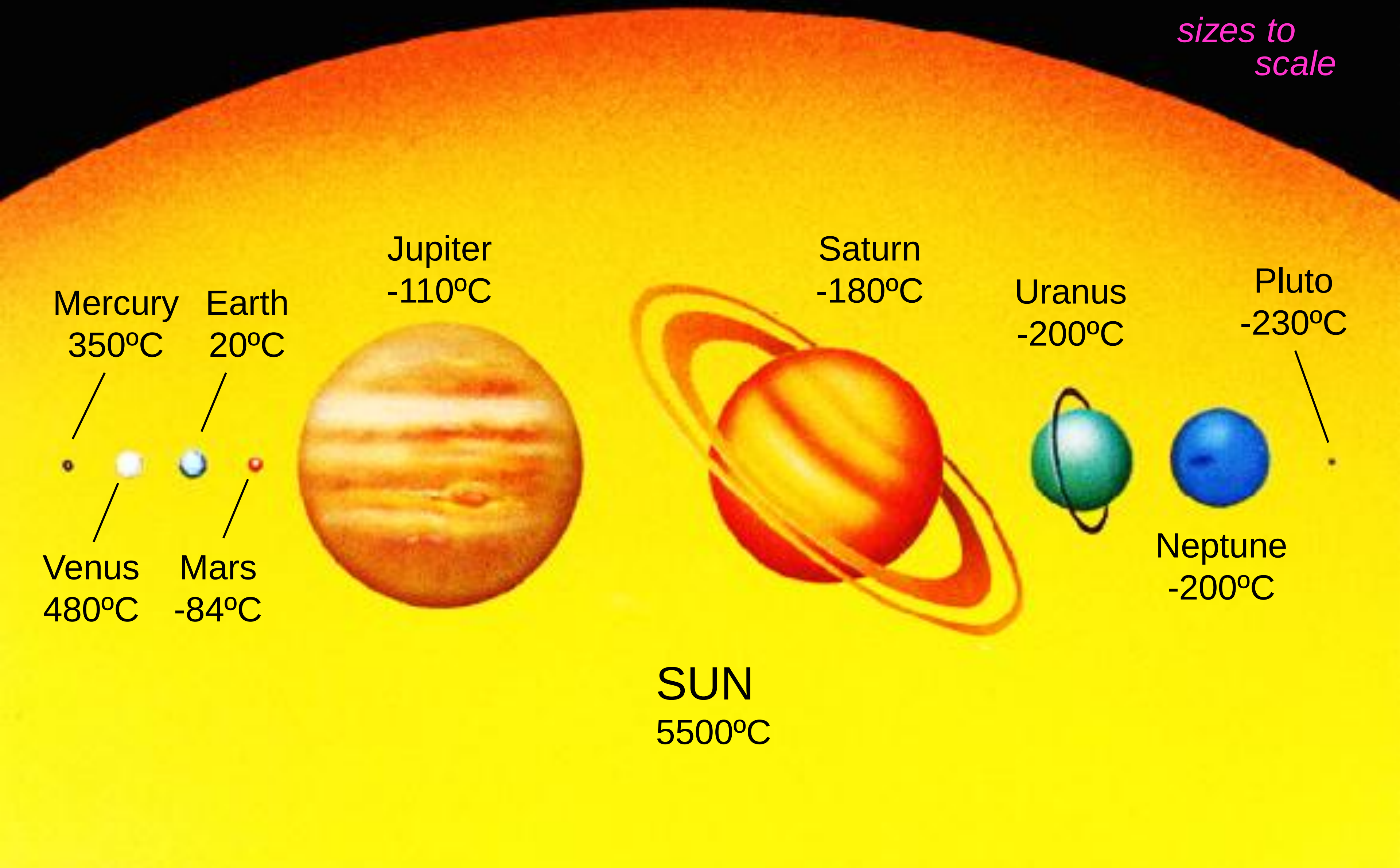
Other worlds

" Innumerable suns exist;
innumerable earths revolve around
these suns in a manner similar to
the way the seven planets
revolve around our Sun.
Living beings inhabit these worlds."

Giordano Bruno
Italian monk of the sixteenth century

The Solar System



Formation of the Solar System

Formation of the Solar System

A theory must explain…

- ✓ planets have nearly circular orbits in nearly the same plane
- ✓ all orbit in the same sense (the same sense as the Sun's rotation)

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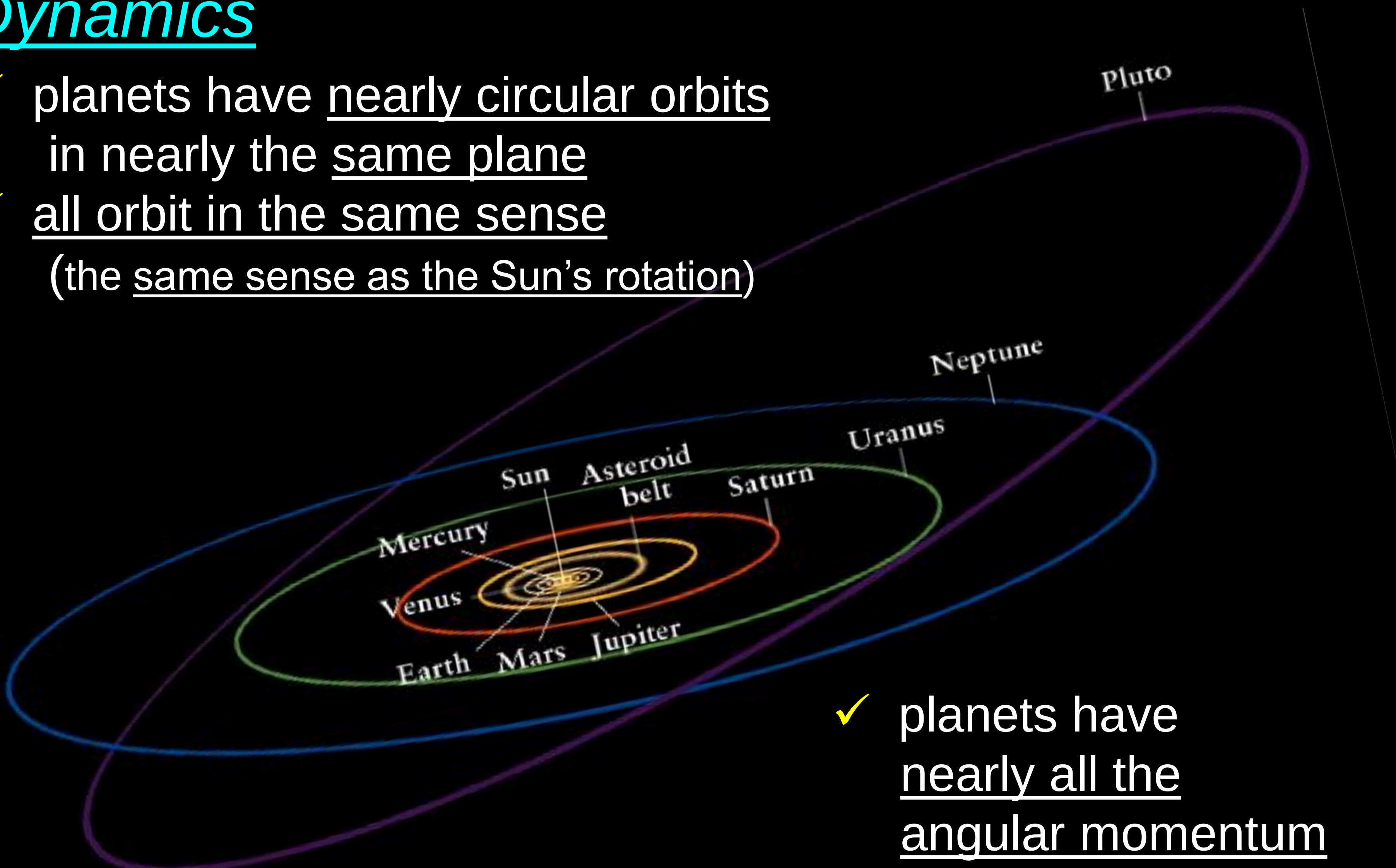
Formation of the Solar System

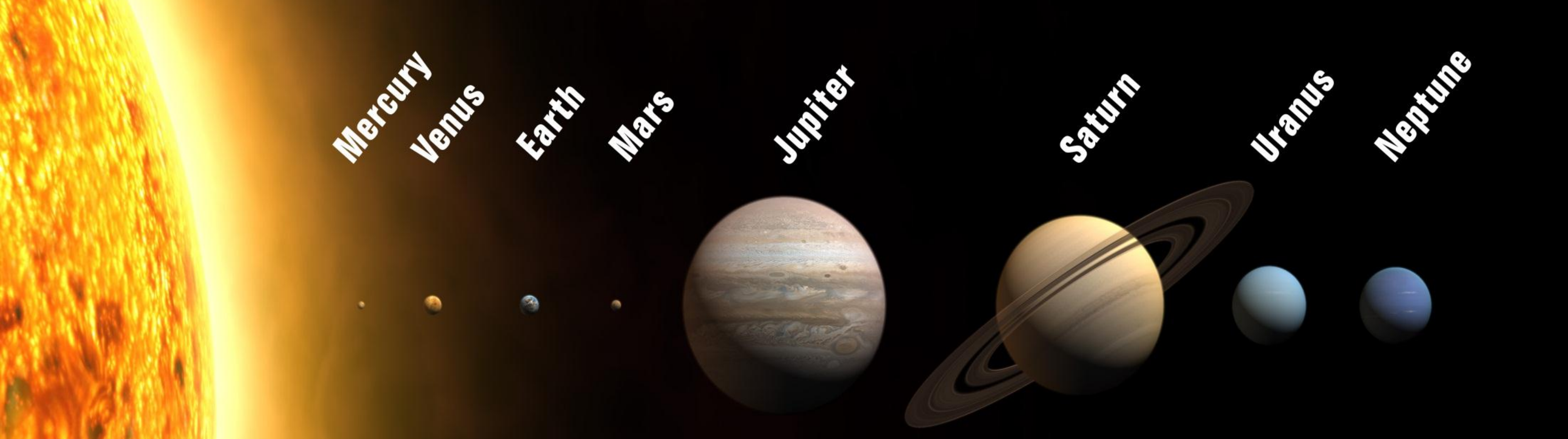
Dynamics

- ✓ planets have nearly circular orbits in nearly the same plane
- ✓ all orbit in the same sense (the same sense as the Sun's rotation)



- ✓ planets have nearly all the angular momentum

Formation of the Solar System



Composition

- ✓ planets close to the Sun are small, metallic and rocky
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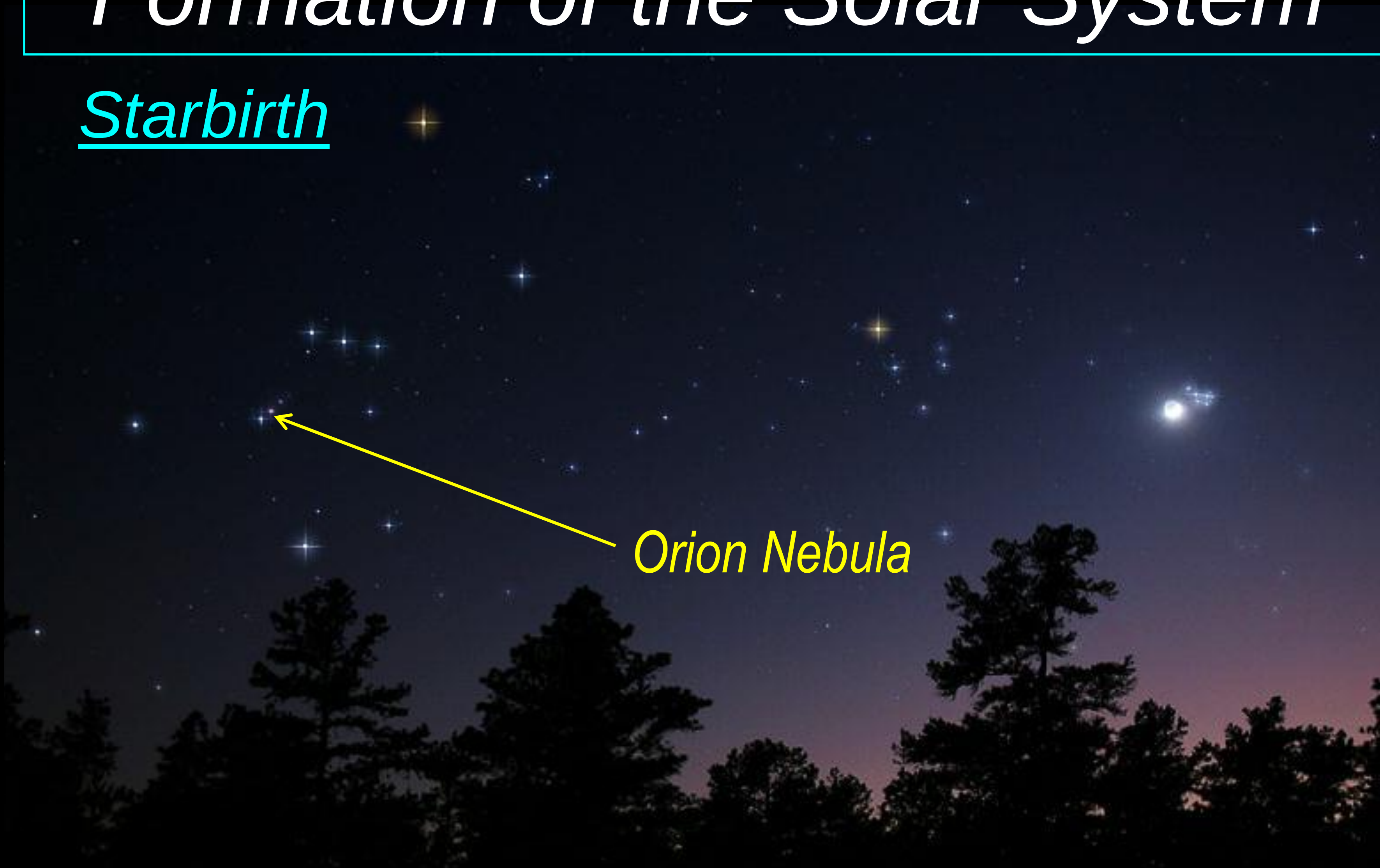
Formation of the Solar System

Starbirth

Stars and their systems of planets are formed from large clouds of gas and dust (*nebulae*)

Formation of the Solar System

Starbirth



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Formation of the Solar System

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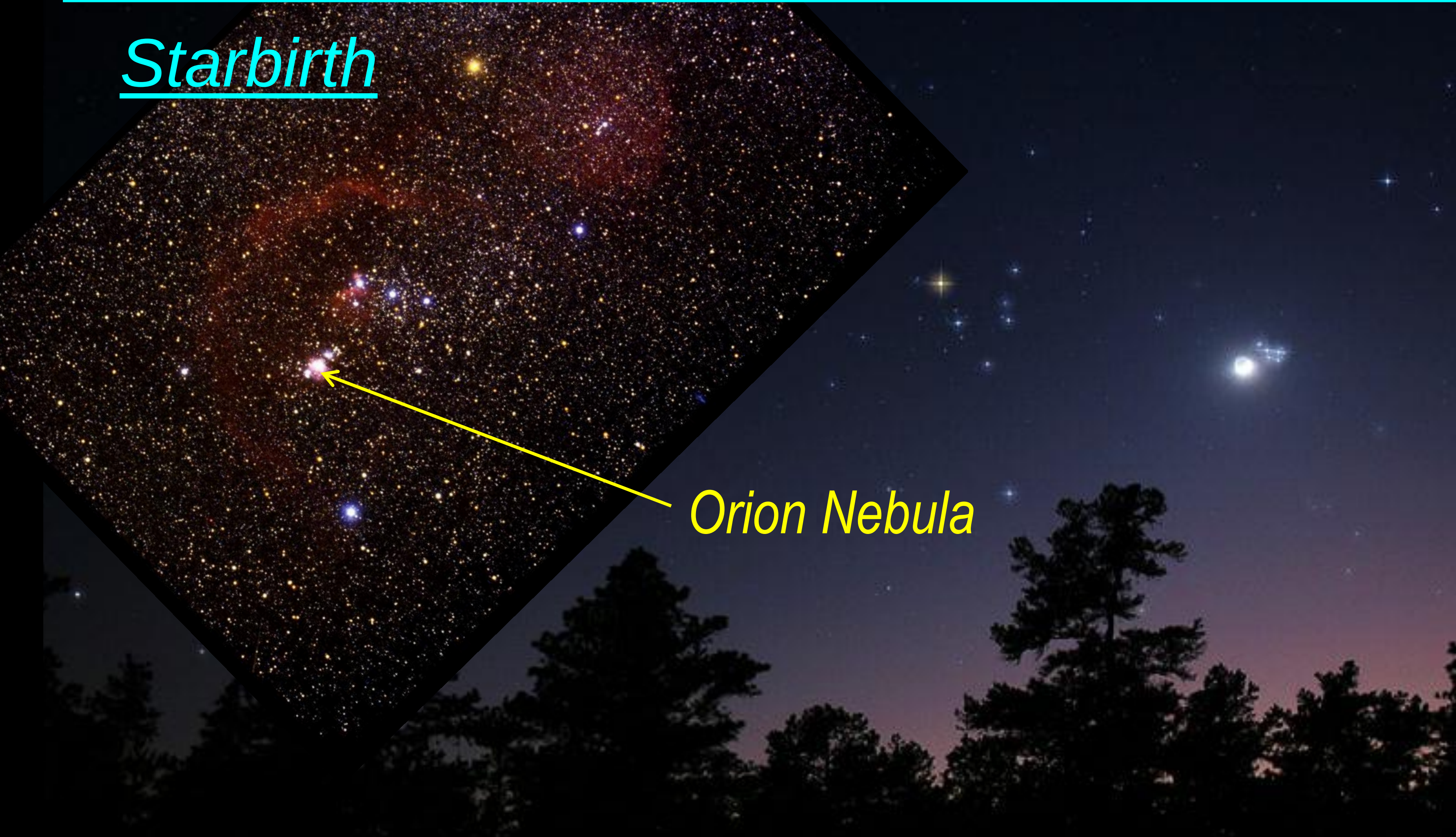

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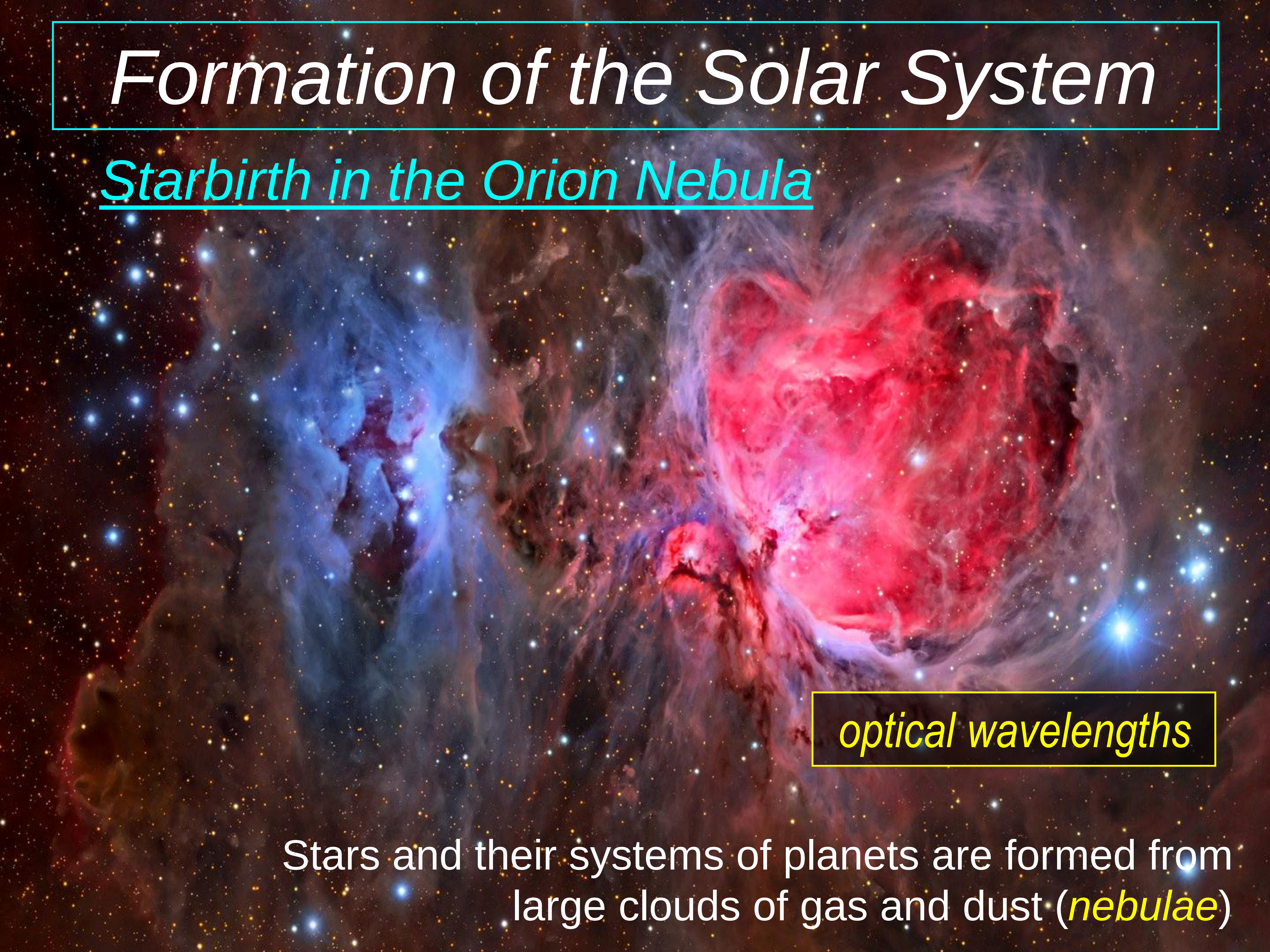
Formation of the Solar System

Starbirth in the Orion Nebula



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Formation of the Solar System

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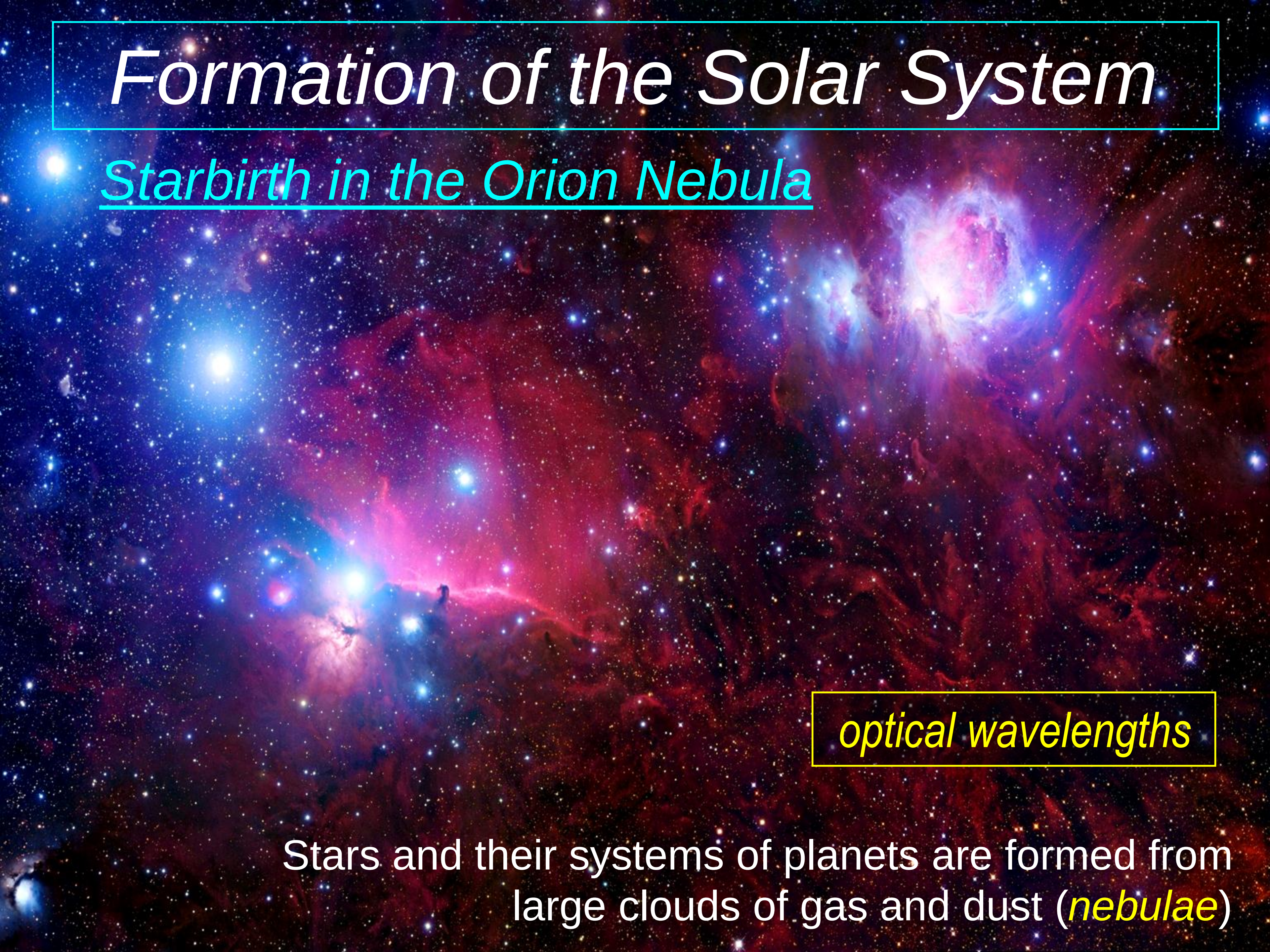

optical wavelengths

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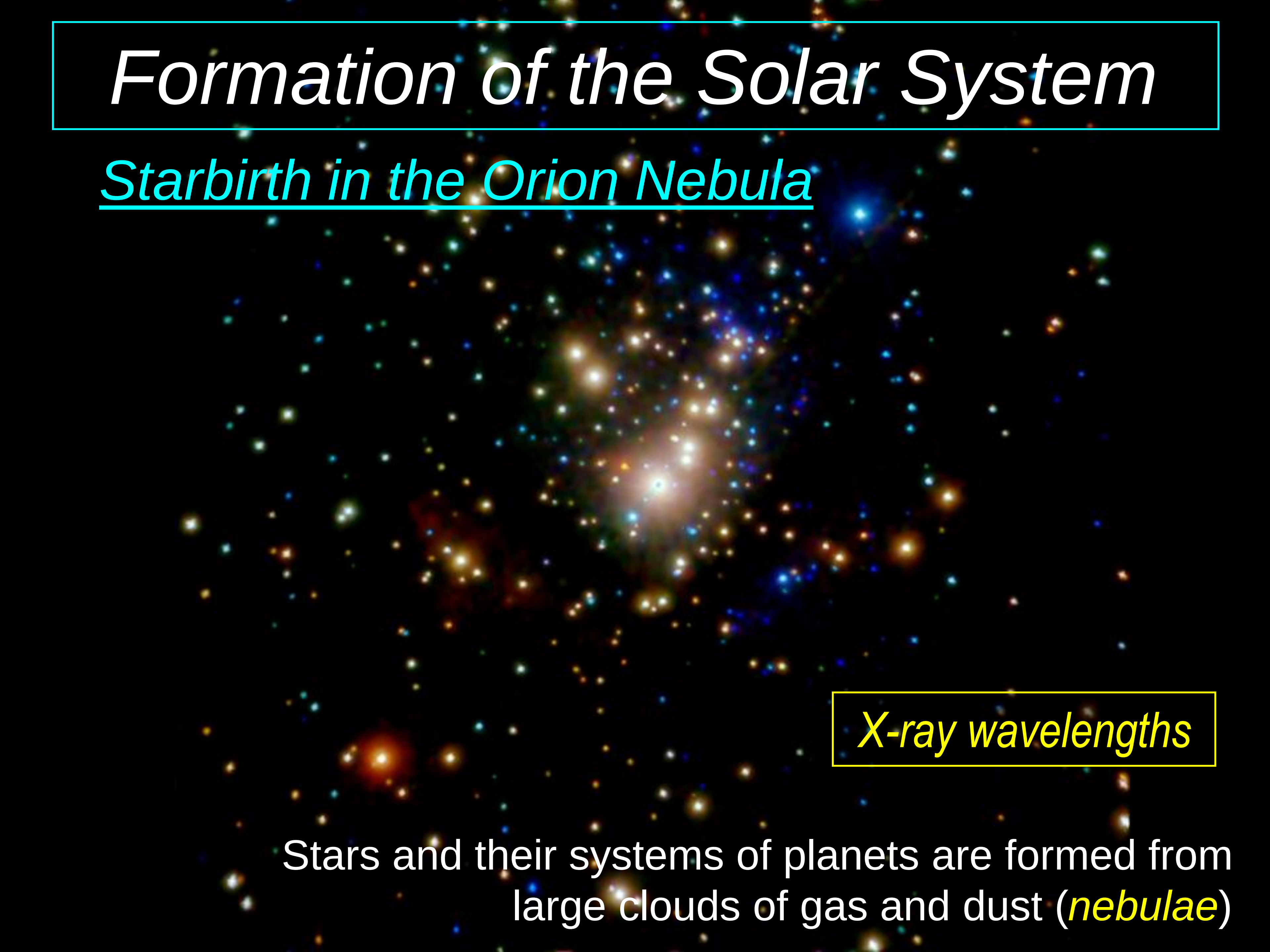
Formation of the Solar System

Starbirth in the Orion Nebula



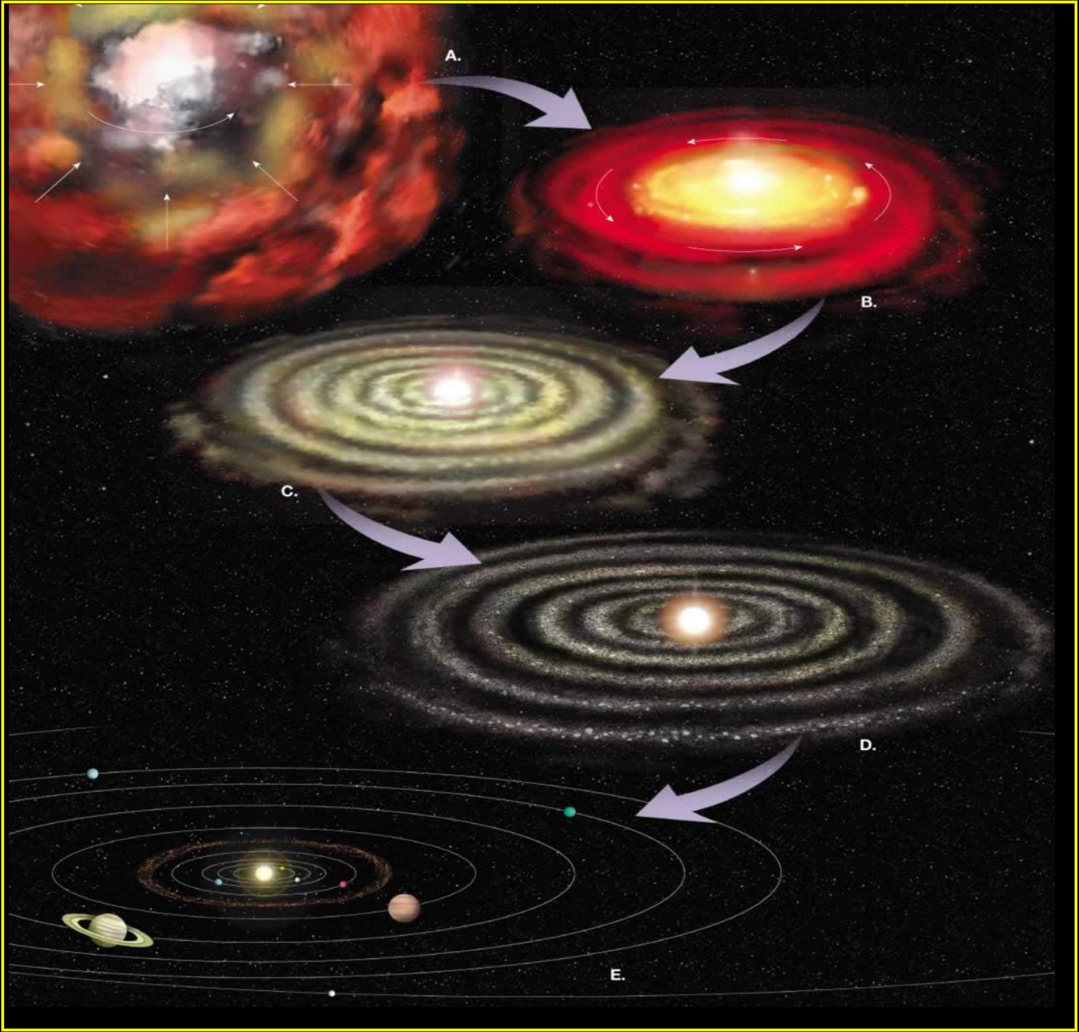
X-ray wavelengths

Stars and their systems of planets are formed from large clouds of gas and dust (*nebulae*)

Formation of the Solar System

Nebular hypothesis

Stars and their systems of planets are formed from large clouds of gas and dust (*nebulae*)



Formation of the Solar System

Nebular hypothesis

The collapsing cloud has
some initial net spin
(angular momentum)

Why?

Formation of the Solar System

Nebular hypothesis

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Stars – and *nebulae* – orbit around the centre of mass of the Galaxy

Formation of the Solar System

Nebular hypothesis

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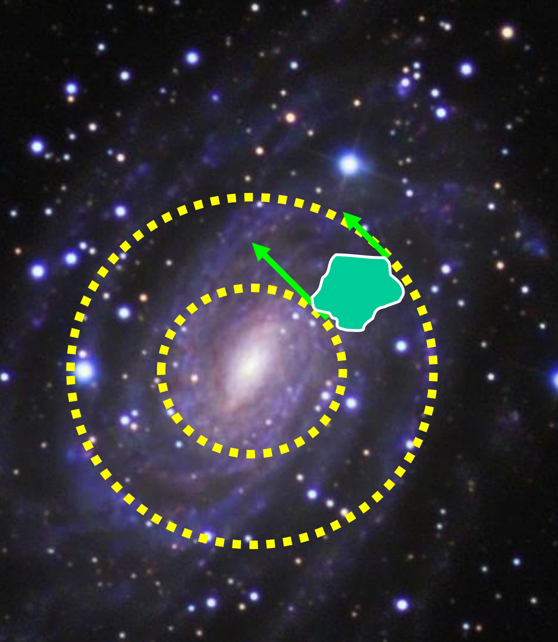


Why?

Stars – and *nebulae* – orbit around the centre of mass of the Galaxy so the outer part of the cloud is moving at a different speed than the inner

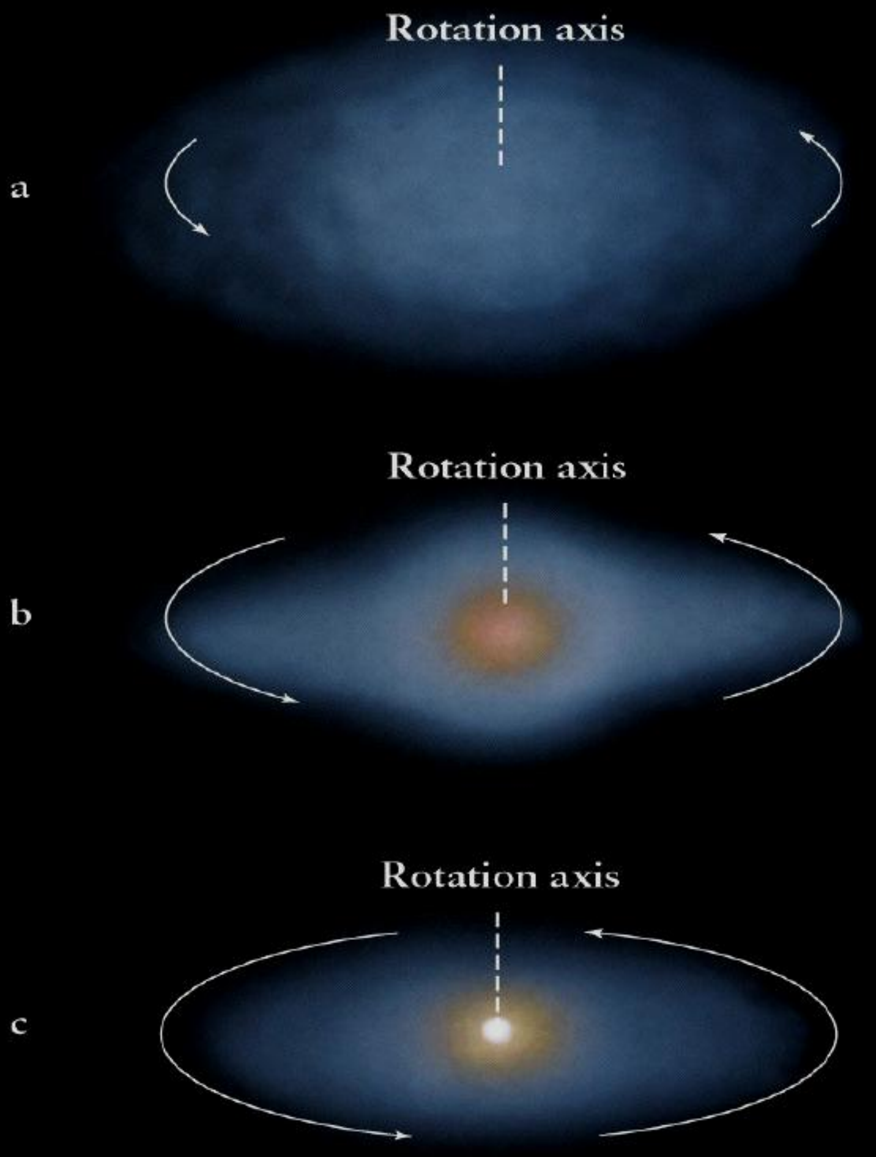
not to scale

Formation of the Solar System

Nebular hypothesis

As the nebula collapses
under its own gravity,
it spins faster and
flattens into a disk

Why?



Formation of the Solar System

Conservation of angular momentum

As the nebula collapses under its own gravity, it spins faster and flattens into a disk

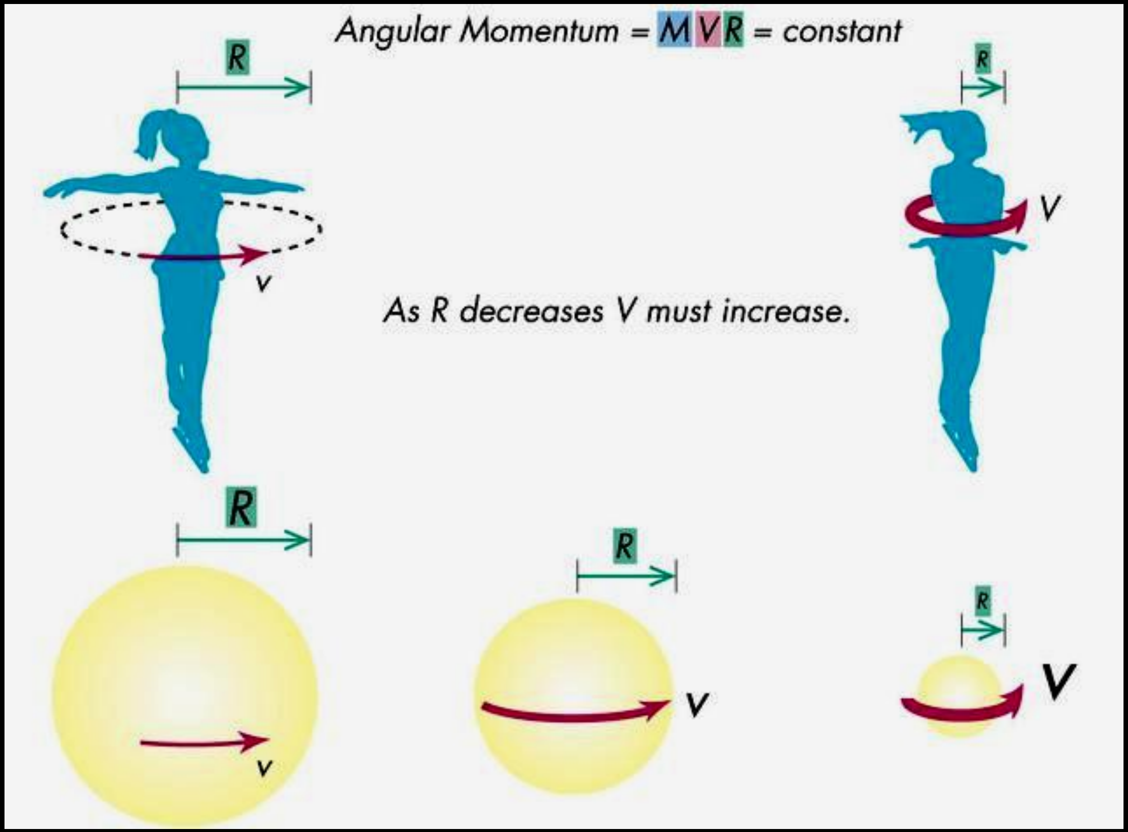
A figure skater instinctively knows physics when s/he performs a pirouette on ice

Formation of the Solar System

Conservation of angular momentum

As the nebula collapses under its own gravity, it spins faster and flattens into a disk

$$L = m\,v\,r$$



A figure skater instinctively knows physics when s/he performs a pirouette on ice

Formation of the Solar System

Angular momentum

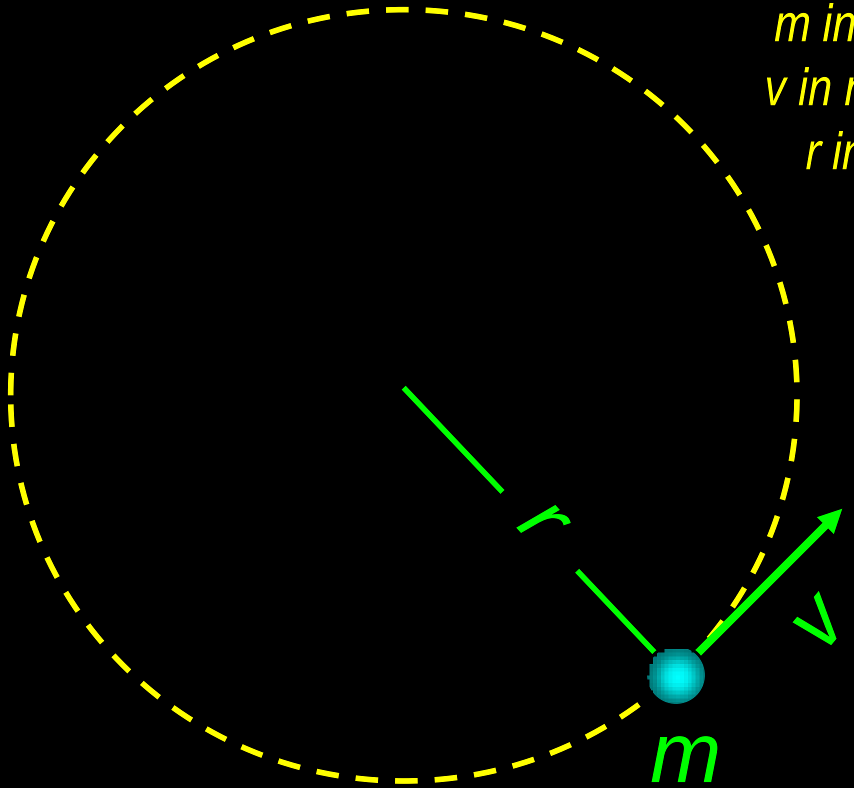
A mass m moving at speed v in a circular path of radius r has angular momentum L

$$L = m\,v\,r$$

m in kg
v in m/s
r in m

This equation can be used to estimate the orbital angular momentum L_{orb} of a planet

All you need are:
its mass m, its speed v
and its semi-major axis a = r
if the orbit is nearly circular



Formation of the Solar System

Angular momentum

A mass *m* moving at speed *v* in a circular path of radius *r* has angular momentum *L*

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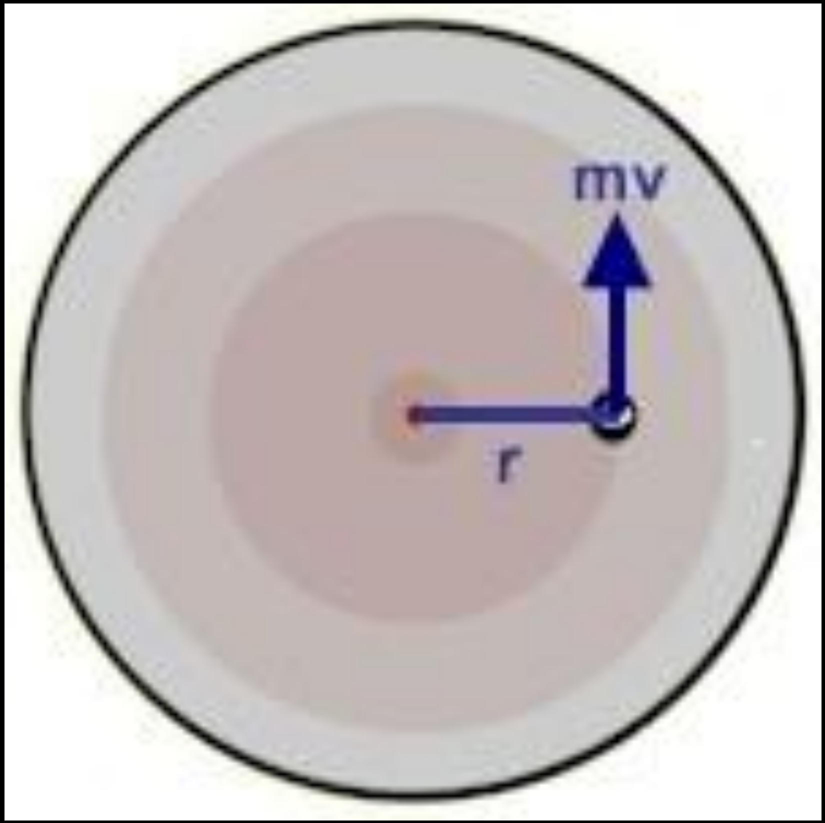


For the angular momentum of a spinning body or mass distribution, you integrate $L = m(r)v(r)r$ over all values of r in the mass distribution

Formation of the Solar System

Angular momentum

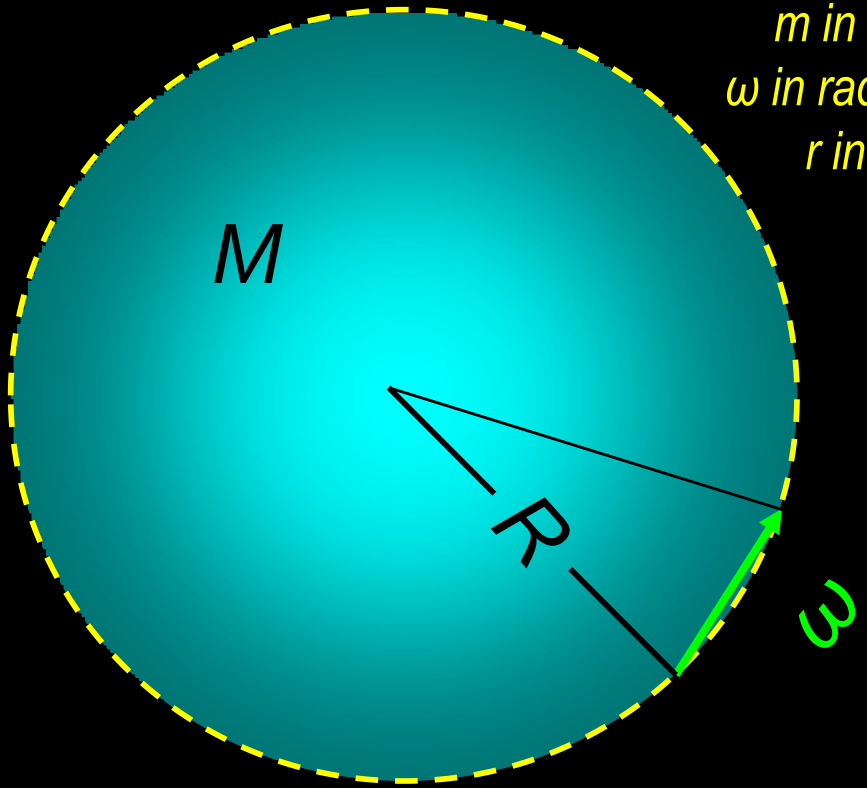
In general, angular momentum $L = I\ \omega$ where I = *moment of inertia* and ω = *angular velocity (rad/s)*

$$L = I_{sphere}\ \omega$$

m in kg
ω in rad/s
r in m

The moment of inertia of a solid sphere of mass M and radius R is given by

$$I_{sphere} = (2/5)\ M\ R^2$$



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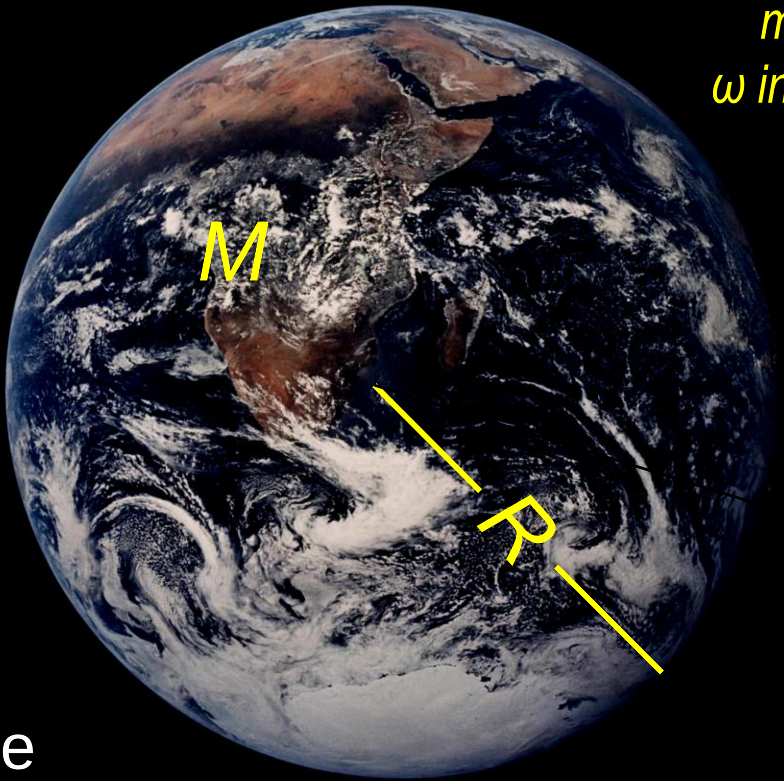

This equation can be used to calculate the rotational angular momentum of a solid planet like Earth, or to estimate $L_{rotation}$ for gaseous bodies like Jupiter

Formation of the Solar System

Angular momentum

$L = I_{disk}\ \omega$

In general, angular momentum $L = I\ \omega$
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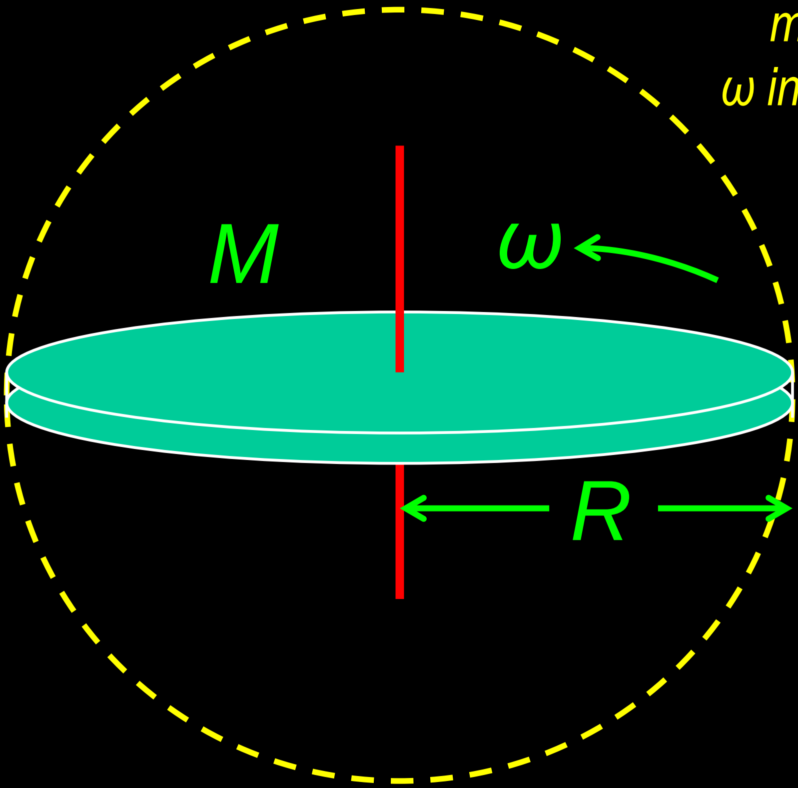
The moment of inertia of a very thin disk of mass M and radius R is given by

$$I_{disk} = (1/2)\ M\ R^2$$



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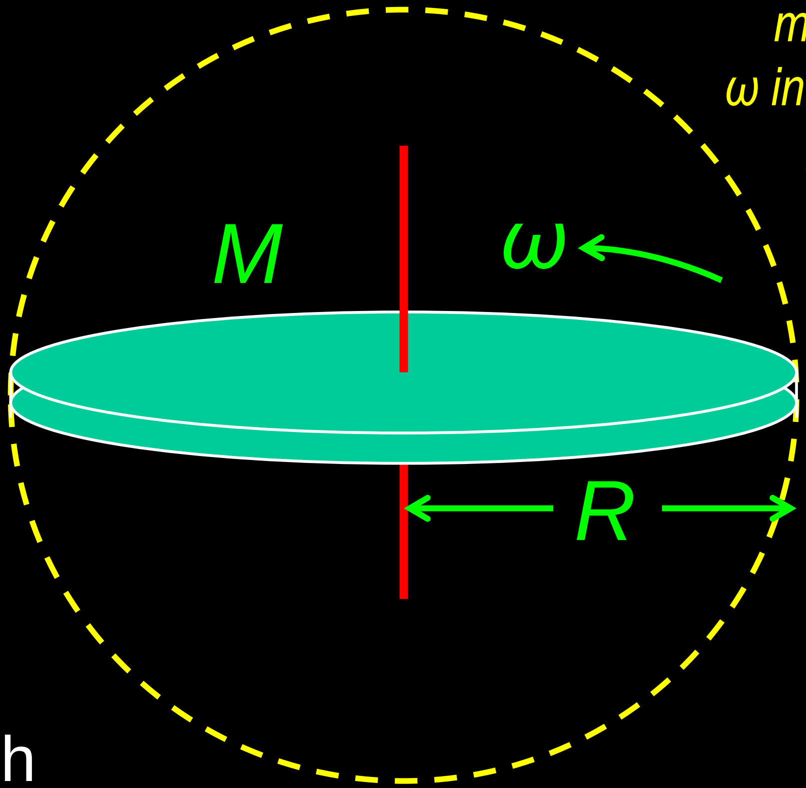
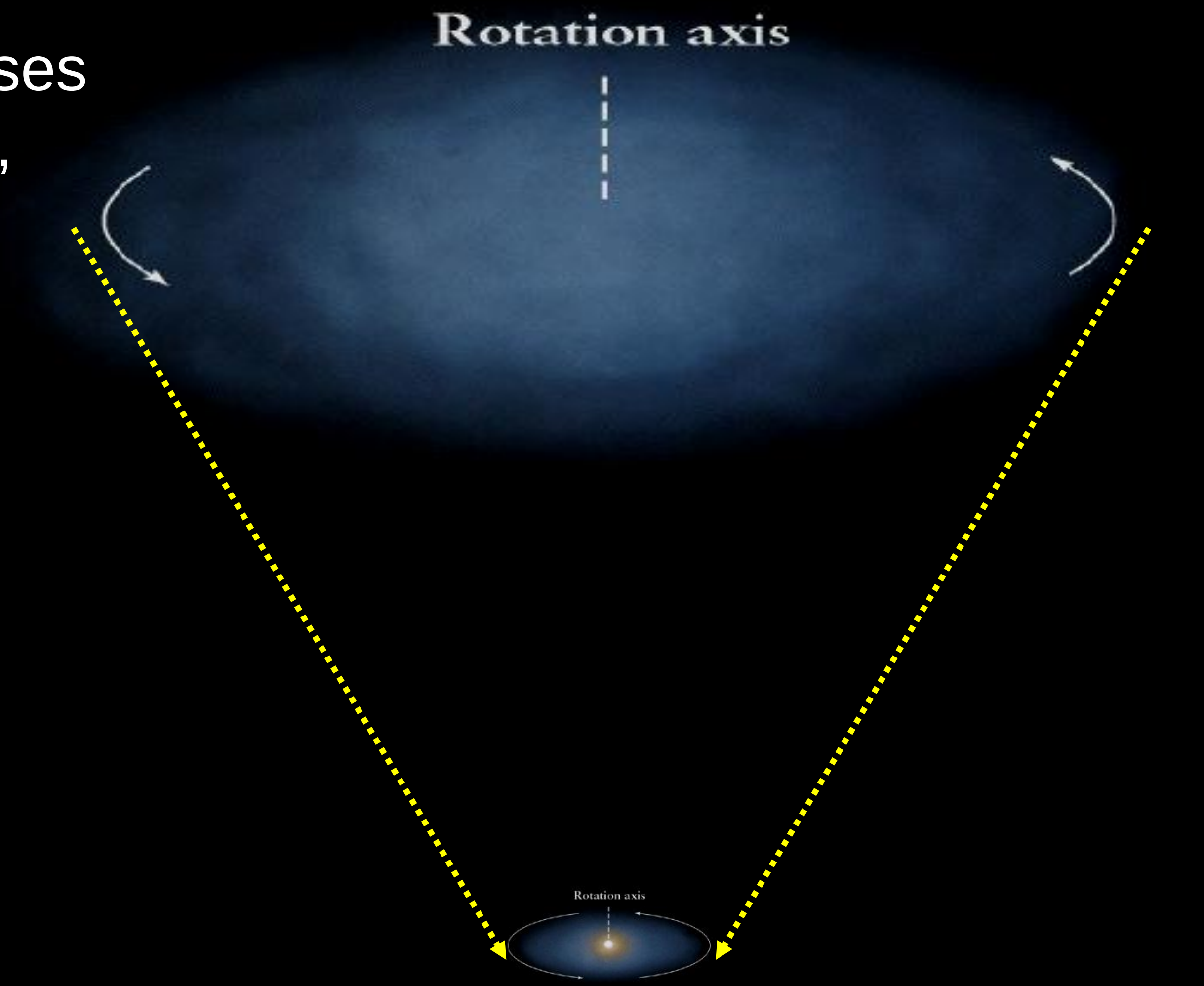


We can use this as a first rough approximation of the angular momentum L of the protoplanetary disk from which the Solar System planets coalesced

Formation of the Solar System

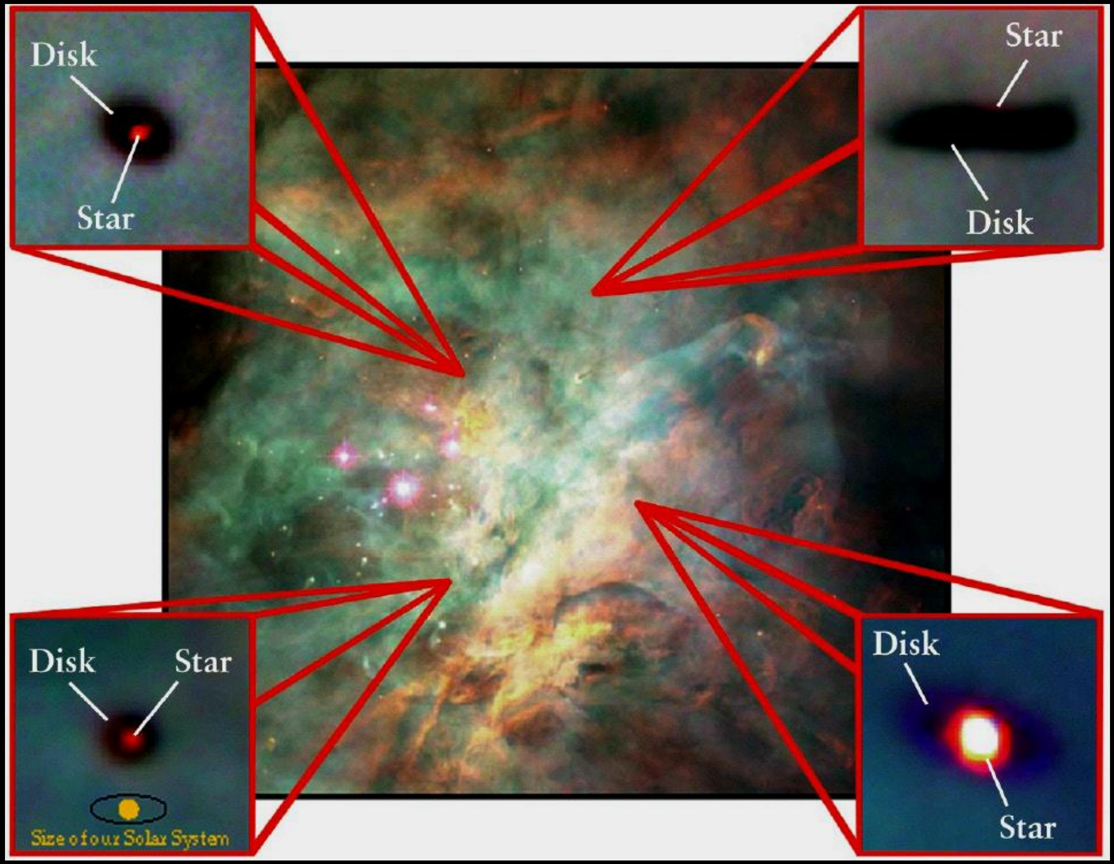
Conservation of angular momentum

As the nebula collapses under its own gravity, it spins faster and flattens into a disk



Formation of the Solar System

Protoplanetary disks

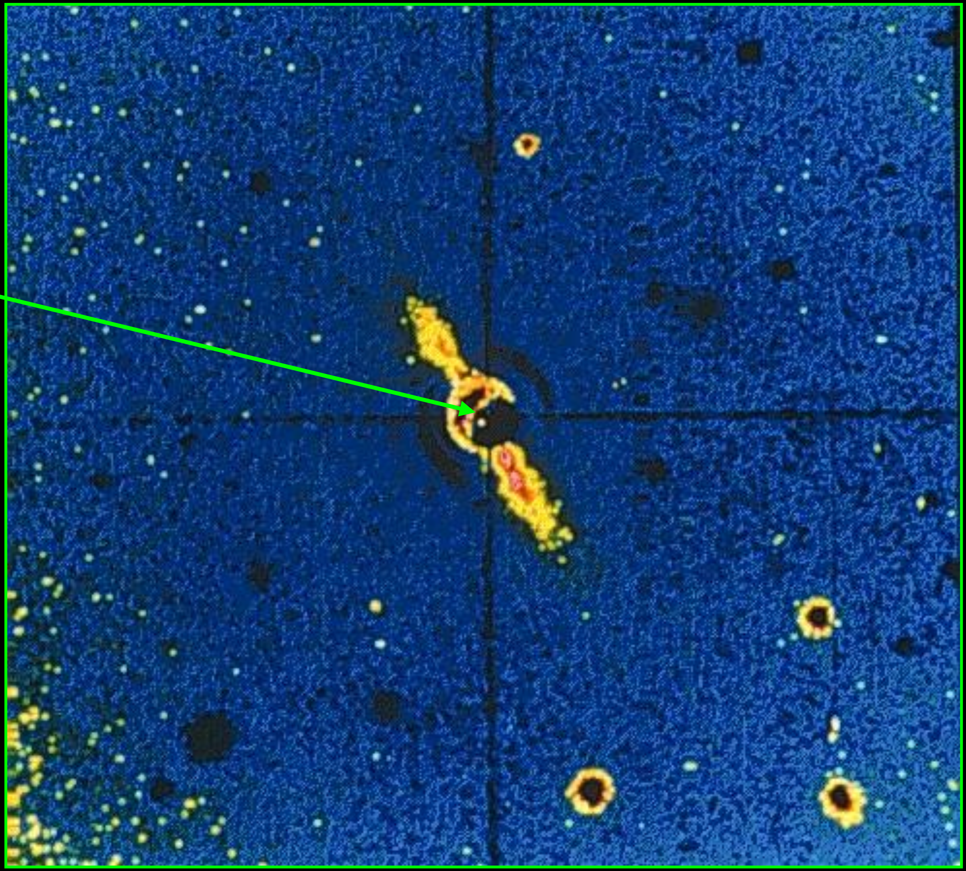


We observe the stages of nebular collapse into disks in knots of gas within the Orion Nebula

Formation of the Solar System

Protoplanetary disks

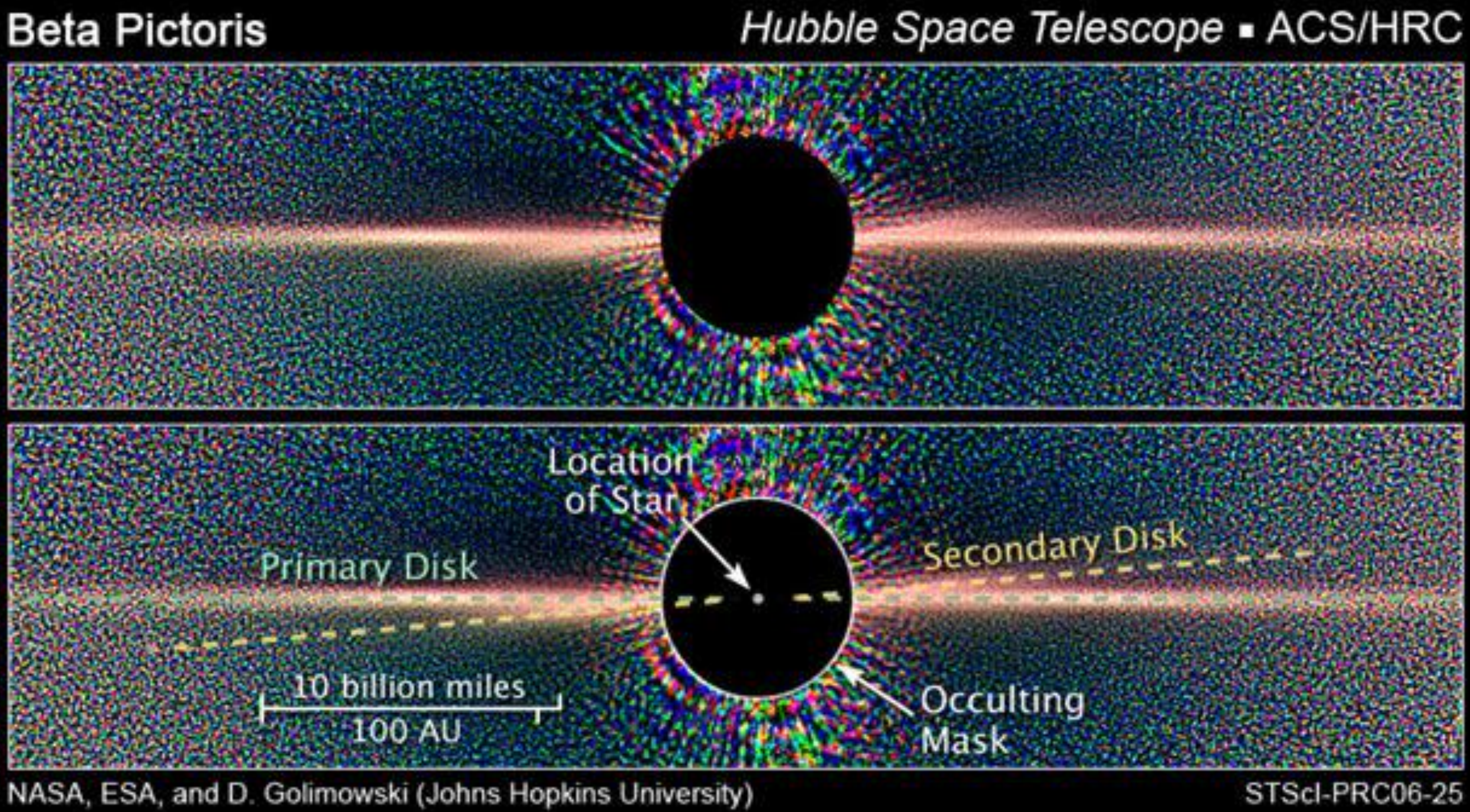
Light from star blocked (occulted) by a mask to observe the faint light from the surrounding disk



We observe the stages of nebular collapse in the disk of the young star β (beta) Pictoris seen edge-on

Formation of the Solar System

Protoplanetary disks



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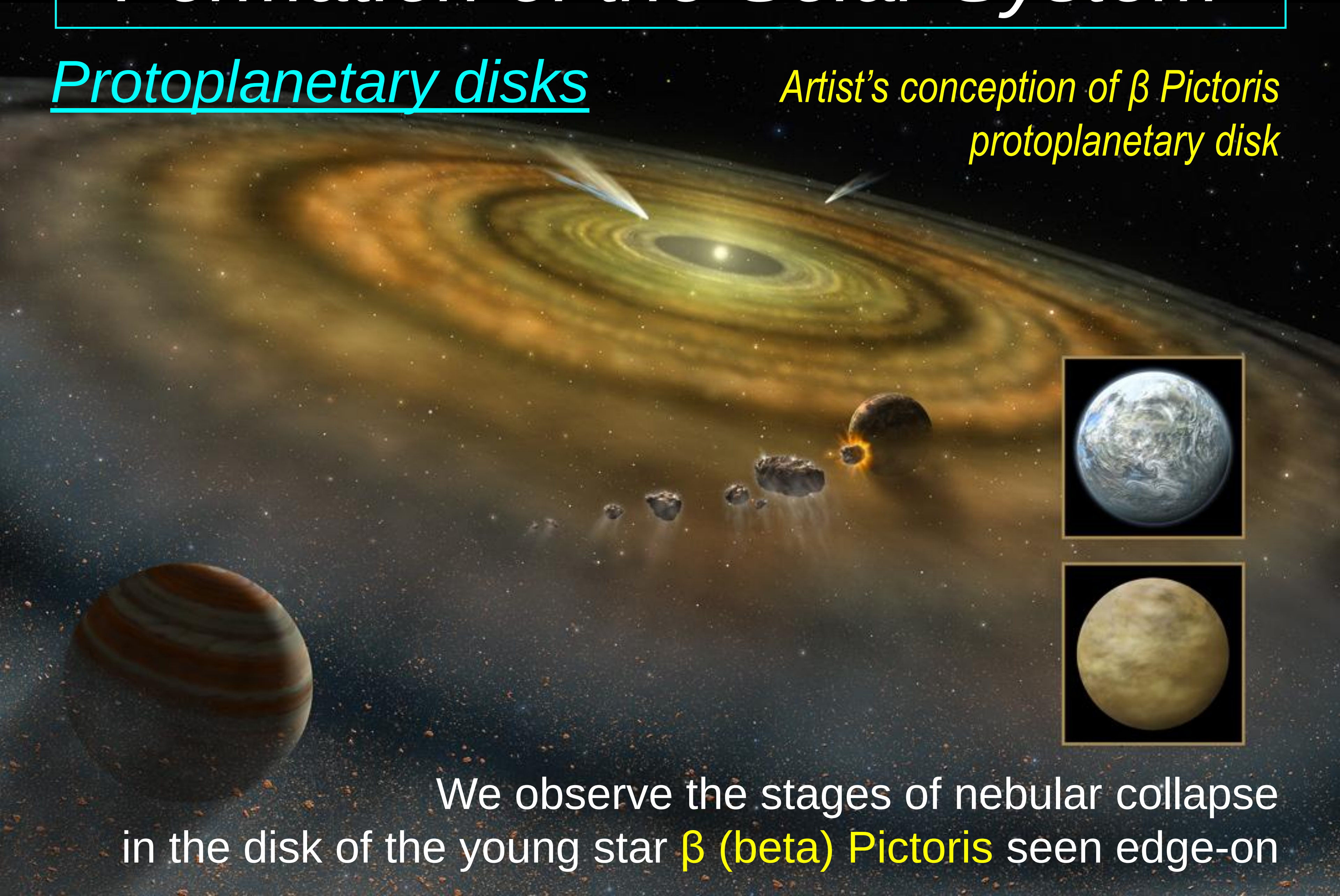
Formation of the Solar System

Protoplanetary disks

Artist's conception of β Pictoris protoplanetary disk



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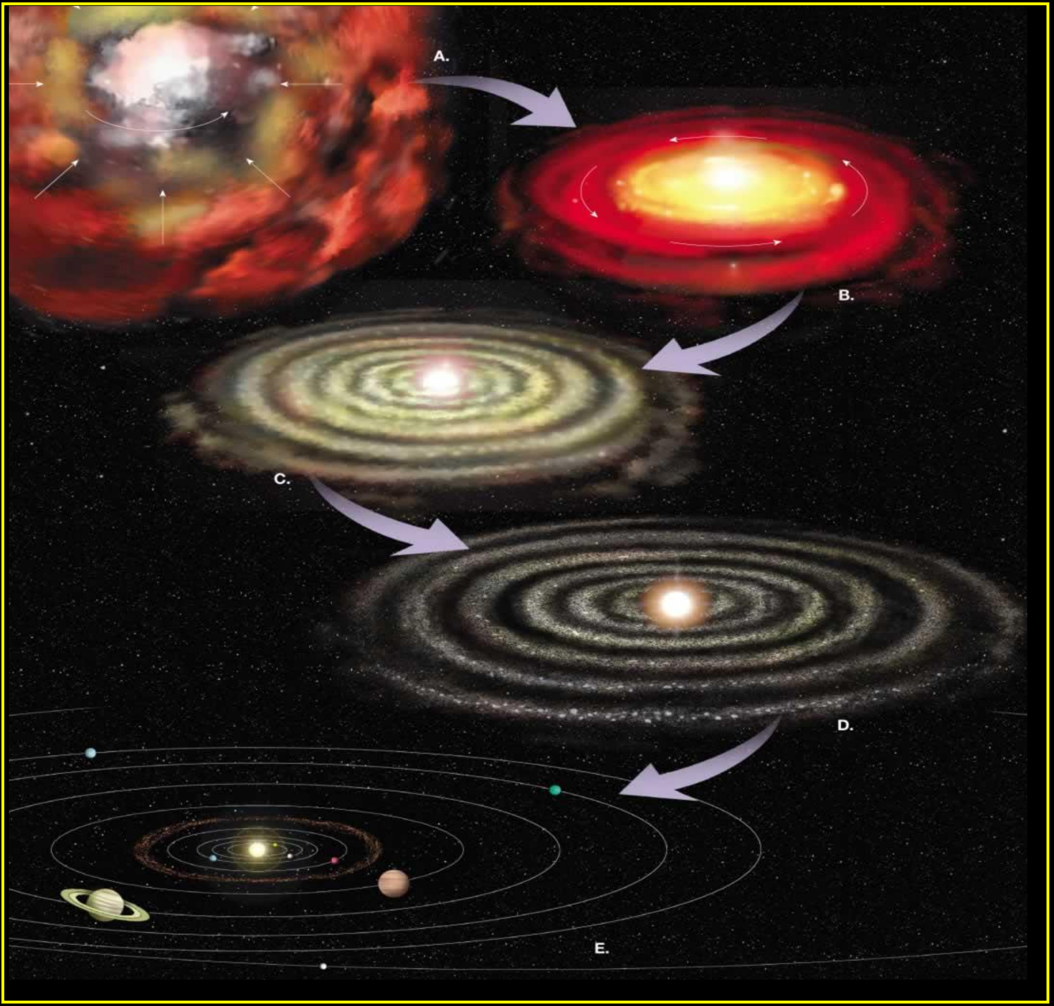
Formation of the Solar System

Protoplanetary disks

As the nebula collapses under its own gravity, it spins faster and flattens into a disk

This is the natural explanation why the planets in the Solar System orbit in nearly the same plane, with nearly circular orbits, all in the same sense



Formation of the Solar System

Four principal stages in Nebular Hypothesis

1) Cool ‘cores' of gas form in molecular clouds, and some collapse under their own gravity

Formation of the Solar System

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Formation of the Solar System

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2) Protostar and disk form at centre of core of gas

with the protostar still cloaked inside the infalling matter

Formation of the Solar System

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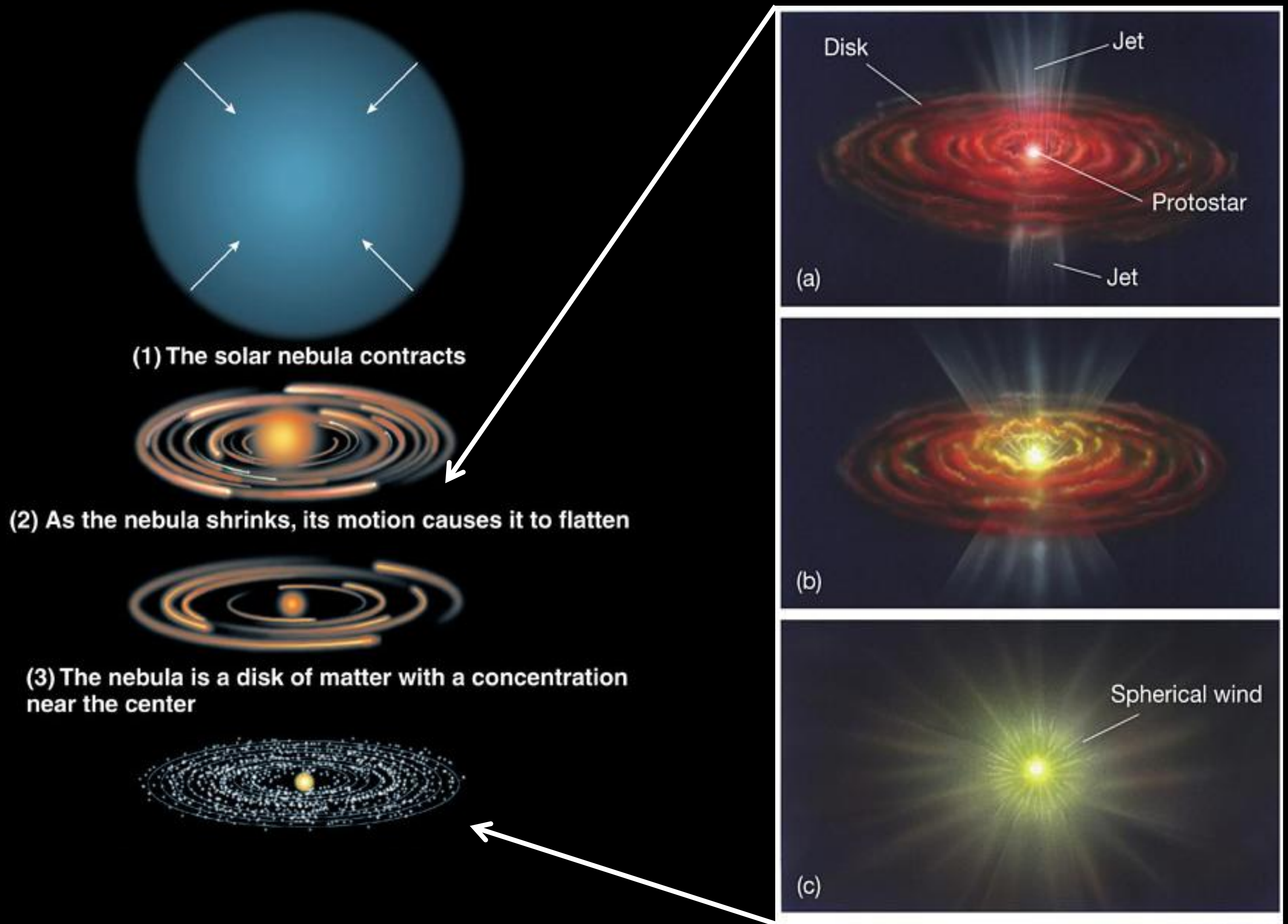
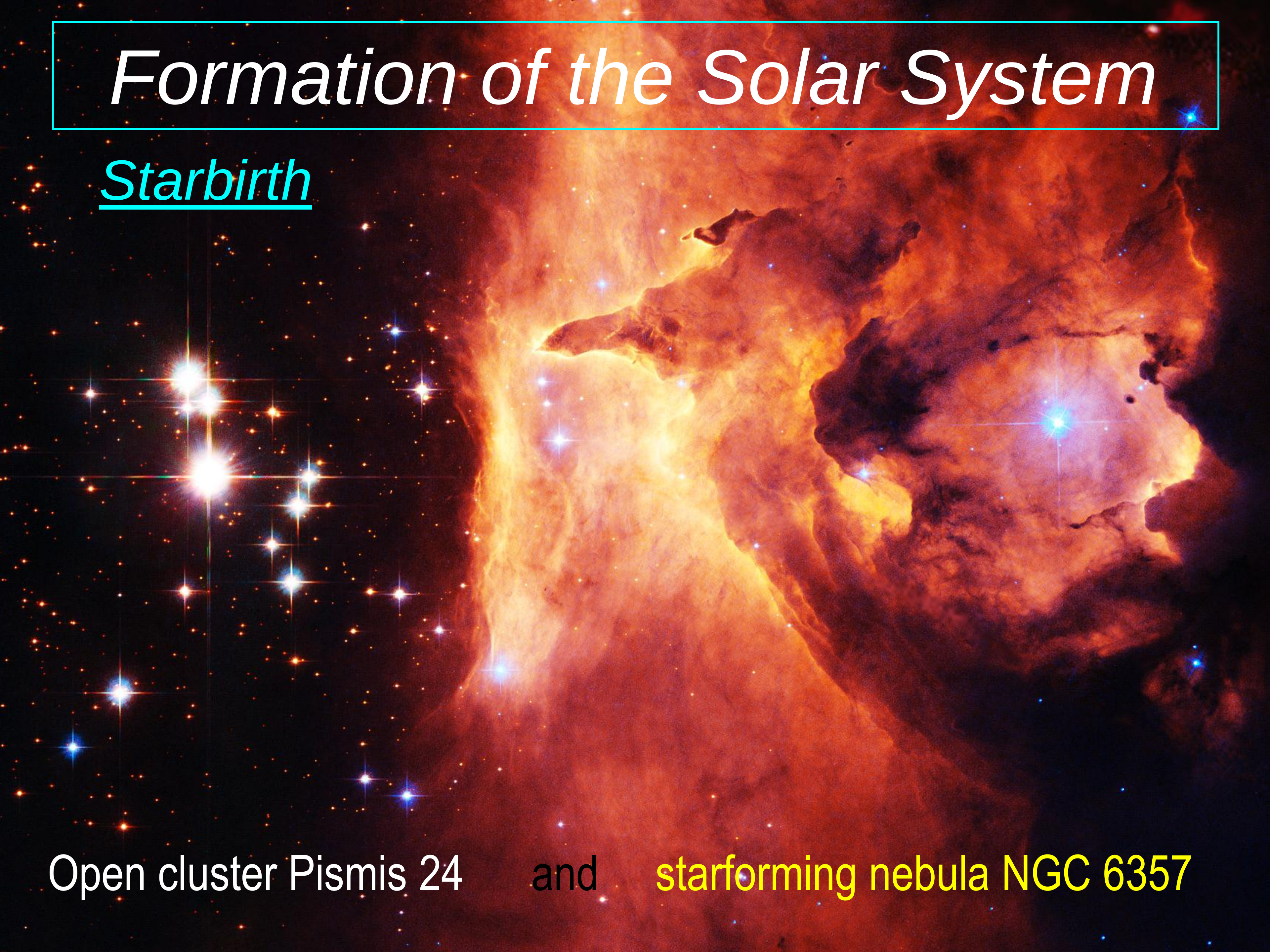
4) Star blows away envelope, leaving a disk from which planets condense

Formation of the Solar System



Formation of the Solar System

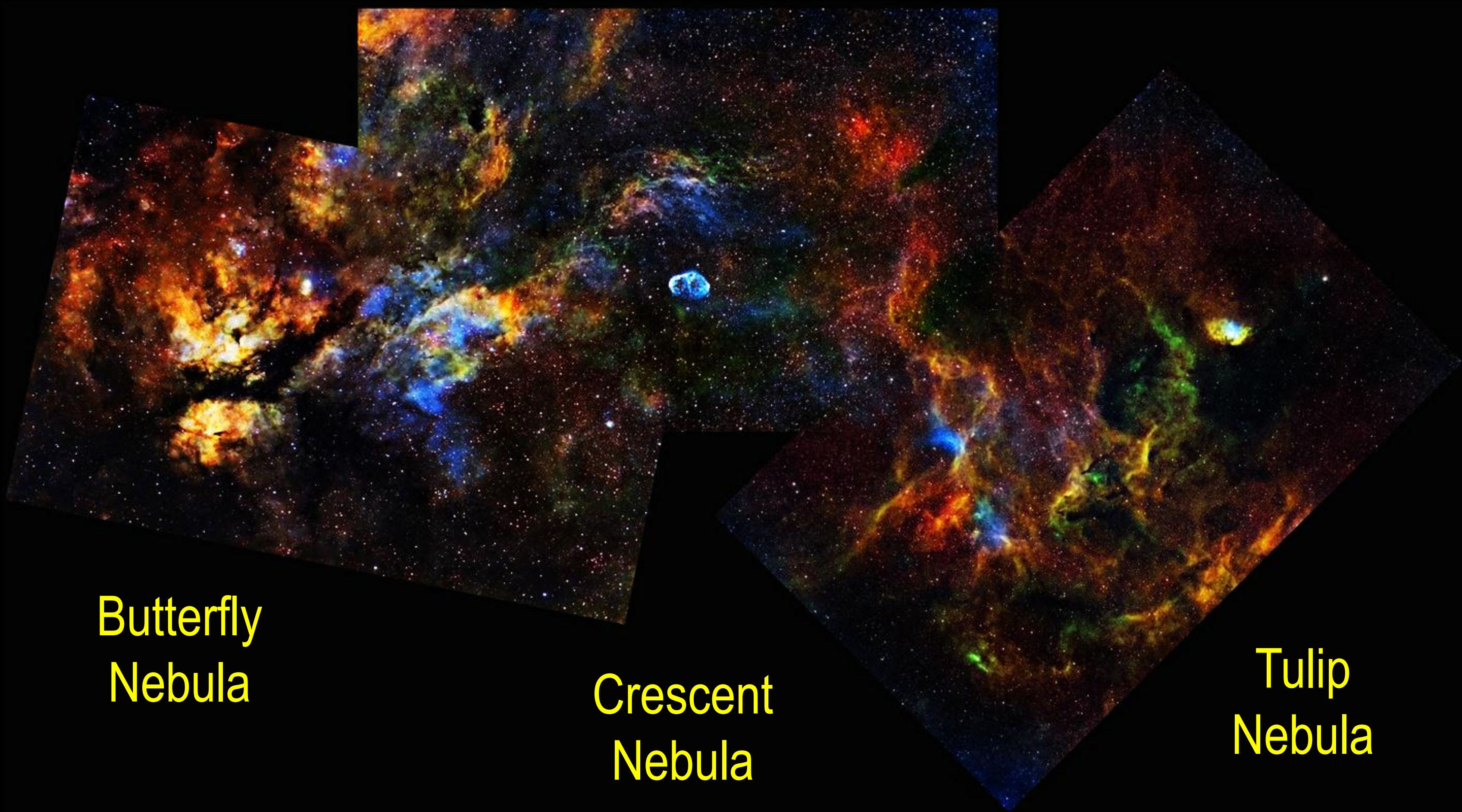
Starbirth



Open cluster Pismis 24 and starforming nebula NGC 6357

Formation of the Solar System

The Cygnus Trio of nebulae



Formation of the Solar System

Condensation in protoplanetary disk

Formation of the Solar System

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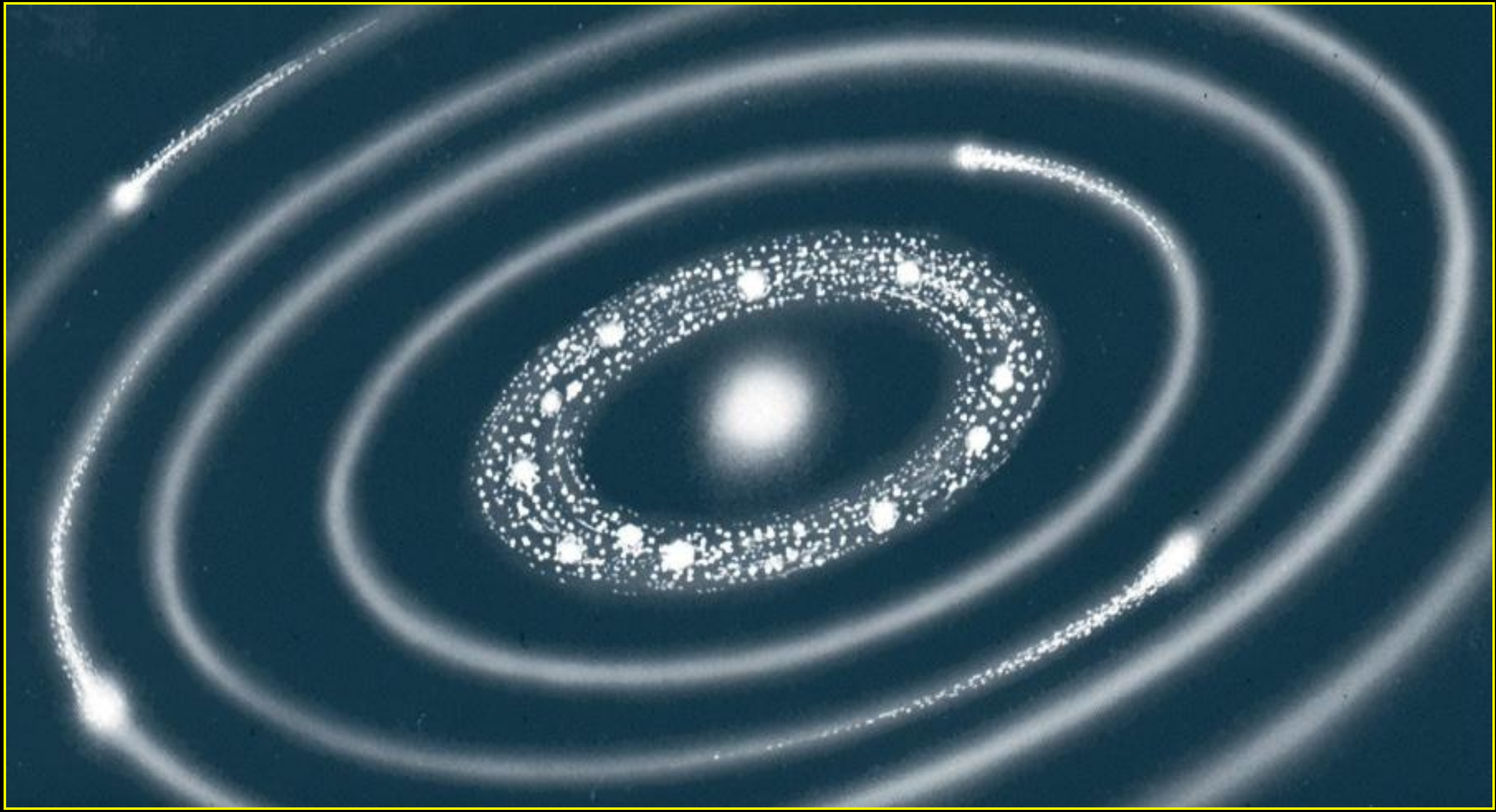

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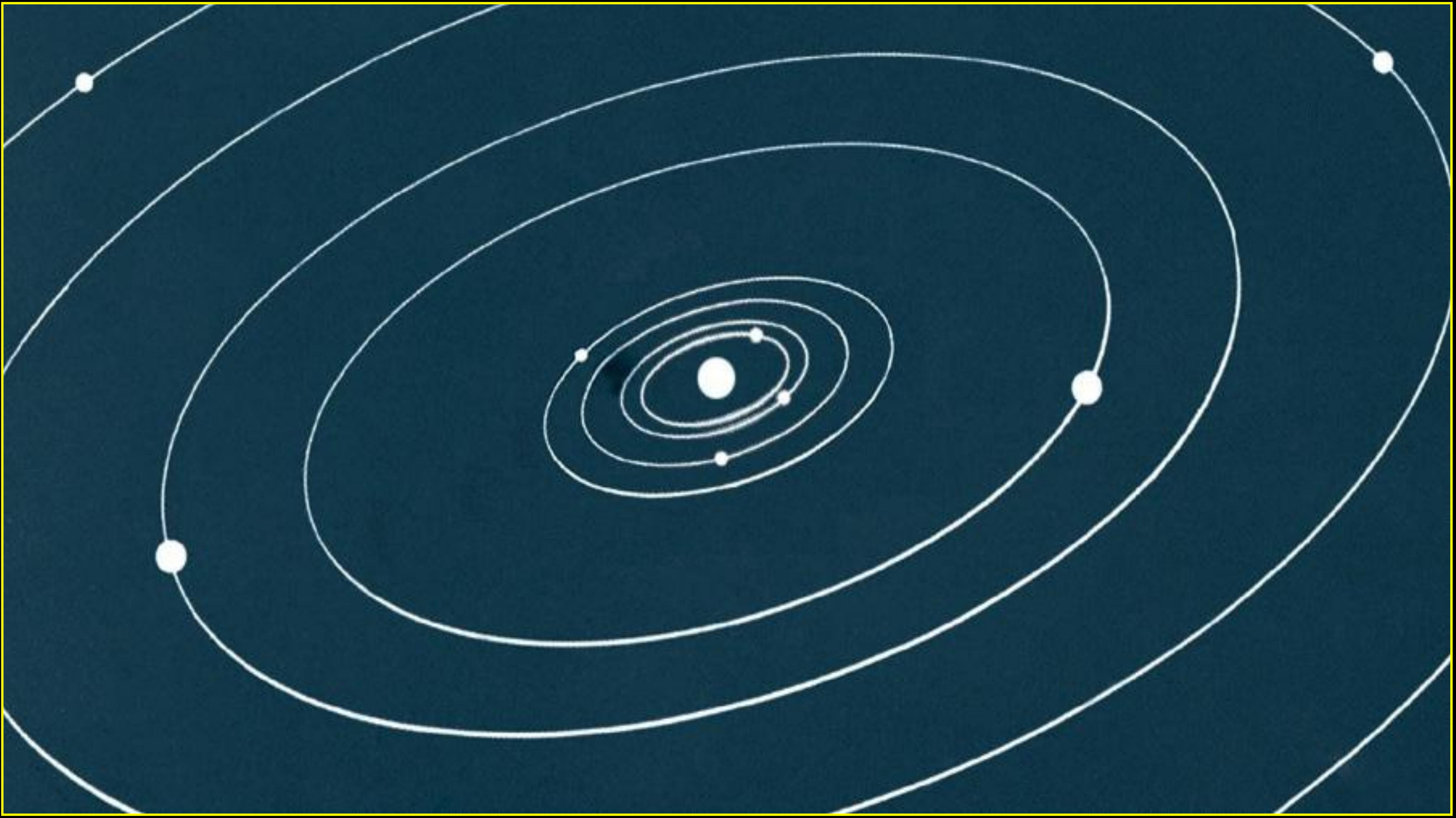
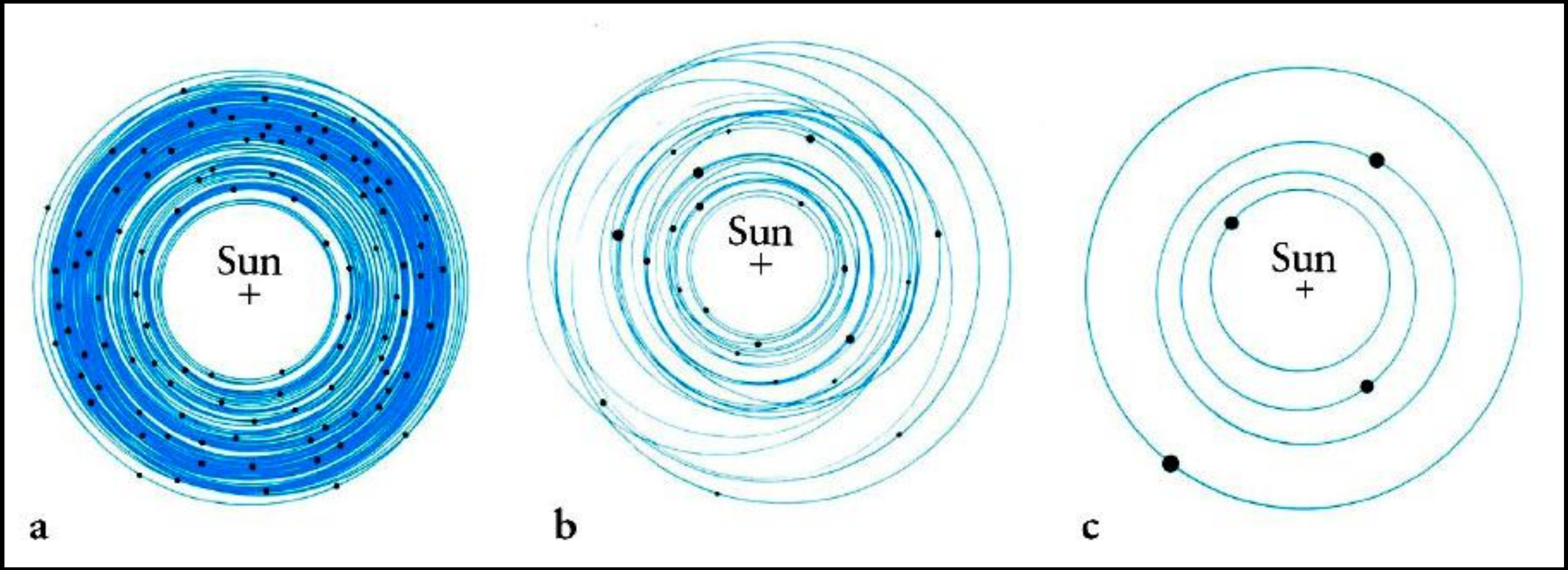


Formation of the Solar System

Condensation in protoplanetary disk

N-body supercomputer simulation of condensation of planets



Terrestrial planets form in about 100 Myr (100 million years)

Formation of the Solar System

Condensation in protoplanetary disk

N-body supercomputer simulation of condensation of planets

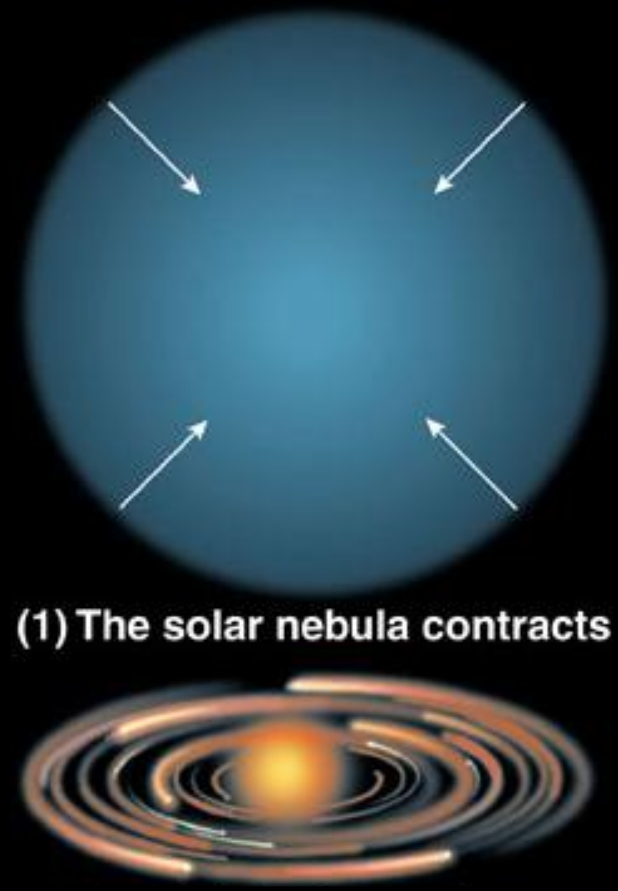
Formation of the Solar System

Kelvin-Helmholtz heating

As the nebula collapses under its own gravity, it spins faster and flattens into a disk

It is also converting gravitational potential energy into thermal energy becoming hottest at the cloud centre

$$E_{grav} = G \int \frac{M(r)}{r} dr$$



Formation of the Solar System

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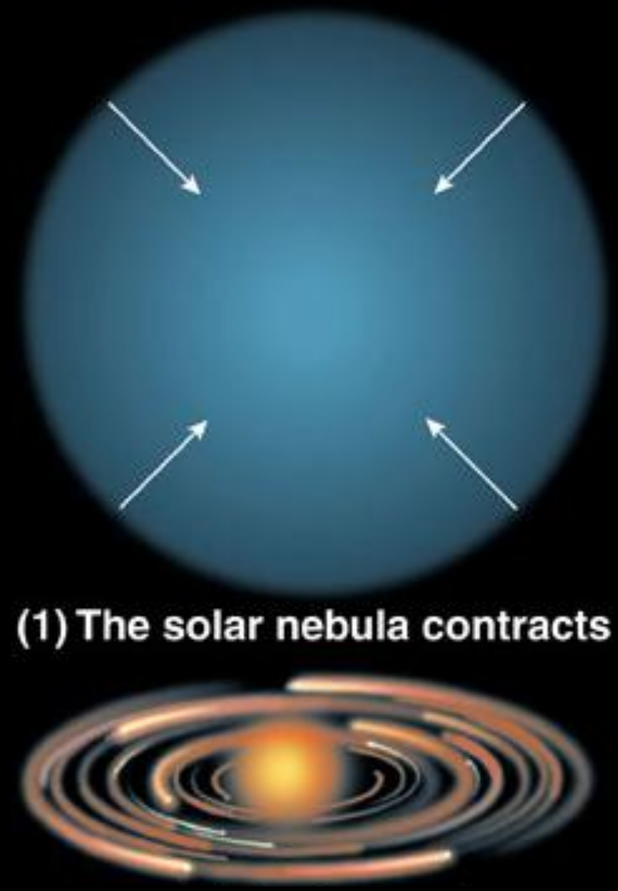
The gas in the cloud is cooler with increasing distance from its core. Only metallic and rocky materials can condense out of the gas at the higher temperatures in the inner cloud.



Formation of the Solar System

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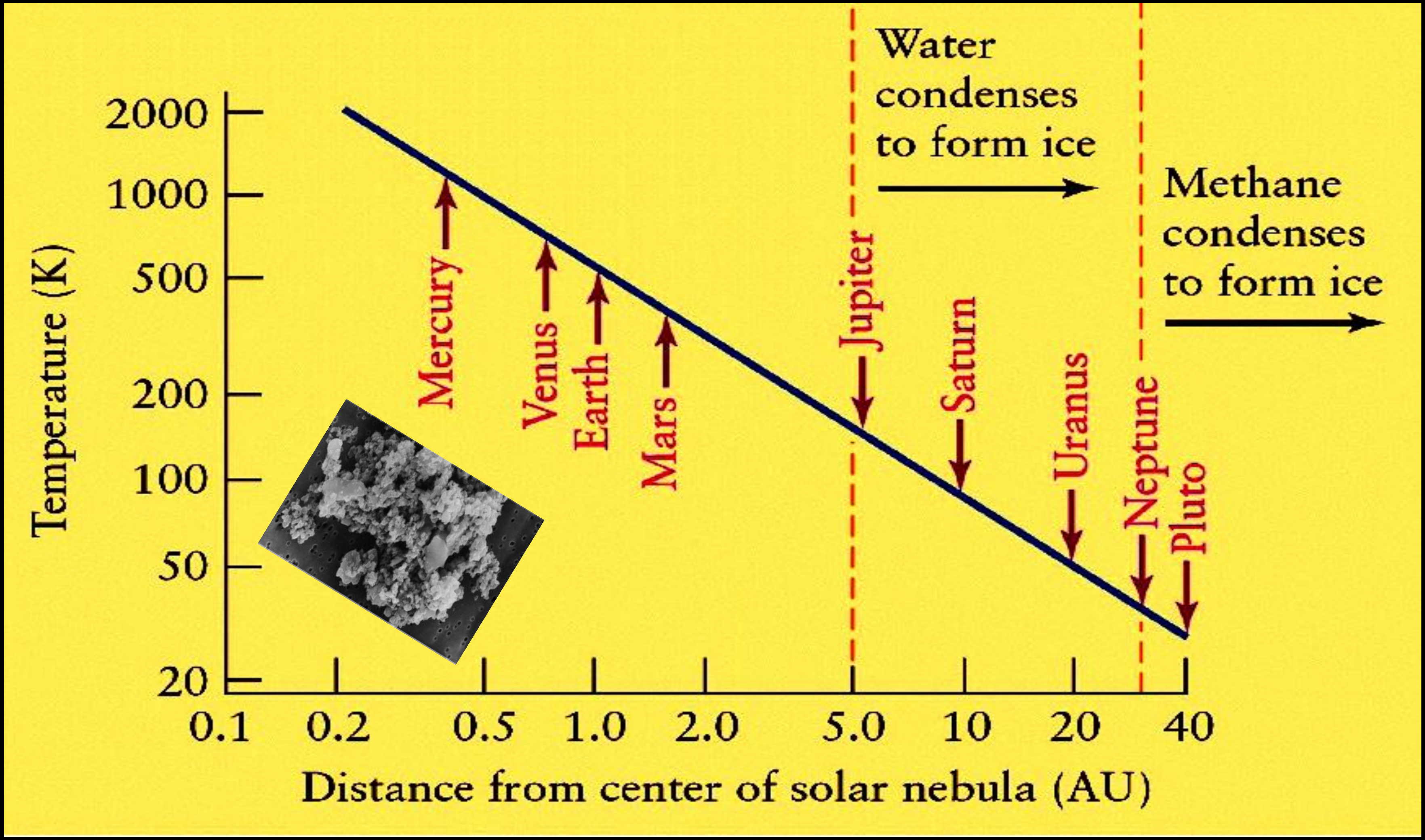

Formation of the Solar System

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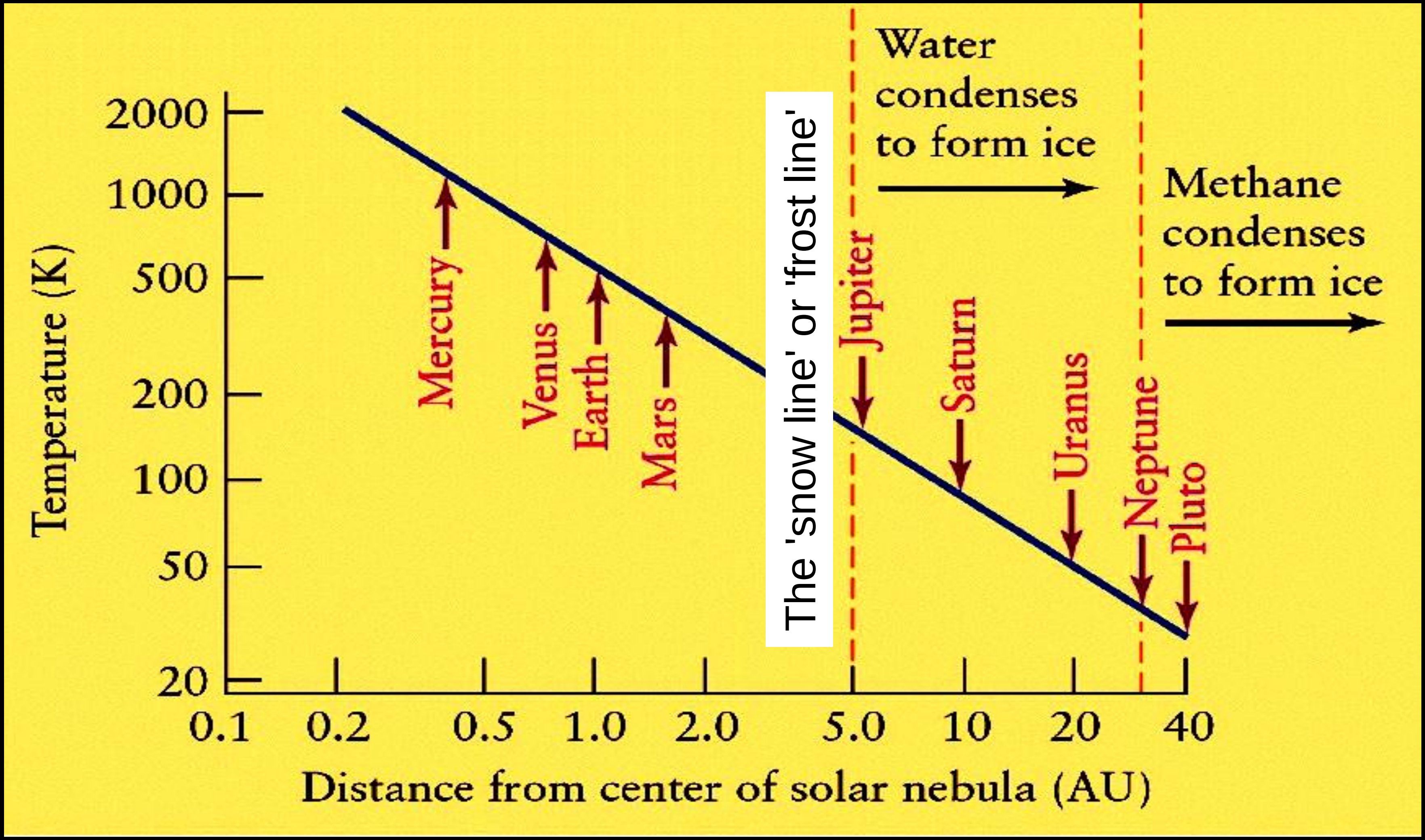

Formation of the Solar System

Lewis Model

A sequence of chemical condensation at low pressure

- As the gas temperature T drops with distance from the centre of the nebula, different chemical species can condense

Formation of the Solar System

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- starting at *T ~ 1600 K* refractory oxides and metals condense out first

Formation of the Solar System

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Formation of the Solar System

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Formation of the Solar System

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- then ammonia ice and methane ice ($T < 100$ K)

Formation of the Solar System

Condensation in the protoplanetary nebula

Condensation sequence

Materials in the Solar Nebula A summary of the four types of materials present in the solar nebula, along with examples of each type and their typical condensation temperatures. The squares represent the relative proportions of each type (by mass).

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

Formation of the Solar System

Cosmic abundances by mass

X is the mass fraction of hydrogen (H),
Y the mass fraction of helium (He), and
Z the mass fraction of all other elements
(called "metals" by astronomers)

For the Sun:

$X = 0.73$

$Y = 0.25$

$Z = 0.02$

Meteorites:

$X = 0.706$

$Y = 0.275$

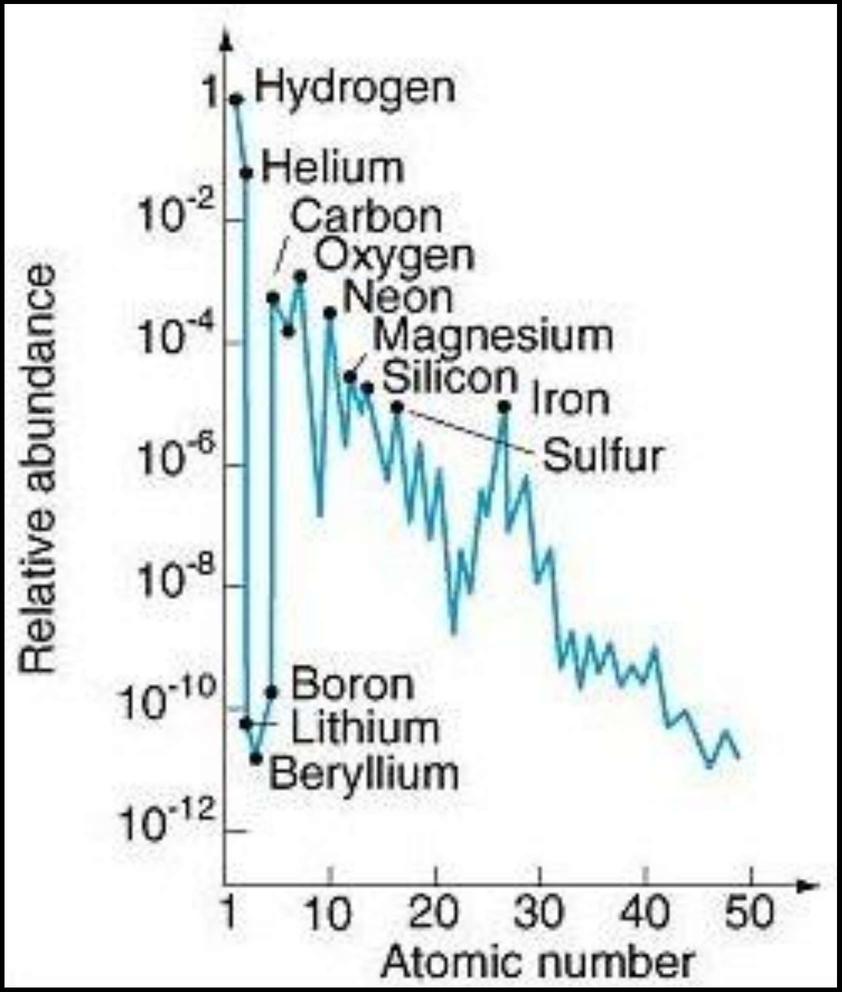
$Z = 0.019$

Anders, E. & Grevesse, N. "Abundances of the Elements: Meteoritic and Solar" Geochim. Cosmochim. Acta 53, 197, 1989

Holt, S. S. & Sonneborn, G. (editors) "Cosmic Abundances" 1995

Formation of the Solar System

Raw materials for planets



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Formation of the Solar System

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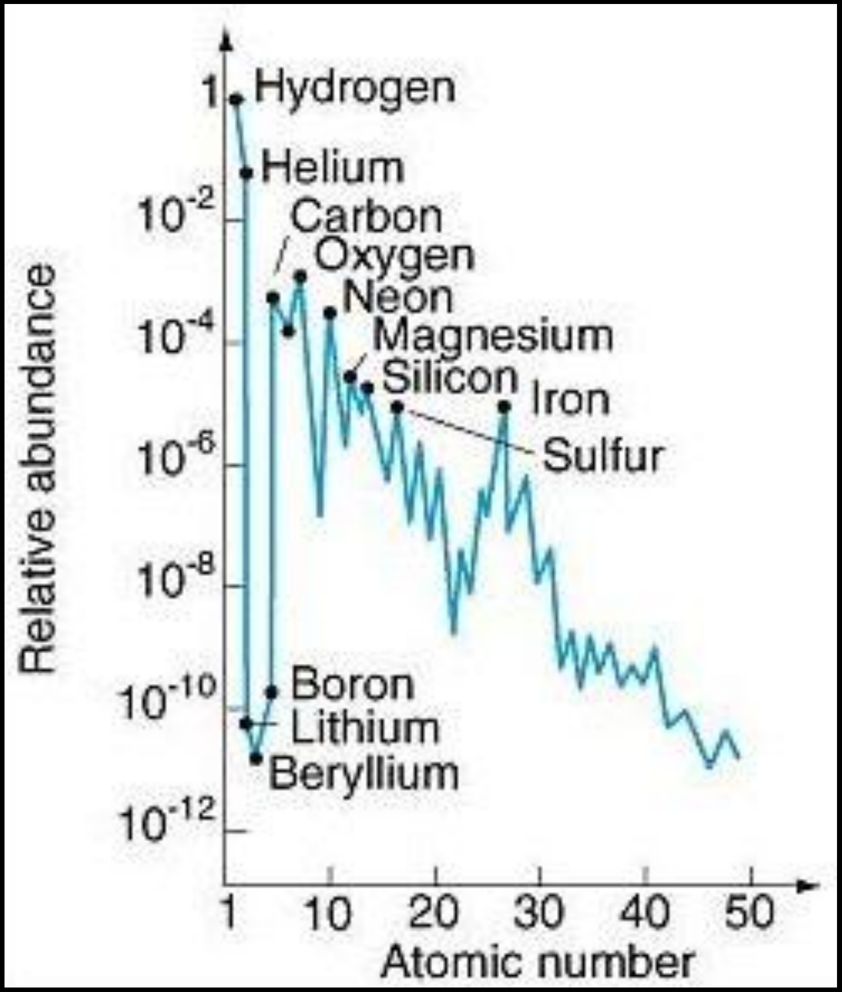
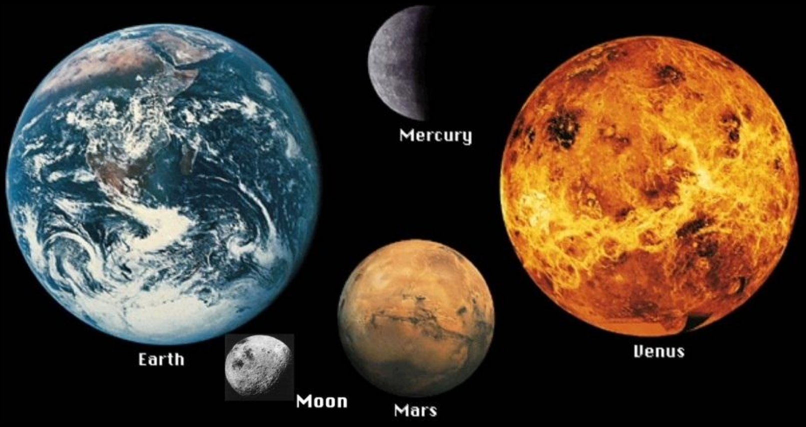
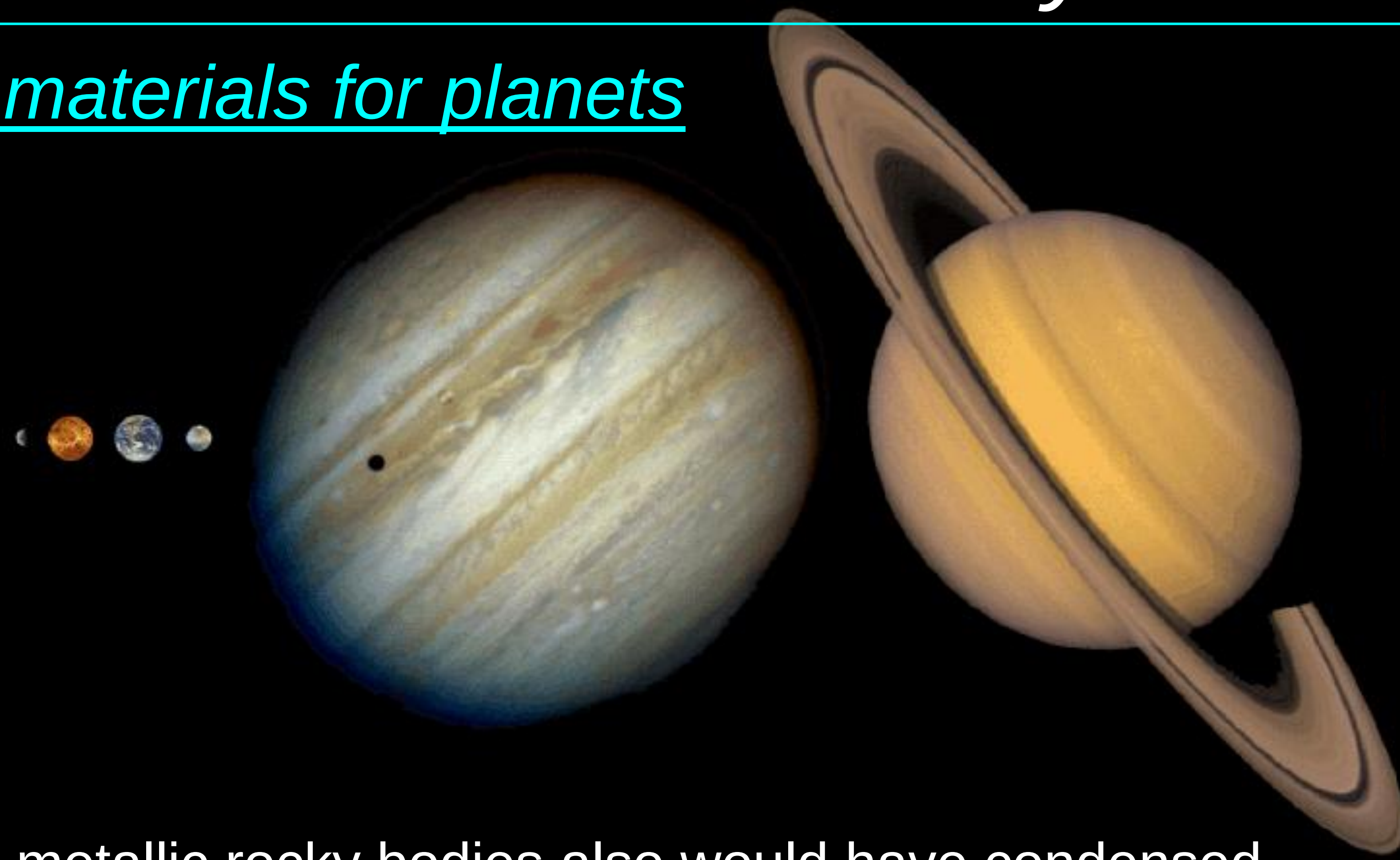




Terrestrial planets made primarily of iron, nickel and rocky materials cannot be massive since there were few of these elements in the original solar nebula

Formation of the Solar System

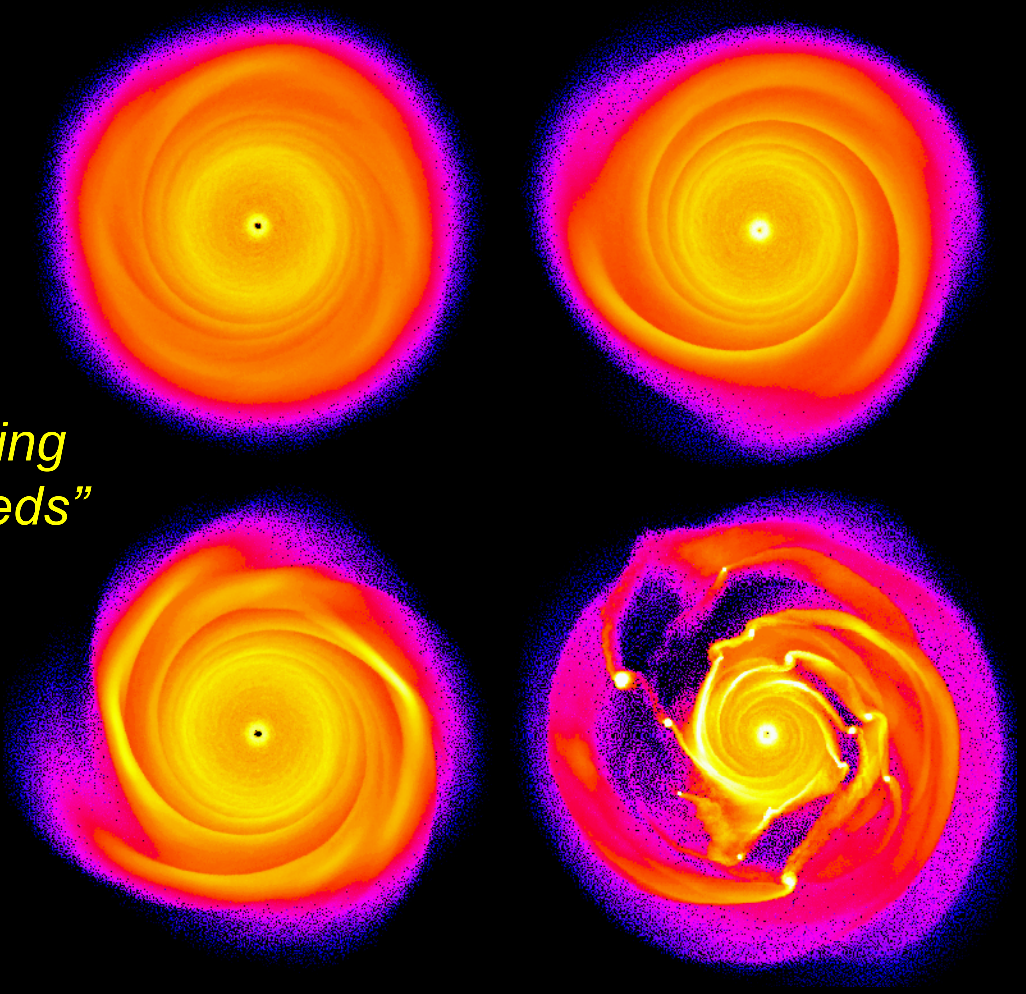
Raw materials for planets



Small metallic rocky bodies also would have condensed in the cold outer regions of the protoplanetary disk, but there the temperature was low enough that the cold hydrogen and helium could be gathered gravitationally to form gas giants

Formation of the Solar System

Gas giants form



N-body supercomputer simulation of gases gathering around protoplanetary "seeds" to become Jovian planets

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Formation of the Solar System

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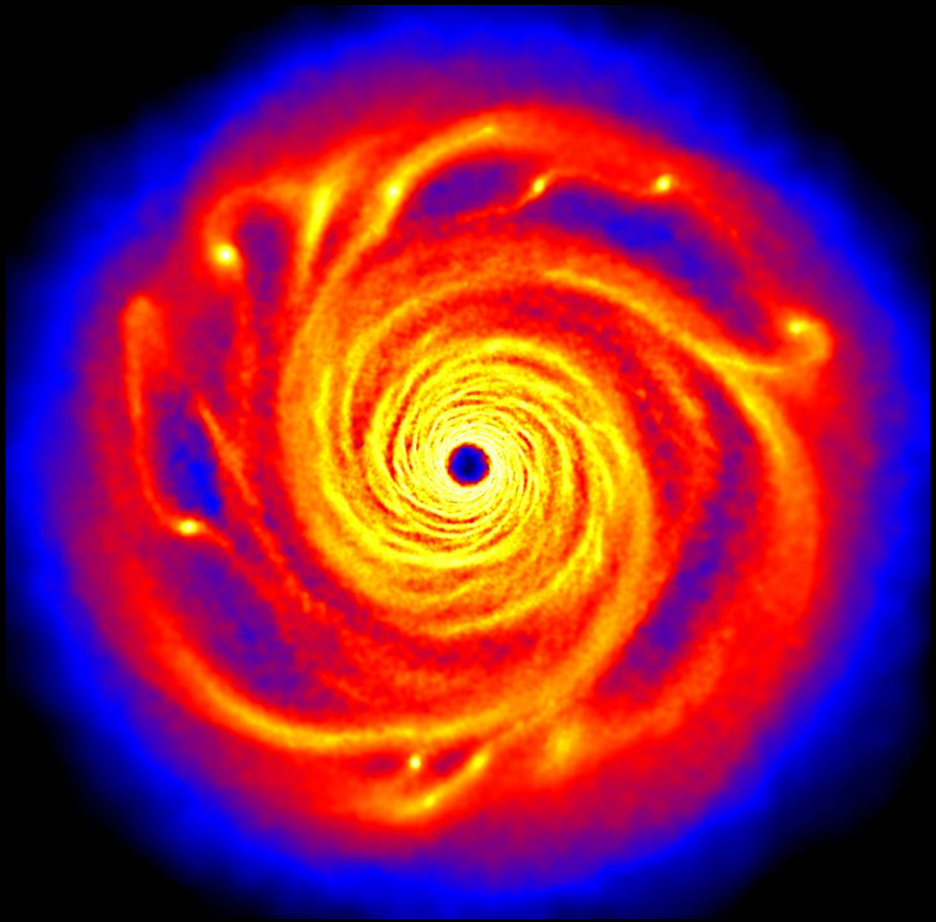

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Formation of the Solar System

Raw materials for moons and comets

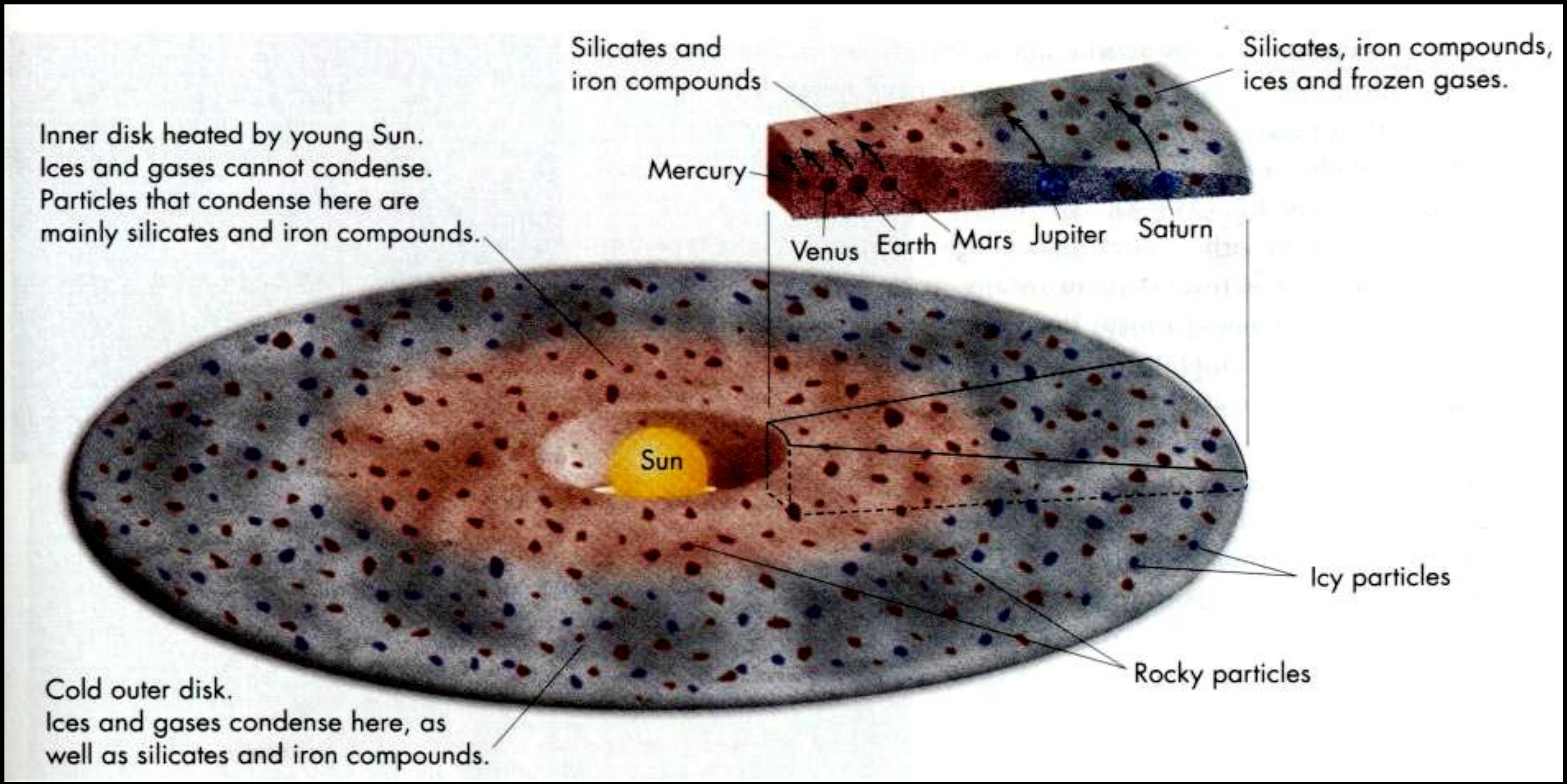
Ices could also freeze out from the gas in the cold outer portions of the nebula, from which formed comets, icy moons of the Jovian planets, Kuiper Belt Objects, and dwarf planets like Pluto and Eris

Iapetus: a moon of Saturn

Comet McNaught

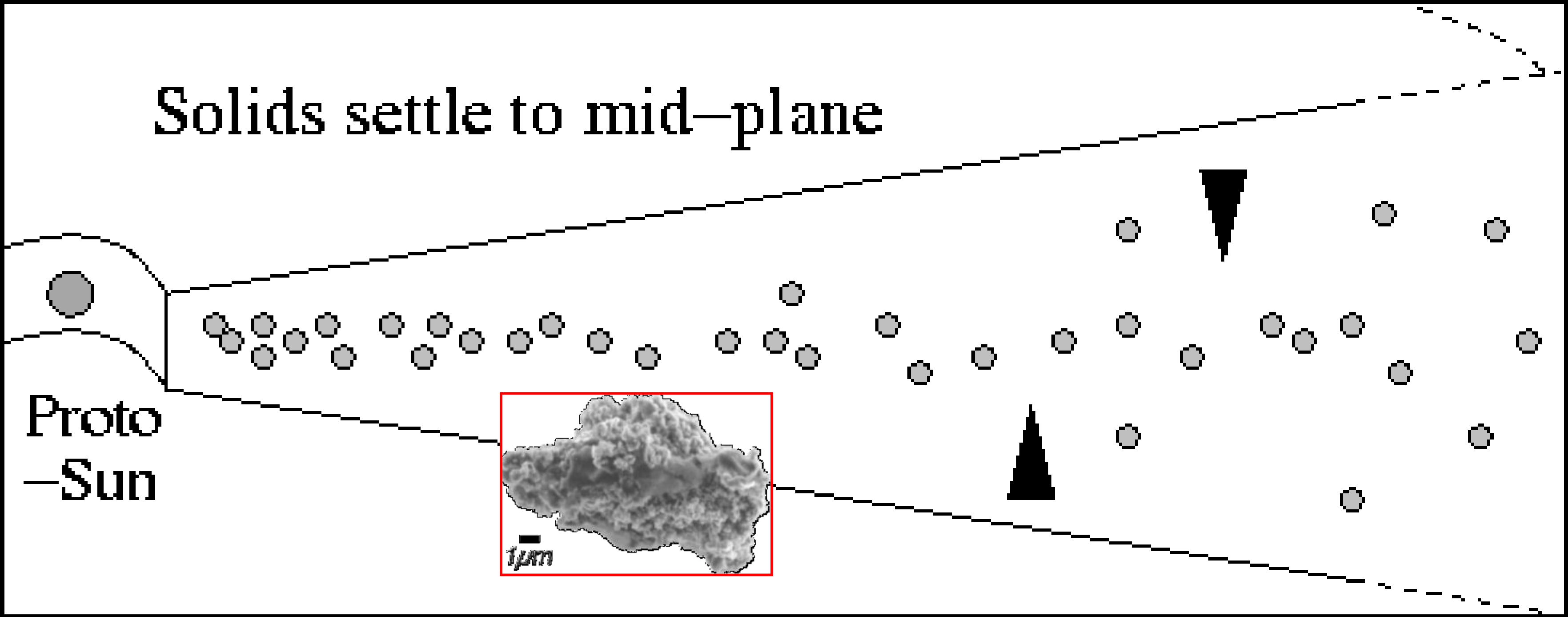
Formation of the Solar System

Condensation in the protoplanetary disk



Formation of the Solar System

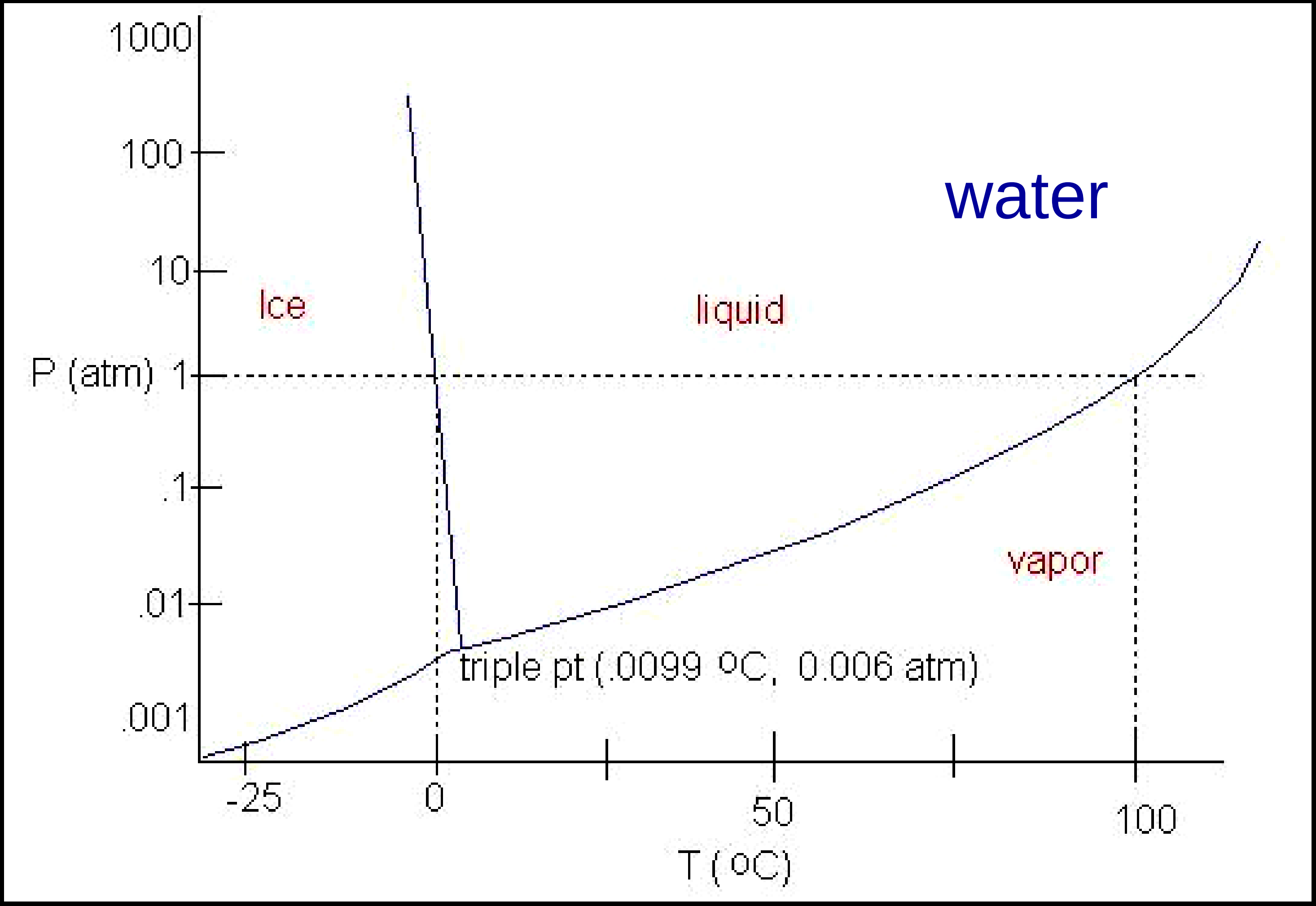
Condensation in the protoplanetary disk



- ✓ No direct planetesimal creation
- ✓ 1 – 100 μm (micron) dust grains settle to disk mid-plane
- ✓ Grains stick together to build macroscopic (~cm and larger) objects

Formation of the Solar System

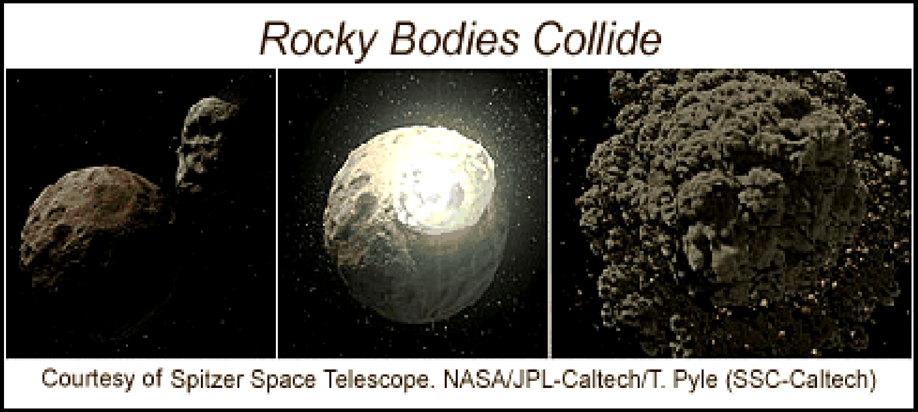
Solids condense from gas at right temperature



Formation of the Solar System

Differentiation of elements

When the Earth – and the other terrestrial planets – had just formed, they were molten. The heavier elements tended to sink to the centre under gravity.



Courtesy of Spitzer Space Telescope. NASA/JPL-Caltech/T. Pyle (SSC-Caltech)

Planetismals gather together under their mutual gravity to build into larger bodies

Formation of the Solar System

Differentiation of elements

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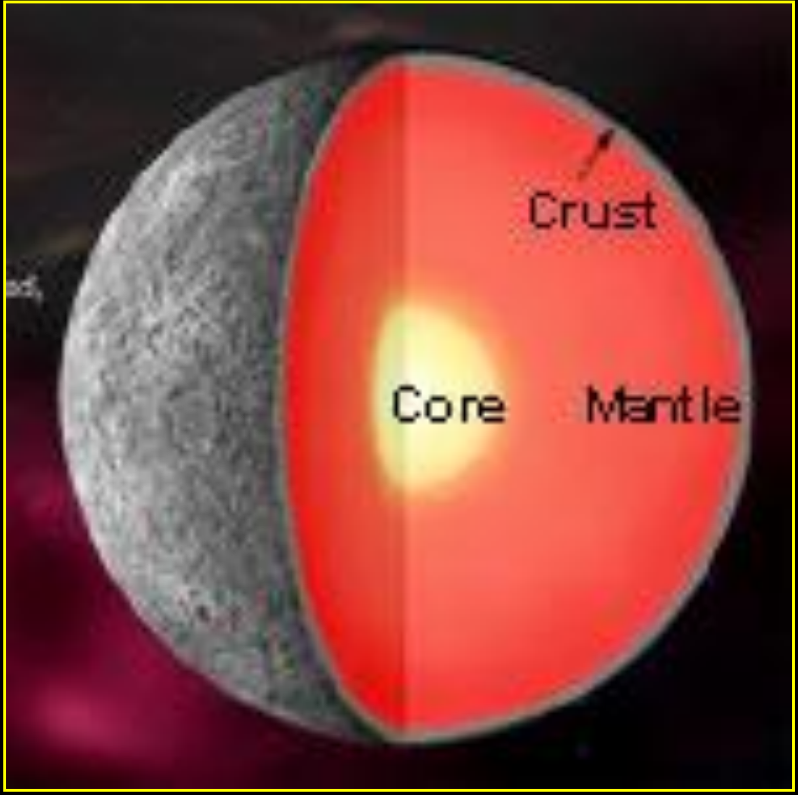

Formation of the Solar System

Differentiation of elements

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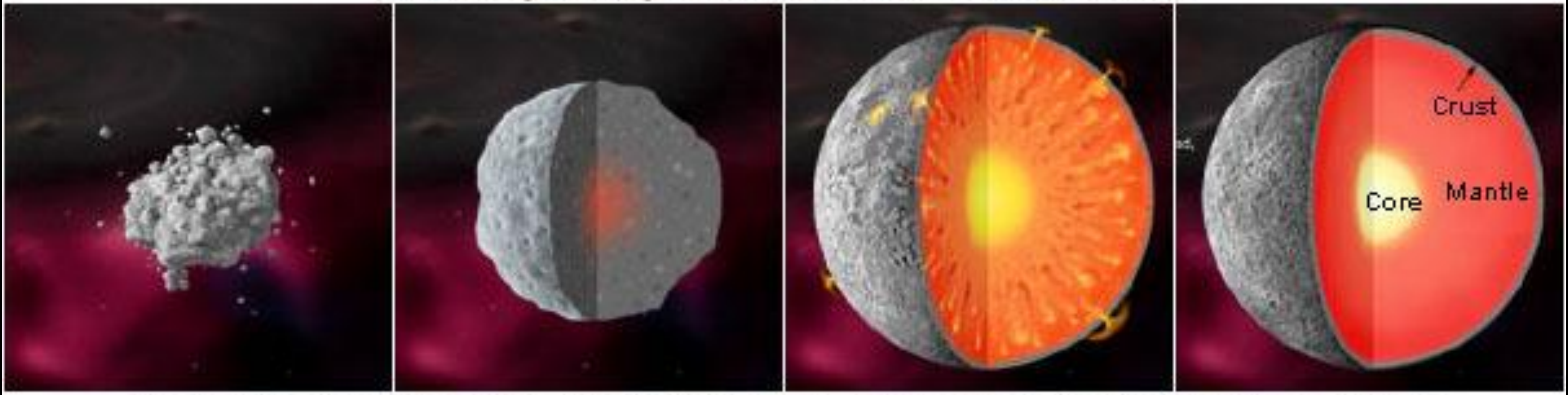
A Rocky Body Forms and Differentiates



(From Smithsonian National Museum of Natural History - http://www.mnh.si.edu/earth/text/5_1_4_0.html)

Formation of the Solar System

Differentiation of elements

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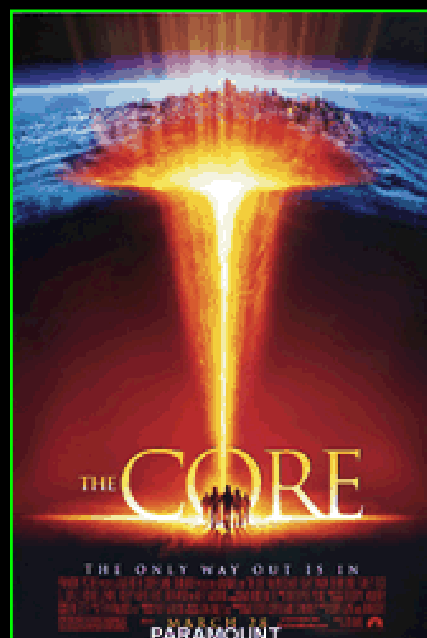
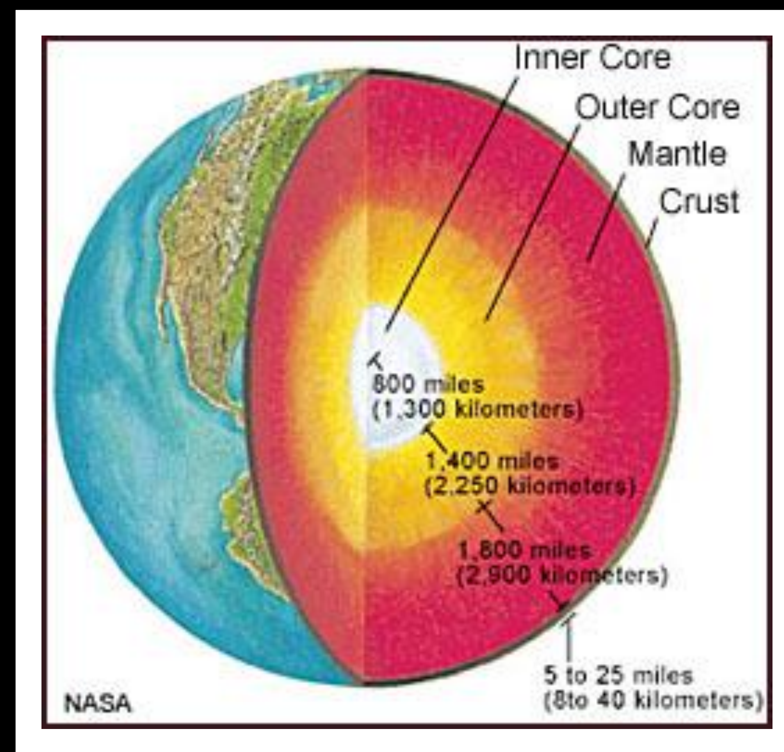
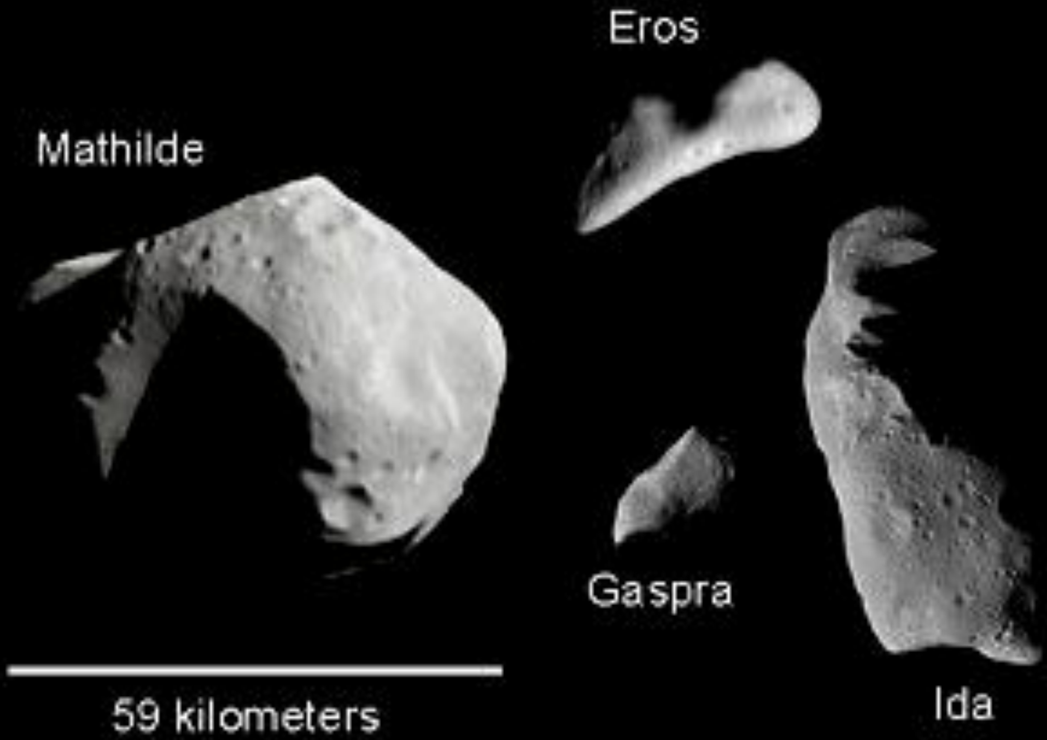




Formation of the Solar System

Asteroids and meteoroids

These smaller bodies are left over from the early history of the Solar System. Some are remnants broken apart from more violent collisions of planetismals. Some never gathered together.



Formation of the Solar System

Asteroids and meteoroids

There are meteorites which represent material from the cores of planetismals (iron) and the mantles and crusts (rocky). There are asteroids and meteorites which contain primordial material.

Allende

Murchison

Formation of the Solar System

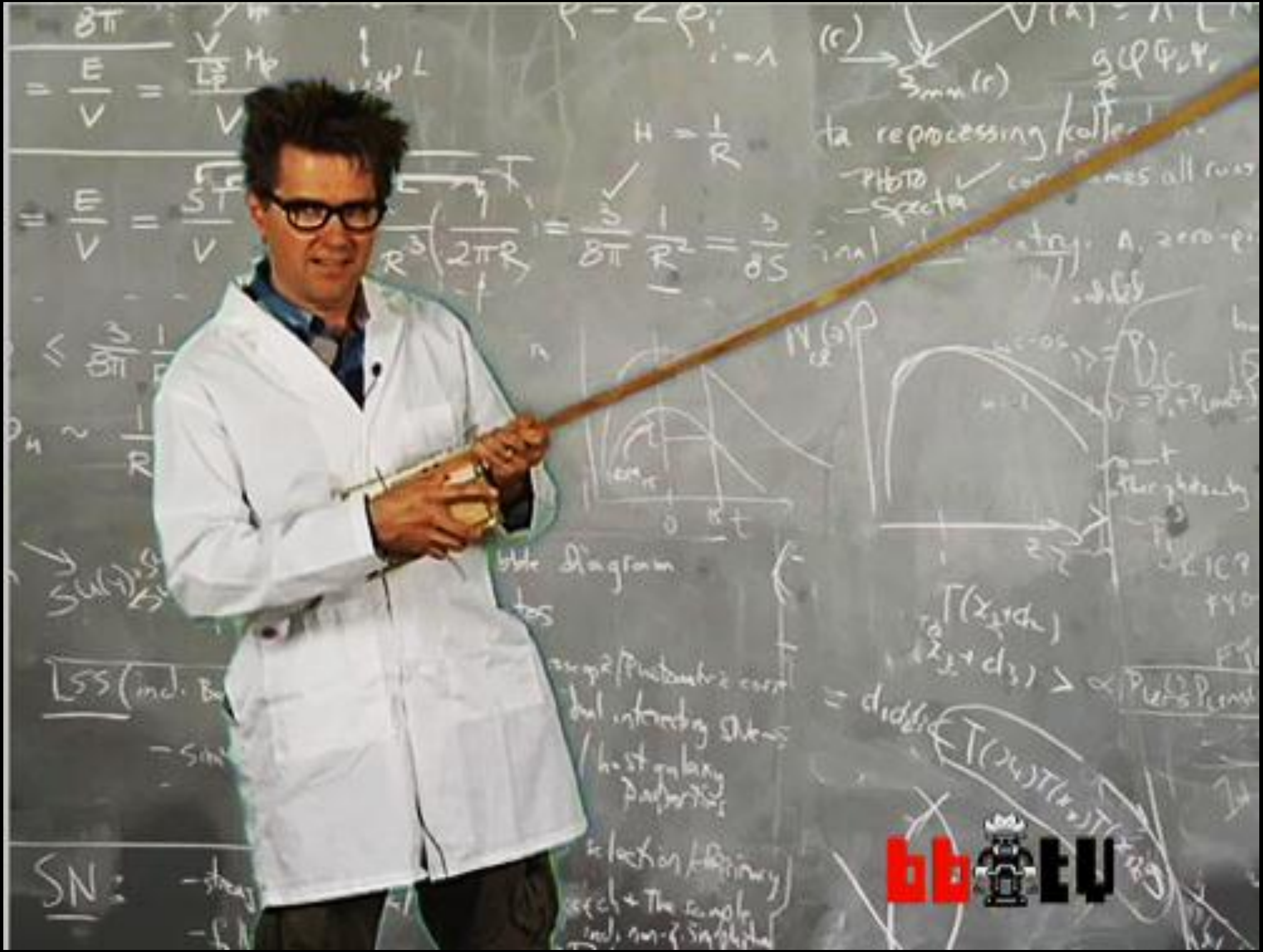
Nebular Hypothesis: Correct predictions

Lewis Model:

A sequence of chemical condensation at low pressure

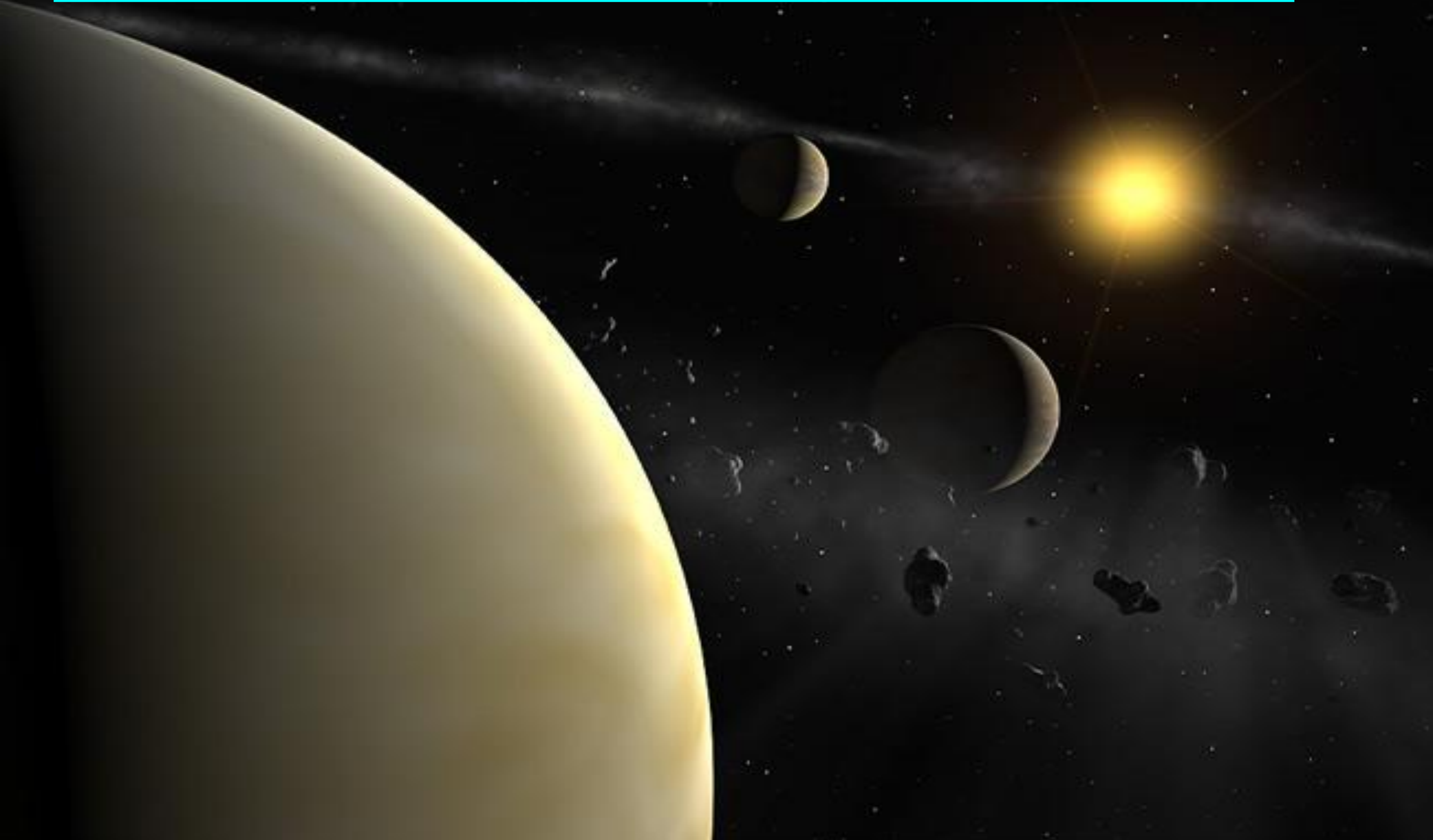
- ✓ metallic/rocky bodies closer to Sun, icy bodies farther out
- ✓ Mercury (closest to Sun and centre of original nebula) has a very large metal core
- ✓ Venus and Earth have larger rocky mantles
- ✓ Mars is predominantly rocky
- ✓ moons of the outer planets are icy
- ✓ comets and Kuiper Belt Objects, Pluto and Eris also icy

Any questions?



Formation of the Solar System

Can we test and refine the model elsewhere?



The Nebular hypothesis

Can we test and refine the model elsewhere?

Until recently, we had only *one* example of a planetary system

Our own

Any scientist will tell you that a sample of *one* is not a reliable test of any model or theory

A sample of <u>one</u>

<u>Can we test and refine the model elsewhere</u>?

Until recently, we had only *<u>one</u>* example of a planetary system

Our own

Any scientist will tell you that a sample of *<u>one</u>*
is not a reliable test of any model or theory

Imagine what our understanding
and appreciation of the world
would be like if we had
<u>only one example</u>
<u>of everything</u>

A sample of <u>one</u>

<u>Architecture</u>

The
Stata Centre
at MIT

A sample of <u>one</u>

<u>Fashion sense</u>

A sample of one

Food

Betcha can't eat just *one*!

A sample of one

Music videos

1980's Finnish pop stars, *Danny & Armi*, and their mega-hit *"I Wanna Love You Tender"*

A sample of <u>one</u>

<u>In science and in life</u> …

Not good!!!

A sample of <u>many</u>

Searching for exoplanets

To fully understand the process of Solar System birth and evolution, we need to have other examples