A night sky filled with stars over a snowy mountain range. The stars are bright and numerous, creating a dense field of light. The mountains are covered in snow and are dark against the bright sky. The overall scene is a beautiful representation of a winter night in a high-altitude environment.

# Worlds with water: are most habitable planets wet or dry?

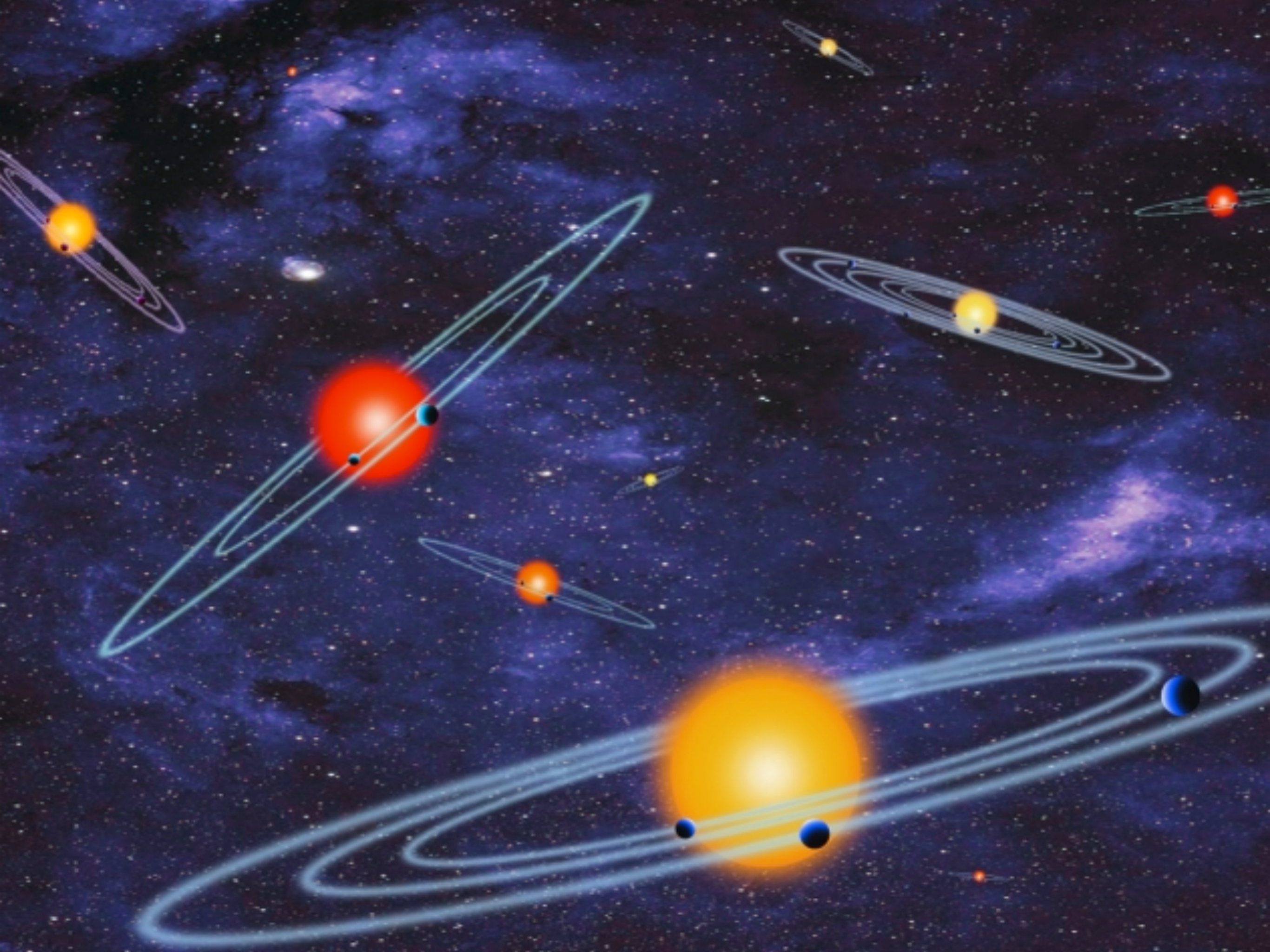
Sean Raymond  
Laboratoire d'Astrophysique de Bordeaux, France

[planetplanet.net](http://planetplanet.net)  
[rayray.sean@gmail.com](mailto:rayray.sean@gmail.com)











# A zoom-in to a massive star forming region

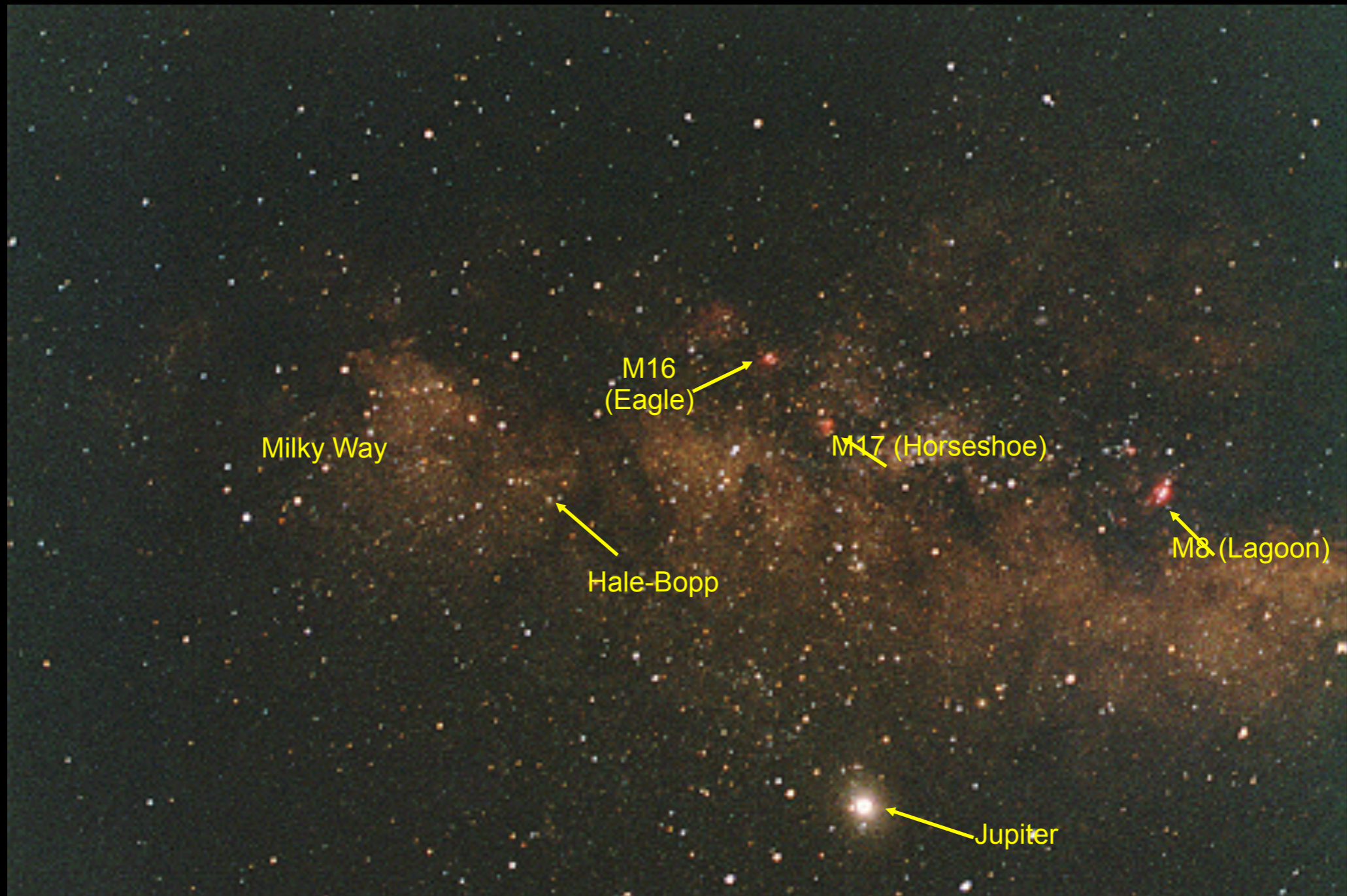


Credit: Dullemond

Picture credit: W. Keel



# A zoom-in to a massive star forming region

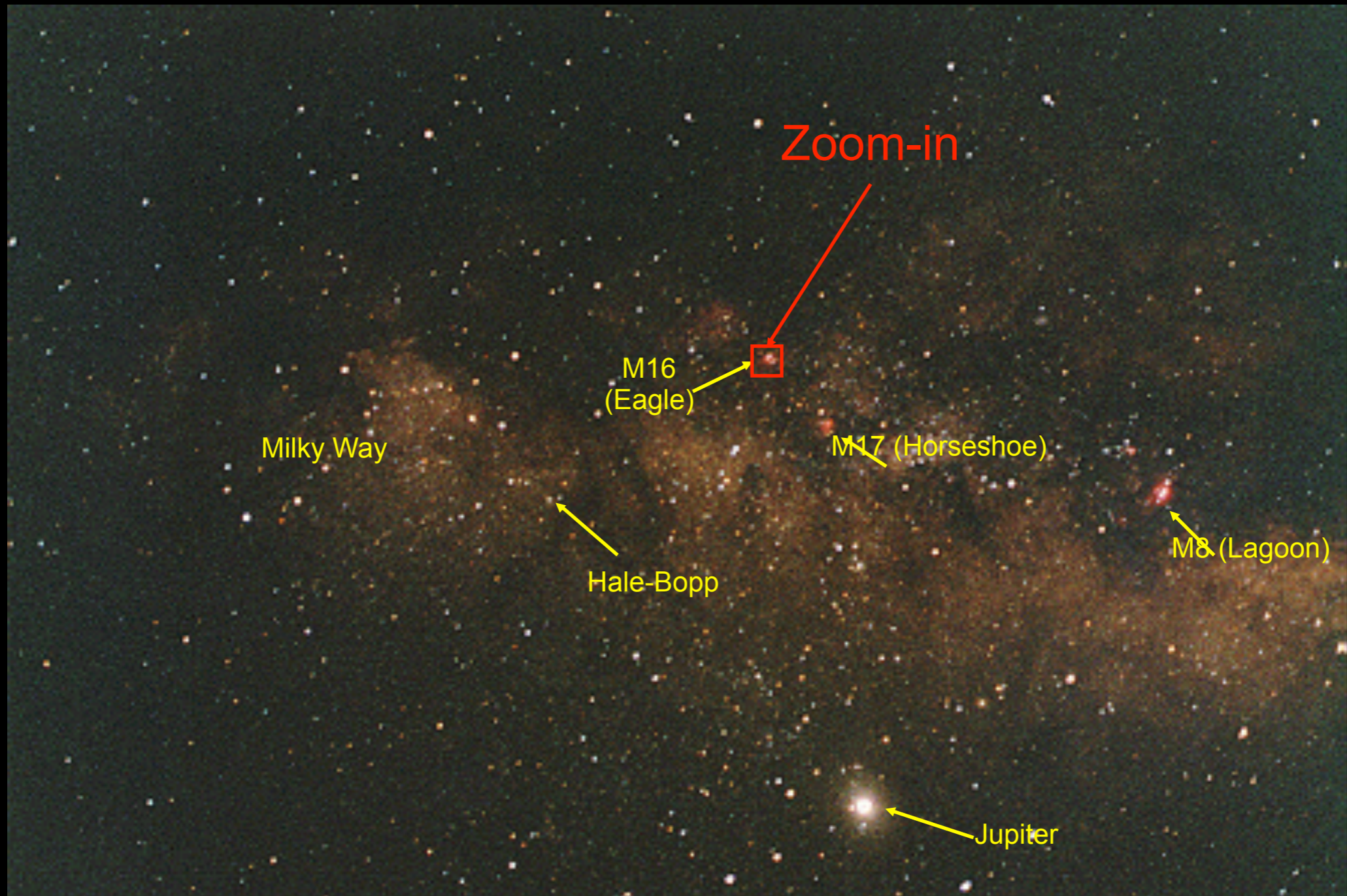


Credit: Dullemond

Picture credit: W. Keel



# A zoom-in to a massive star forming region



Credit: Dullemond

Picture credit: W. Keel



# A zoom-in to a massive star forming region



Eagle  
Nebula  
(M16)



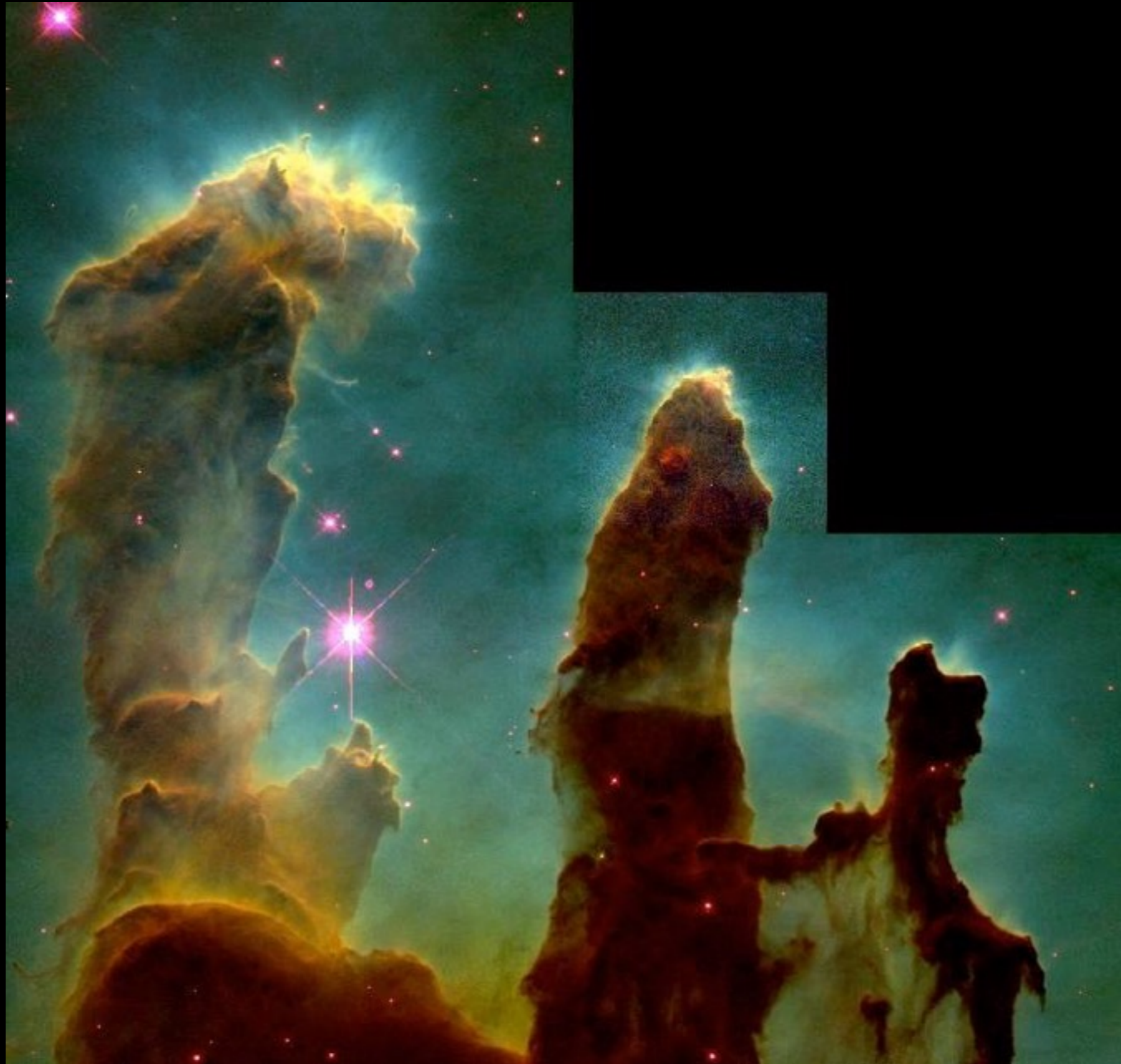
# A zoom-in to a massive star forming region



Eagle  
Nebula  
(M16)



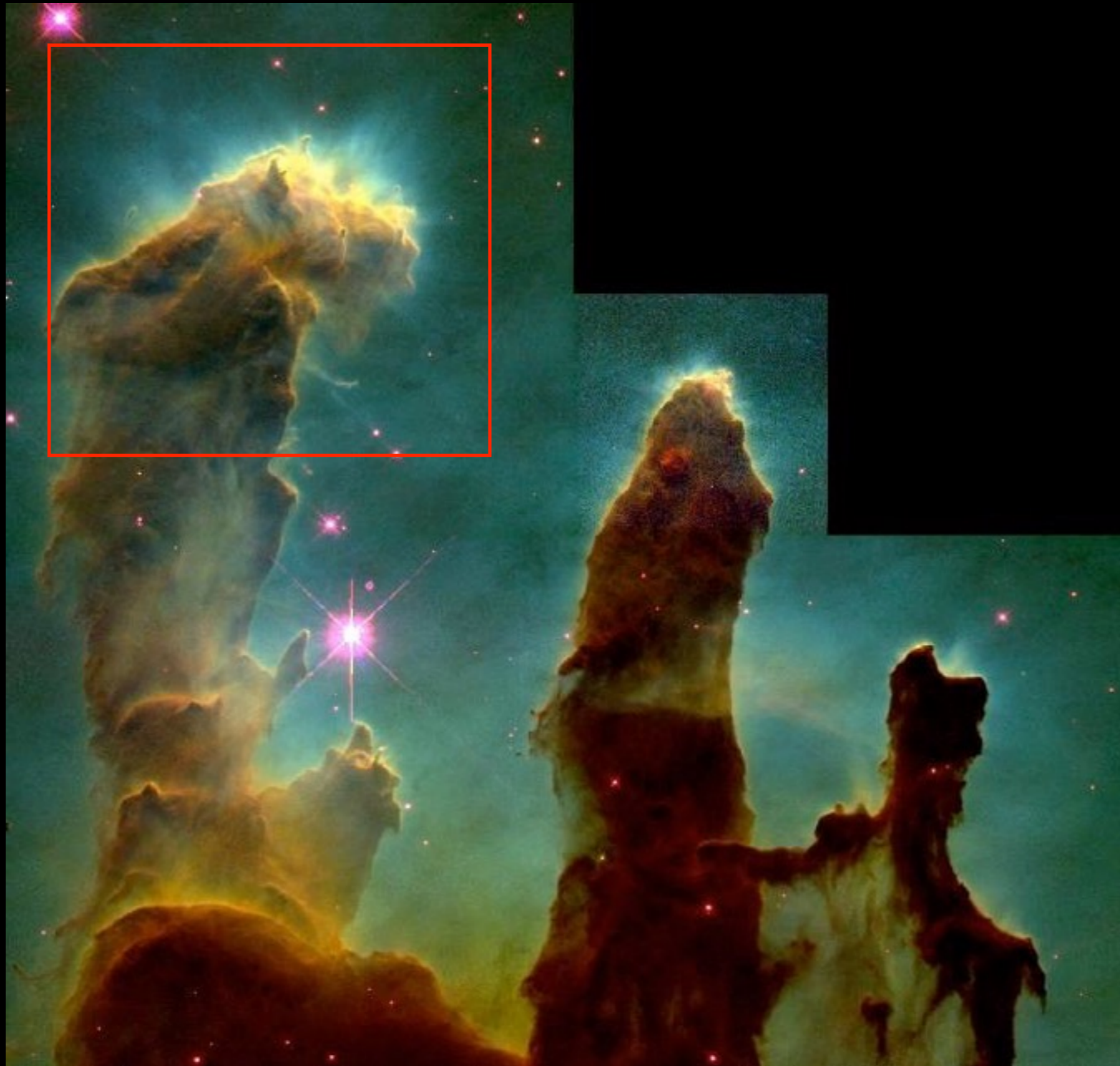
# A zoom-in to a massive star forming region



Eagle  
Nebula  
(M16)



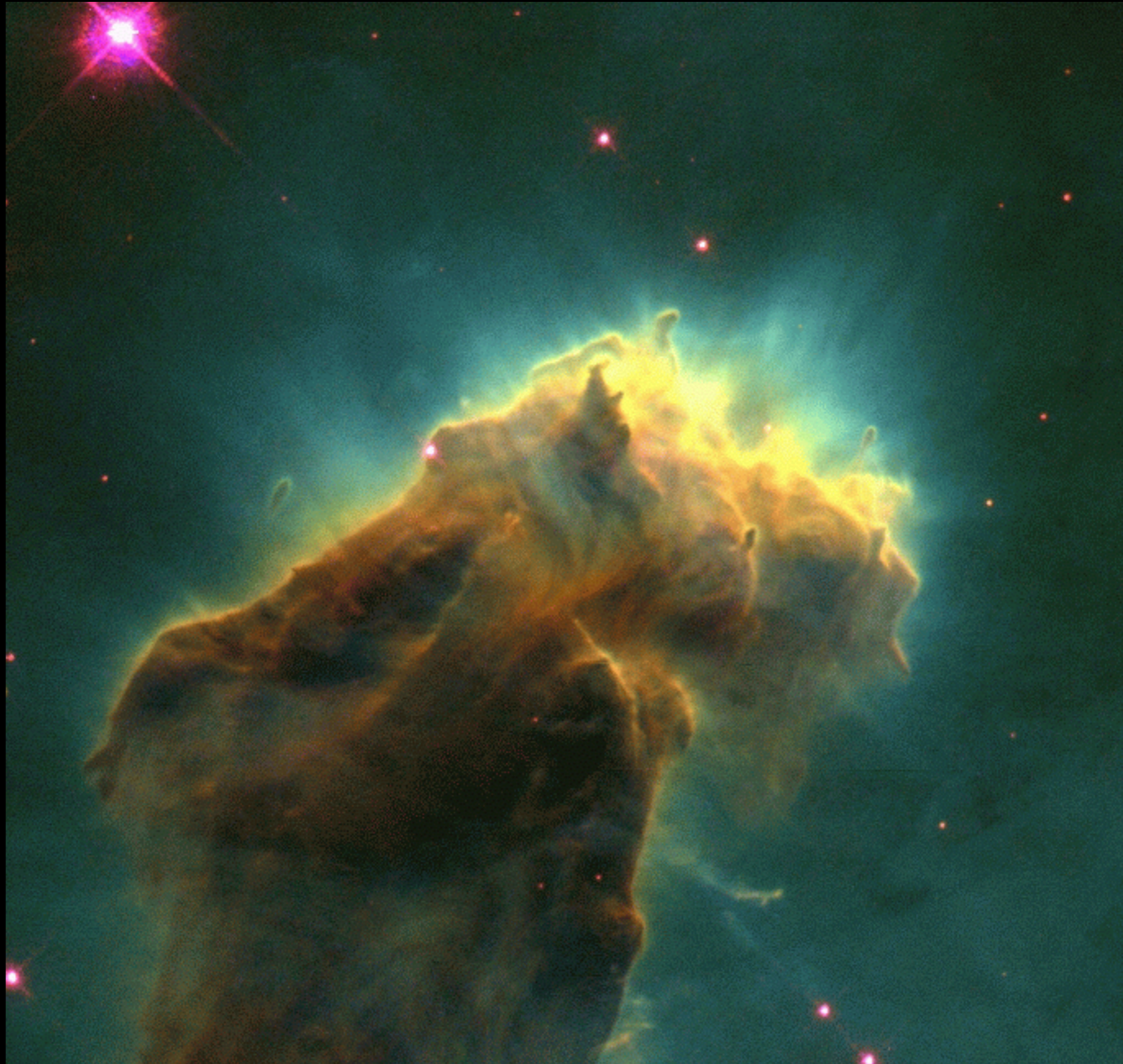
# A zoom-in to a massive star forming region



Eagle  
Nebula  
(M16)



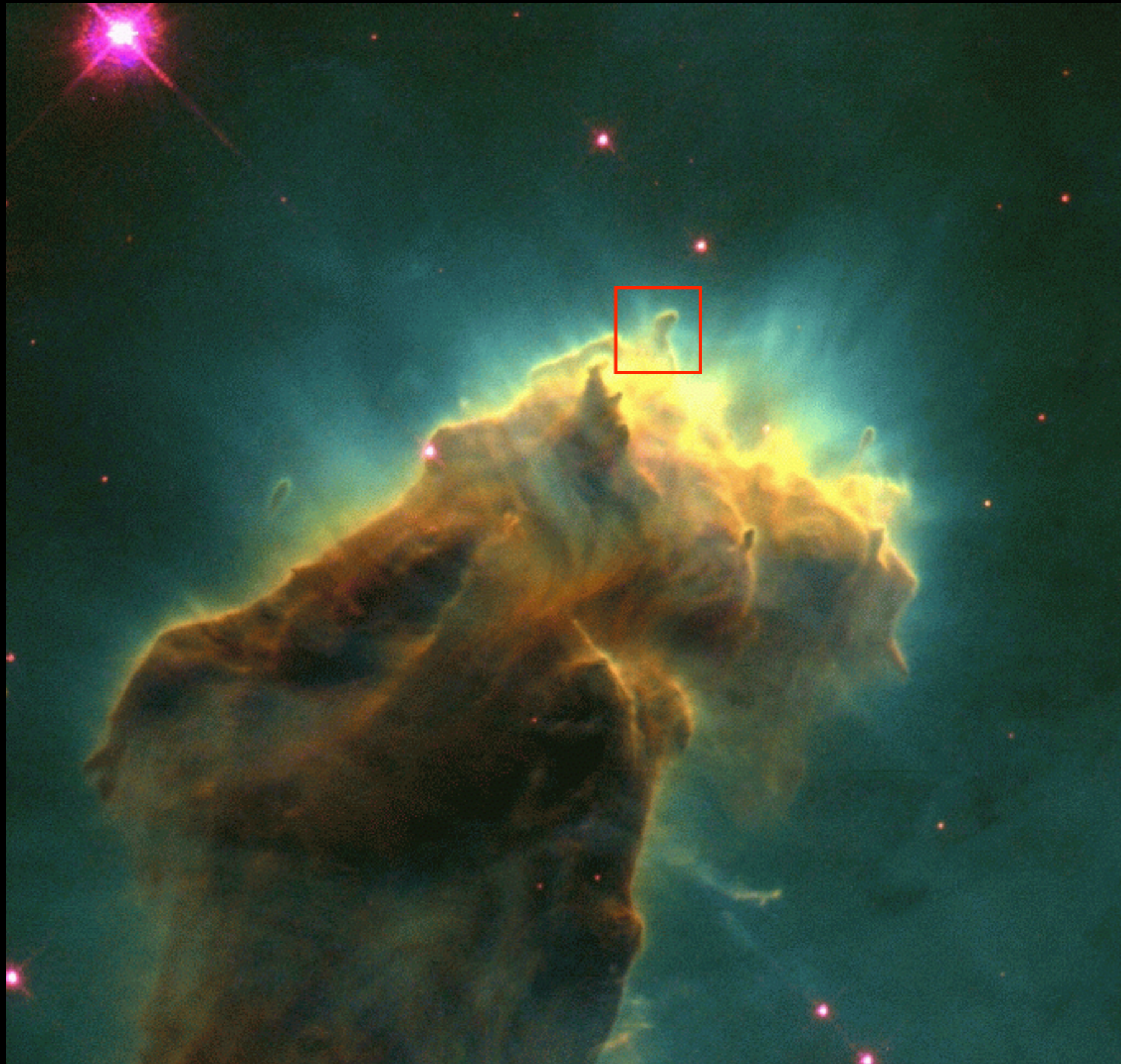
# A zoom-in to a massive star forming region



Eagle  
Nebula  
(M16)



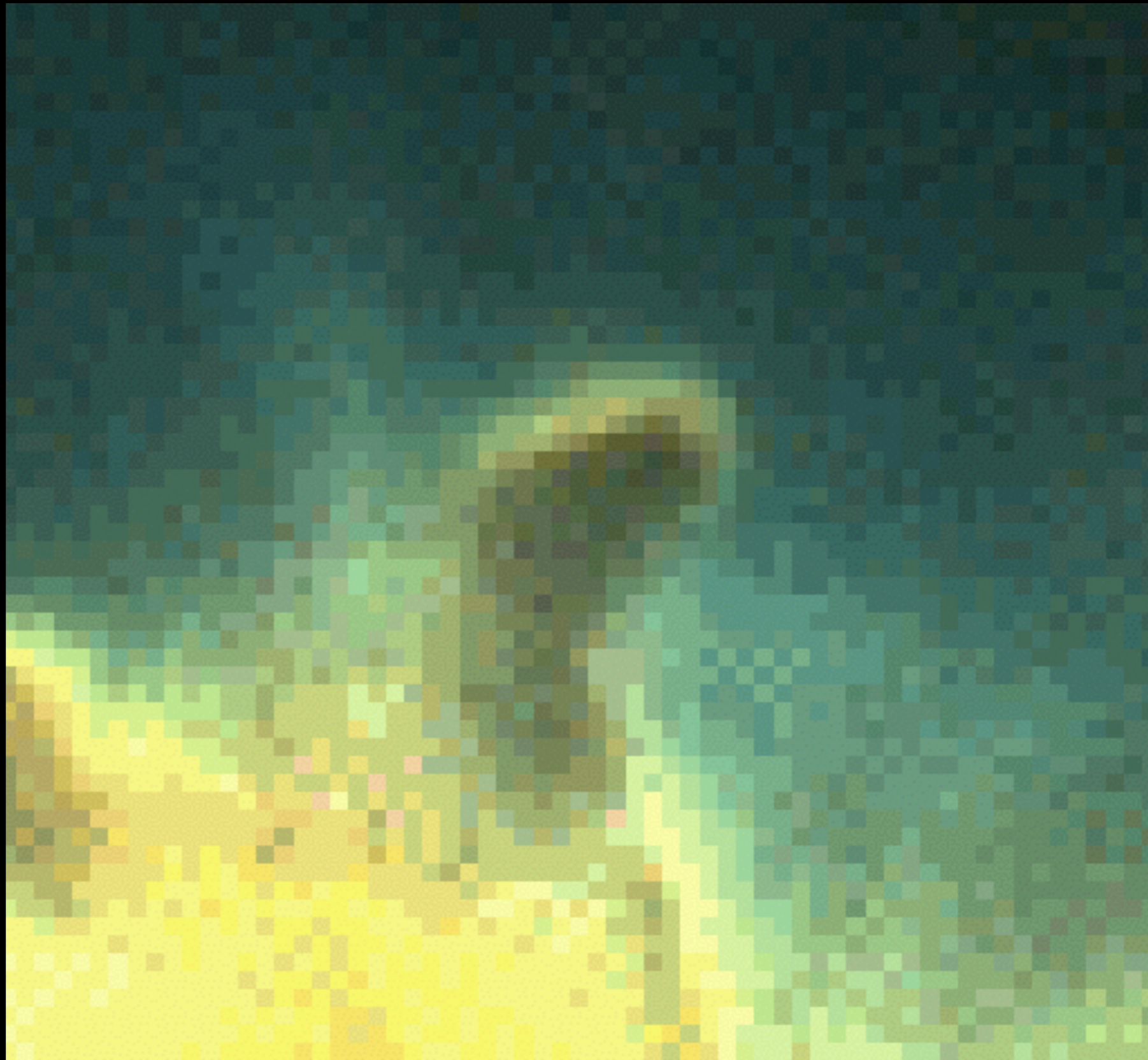
# A zoom-in to a massive star forming region



Eagle  
Nebula  
(M16)



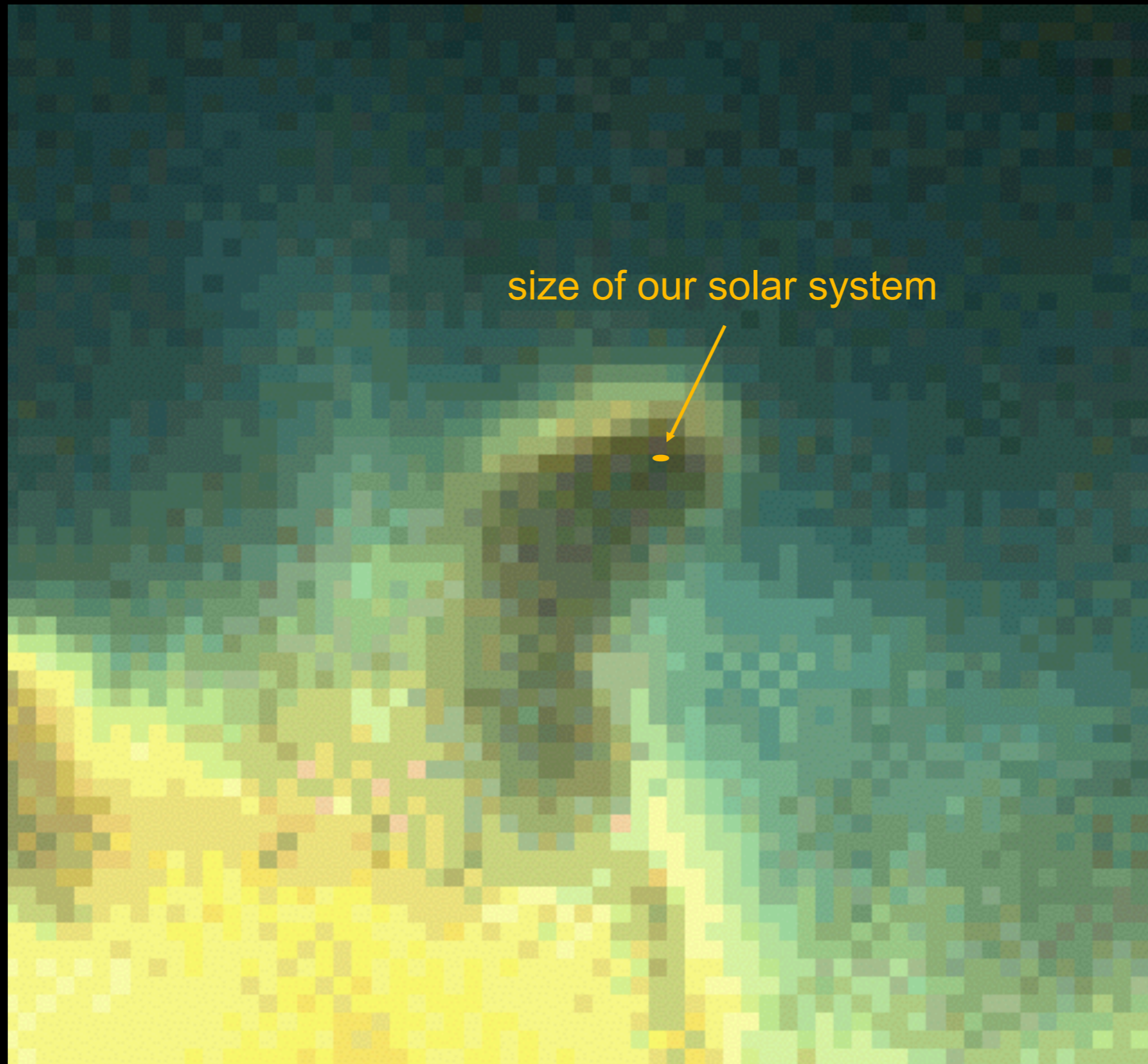
# A zoom-in to a massive star forming region



Eagle  
Nebula  
(M16)



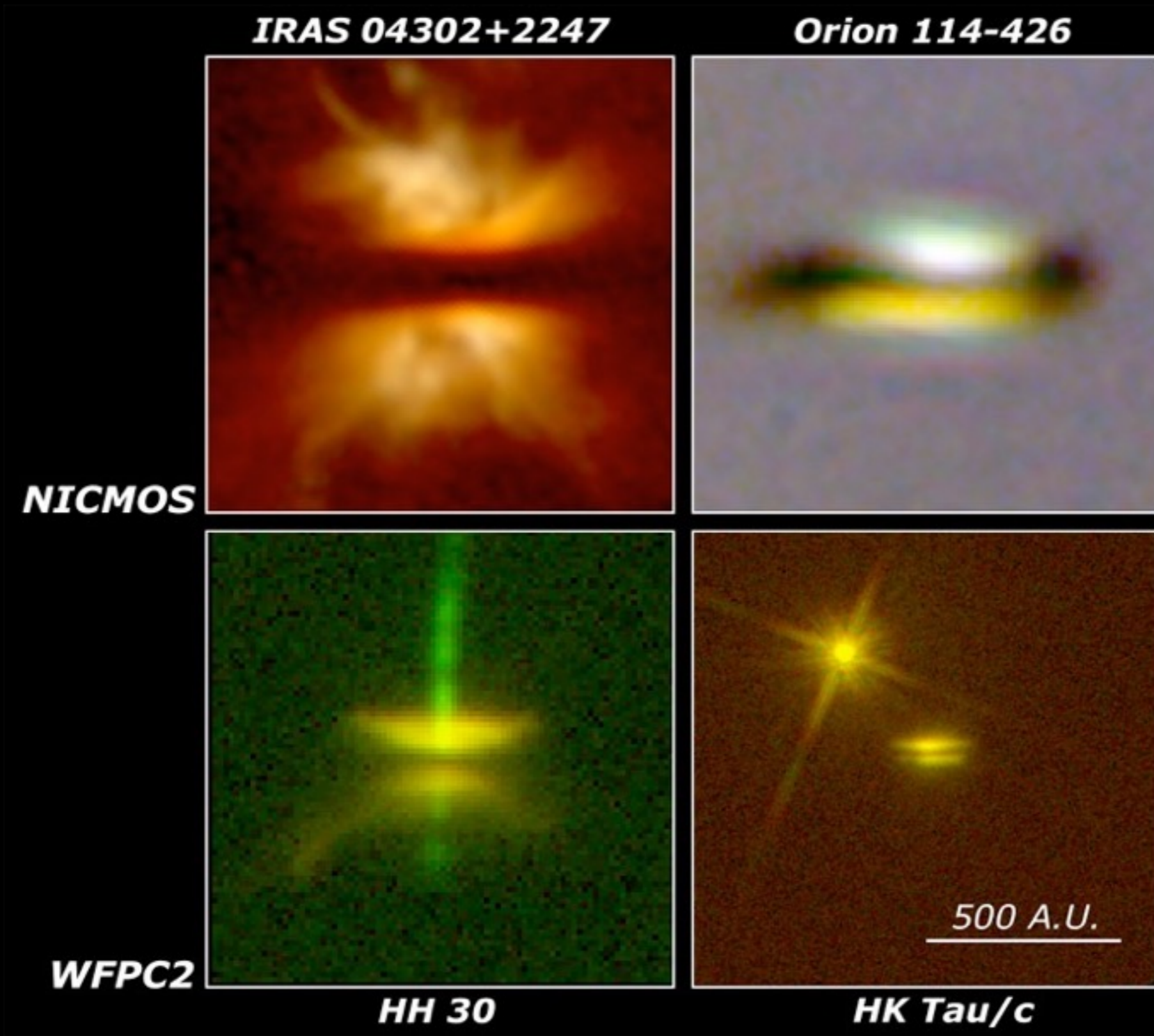
# A zoom-in to a massive star forming region



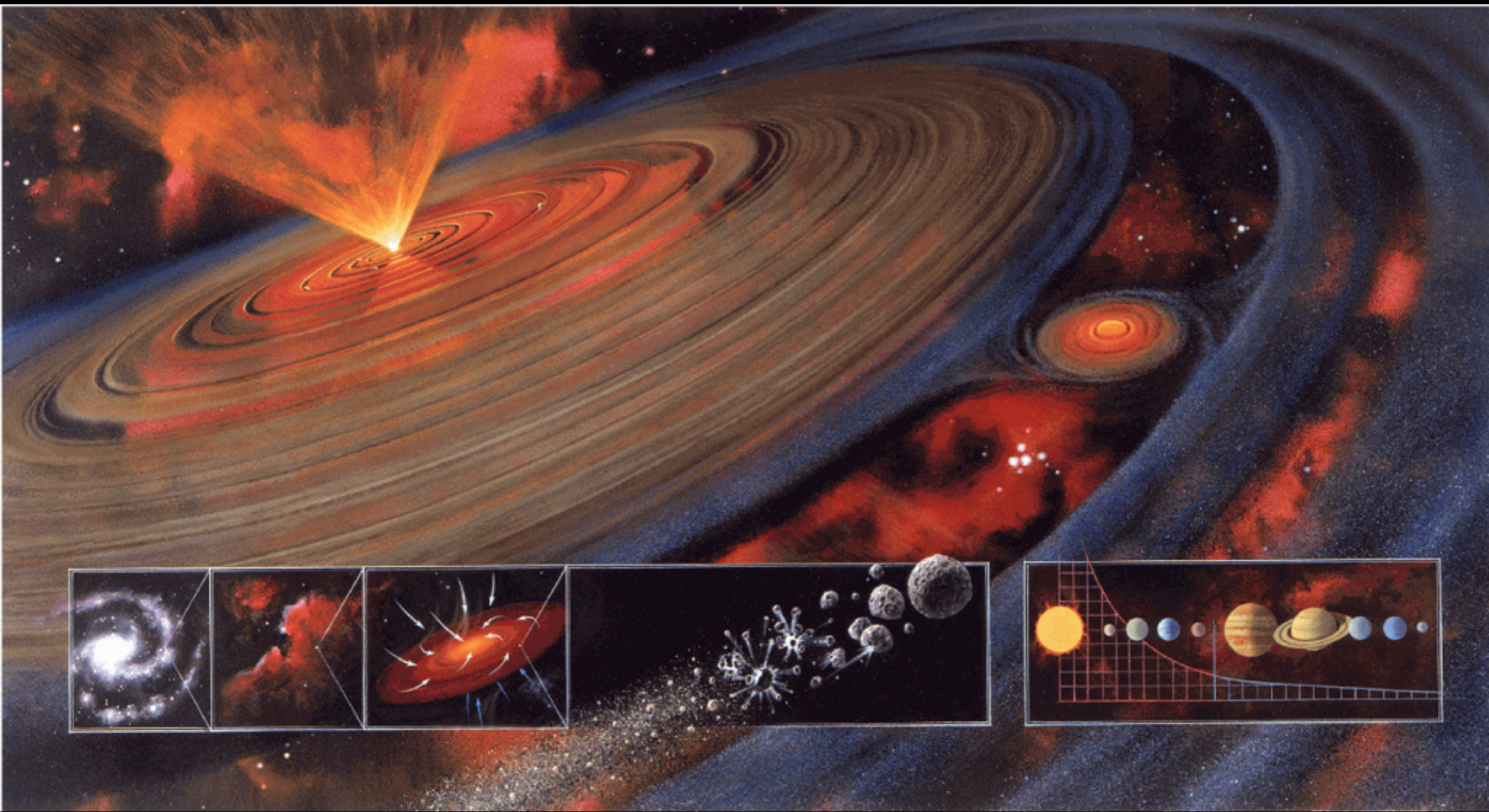
Eagle  
Nebula  
(M16)



# Disks around young stars

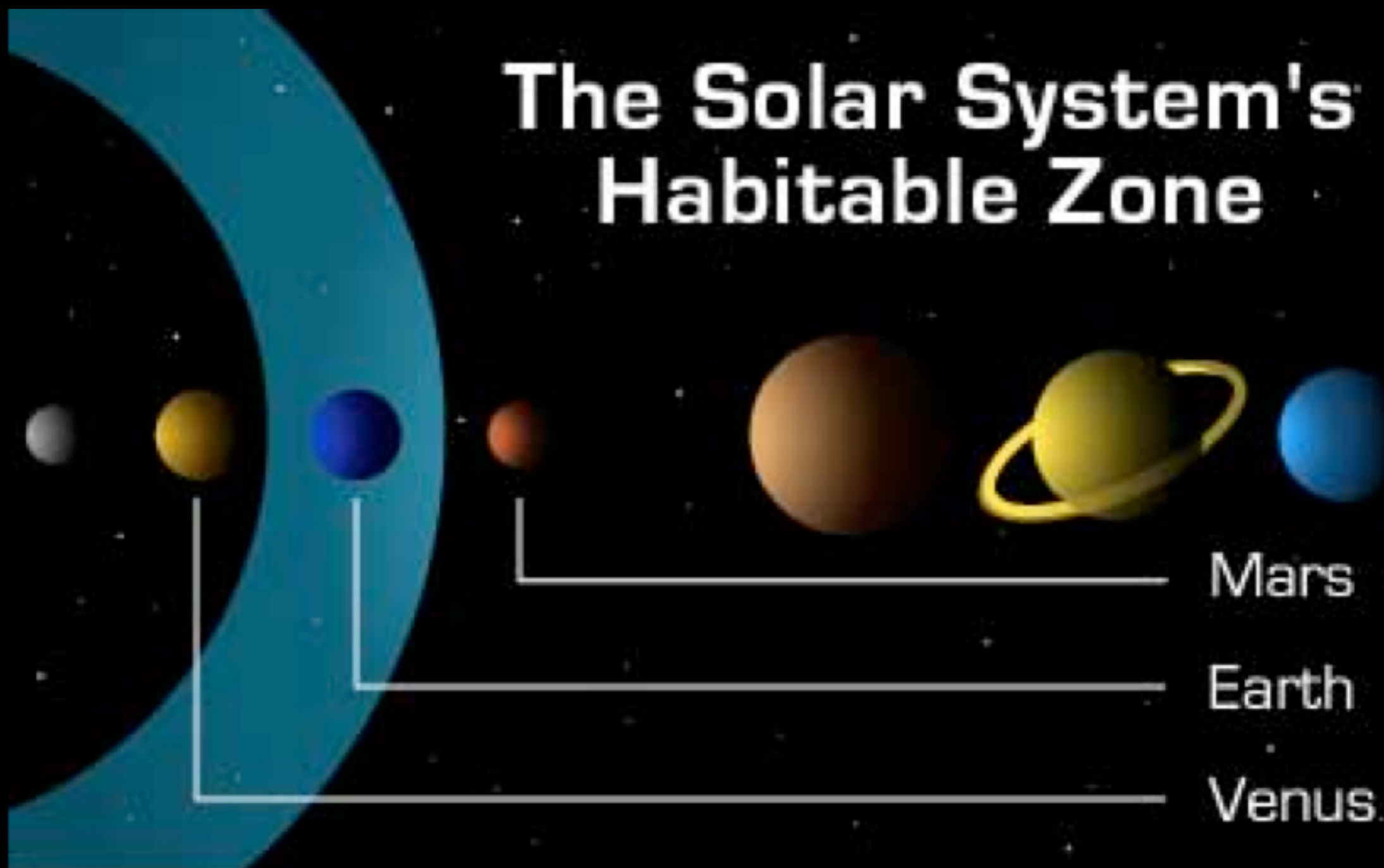






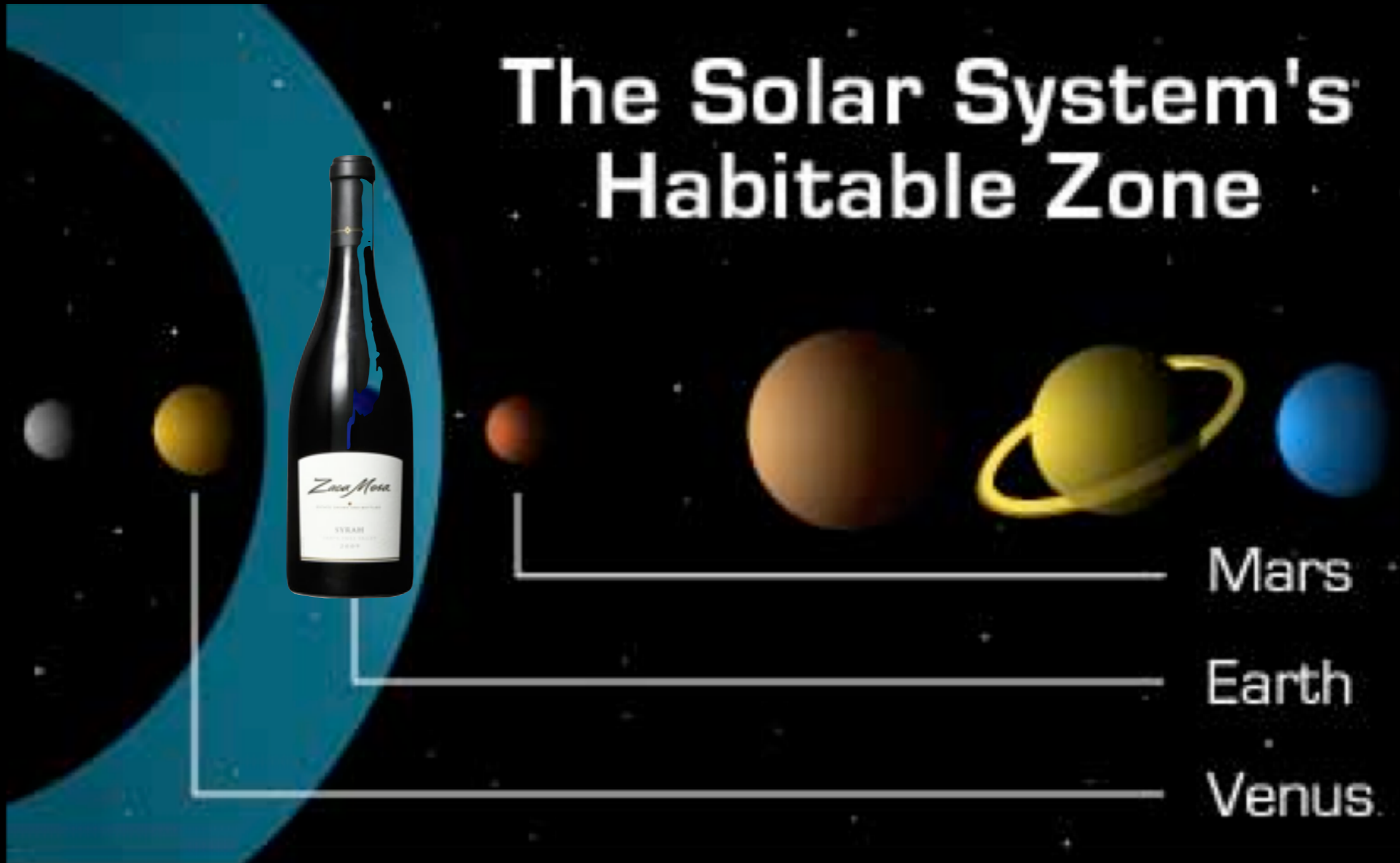


# The Solar System's Habitable Zone





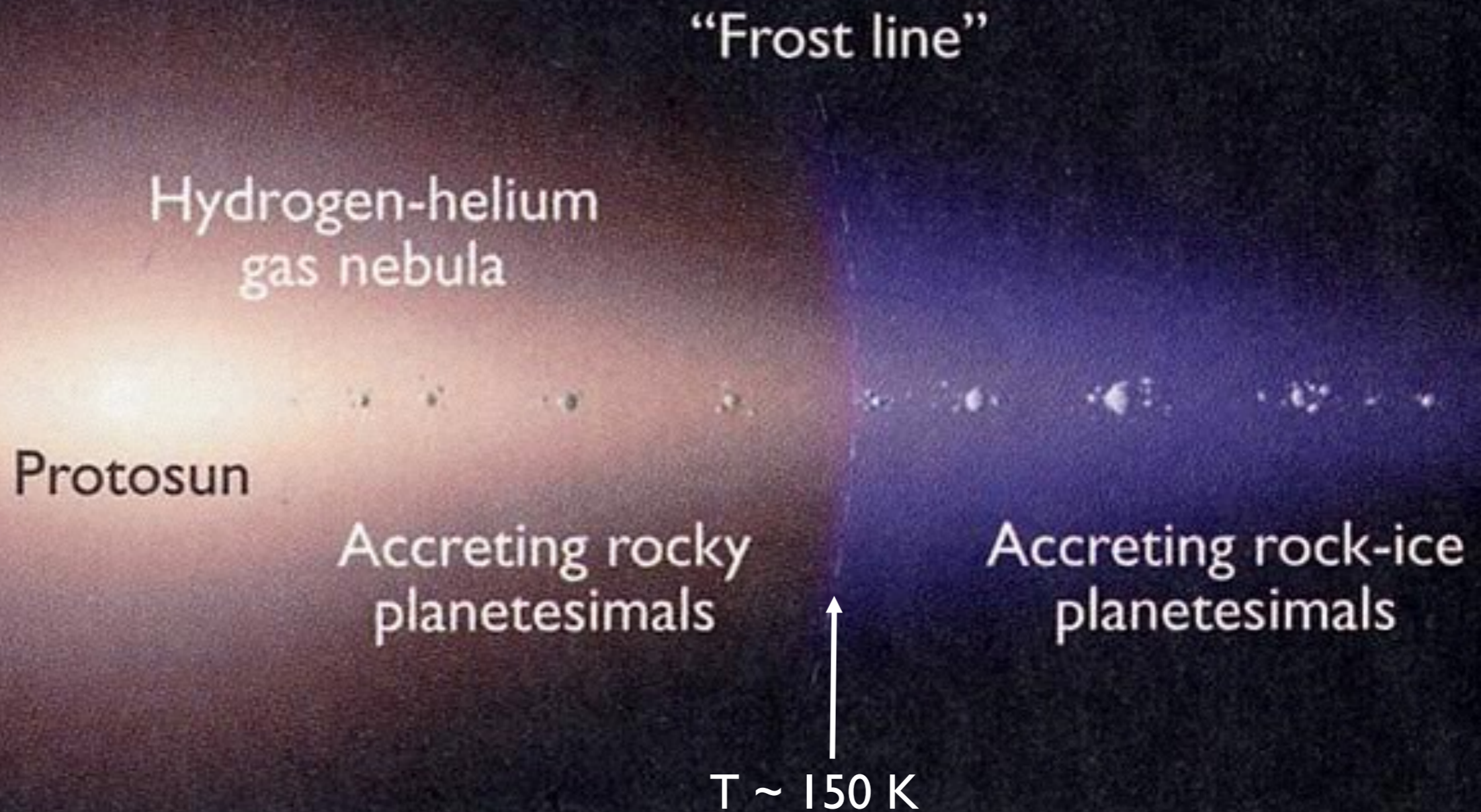
# The Solar System's Habitable Zone



Habitable planets need water!

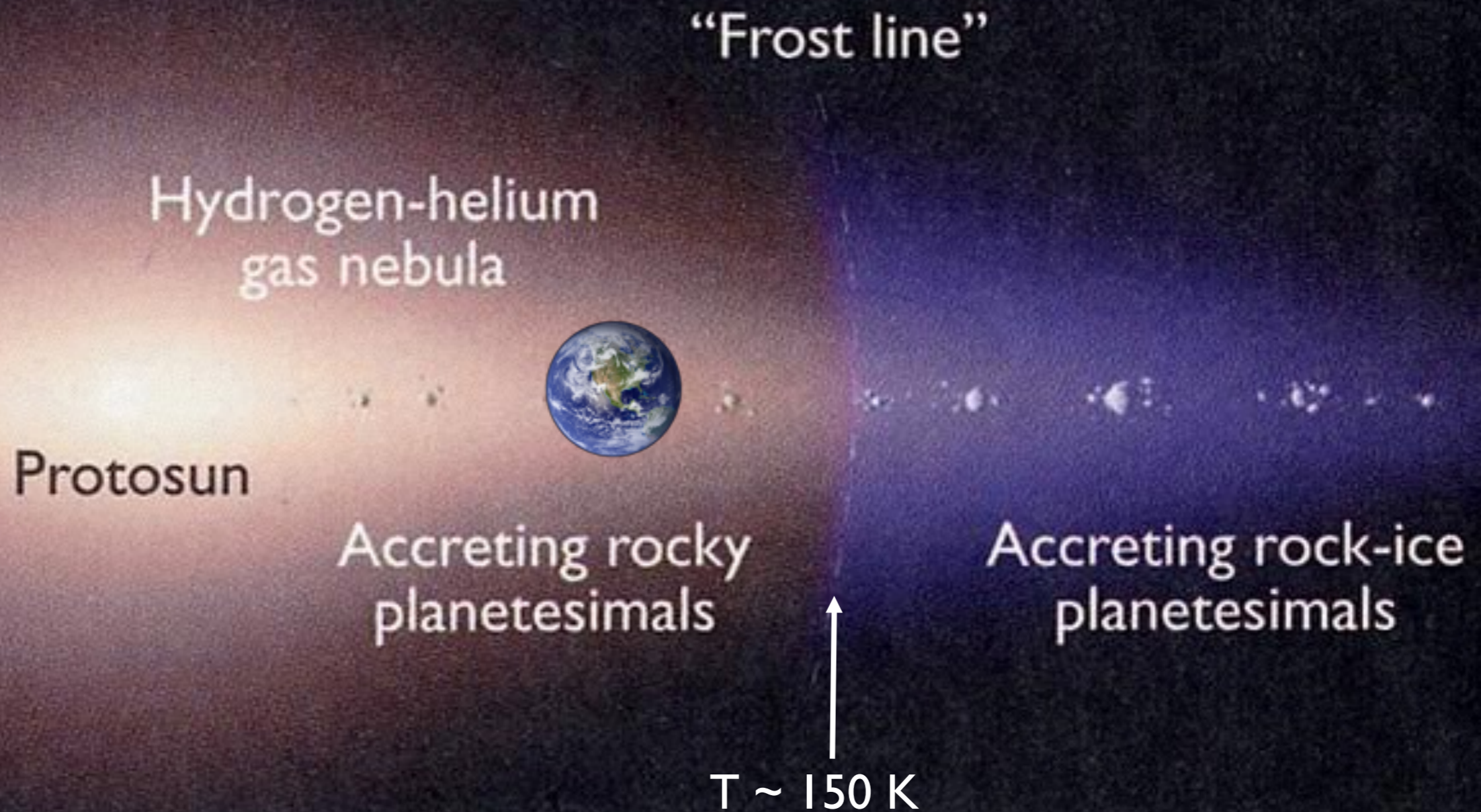


# Water delivery





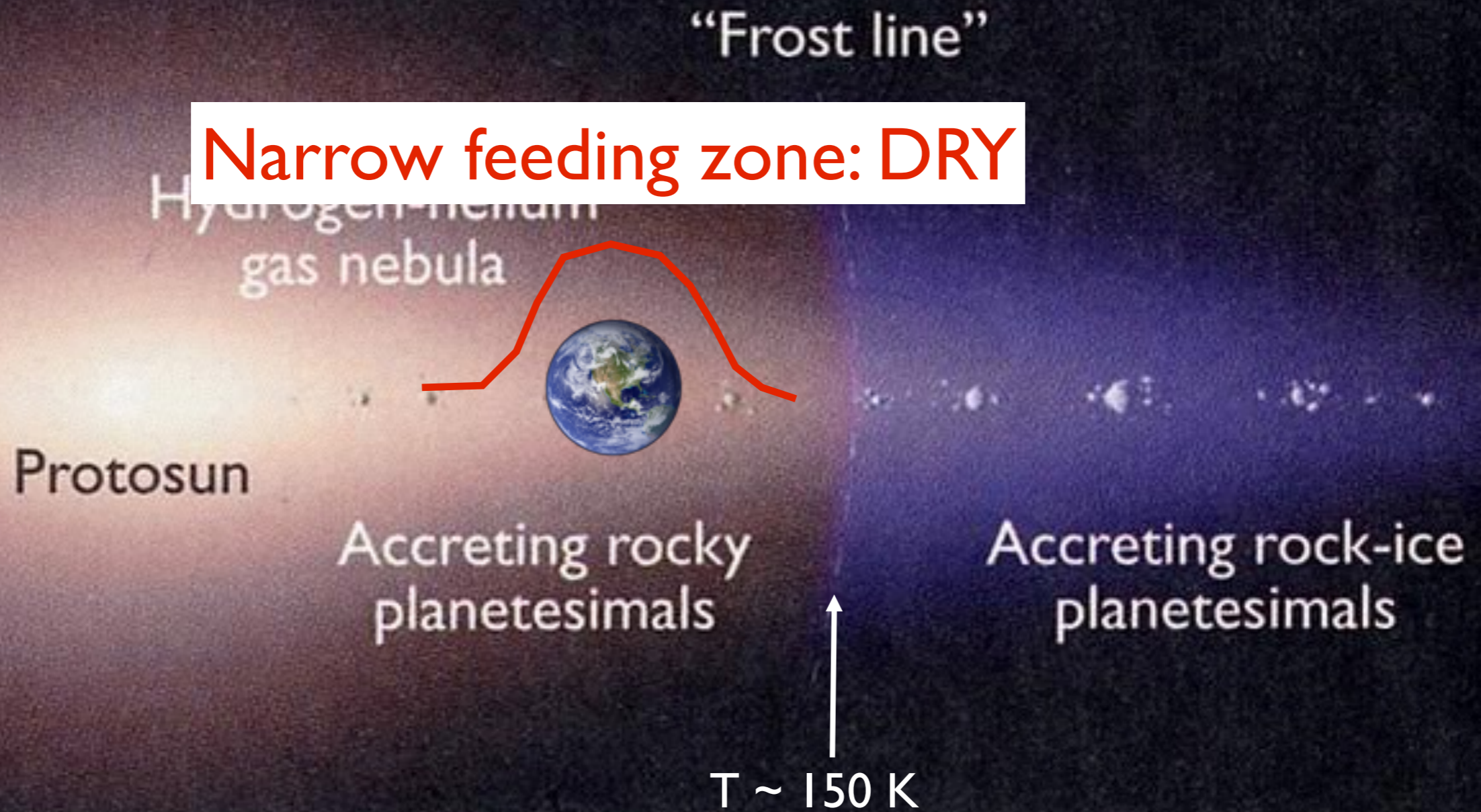
# Water delivery





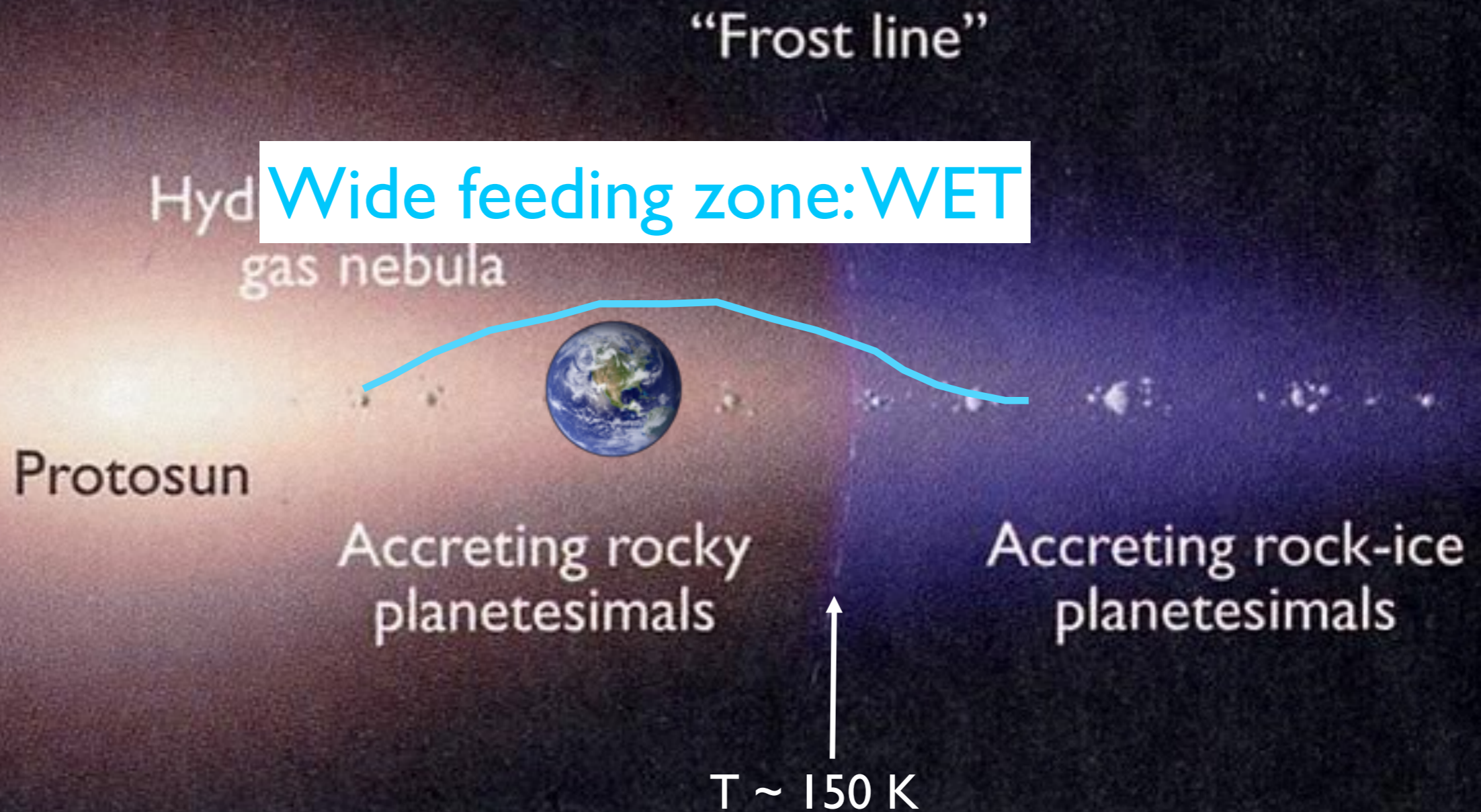
# Water delivery

**Narrow feeding zone: DRY**





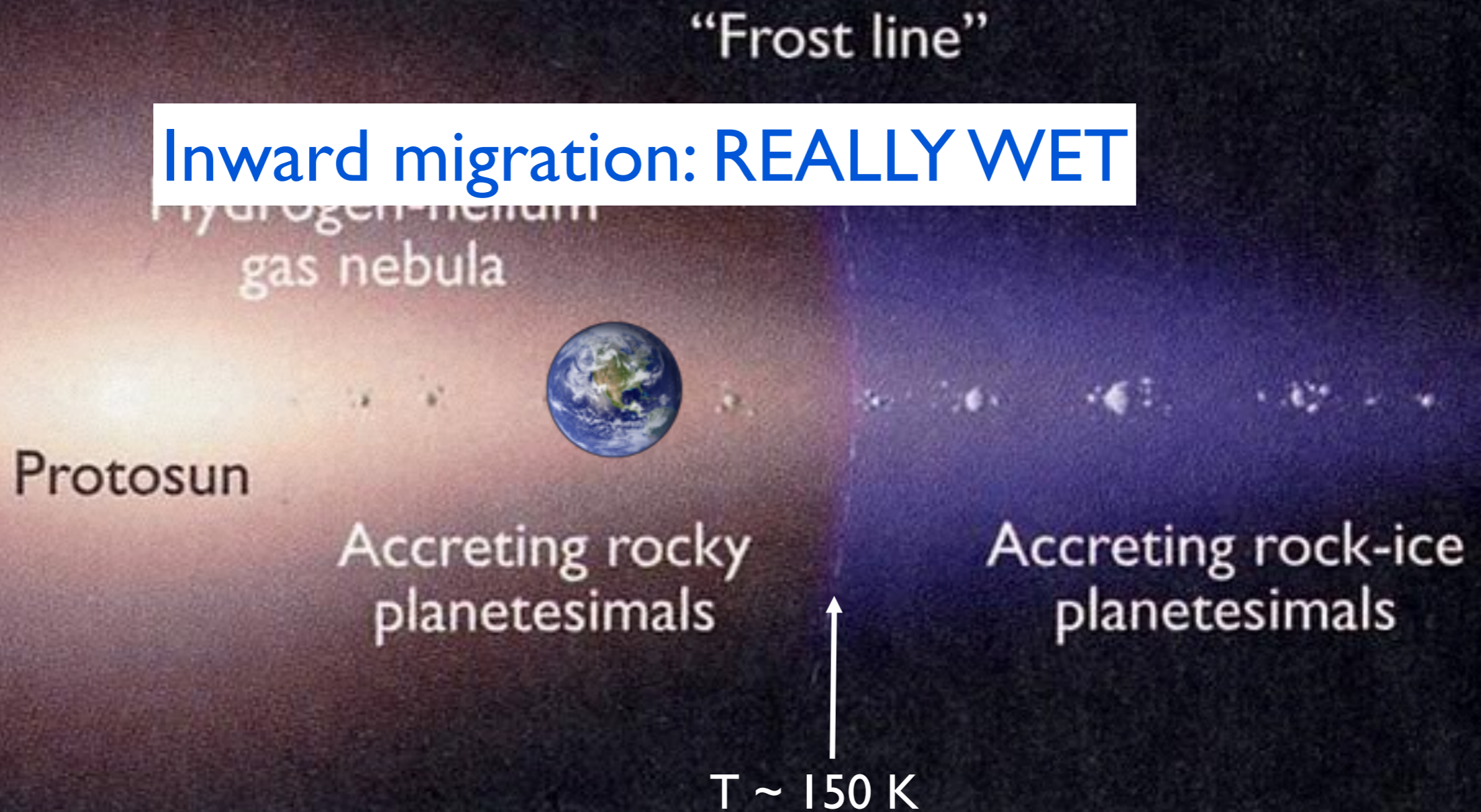
# Water delivery



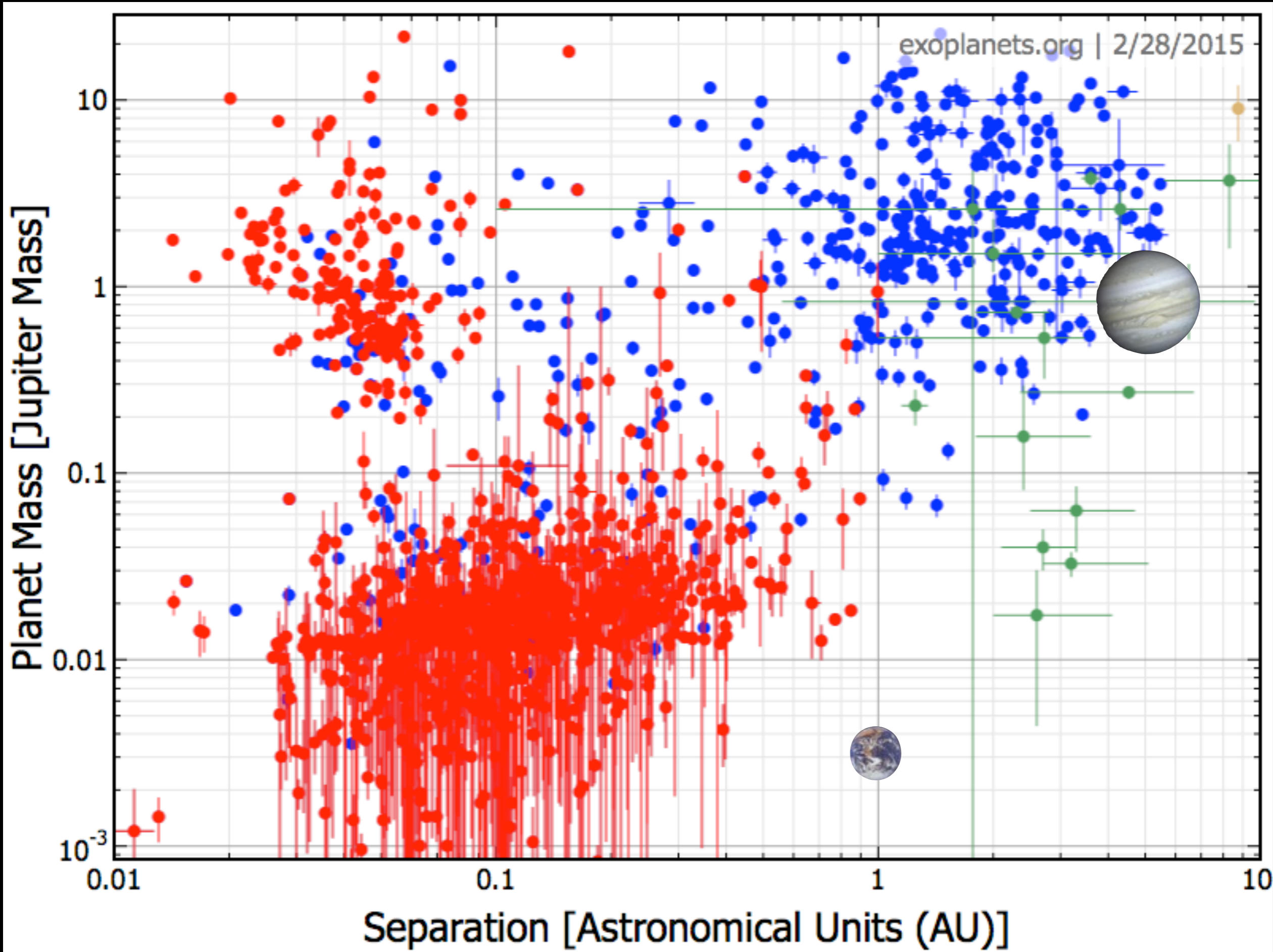


# Water delivery

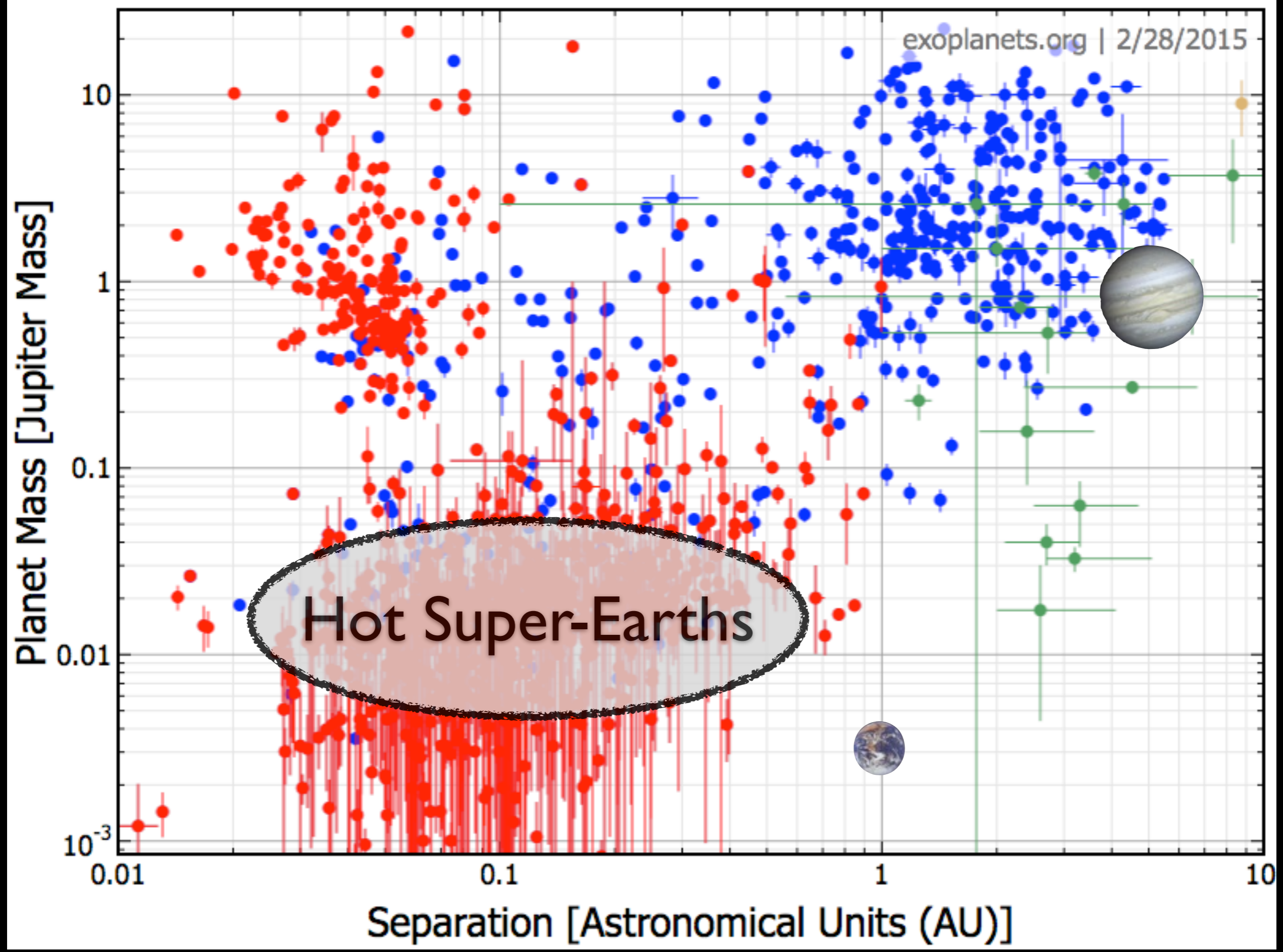
Inward migration: REALLY WET



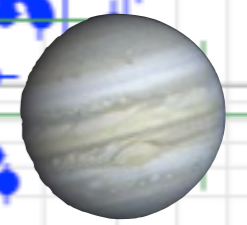




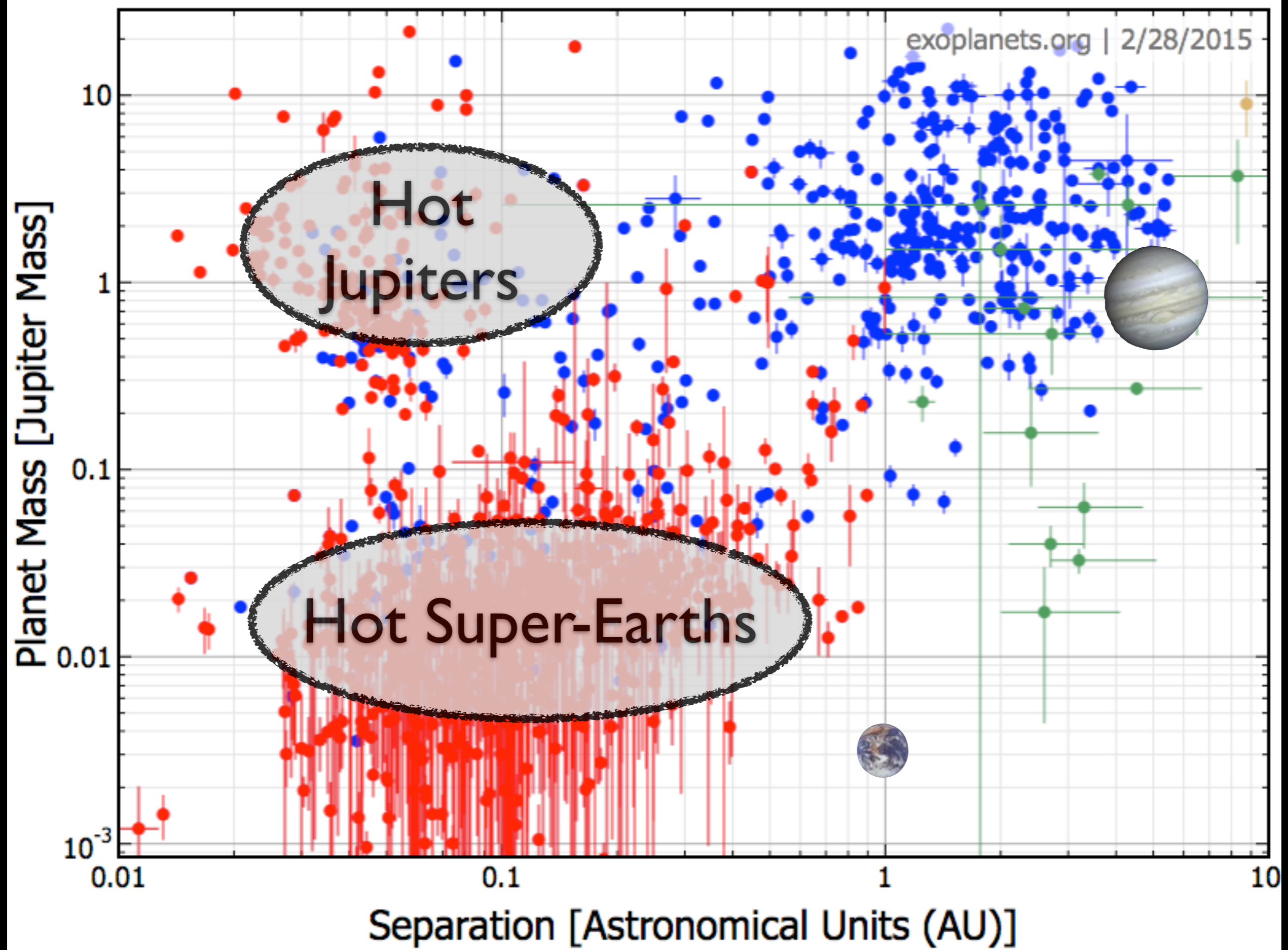




Hot Super-Earths



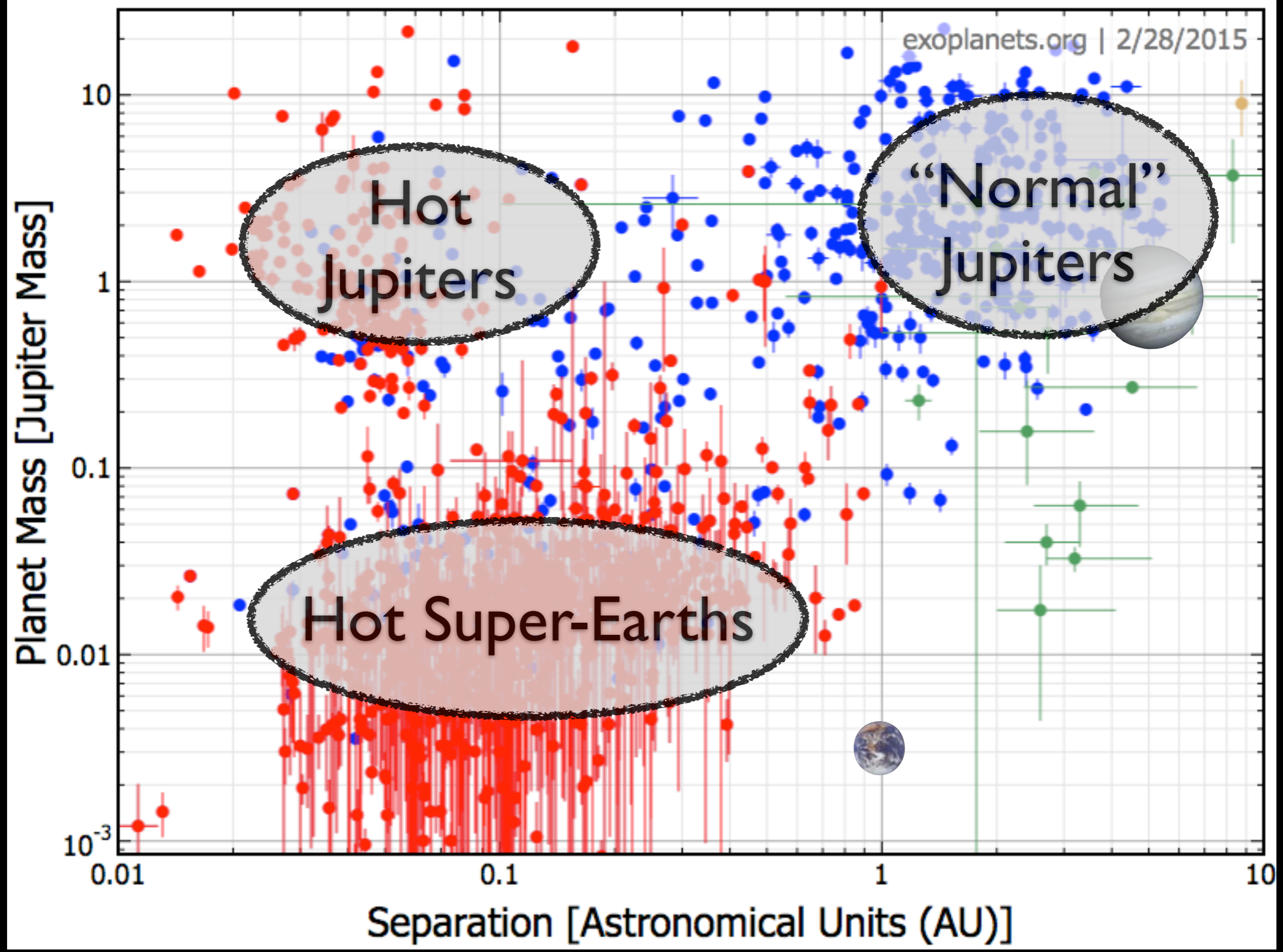




Hot Jupiters

Hot Super-Earths





Hot Jupiters

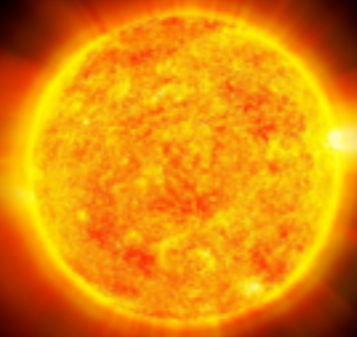
“Normal” Jupiters

Hot Super-Earths









**Most stars have planets**  
(e.g., Cassan et al 2012)





**>15%**

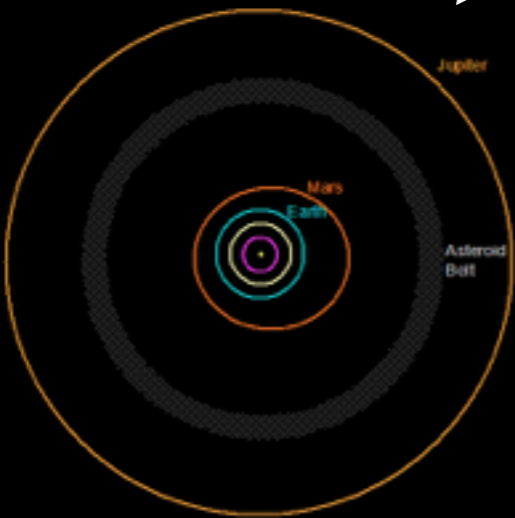
(Cumming et al 2008; Gould et al 2010;  
Mayor et al 2011)





**>15%**

(Cumming et al 2008; Gould et al 2010; Mayor et al 2011)



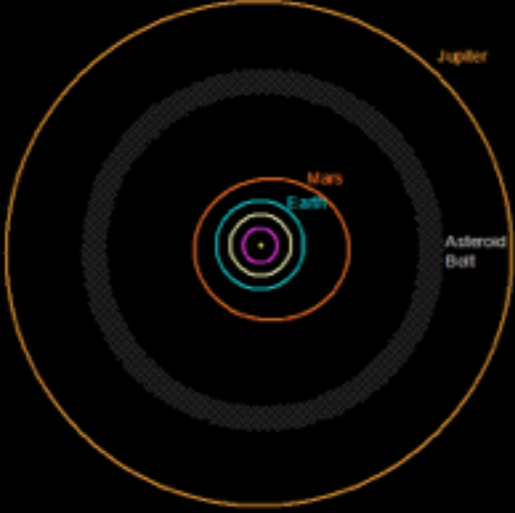
**10%**



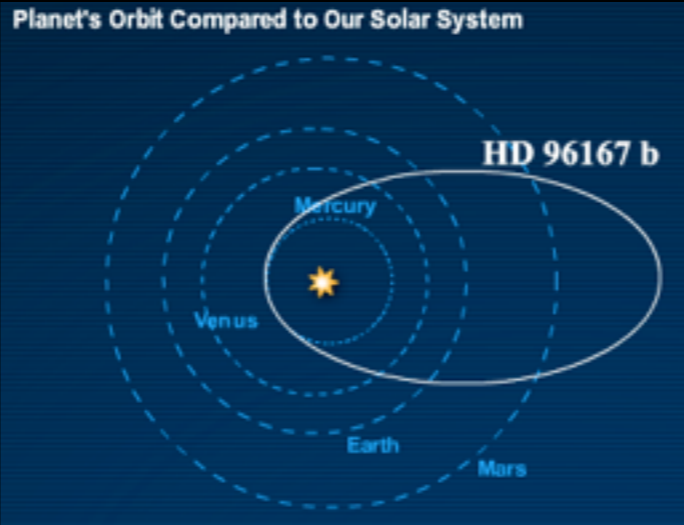


>15%

(Cumming et al 2008; Gould et al 2010; Mayor et al 2011)



10%



90%

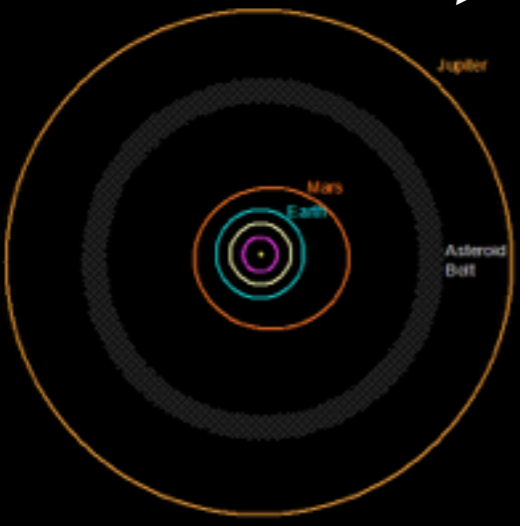




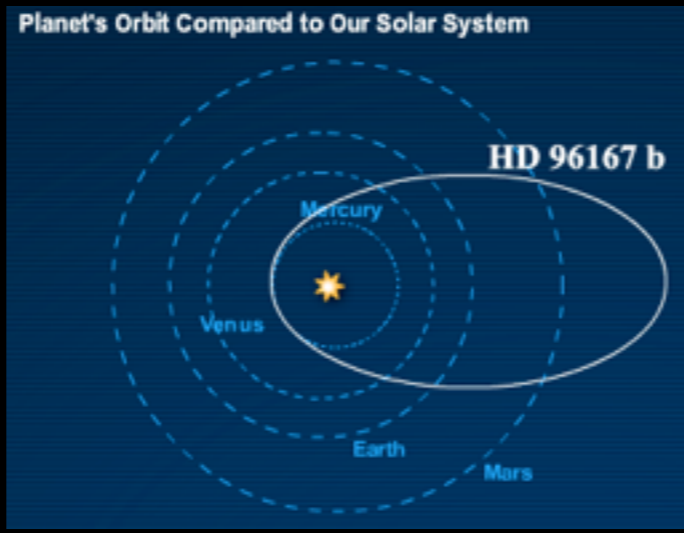
>15%

(Cumming et al 2008; Gould et al 2010; Mayor et al 2011)

<85%



10%



90%

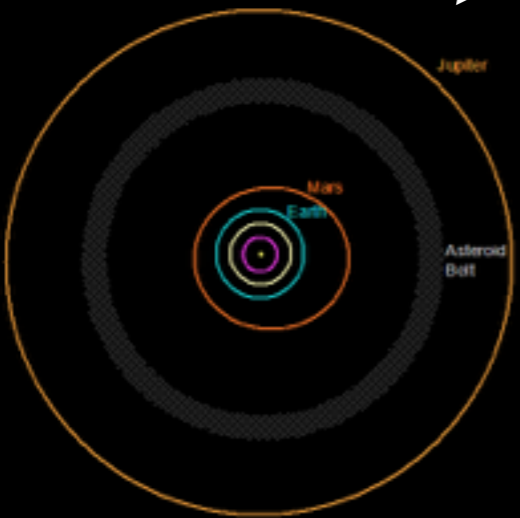




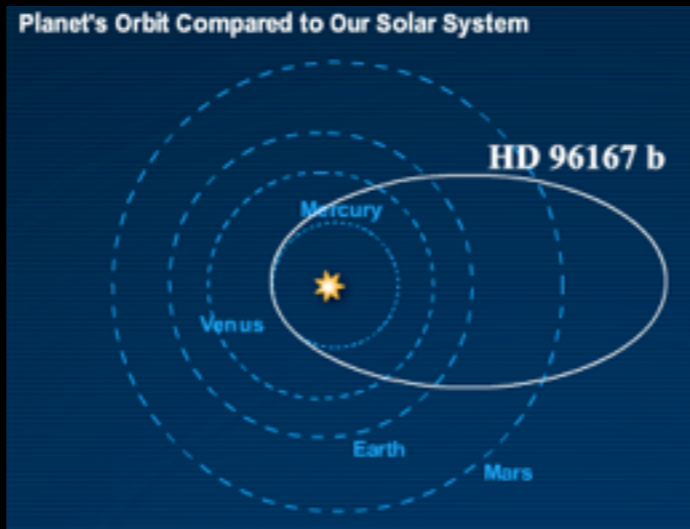
>15%

(Cumming et al 2008; Gould et al 2010; Mayor et al 2011)

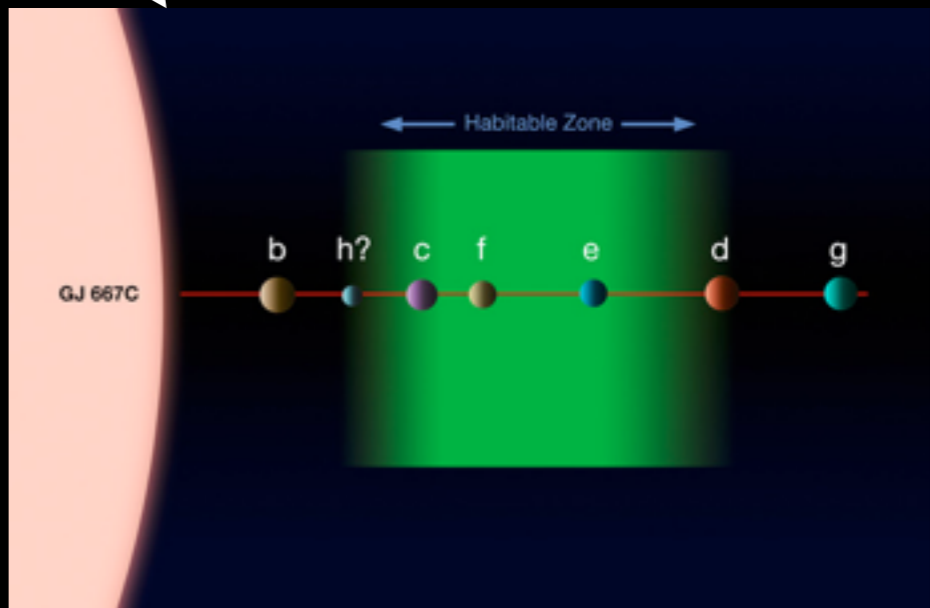
<85%



10%



90%



30-50+% of all stars

(Mayor et al 2011, Howard et al 2010, 2012)





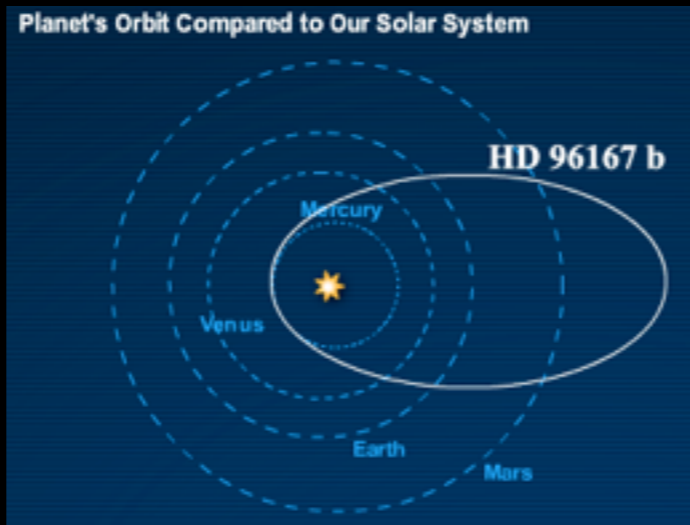
>15%

(Cumming et al 2008; Gould et al 2010; Mayor et al 2011)

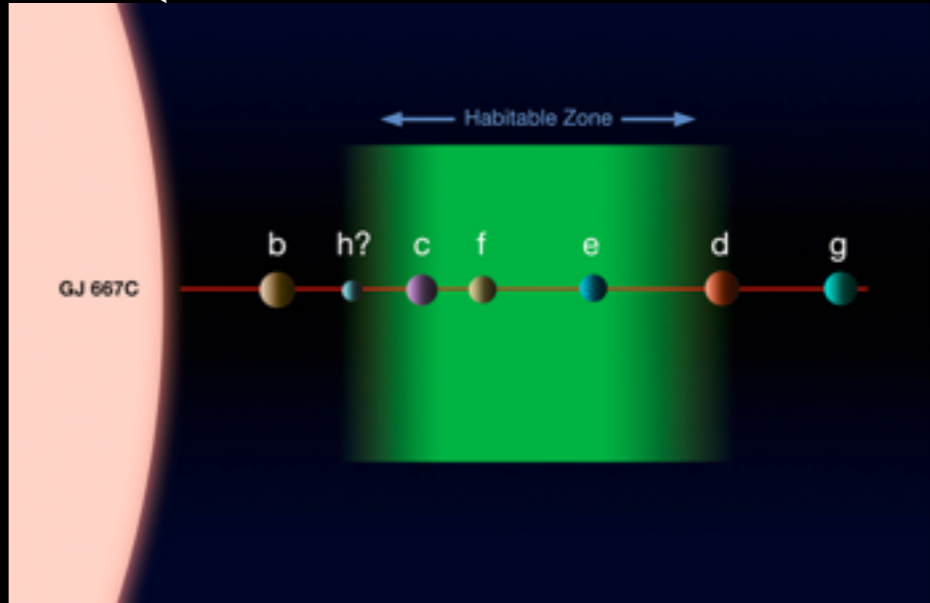
<85%



Solar System(-like)



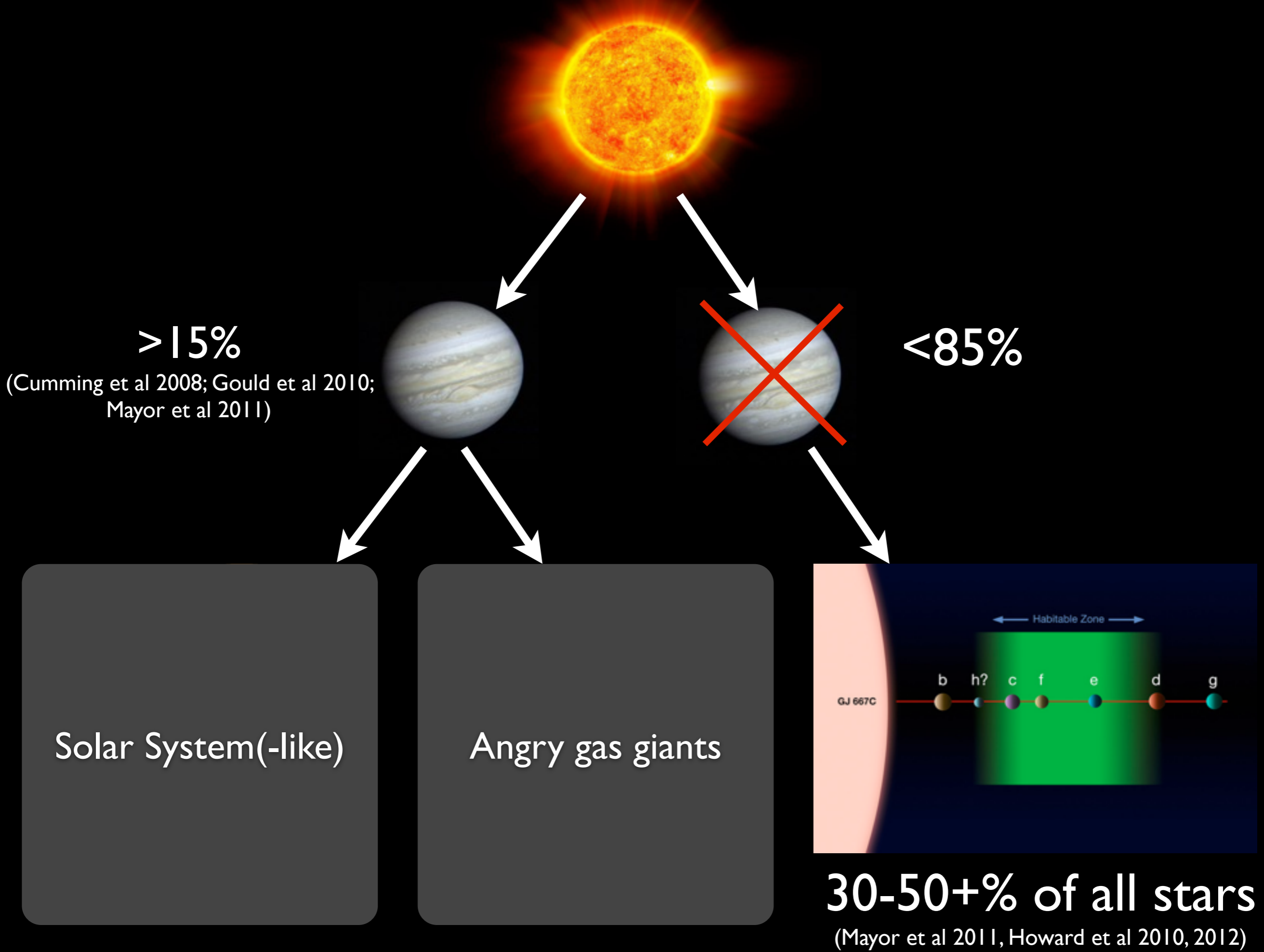
90%



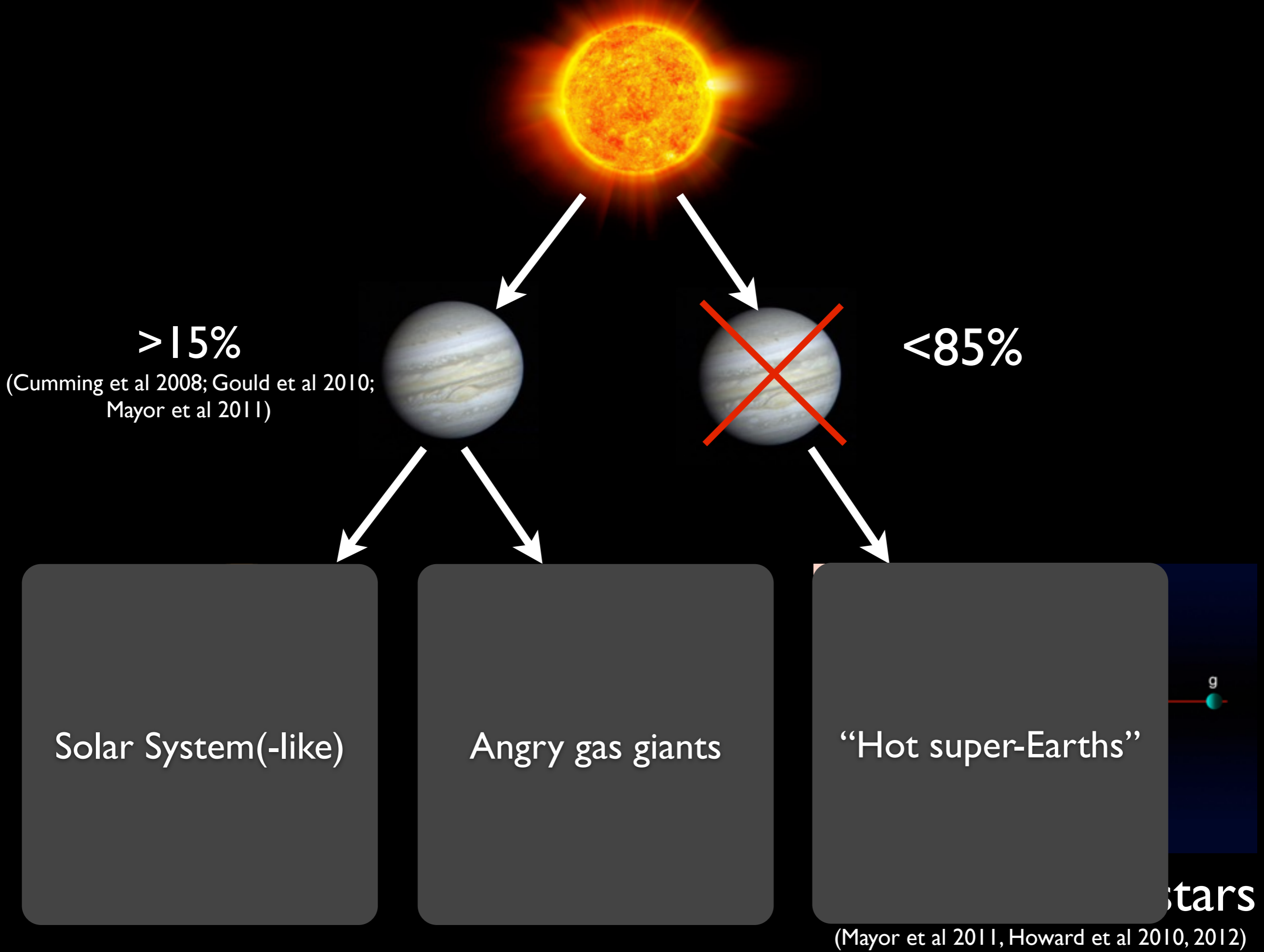
30-50+% of all stars

(Mayor et al 2011, Howard et al 2010, 2012)









>15%

(Cumming et al 2008; Gould et al 2010; Mayor et al 2011)

<85%

Solar System(-like)

Angry gas giants

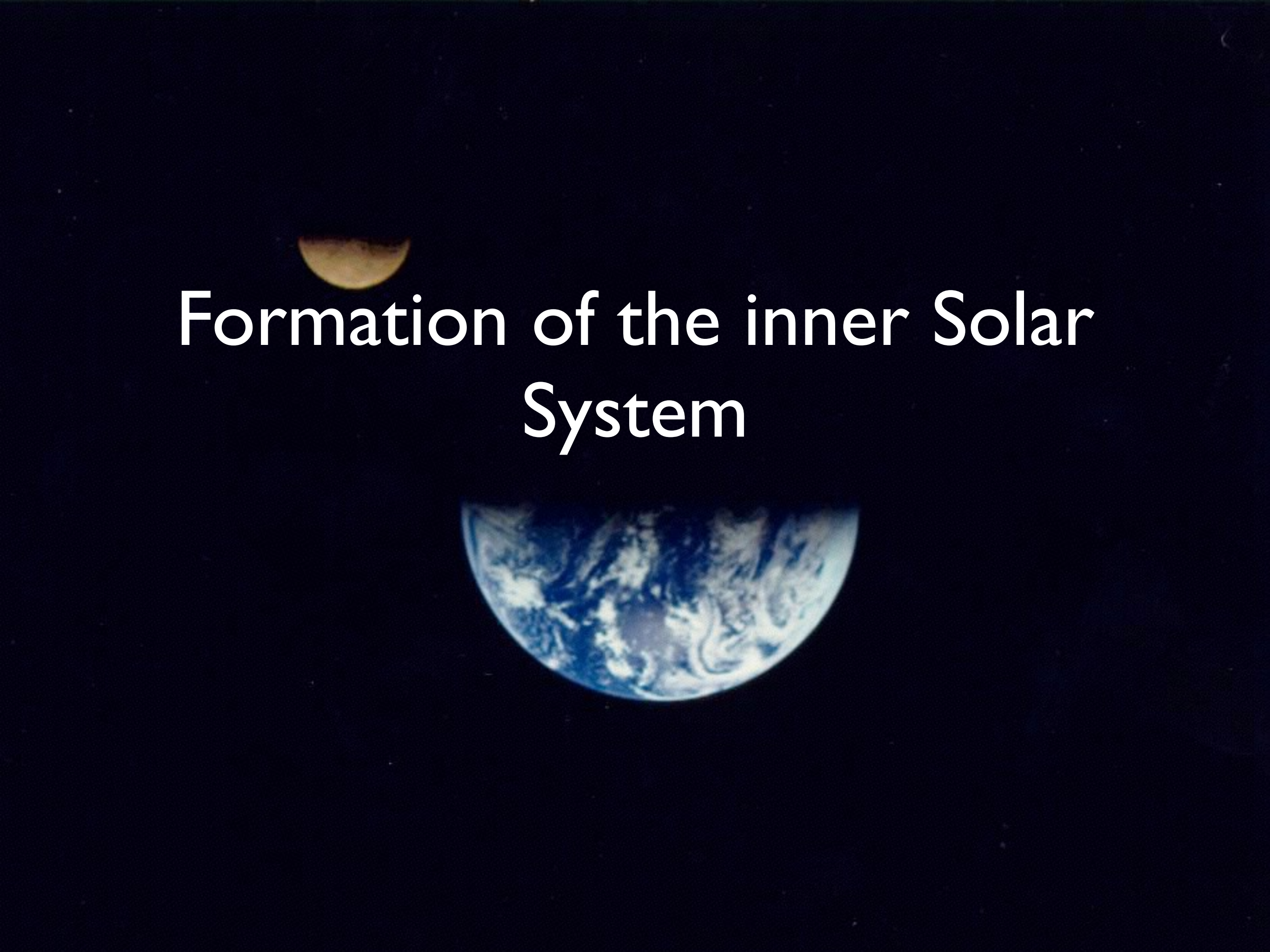
"Hot super-Earths"

(Mayor et al 2011, Howard et al 2010, 2012)

g

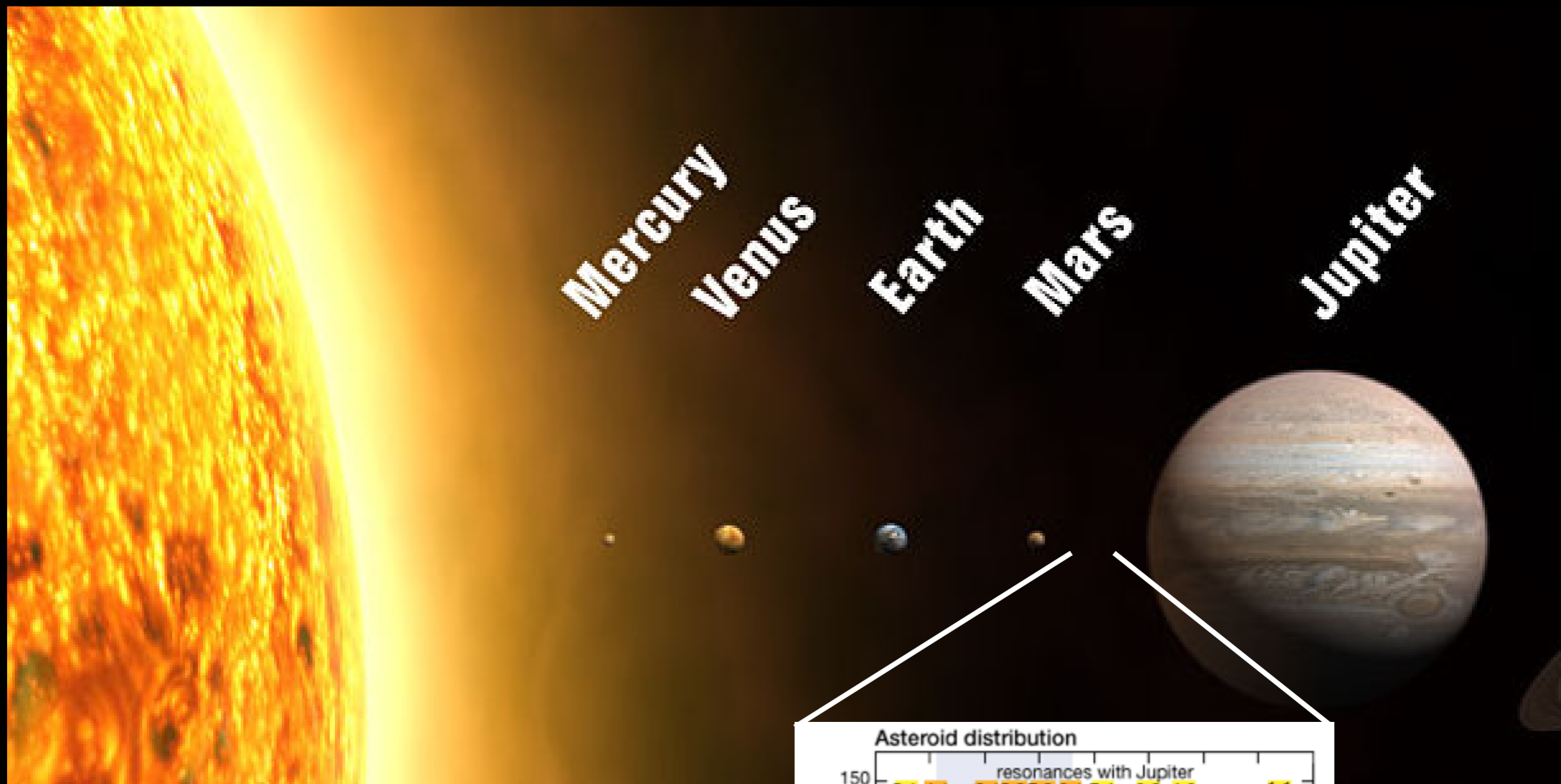
stars



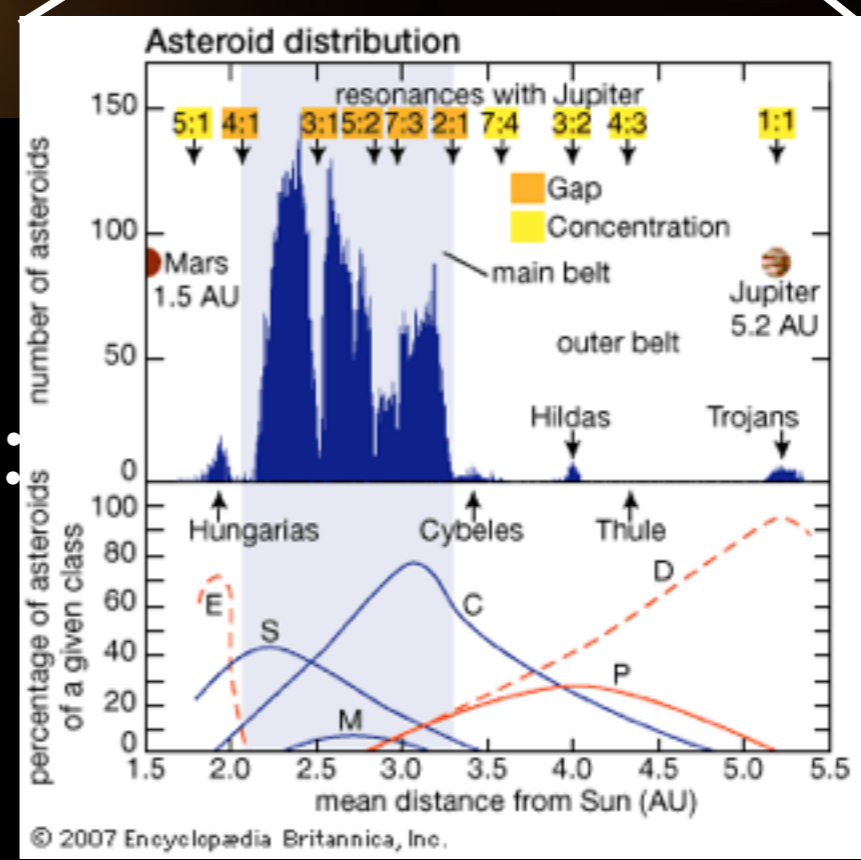
A composite image featuring a crescent moon in the upper left and a larger crescent of the Earth in the lower right, set against a dark, starry background. The text "Formation of the inner Solar System" is centered in white.

# Formation of the inner Solar System





Total asteroid mass:  
 $\sim 10^{-3}$  Earth masses



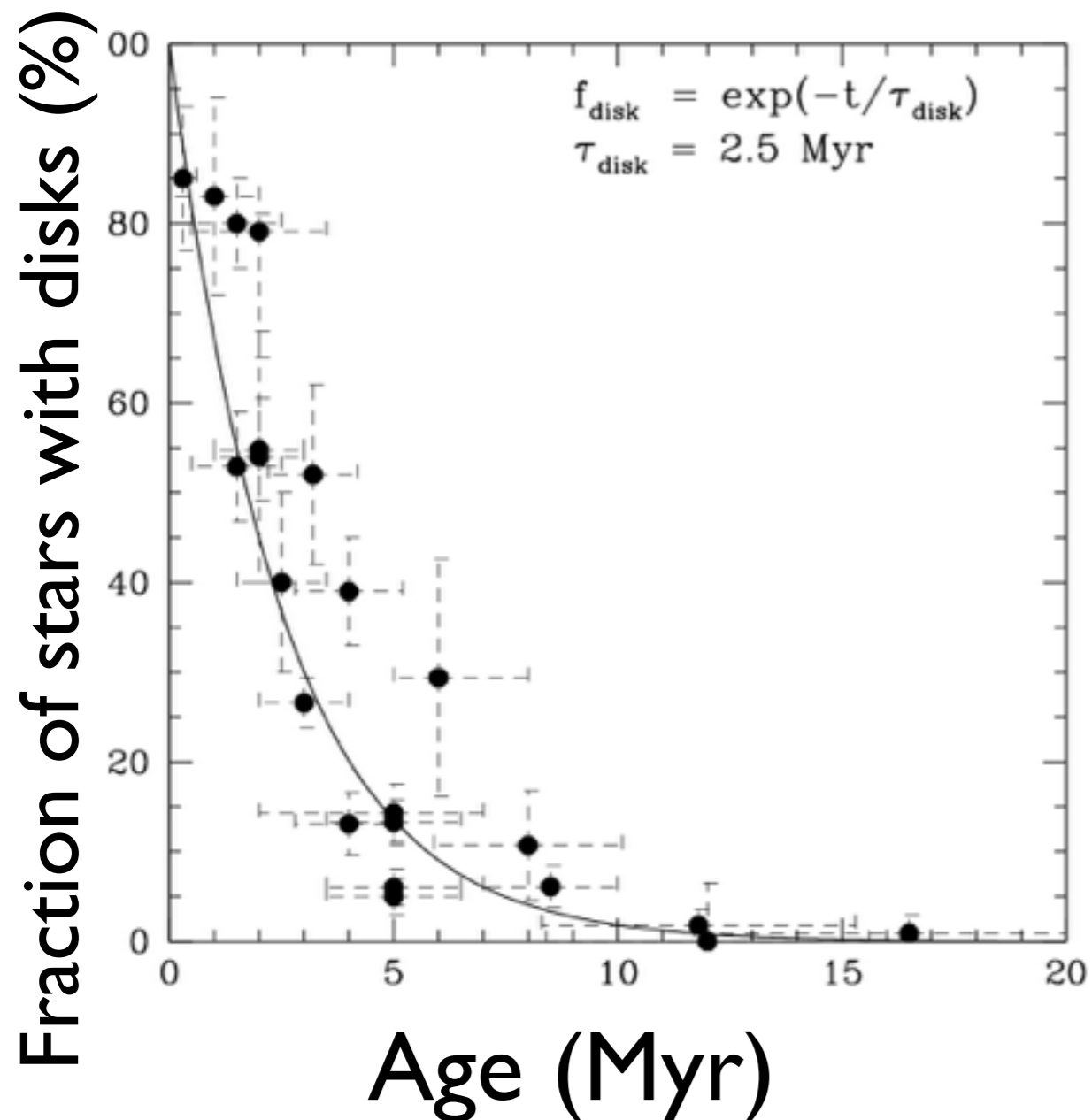


# Sequence of events



# Sequence of events

Gas giants form fast (a few million years)

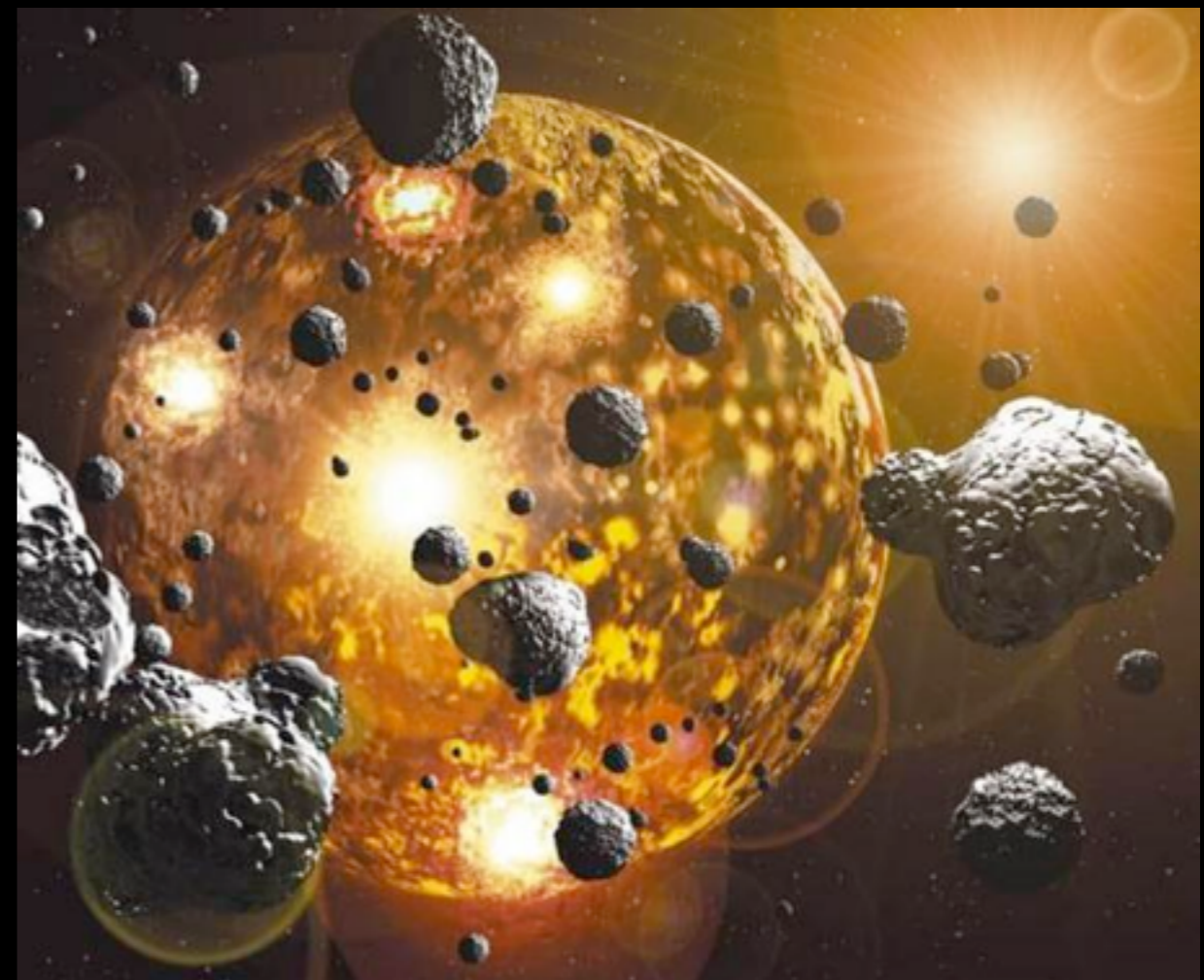
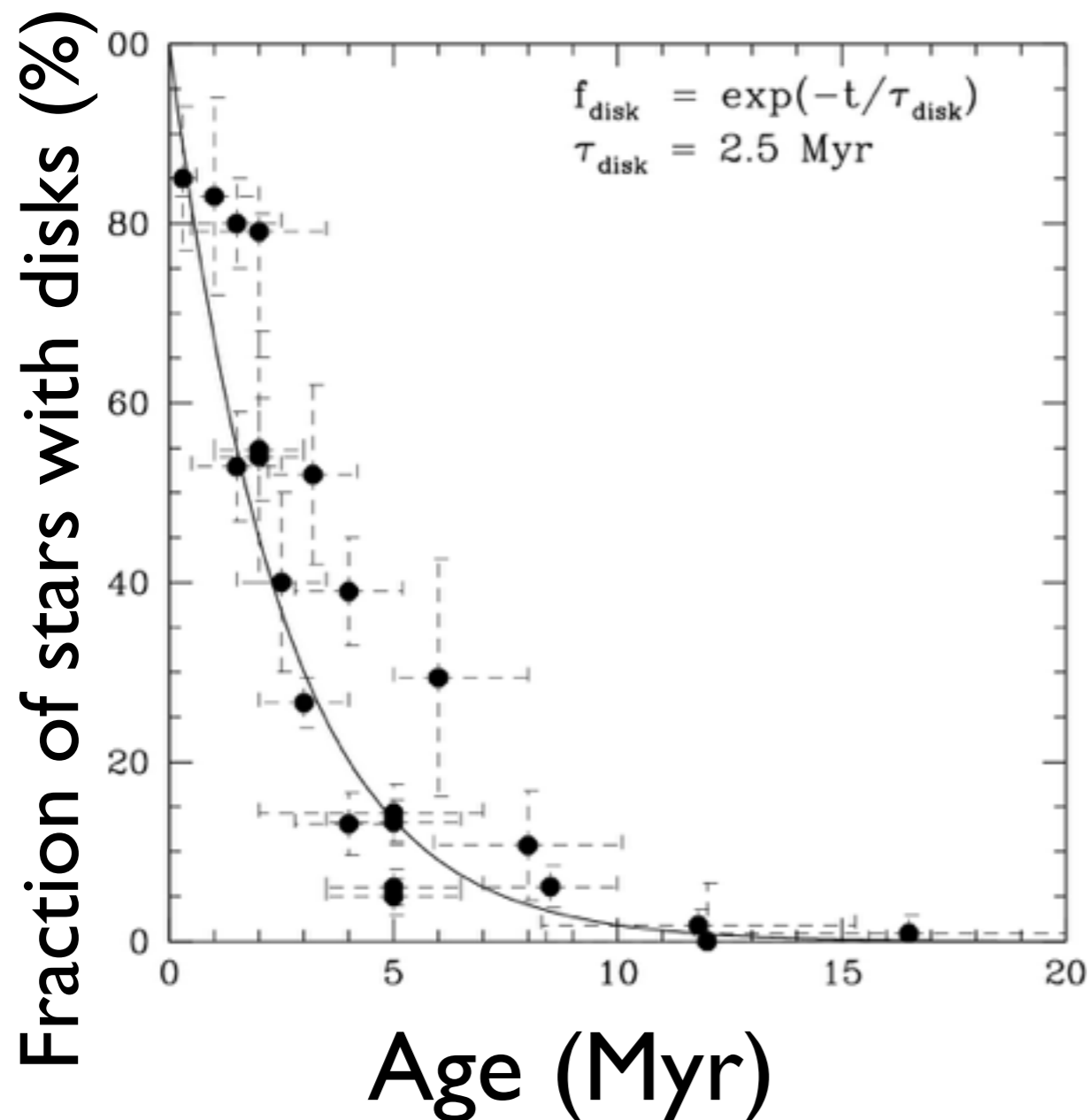




# Sequence of events

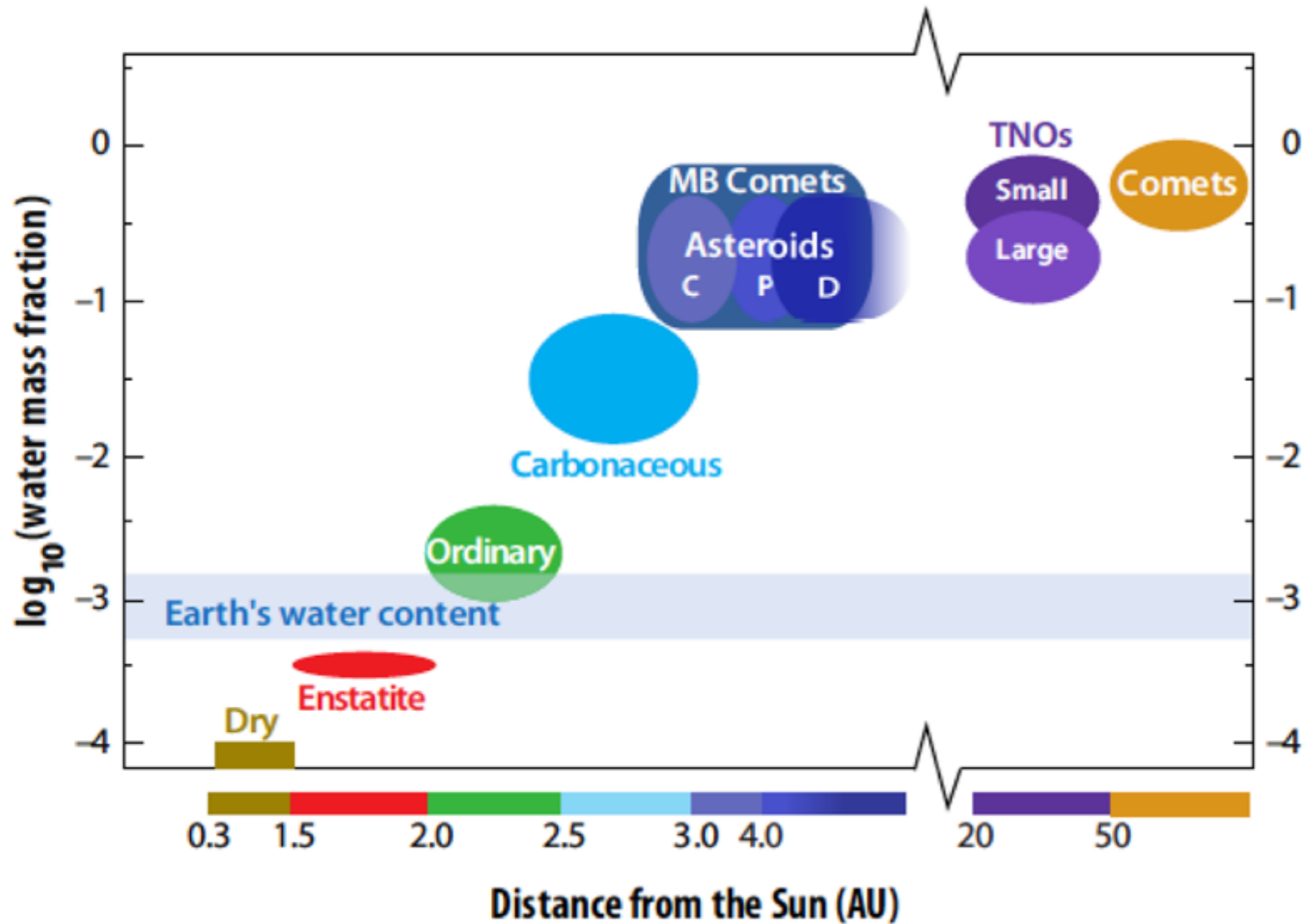
Gas giants form fast (a few million years)

Earth formed slow (~100 million years)





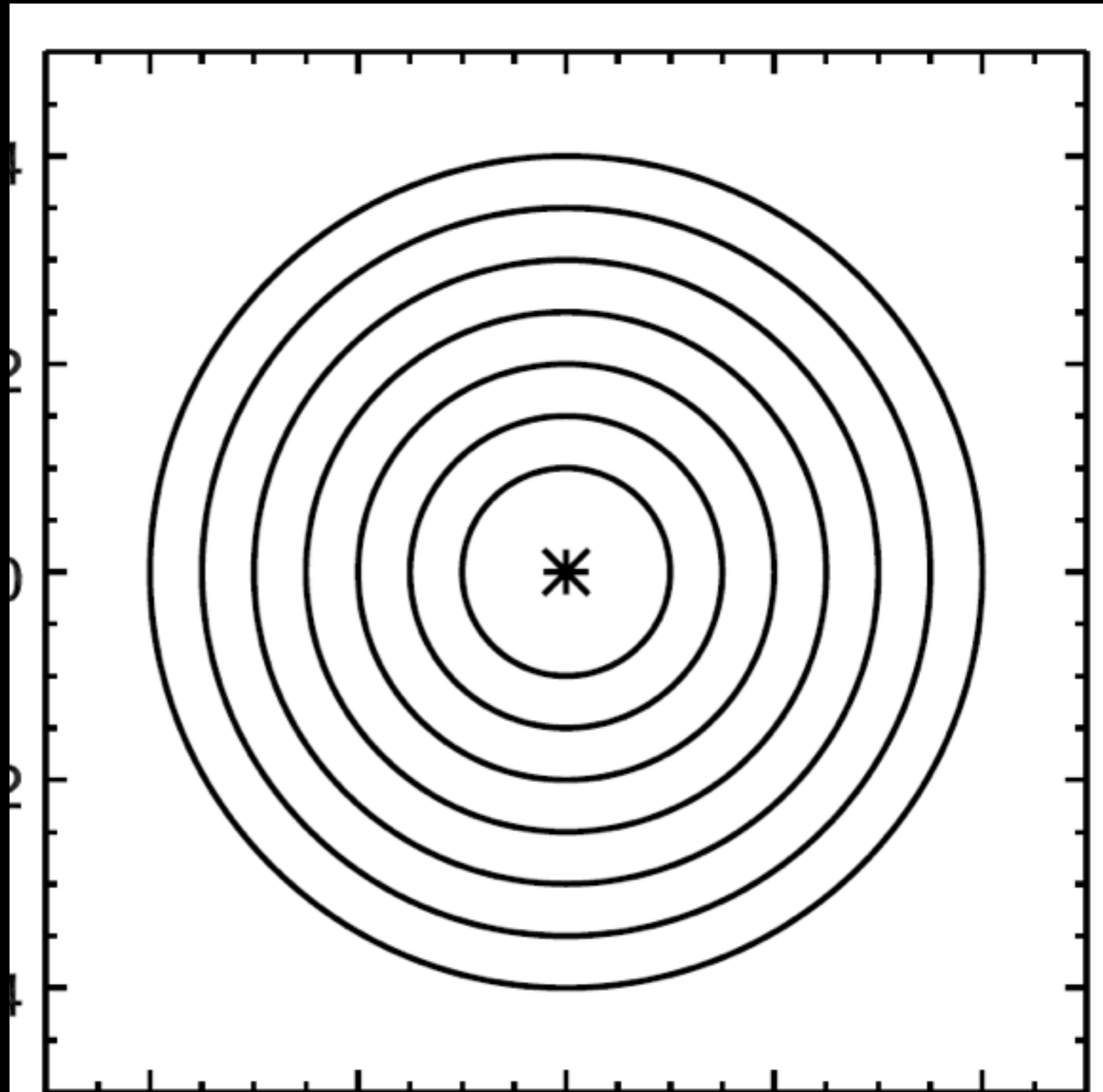
# Water content of planetary building blocks





# Need eccentric orbits for collisions to happen

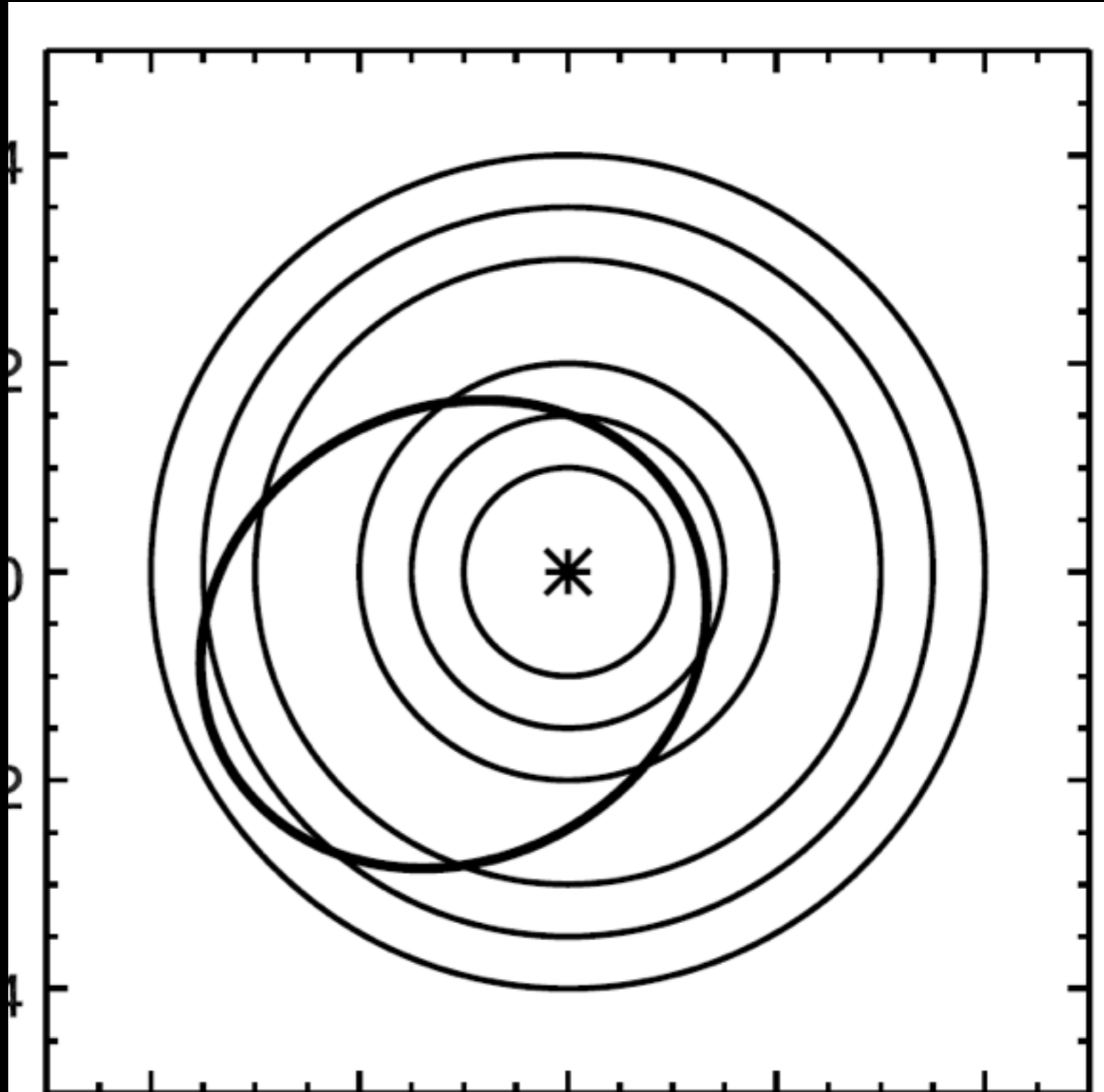
- Semimajor axis  $a$  = average distance between planet, star
- Eccentricity  $e$  = measure of how elliptical an orbit is



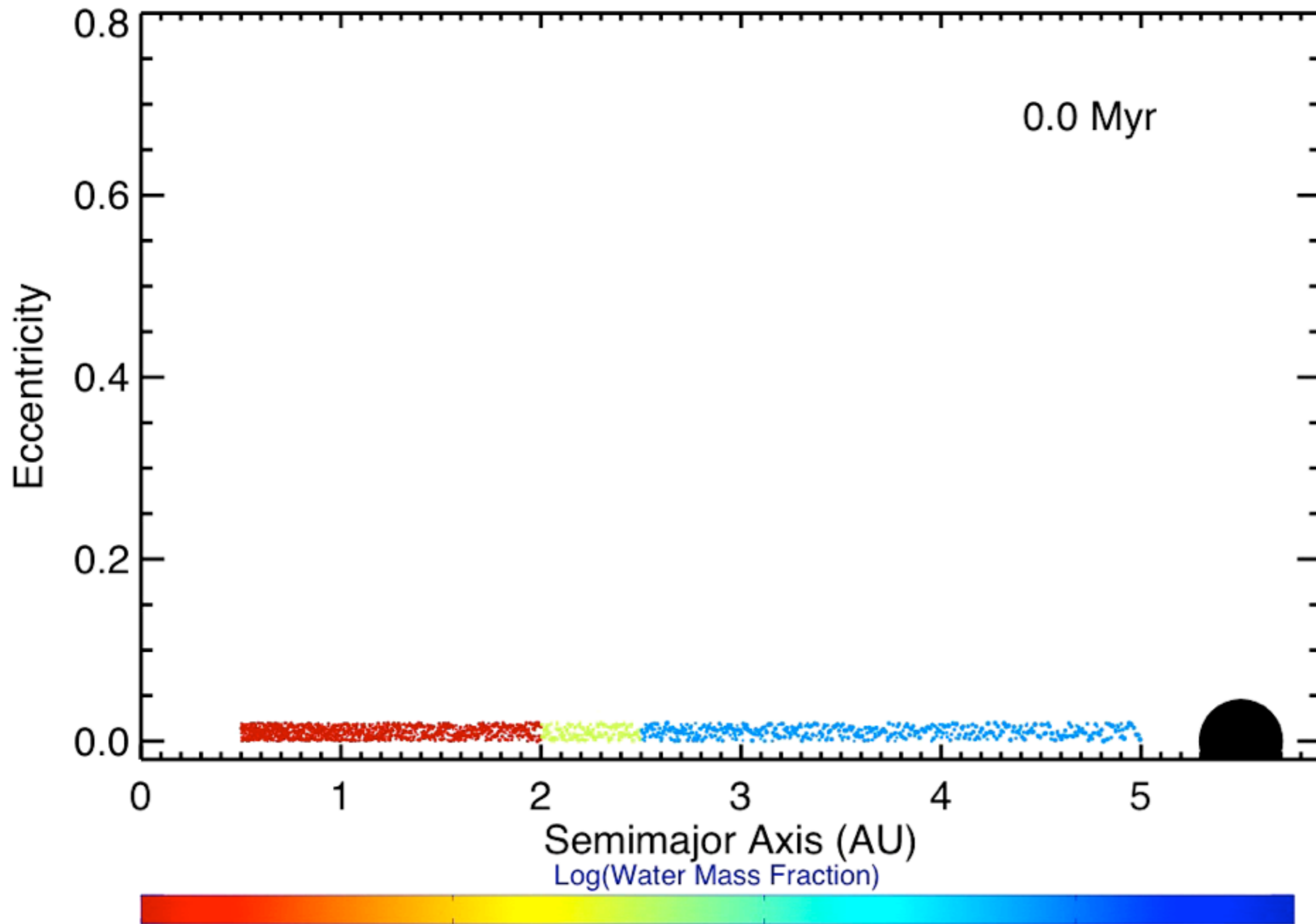


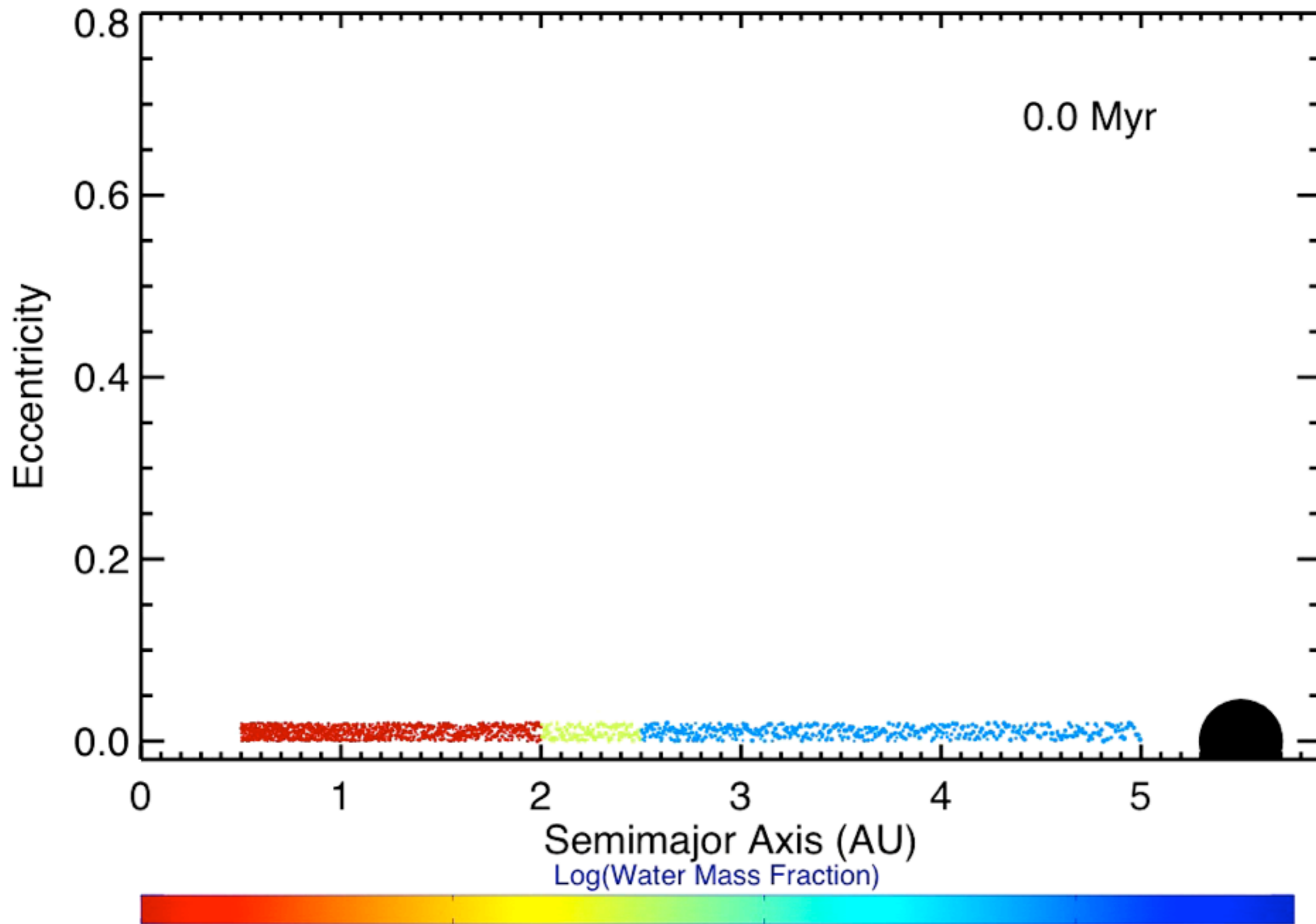
# Need eccentric orbits for collisions to happen

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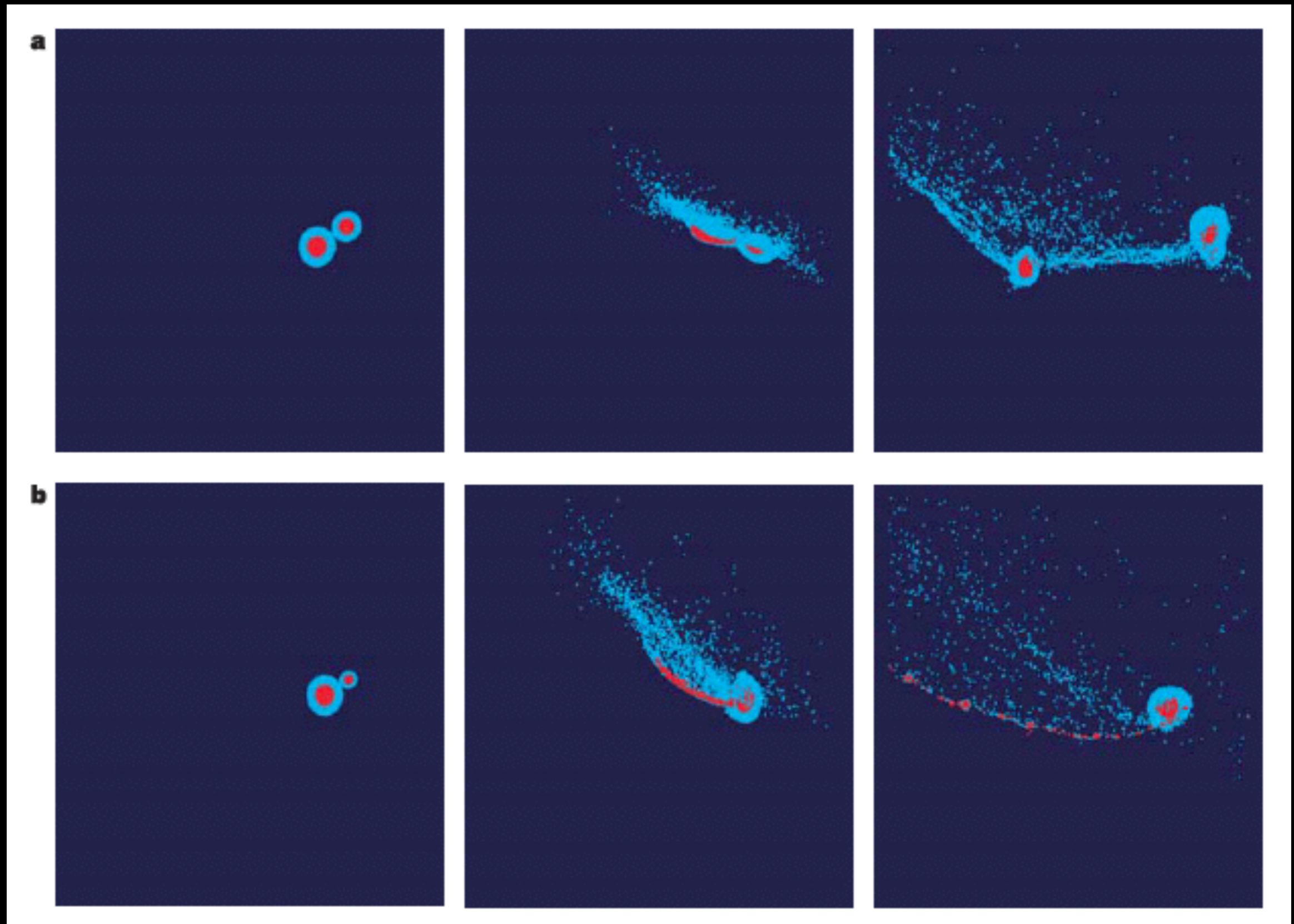








# Hit-and-run collisions



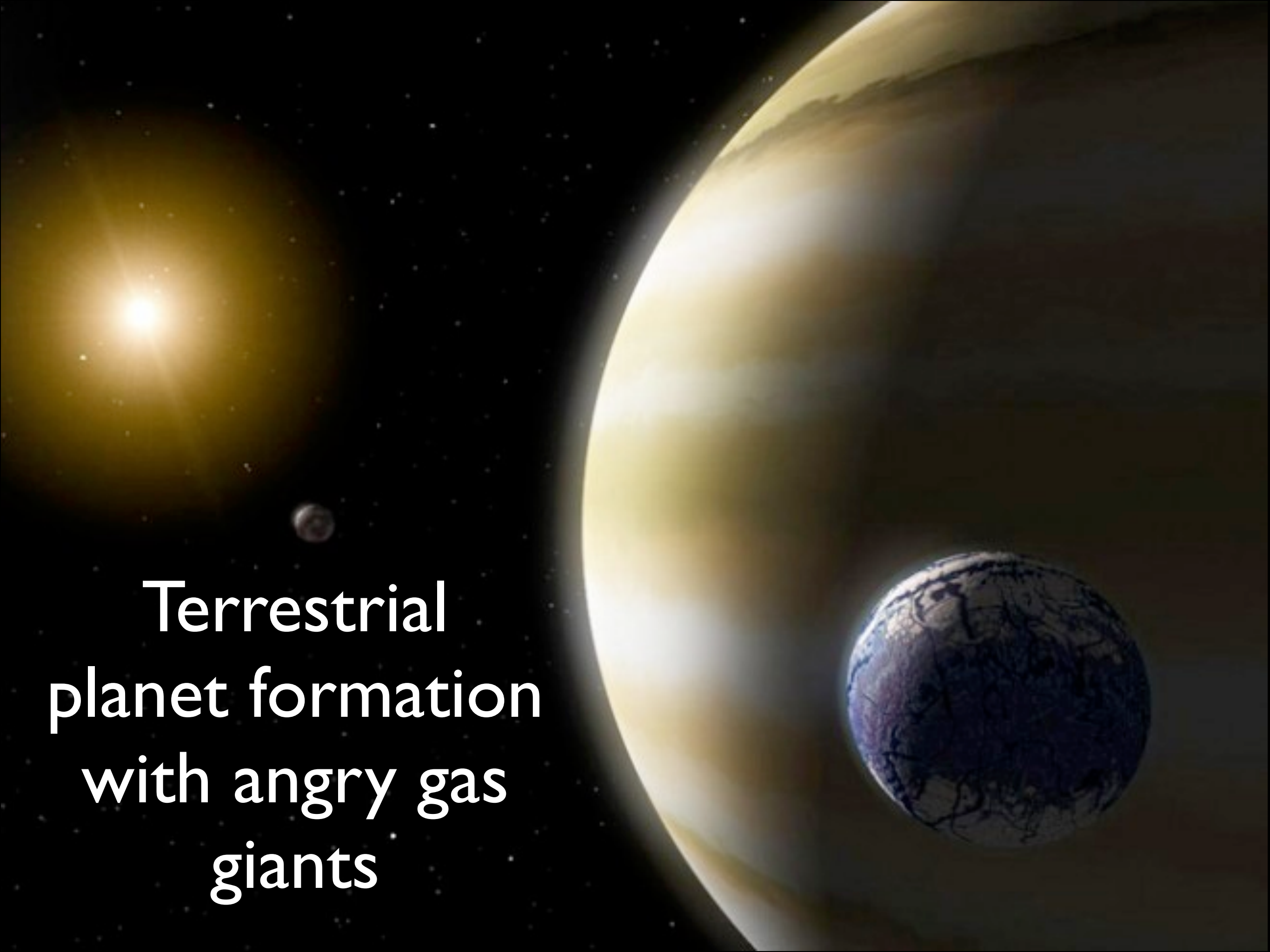
Asphaug et al 2006



The Moon formed from debris in the last giant impact on the proto-Earth

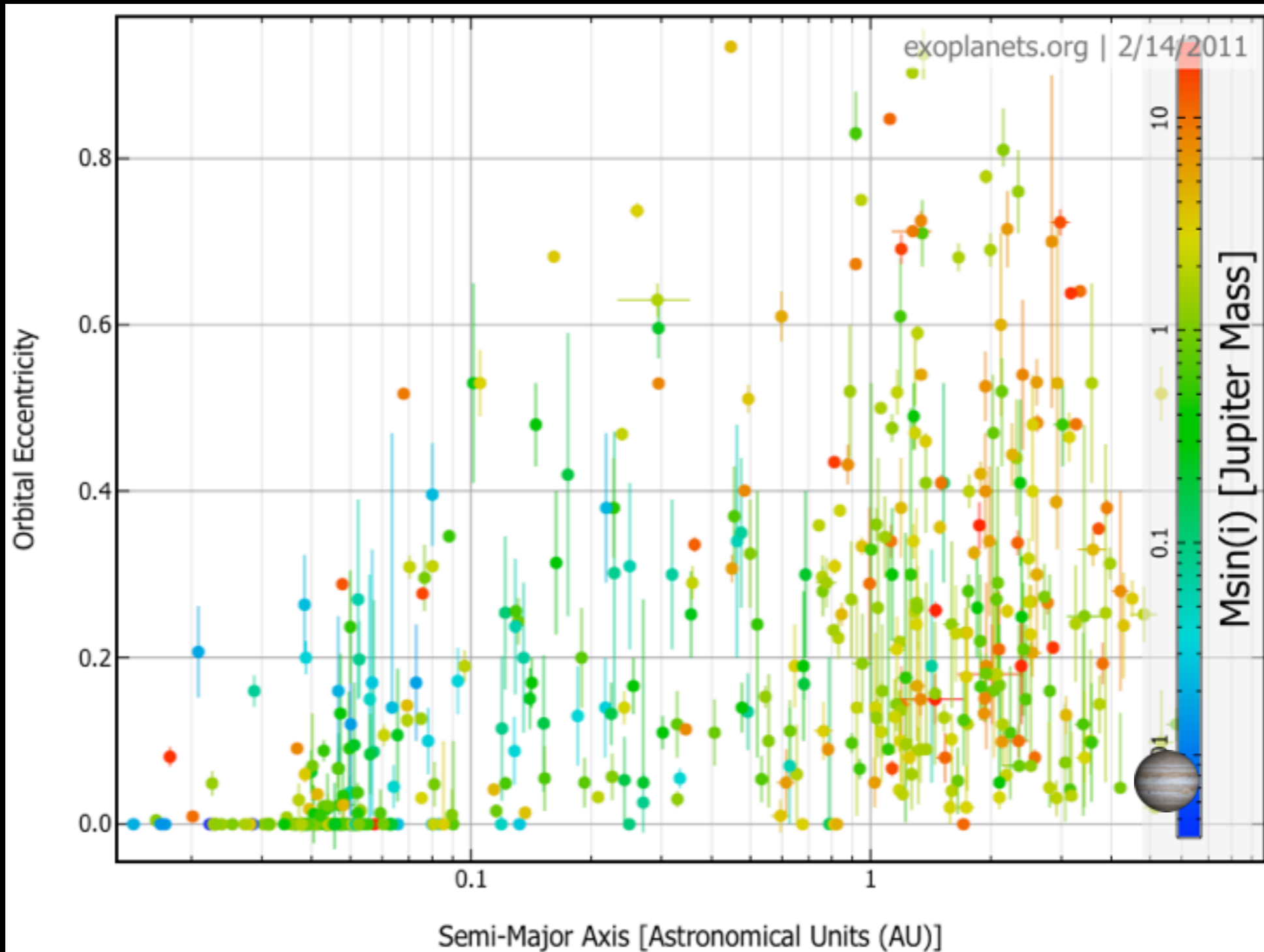




A space scene featuring a bright yellow star on the left, a large gas giant planet on the right, and a smaller rocky planet in the foreground. The background is dark with scattered stars.

Terrestrial  
planet formation  
with angry gas  
giants

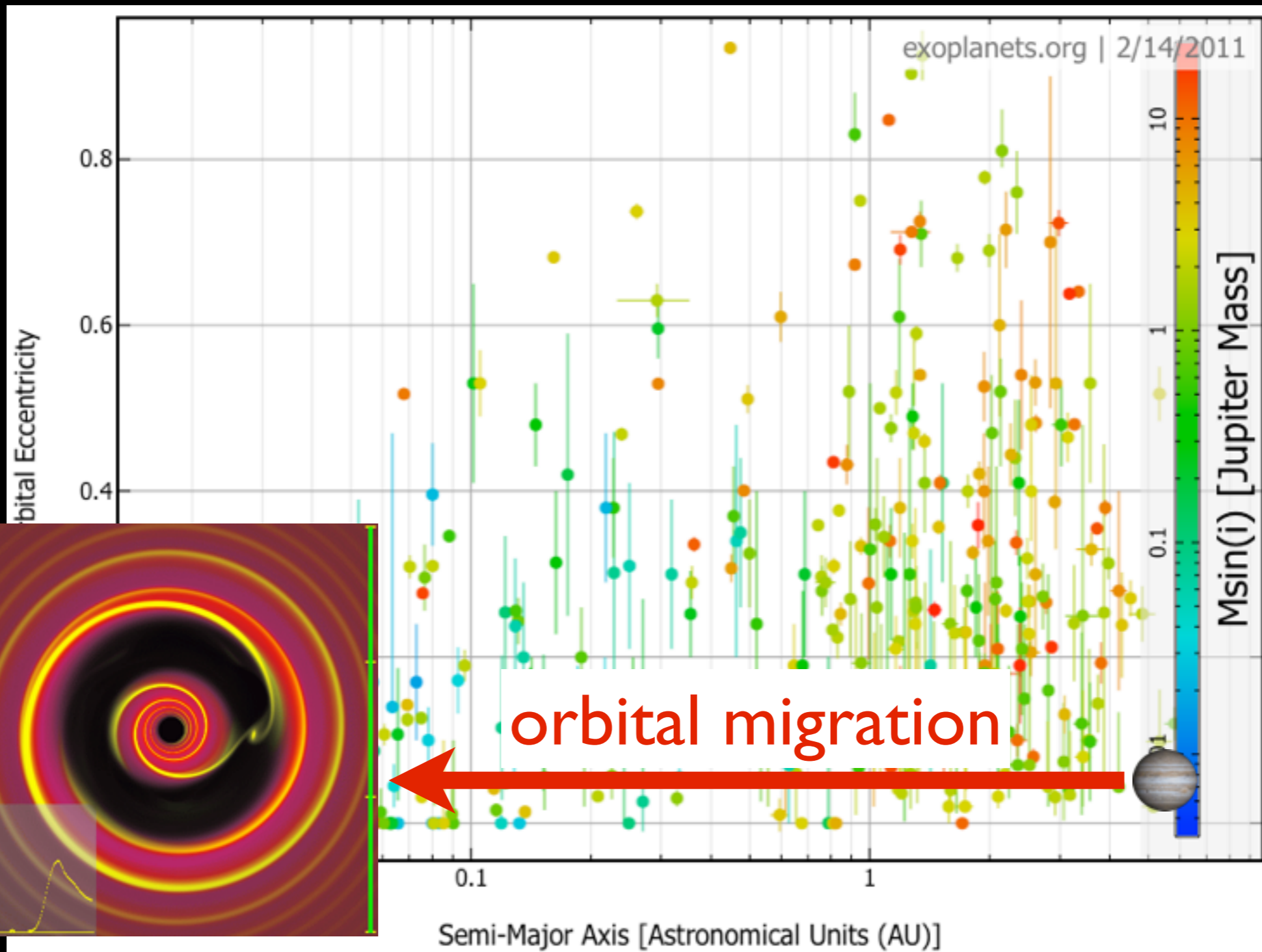
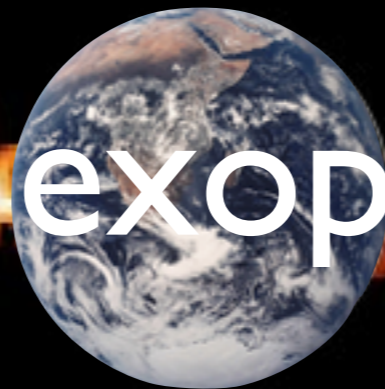
# Giant exoplanets



Wright et al  
2011

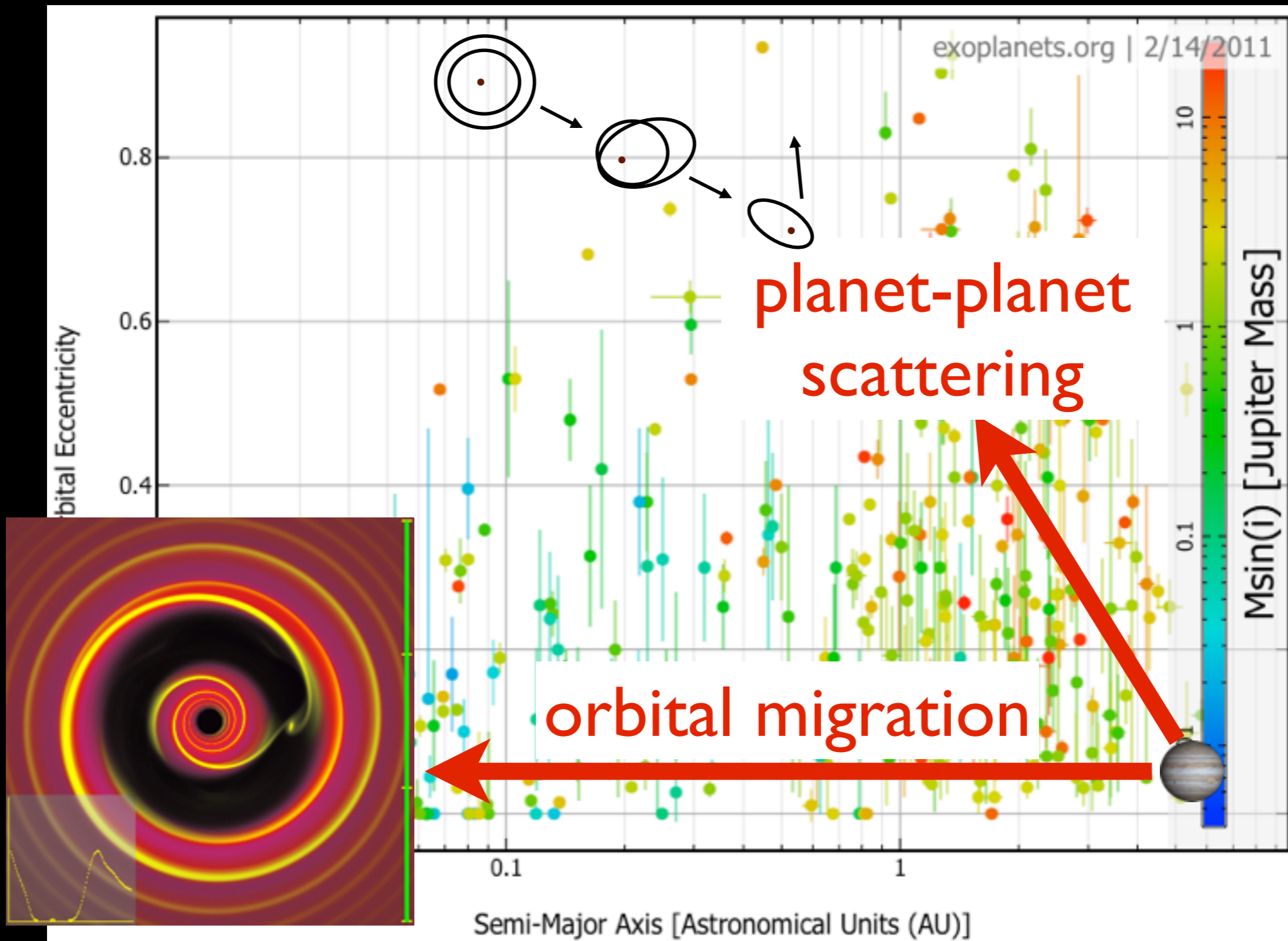


# Giant exoplanets



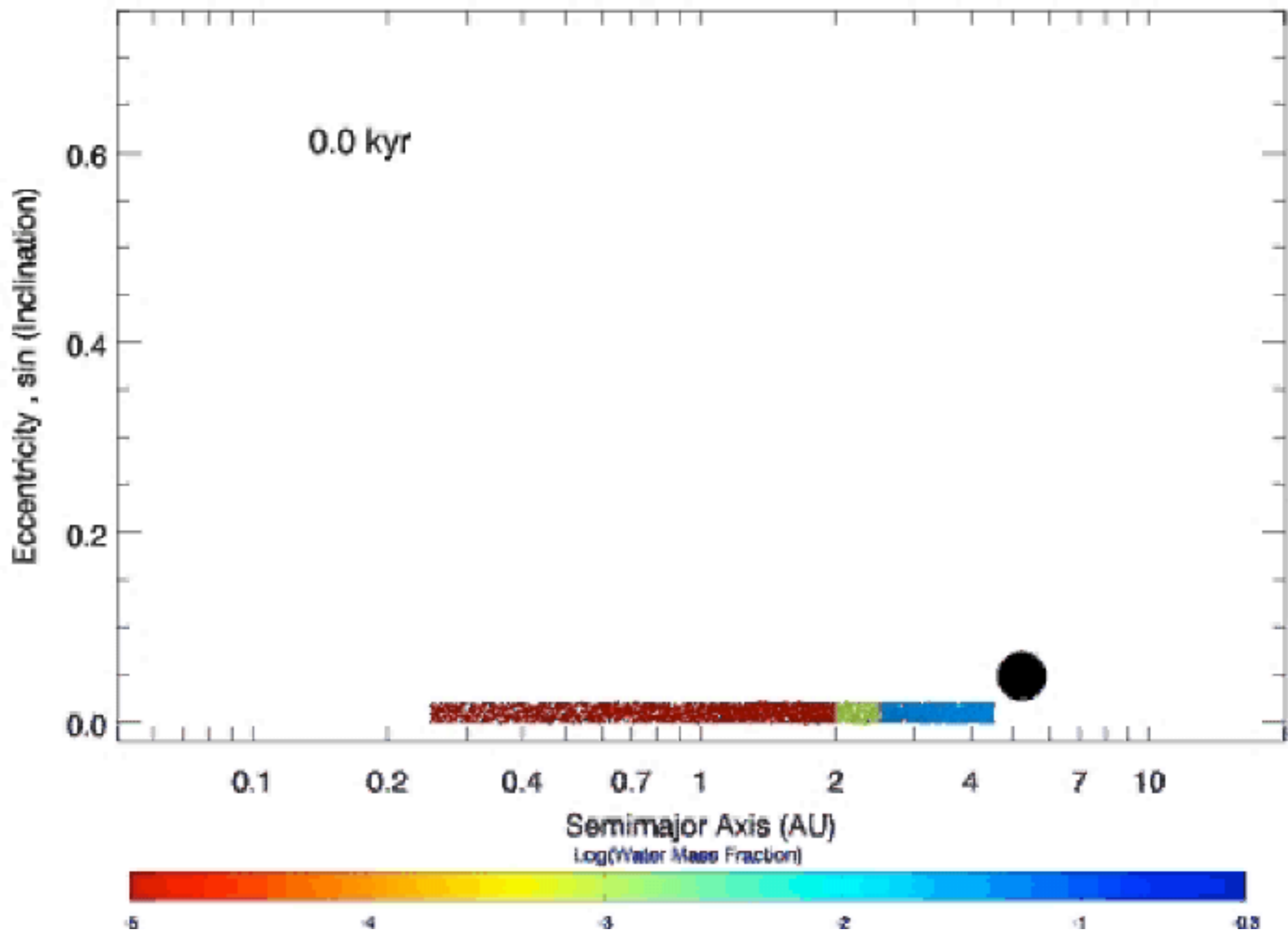
Wright et al  
2011

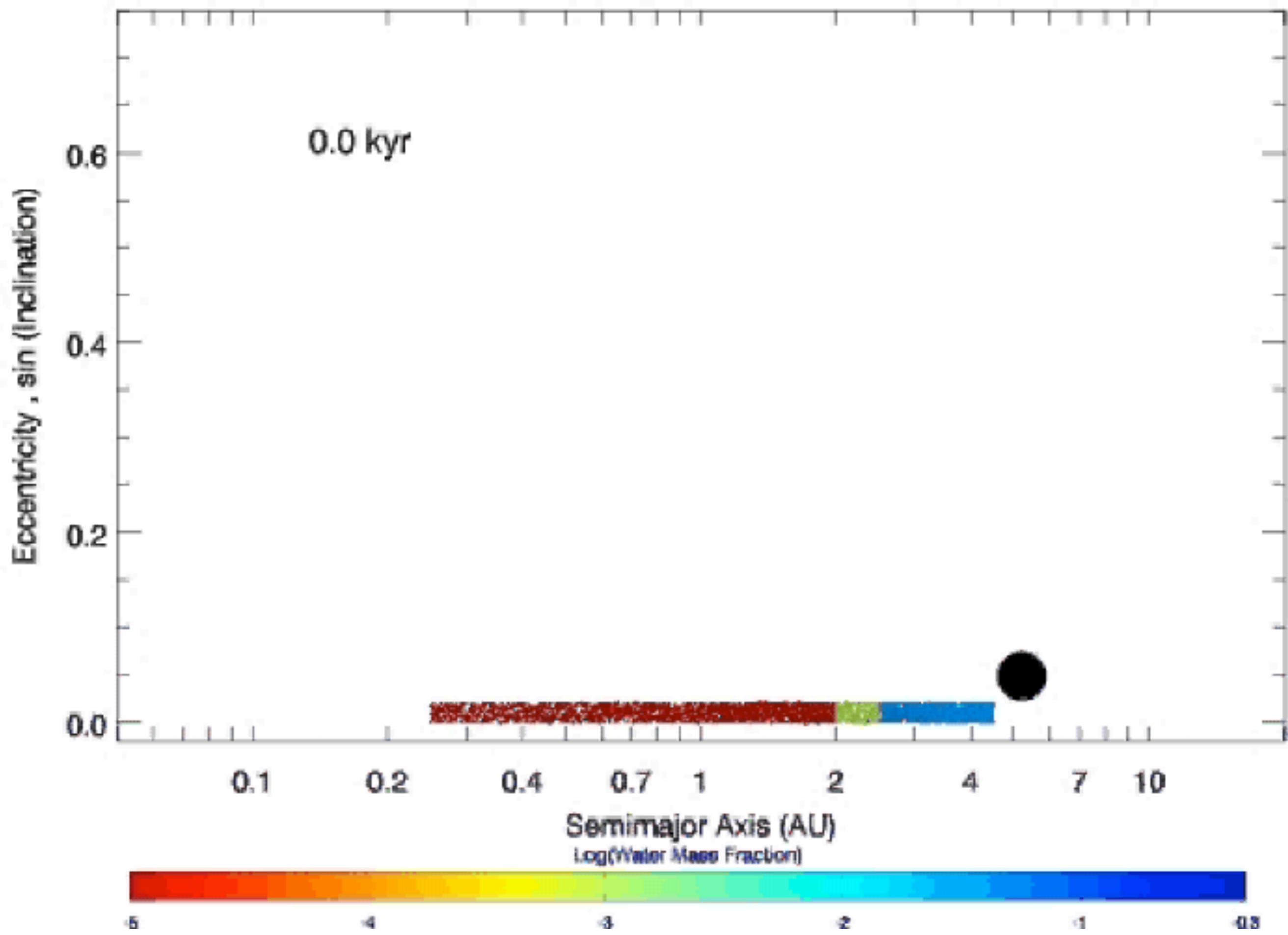
# Giant exoplanets



Wright et al  
2011



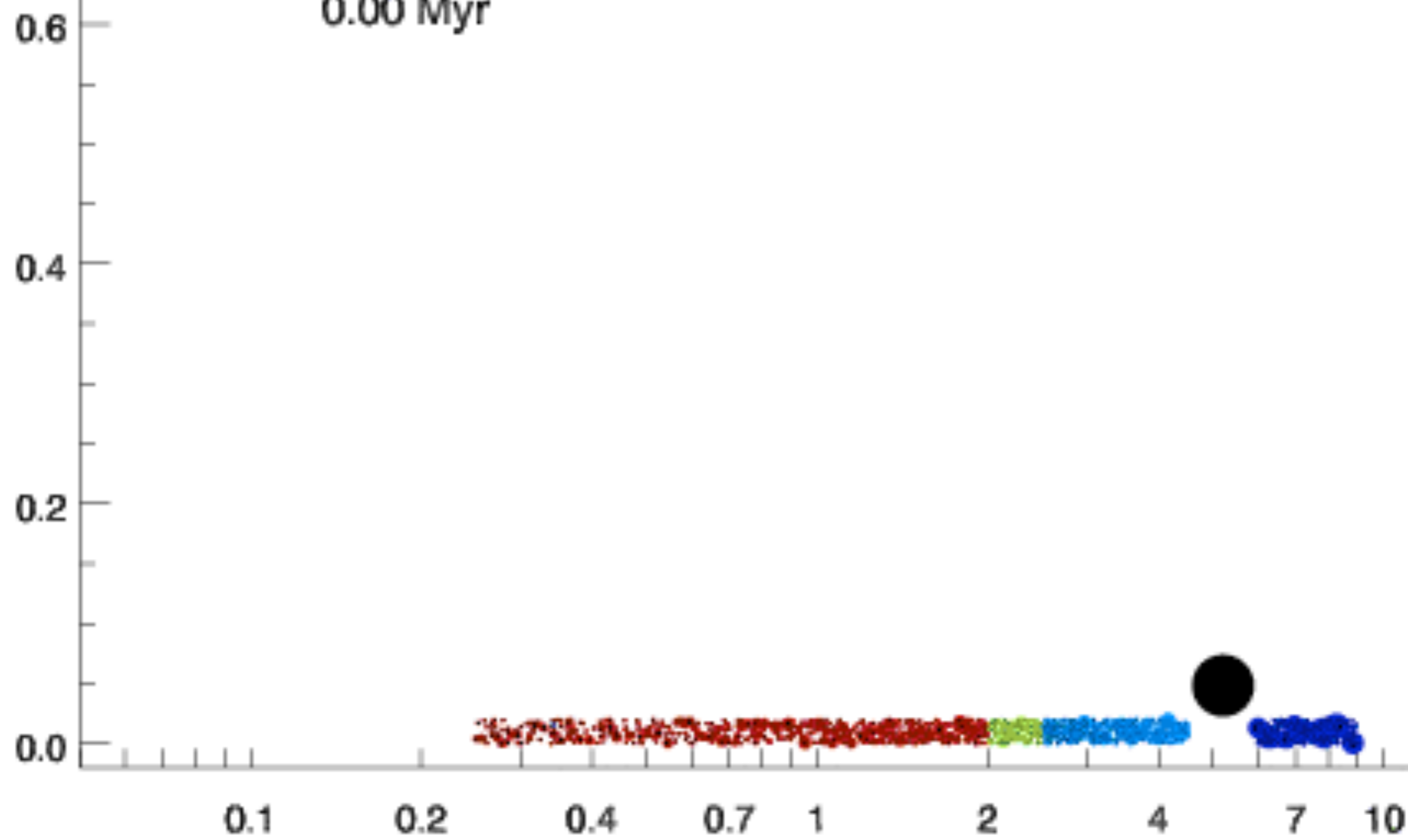






Eccentricity,  $\sin$  (Inclination)

0.00 Myr



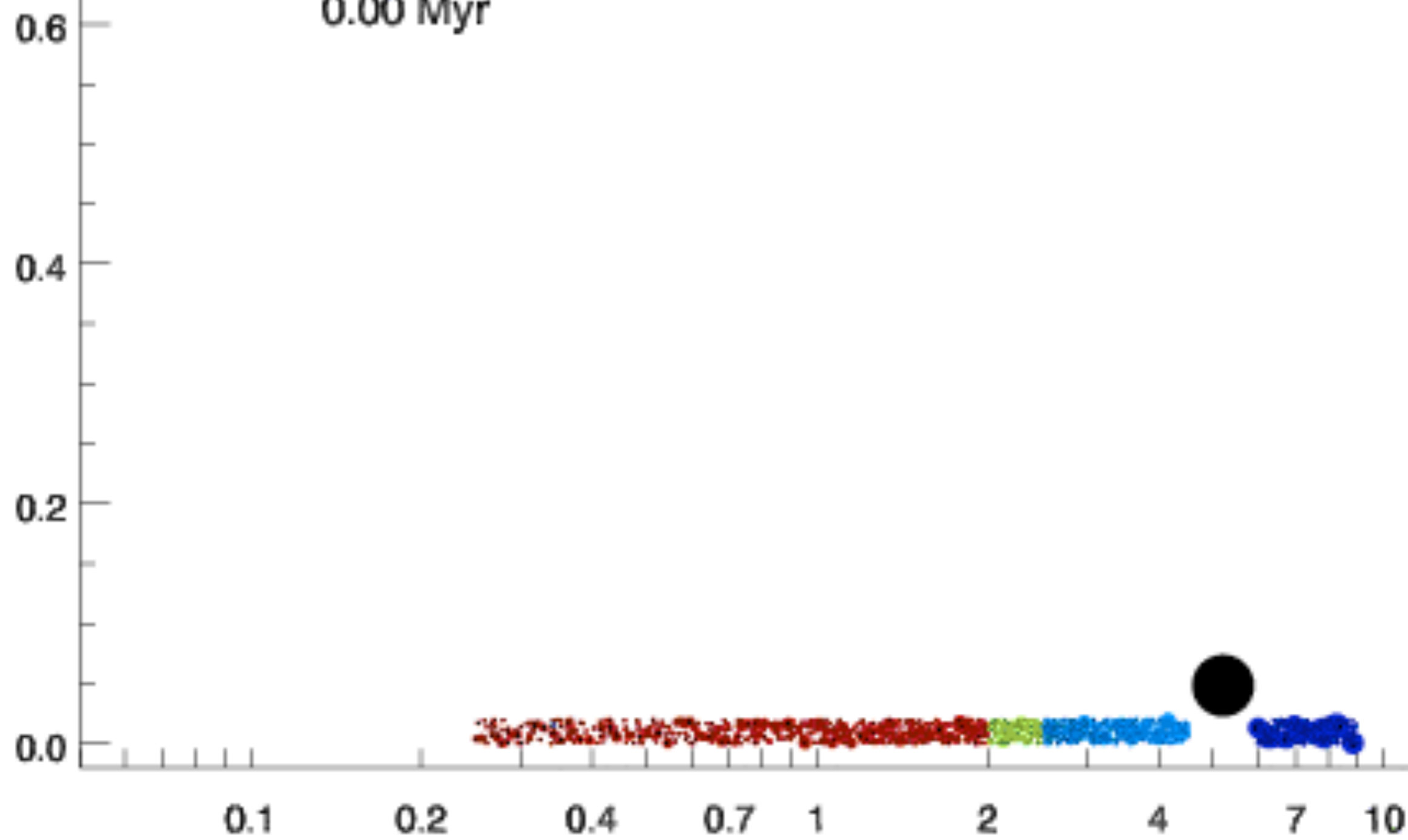
Semimajor Axis (AU)

Log(Water Mass Fraction)



Eccentricity,  $\sin$  (Inclination)

0.00 Myr



Semimajor Axis (AU)

Log(Water Mass Fraction)











# Planet-planet scattering



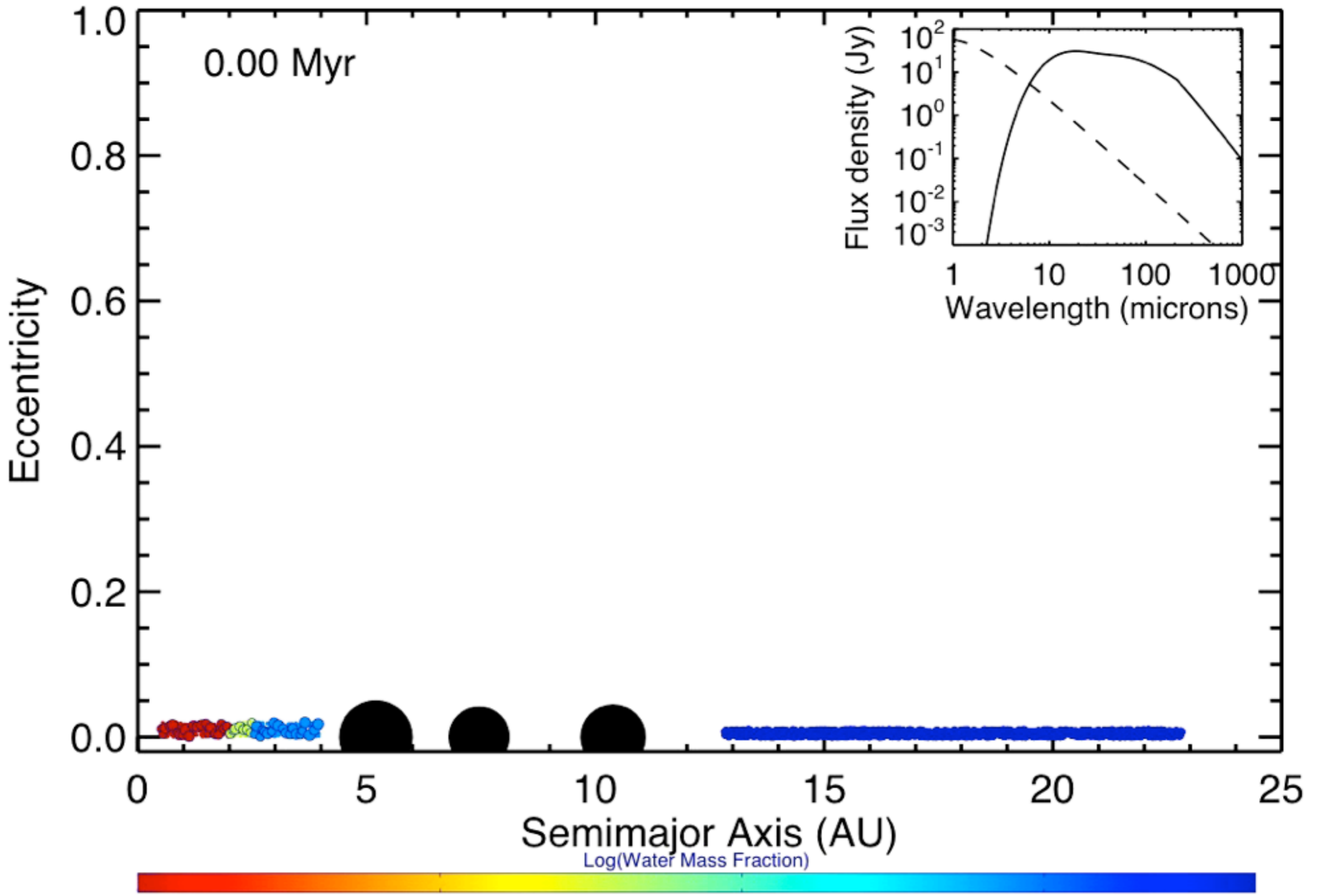
Simulation Time: 00.0 years

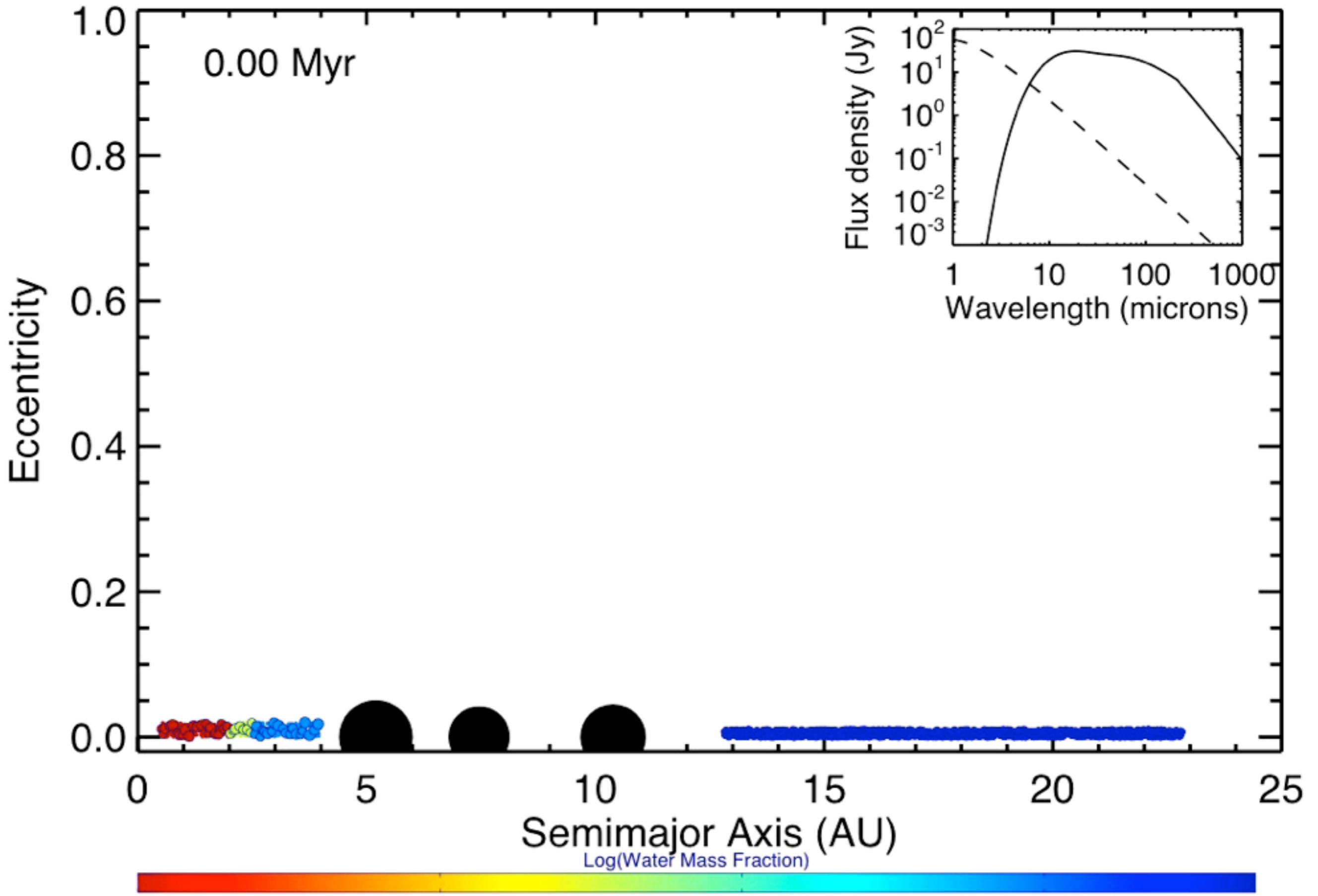
# Planet-planet scattering



Simulation Time: 00.0 years

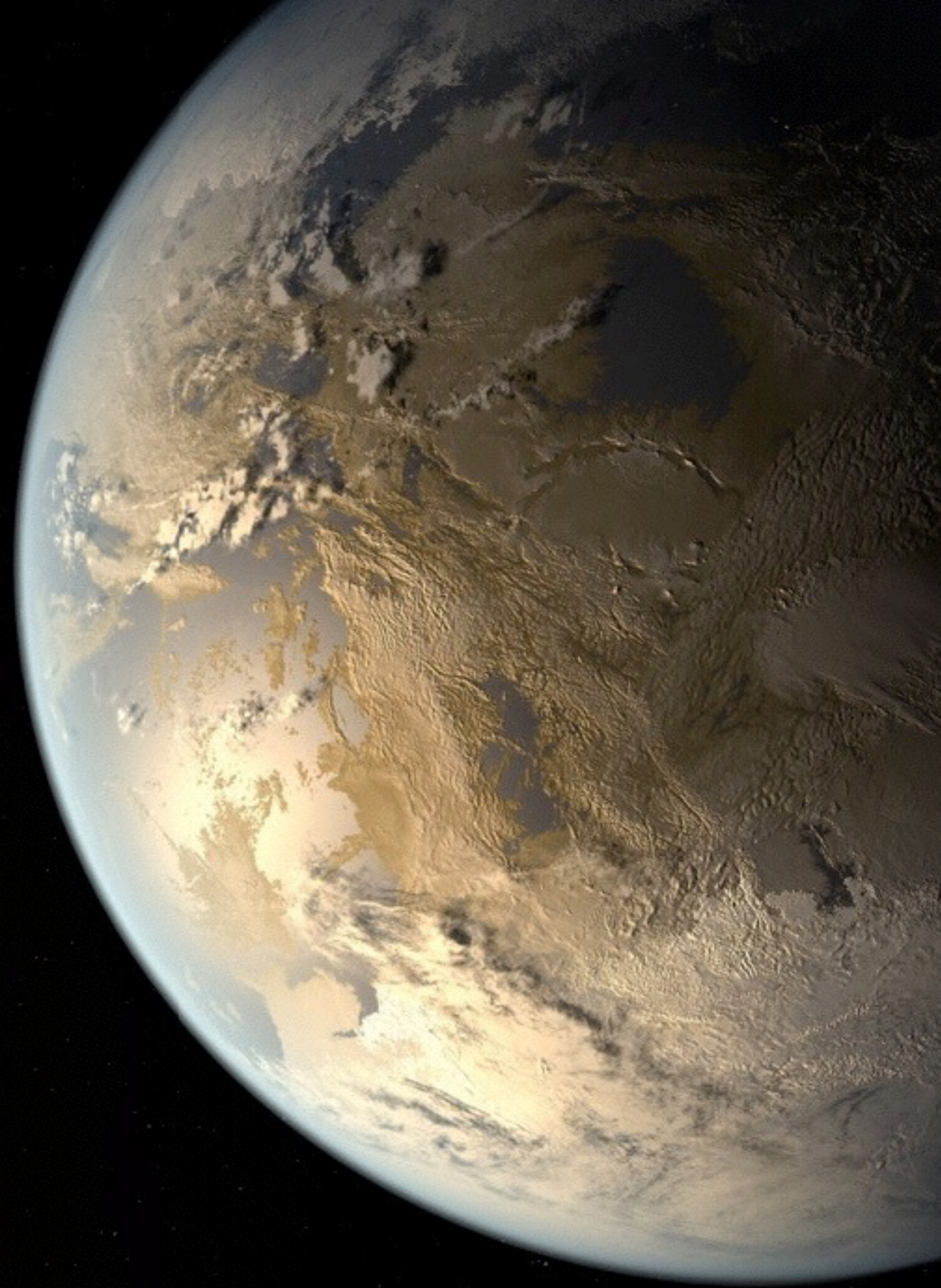






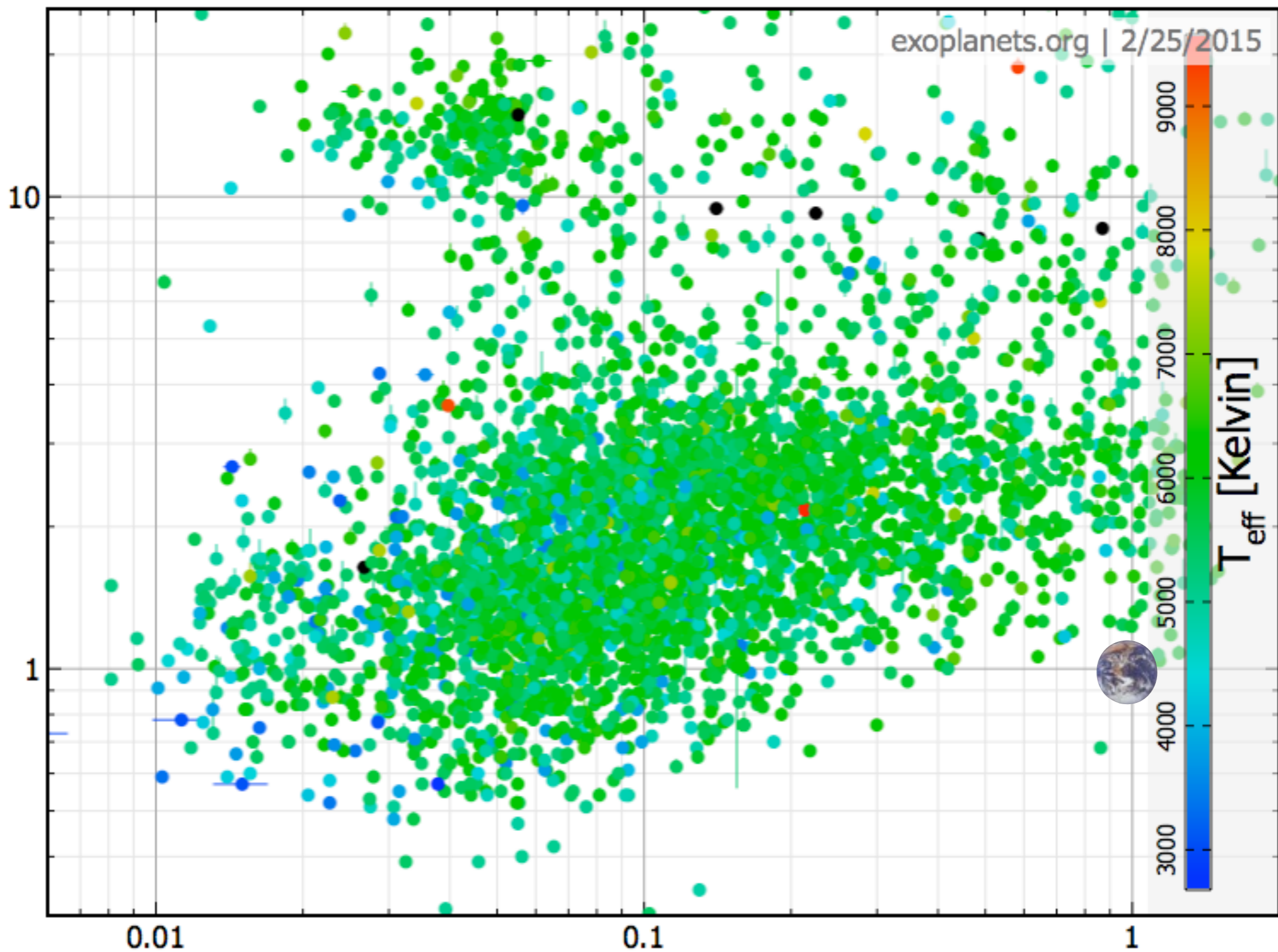


# Formation of systems of hot super-Earths





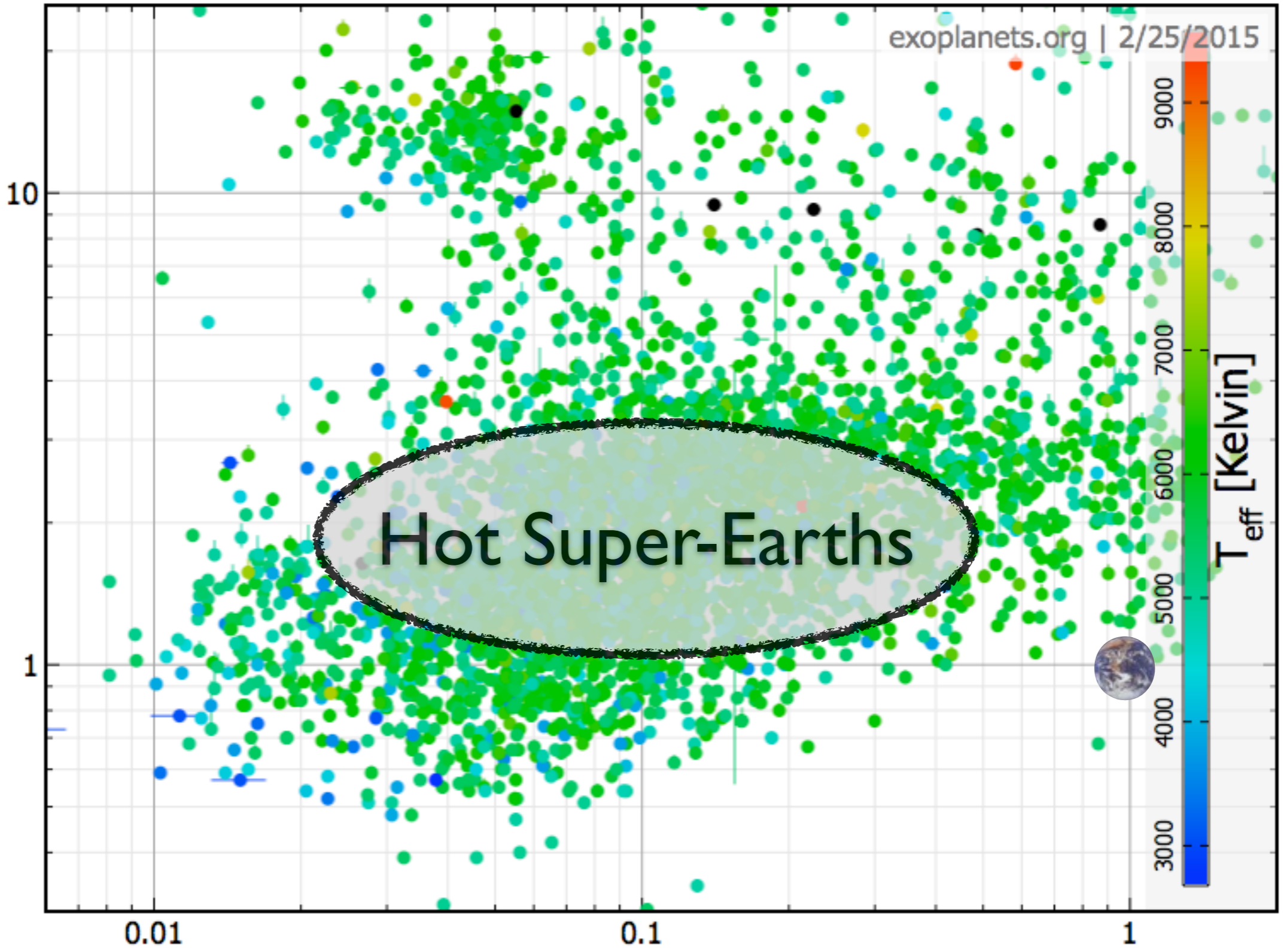
Planetary Radius [Earth Radii]



Semi-Major Axis [Astronomical Units (AU)]



Planetary Radius [Earth Radii]



Hot Super-Earths

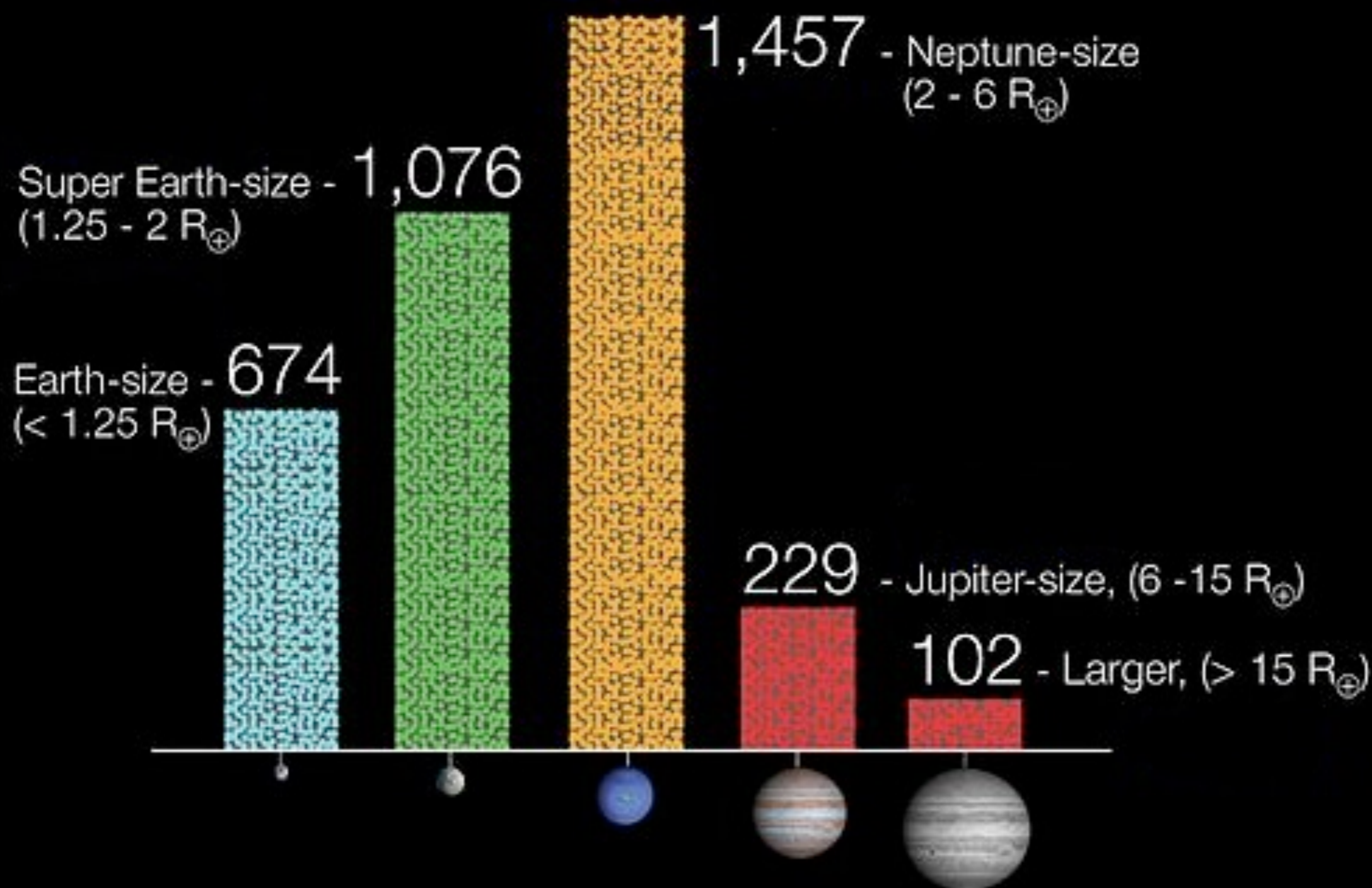
Semi-Major Axis [Astronomical Units (AU)]

$T_{\text{eff}}$  [Kelvin]



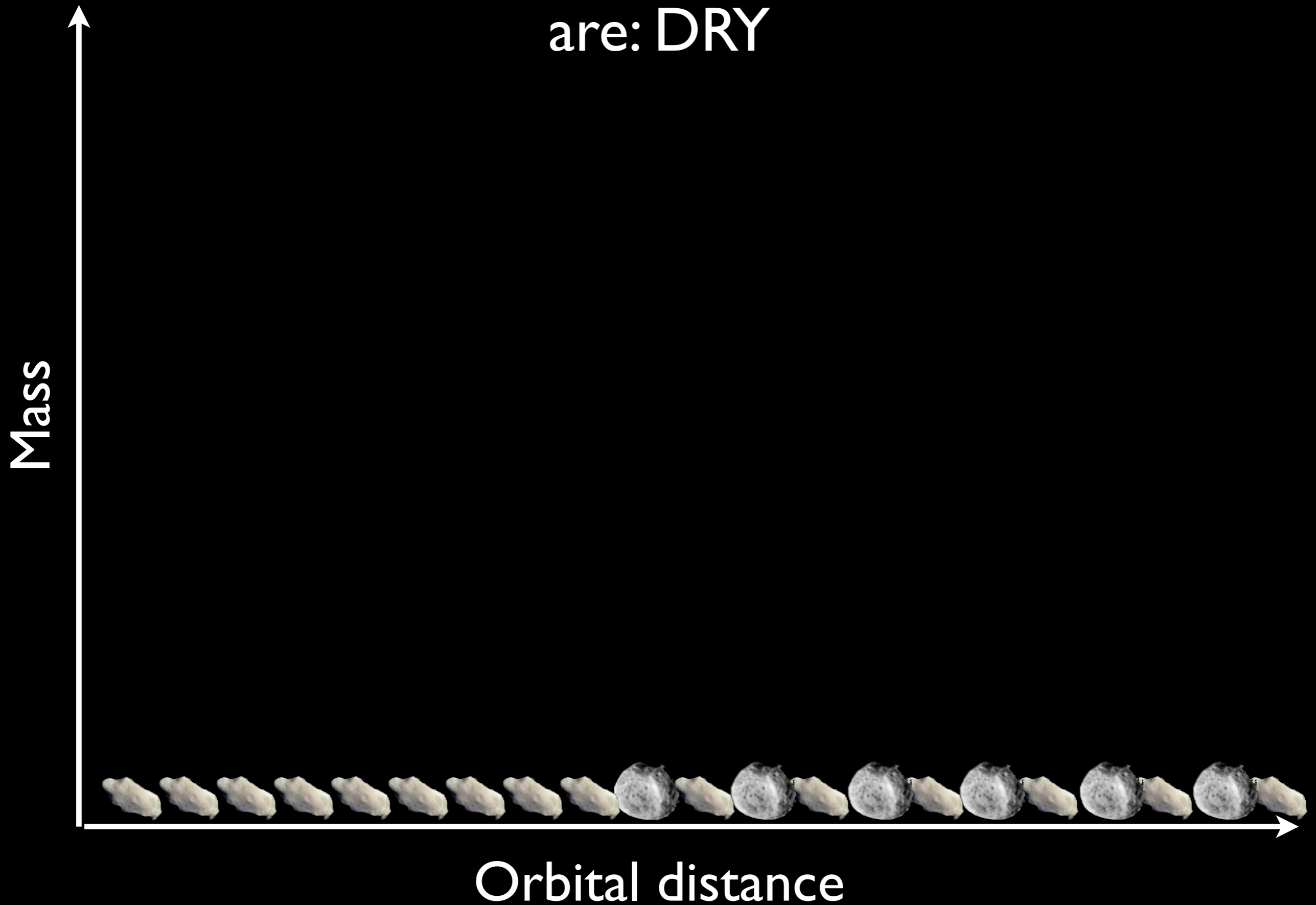
# Sizes of Planet Candidates

Totals as of November, 2013

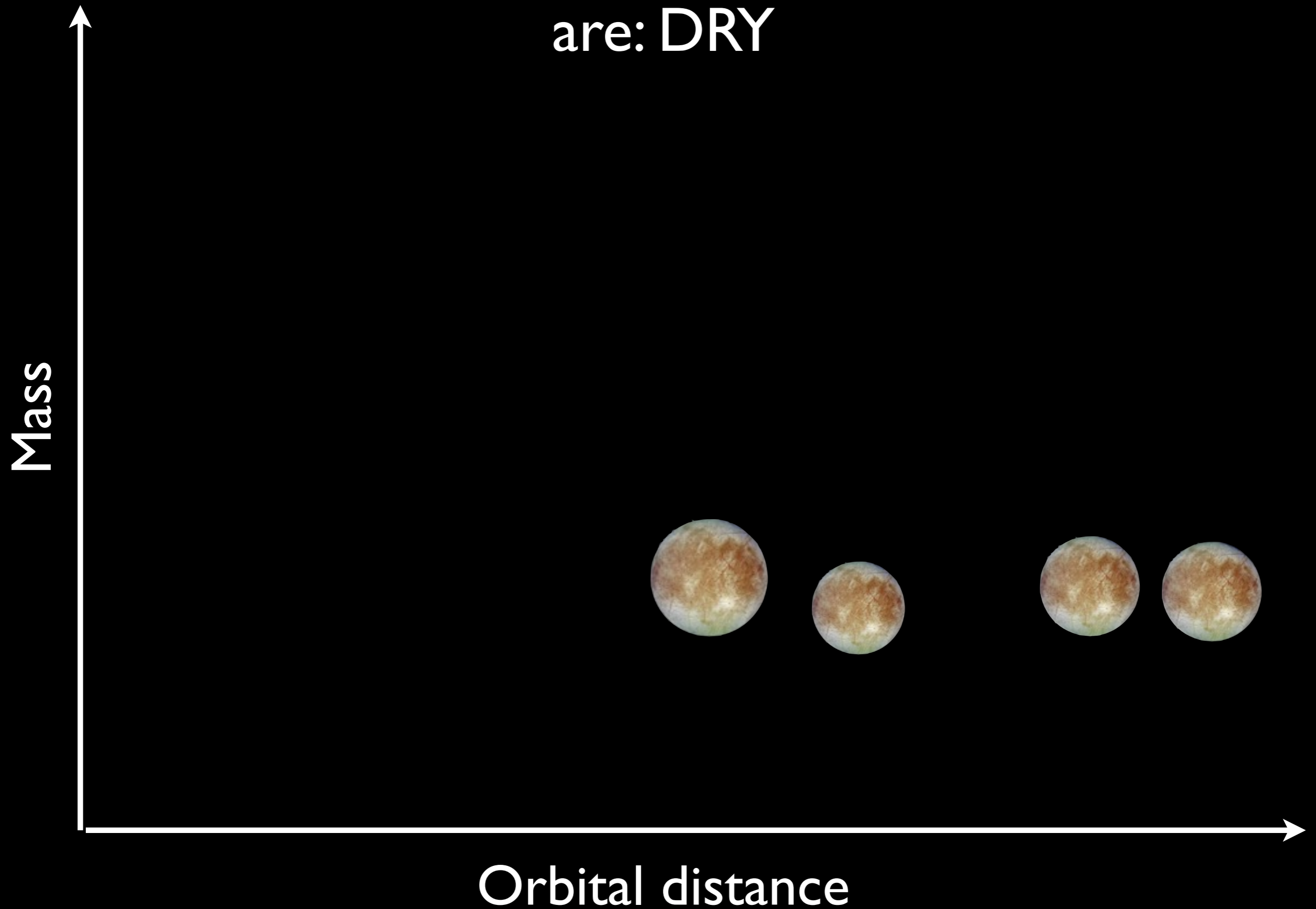




# Model 1. Hot super-Earths formed where they are: DRY

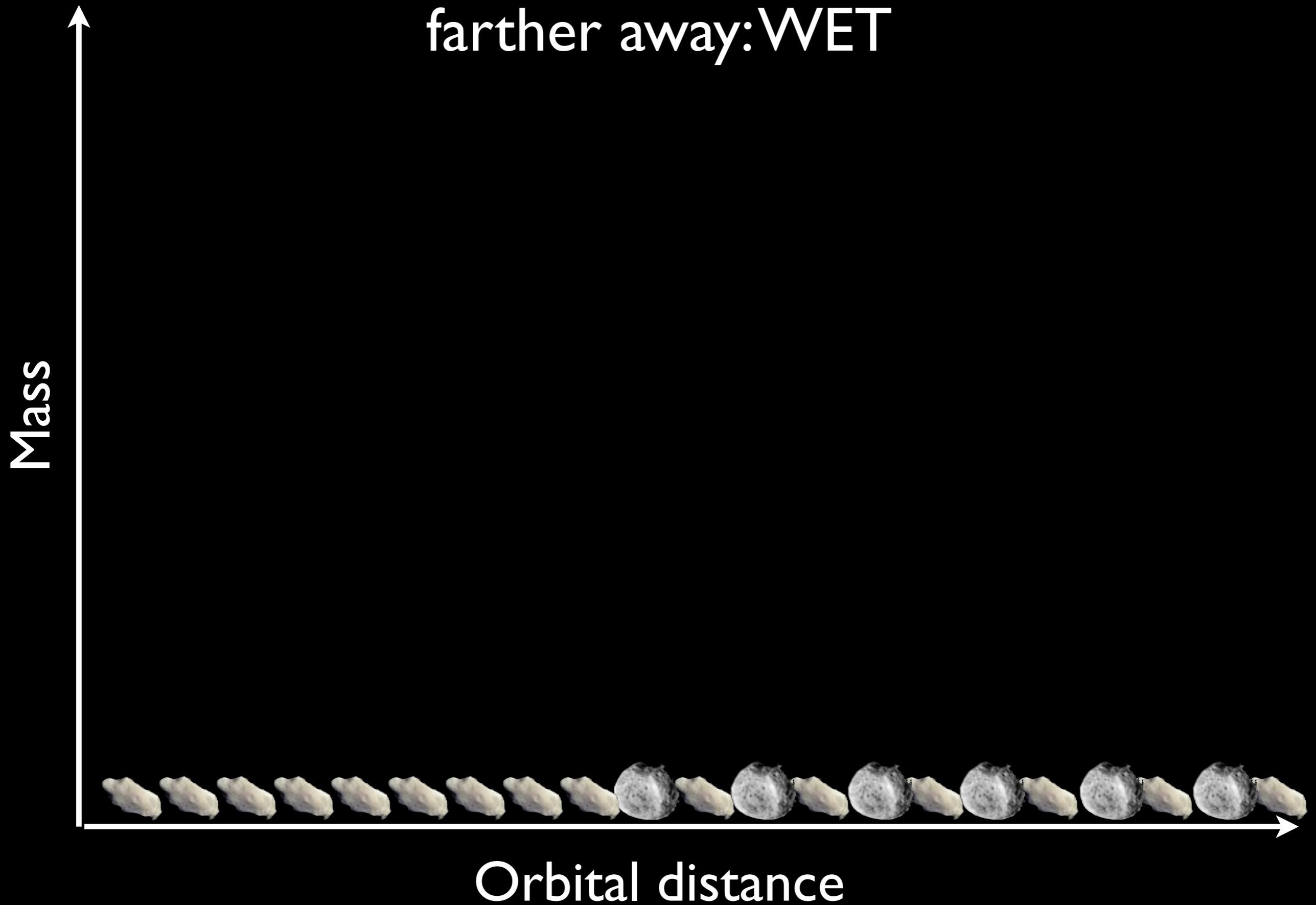


# Model 1. Hot super-Earths formed where they are: DRY

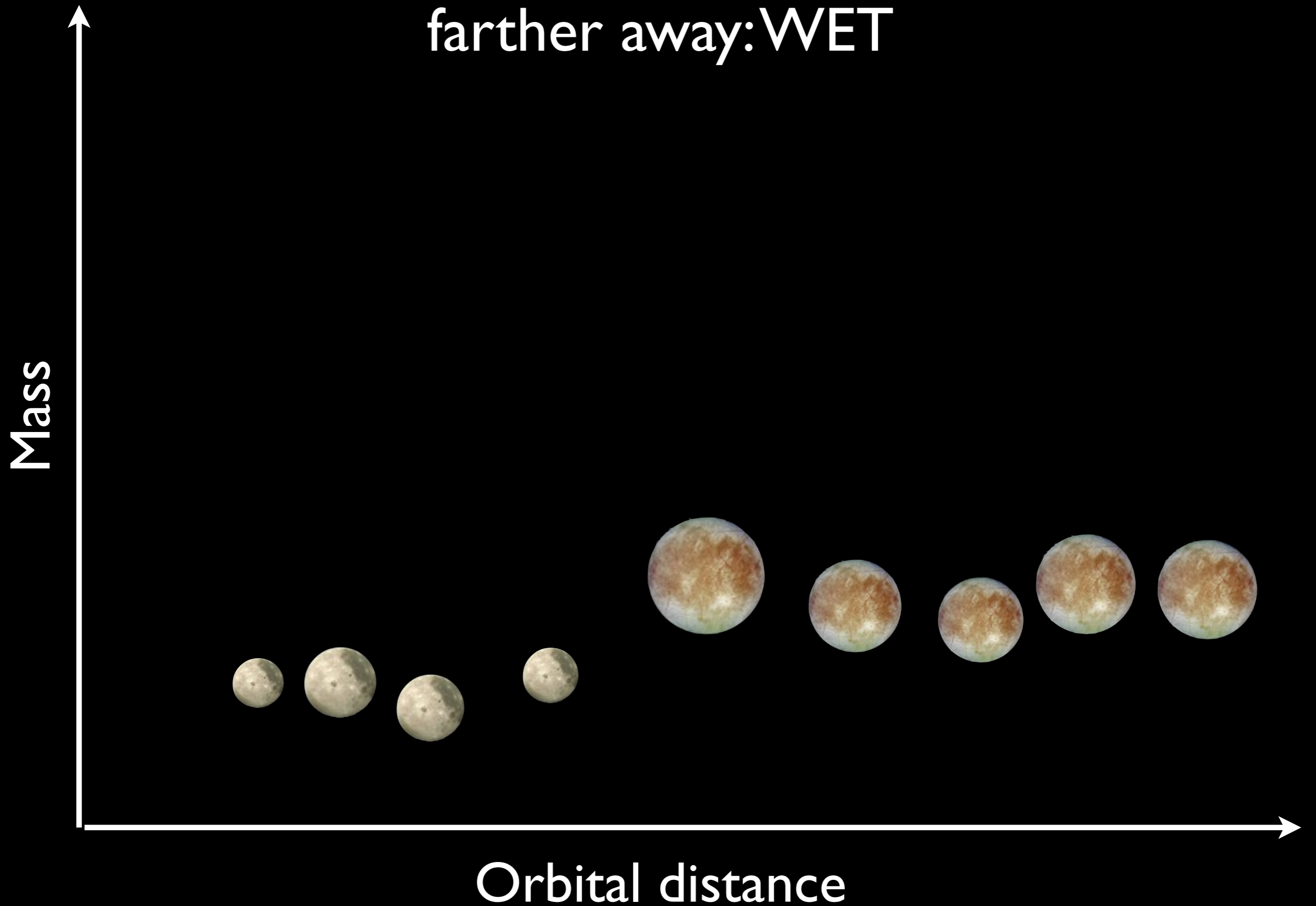




# Model 2. Hot super-Earths migrate inward from farther away: WET



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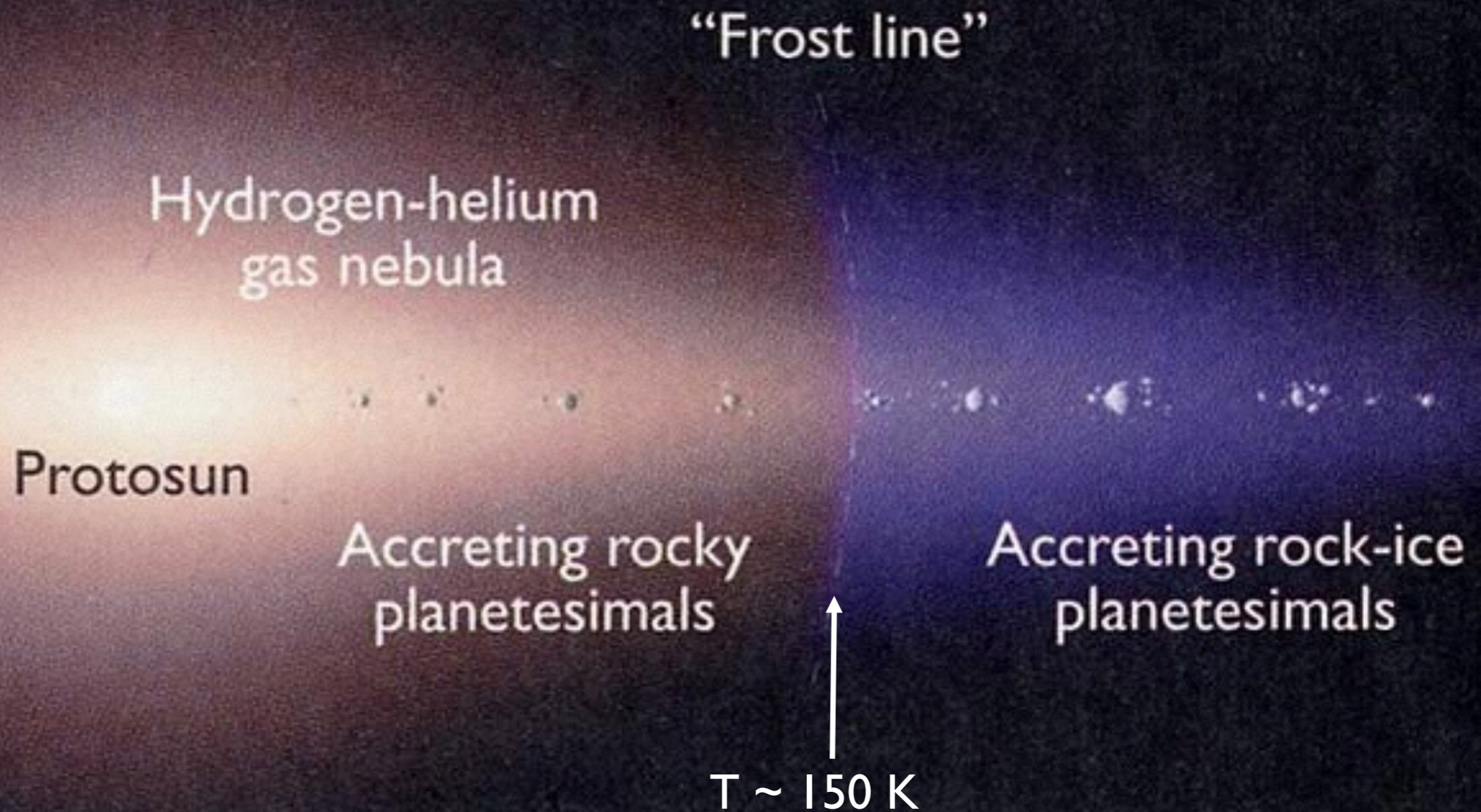




# Model 2. Hot super-Earths migrate inward from farther away: WET

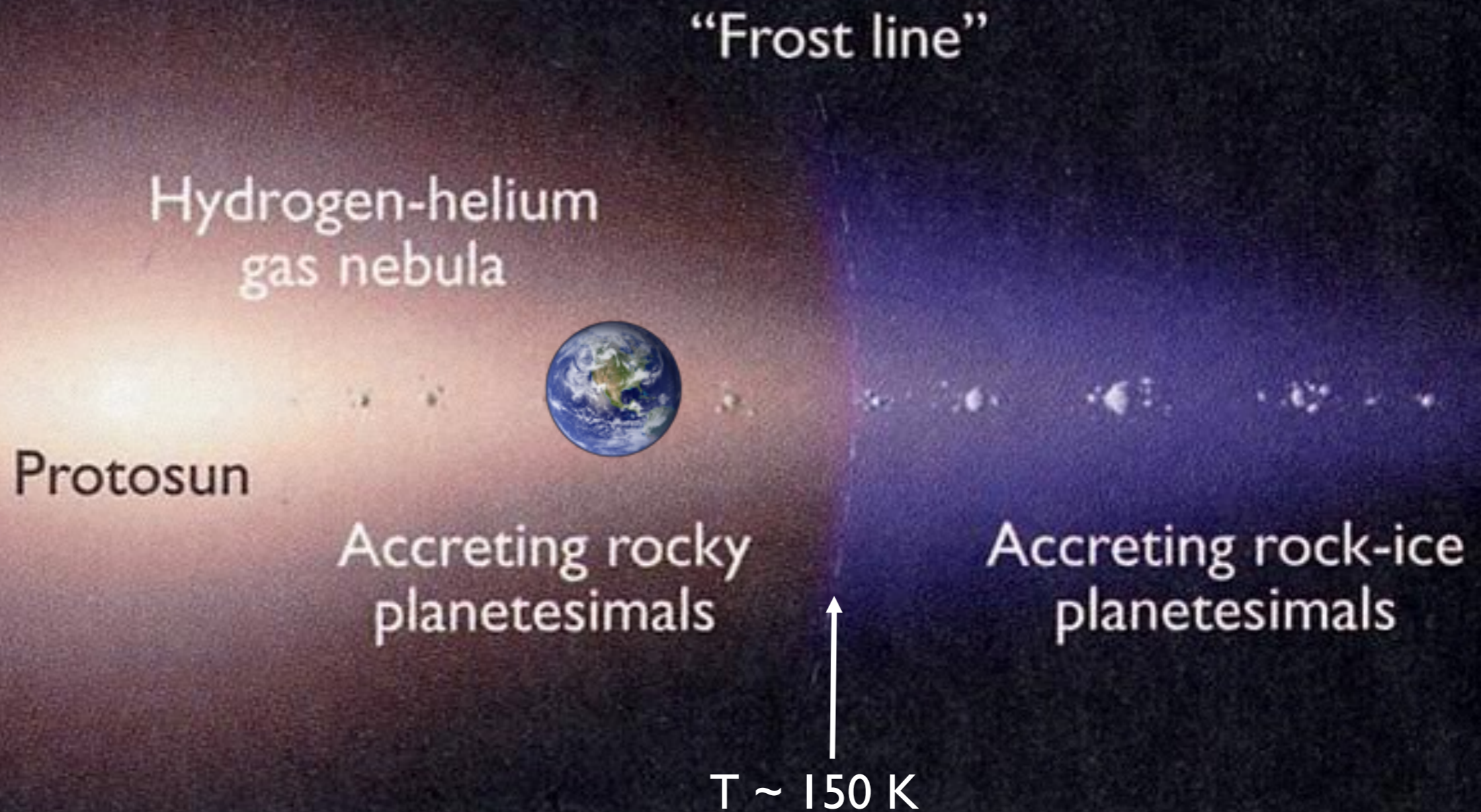


# Water delivery





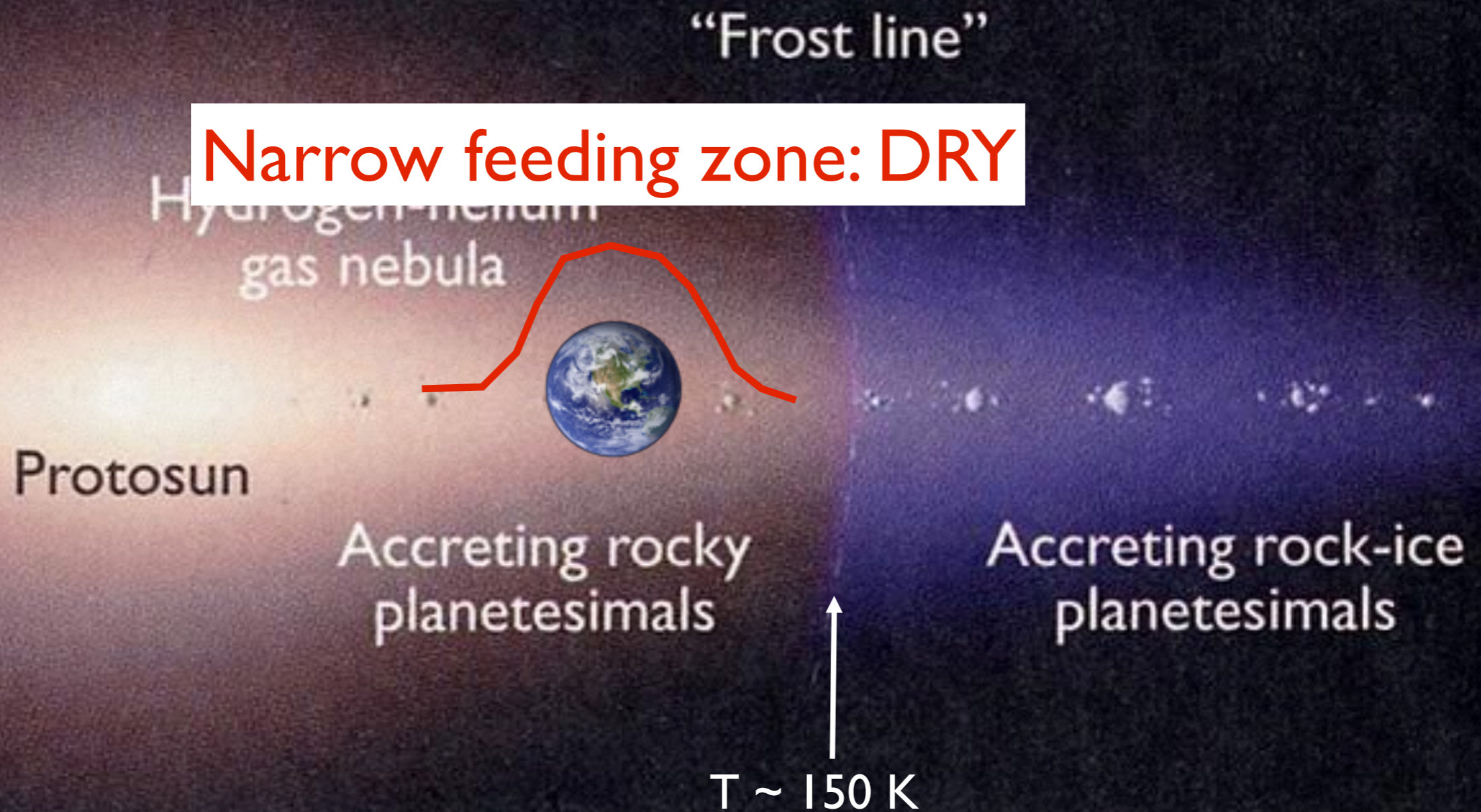
# Water delivery





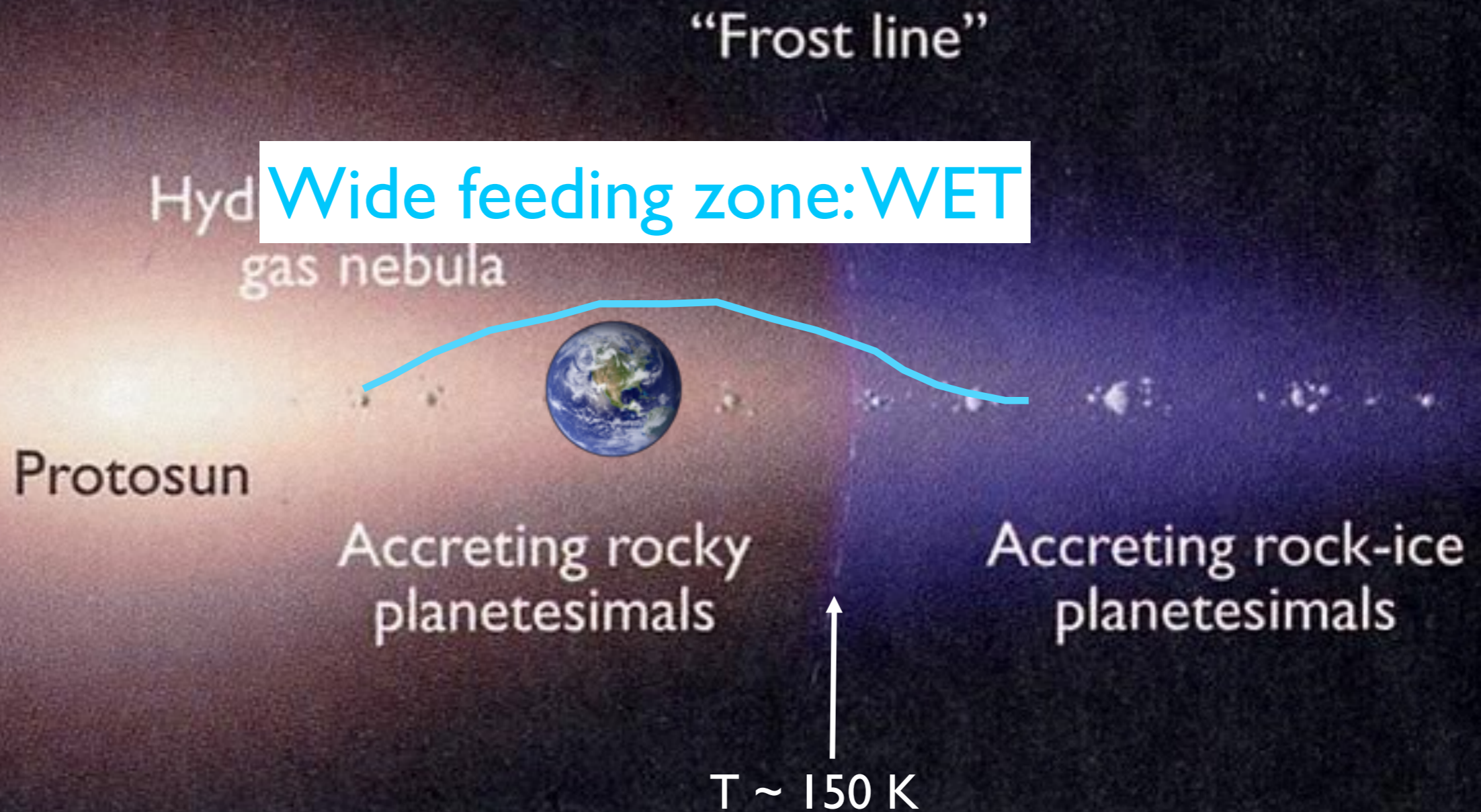
# Water delivery

**Narrow feeding zone: DRY**





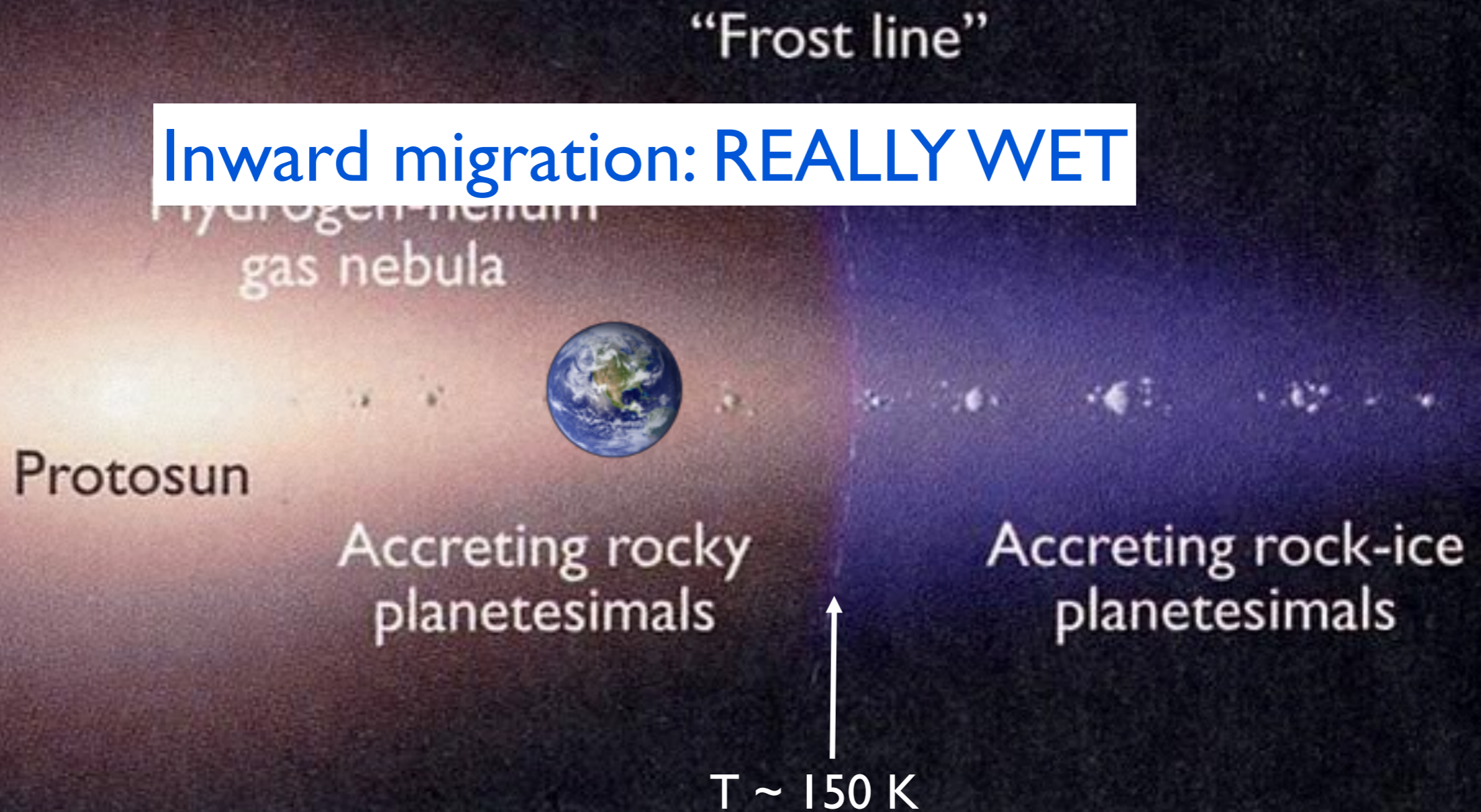
# Water delivery



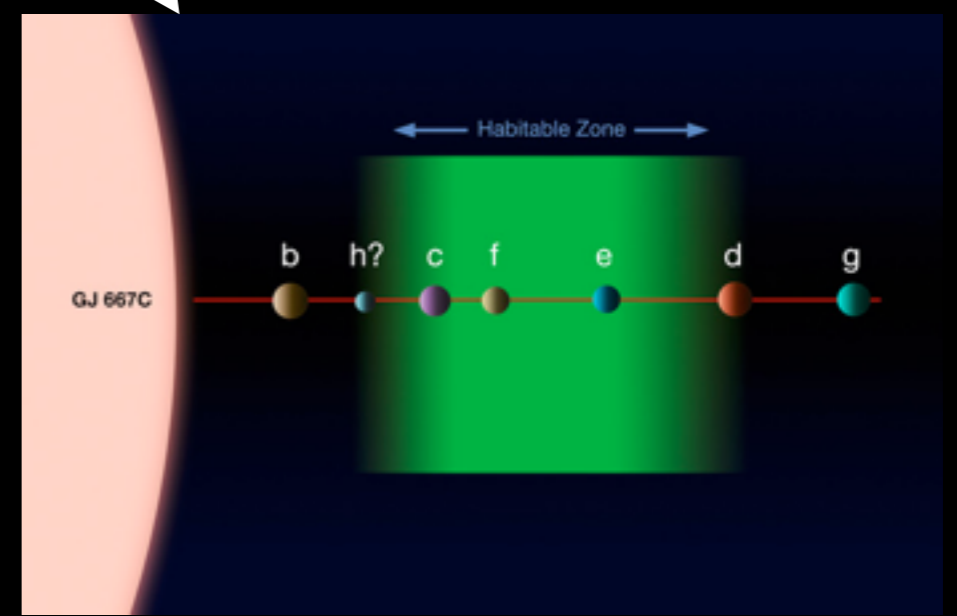
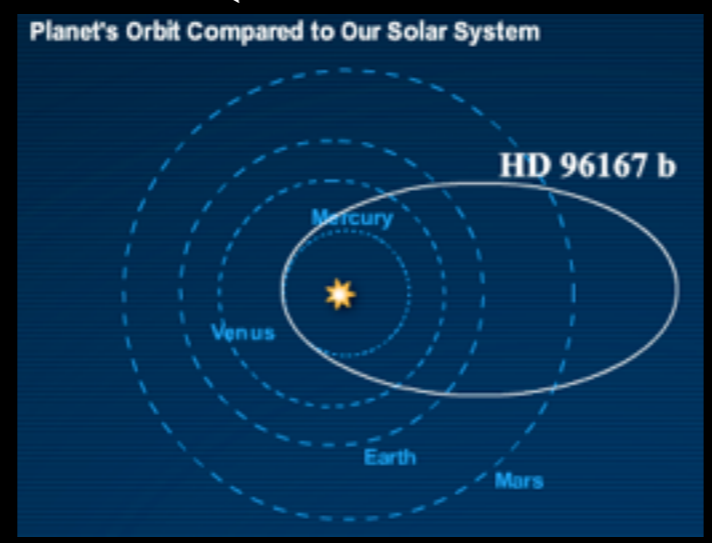
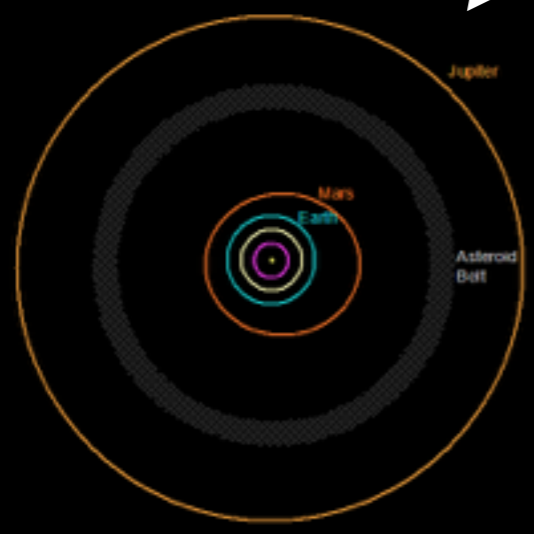
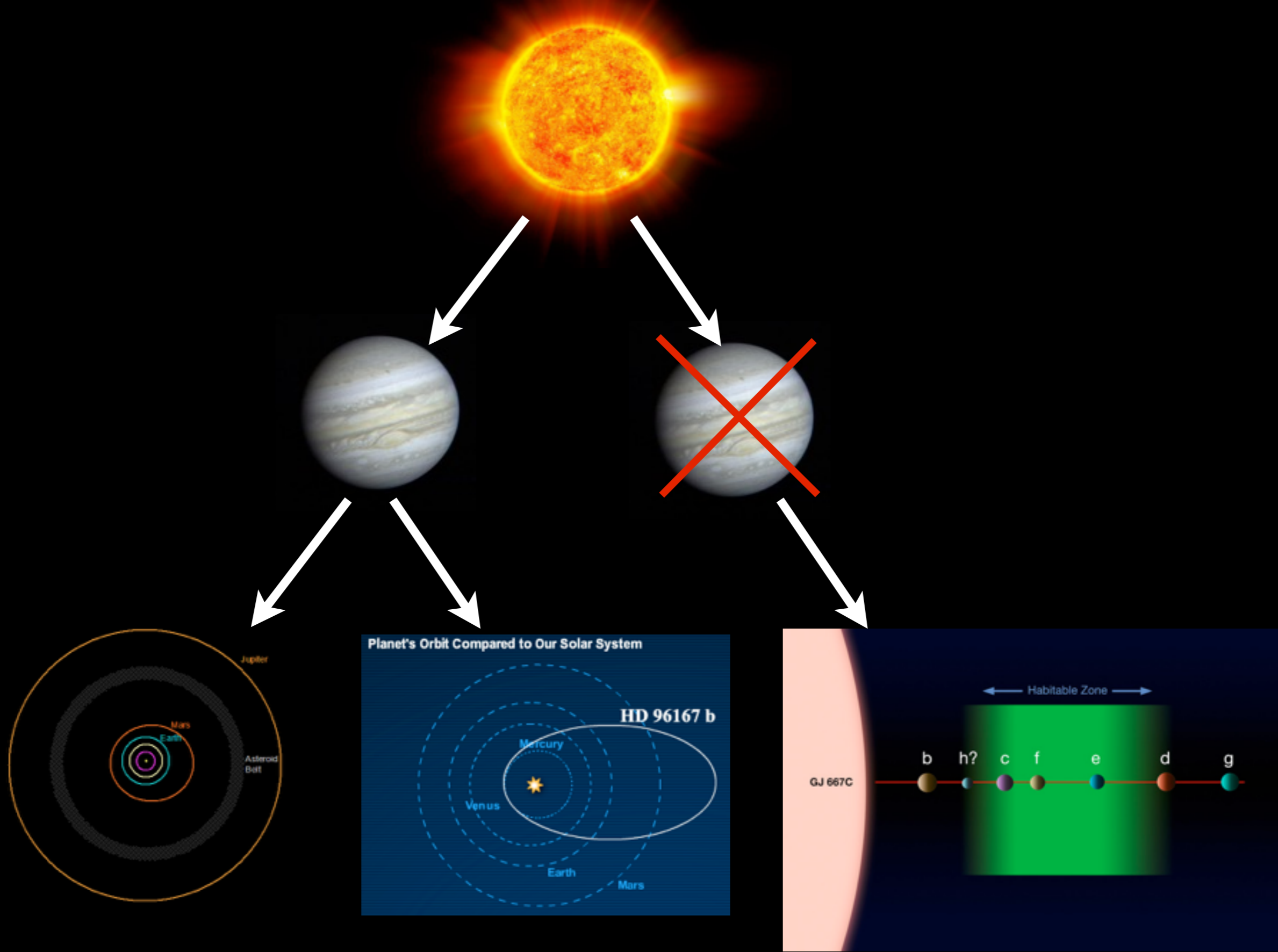


# Water delivery

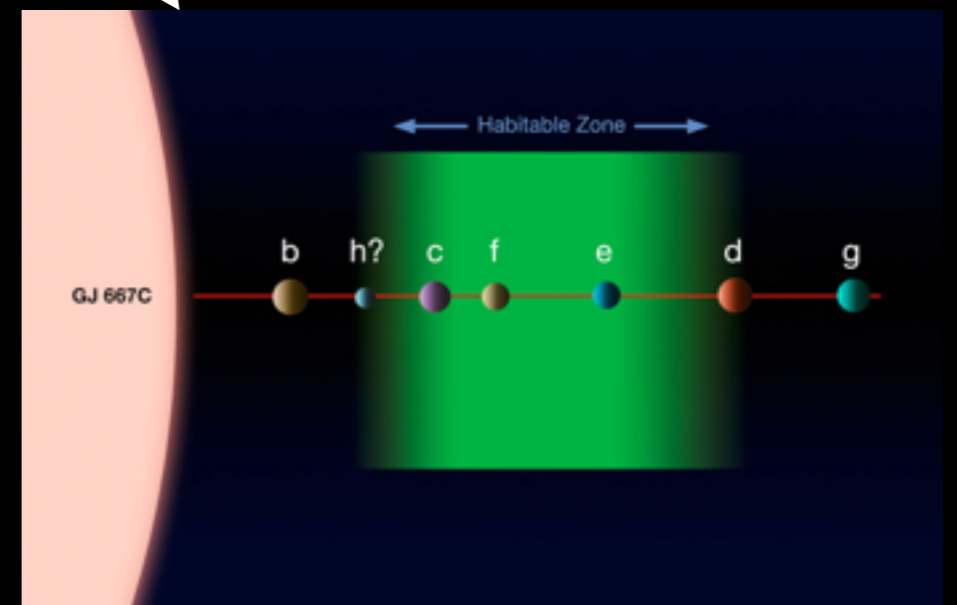
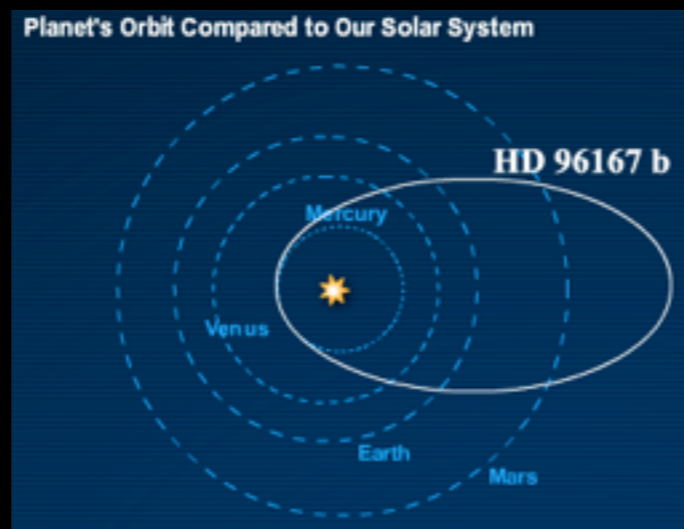
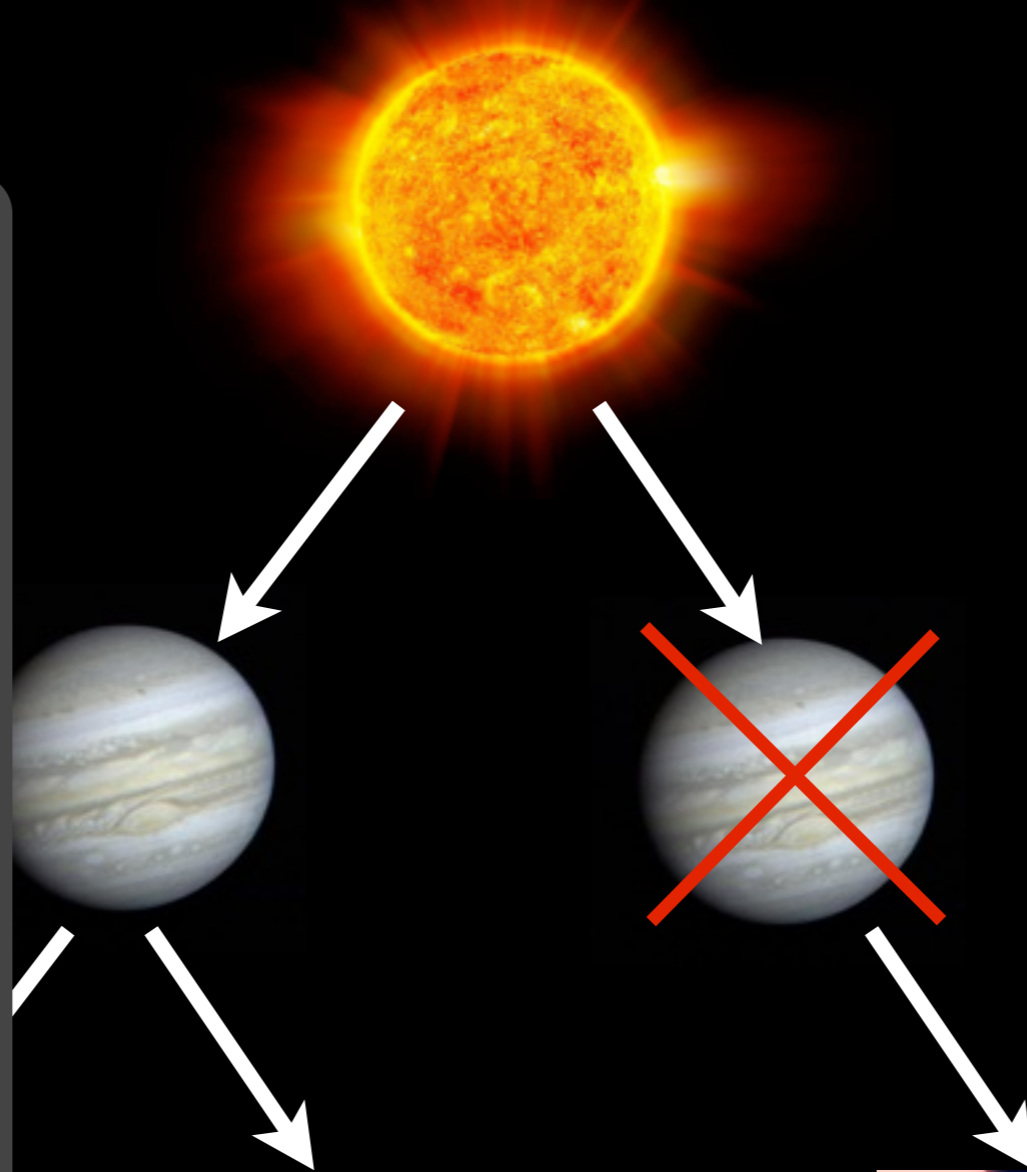
Inward migration: REALLY WET





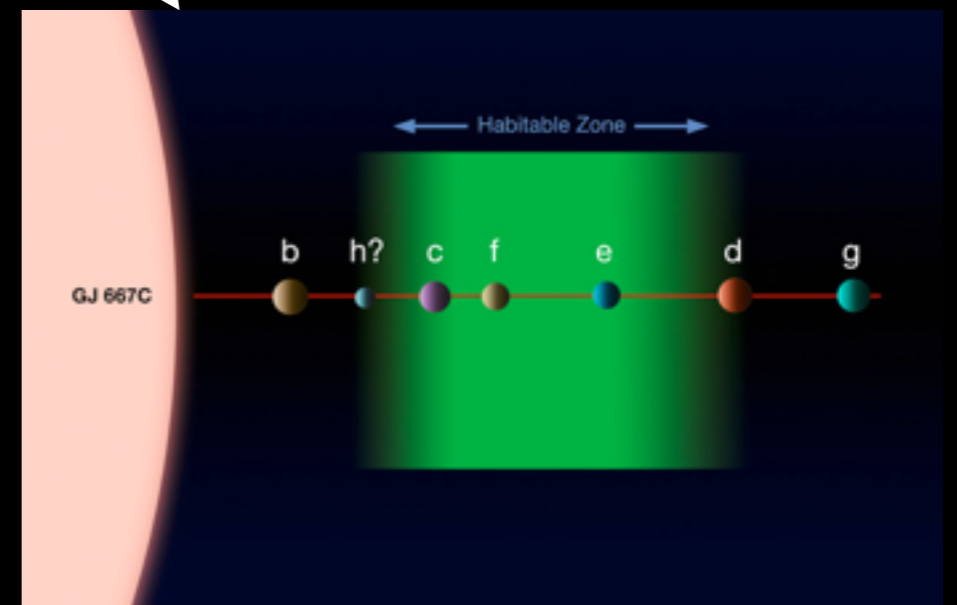
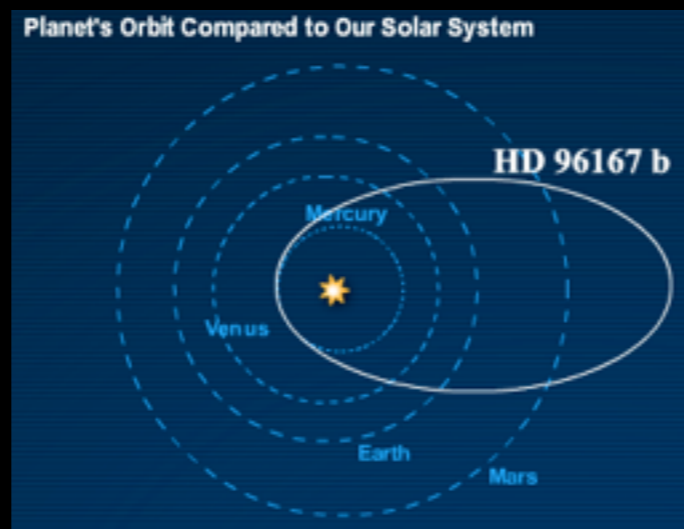
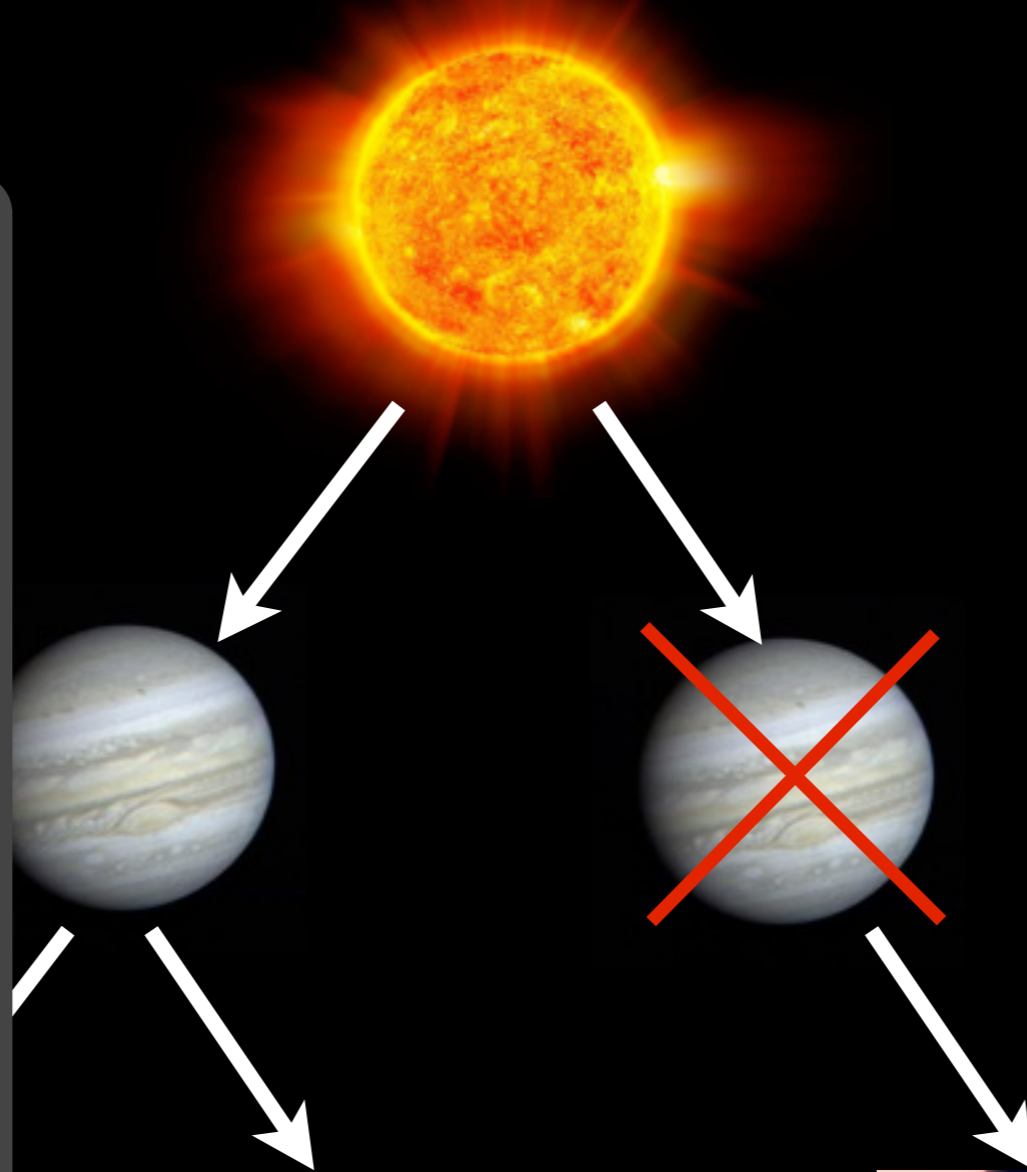


# Solar System

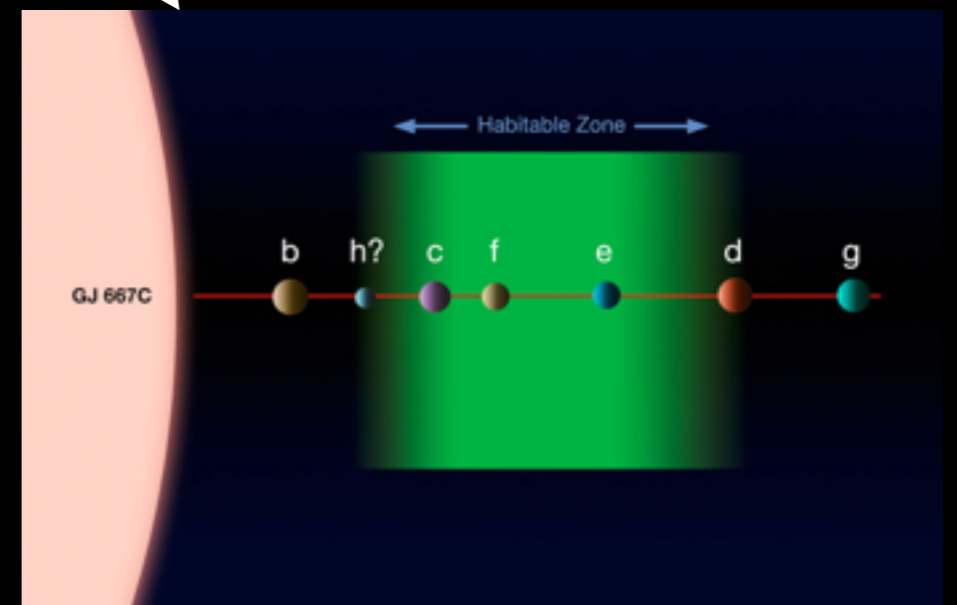
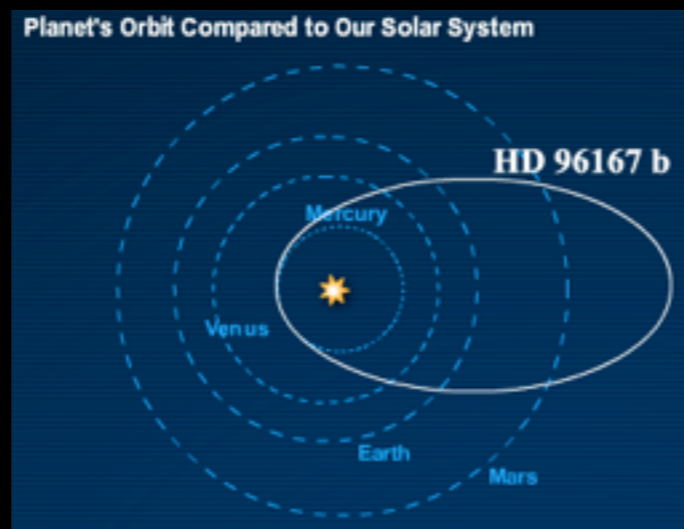
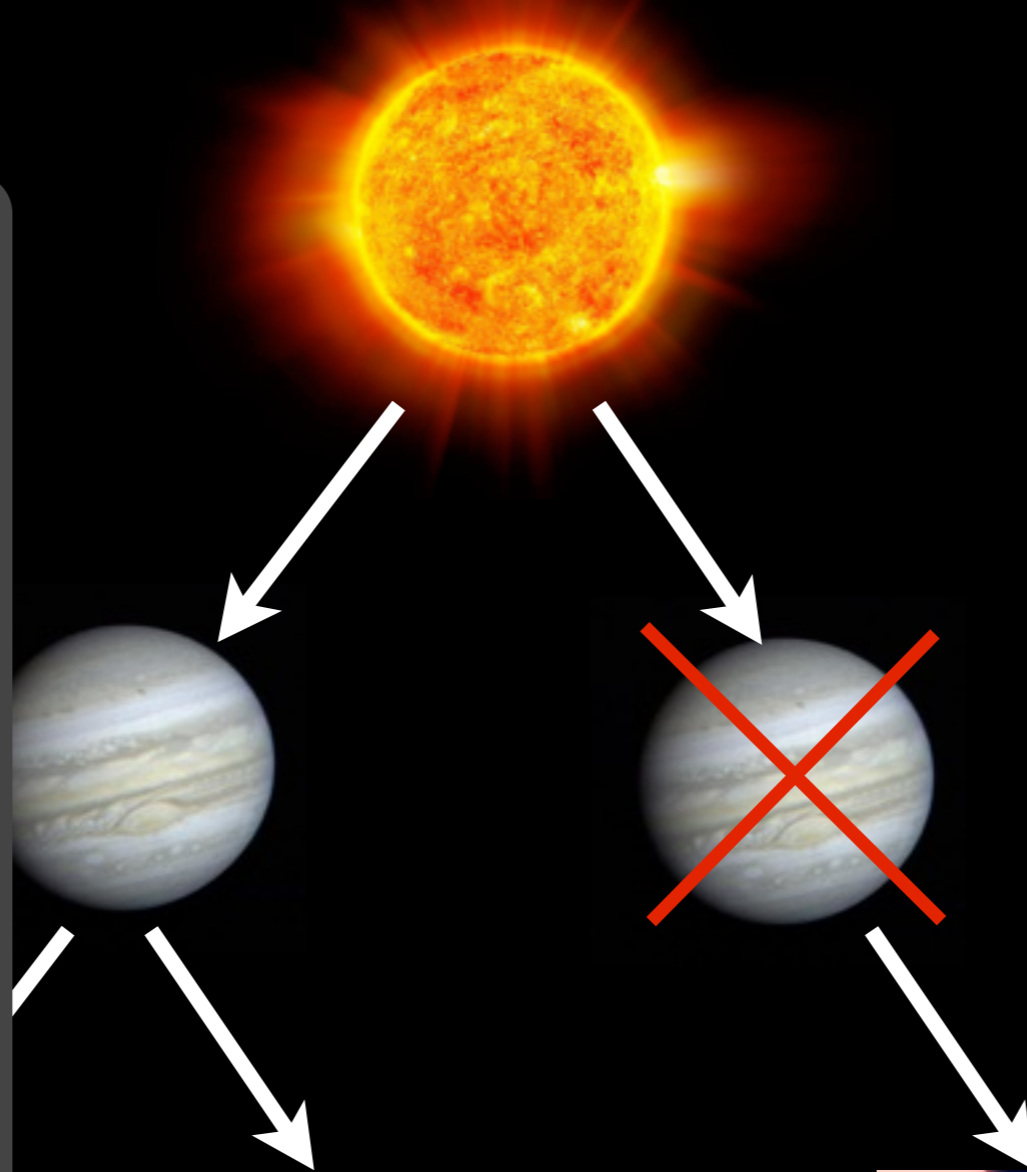




# Solar System



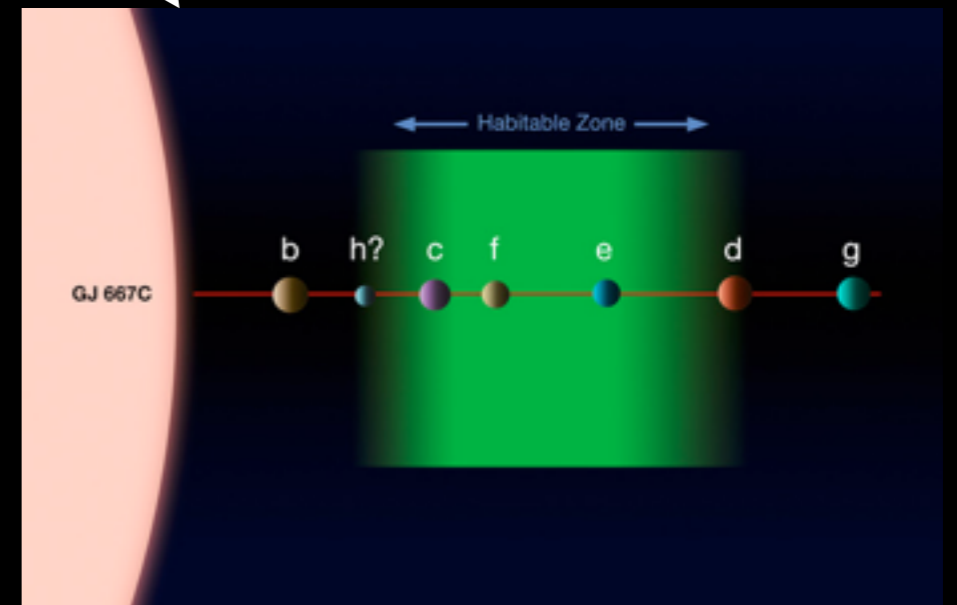
# Solar System





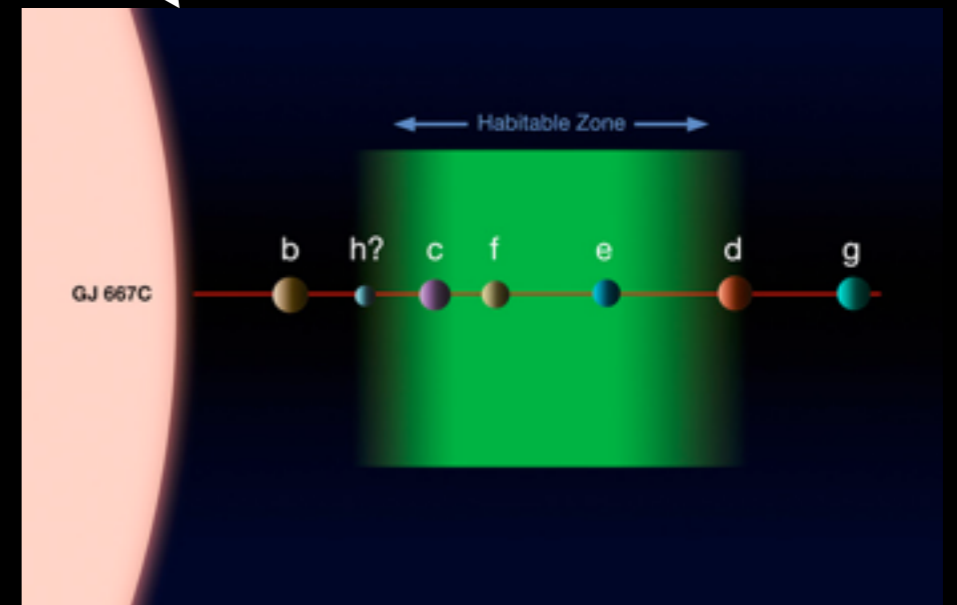
Solar  
System

Angry gas  
giants



Solar  
System

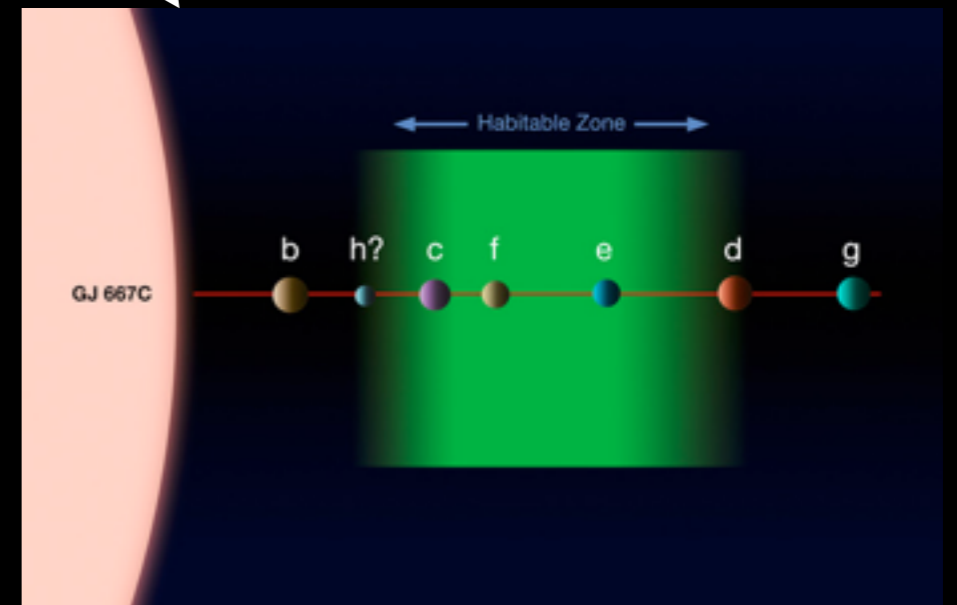
Angry gas  
giants





Solar  
System

Angry gas  
giants



**Solar  
System**

**Angry gas  
giants**

**Hot super-  
Earths**

g



**Solar  
System**

**Angry gas  
giants**

**Hot super-  
Earths**

g

**Solar  
System**

**Angry gas  
giants**

**Hot super-  
Earths**

g

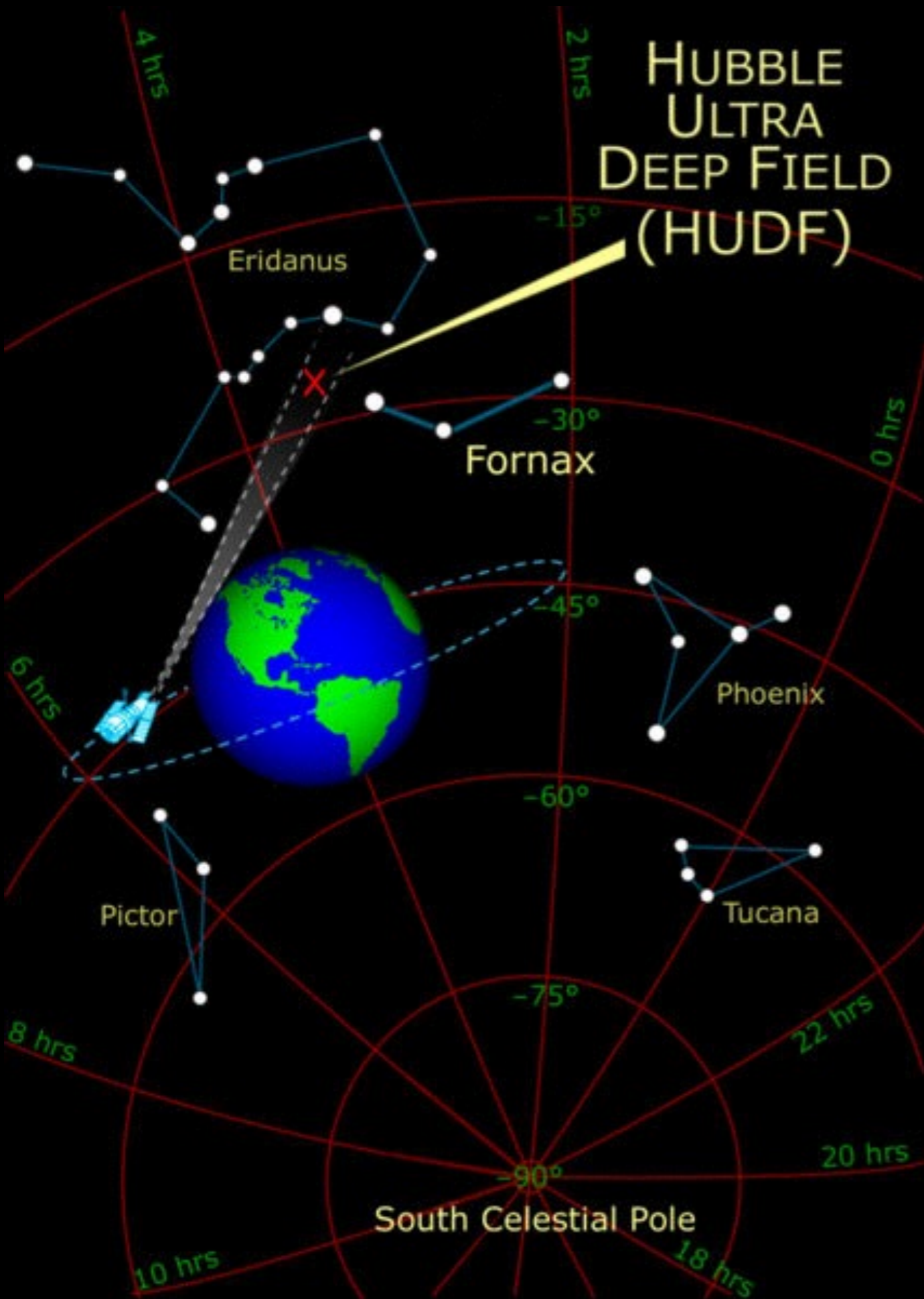


Extra slides

A composite image showing the Moon in the upper left and the Earth in the lower right against a black background. The Moon is a small, yellowish sphere, and the Earth is a larger, blue and white sphere showing continents and clouds. The text "How many planets are out there?" is centered in the middle of the image in a white, serif font.

**How many planets are out there?**






The Hubble Space Telescope stared at a dark patch of sky for 15 days straight








A vast field of galaxies, including spiral, elliptical, and irregular shapes, scattered across a dark background. The galaxies are in various colors, including blue, white, yellow, orange, and red. Some are bright and prominent, while others are faint and small. The overall appearance is a rich, multi-colored population of galaxies.

\* 100s of billions stars in our galaxy



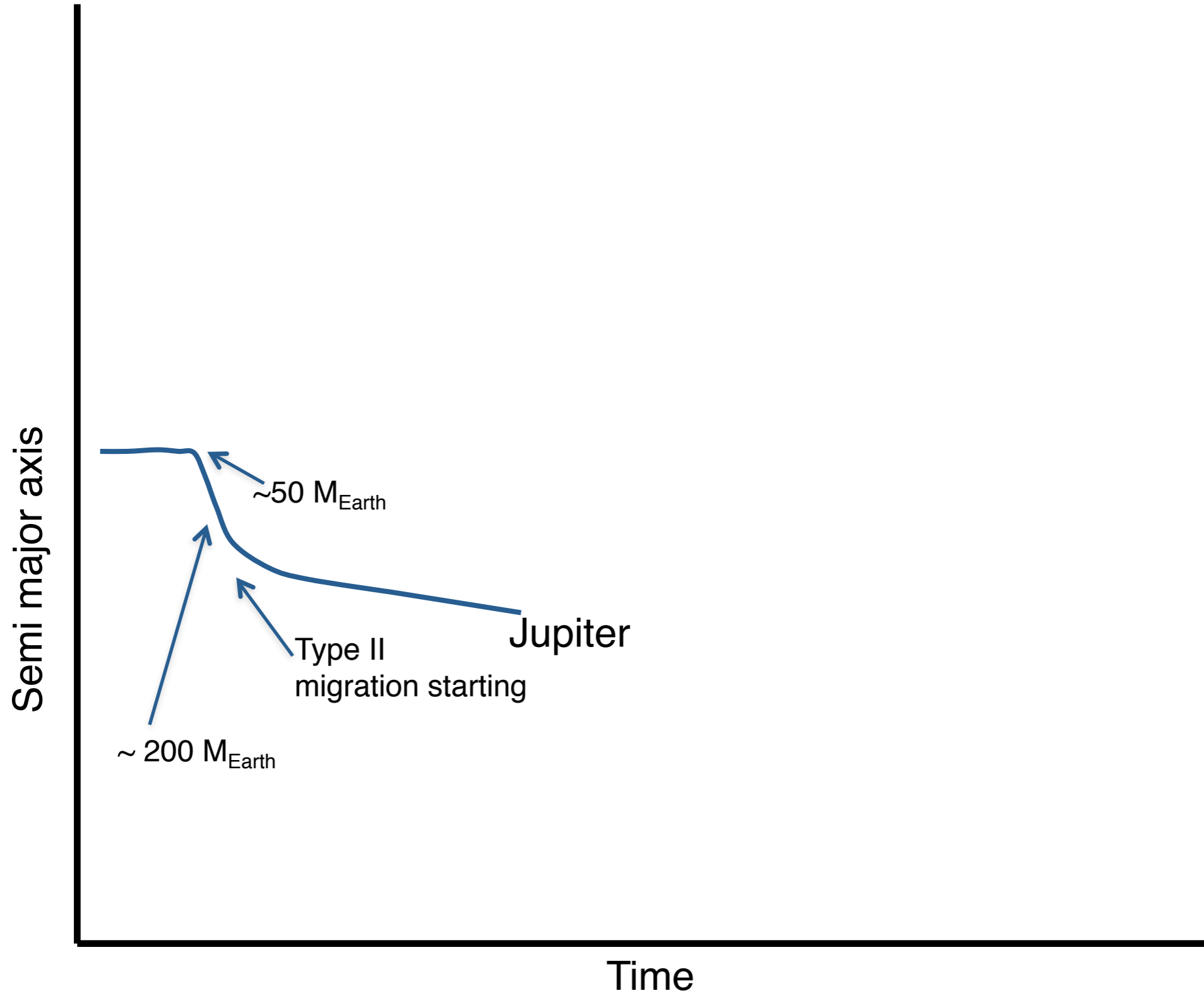
- 
- \* 100s of billions stars in our galaxy
  - \* 100s of billions of galaxies in the Universe



- 
- A deep field image of the universe, showing a vast field of galaxies and stars. The background is a dark, starry sky filled with numerous galaxies of various shapes and colors, including spirals, ellipticals, and irregular forms. The stars are scattered throughout, with some appearing as bright, multi-pointed sources. The overall scene is a rich, multi-colored tapestry of cosmic objects.
- \* 100s of billions stars in our galaxy
  - \* 100s of billions of galaxies in the Universe
  - \* **Probably quintillions of planets**  
(1,000,000,000,000,000,000)

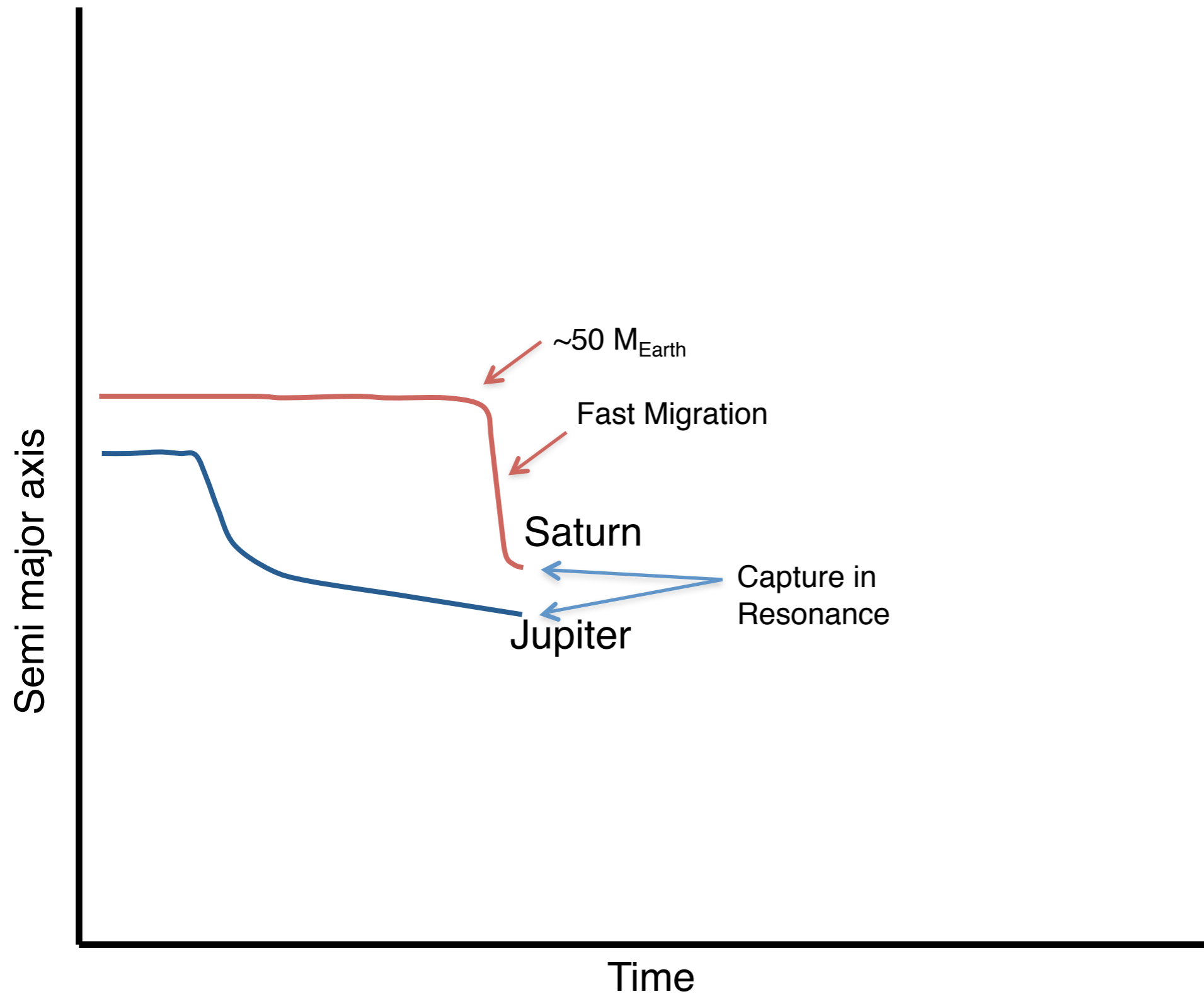


# Jupiter in the gaseous disk

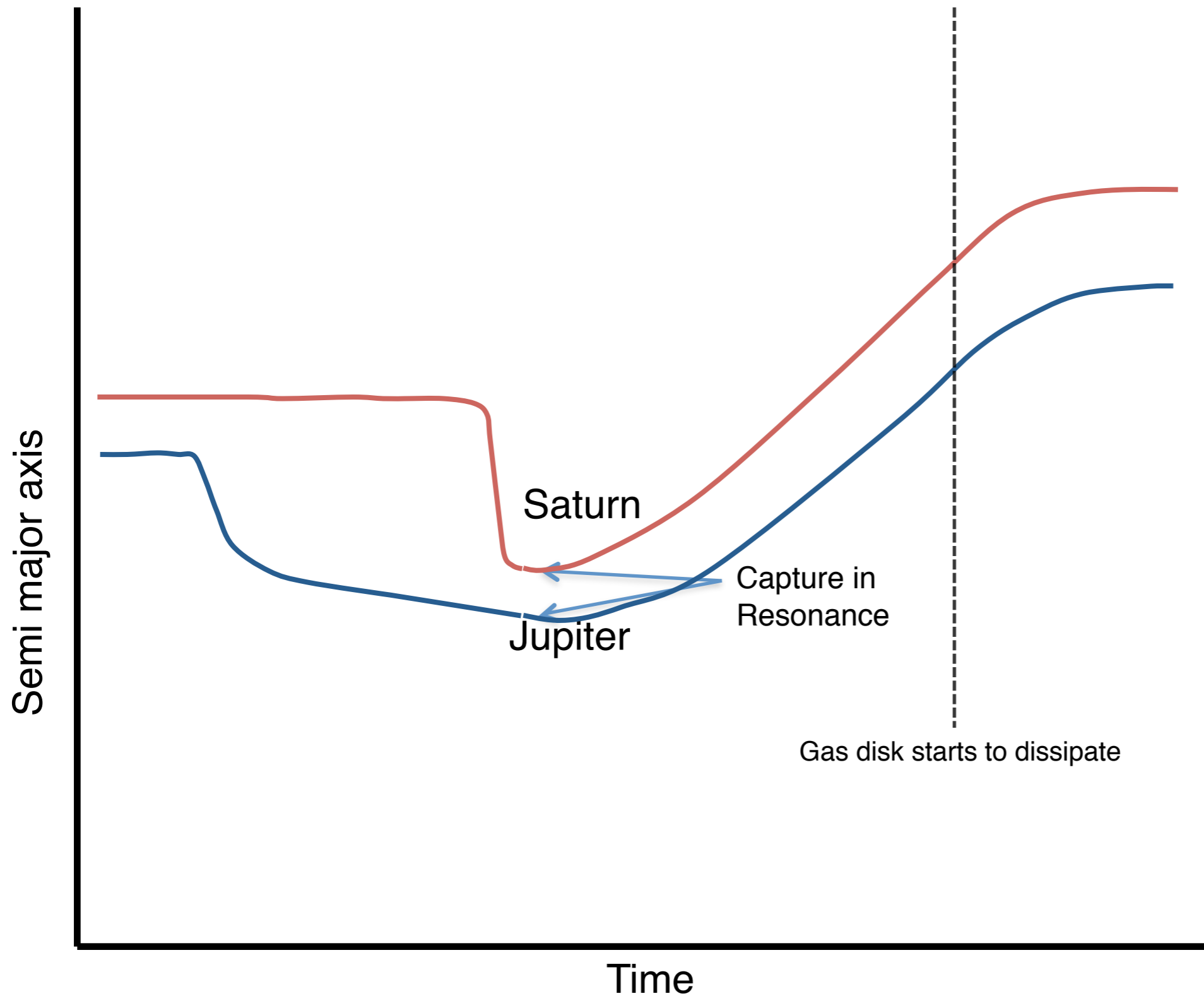




# Jupiter and Saturn in the gaseous disk



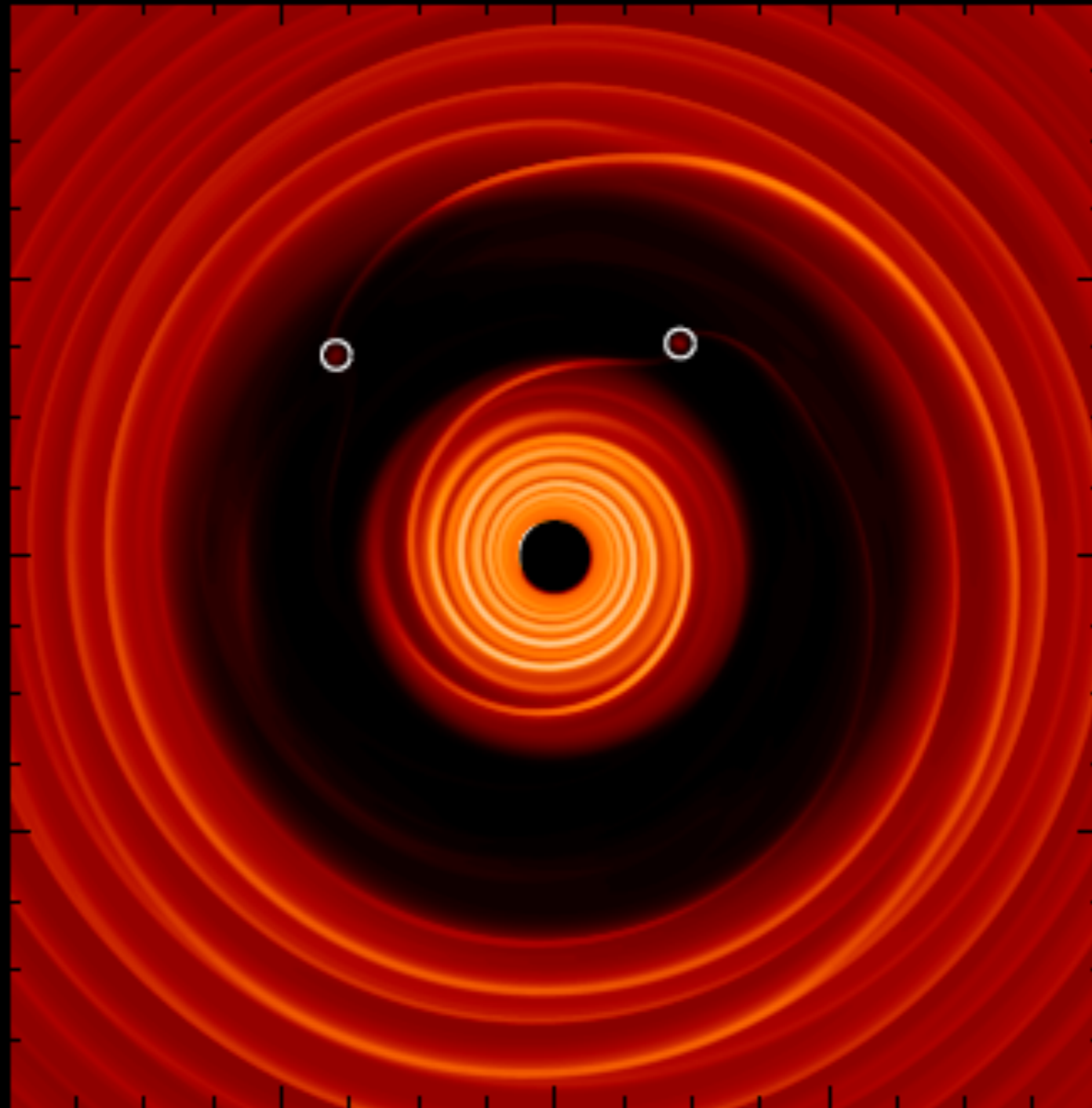
# Jupiter and Saturn in the gaseous disk



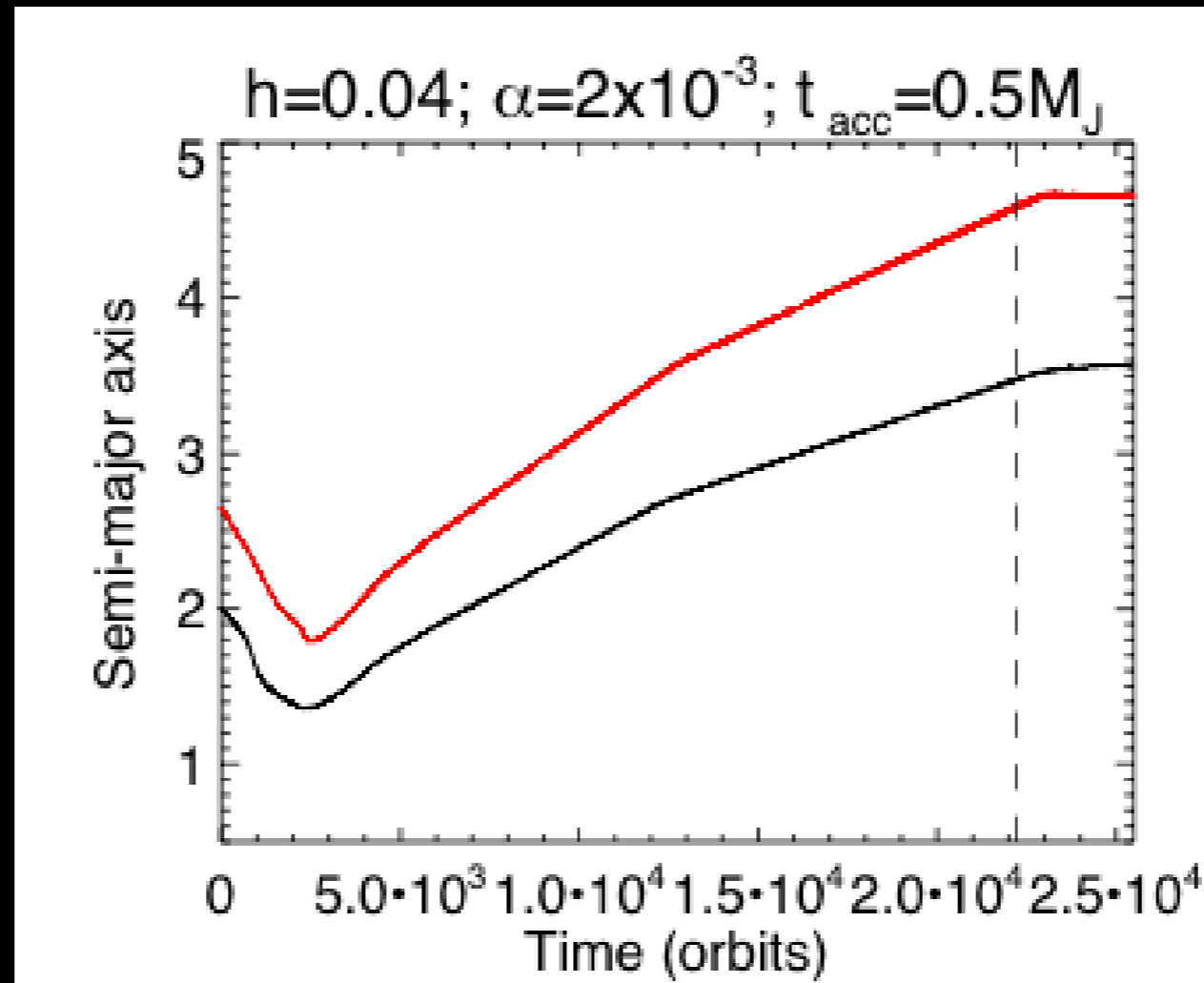
Masset & Snellgrove 2001;  
Morbidelli & Crida 2007;  
Pierens & Nelson 2008;  
Crida et al 2009;  
Pierens & Raymond 2011;  
Pierens et al 2014

slide by Kevin Walsh





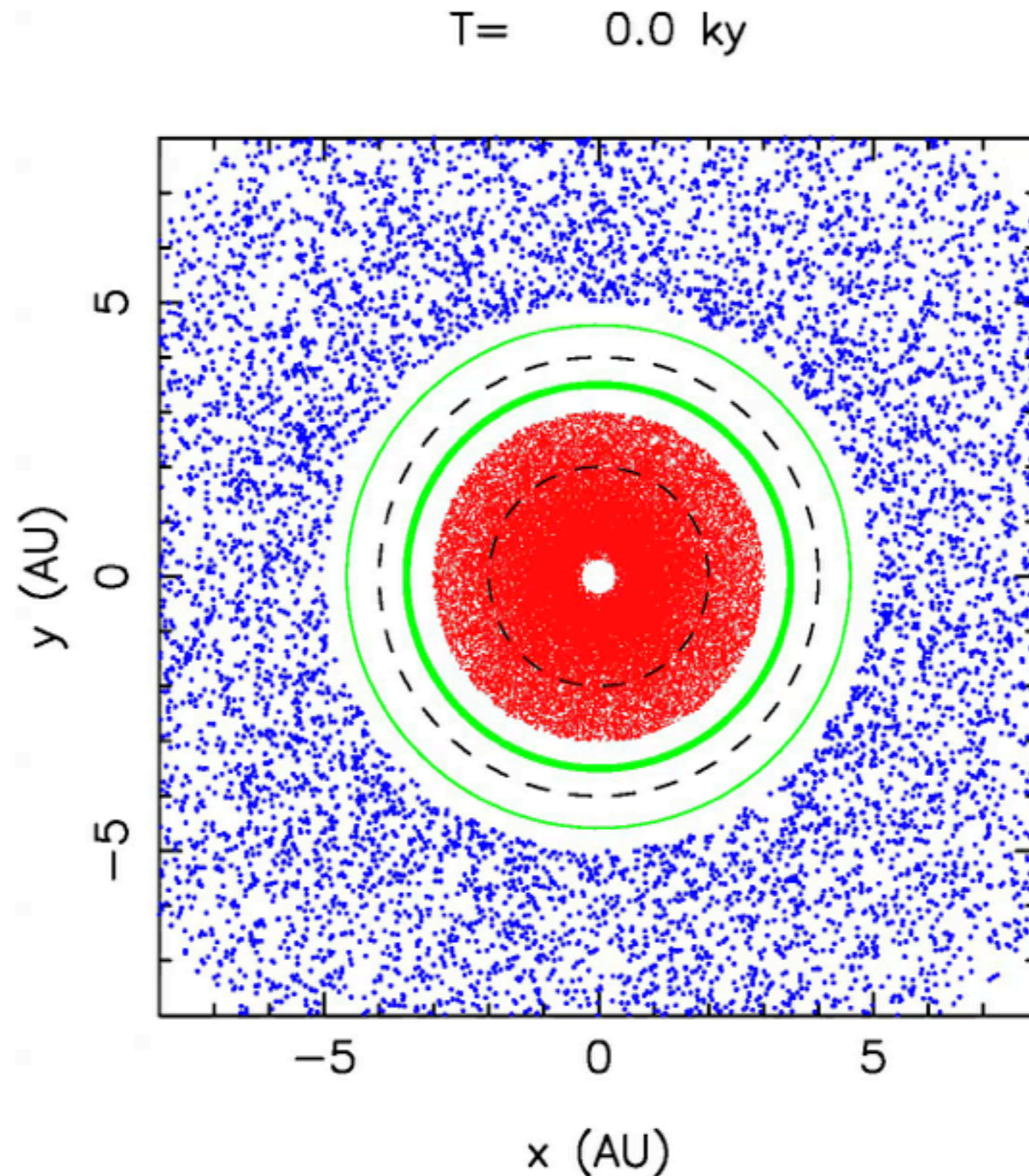
Hydrodynamical simulation with Jup, Sat  
accreting gas from disk (Pierens & Raymond 2011)



Hydrodynamical simulation with Jup, Sat  
accreting gas from disk (Pierens & Raymond 2011)



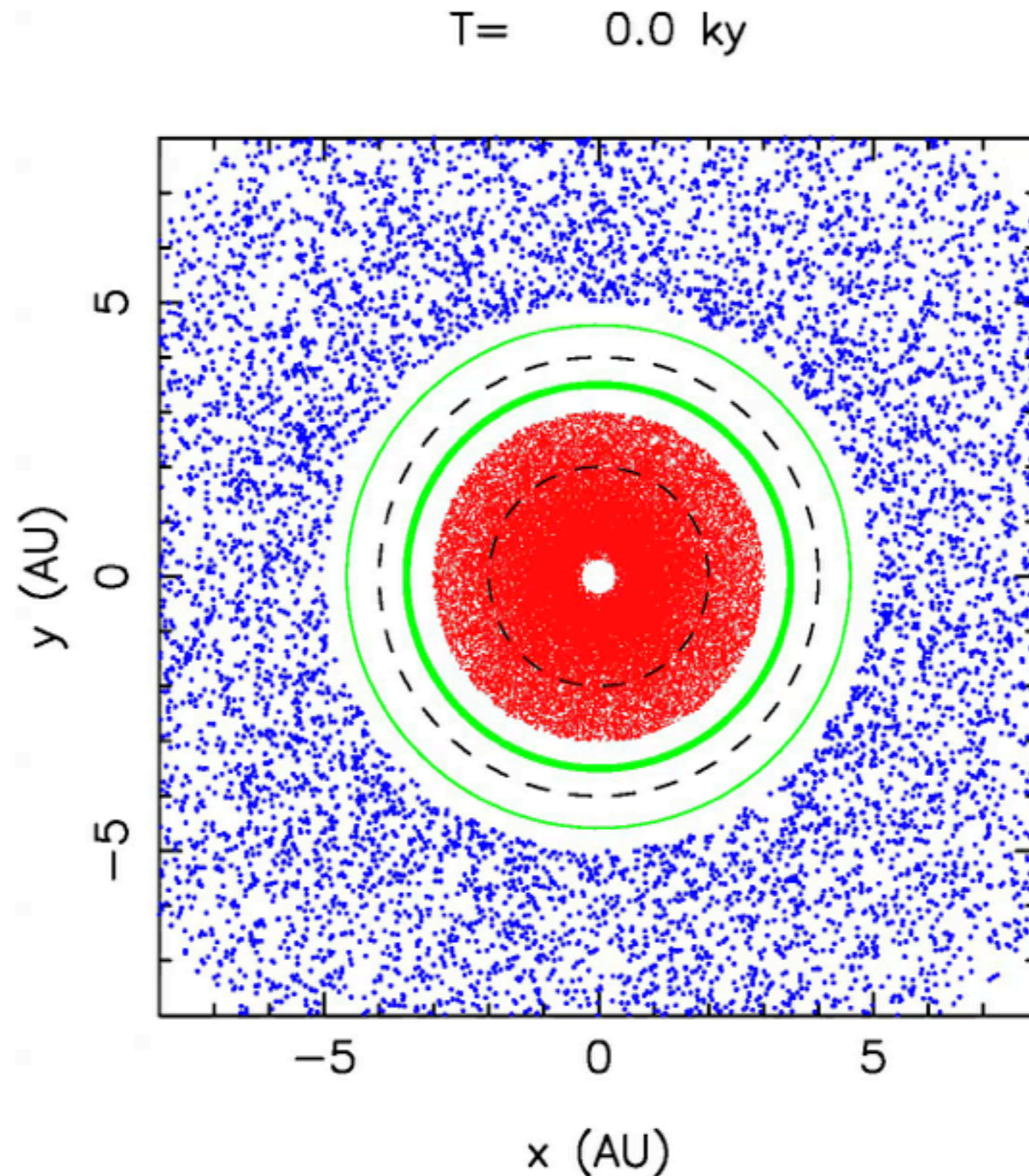
# The Grand Tack model



Walsh, Morbidelli,  
Raymond, O'Brien,  
Mandell 2011, Nature,  
475, 206



# The Grand Tack model



Walsh, Morbidelli,  
Raymond, O'Brien,  
Mandell 2011, Nature,  
475, 206



# The Grand Tack

