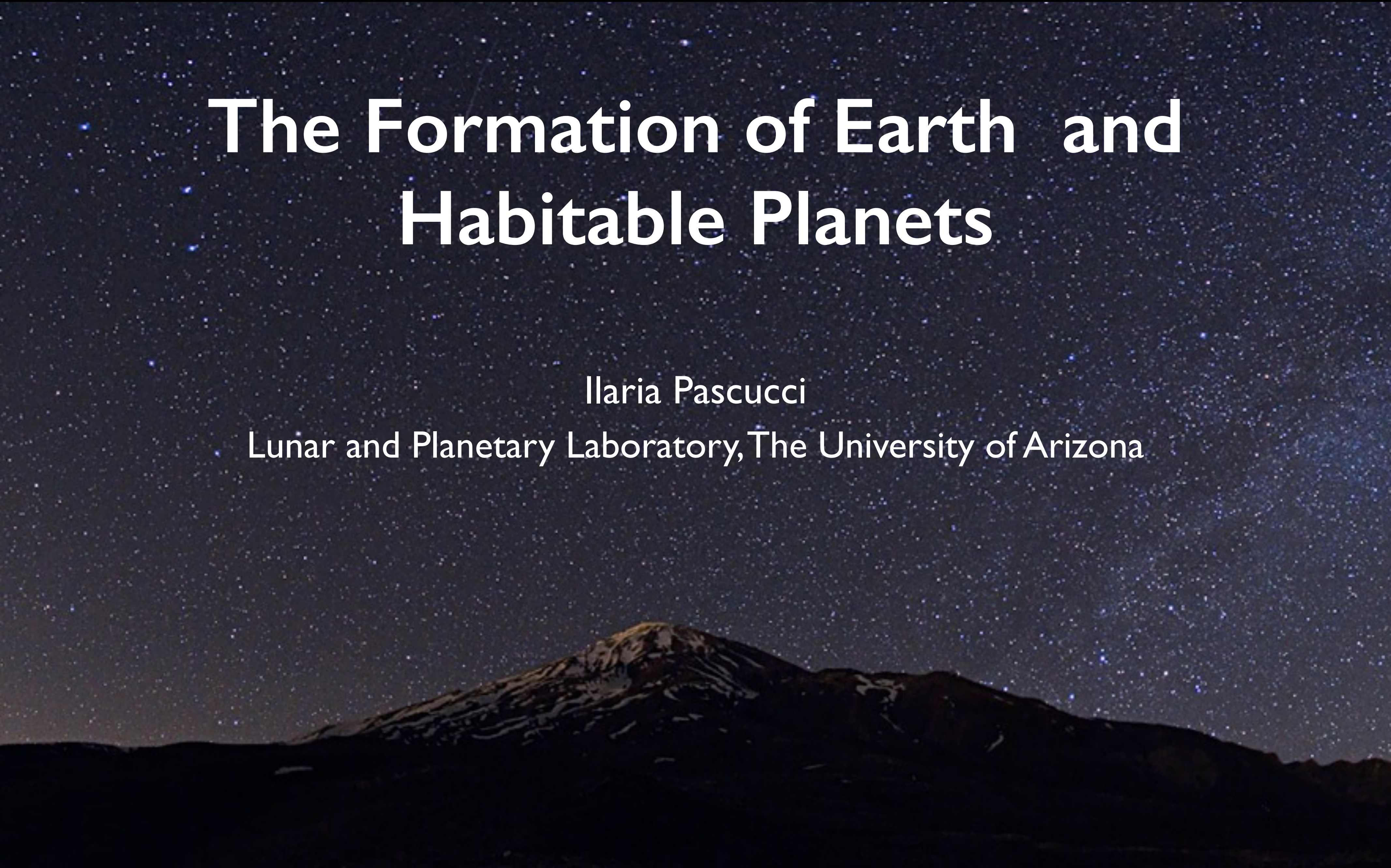
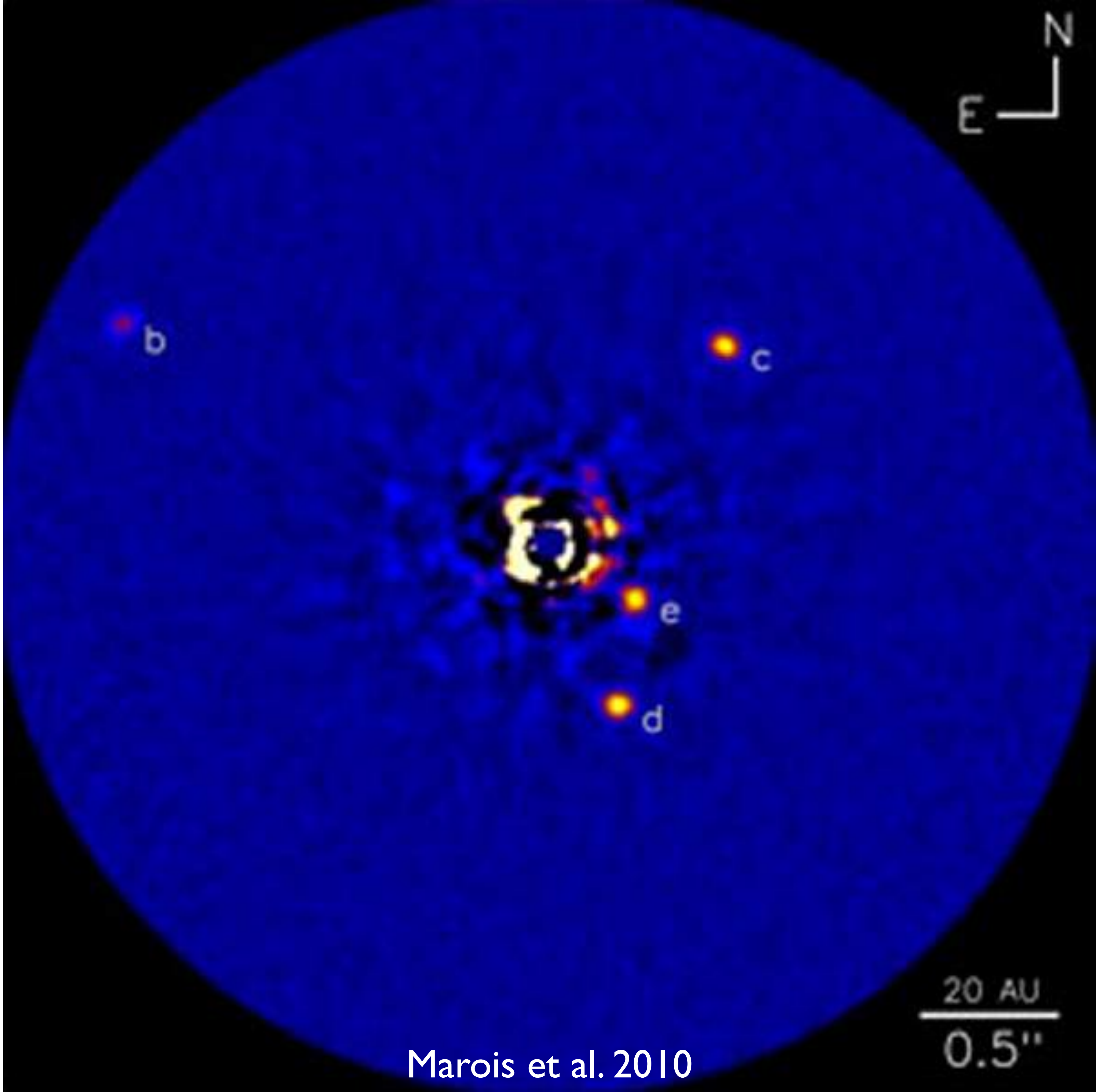


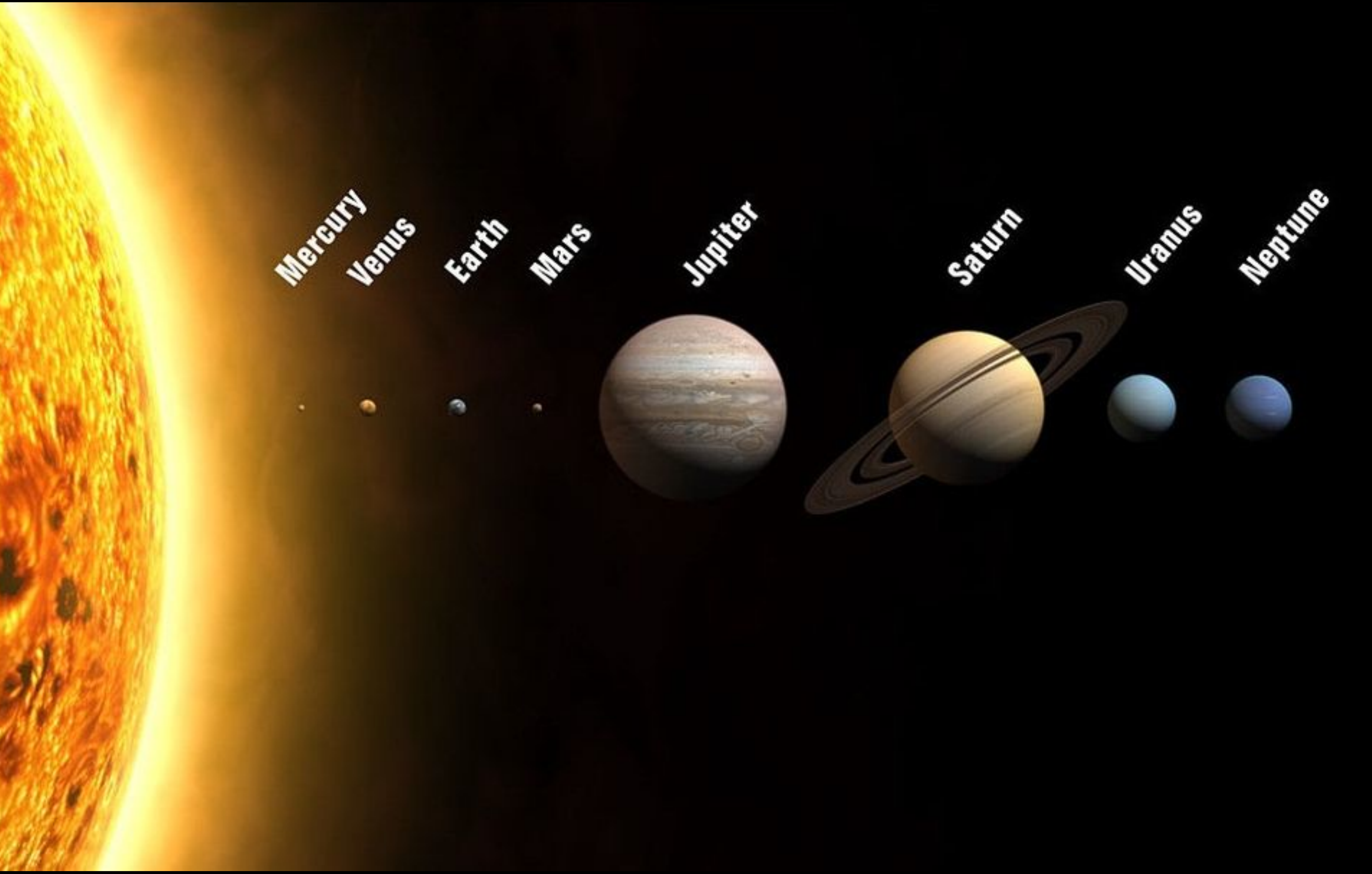
The Formation of Earth and Habitable Planets

Ilaria Pascucci
Lunar and Planetary Laboratory, The University of Arizona



Marois et al. 2010

Which planets are habitable? What factors contribute to making a planet habitable?

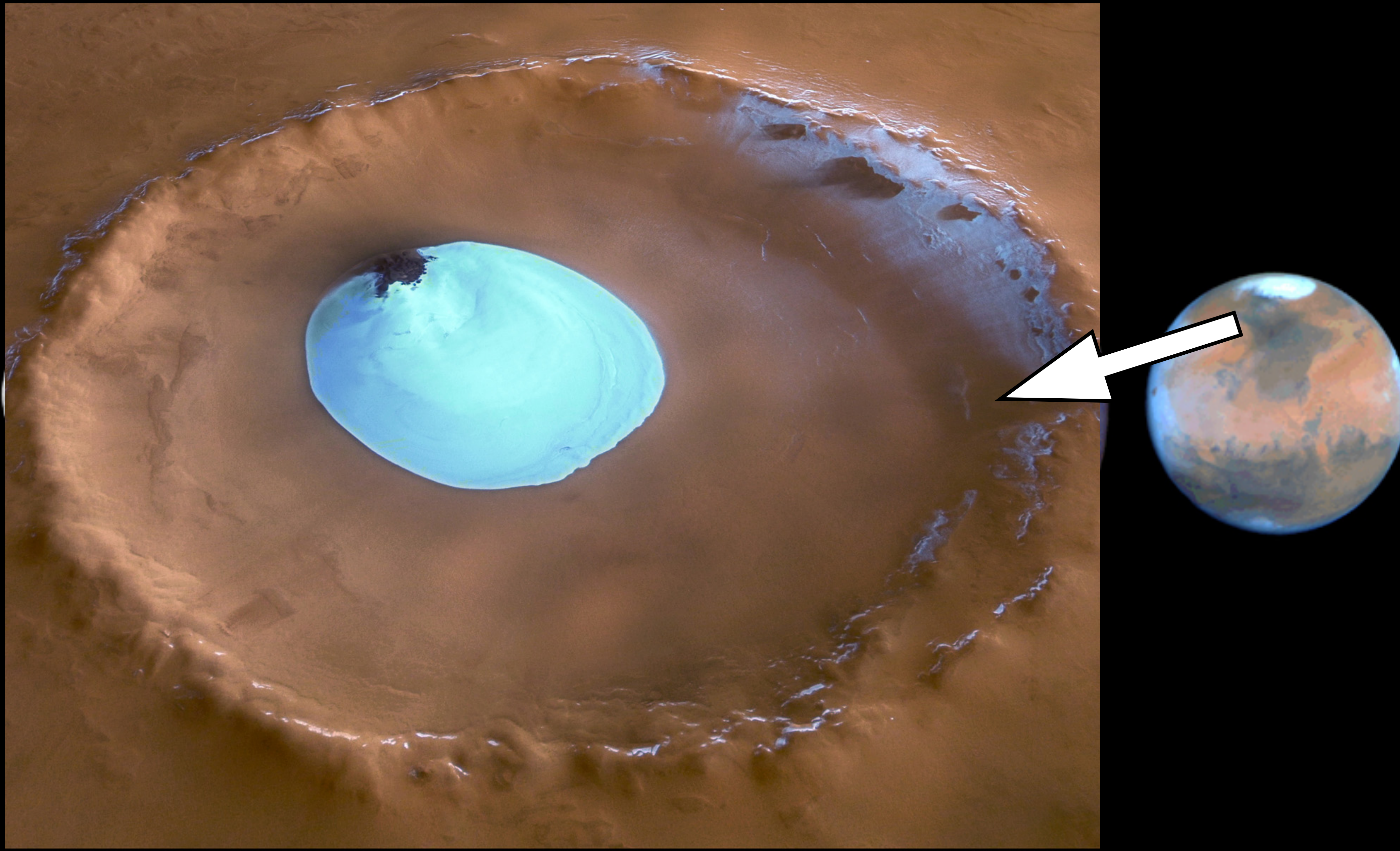


NOTE: sizes are to scale, distances not

Life in the atmosphere of gas giants?

Possible but very challenging due e.g. to extreme vertical winds/gradient in temperature

A rocky surface is better for the development of (and to sustain) life



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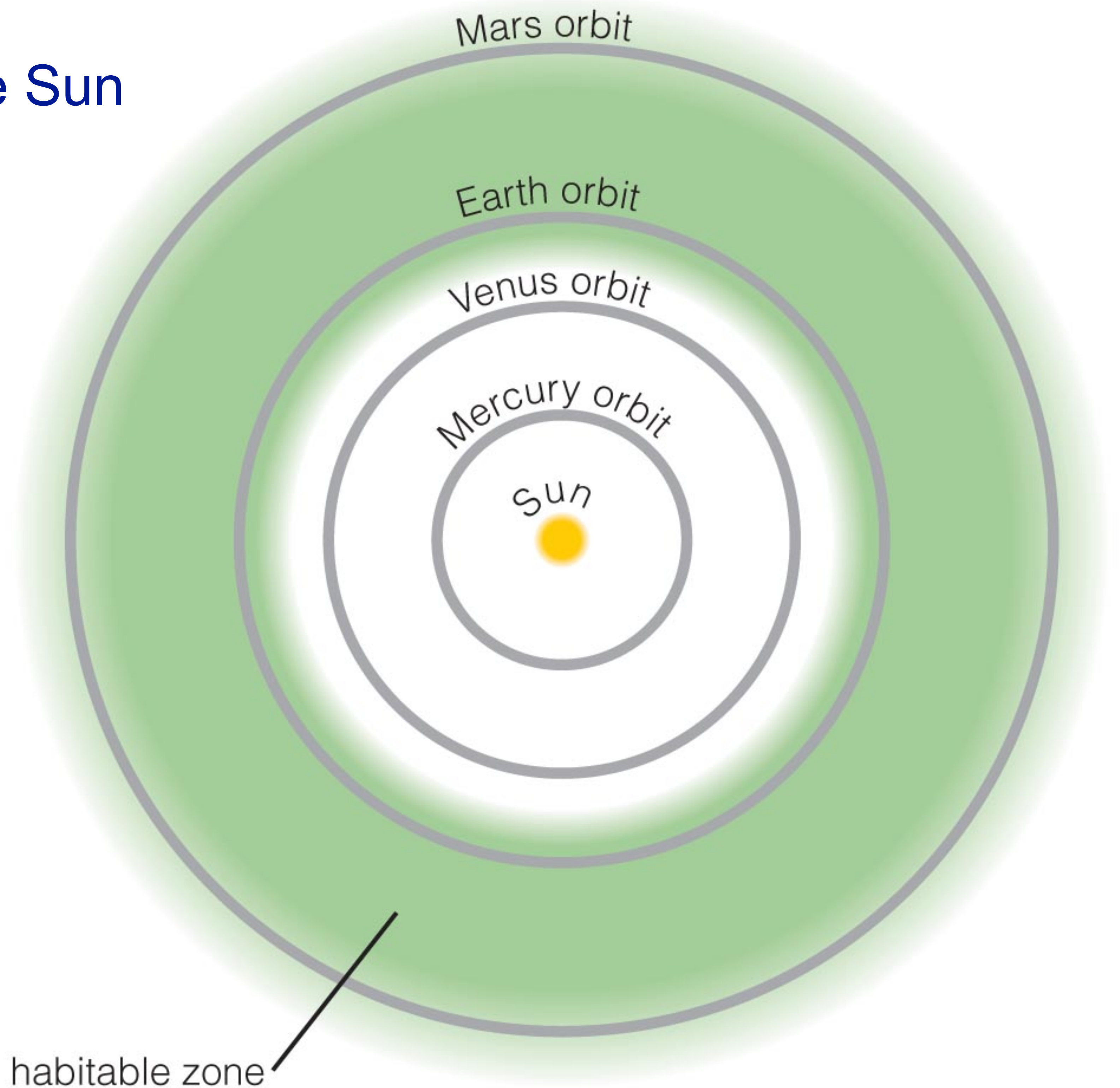
Which planets are habitable? What factors contribute to making a planet habitable?

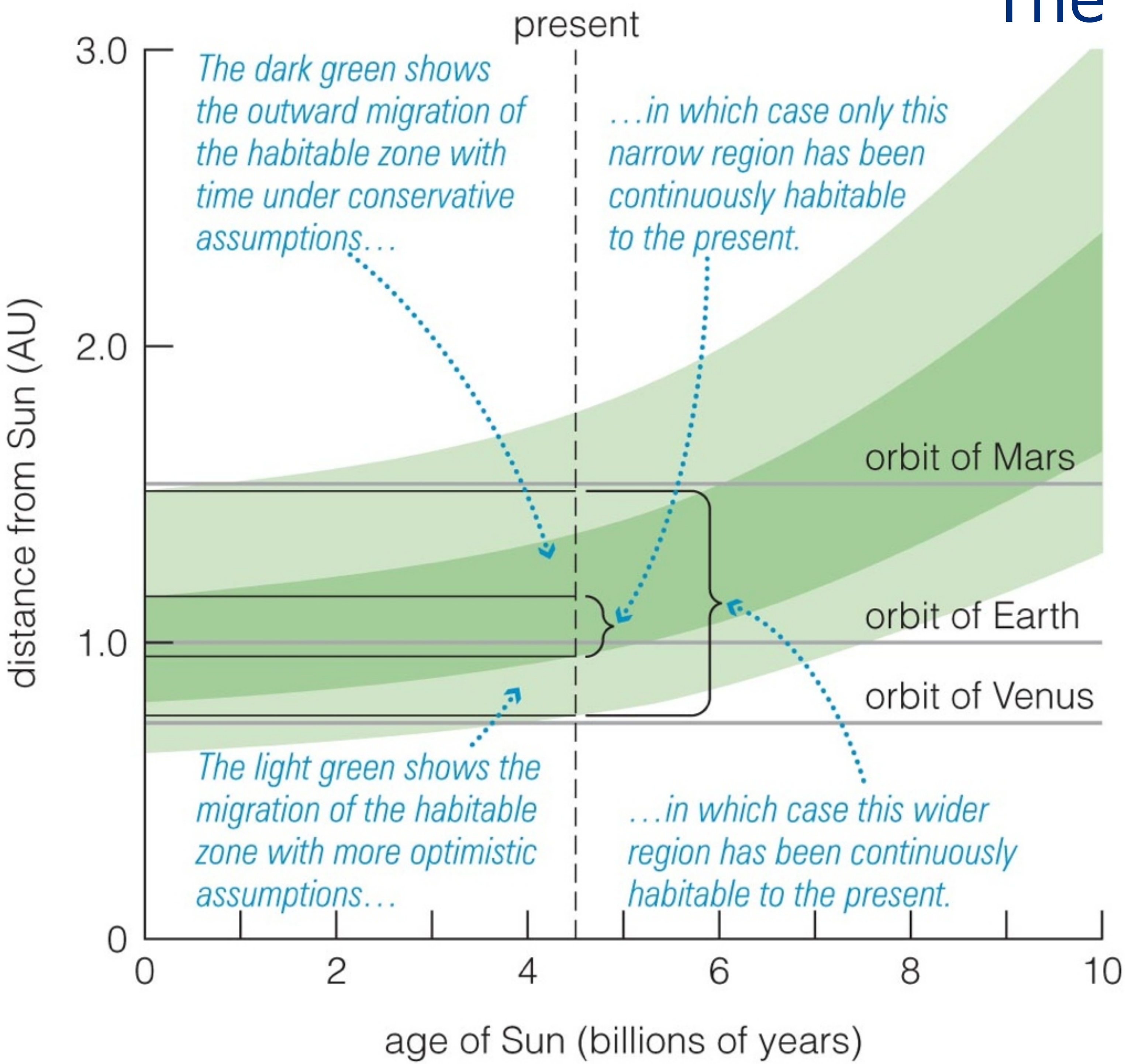
1. Rocky surface

2. Liquid water on the surface

HZ around the Sun (TODAY)



The Evolving HZ



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the Sun becomes brighter with time

Earth will be out of the HZ in ~1Gyr

How do planets form?


Dennis di Cicco/Sean Walker


Dennis di Cicco/Sean Walker

All stars are born with disks

There is enough material to form planets like Earth

Material in Protoplanetary Disks

Gas: mostly H (molecular, H_2)

Dust grains: from micron to cm in size
(we cannot detect larger grains e.g. boulders)



From Dust to Planets

growth of at least 12 orders of magnitude in size scale!

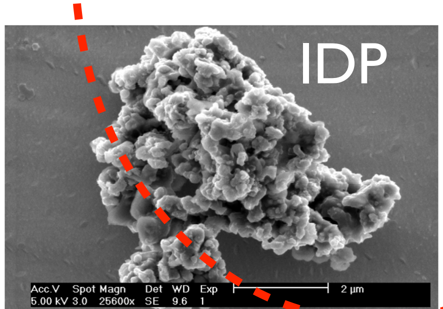
ONLY THEORY

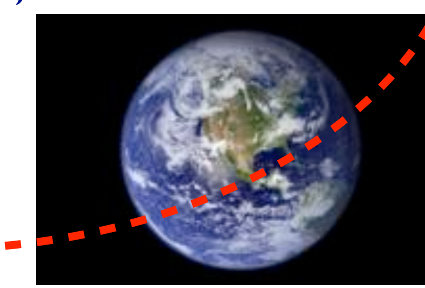
~ µm

~ mm

~ km

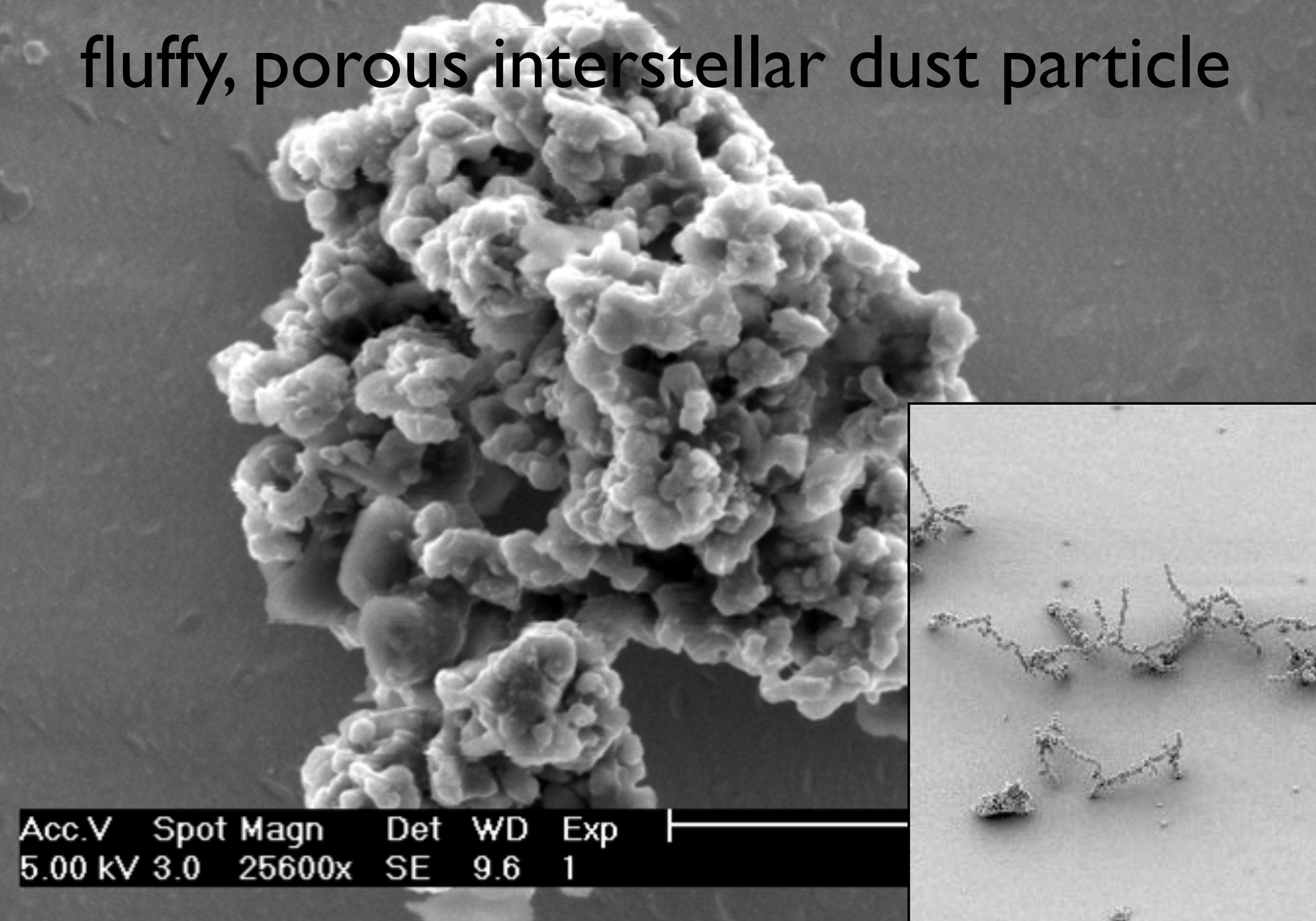
~ 1,000 km

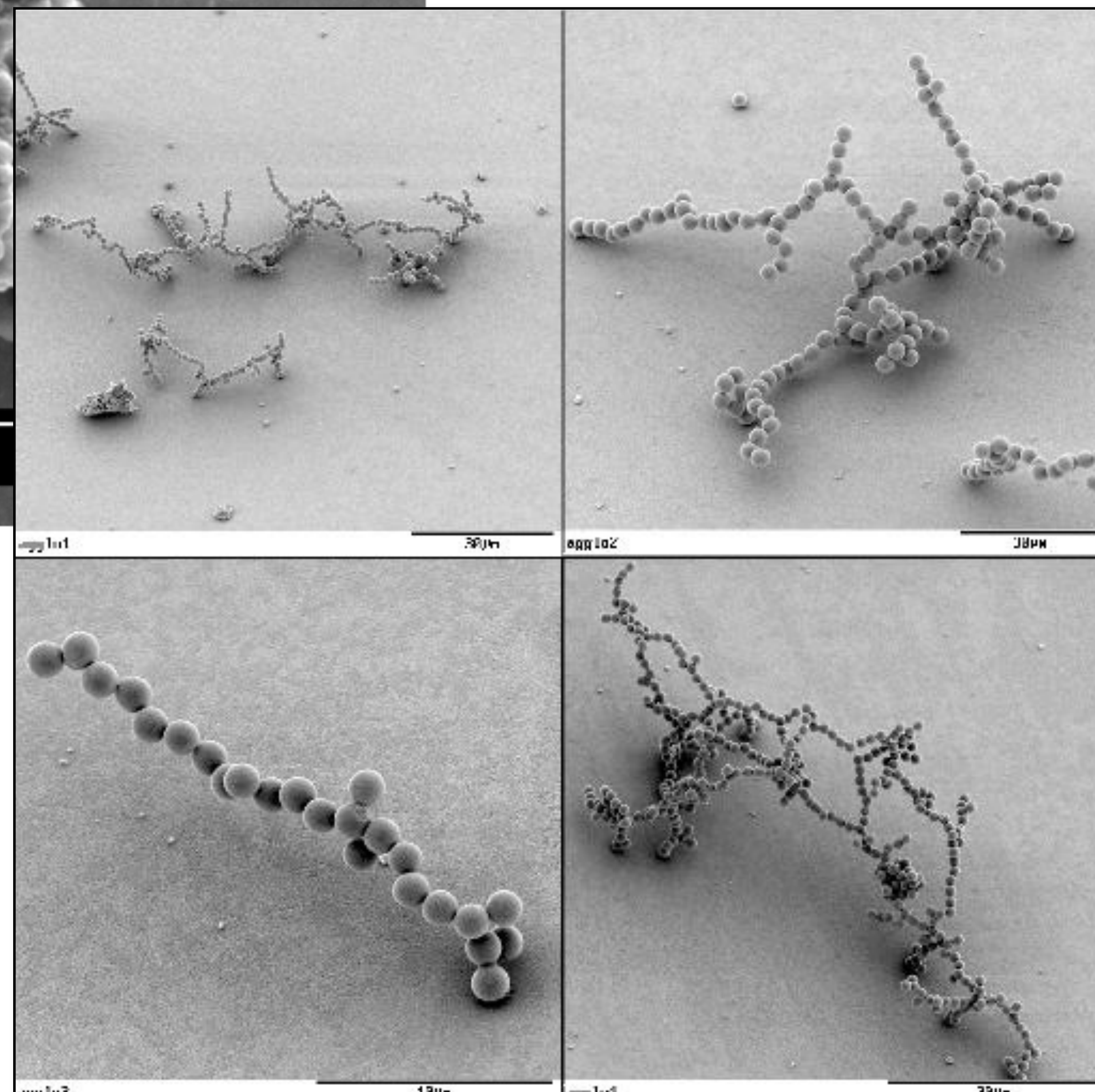




Observables: dust AND end state (asteroids, exoplanets...)

fluffy, porous interstellar dust particle





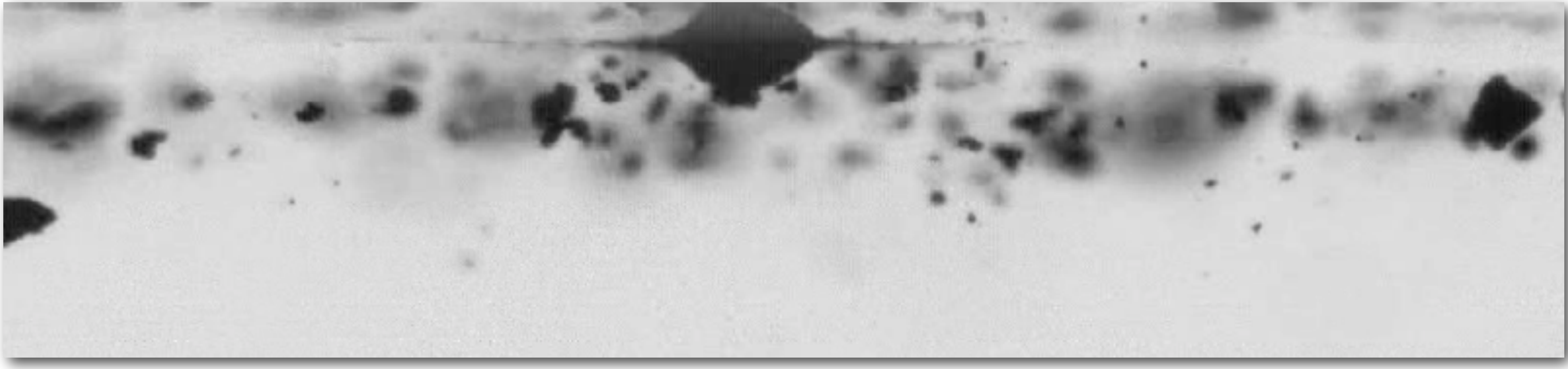
1mm size aggregates colliding at 9mm/s

<u>Outcome</u>: aggregates stick together, net growth

movie available in Weidling et al. 2012, Icarus, 218, 688

Small projectile vs large target colliding at 2m/s

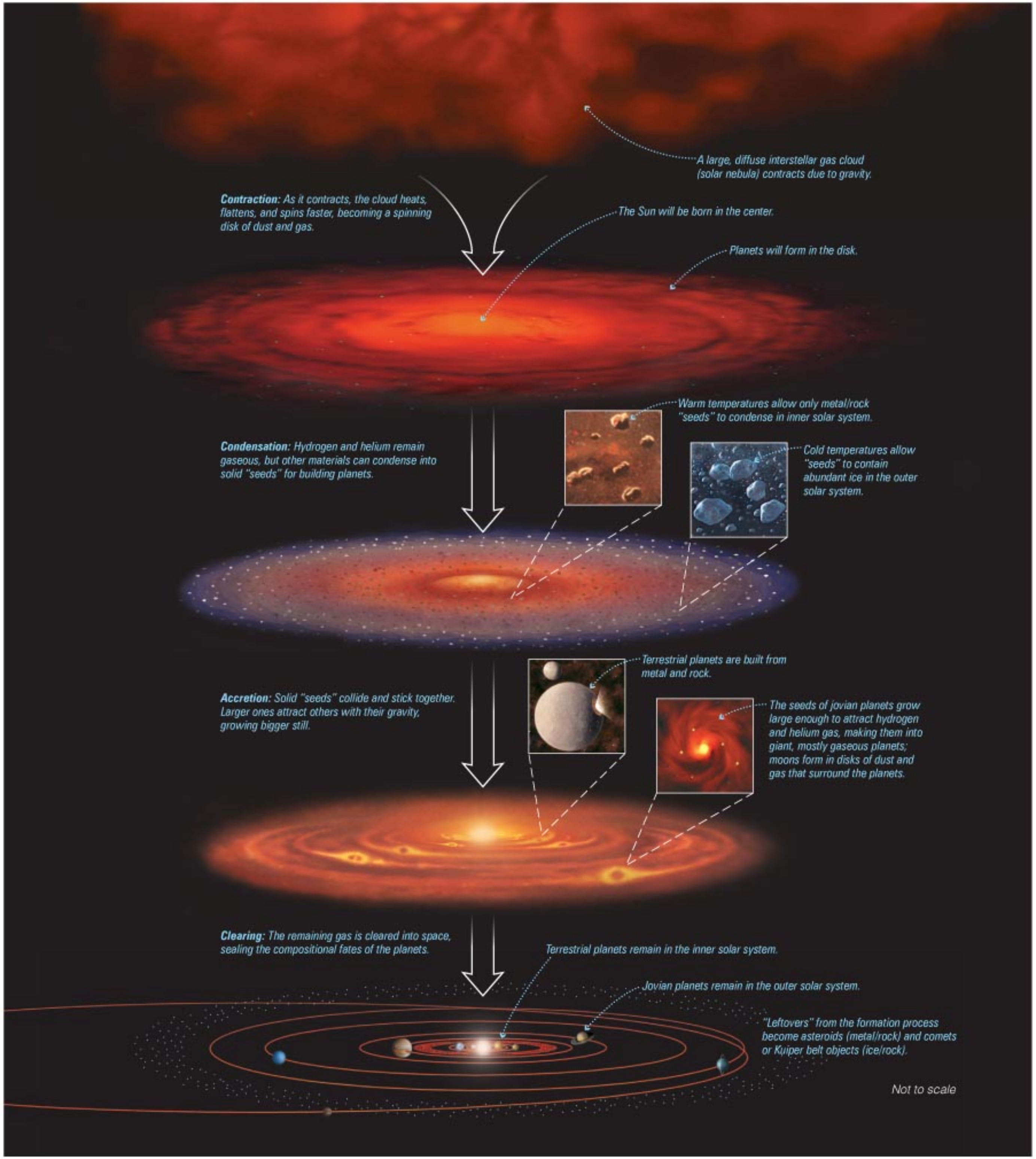
Outcome: some fragmentation but net growth



Guettler et al.2010,A&A

illustration of the sequence of hit and stick collisions (v between 2 and 6cm/s). Main result: clusters of dust aggregates (fluffy particles) stick together at v where compact dust would bounce

movie available in Kothe et al. 2012, Icarus, 225, 75



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The Solar Nebula Theory

from micron-sized grains

↓

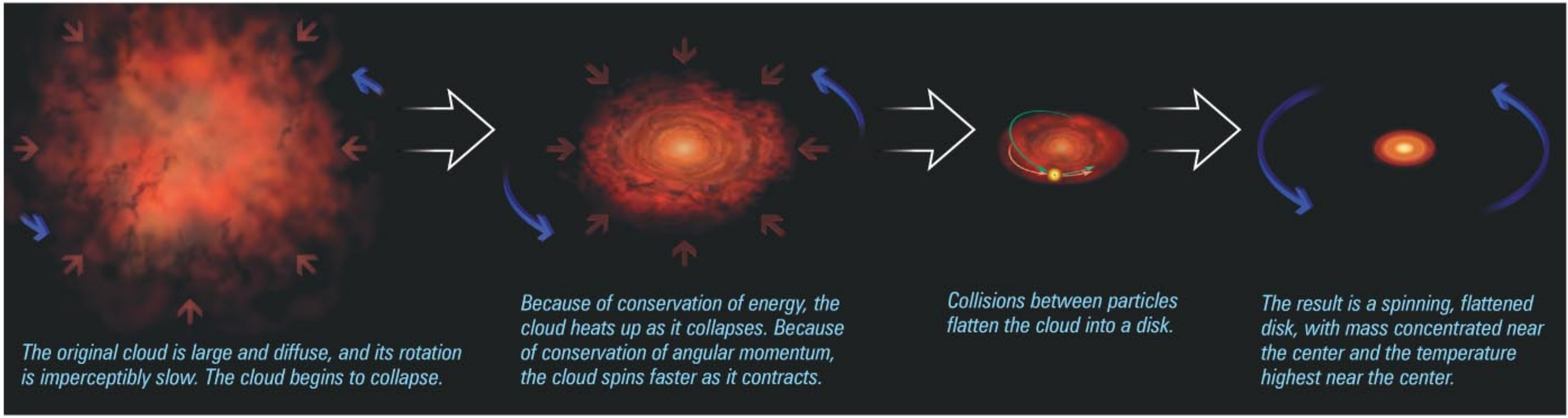
planetesimals (~km)

↓

planets

Formation of the protosun and of a protoplanetary disk

Key physics laws:
– conservation of energy (from gravitational potential to thermal)
– conservation of angular momentum (faster spin as the clouds contracts)



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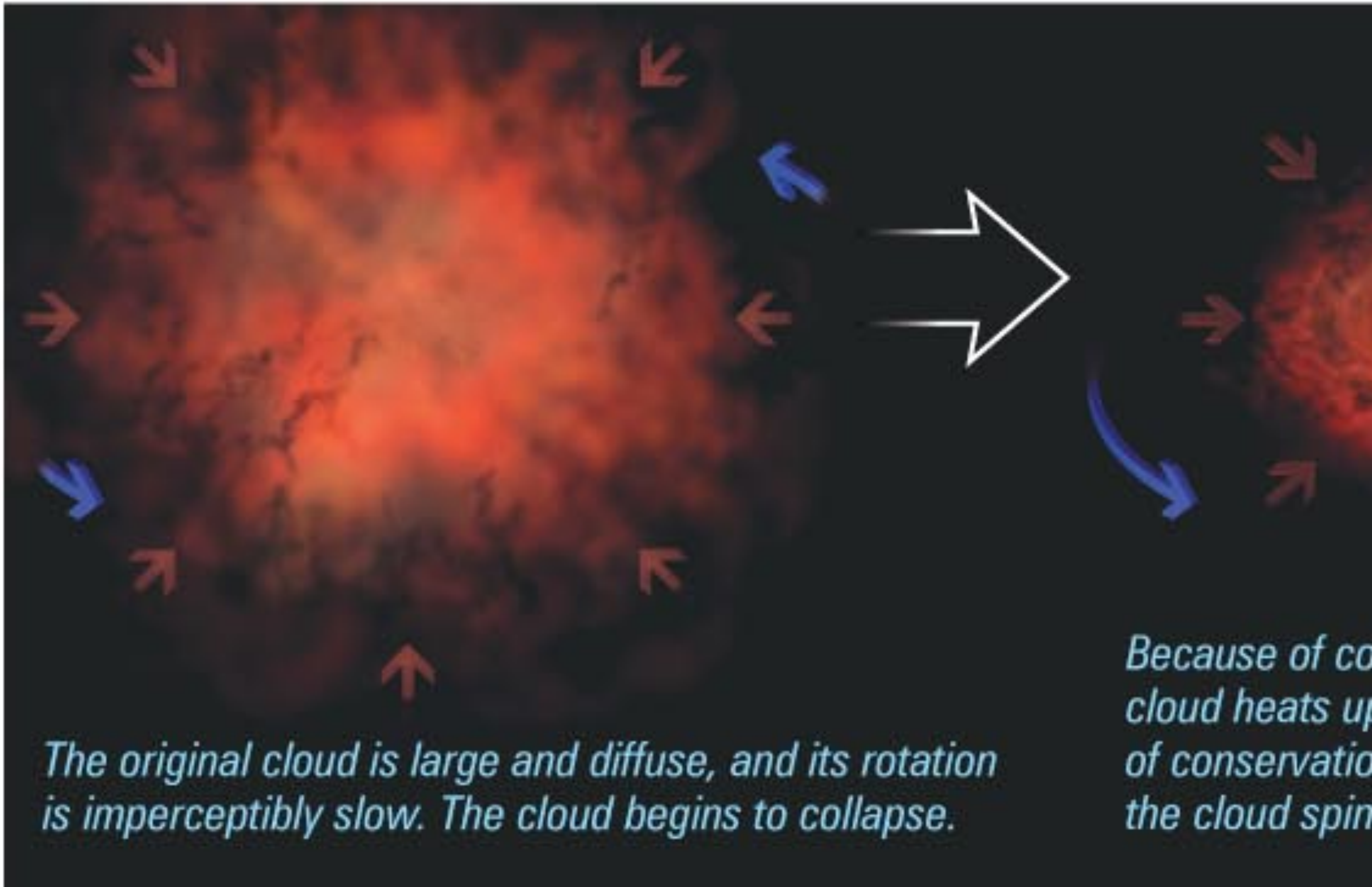

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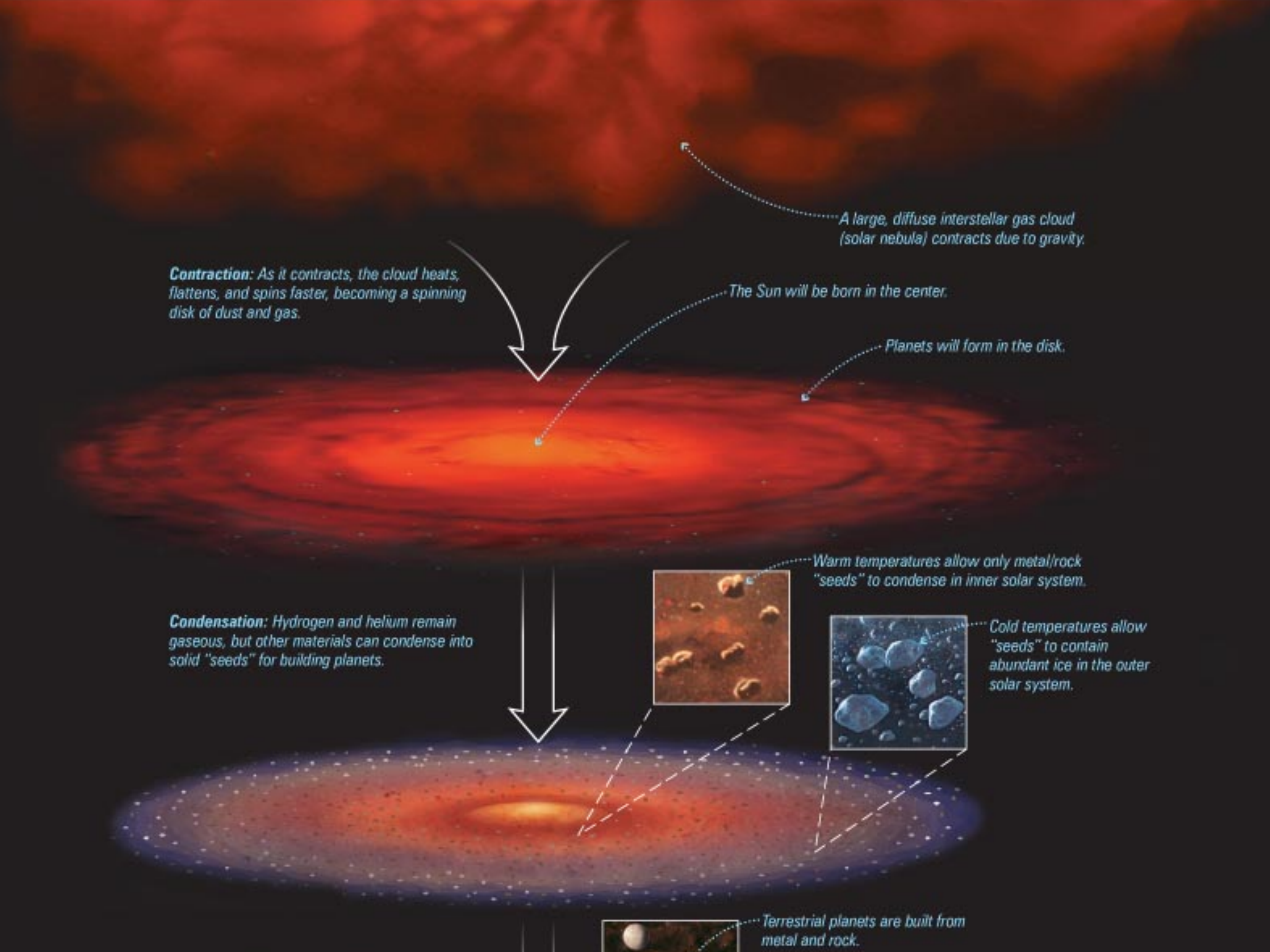
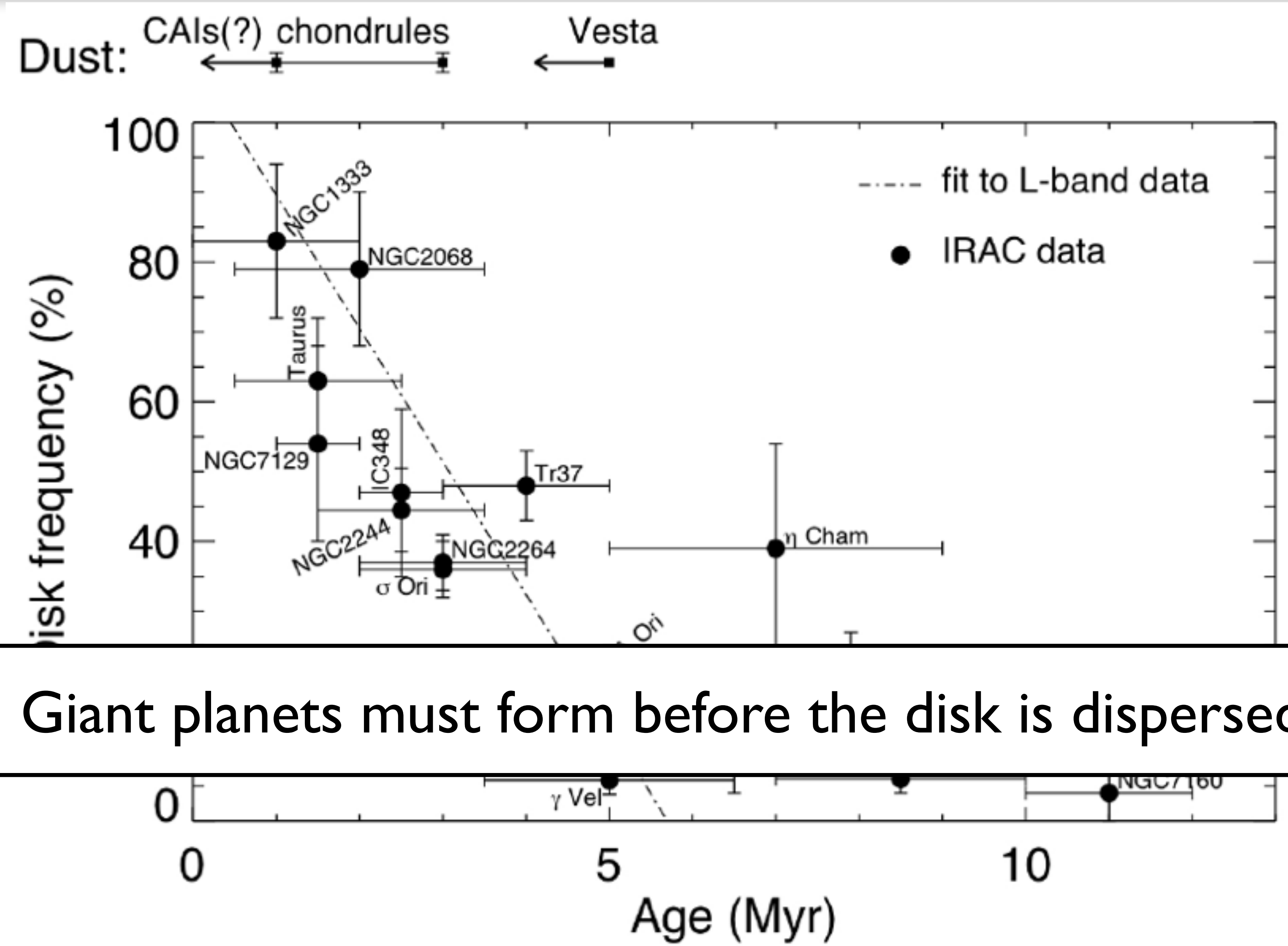

A large, diffuse interstellar gas cloud (solar nebula) contracts due to gravity.
Contraction: As it contracts, the cloud heats, flattens, and spins faster, becoming a spinning disk of dust and gas.
The Sun will be born in the center.
Planets will form in the disk.
Warm temperatures allow only metal/rock "seeds" to condense in inner solar system.
Condensation: Hydrogen and helium remain gaseous, but other materials can condense into solid "seeds" for building planets.
Cold temperatures allow "seeds" to contain abundant ice in the outer solar system.
Terrestrial planets are built from metal and rock.

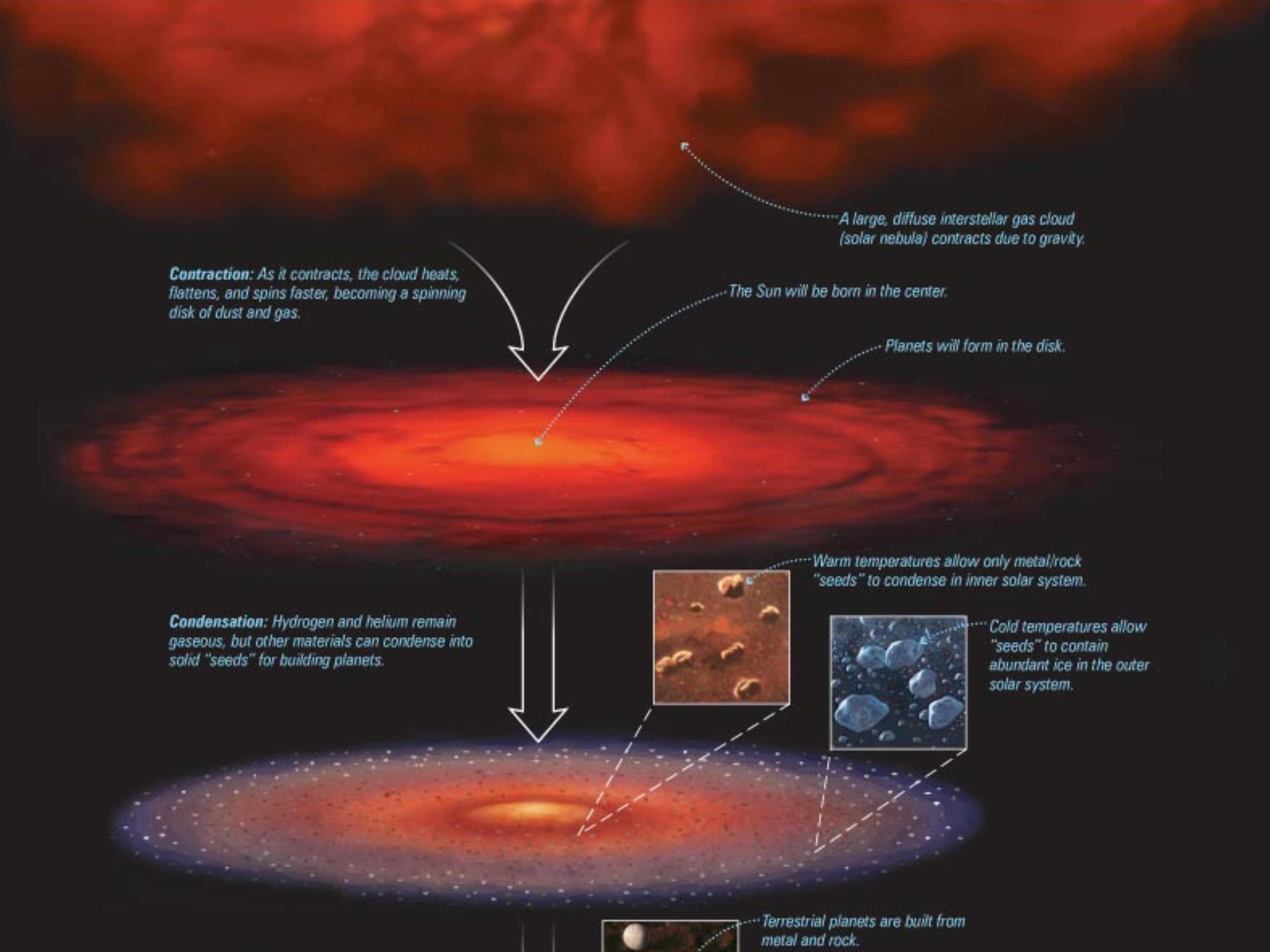
What is the lifetime of protoplanetary disks?

Typical disk lifetimes are a few Myr



Giant planets must form before the disk is dispersed

Pascucci & Tachibana 2010, 263, "Protoplanetary Dust", eds. Apai & Lauretta, Cambridge University Press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Cold temperatures allow "seeds" to contain abundant ice in the outer solar system.
Terrestrial planets are built from metal and rock.

Gas giant vs rocky planets

Temperature in the disk: the snowline

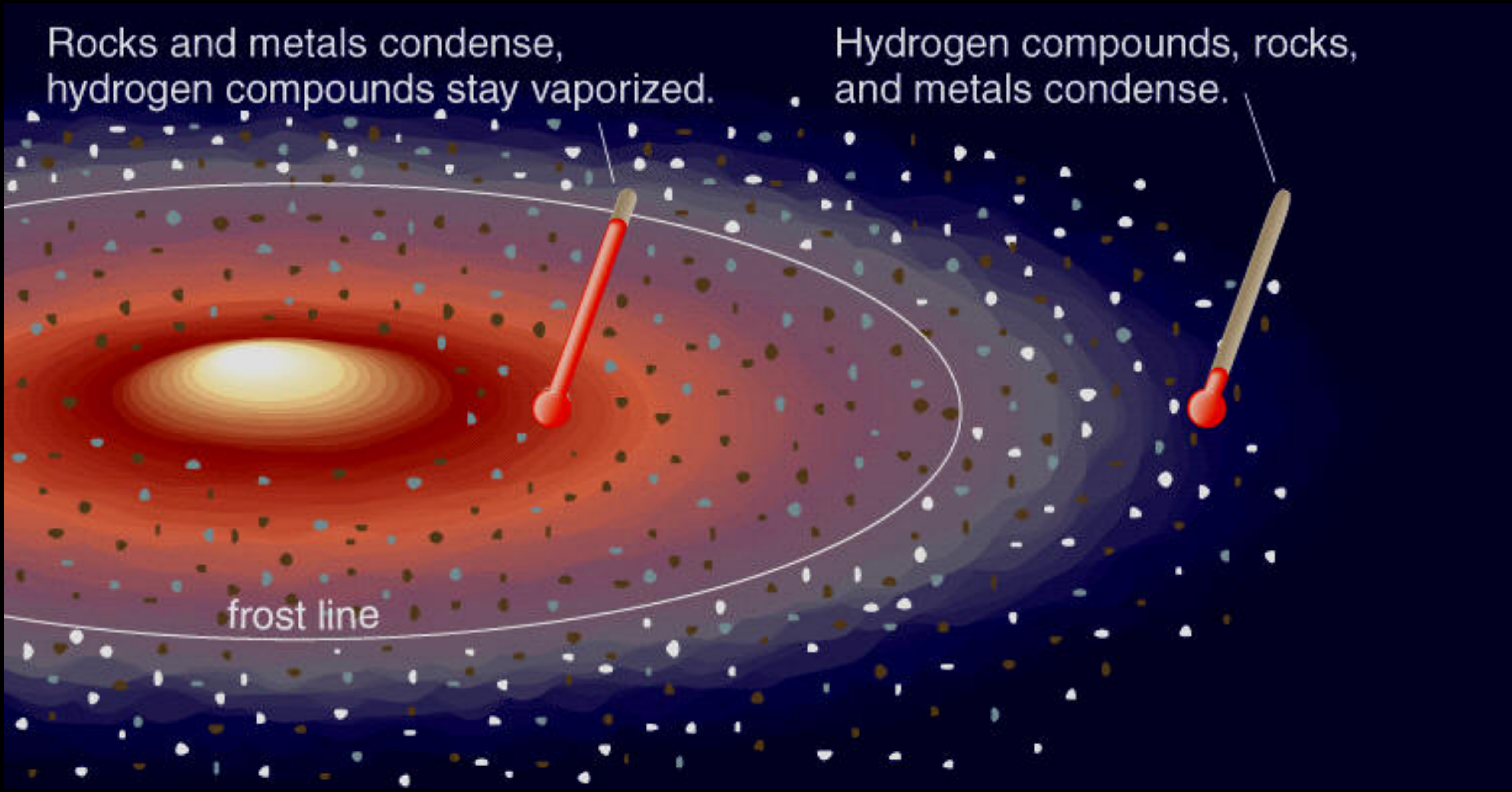
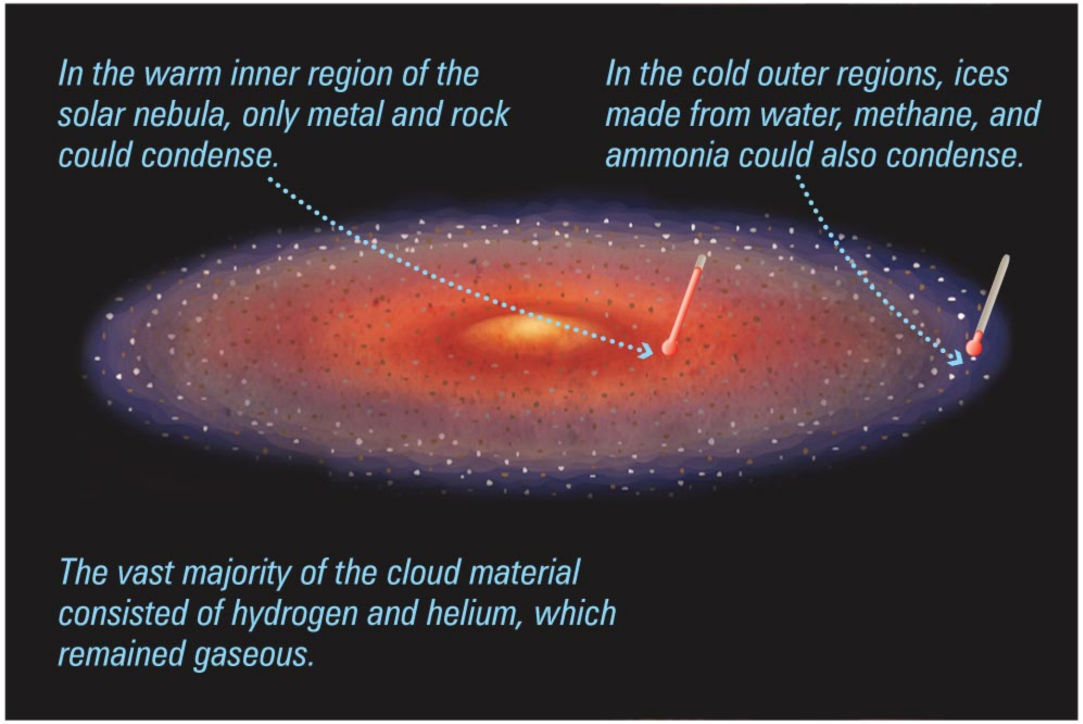


TABLE 3.1 *Materials in the Solar Nebula*

A summary of the four types of materials present in the solar nebula. The squares in the final column represent the relative proportions of each type (by mass).

	Examples	Typical Condensation Temperature	Relative Abundance (by mass)
Hydrogen and Helium Gas 	hydrogen, helium in nebula	do not condense	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%

The snowline was between Mars and Jupiter when the planets formed



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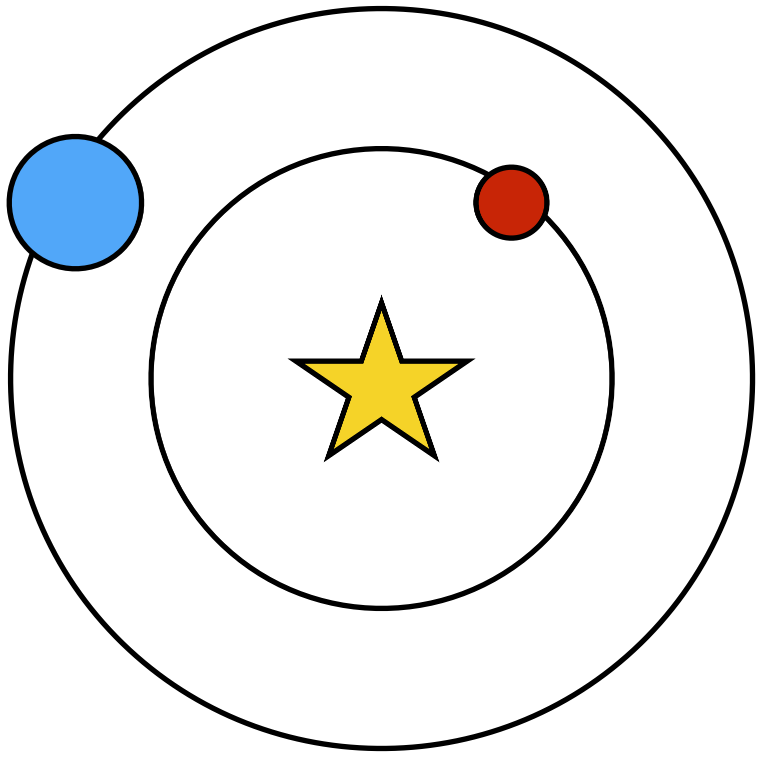
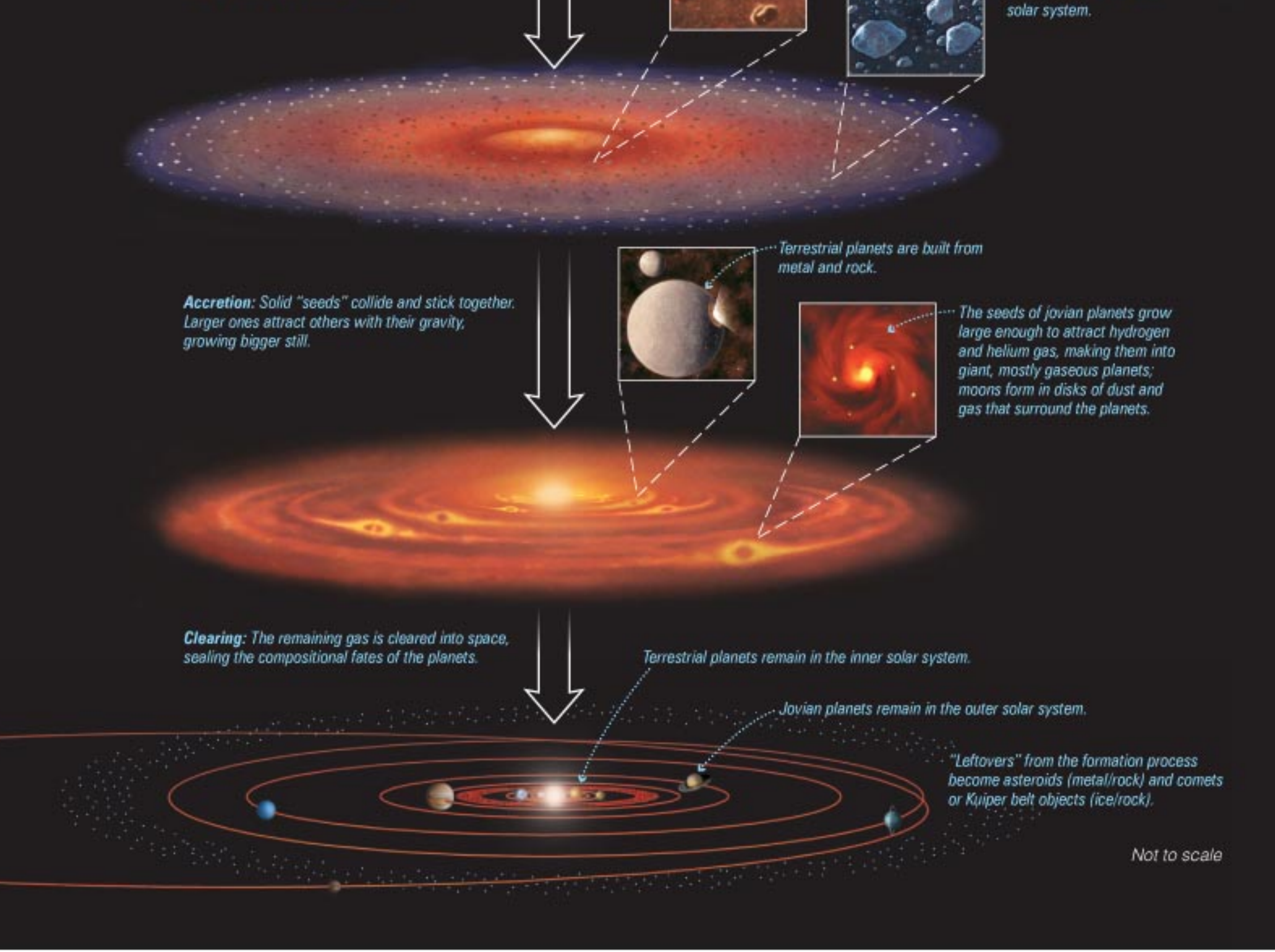
Giant planets form first

Beyond the snow line there is more mass:
the growth of planetary cores (of giant planets) is faster

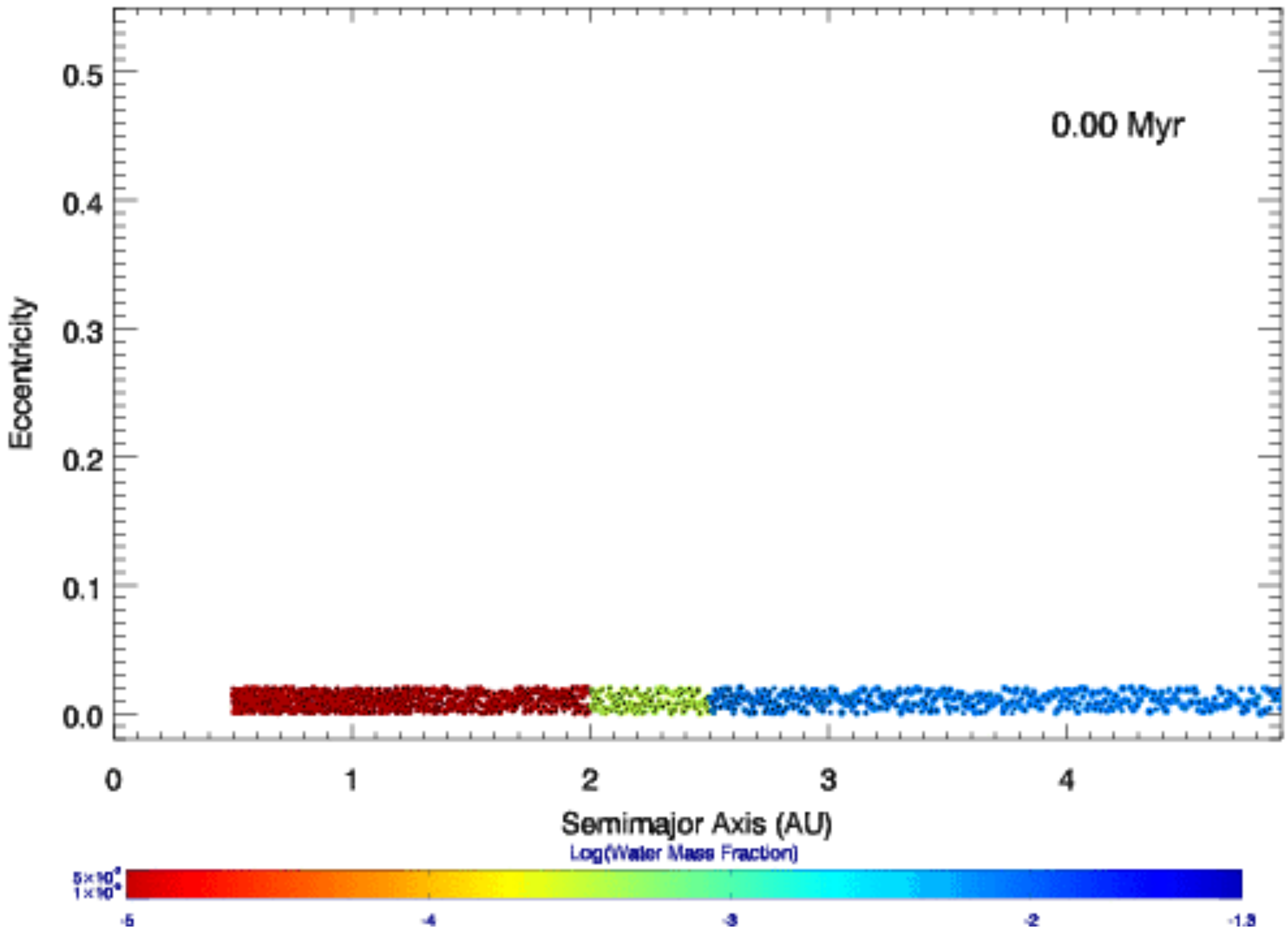


Why is there water on Earth?

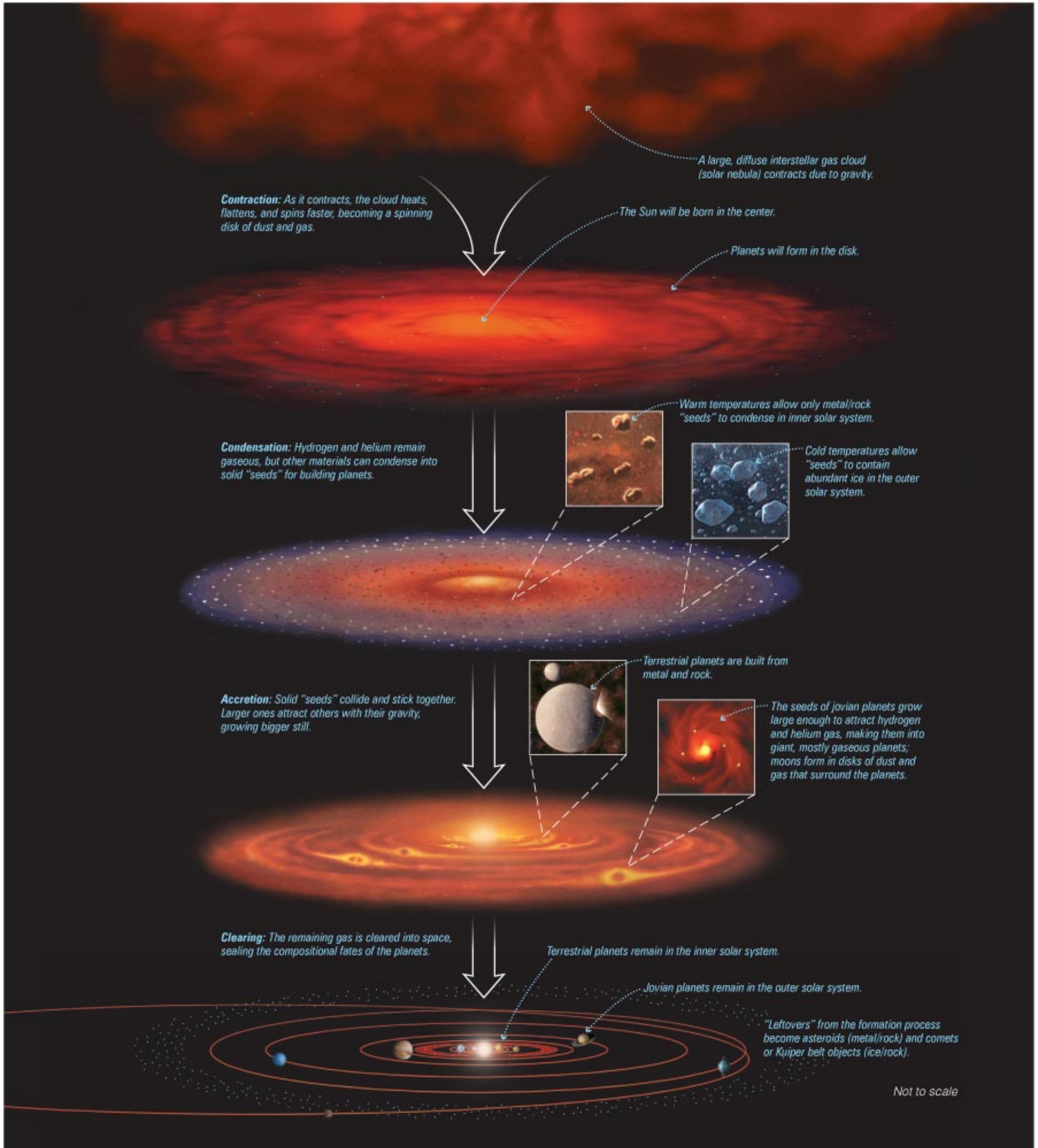

solar system.
Terrestrial planets are built from metal and rock.
Accretion: Solid "seeds" collide and stick together. Larger ones attract others with their gravity, growing bigger still.
The seeds of jovian planets grow large enough to attract hydrogen and helium gas, making them into giant, mostly gaseous planets; moons form in disks of dust and gas that surround the planets.
Clearing: The remaining gas is cleared into space, sealing the compositional fates of the planets.
Terrestrial planets remain in the inner solar system.
Jovian planets remain in the outer solar system.
"Leftovers" from the formation process become asteroids (metal/rock) and comets or Kuiper belt objects (ice/rock).
Not to scale

Growth from km-sized rocks to planets

(mixing of inner and outer planetesimals)



from S. Raymond



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The Solar Nebula Theory

from micron-sized grains

↓

planetesimals (~km)

↓

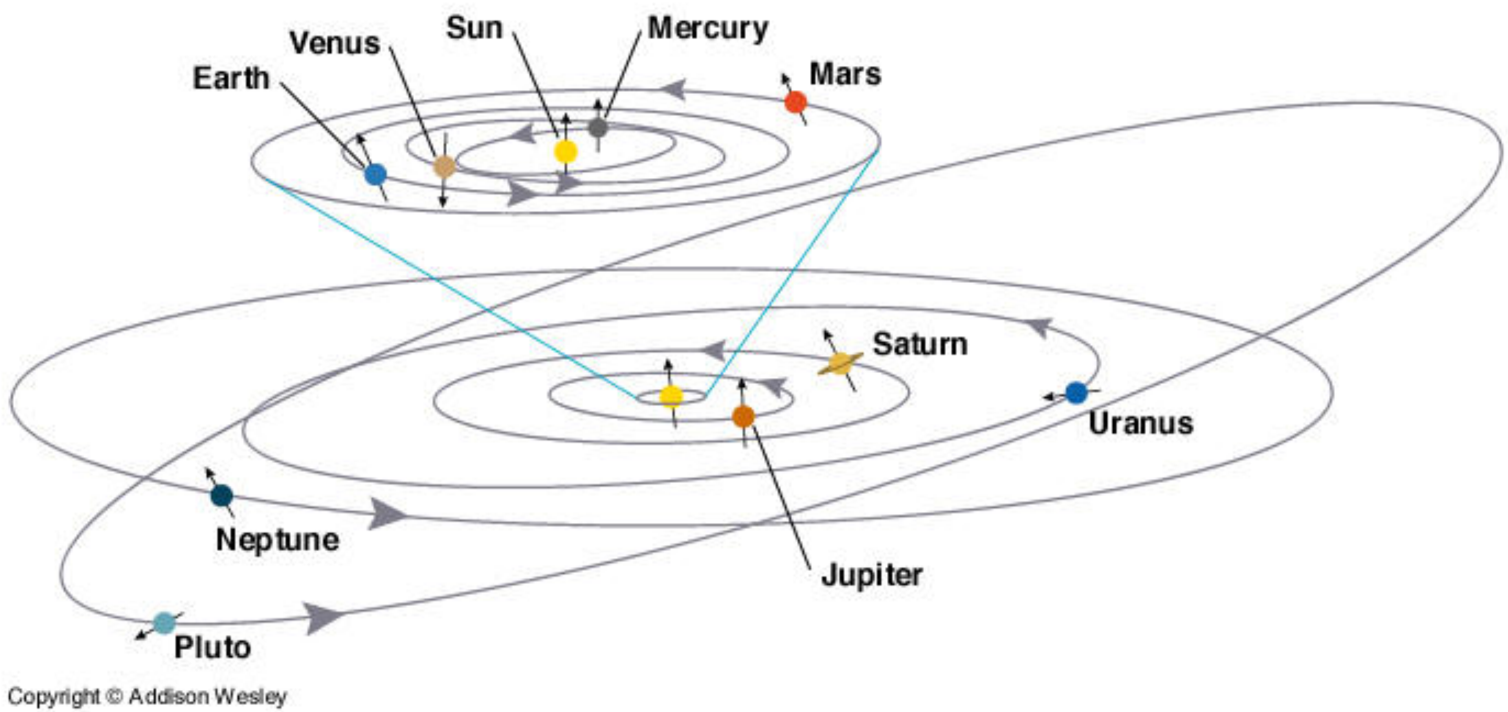
planets

The Solar Nebula Theory vs Observations

Spinning, flattening ➔ circumstellar disk explains:

– Planets orbit in the same plane (almost circular orbits)

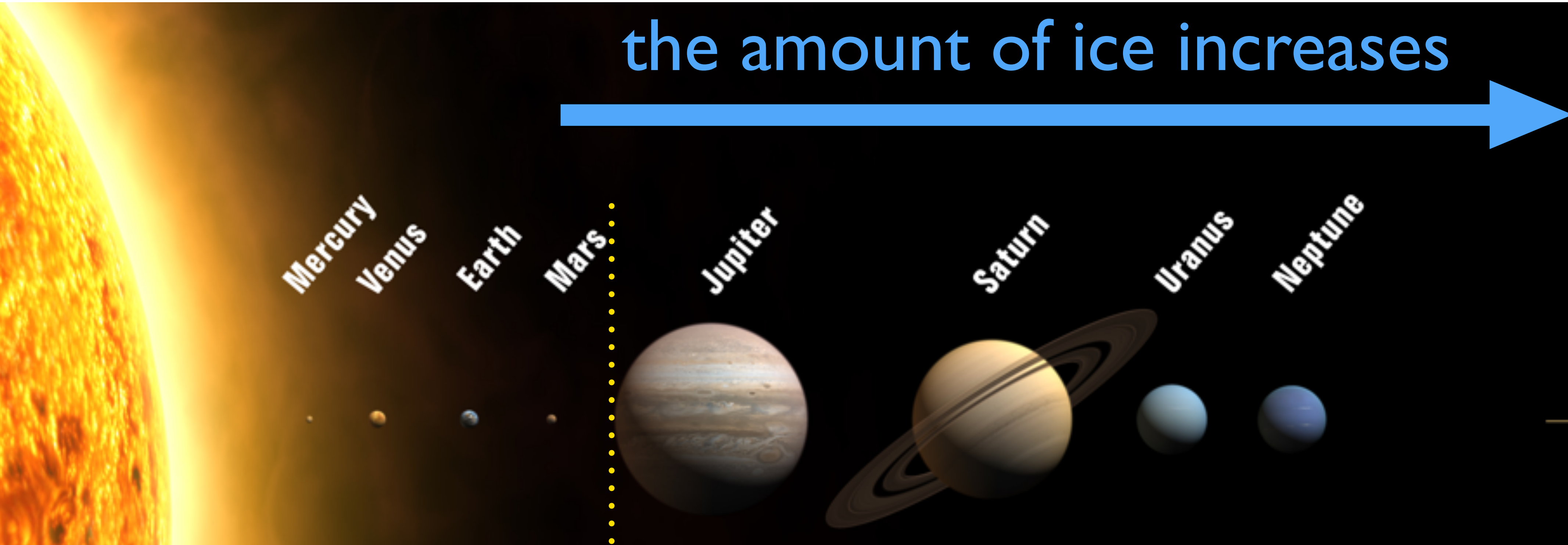
– Planets orbit & rotate in same direction

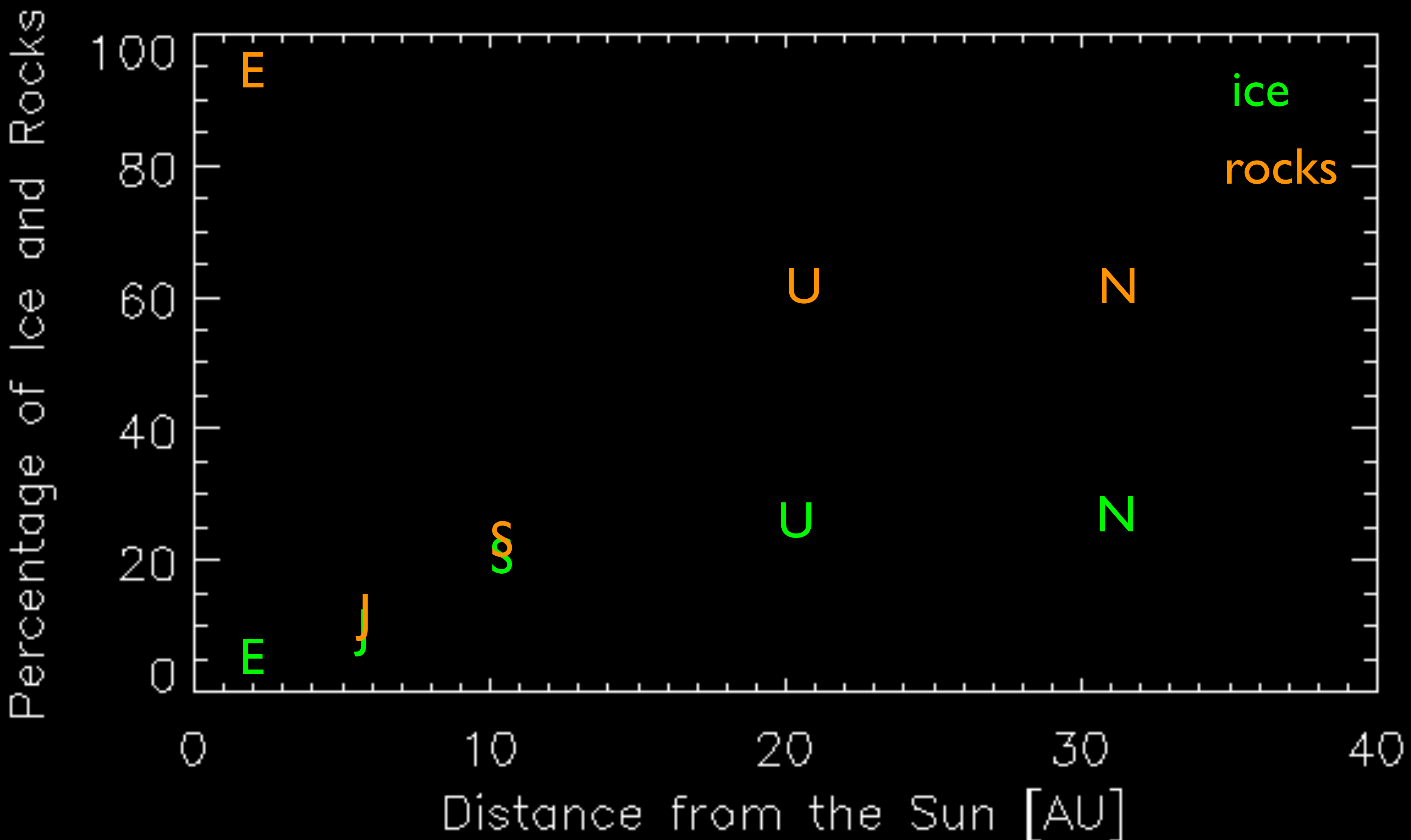


The Solar Nebula Theory vs Observations

Temperature gradient in the disk explains:

– Different composition of close-in vs further out planets in the solar system

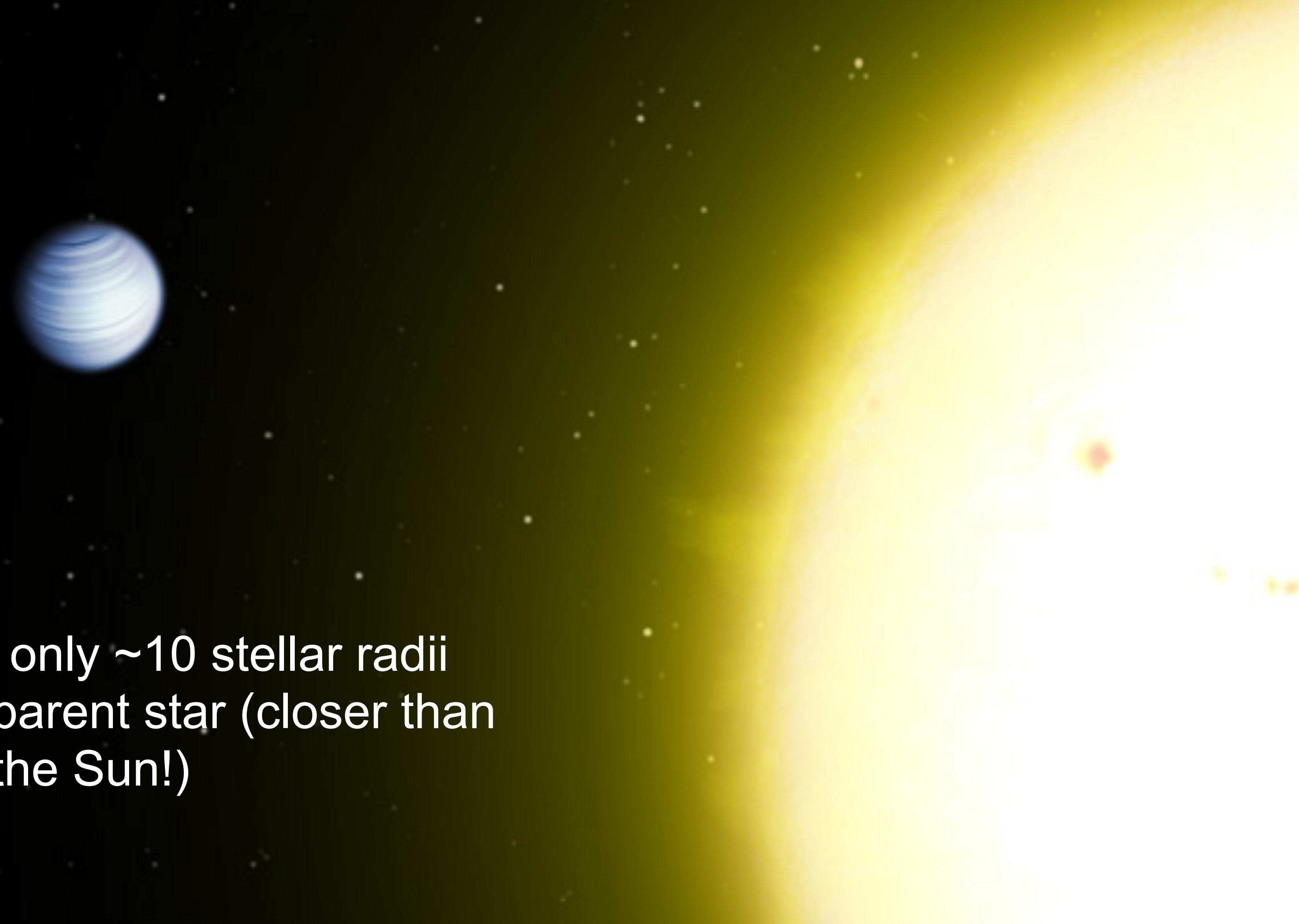



Percentage of Ice and Rocks
100
80
60
40
20
0
0
10
20
30
40
Distance from the Sun [AU]
ice
rocks
E
E
J
J
S
S
U
U
N
N

Strange new worlds

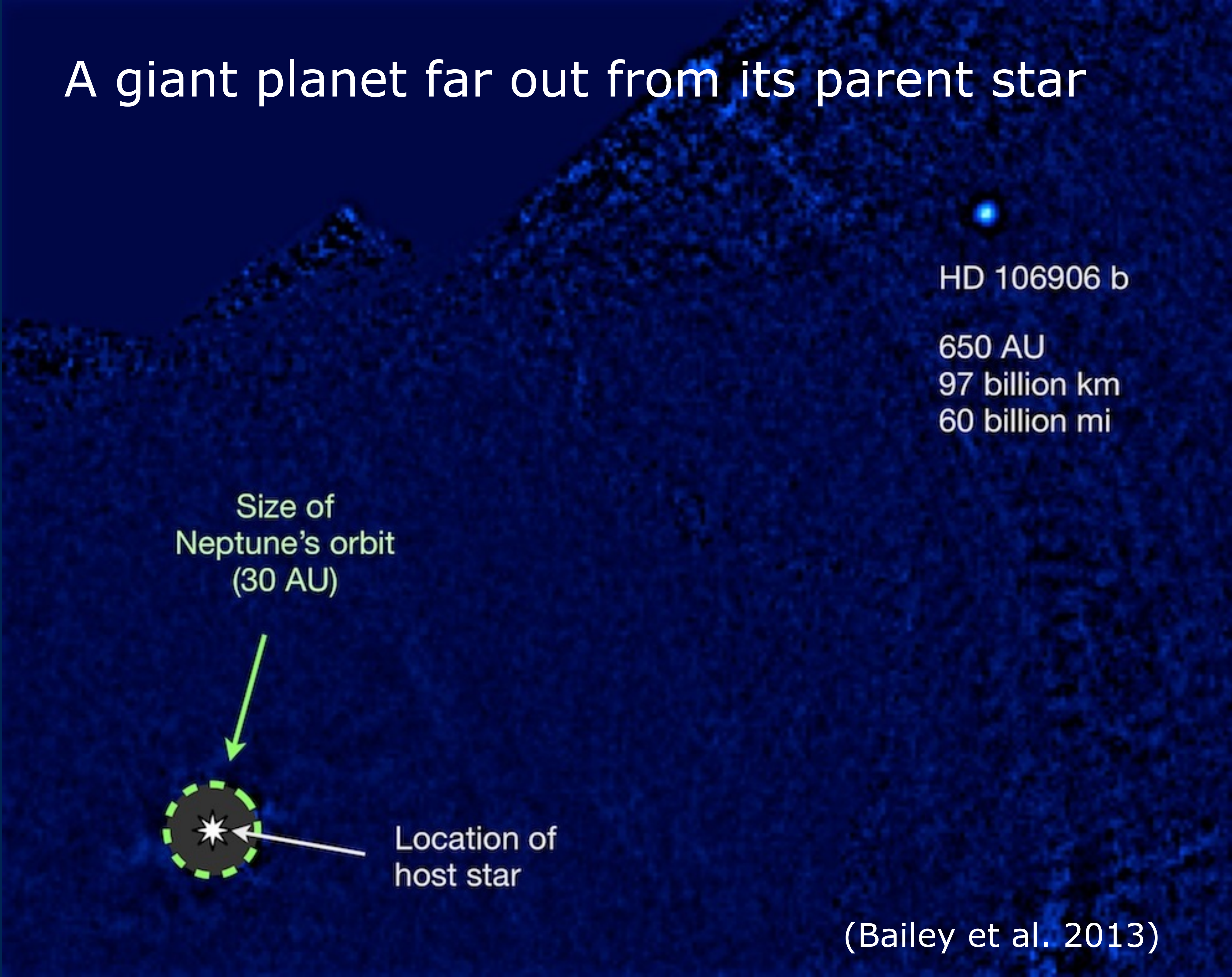
51Pegb: the first exoplanet is a Hot Jupiter

(Mayor & Queloz 1995)



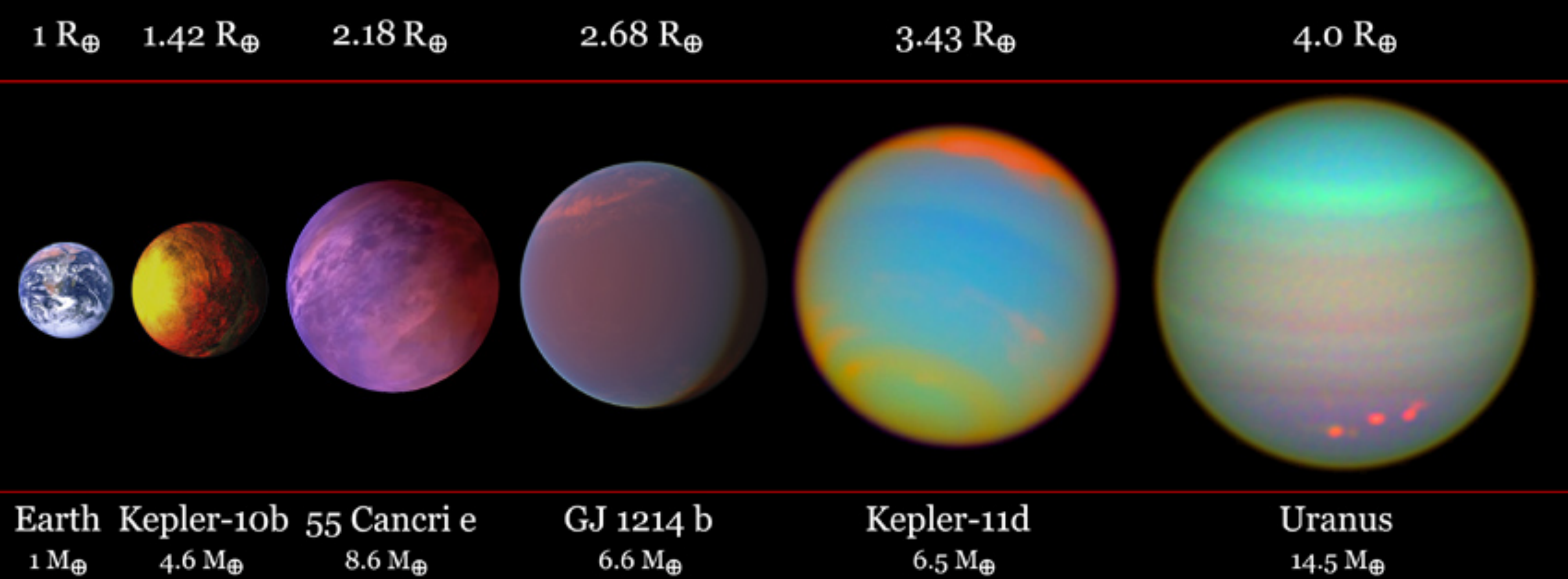
51 Pegasi b is only ~10 stellar radii away from its parent star (closer than Mercury from the Sun!)

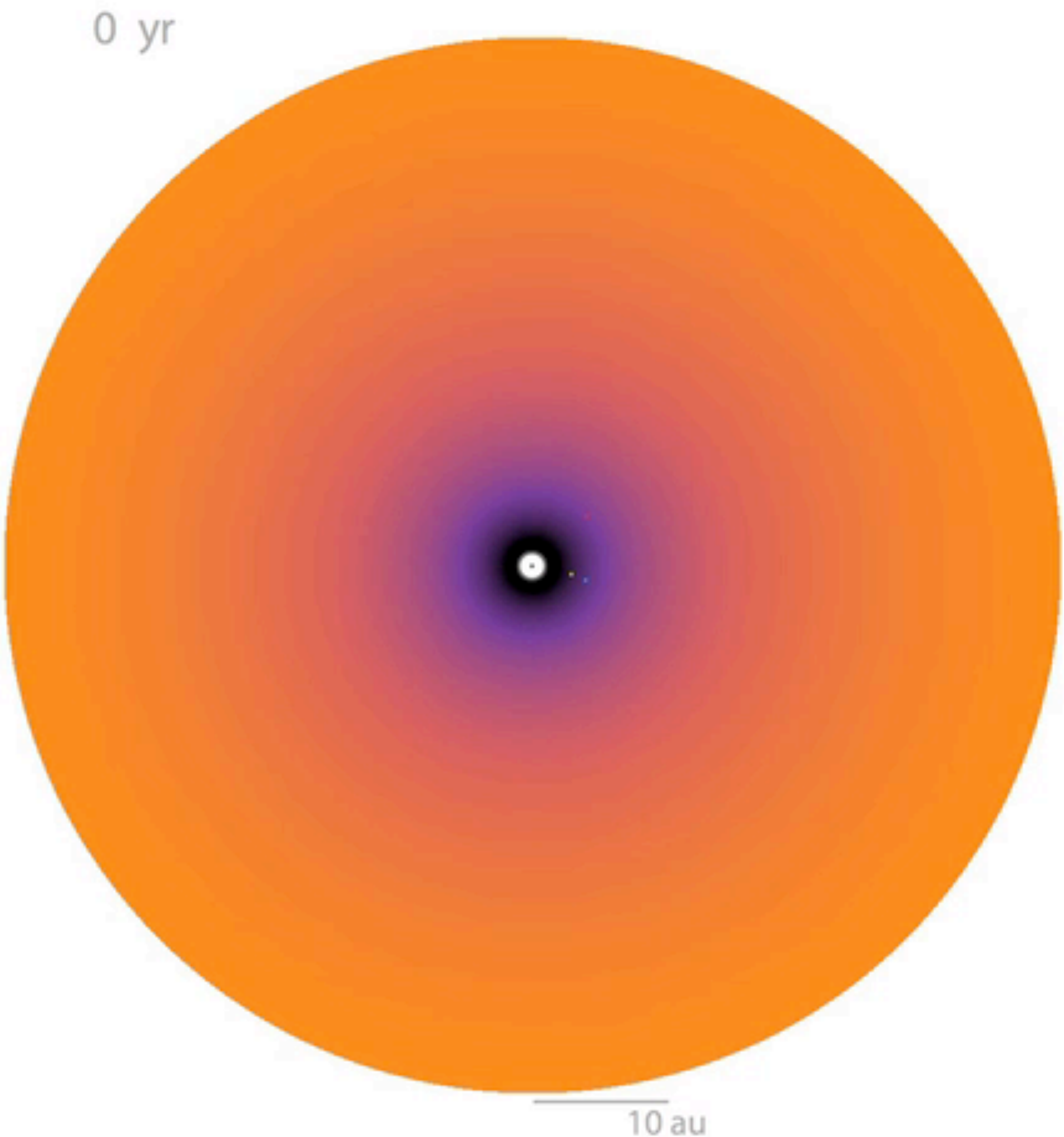
A giant planet far out from its parent star



(Bailey et al. 2013)

Super Earths: what is their composition?

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