's). Collisions build-up inner planets and outer planet cores.

3. Collisions can also account for odd motions of Venus (backwards), Uranus (rotates on its side), and Pluto (high inclination of orbit). Proof of period of high collision evident on moon

Why are there two types of planets?



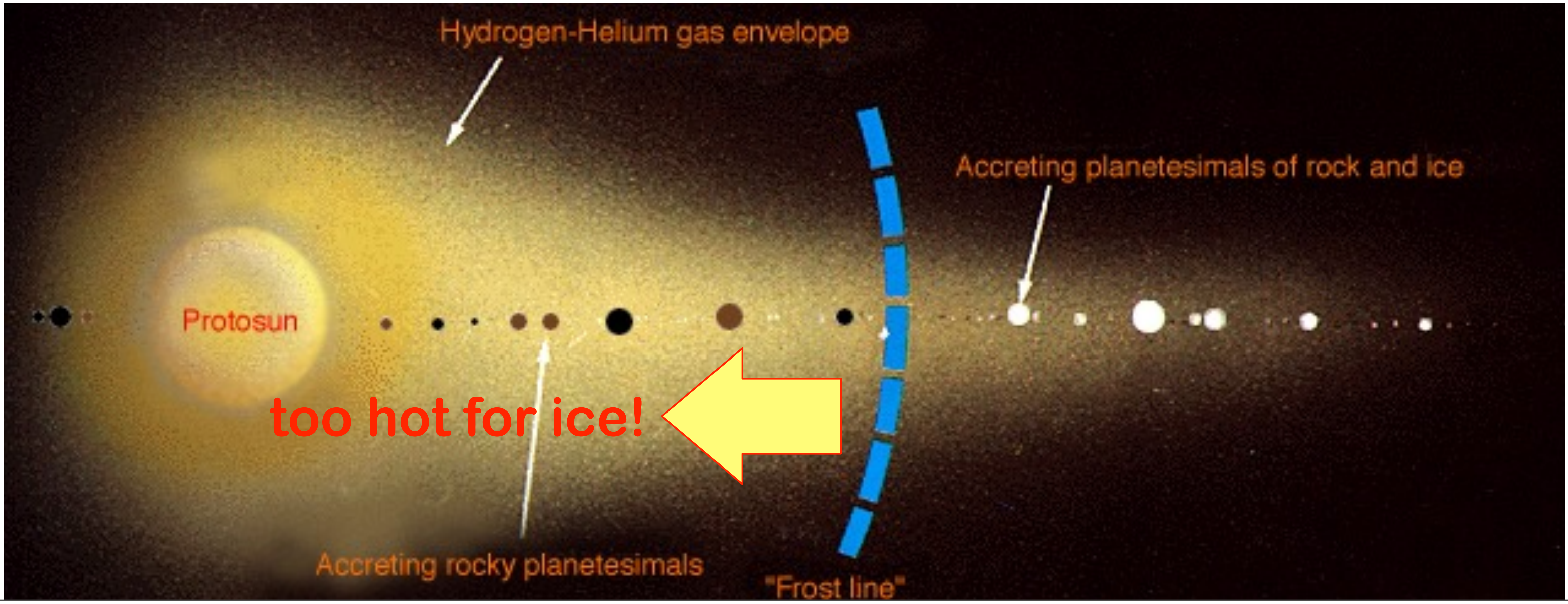
Temperature Controls Planet Formation

The inner nebula was hot:

- and only metals and rock could condense there
- no ices can form

The outer nebula was cold,

- ices could condense



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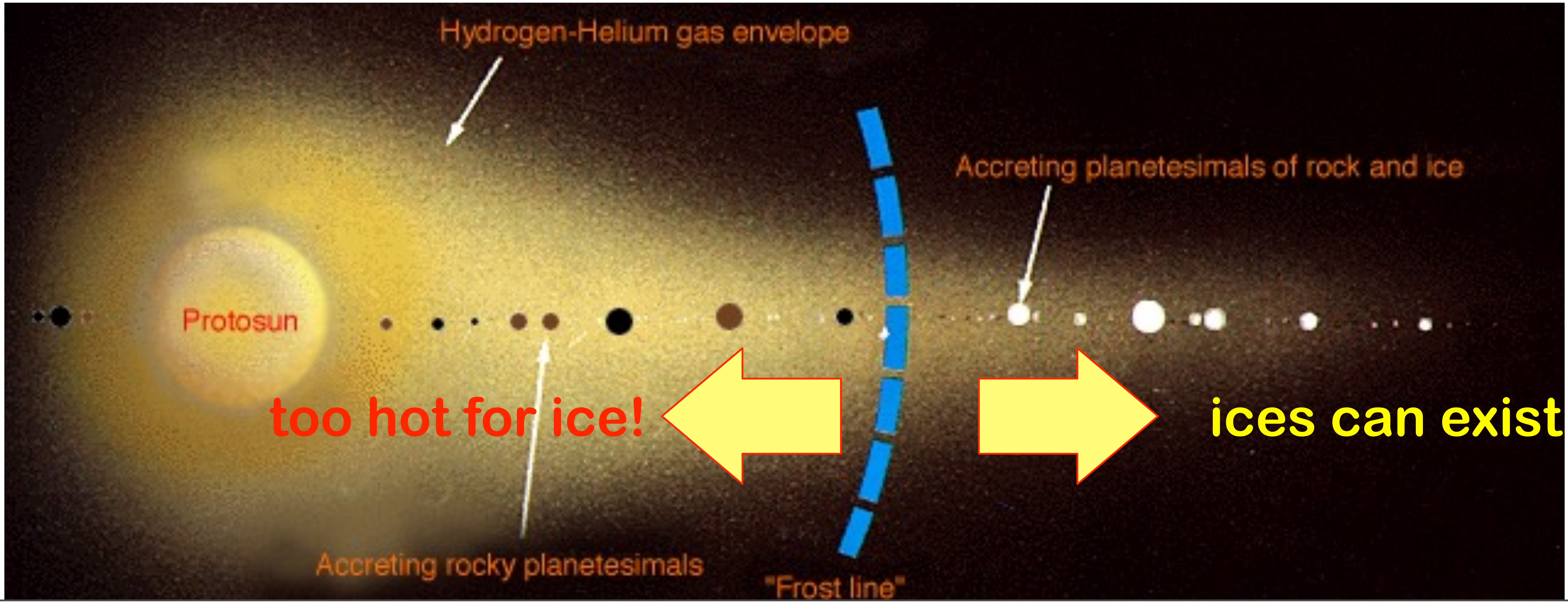

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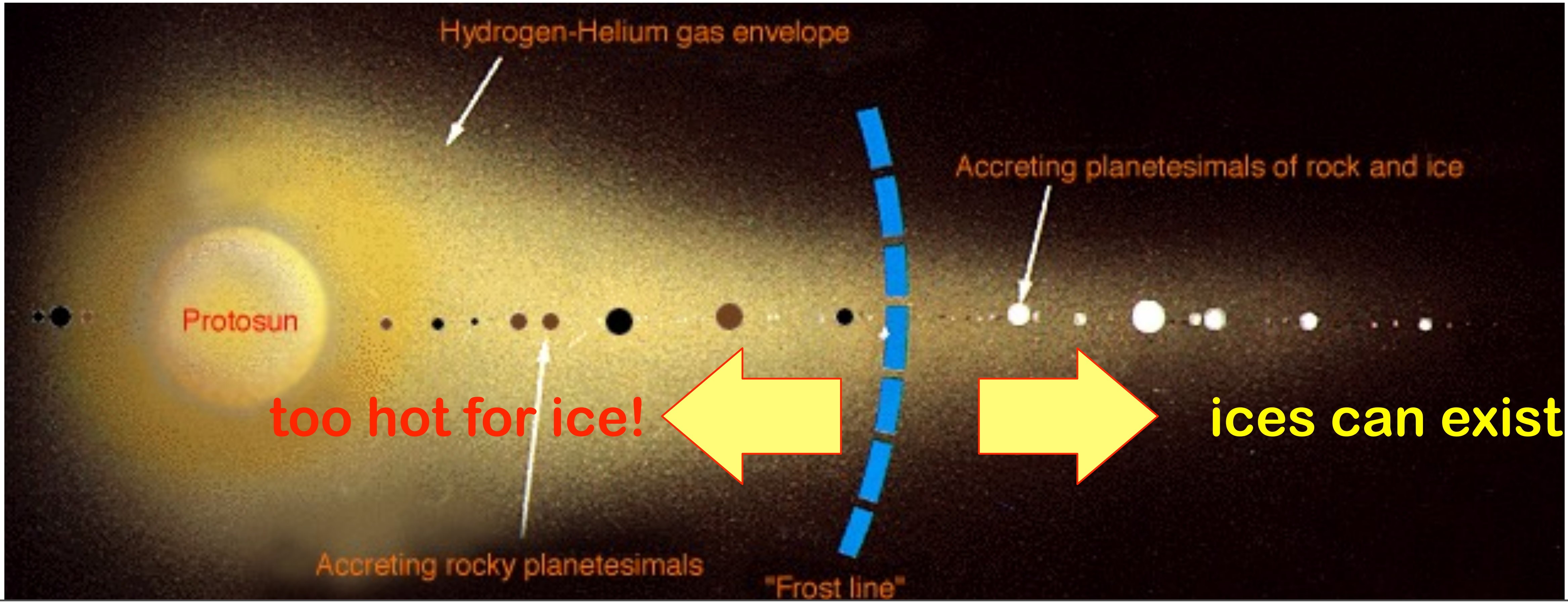
Boundary: “snow line” or “frost line”

- closest place where ice can survive



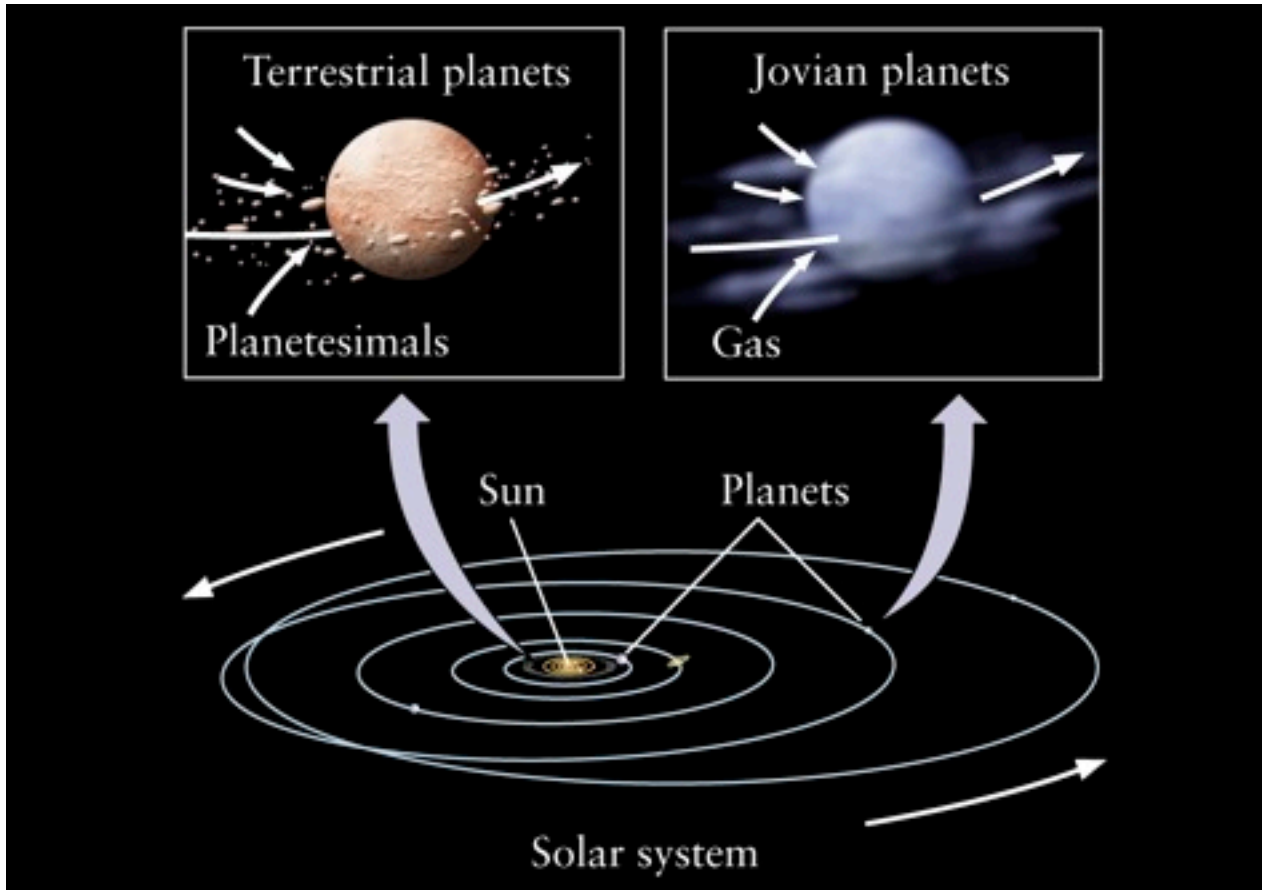
Terrestrials vs. Jovians

Inner solar system

- Metal & rock seeds
- Less material
- Small, rocky planets

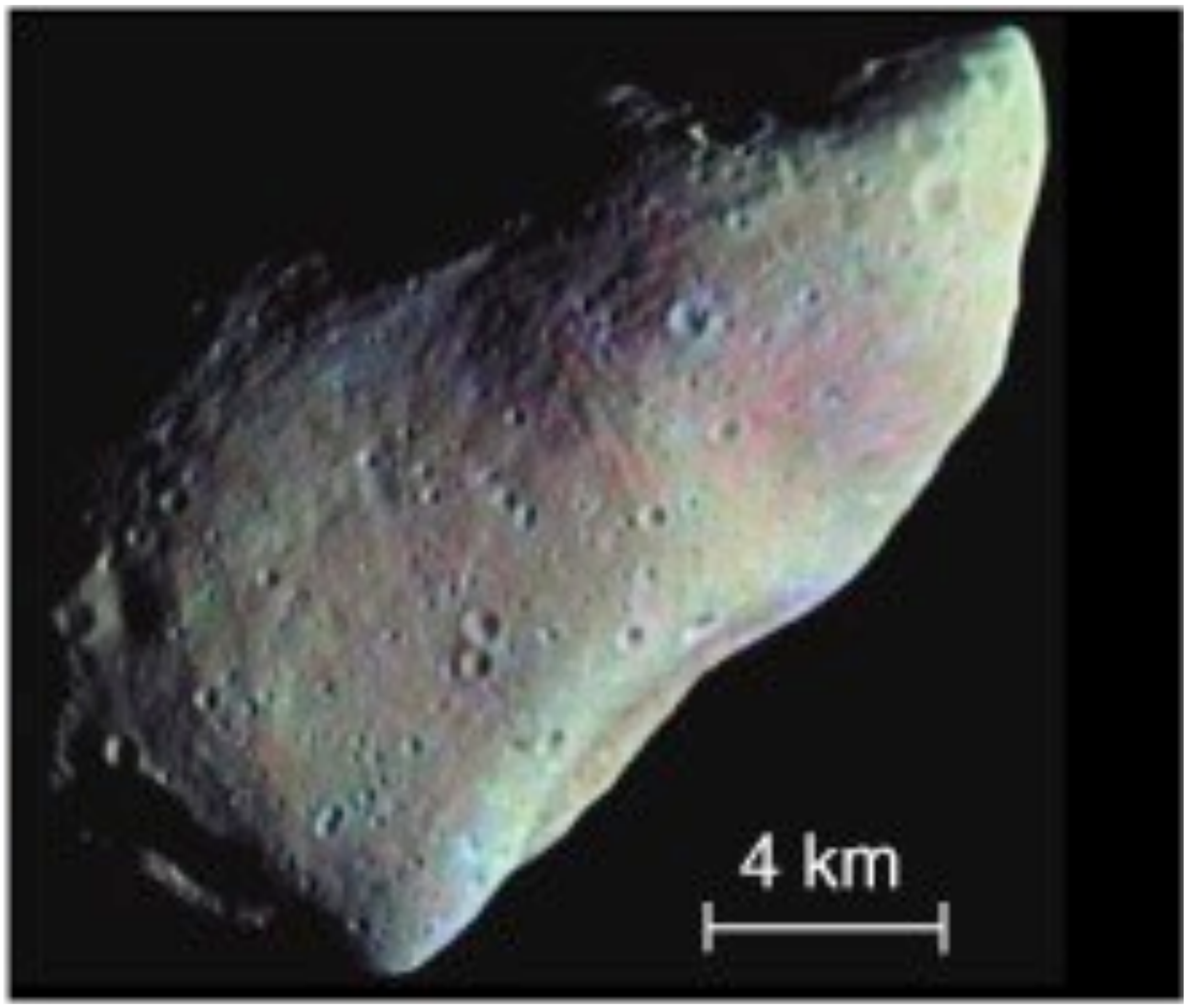
Outer solar system

- Ices, rock & metal seeds
- More material
- Proto-planets grow big
- Gravity captures large amounts of H and He gas
- Large, gaseous planets



Jovian planets grew massive enough to gravitationally capture gas from disk

Where did the asteroids and comets come from?

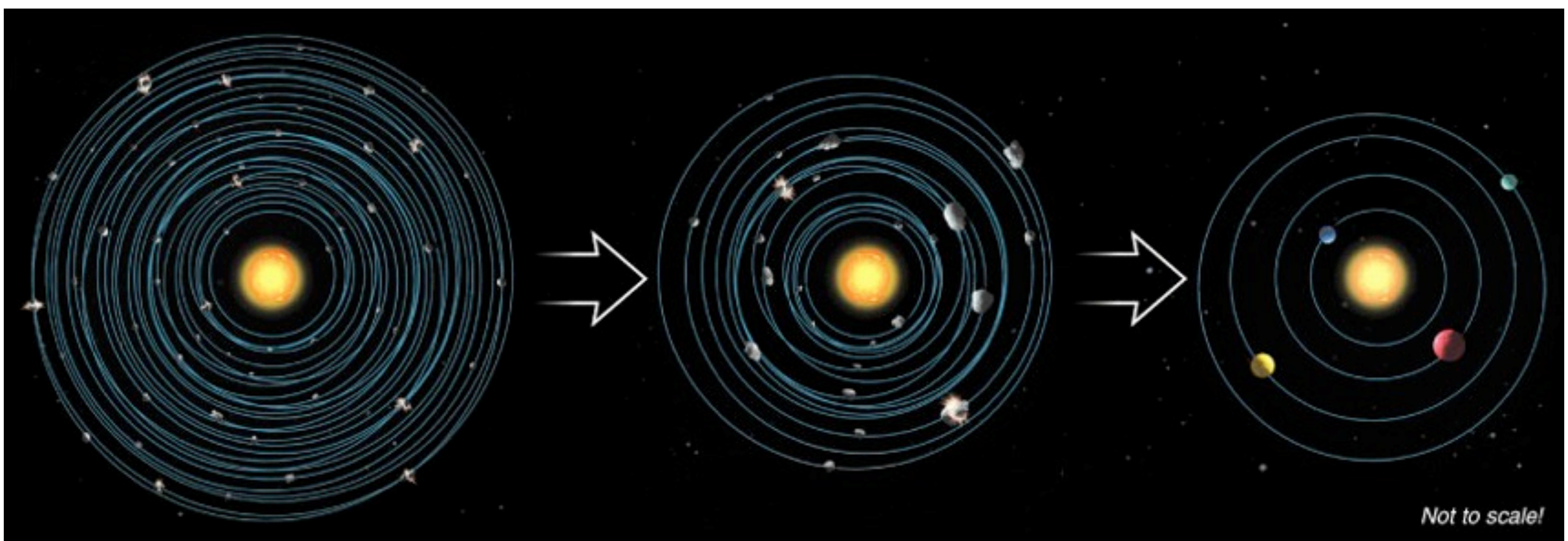


Planetesimals

The young solar system was filled with trillions of planetesimals

Many were swept up to become parts of the forming planets

What happened to the rest?



Heavy Bombardment

Leftover planetesimals bombarded other objects in the late stages of solar system formation

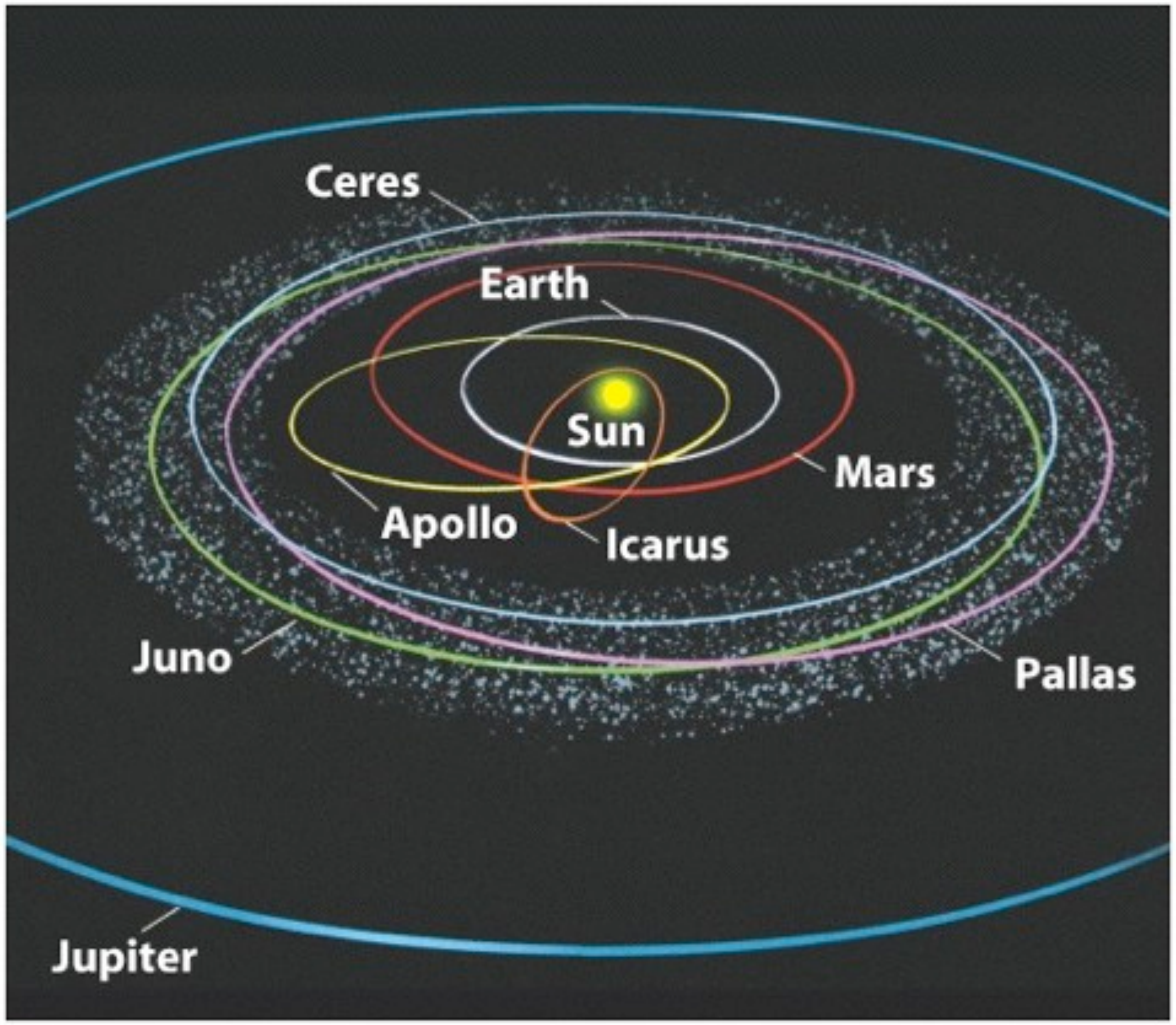
Evidenced by the cratered surfaces of the Moon & Mercury!

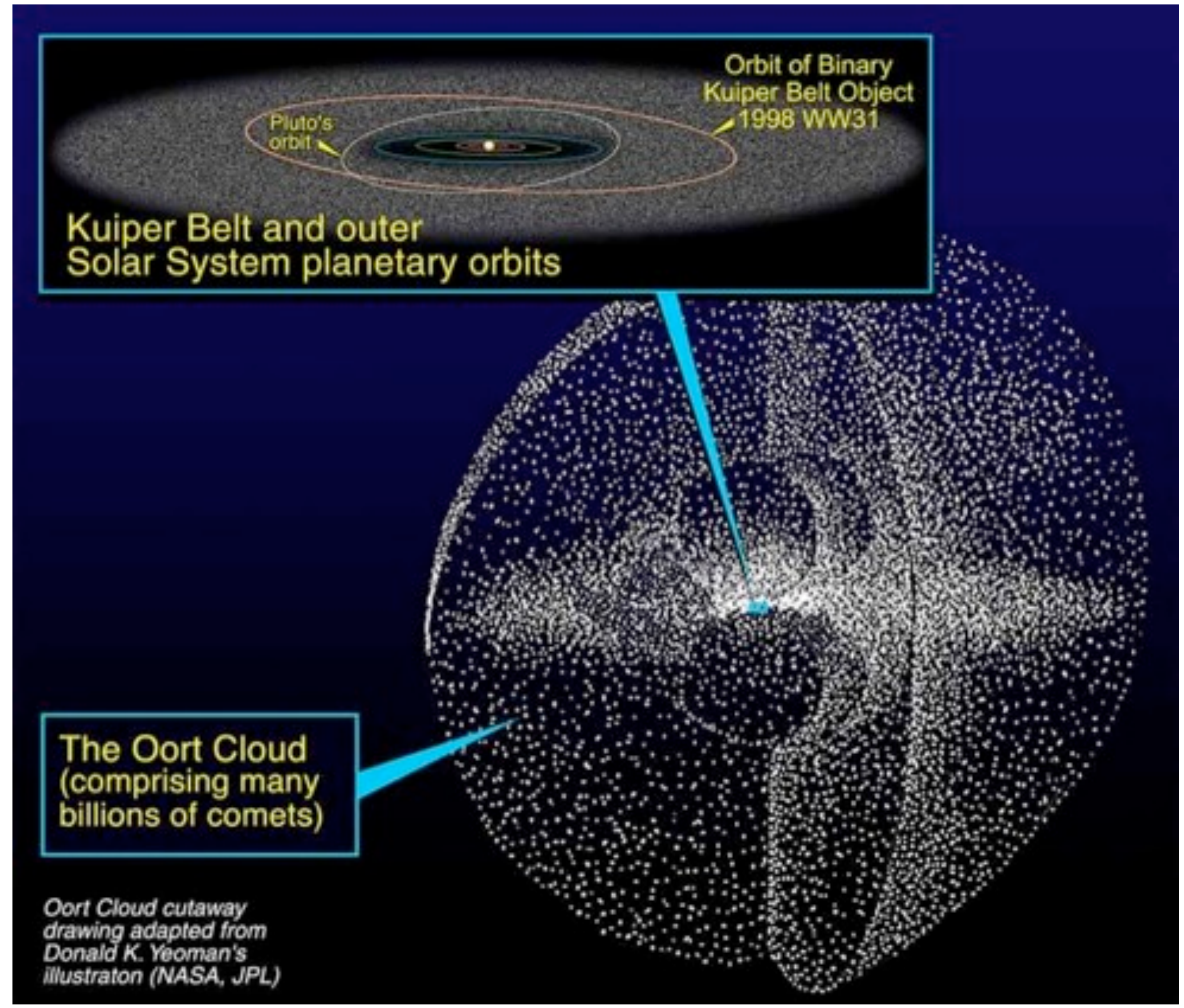
Period of heavy bombardment

Lasted for about 800 million years

The Moon's surface shows the scars of the heavy bombardment

Asteroids and comets are leftover planetesimals!



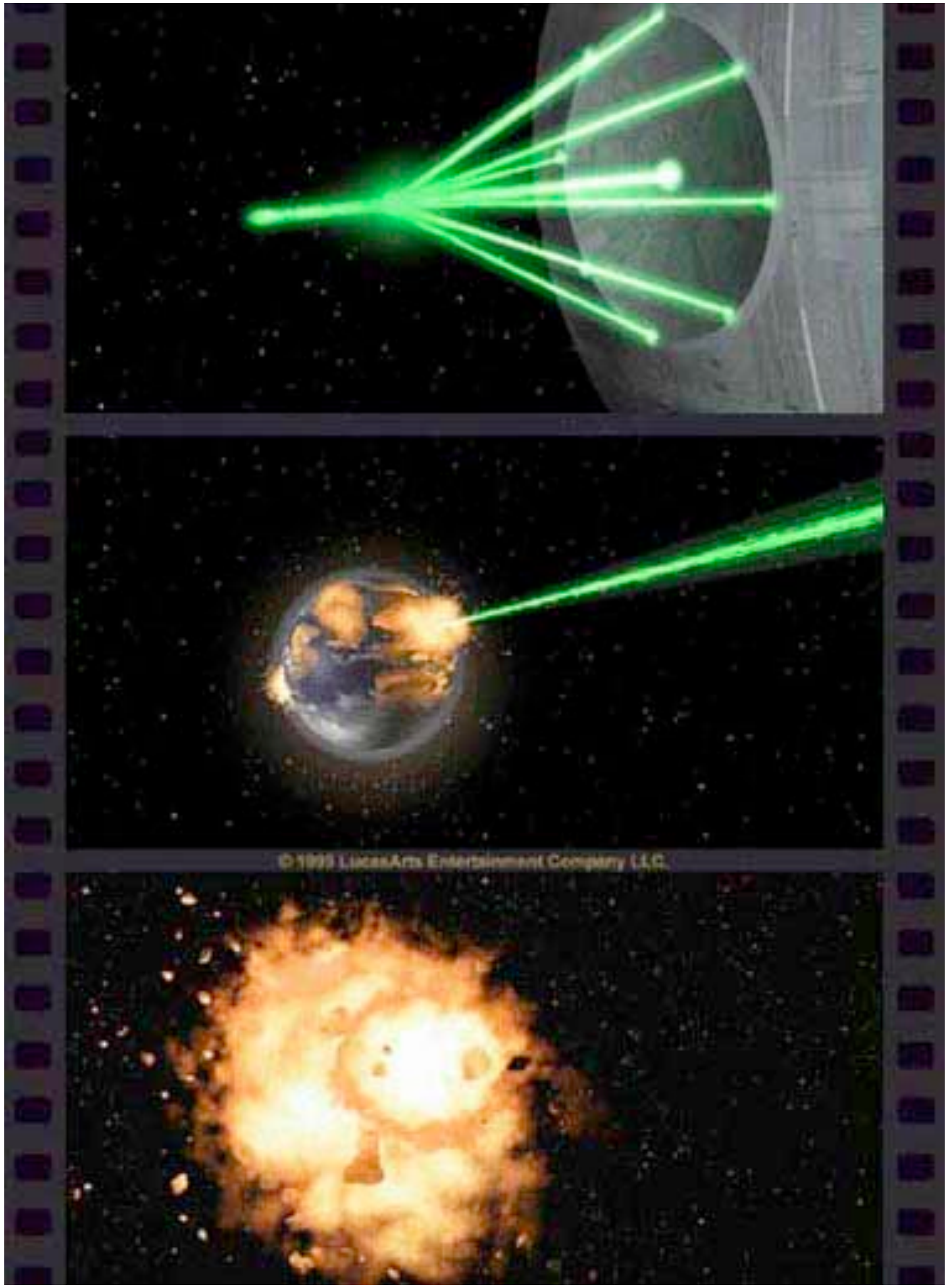


Asteroids are rocky because they formed inside the frostline

Comets are icy because they formed outside the frostline

Origin of Asteroid Belt

- Planetesimals between Mars and Jupiter did not gravitationally clump into a planet
- Jupiter's gravity stirred up these planetesimal orbits and prevented clumping
- Asteroid belt is leftover planetesimals prevented from ever forming a planet



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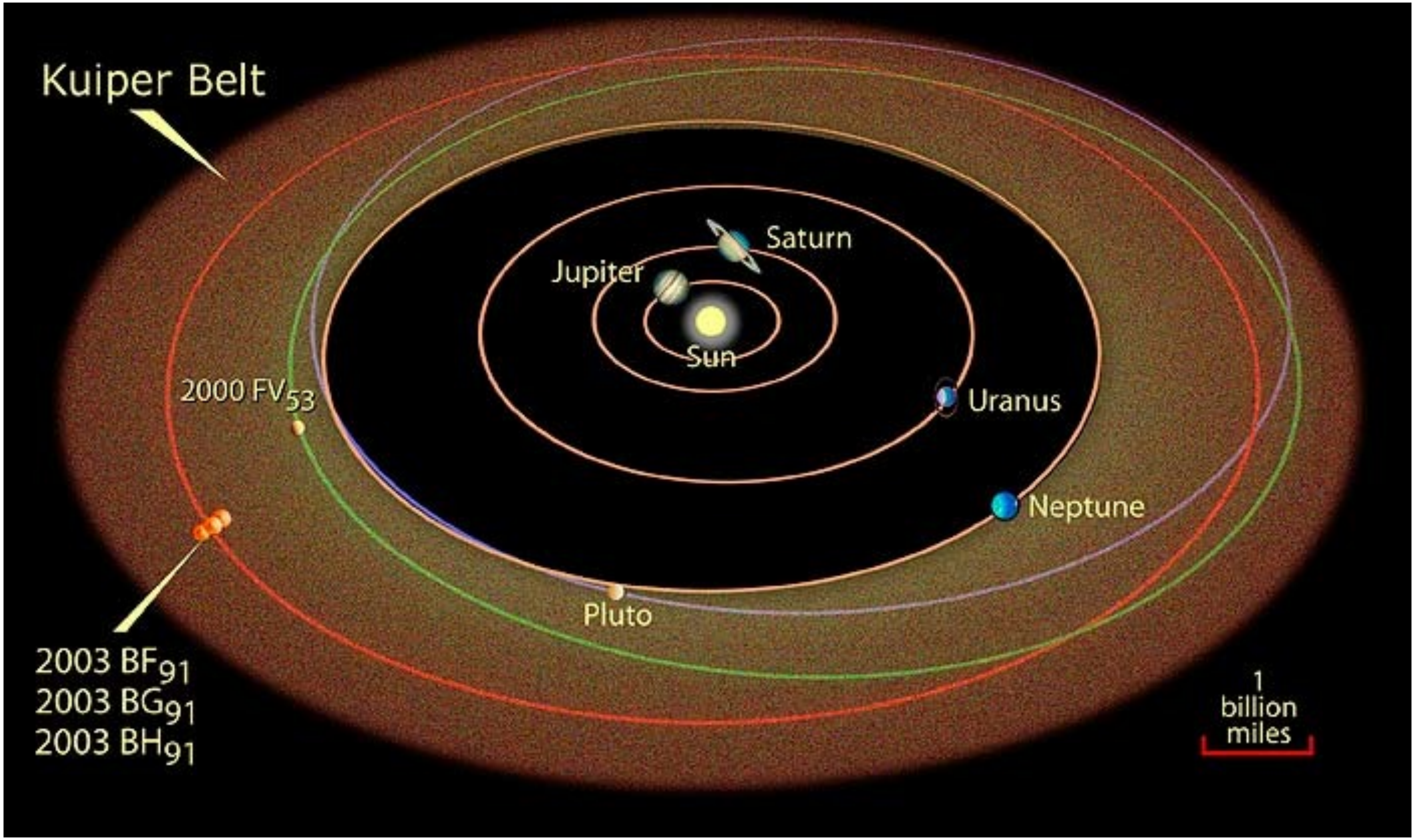
The asteroid belt is <u>not</u> the remains of a destroyed terrestrial planet

Kuiper Belt Objects: Formed beyond the orbit of Neptune



Not enough material to form another Jovian planet

Oort Cloud Comets: Ejected to deep freeze

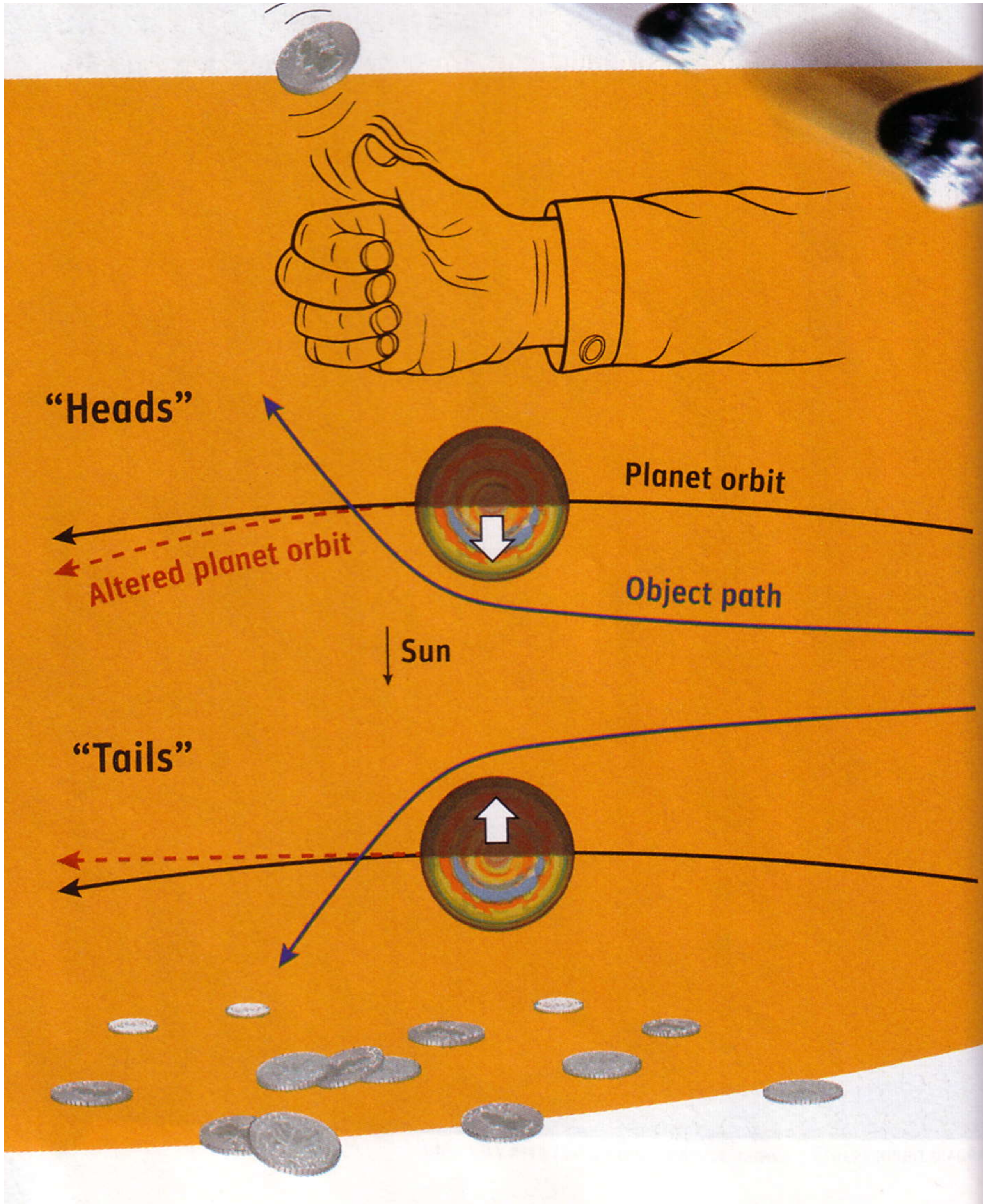
Oort Cloud comets formed in the Jovian planet region

Gravitational interactions with the proto-Jovians changed their orbits

- Launched them to the Oort Cloud

  OR

- Sent them into the inner solar system!

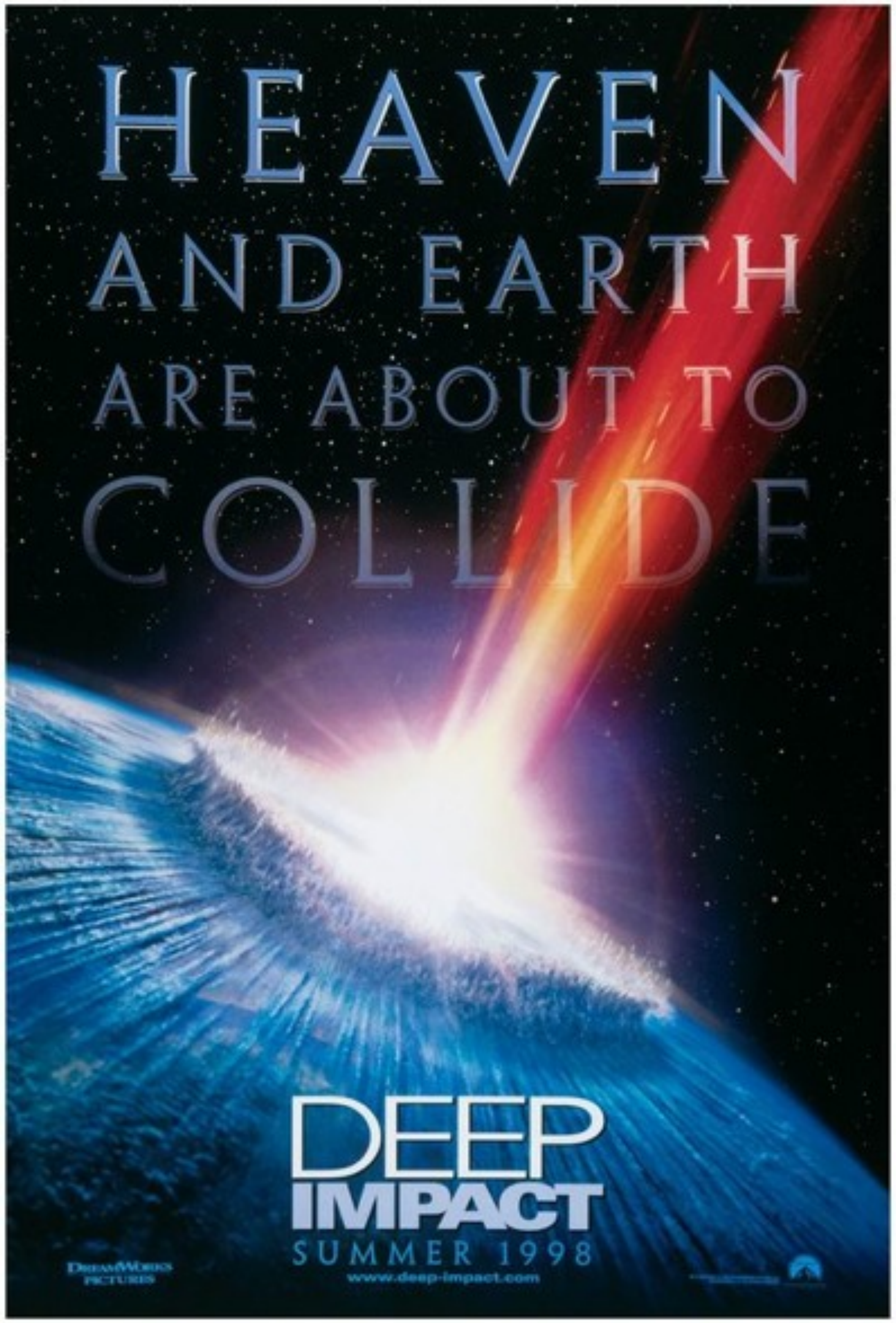


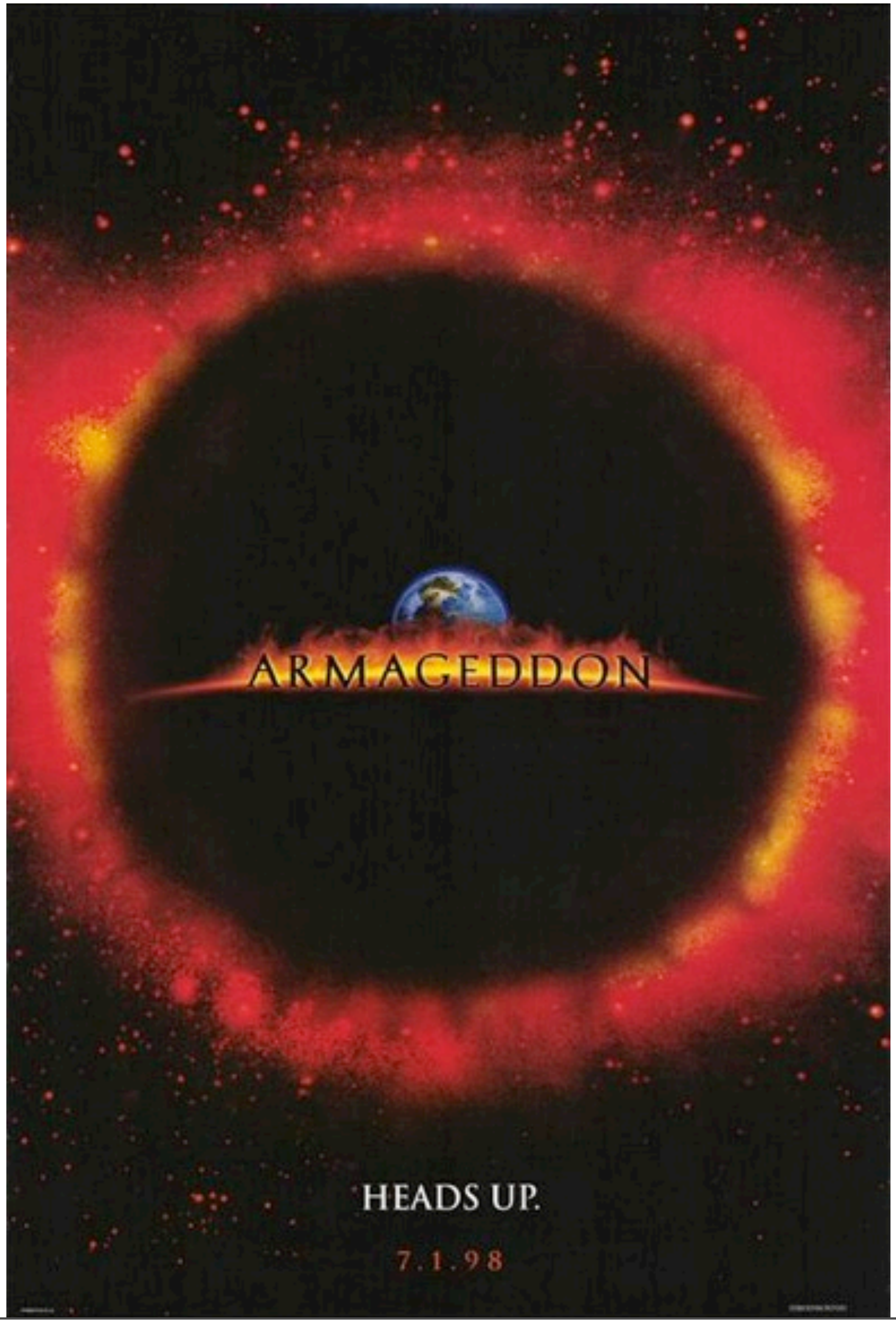
Earth's Cosmic Water Source?

Interactions with Jovians may have sent water-bearing planetesimals to a young Earth

Impacts and the Earth

Is the impact threat a real danger or just media hype?





Meteor Crater

Near Winslow, Arizona

- on your way to the Grand Canyon: must-see detour!

Occurred 50,000 years ago

impactor:

- 50 meter across
- impact speed approximately 13 km/sec = 30,000 mph!

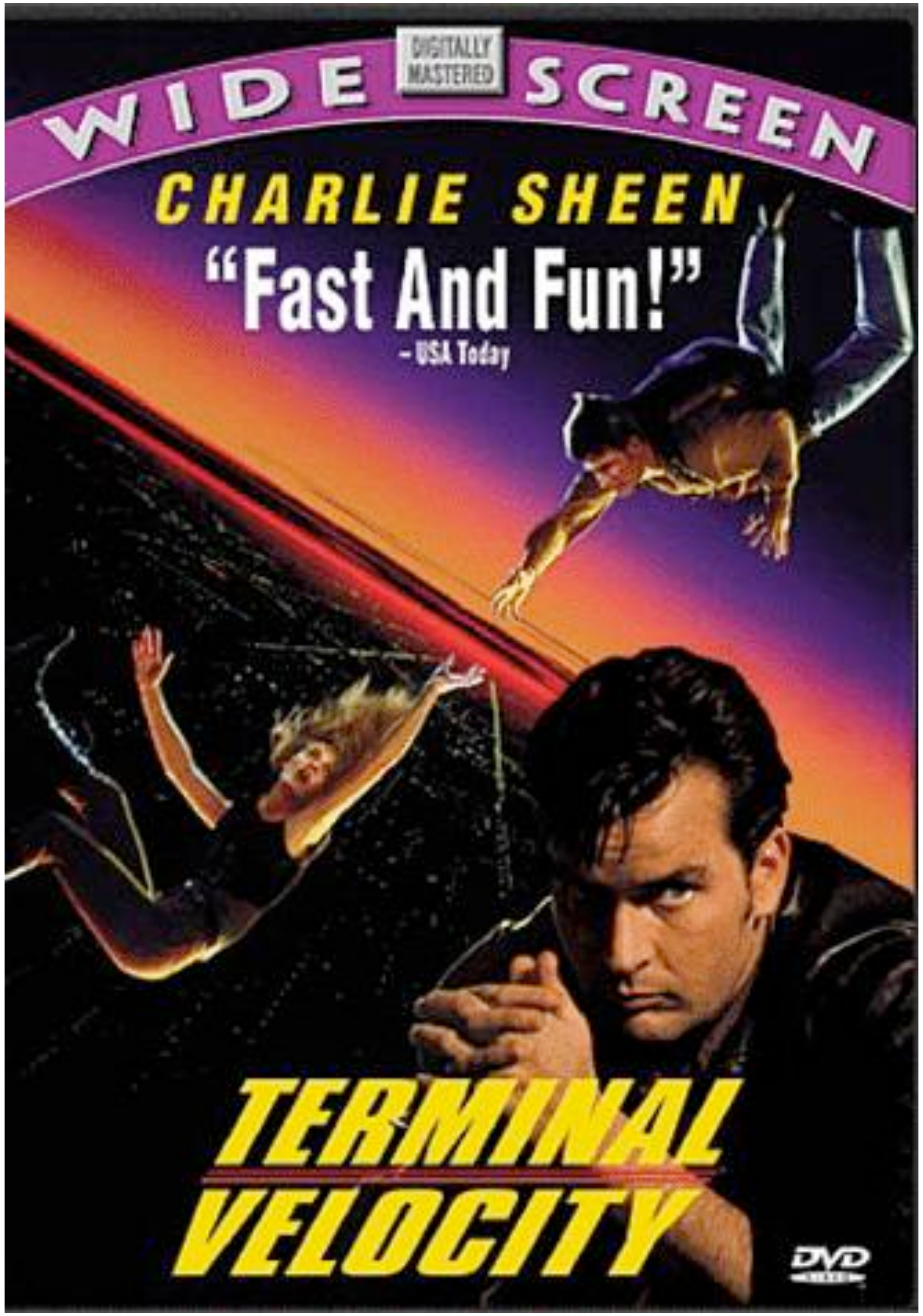
Energy of explosion equal to 25 megatons of TNT!

How can falling objects cause so much damage?
Impacts occur at enormous speed!

- Space debris moving at high speeds
- Earth's orbital speed: 30 km/s (67,000 mph)
- Impactor speeds **entering the atmosphere**
  - Range: 11-72 km/s
  - $\text{Mean}_{\text{Asteroid}}$: 17 km/s
  - $\text{Mean}_{\text{Comet}}$: 51 km/s

Terminal Velocity

- Air causes resistance
- An object falling in the atmosphere will have gravity pulling downward, and air resistance pushing upward
- When the two cancel, the object reaches its maximum velocity, or its **terminal velocity**



Terminal Velocity

Consider a skydiver:

1. At the start of the jump, no air resistance, so diver accelerates downwards, speed increasing.
2. As the speed increases, air resistance increases. Diver still accelerates, but less than before, speed still increasing.
3. Air resistance equals the pull of gravity, and the diver no longer accelerates. The speed is at the **terminal velocity**.

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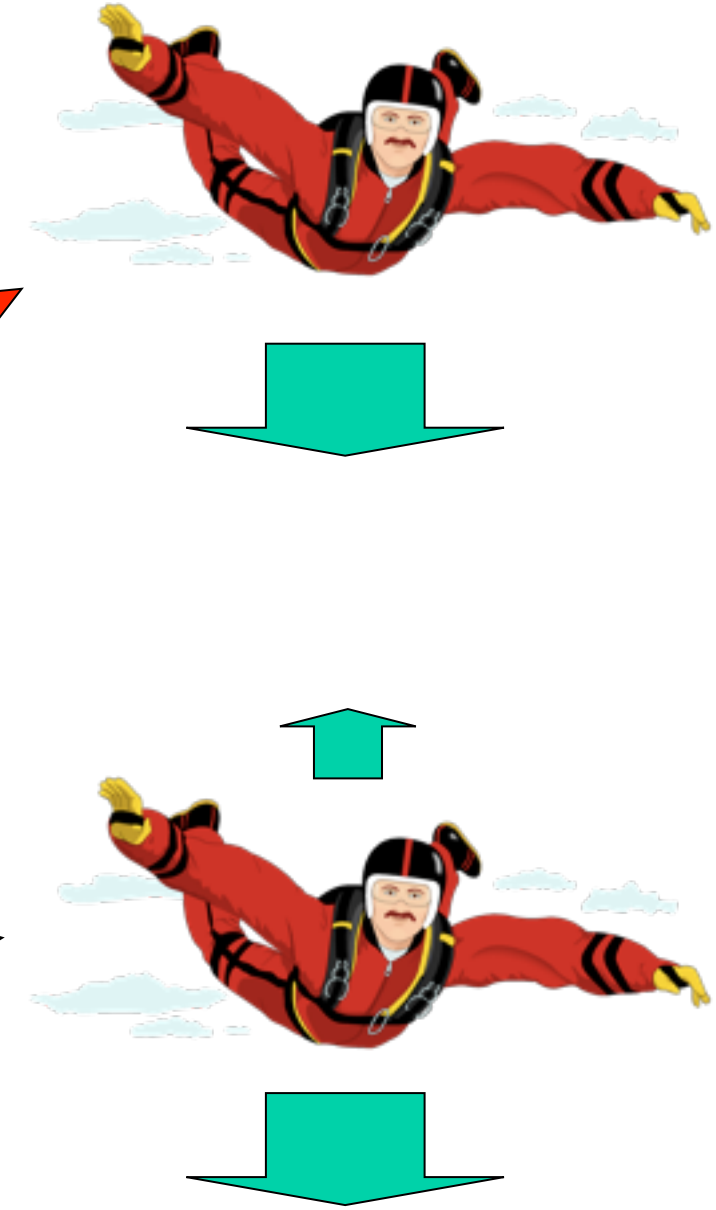

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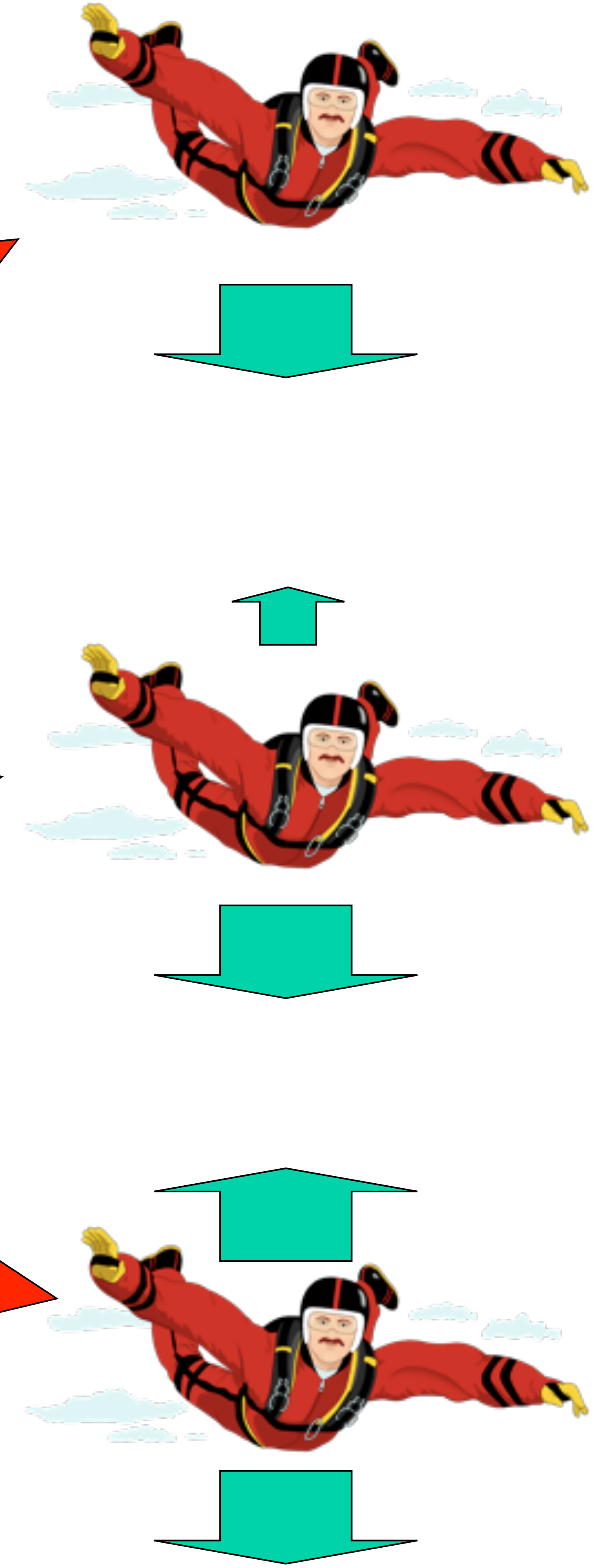

Terminal Velocity

Still considering a skydiver:

4. When opening the parachute, shape changes, more air resistance, so diver decelerates, speed decreases
5. Because object is slowing down the air resistance decreases until it balances gravity. Diver has now reached a new, lower terminal velocity, allowing him to land safely.

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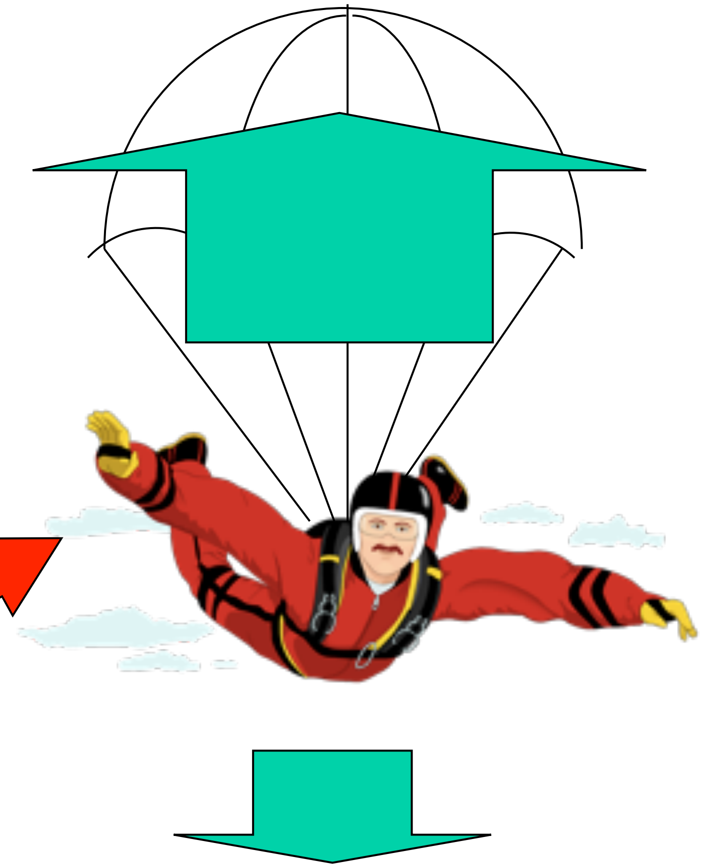
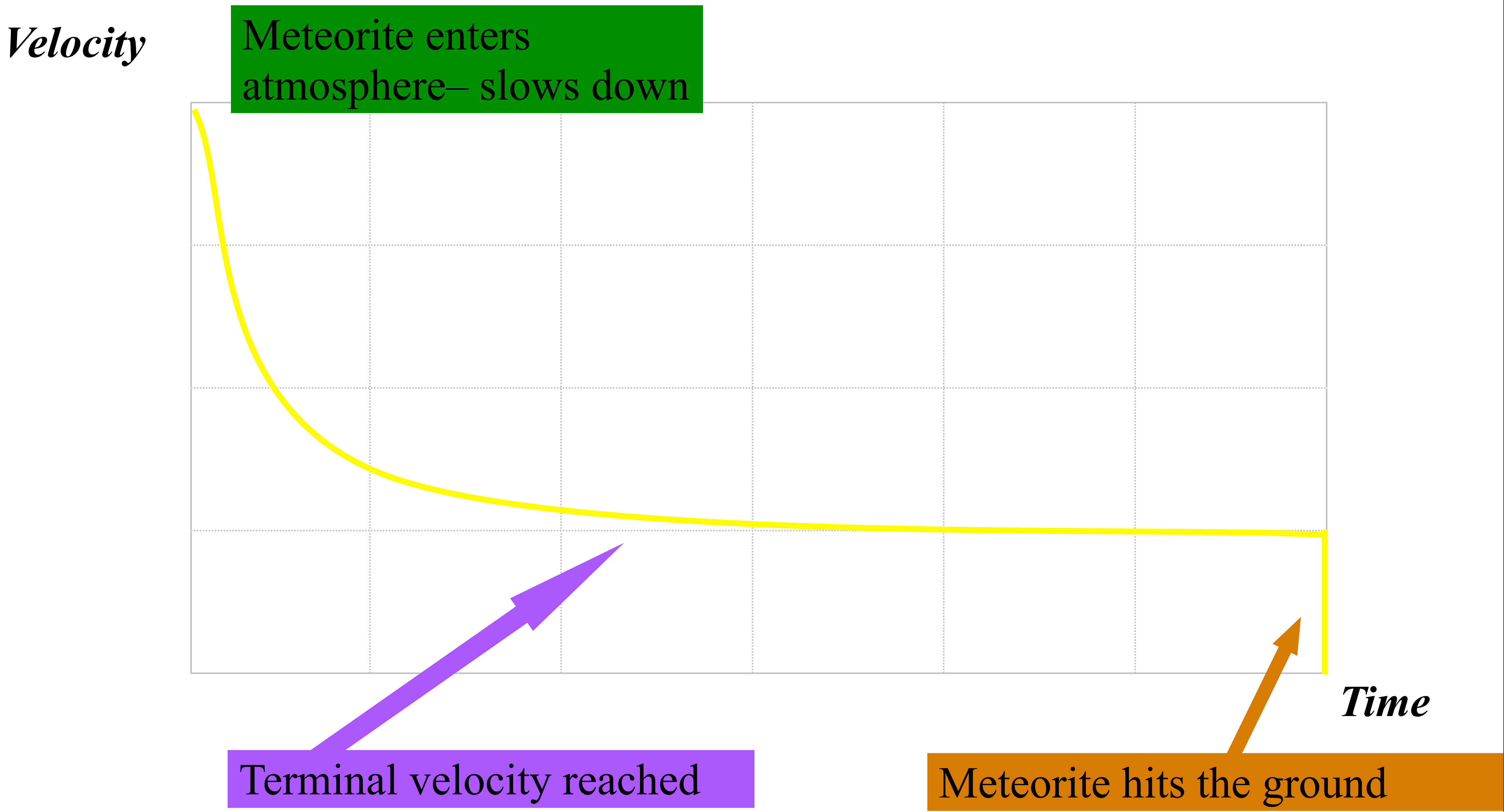


Meteoroid terminal velocity graph



Velocity-time graph for terminal velocity…

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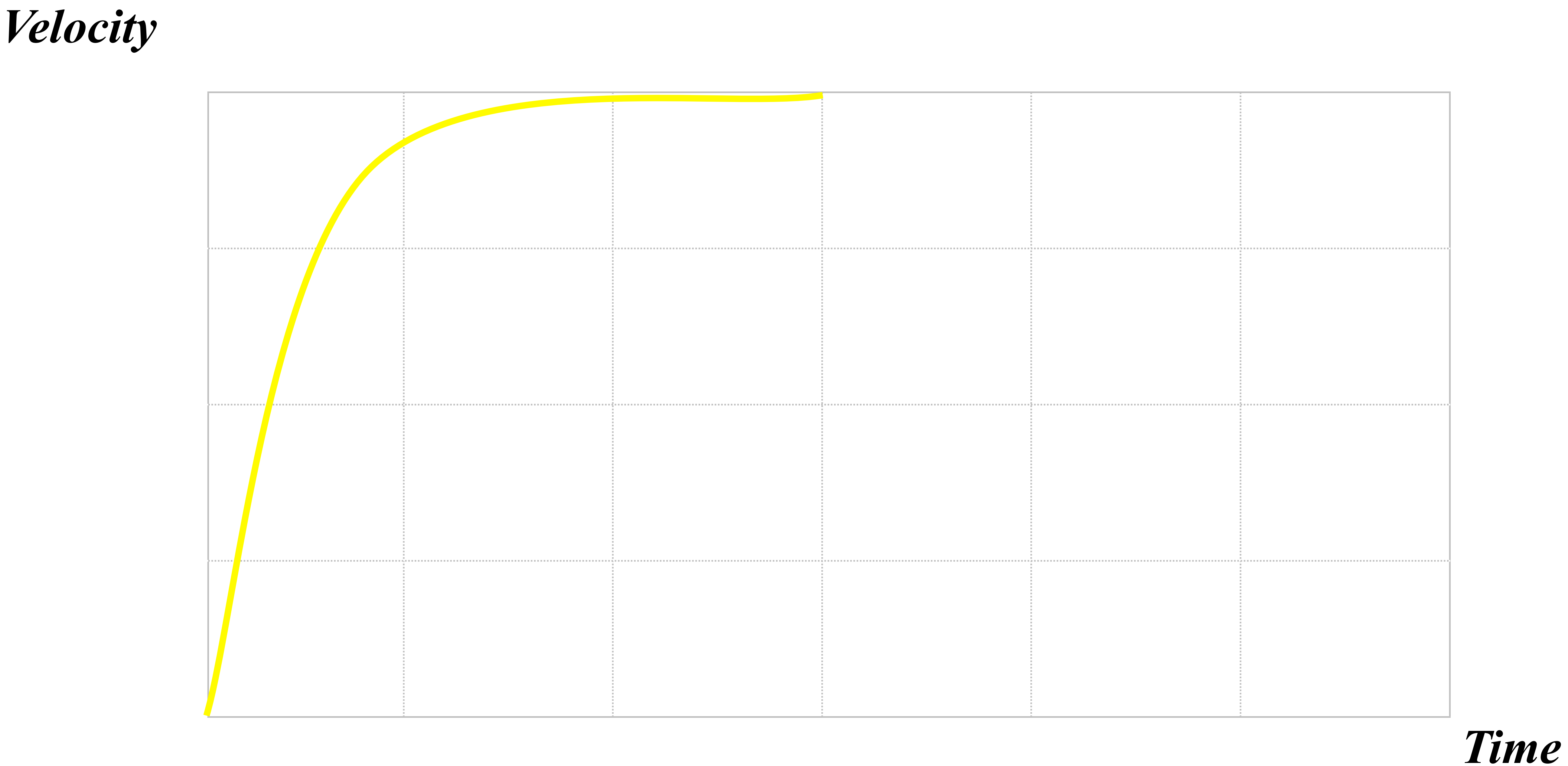

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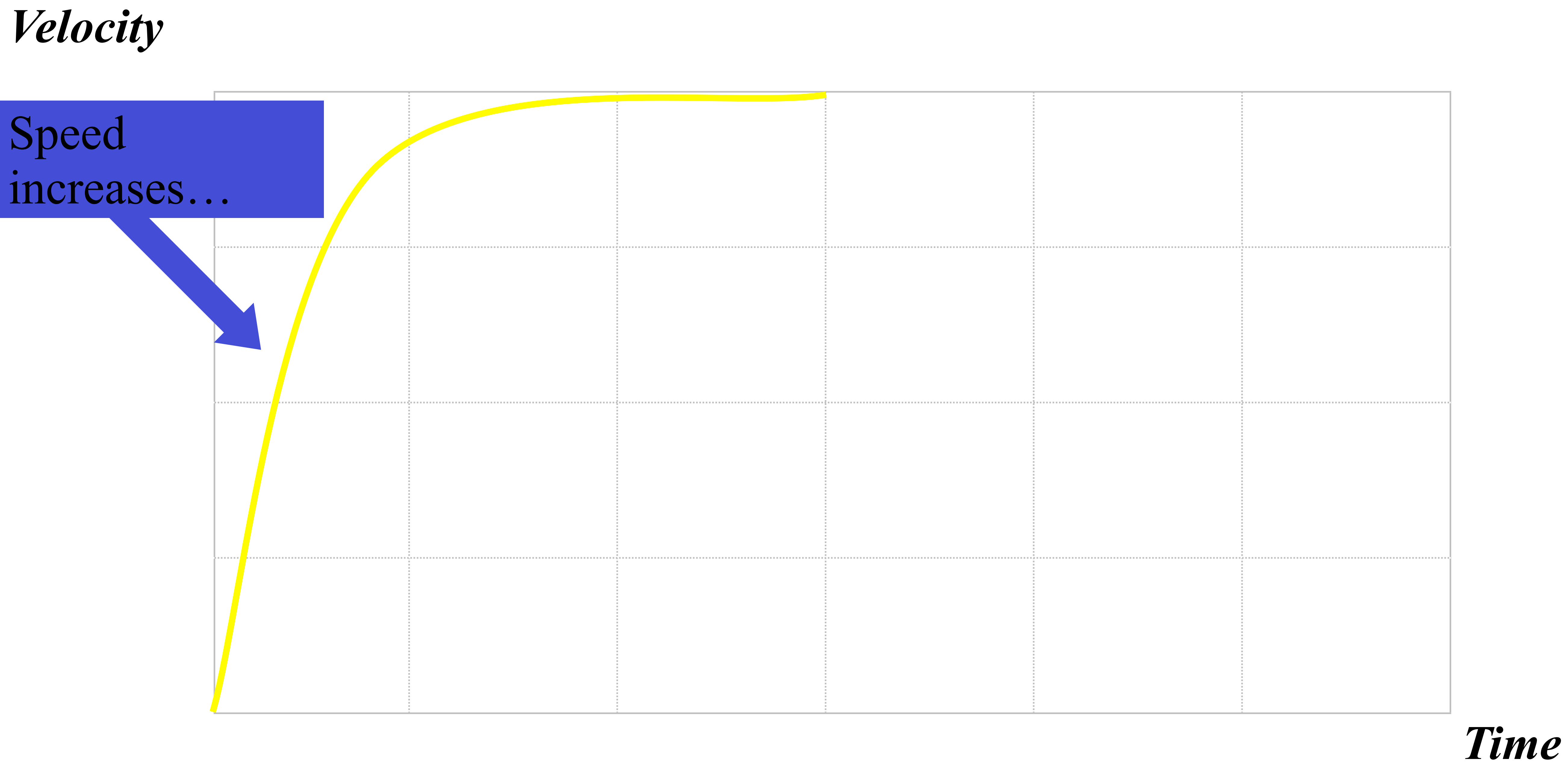

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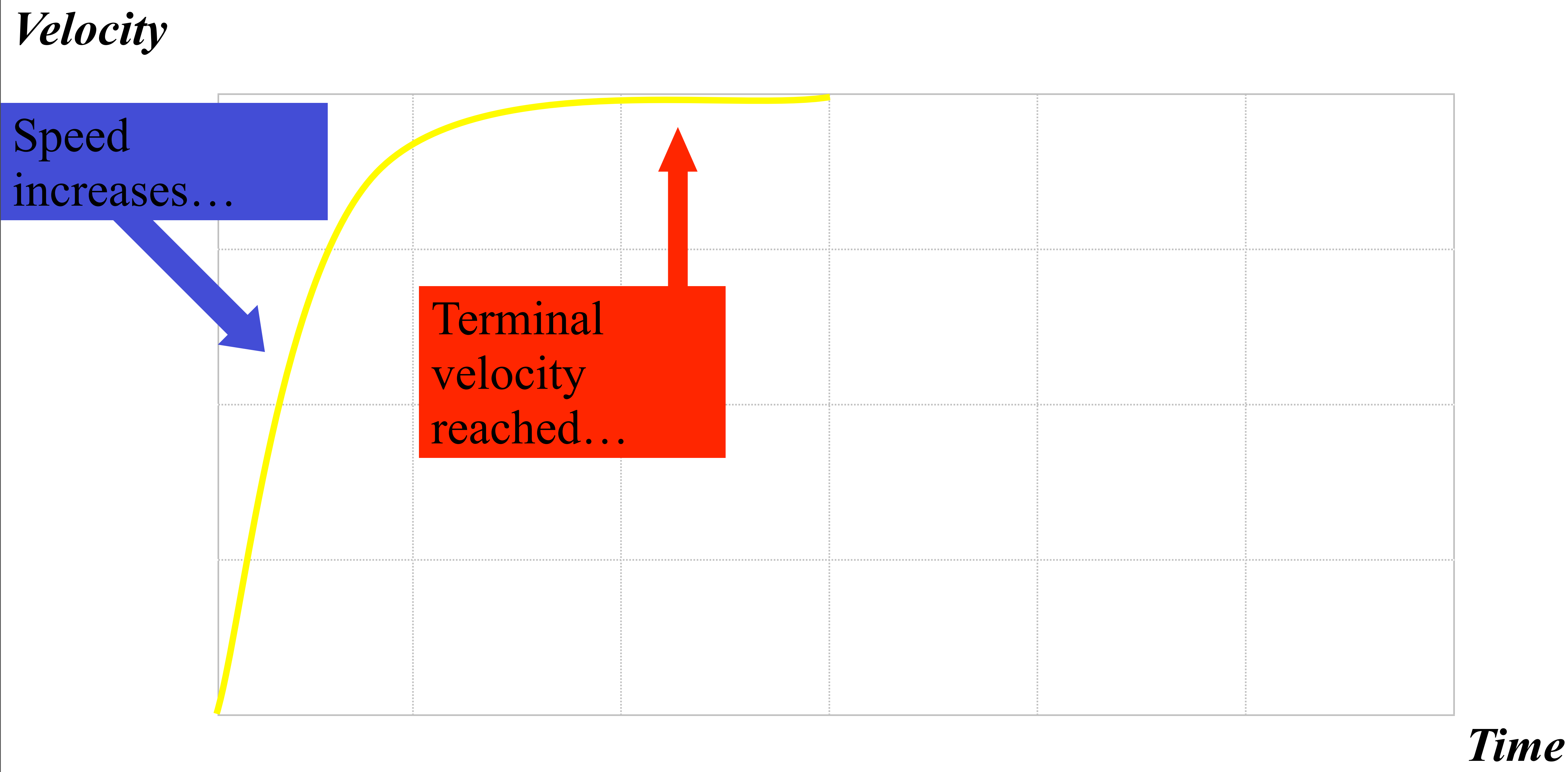

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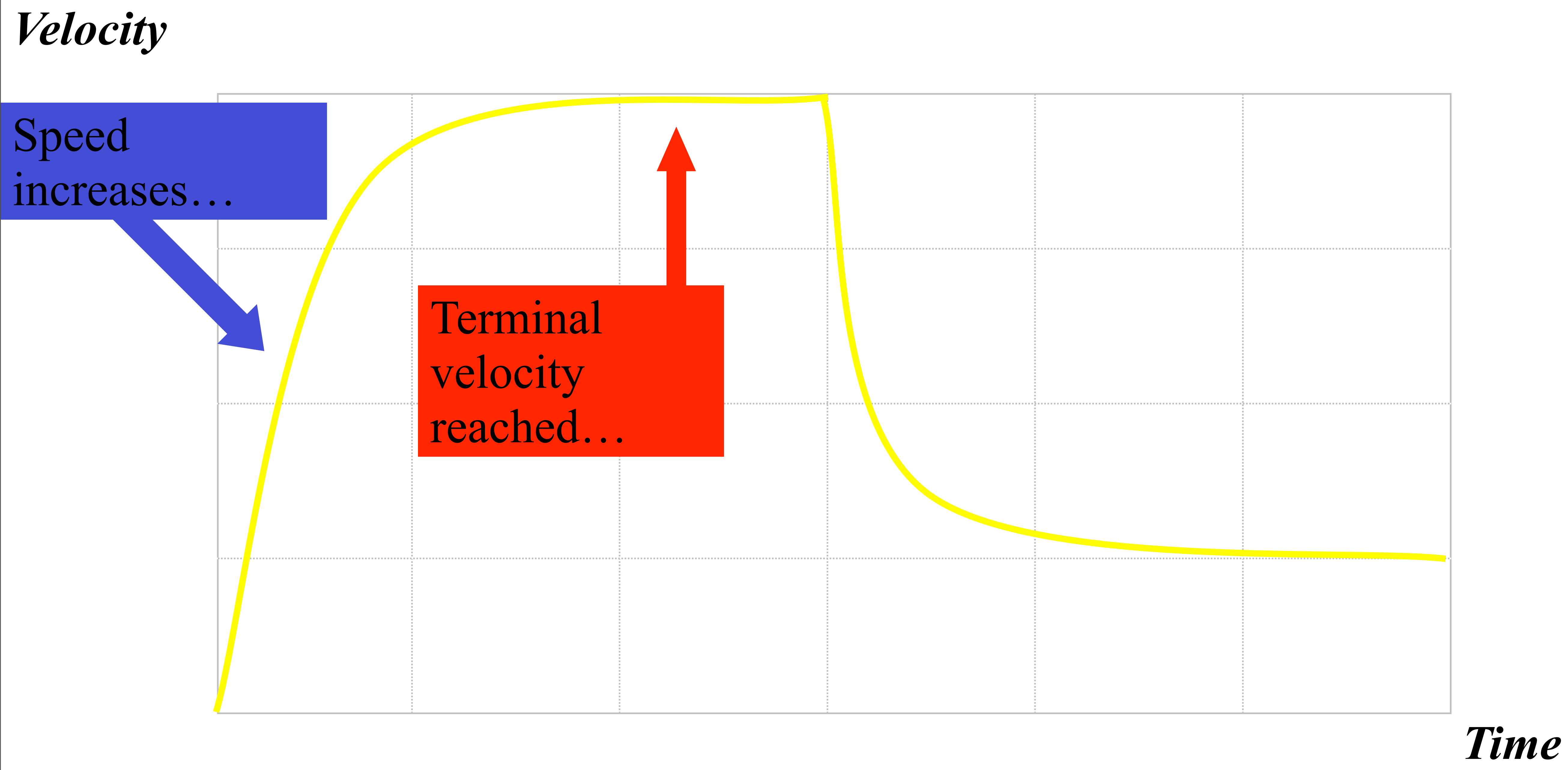

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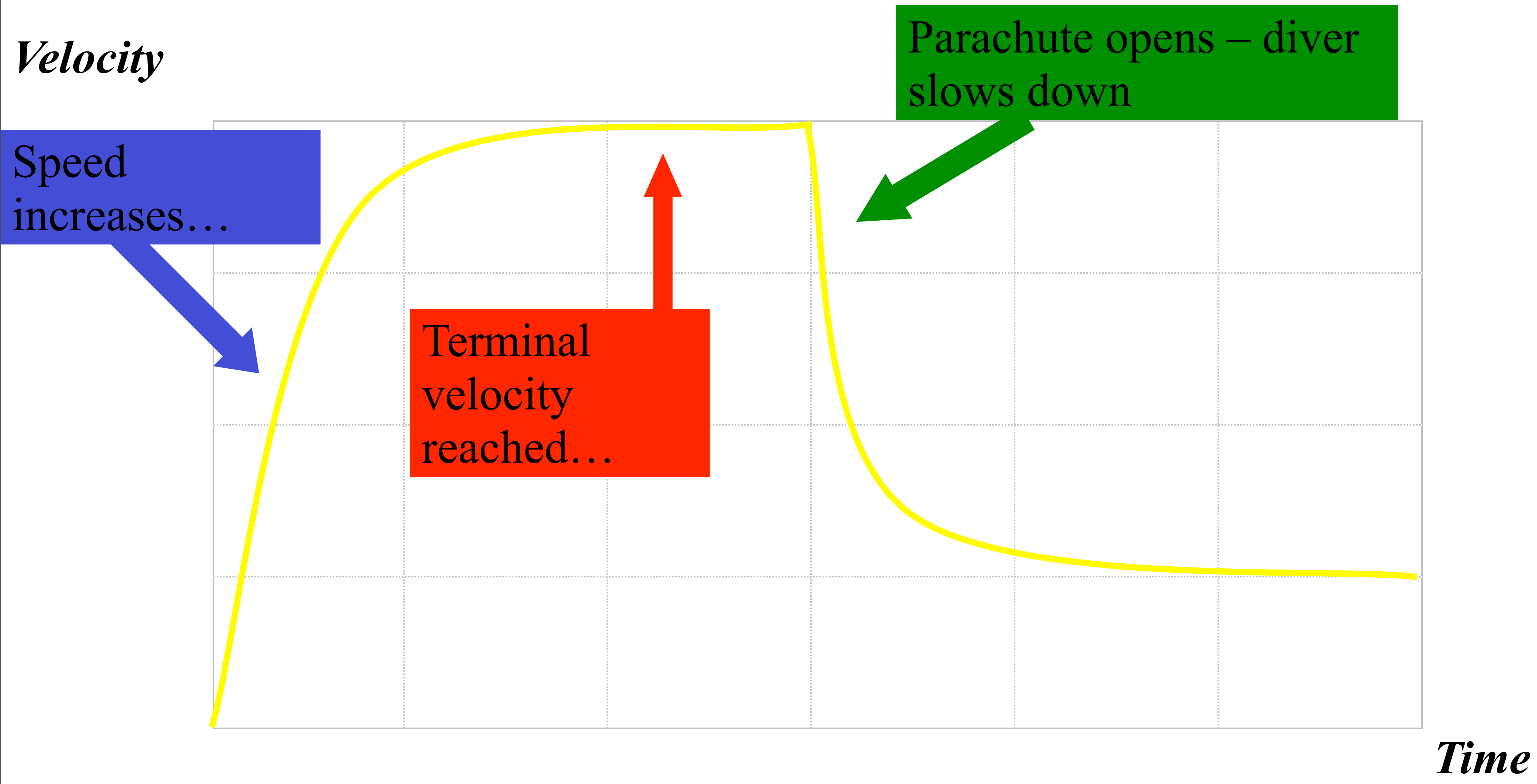

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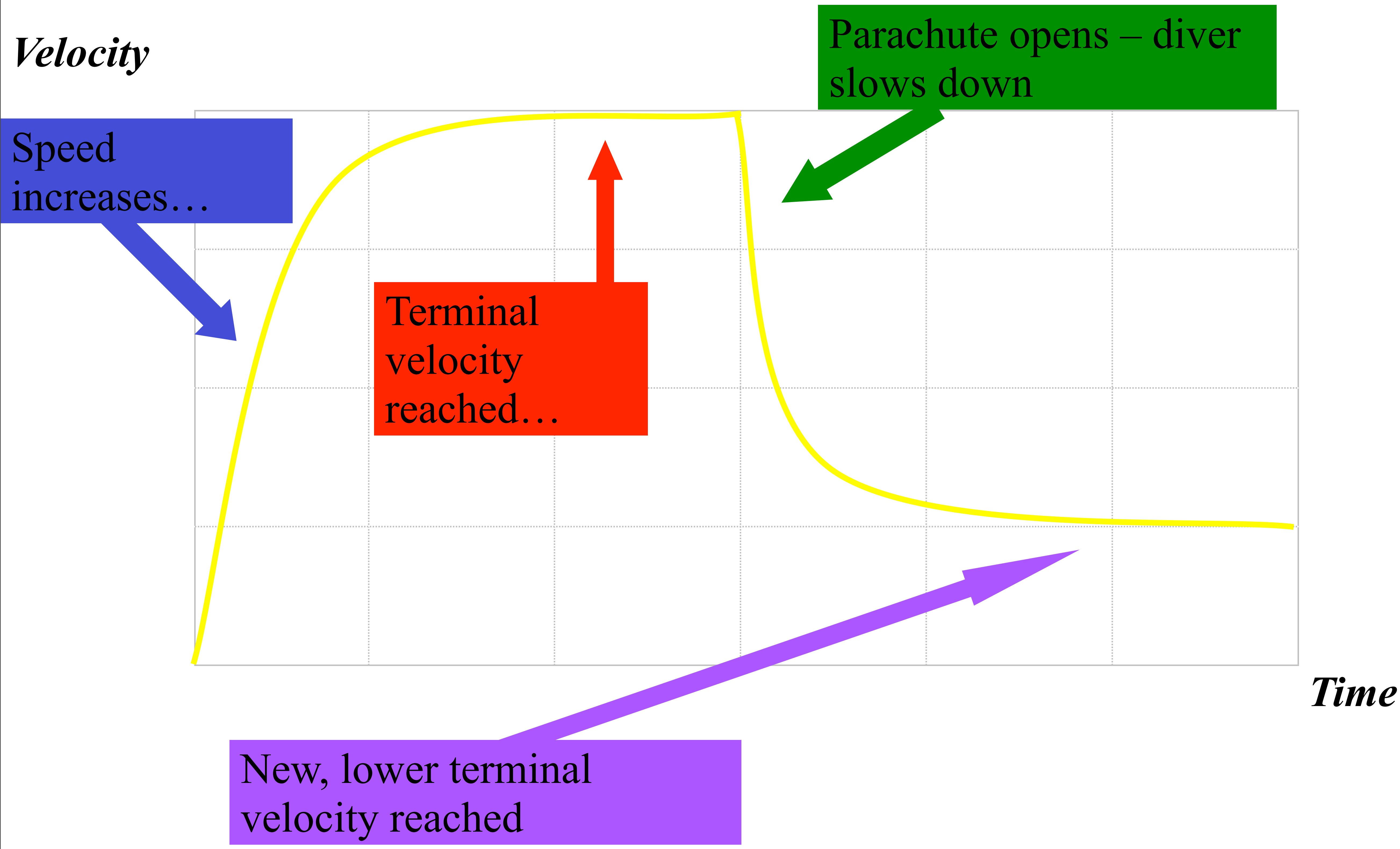

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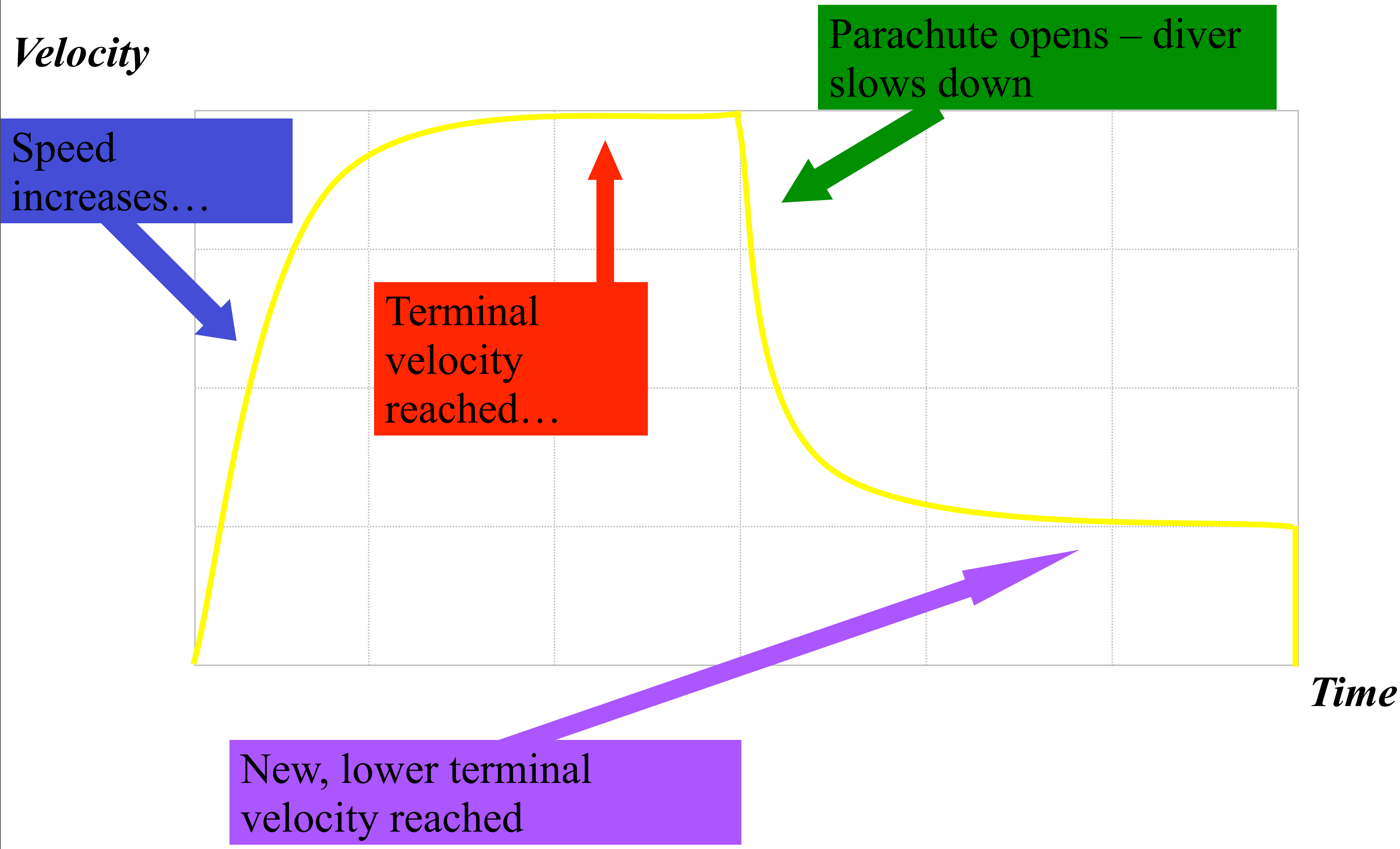

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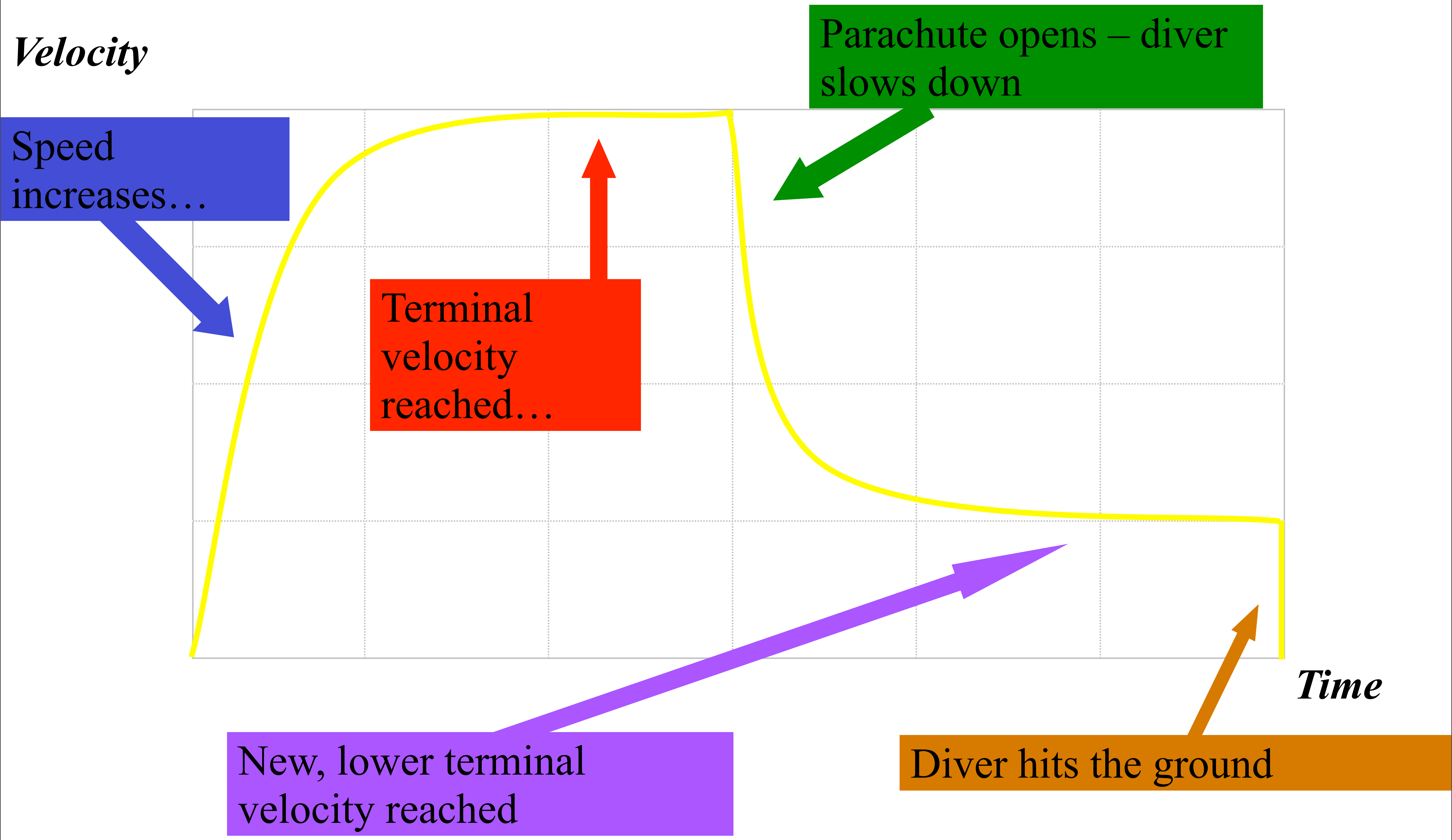

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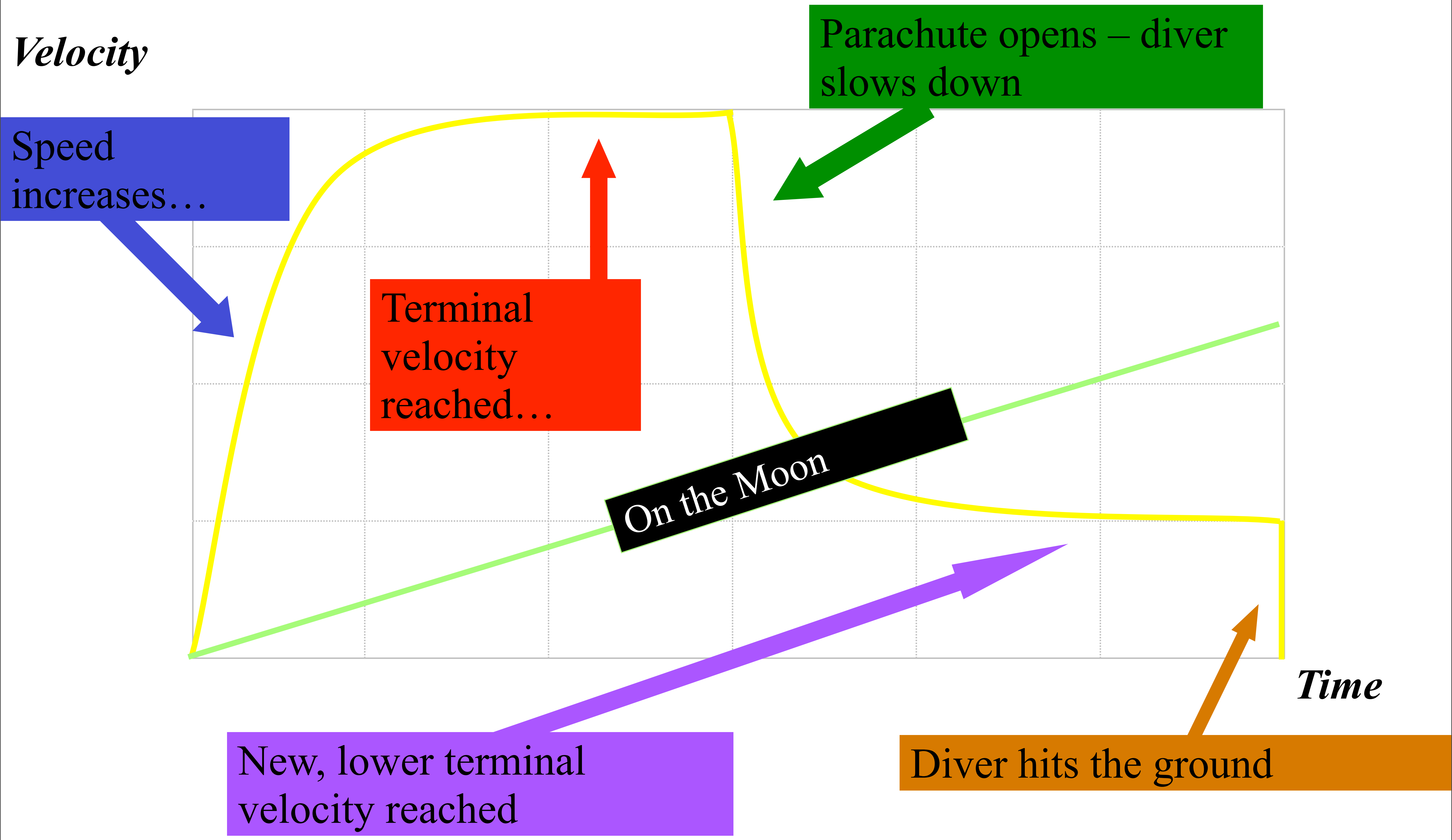

i>clicker question

Why would a skydiver not have a terminal velocity on the Moon?

A. No air.
B. No gravity.
C. No parachutes.
D. No time.
E. No sky.

Up on Speed

- Terminal velocity depends on
  - Shape of the object
  - Mass of the object
  - Size of the object
- Rougher shape = lower terminal velocity
- More mass = higher terminal velocity
- Bigger size = lower terminal velocity

Ramming Speed!

- Objects less than a few kilograms will burn up completely in the atmosphere
- Objects a few kg to 7000 kg will slow down due to the atmospheric drag
- These reach their terminal velocity – about 90-180 m/s (200-400 mph)

The Big One

- Objects ~9,000 kg will keep some of their initial velocity – impact at ~2-4 km/s (1.5 mps)
- Really big objects (~10^6 kg) won't be noticably slowed, impacting at near their initial velocities (>11 km/s!)