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

Sean Raymond
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planetplanet.net
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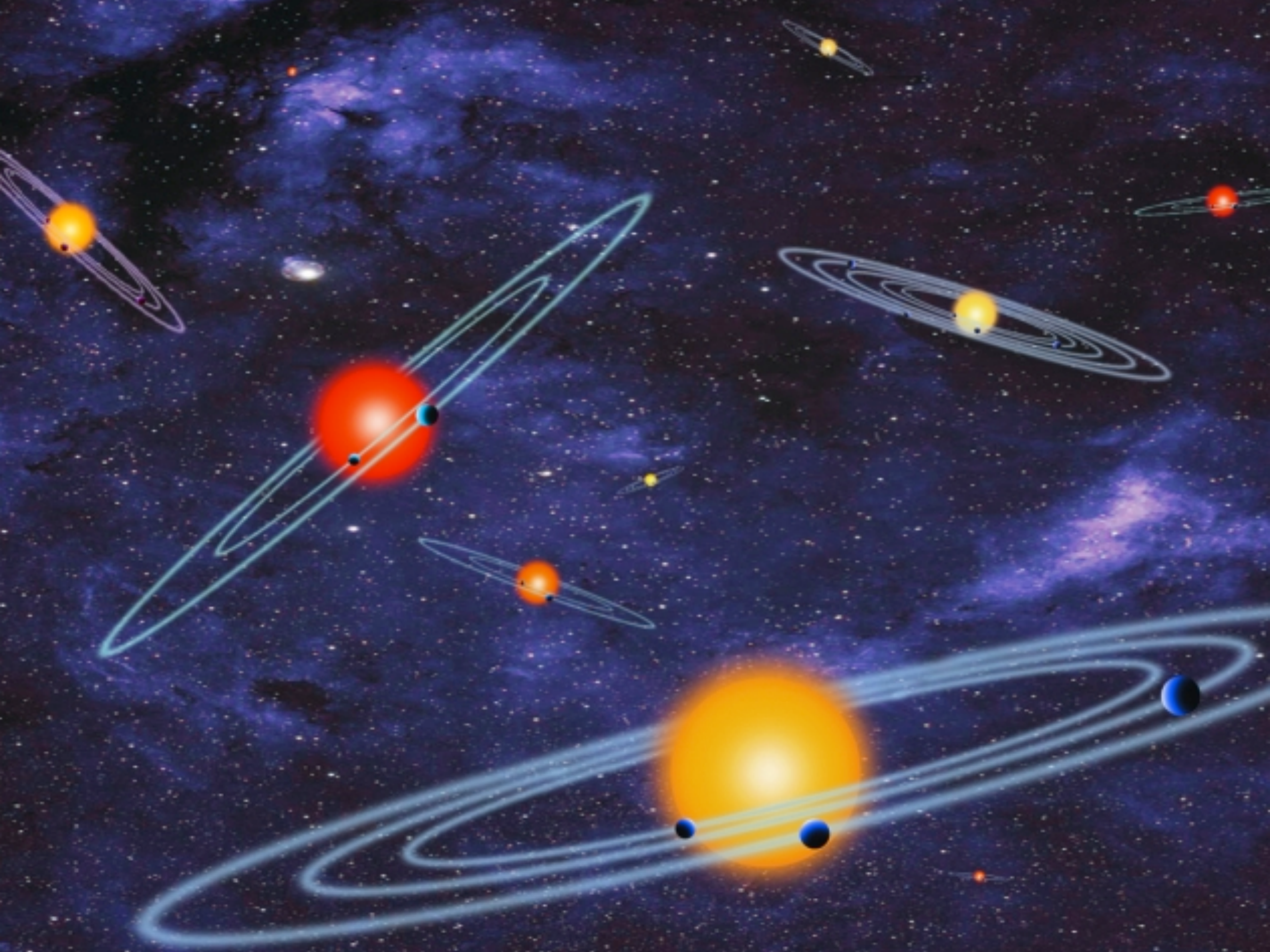

A zoom-in to a massive star forming region

Credit: Dullemond

Picture credit: W. Keel

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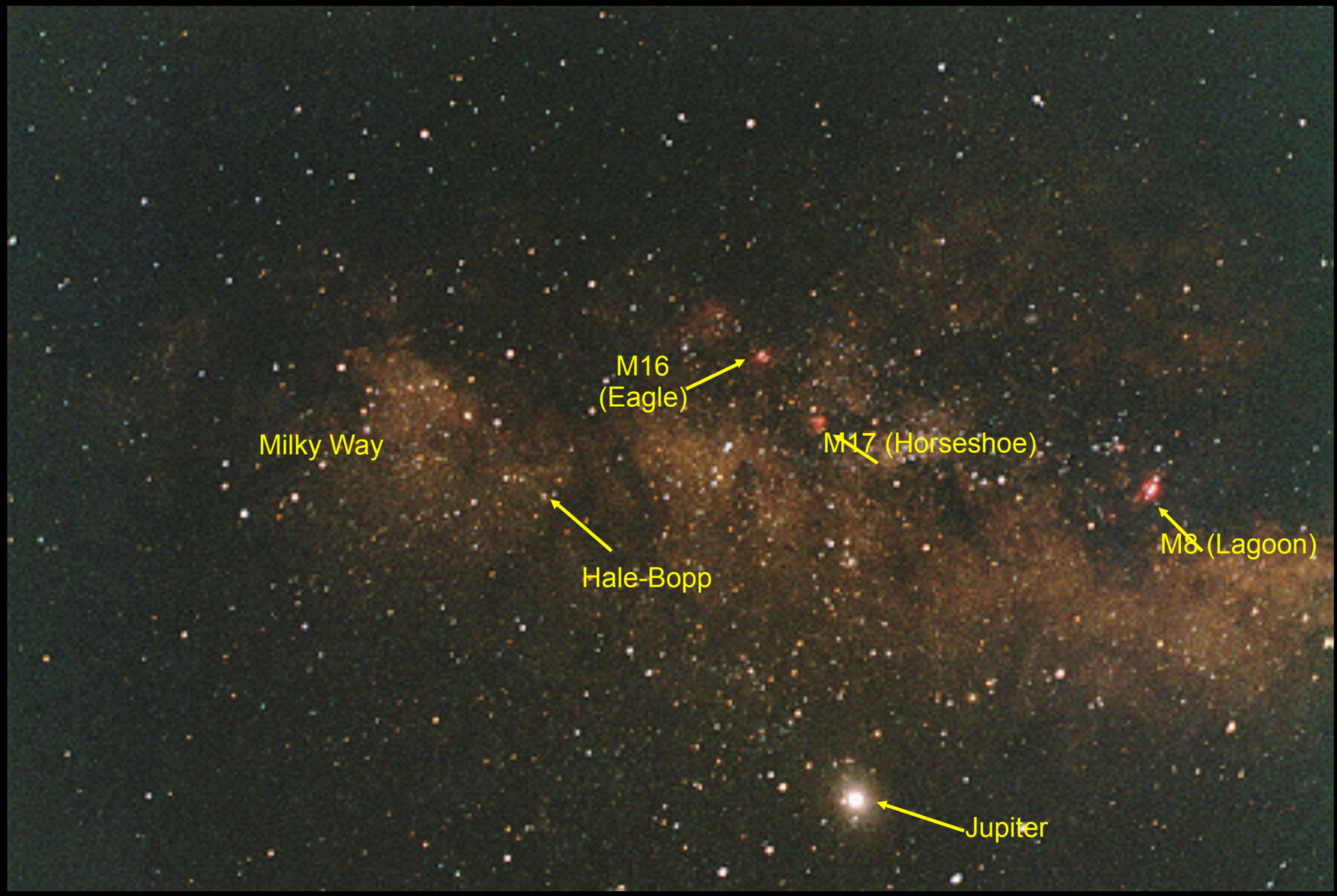

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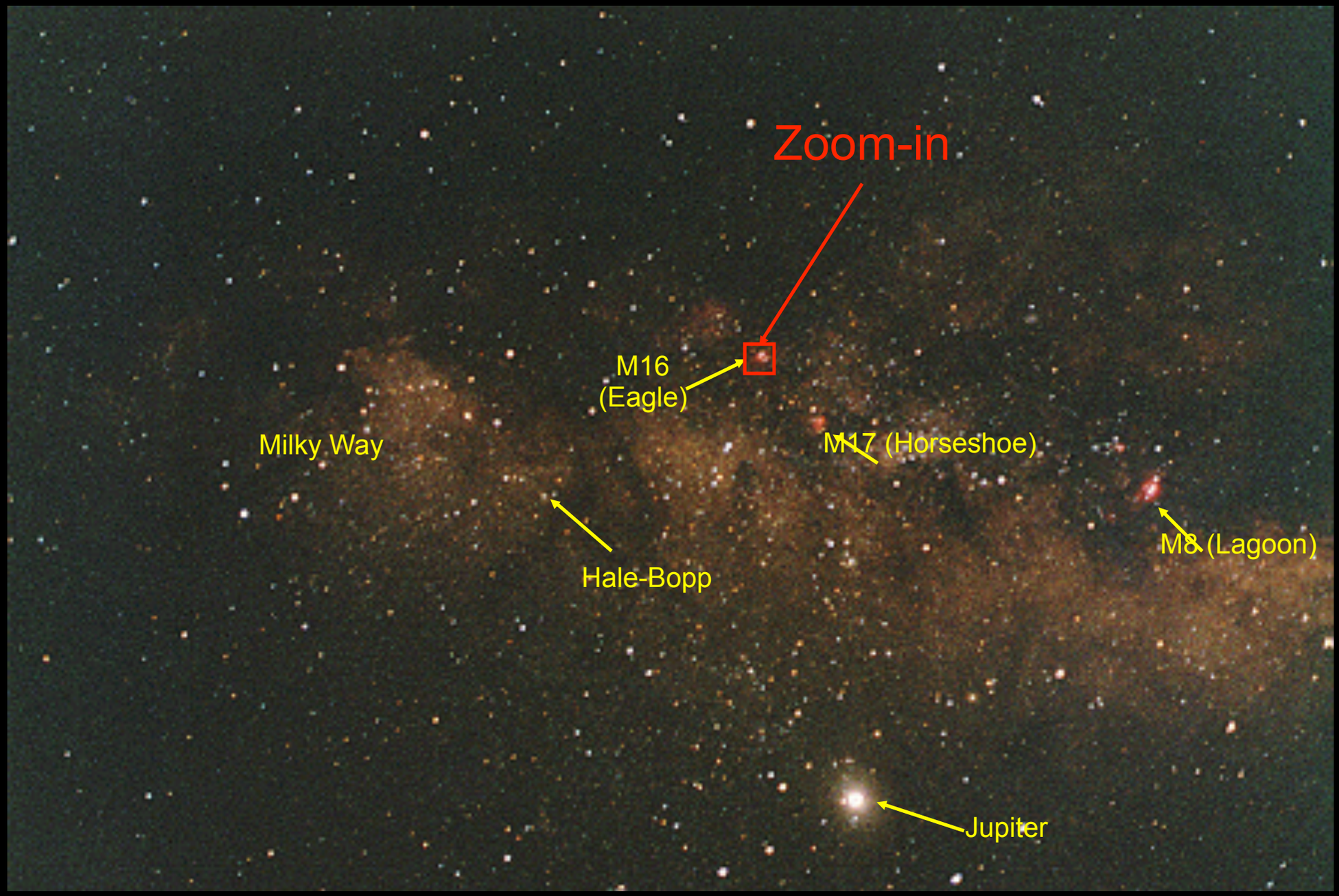

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A zoom-in to a massive star forming region

Eagle Nebula (M16)

Picture credit: T.A. Rector & B.A. Wolpa

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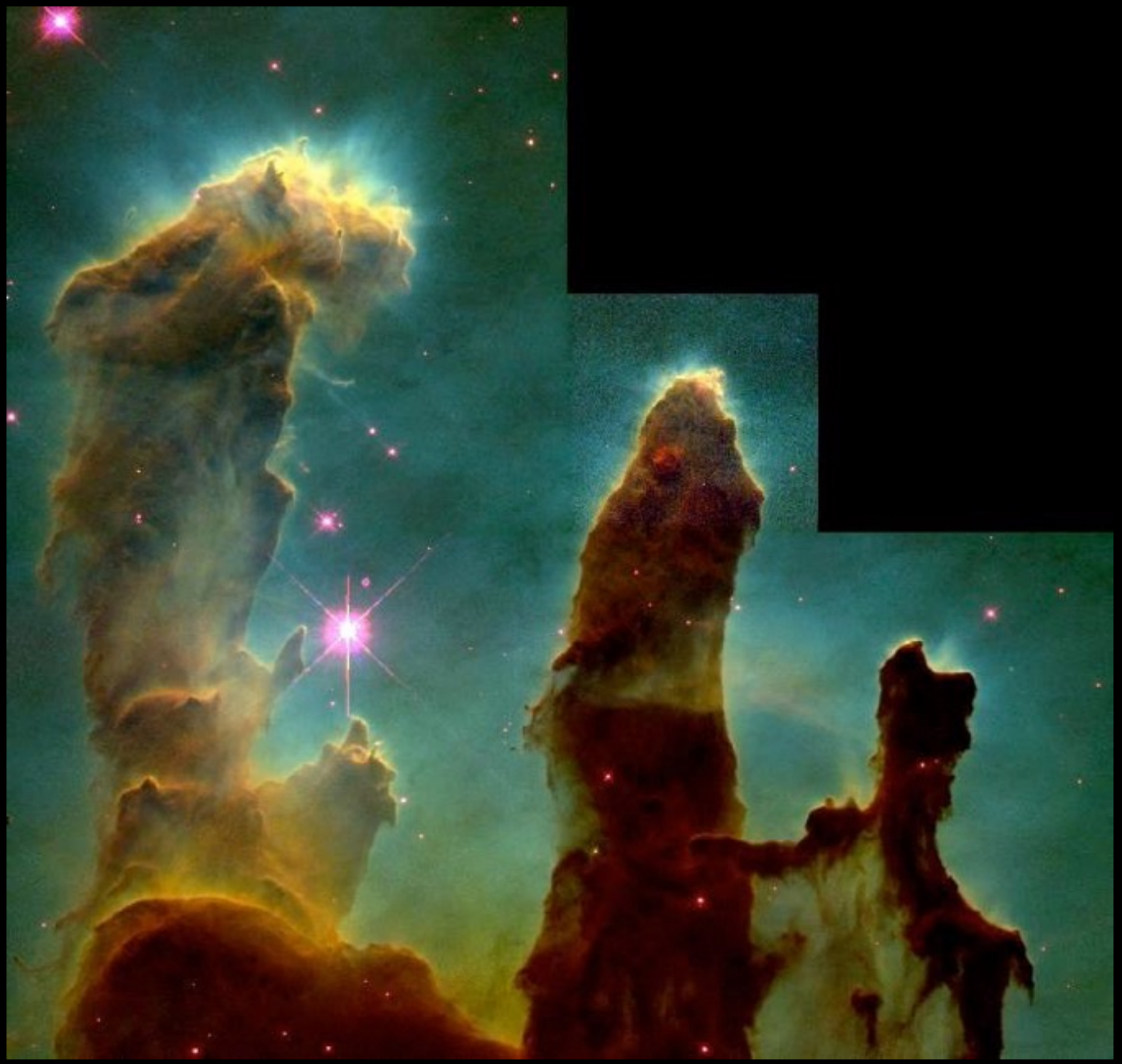

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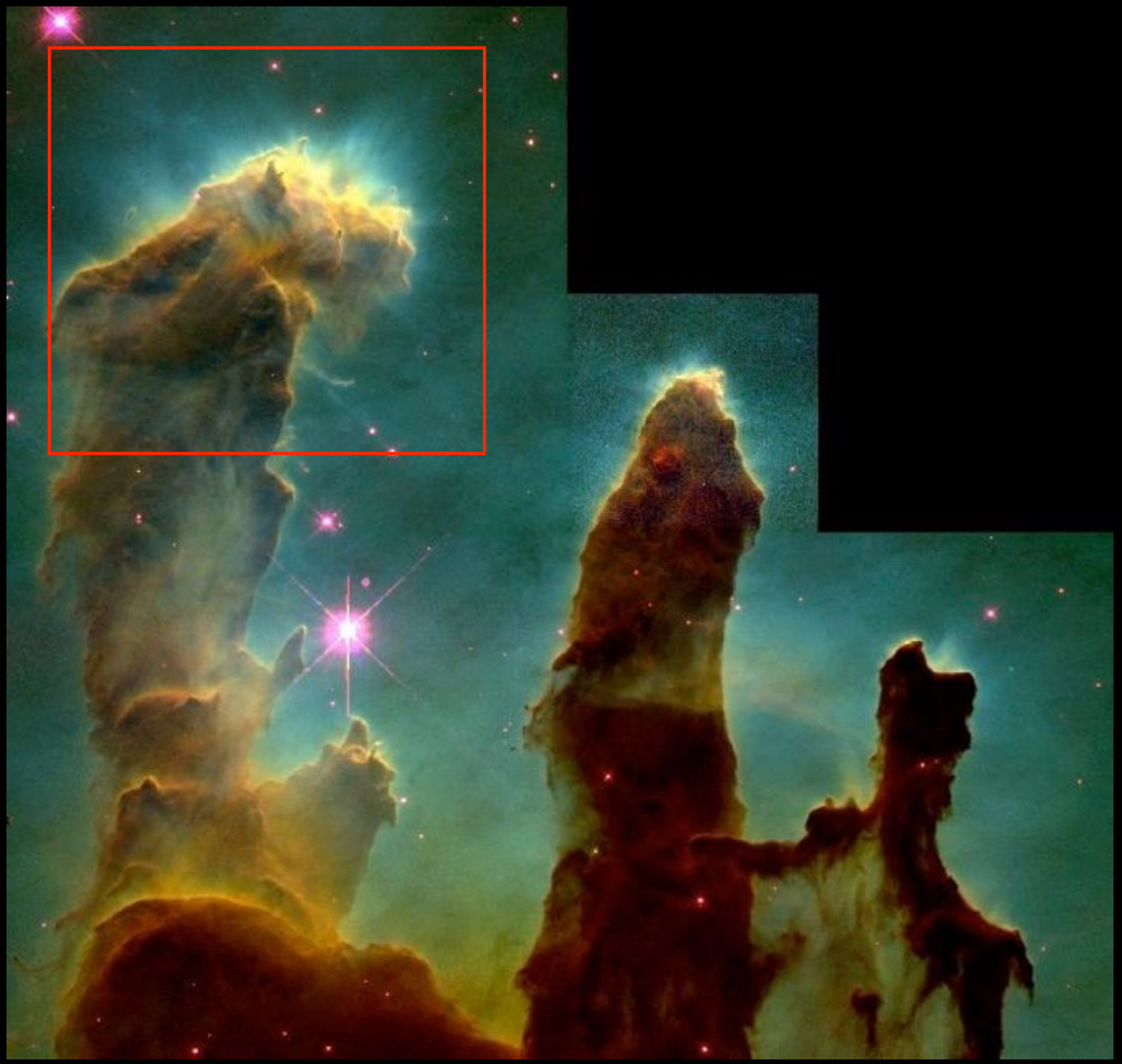

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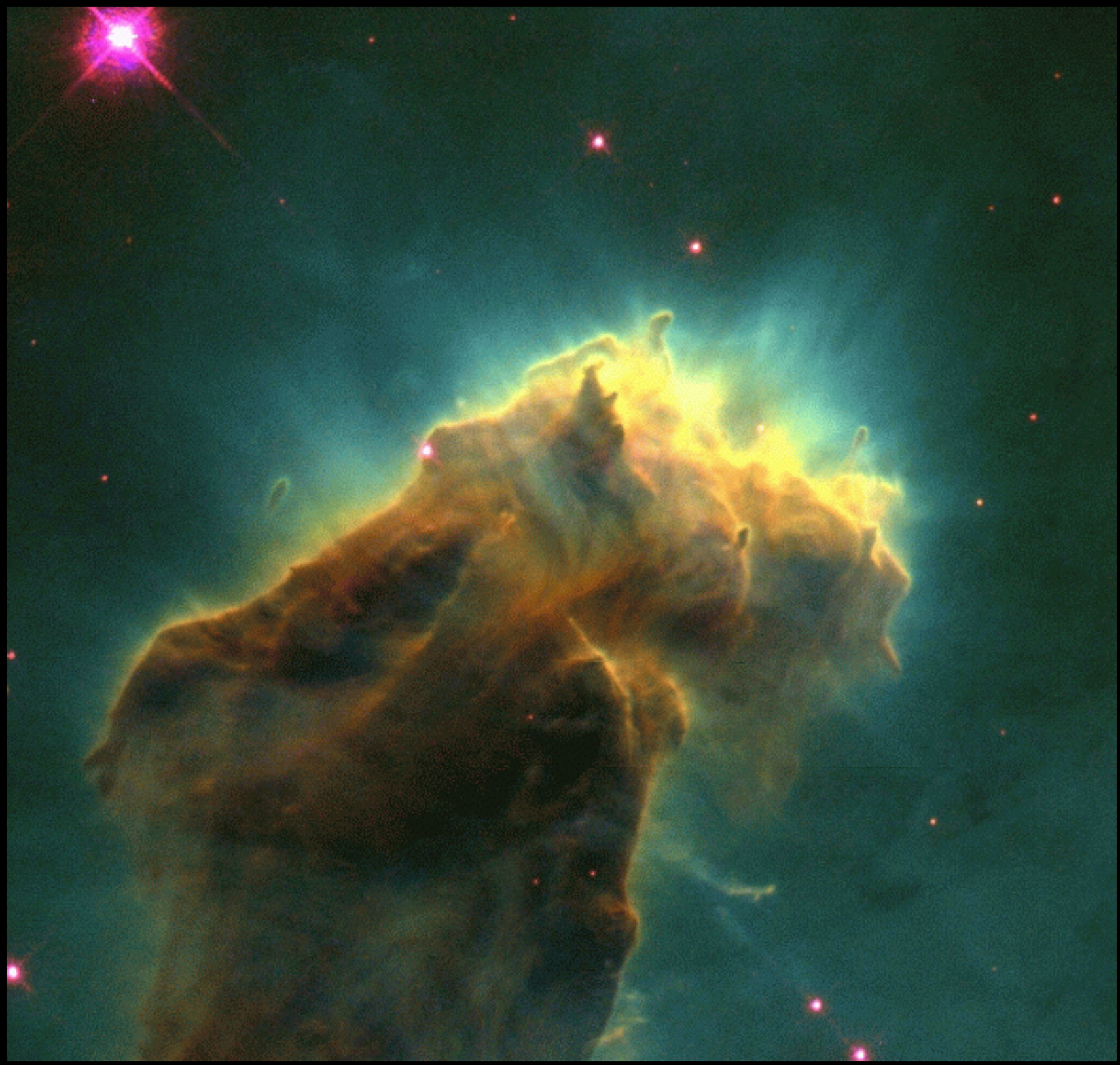

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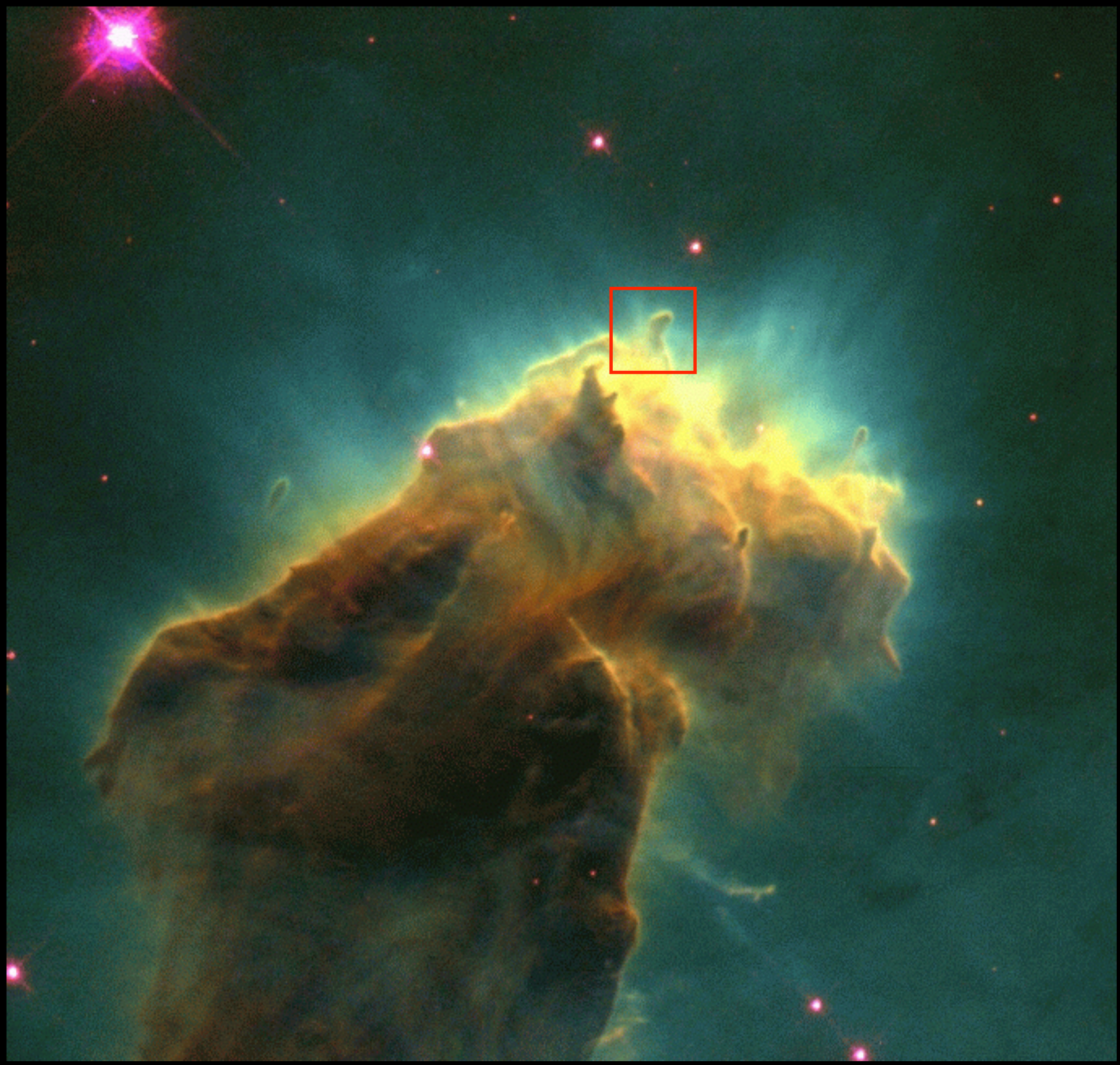

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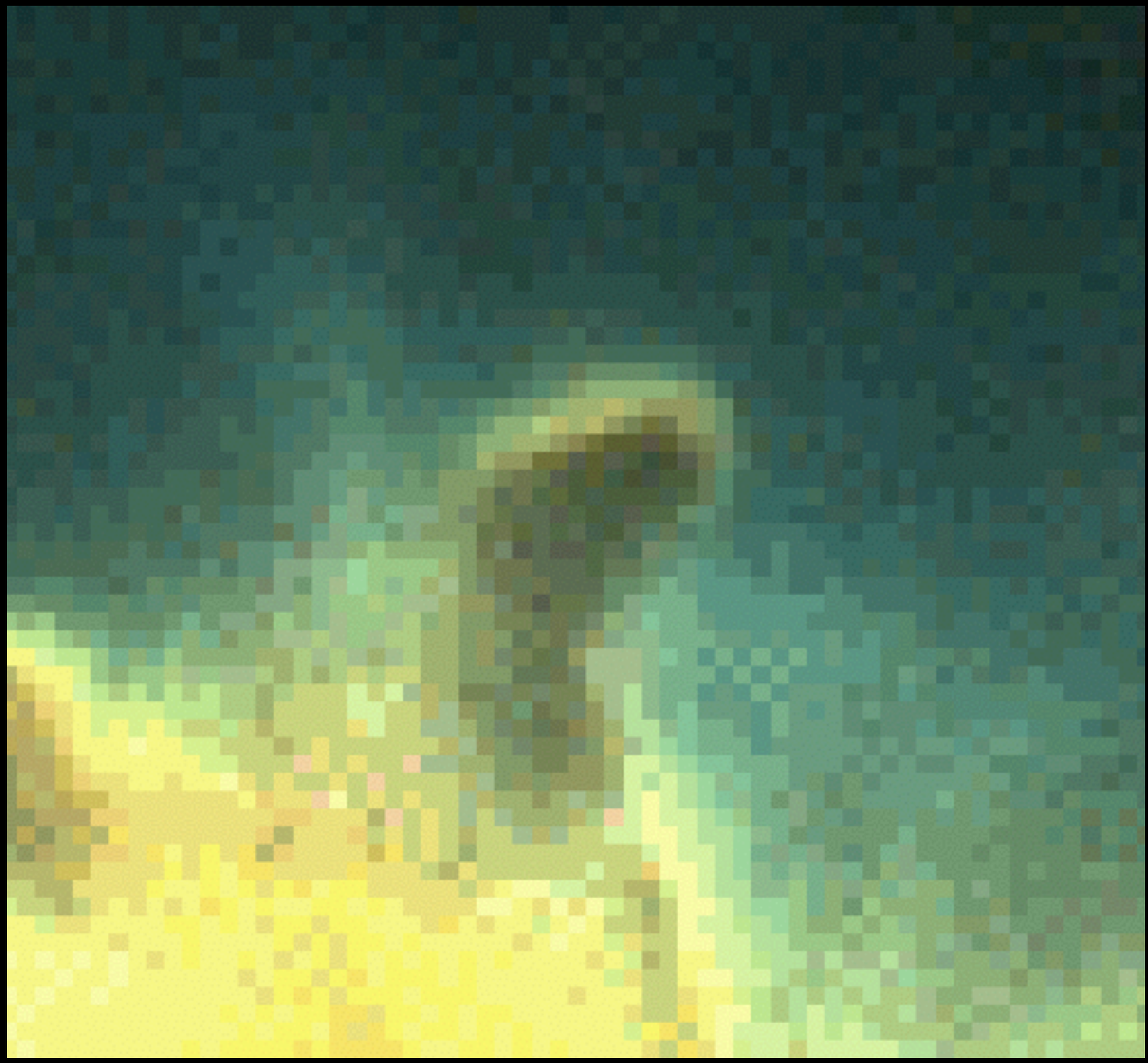

Eagle Nebula (M16)

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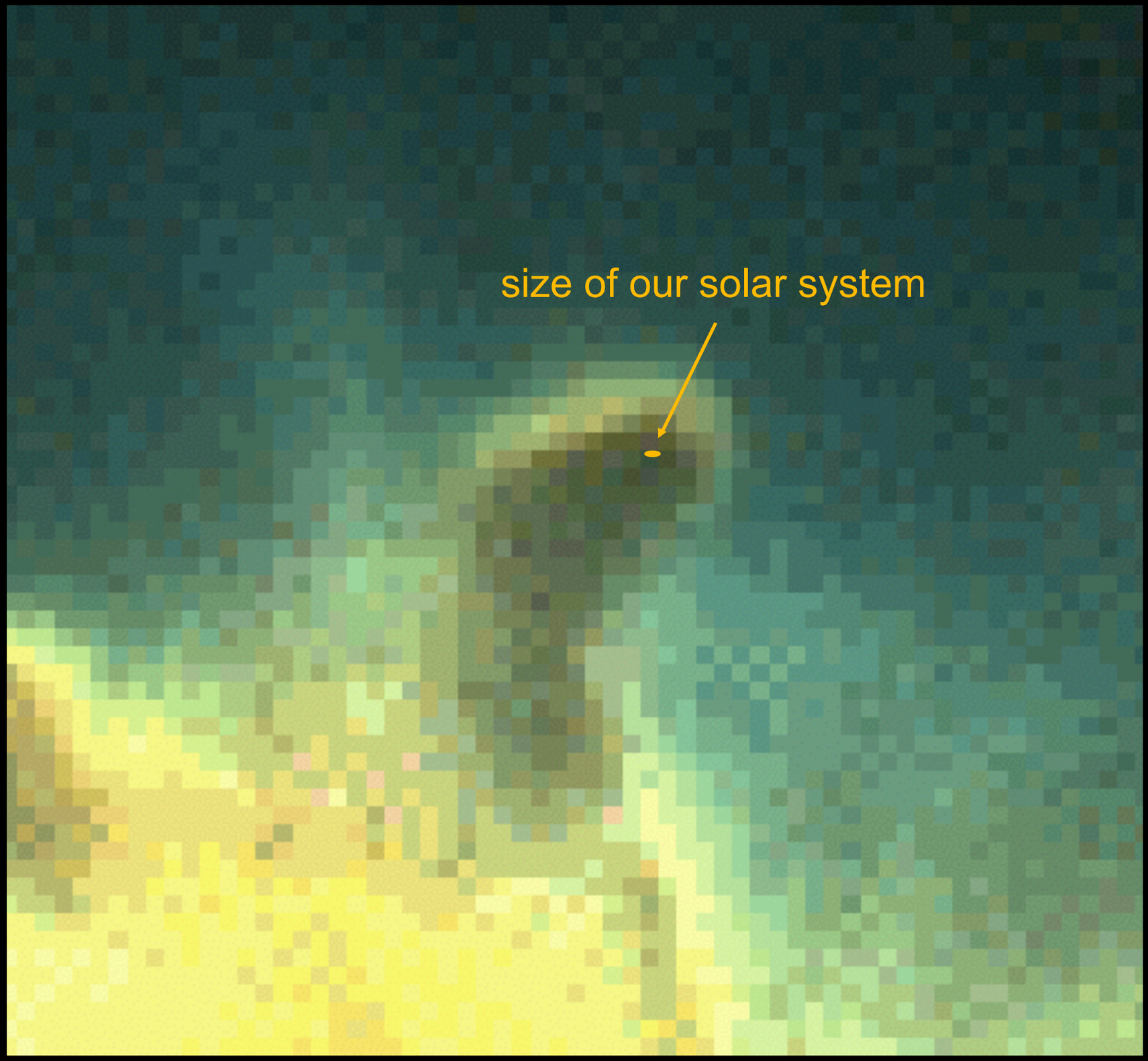
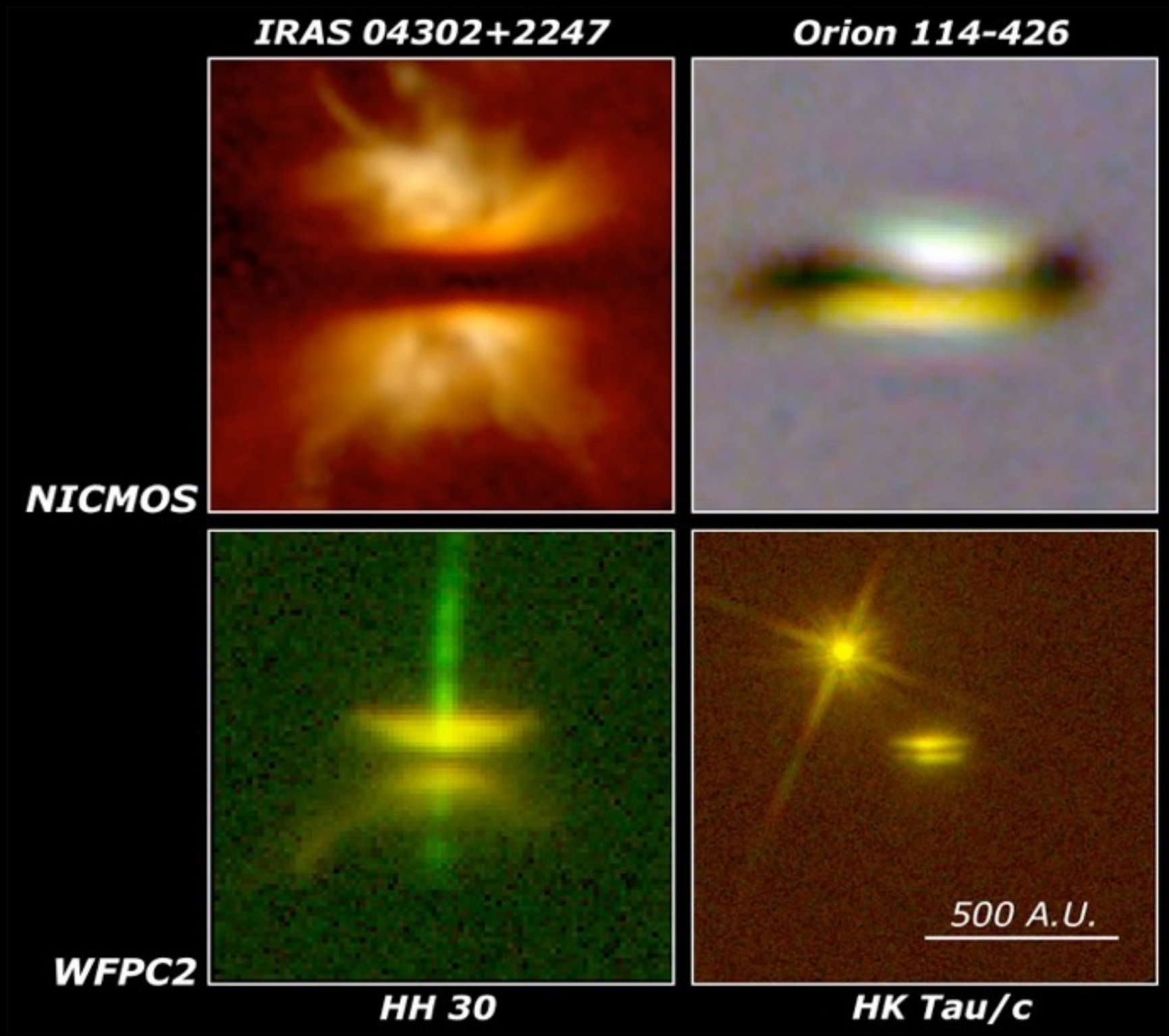
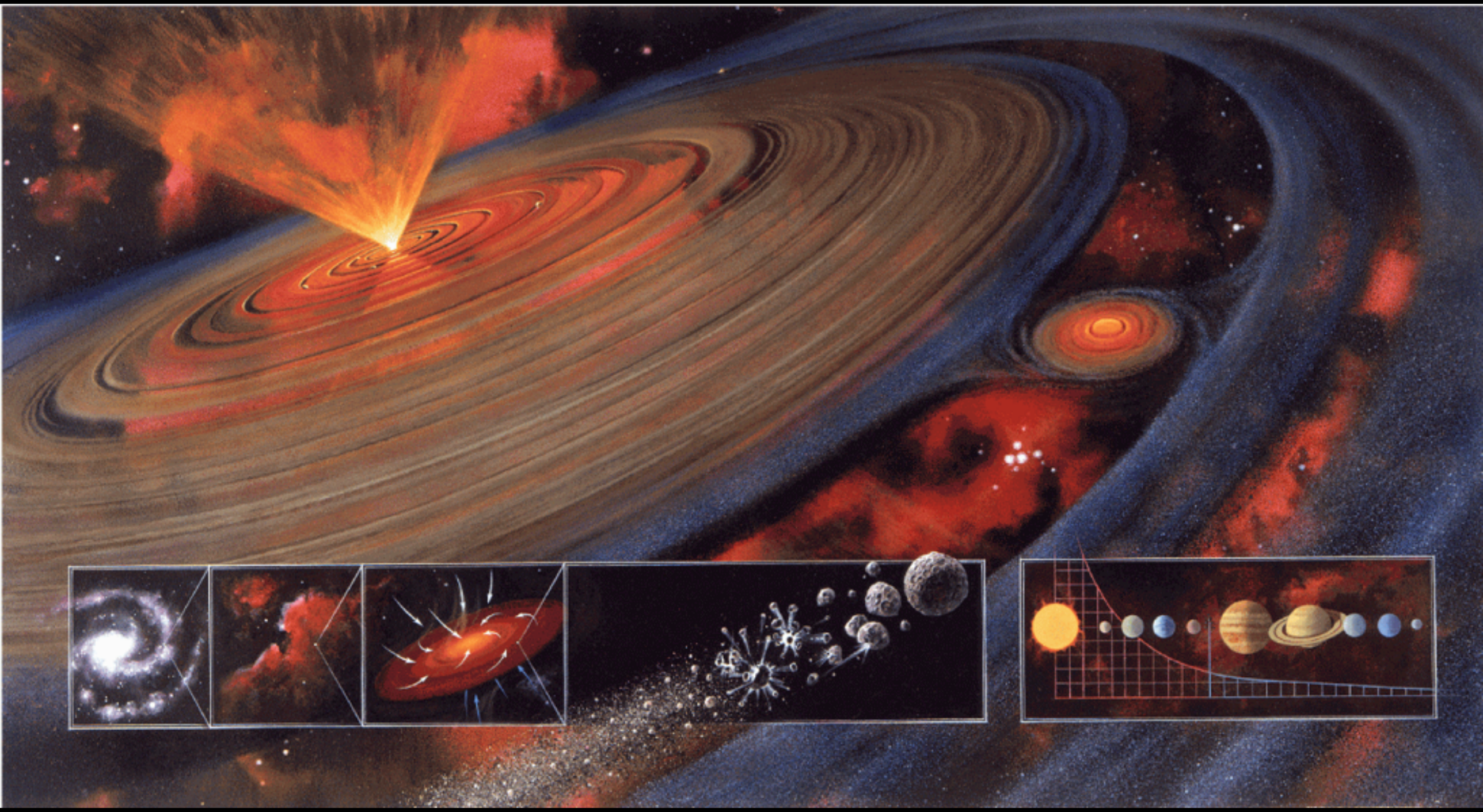


Eagle Nebula (M16)

Picture Credit: J. Hester & P. Scowen

Disks around young stars



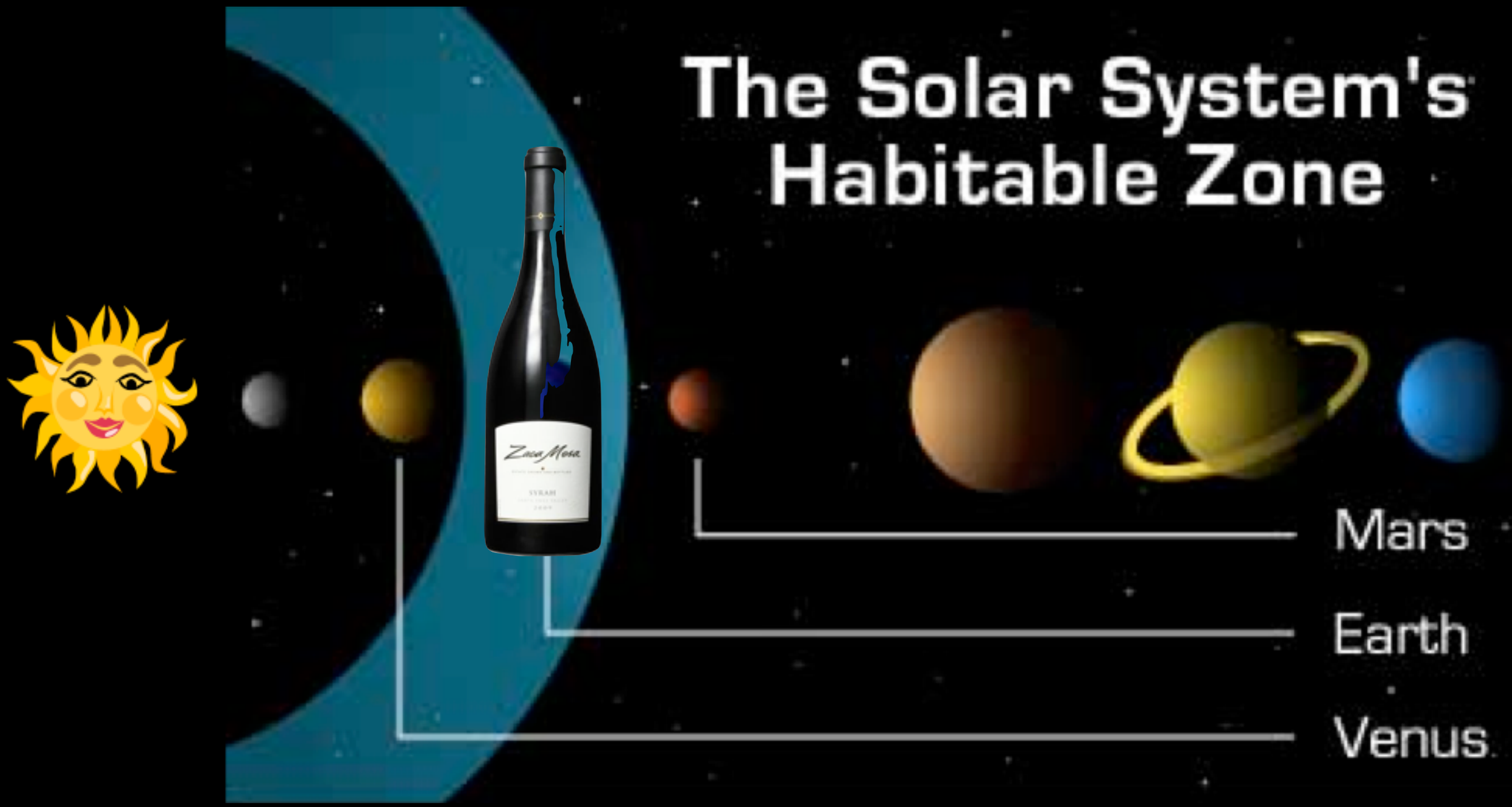


The Solar System's Habitable Zone

Mars

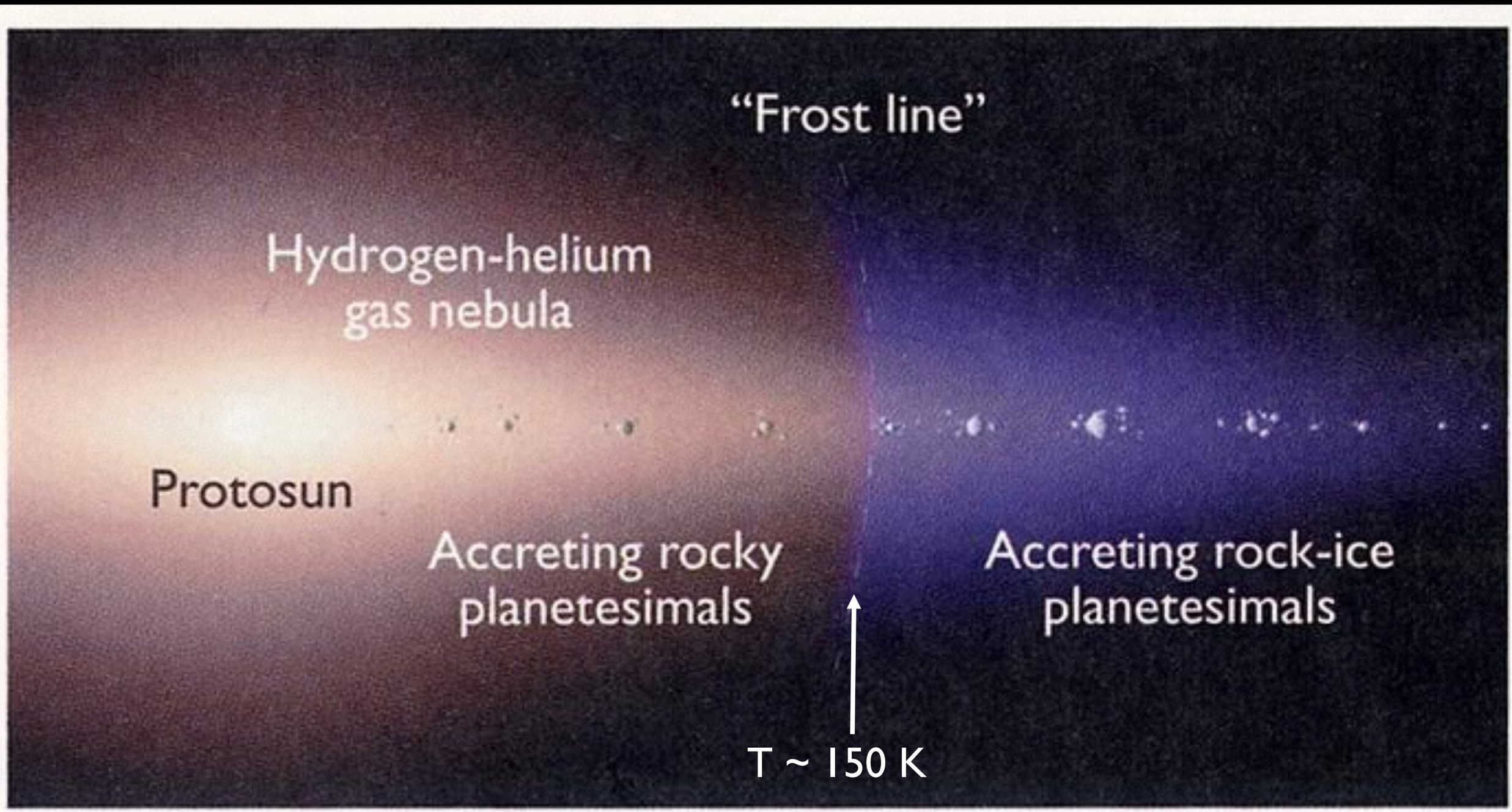
Earth

Venus

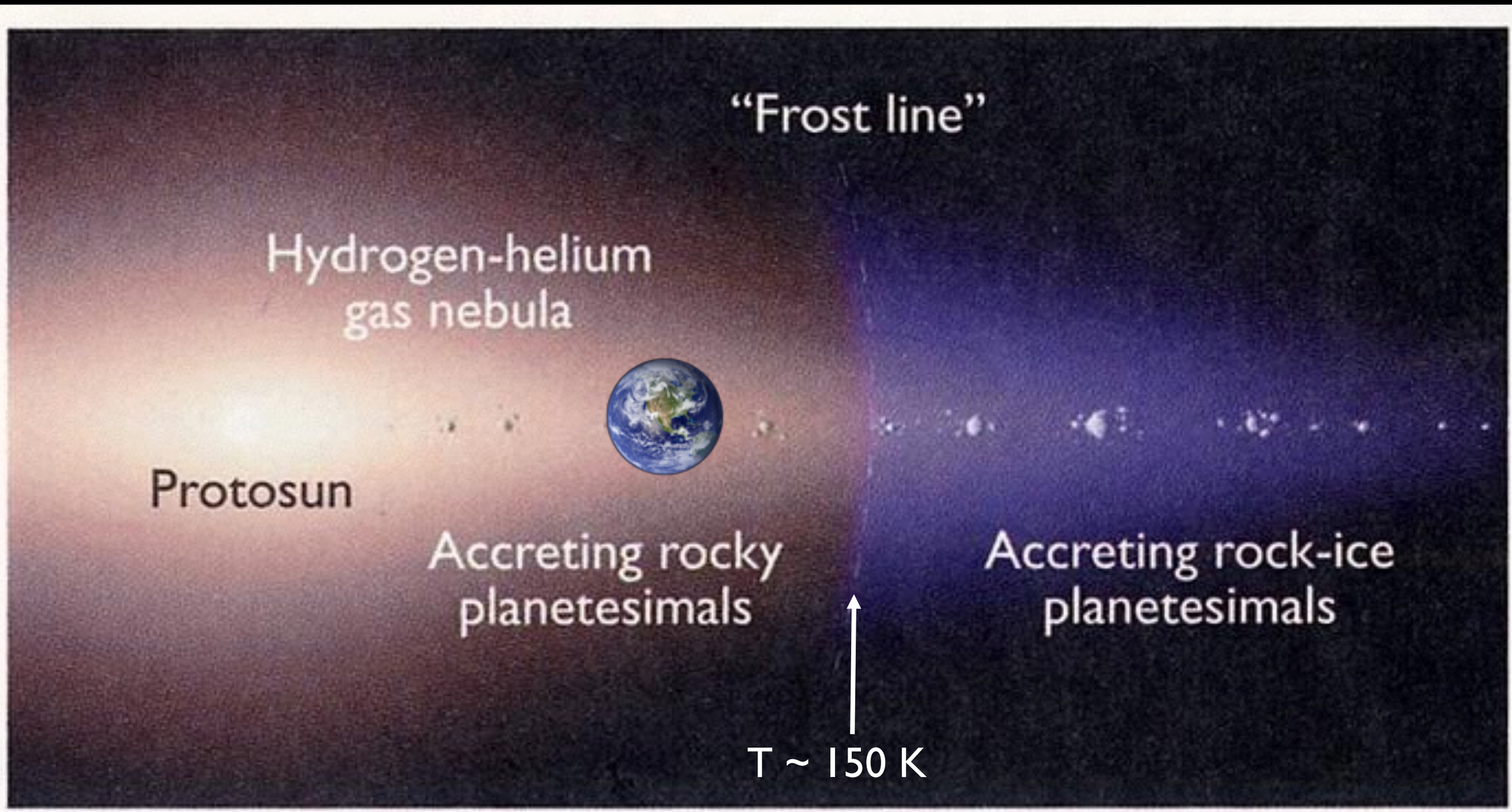


Habitable planets need water!

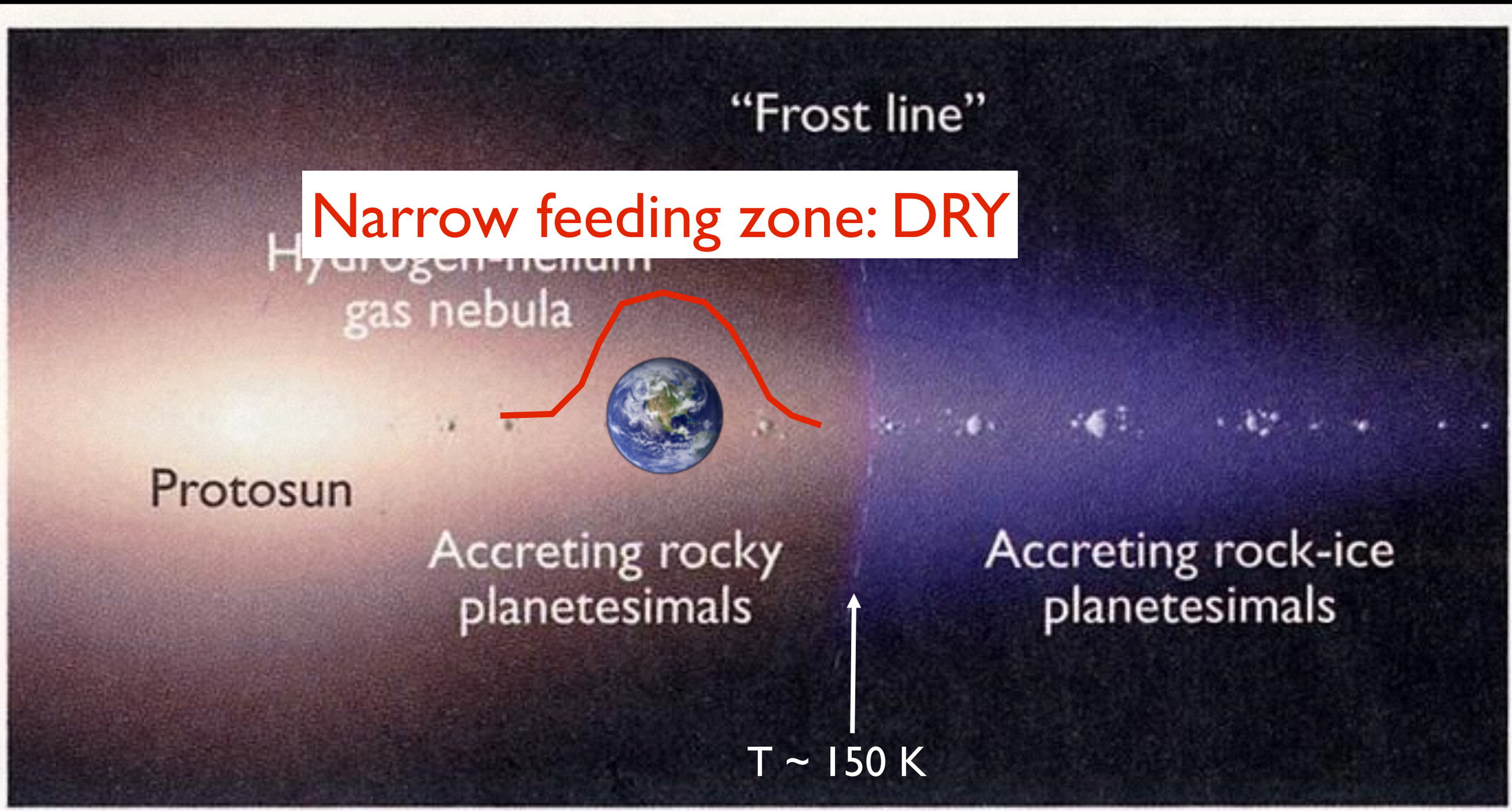
Water delivery



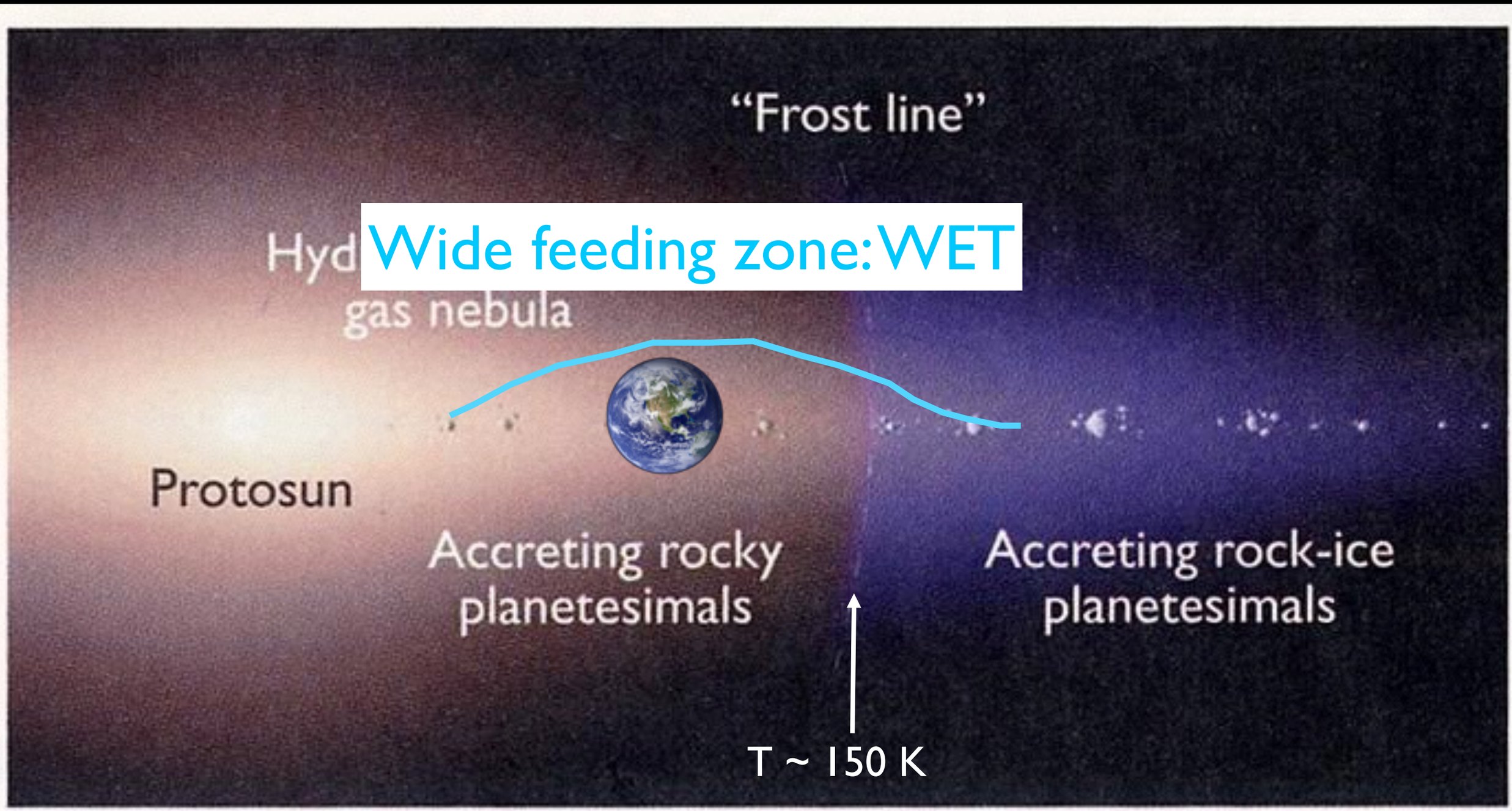
Water delivery



Water delivery



Water delivery



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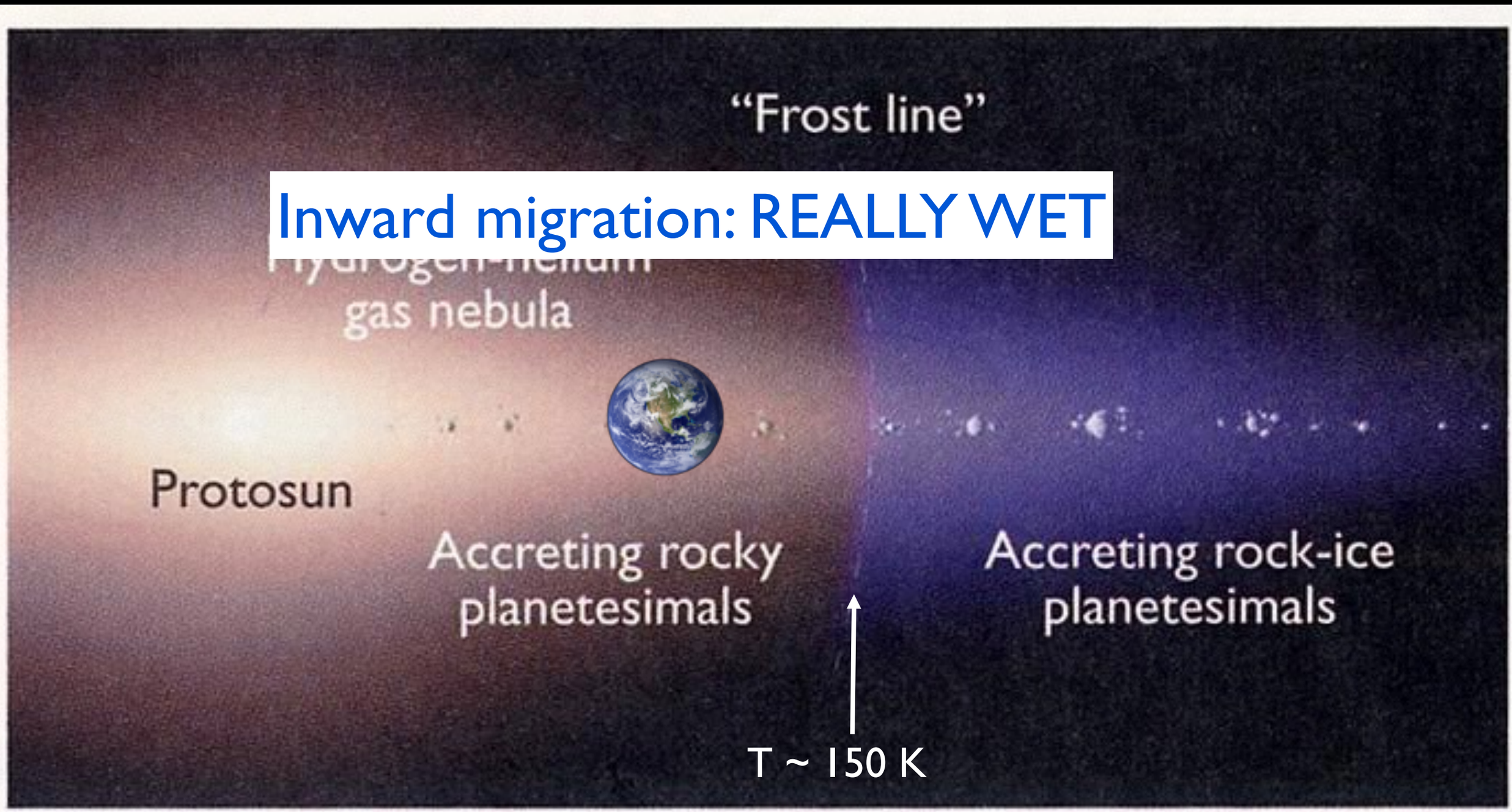

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Planet Mass [Jupiter Mass]

10
1
0.1
0.01
10^{-3}

0.01
0.1
1
10

Separation [Astronomical Units (AU)]

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Hot Super-Earths

Planet Mass [Jupiter Mass]

10
1
0.1
0.01
10^{-3}

0.01
0.1
1
10

Separation [Astronomical Units (AU)]

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Hot Jupiters

Hot Super-Earths

Planet Mass [Jupiter Mass]

10
1
0.1
0.01
10^{-3}

0.01
0.1
1
10

Separation [Astronomical Units (AU)]

exoplanets.org | 2/28/2015

Hot Jupiters

"Normal" Jupiters

Hot Super-Earths

Planet Mass [Jupiter Mass]

10

1

0.1

0.01

10^{-3}

0.01

0.1

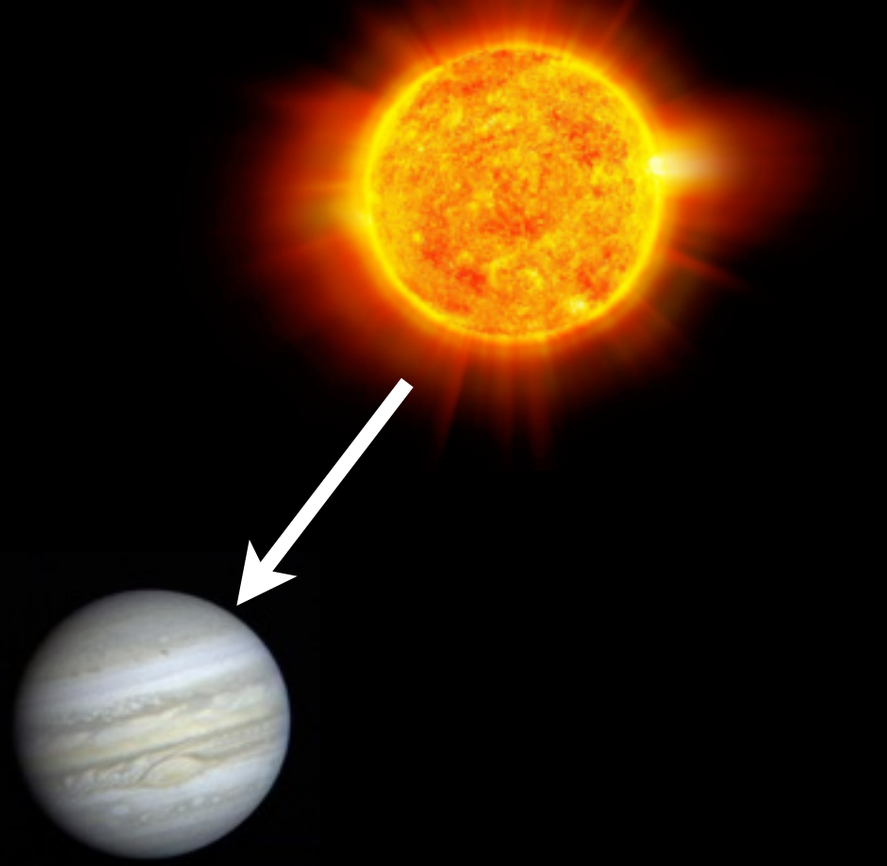
1

10

Separation [Astronomical Units (AU)]

Most stars have planets

(e.g., Cassan et al 2012)



>15%

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

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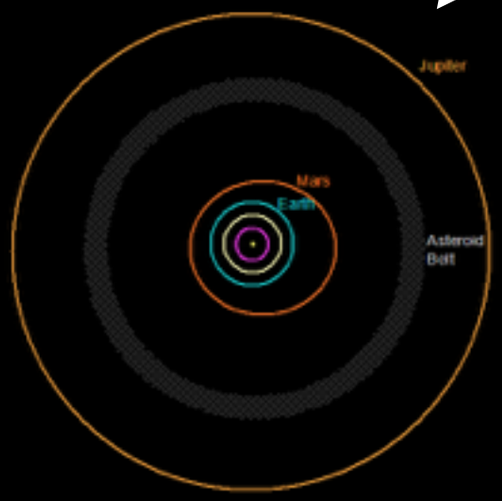
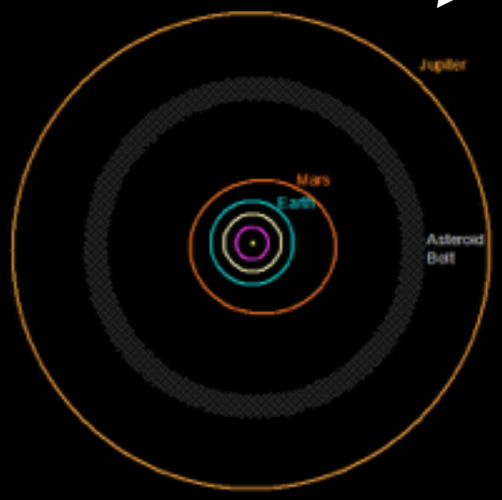


10%

>15%

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



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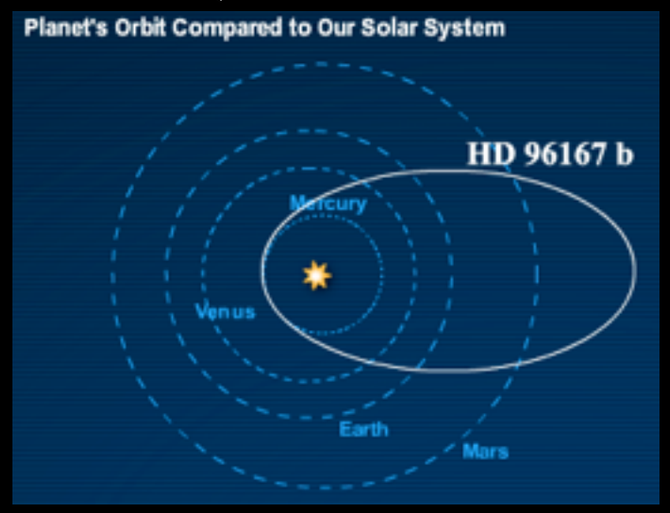
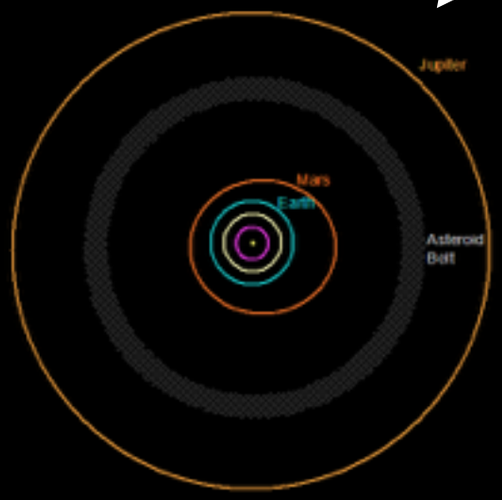


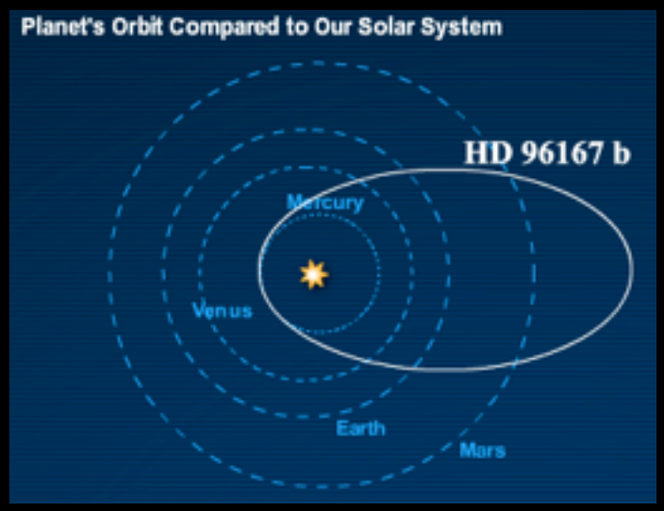
90%

>15%

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

<85%





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90%

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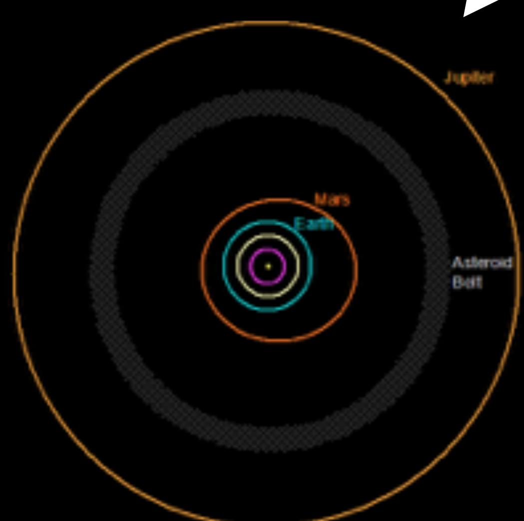
(Cumming et al 2008; Gould et al 2010; Mayor et al 2011)

<85%



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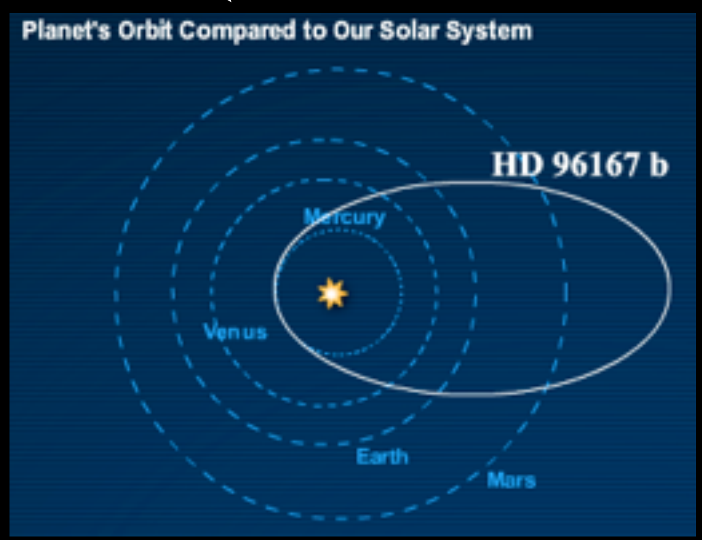

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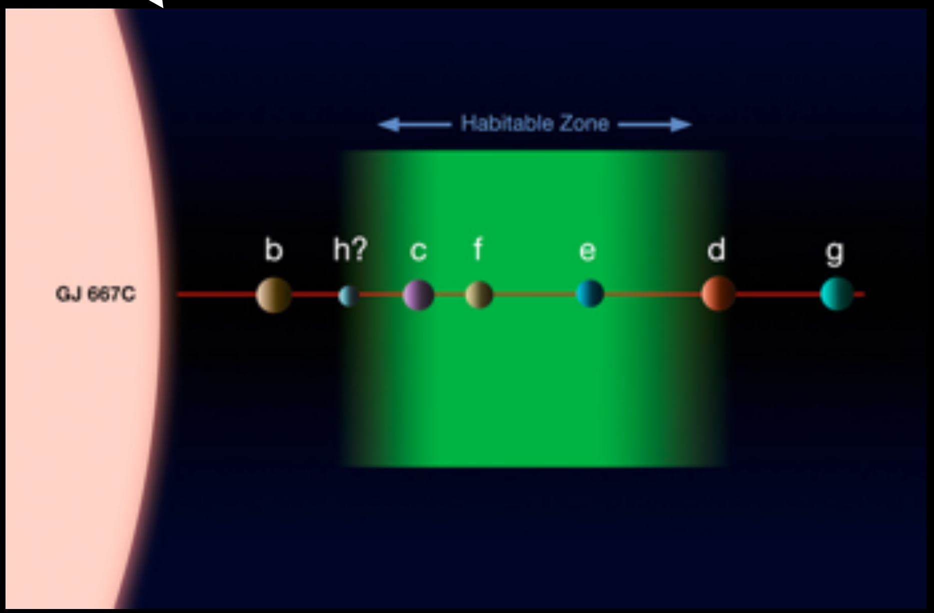


30-50+% of all stars

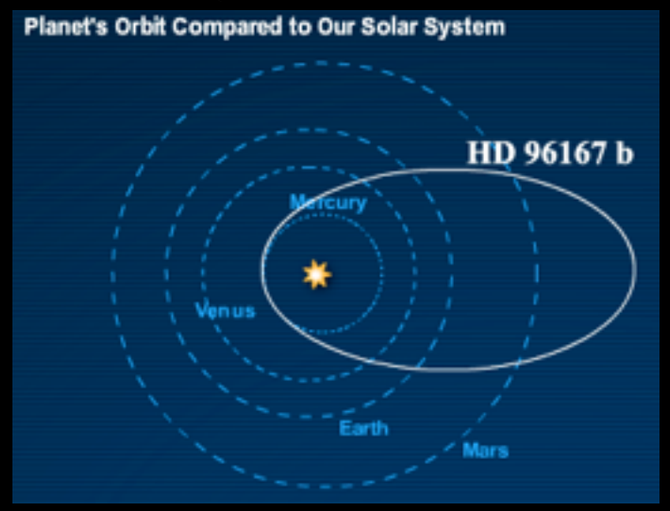
(Mayor et al 2011, Howard et al 2010, 2012)

>15%

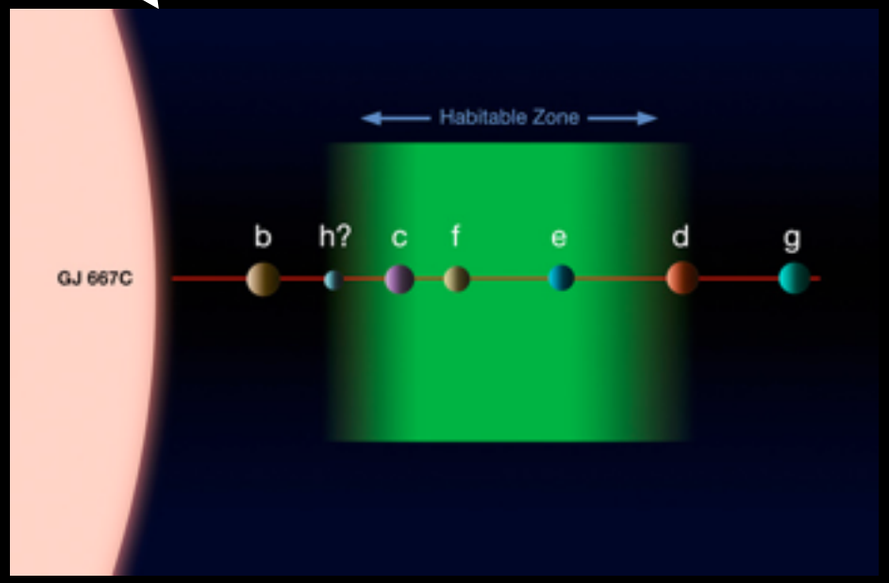
(Cumming et al 2008; Gould et al 2010; Mayor et al 2011)

<85%

Solar System(-like)



90%



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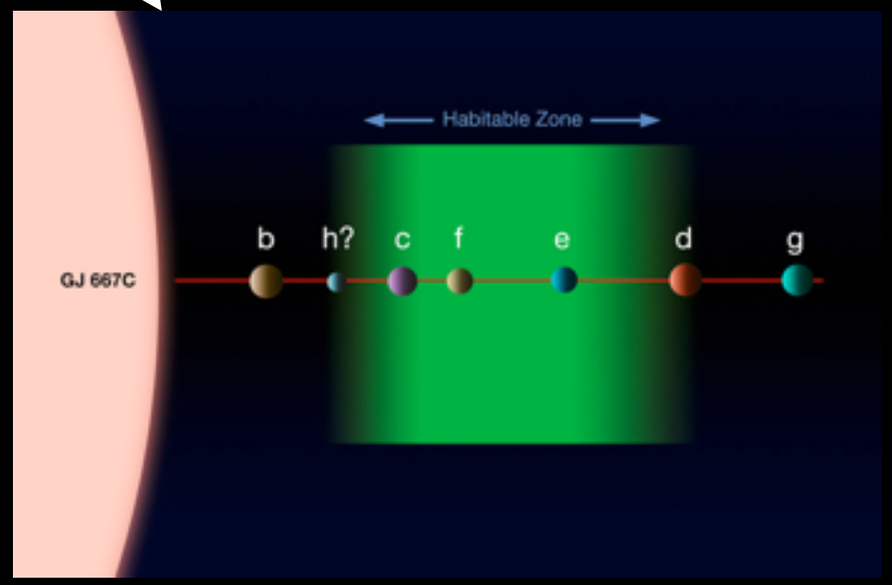
>15%

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

<85%

Solar System(-like)

Angry gas giants



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>15%

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

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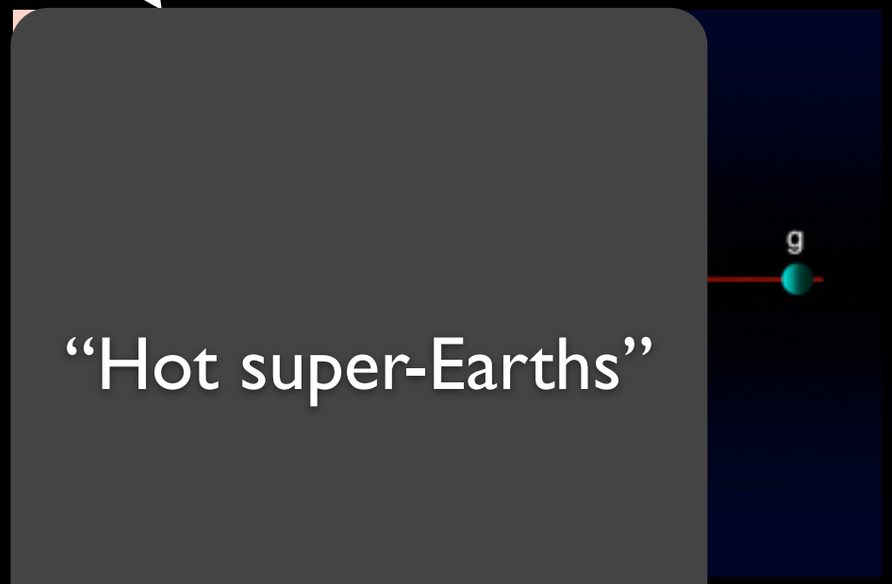
Solar System(-like)

Angry gas giants

“Hot super-Earths”

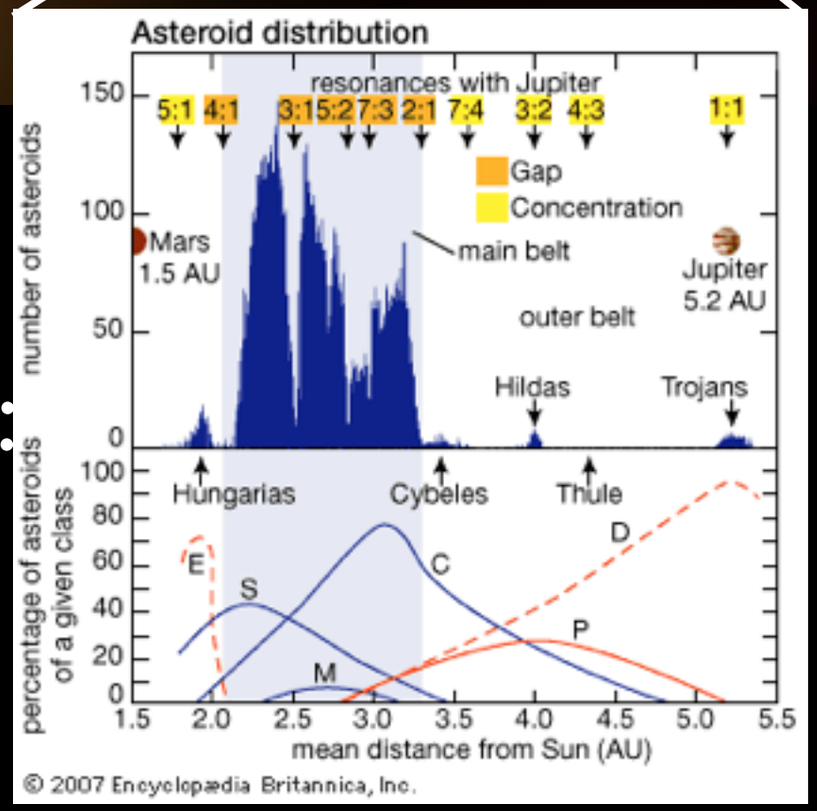


stars

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

Formation of the inner Solar System

Mercury
Venus
Earth
Mars
Jupiter

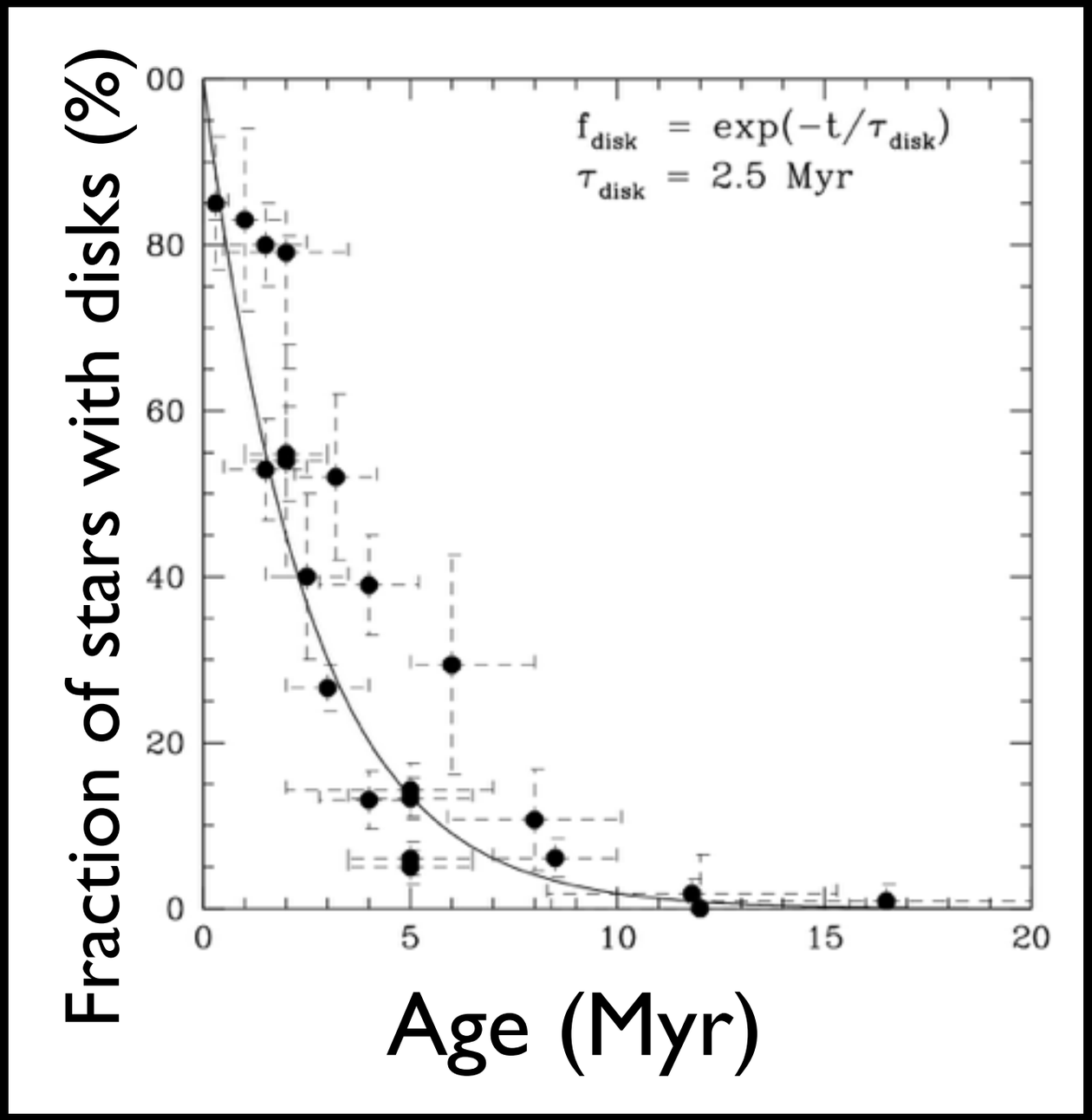


Total asteroid mass:
~10^{-3} Earth masses

Sequence of events

Sequence of events

Gas giants form fast (a few million years)



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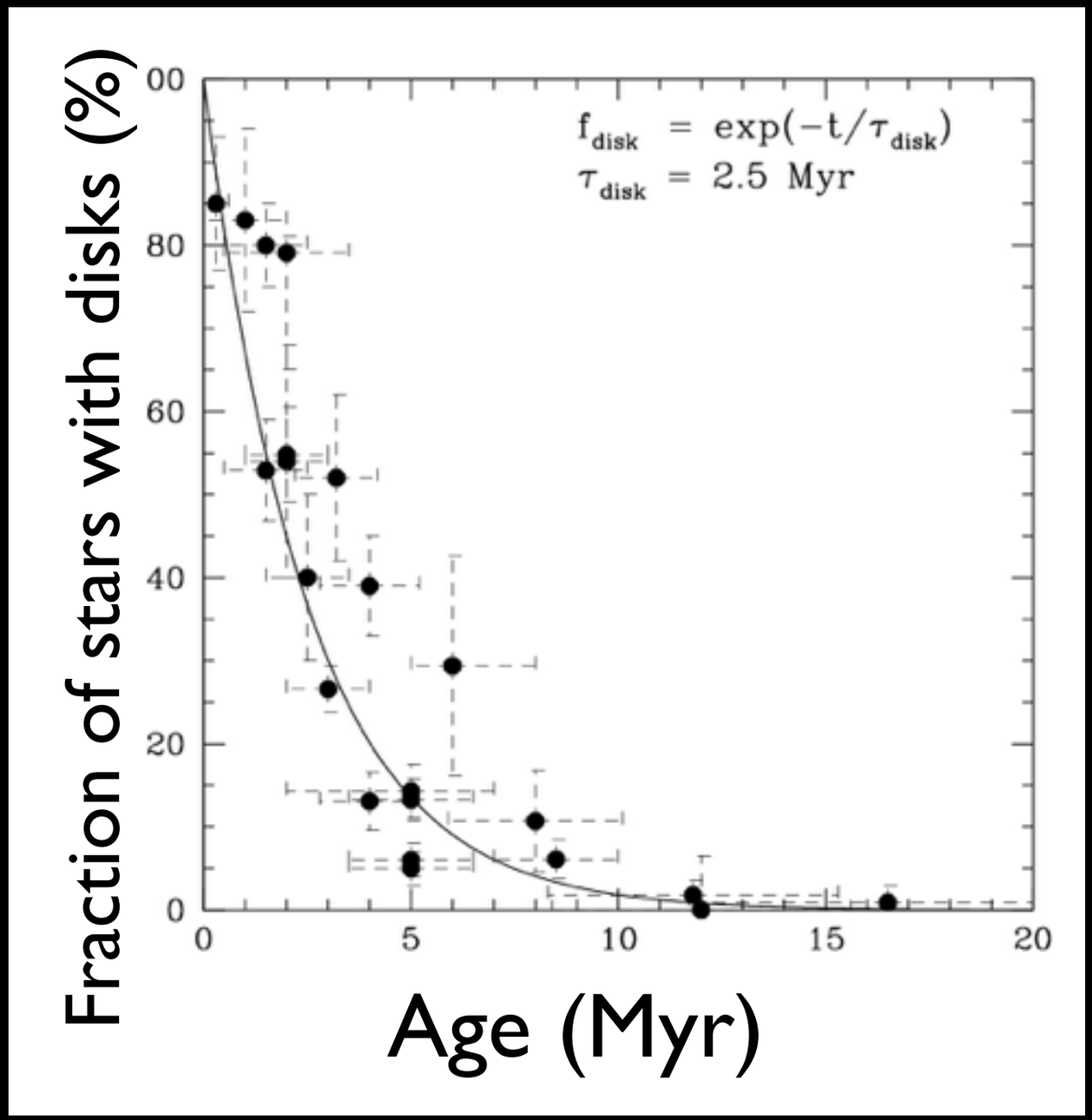
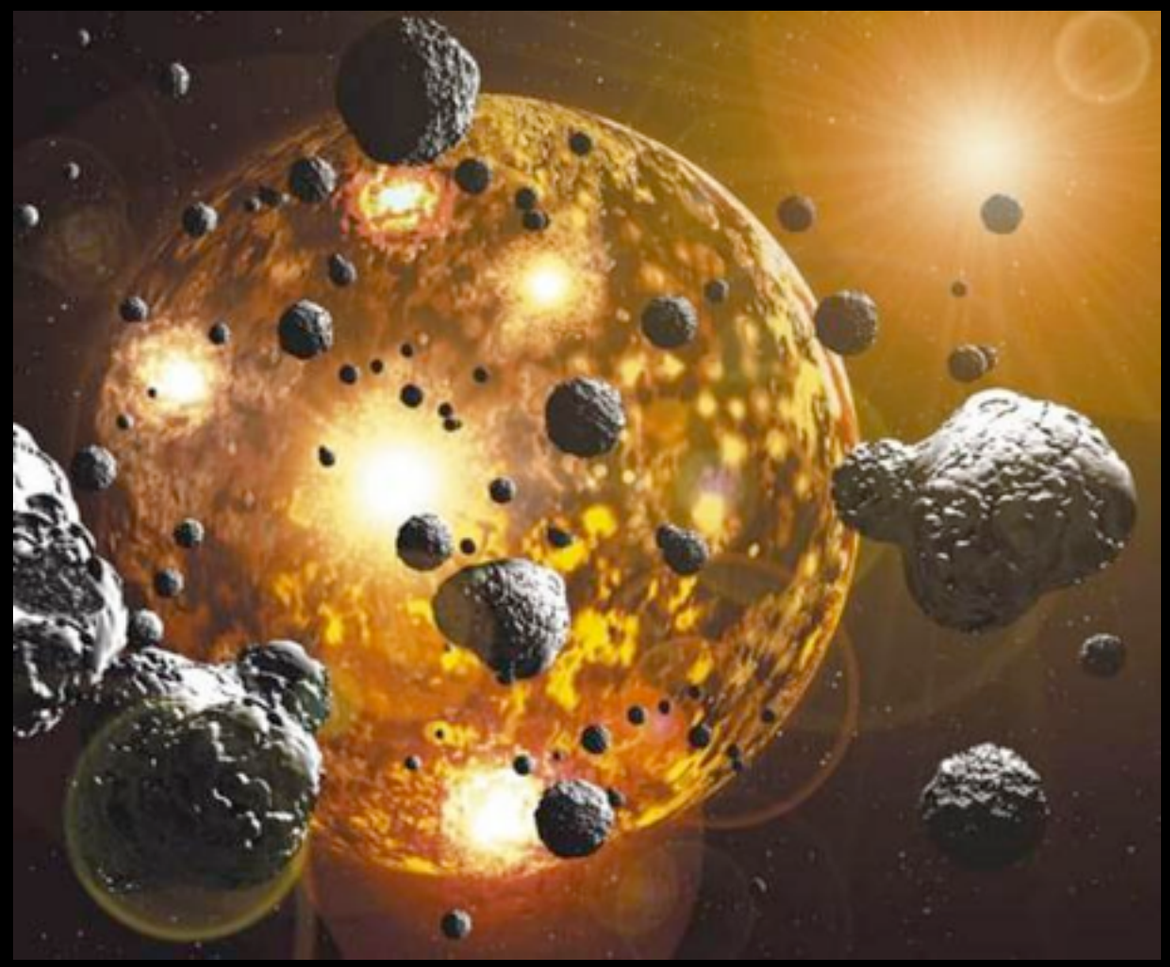
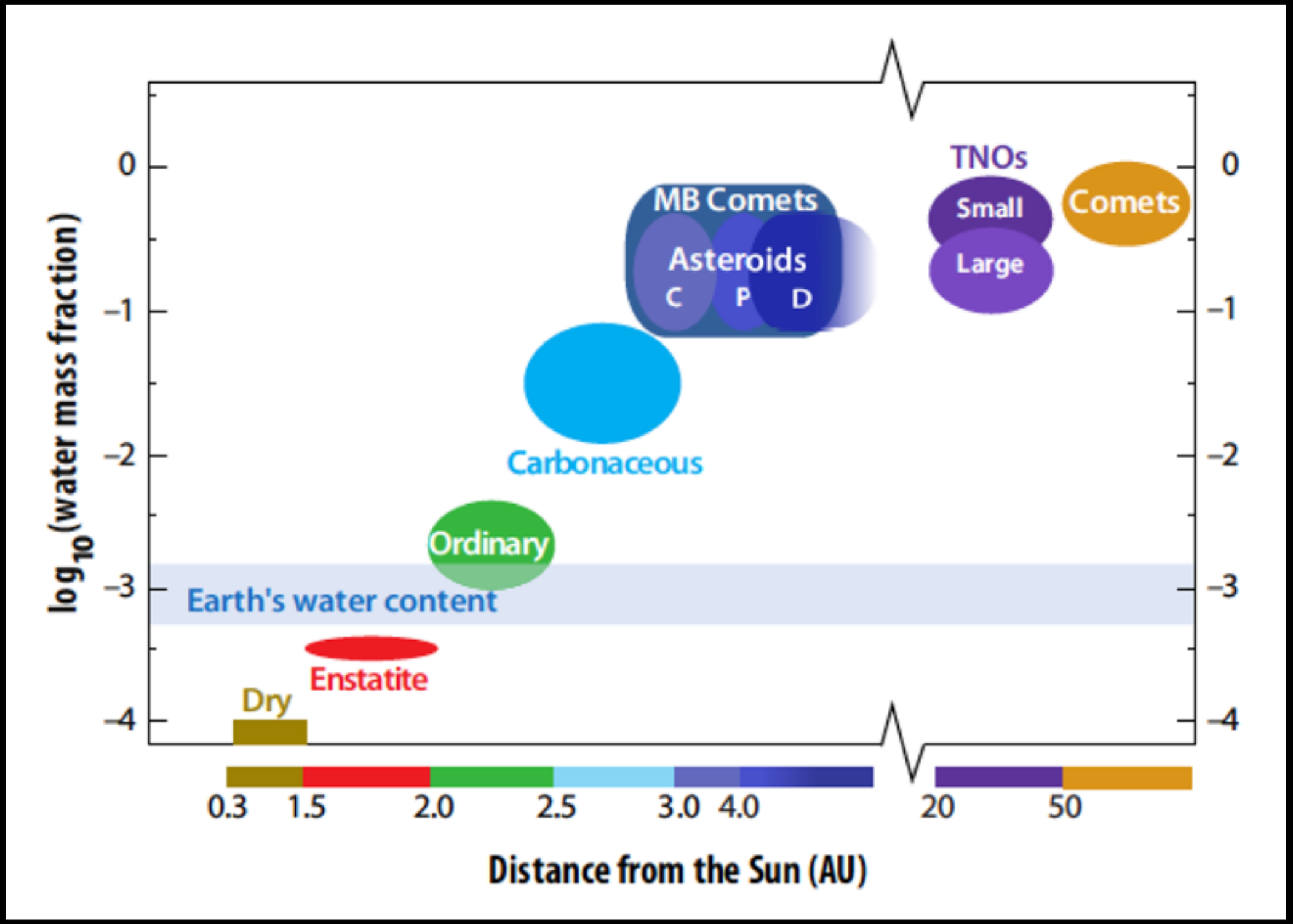


Earth formed slow (~100 million years)



Water content of planetary building blocks

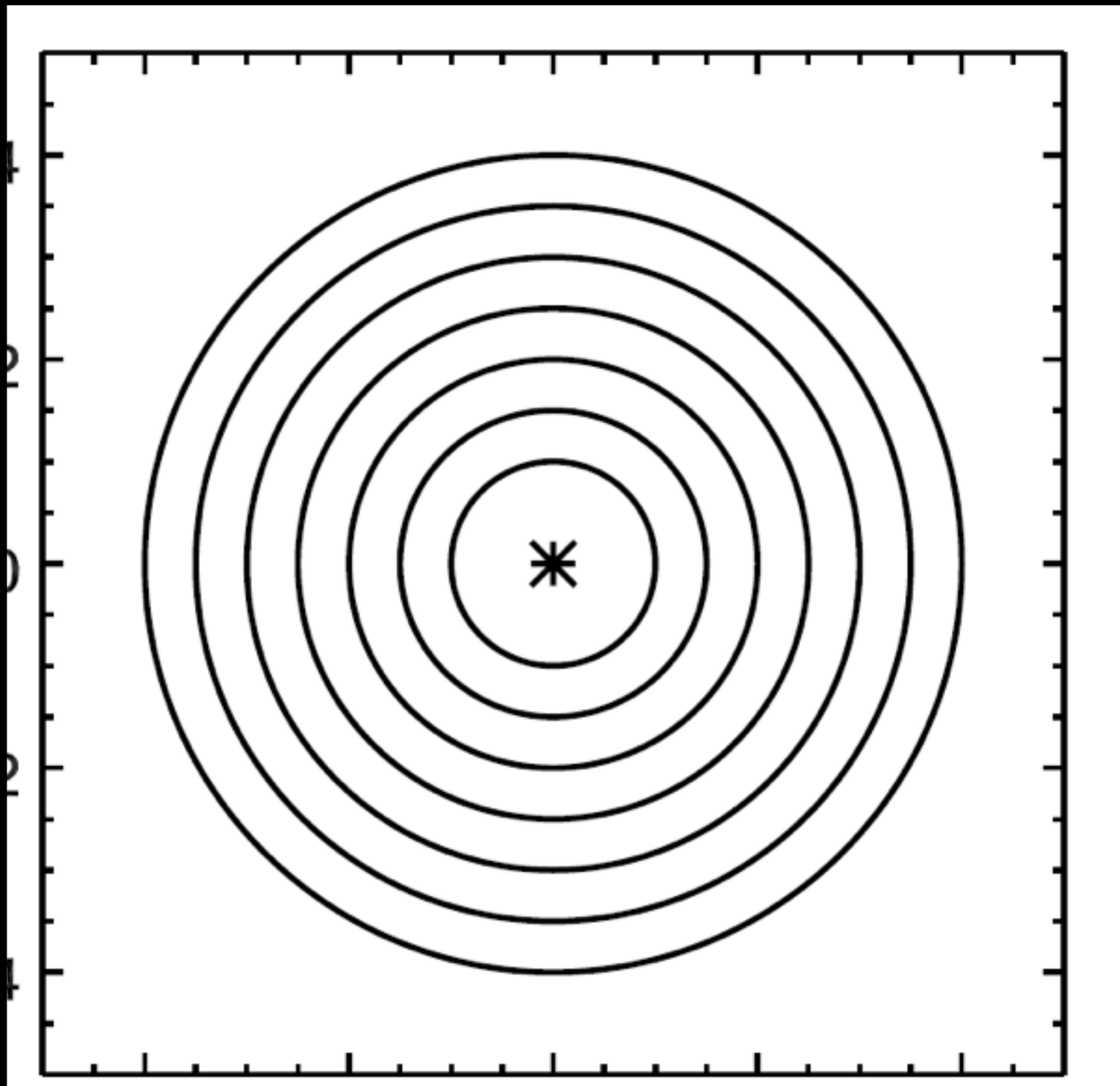


von Dishoeck et al 2014

Need eccentric orbits for collisions to happen

- Semimajor axis a = average distance between planet, star

- Eccentricity e = measure of how elliptical an orbit is



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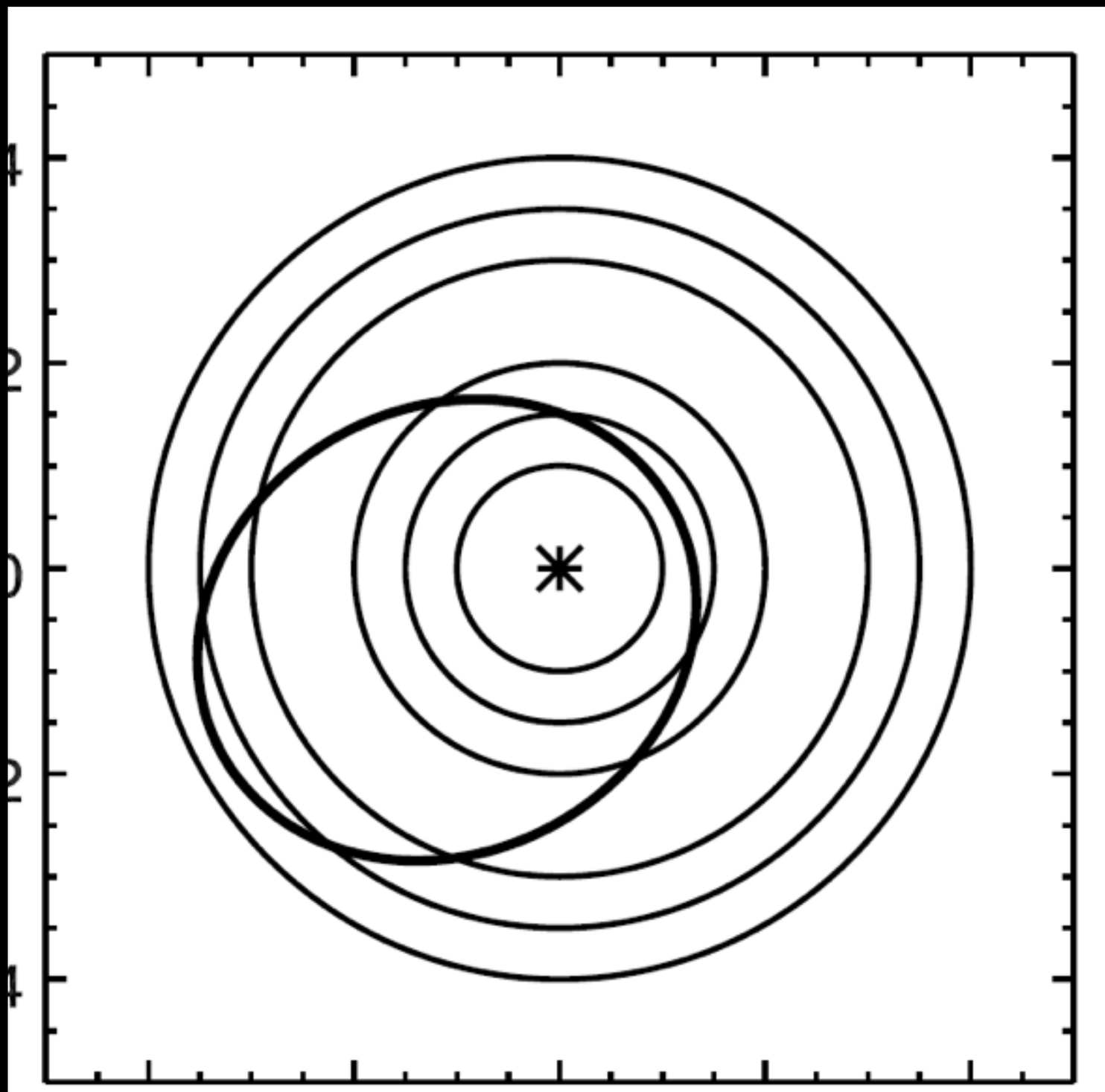
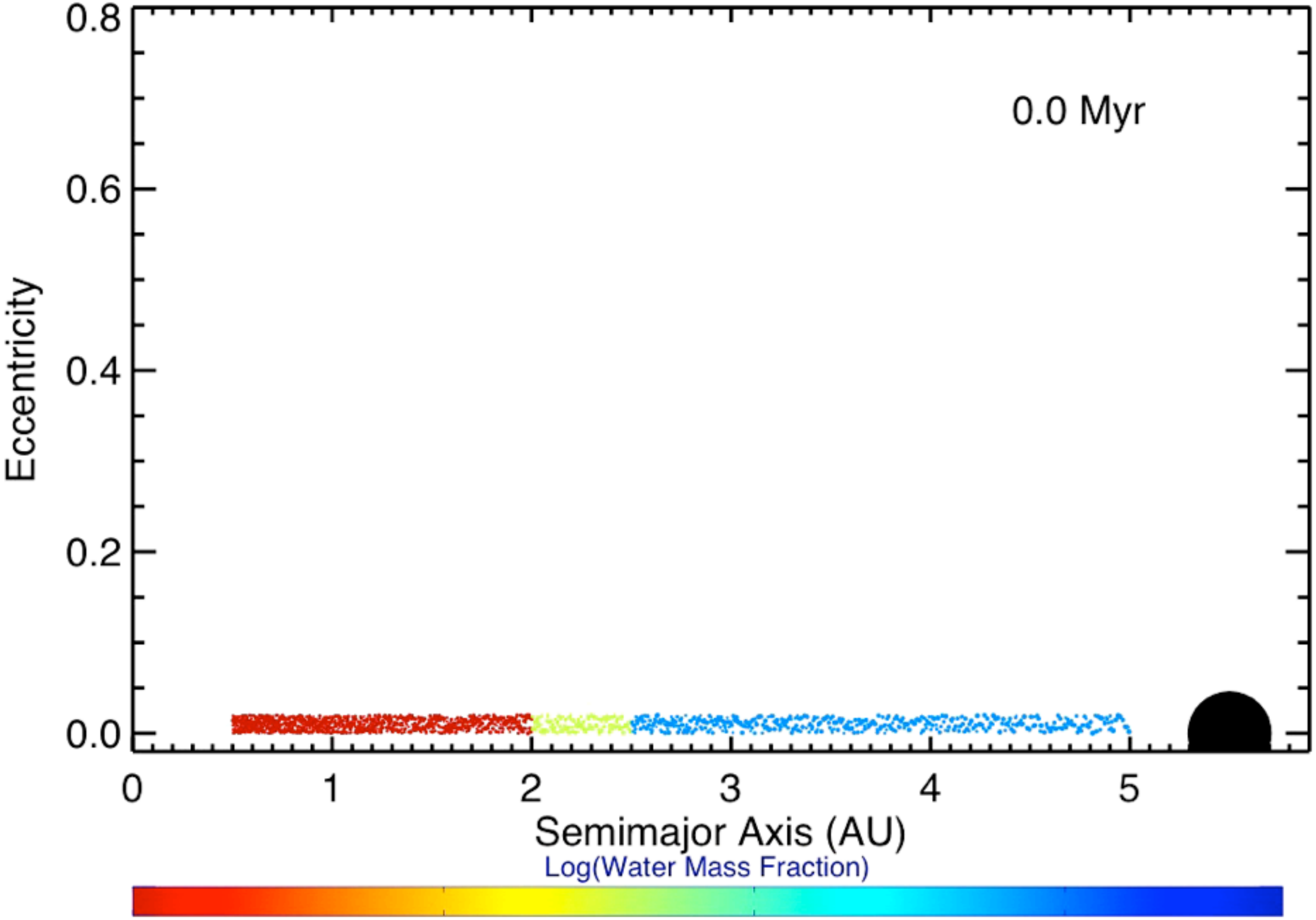
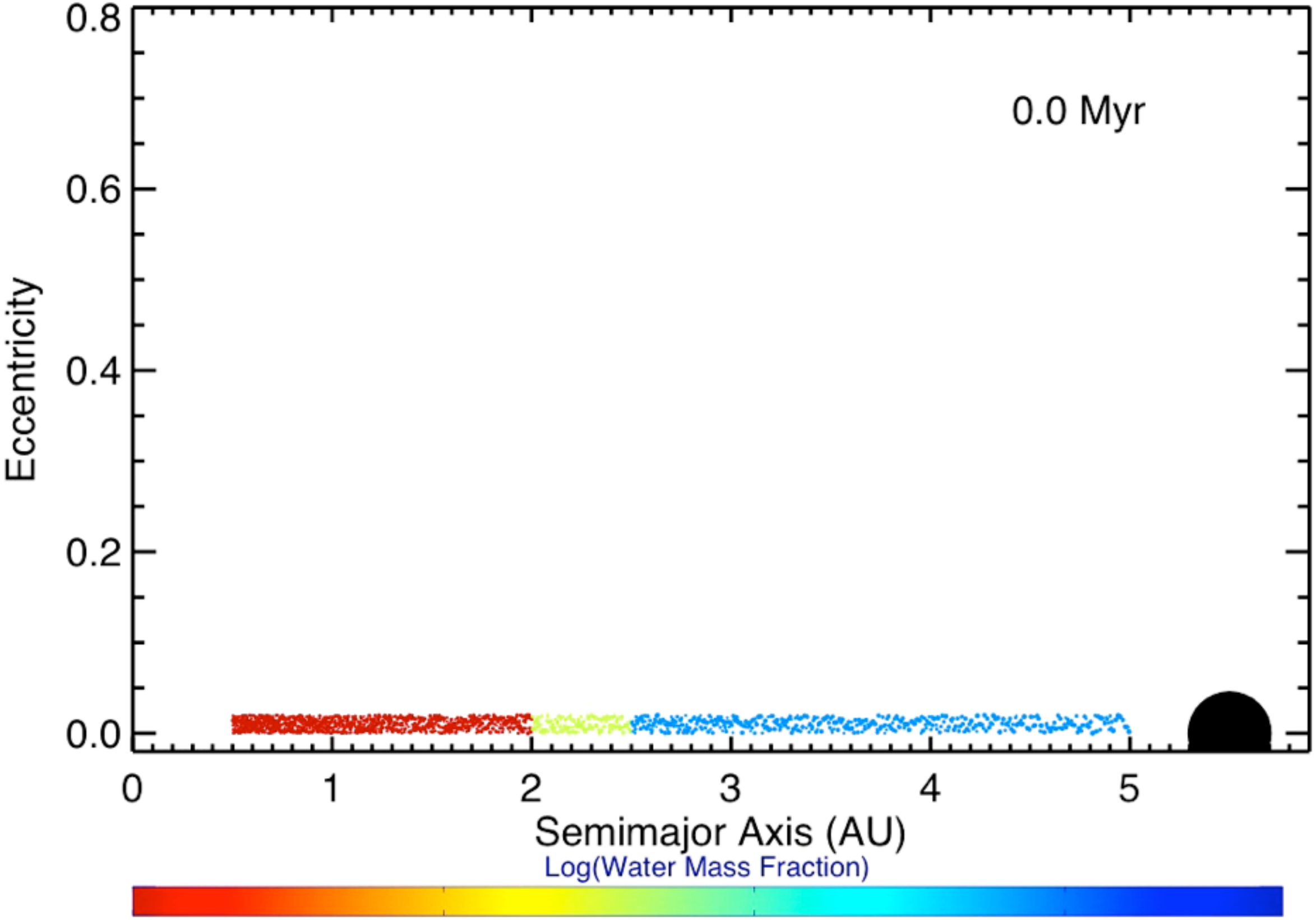


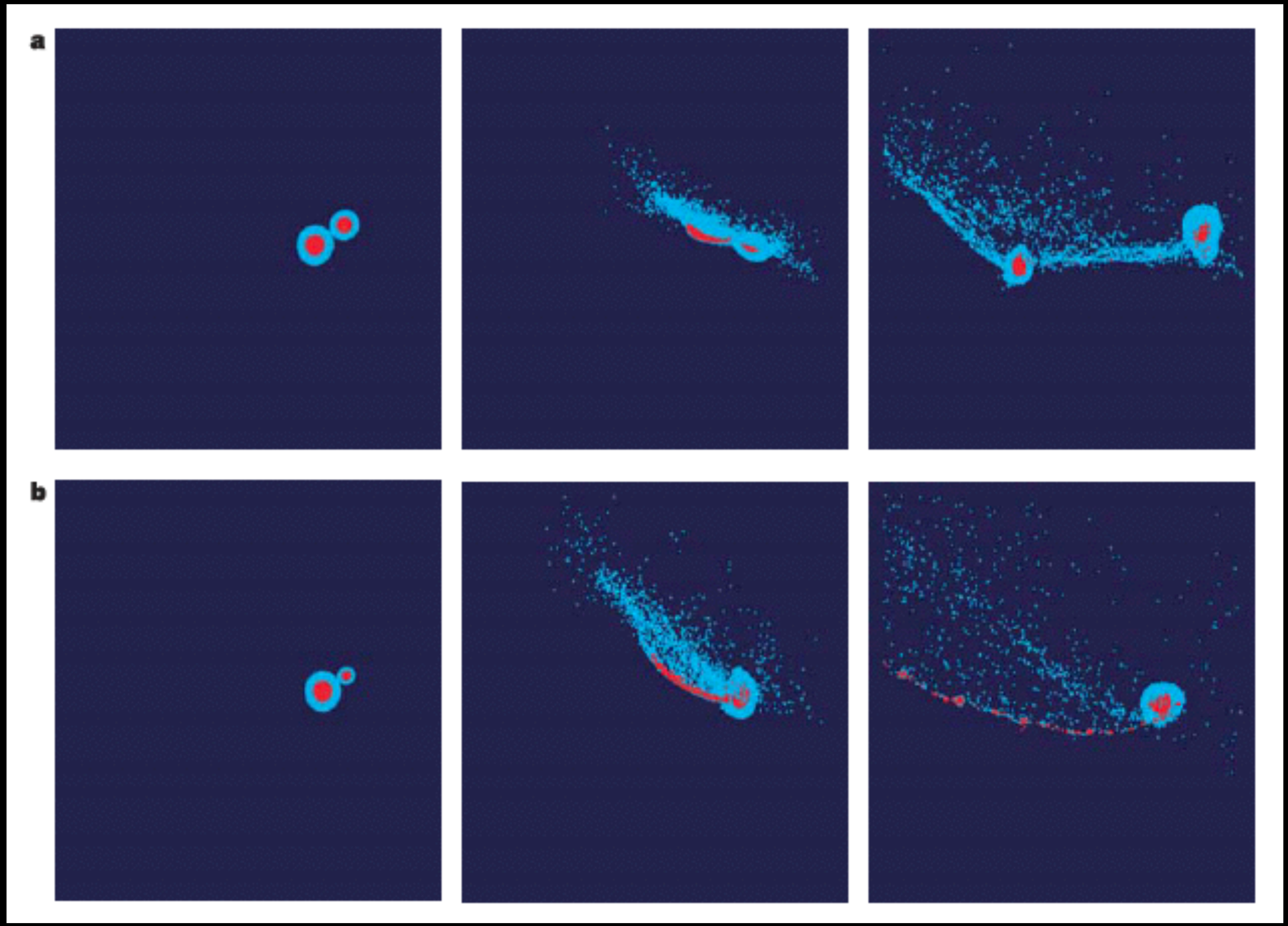


Raymond et al 2006



Raymond et al 2006

Hit-and-run collisions

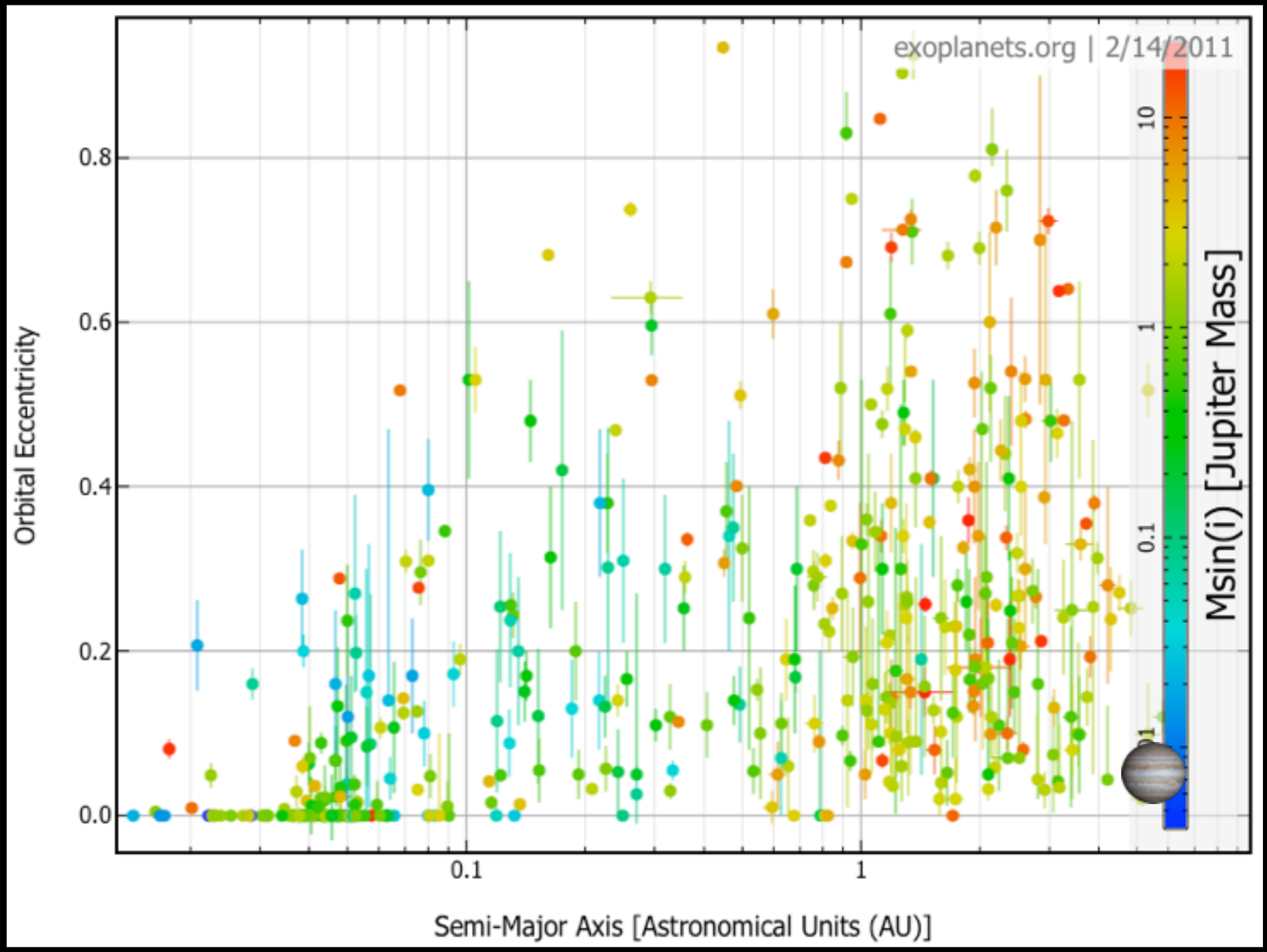


Asphaug et al 2006

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

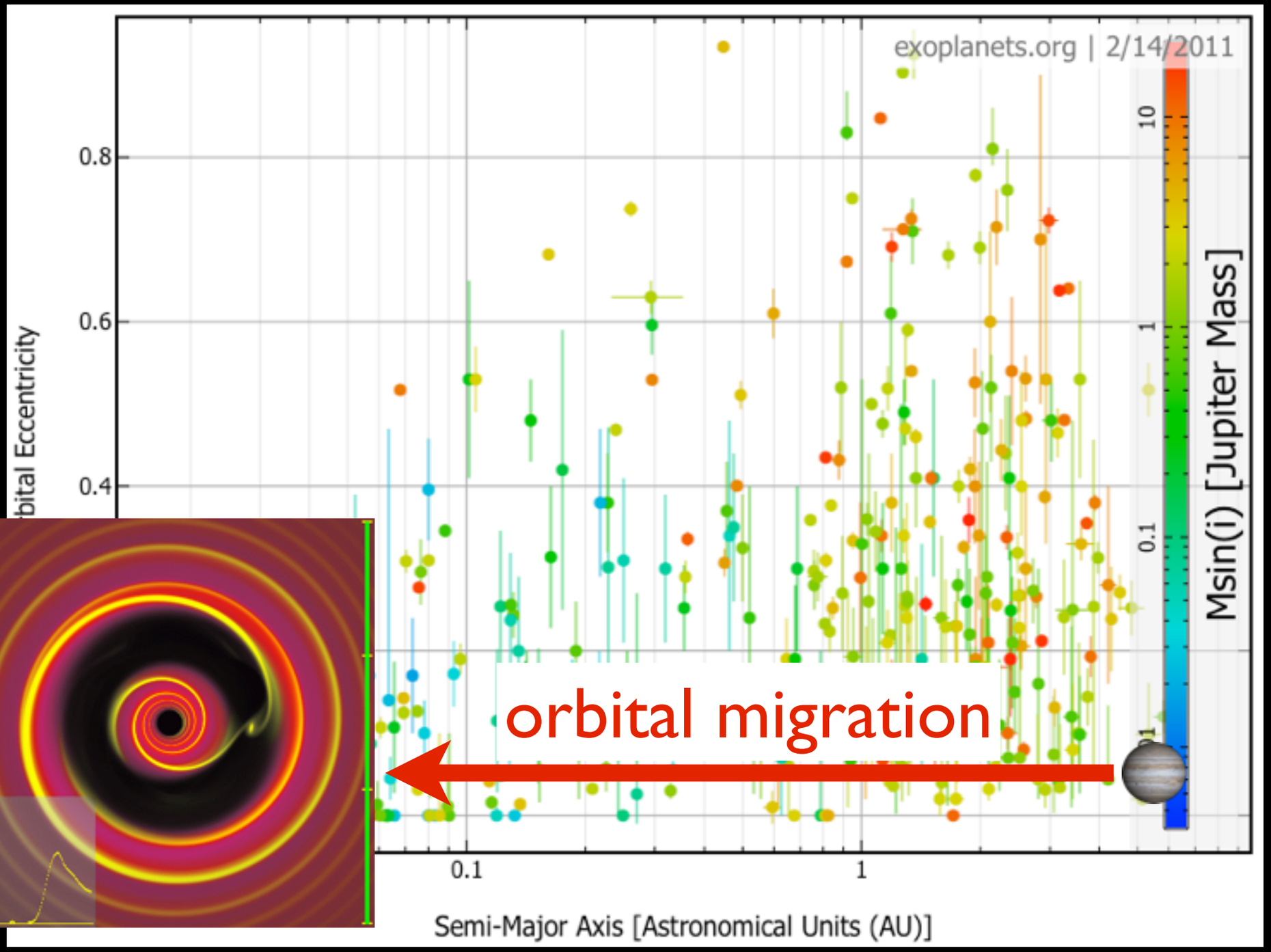
Terrestrial planet formation with angry gas giants

Giant exoplanets



Wright et al 2011

Giant exoplanets



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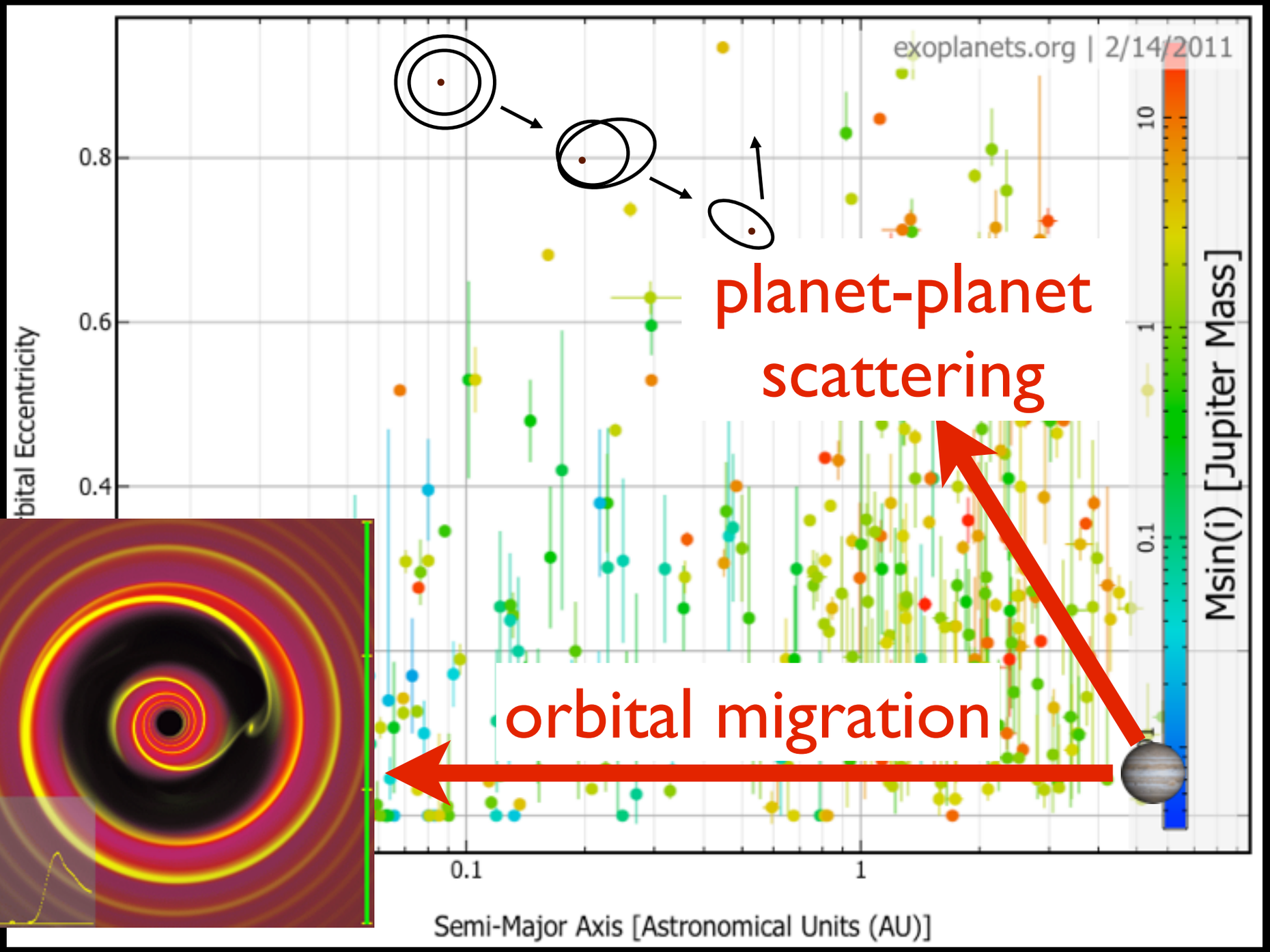
Giant exoplanets



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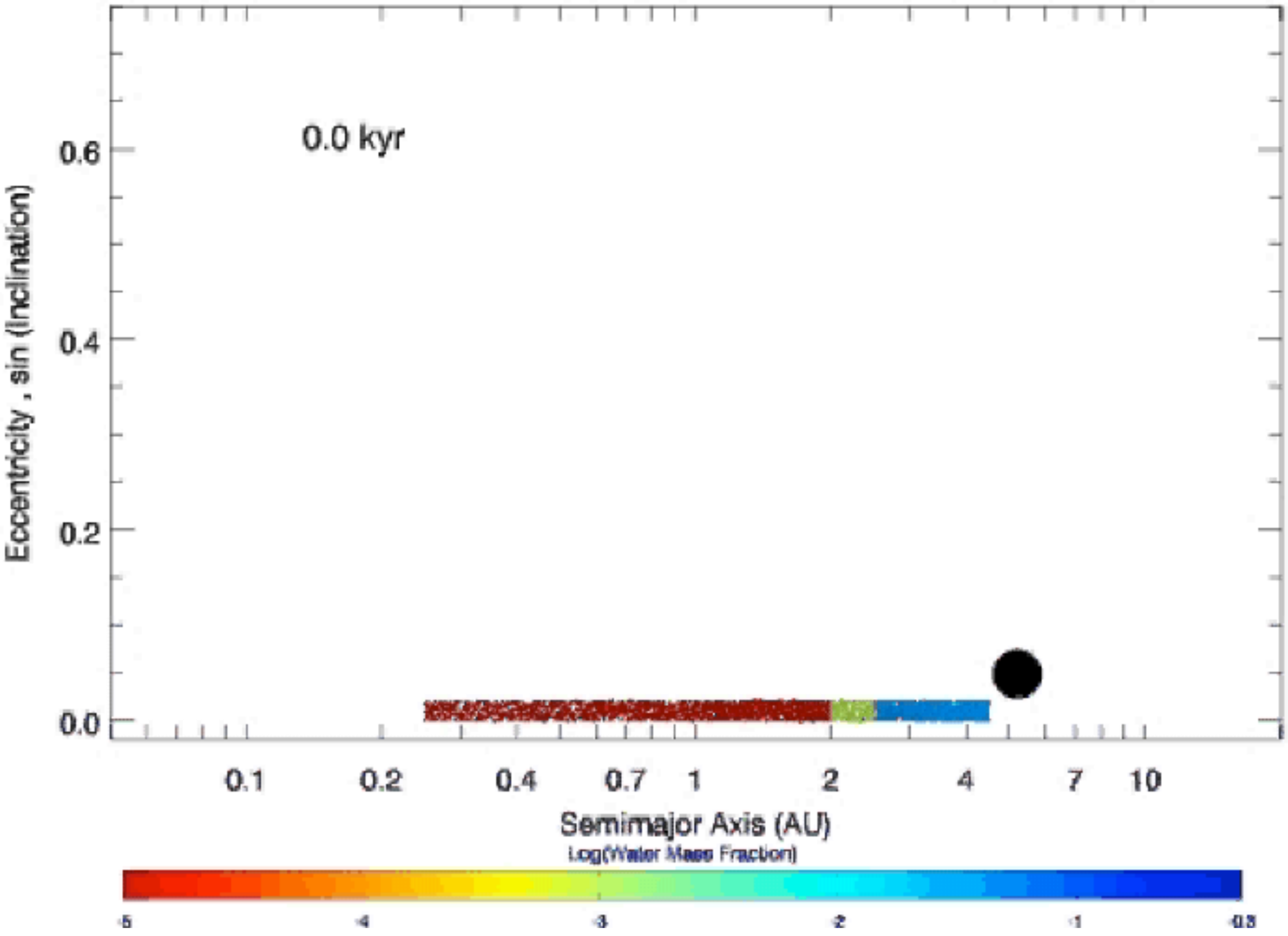
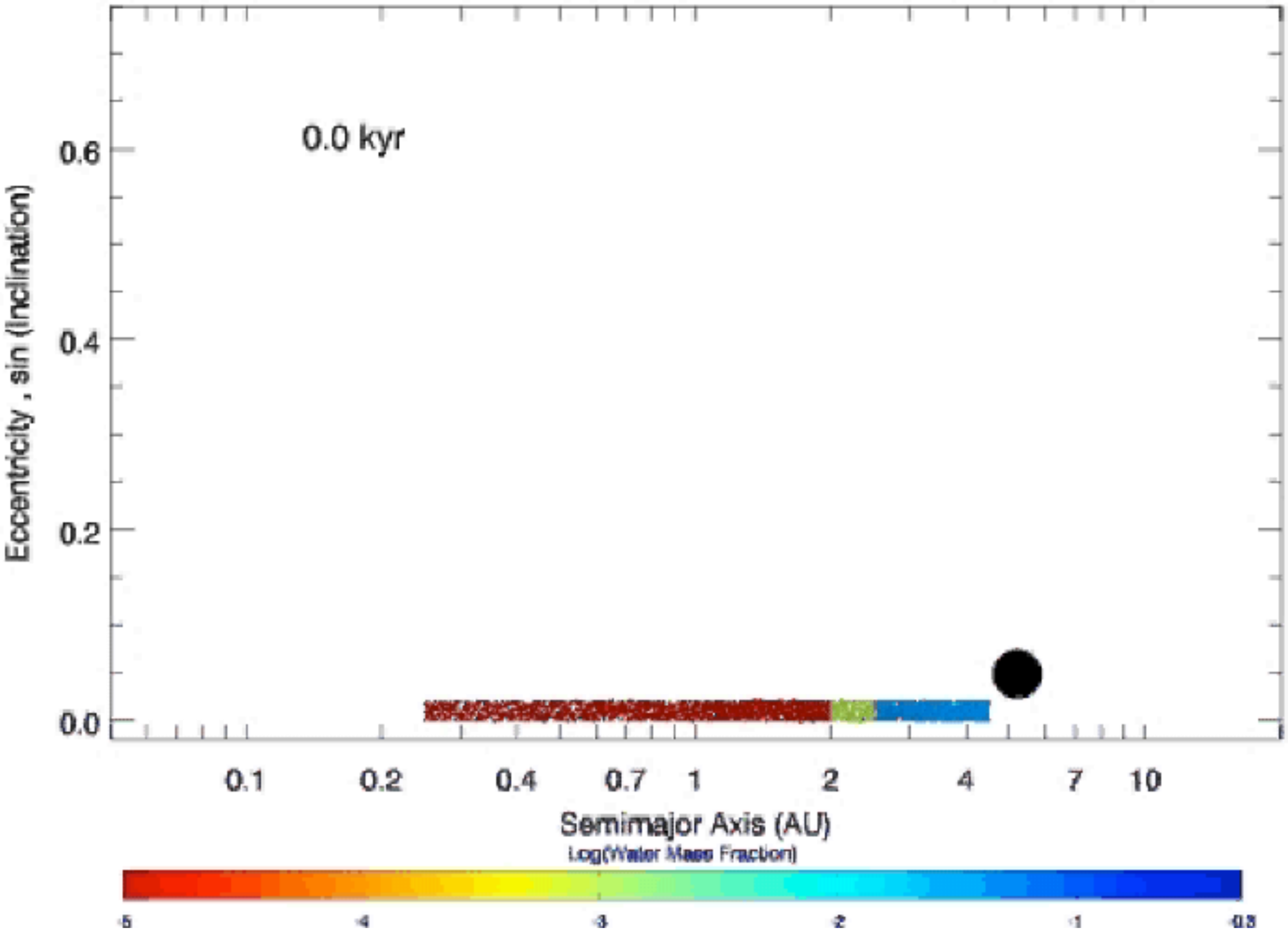

0.0 kyr
0.6
0.4
0.2
0.0
Eccentricity , sin (Inclination)
0.1
0.2
0.4
0.7
1
2
4
7
10
Semimajor Axis (AU)
Log(Water Mass Fraction)
-5
-4
-3
-2
-1
-0.3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Eccentricity , sin (Inclination)
0.1
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Semimajor Axis (AU)
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-5
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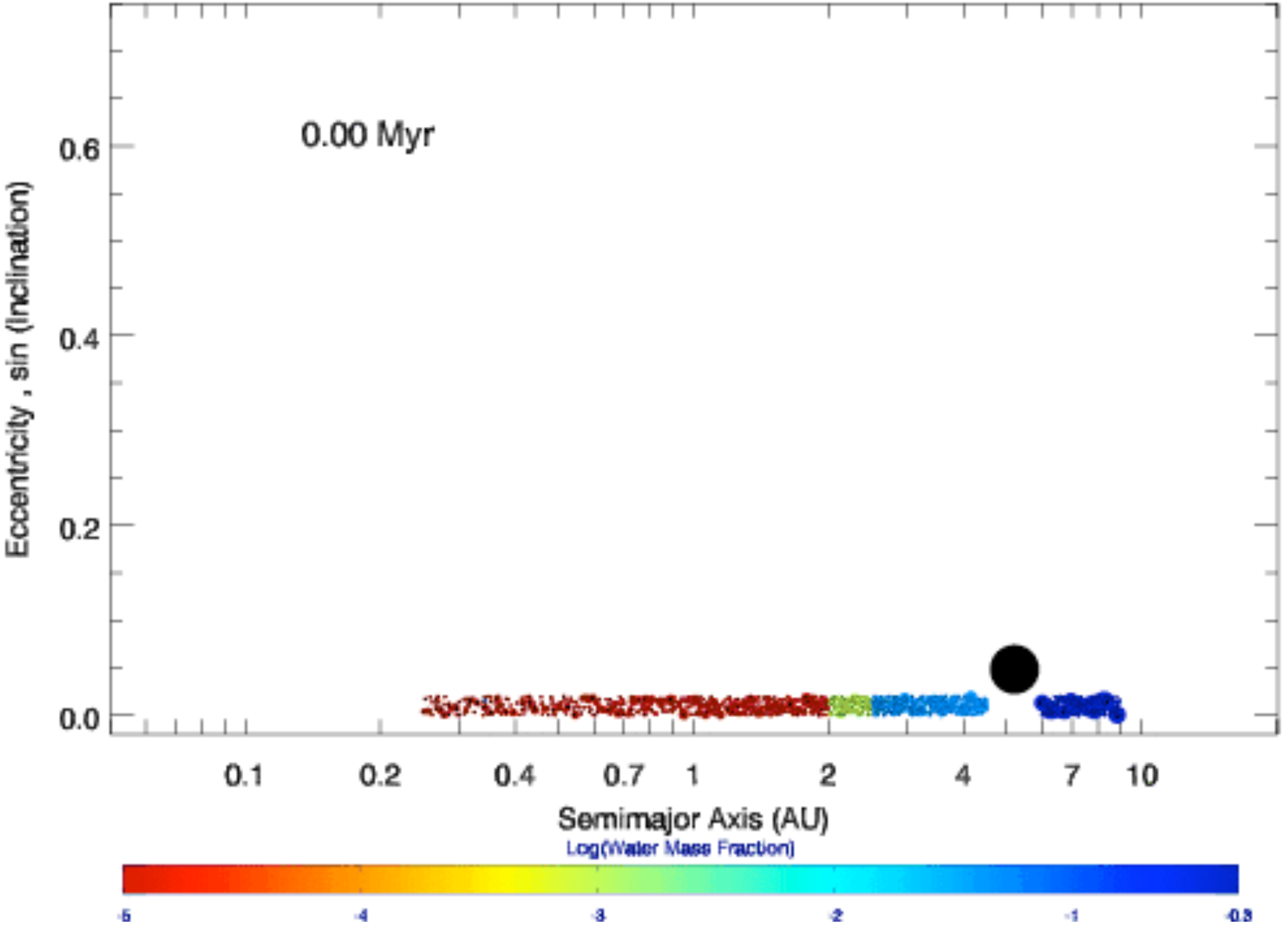
-2
-1
-0.3


0.00 Myr
Eccentricity , sin (Inclination)
0.6
0.4
0.2
0.0
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0.4
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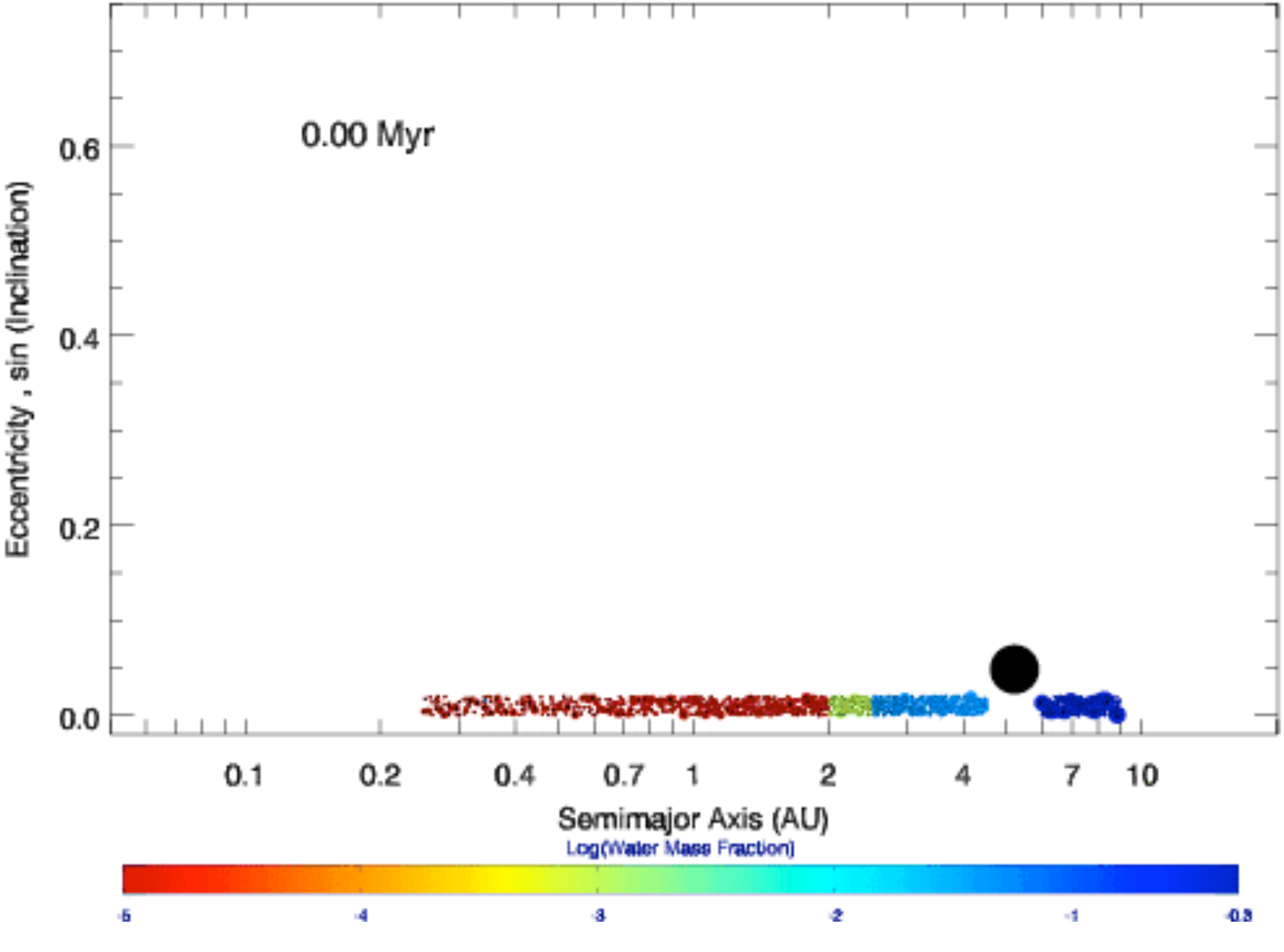
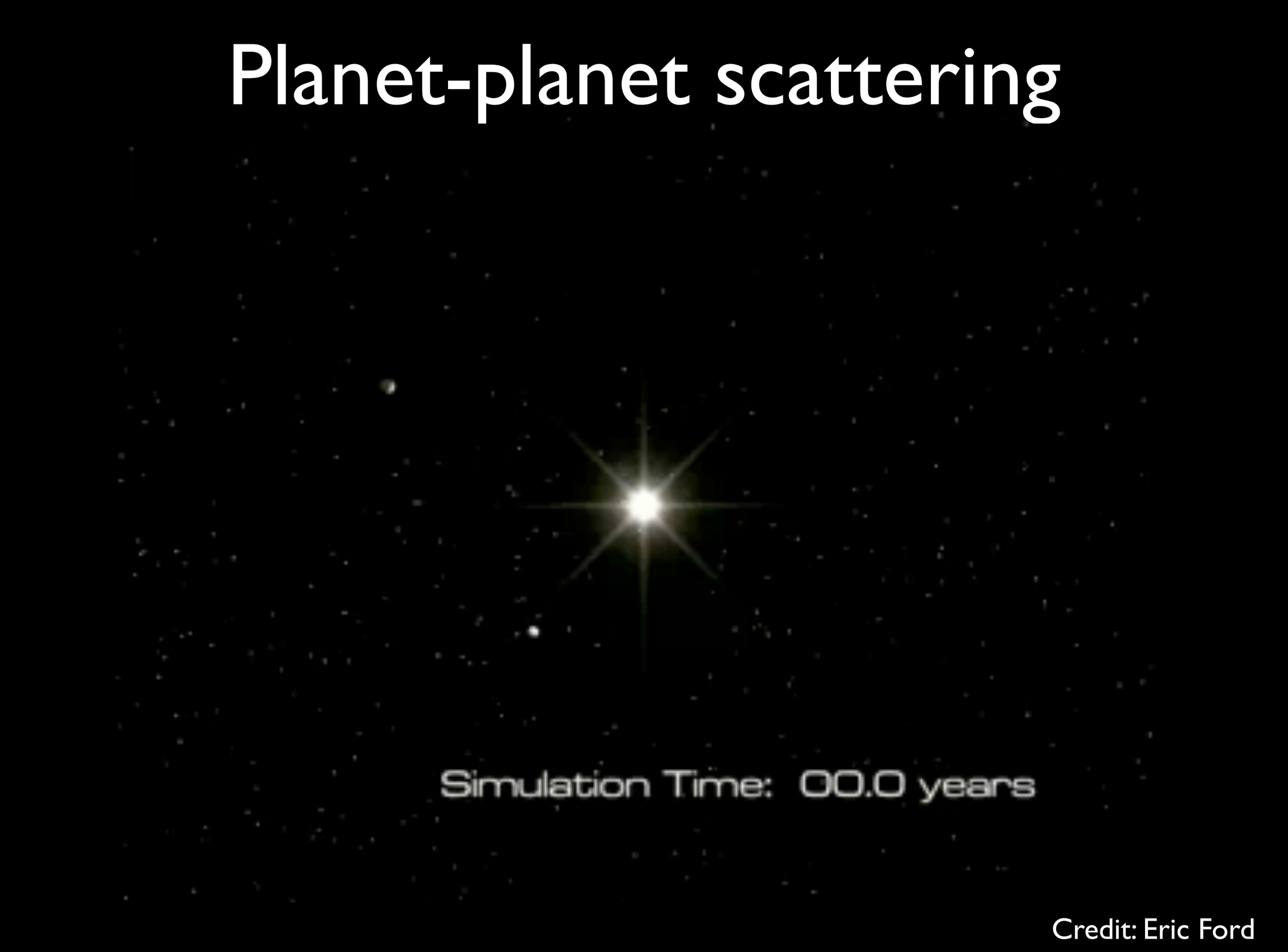

0.00 Myr
Eccentricity , sin (Inclination)
0.6
0.4
0.2
0.0
0.1
0.2
0.4
0.7
1
2
4
7
10
Semimajor Axis (AU)
Log(Water Mass Fraction)
-5
-4
-3
-2
-1
-0.3

Credit: Nahks Tr’Enhl

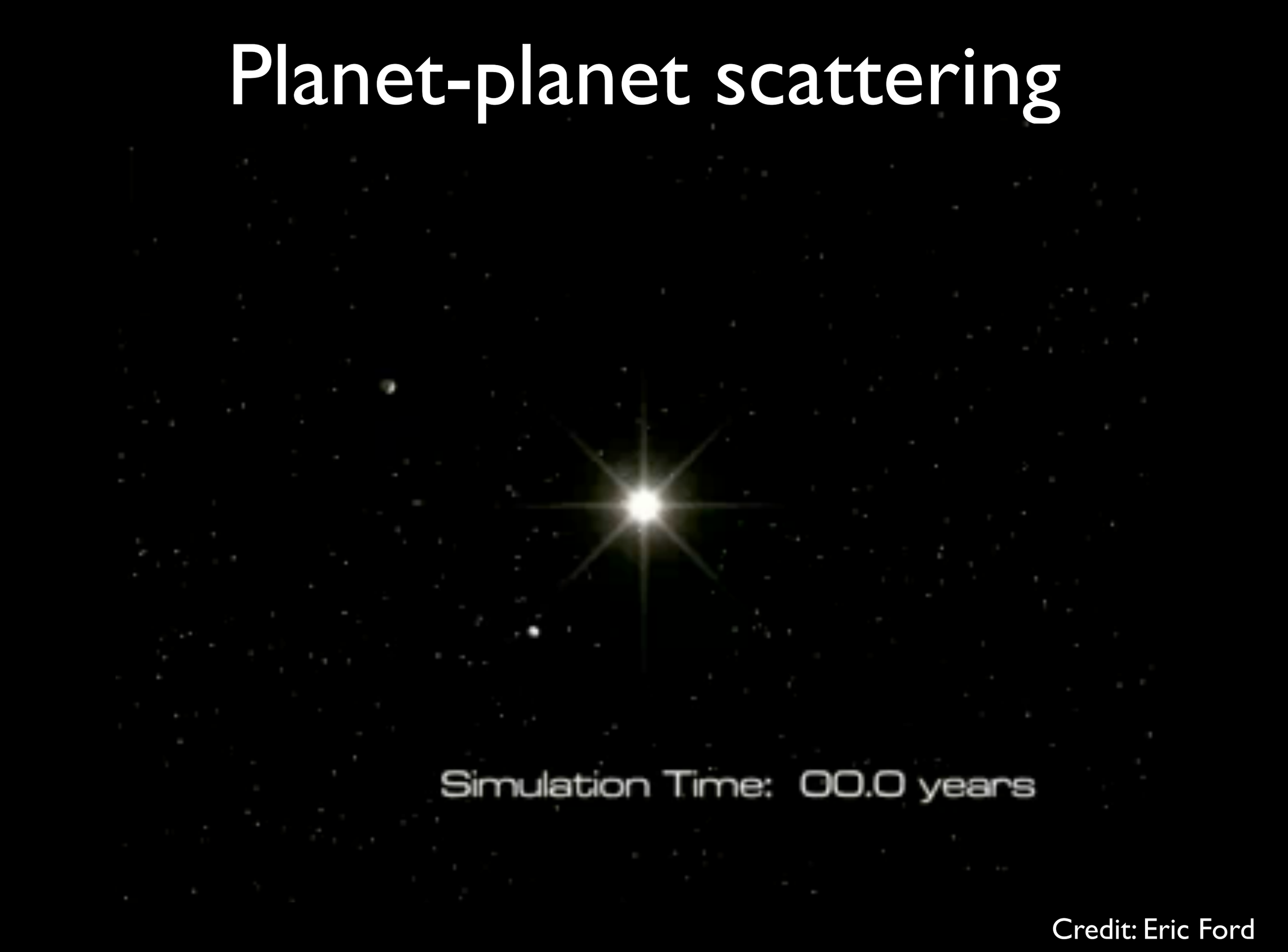
Credit: Nahks Tr’Enhl

Planet-planet scattering

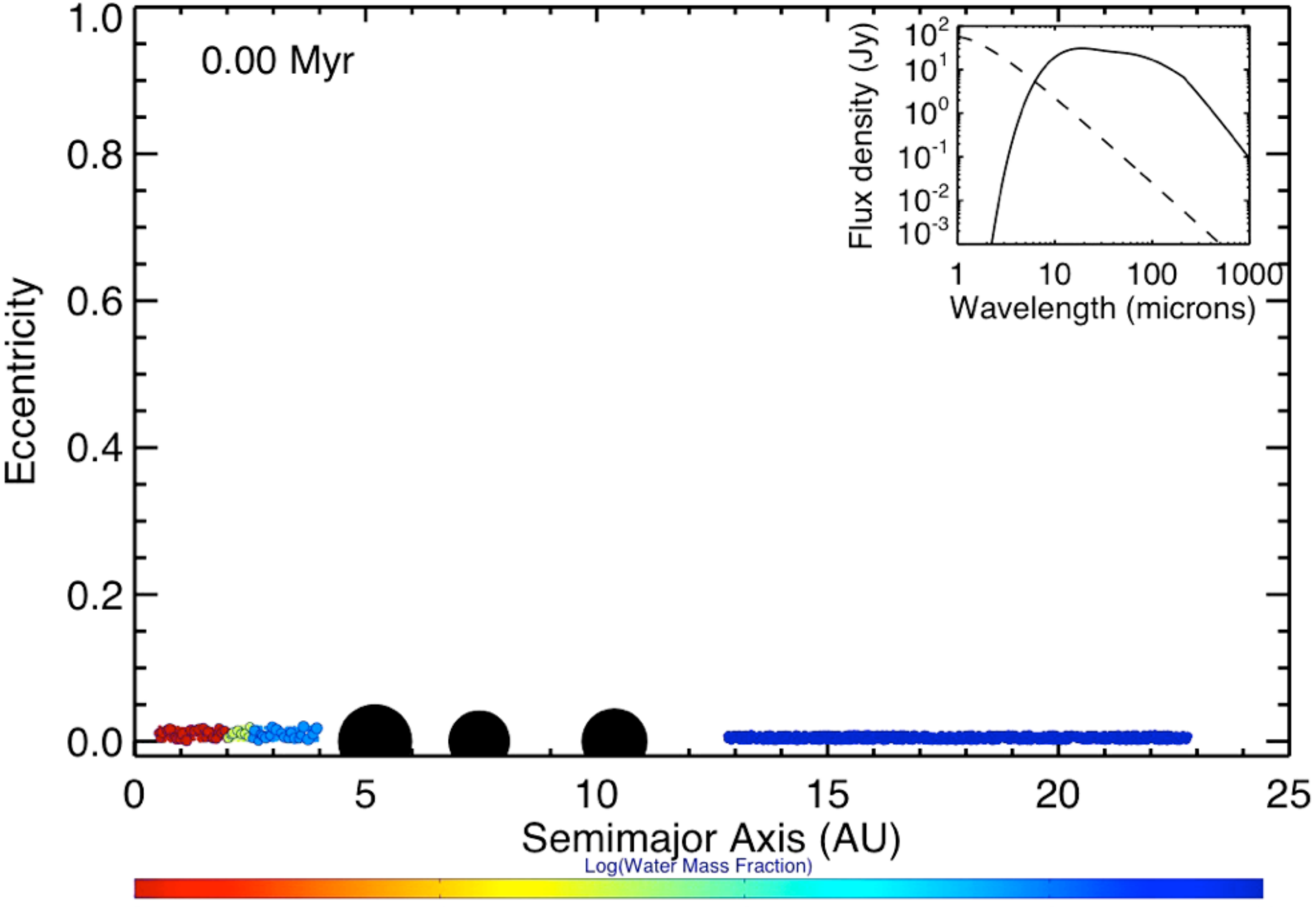


Credit: Eric Ford

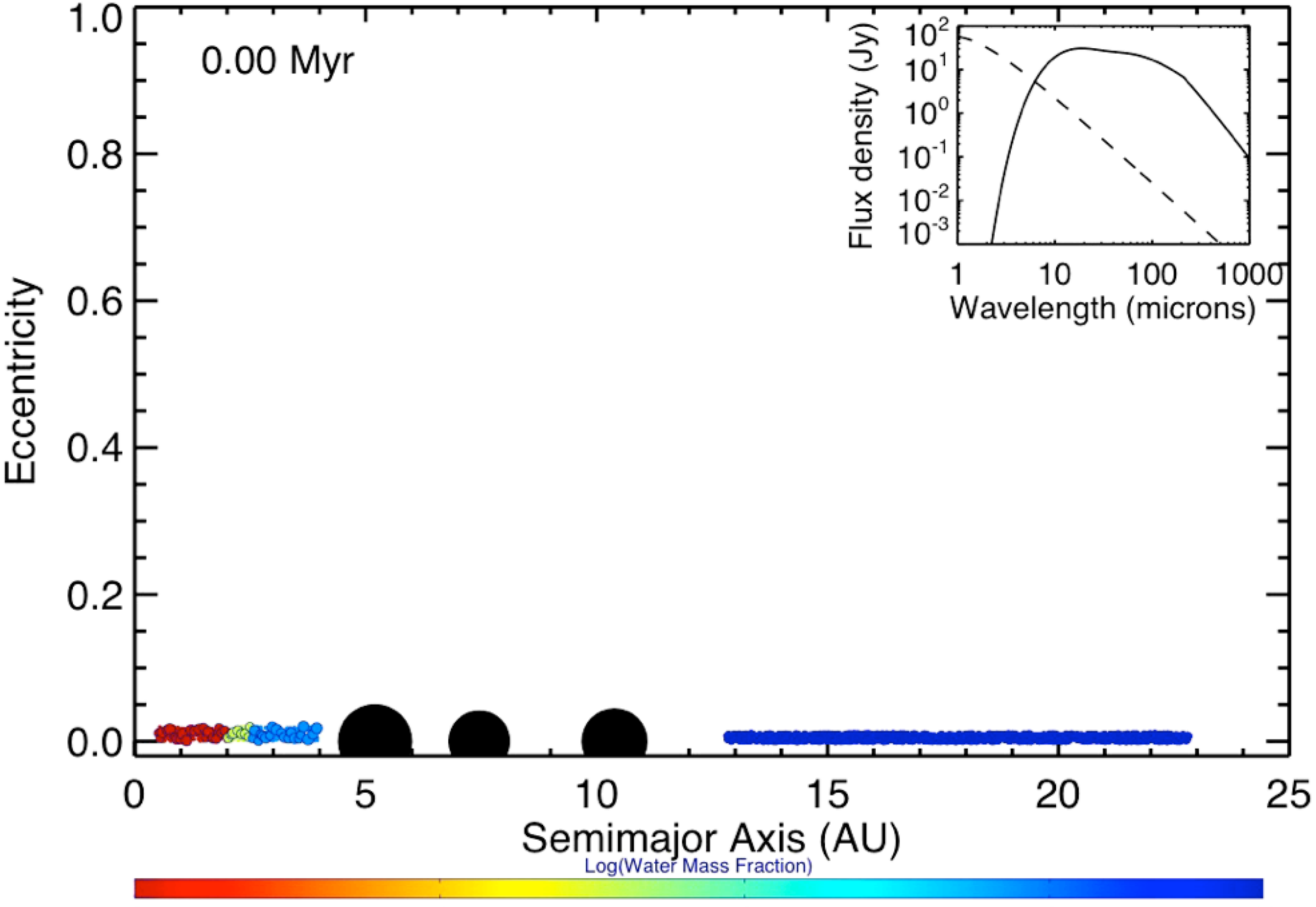
Planet-planet scattering



Credit: Eric Ford

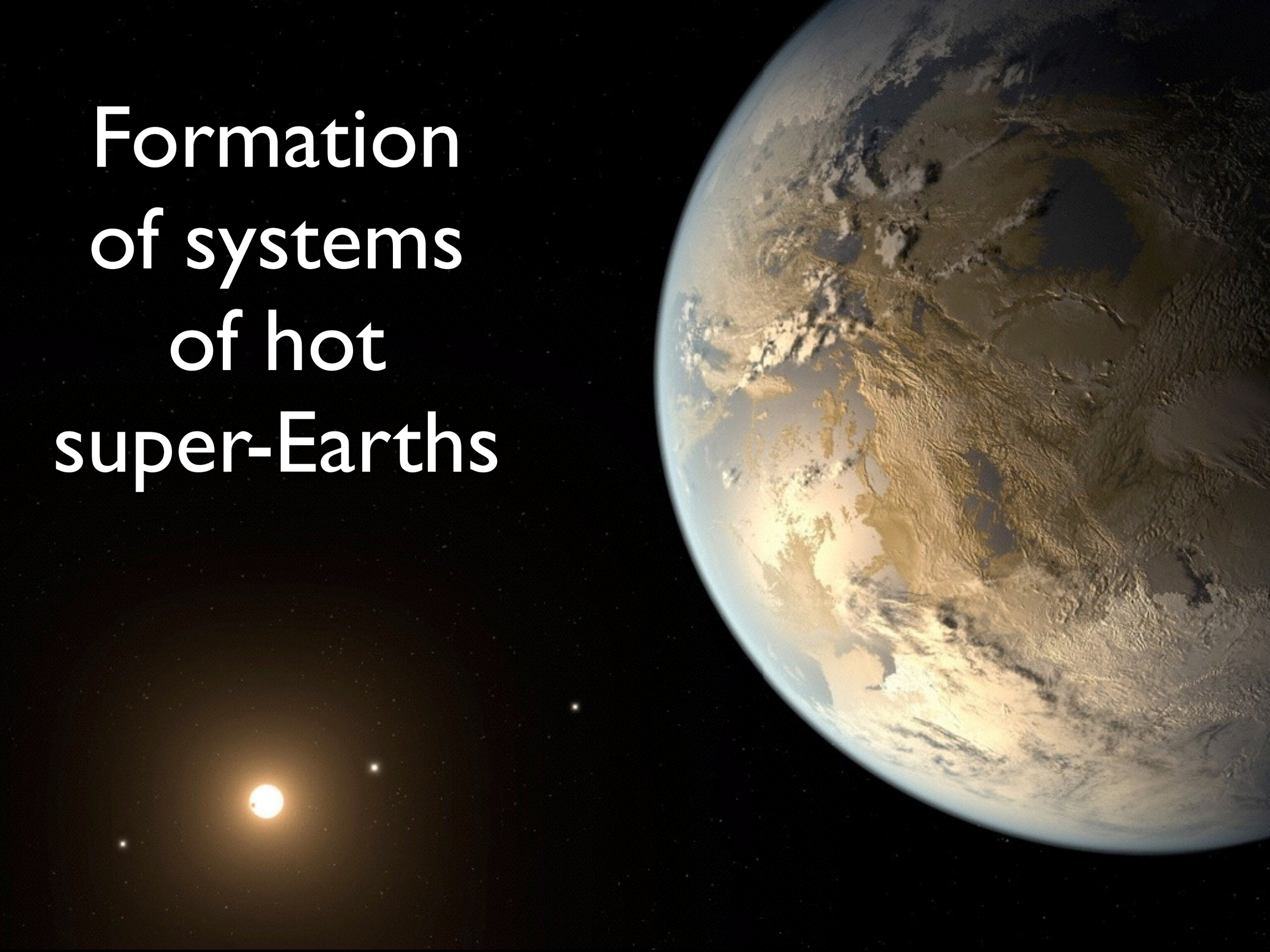


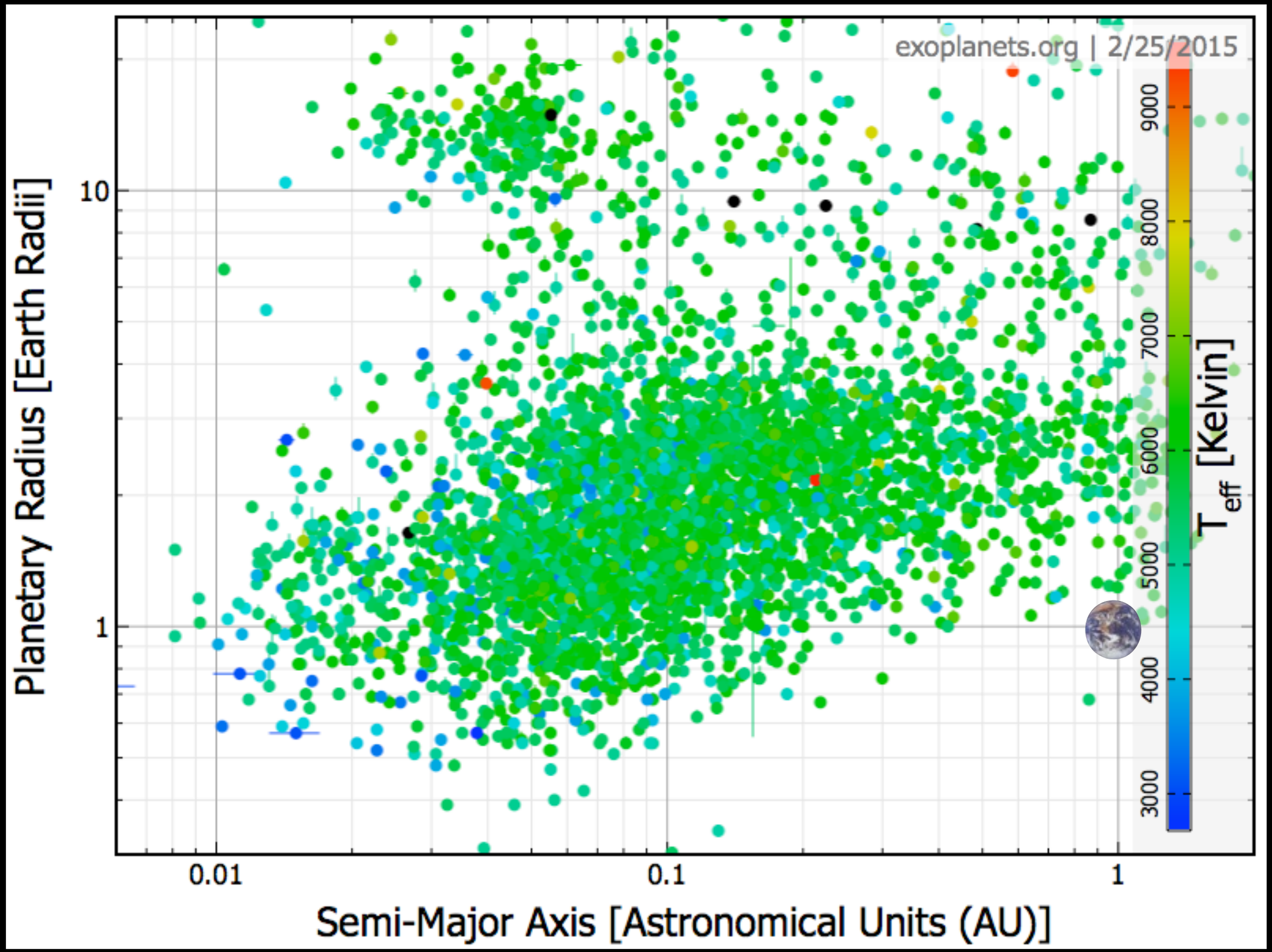
Raymond et al 2012

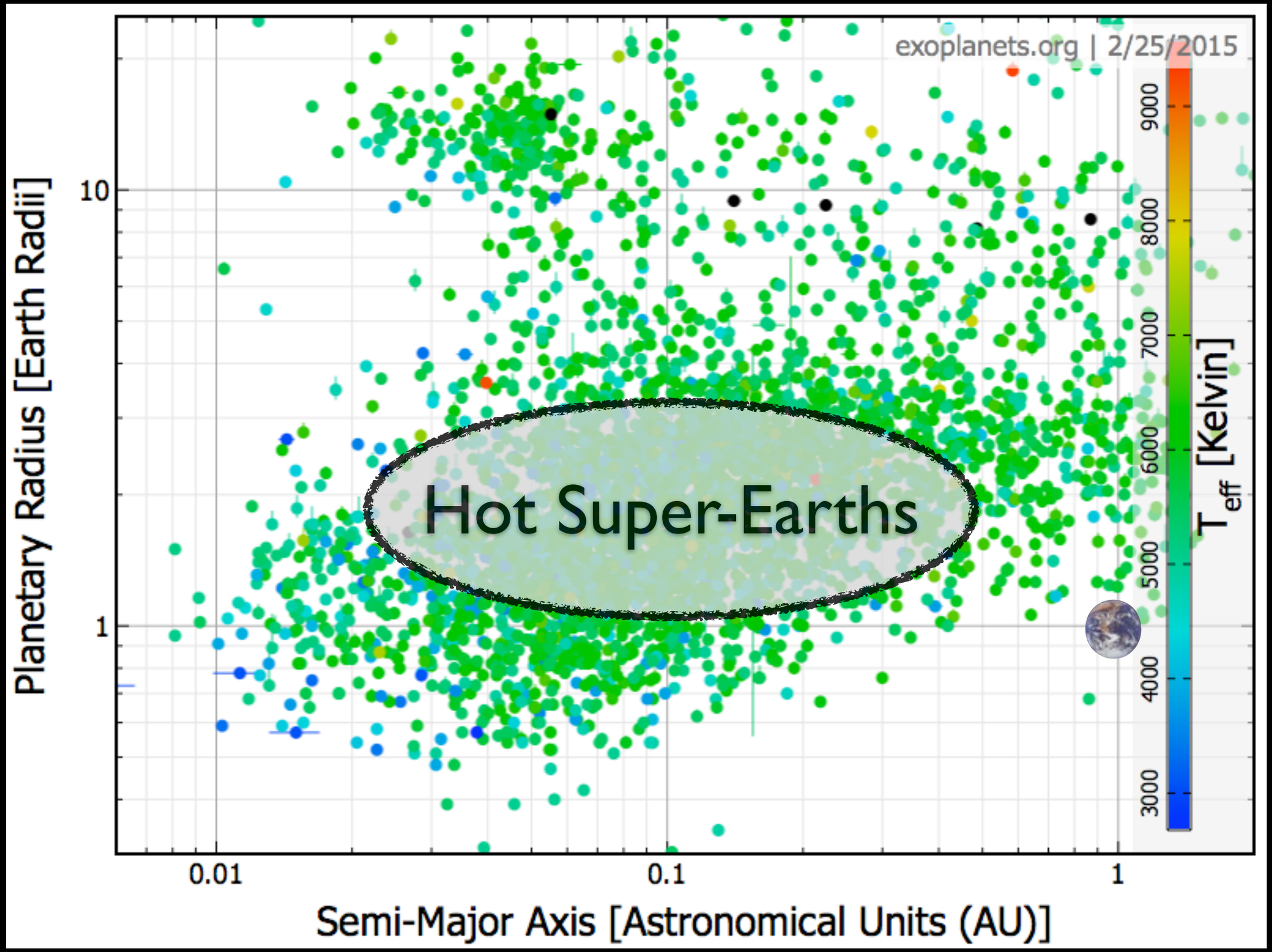


Raymond et al 2012

Formation of systems of hot super-Earths




exoplanets.org | 2/25/2015
Planetary Radius [Earth Radii]
10
1
0.01
0.1
1
Semi-Major Axis [Astronomical Units (AU)]
T_{eff} [Kelvin]
9000
8000
7000
6000
5000
4000
3000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Hot Super-Earths
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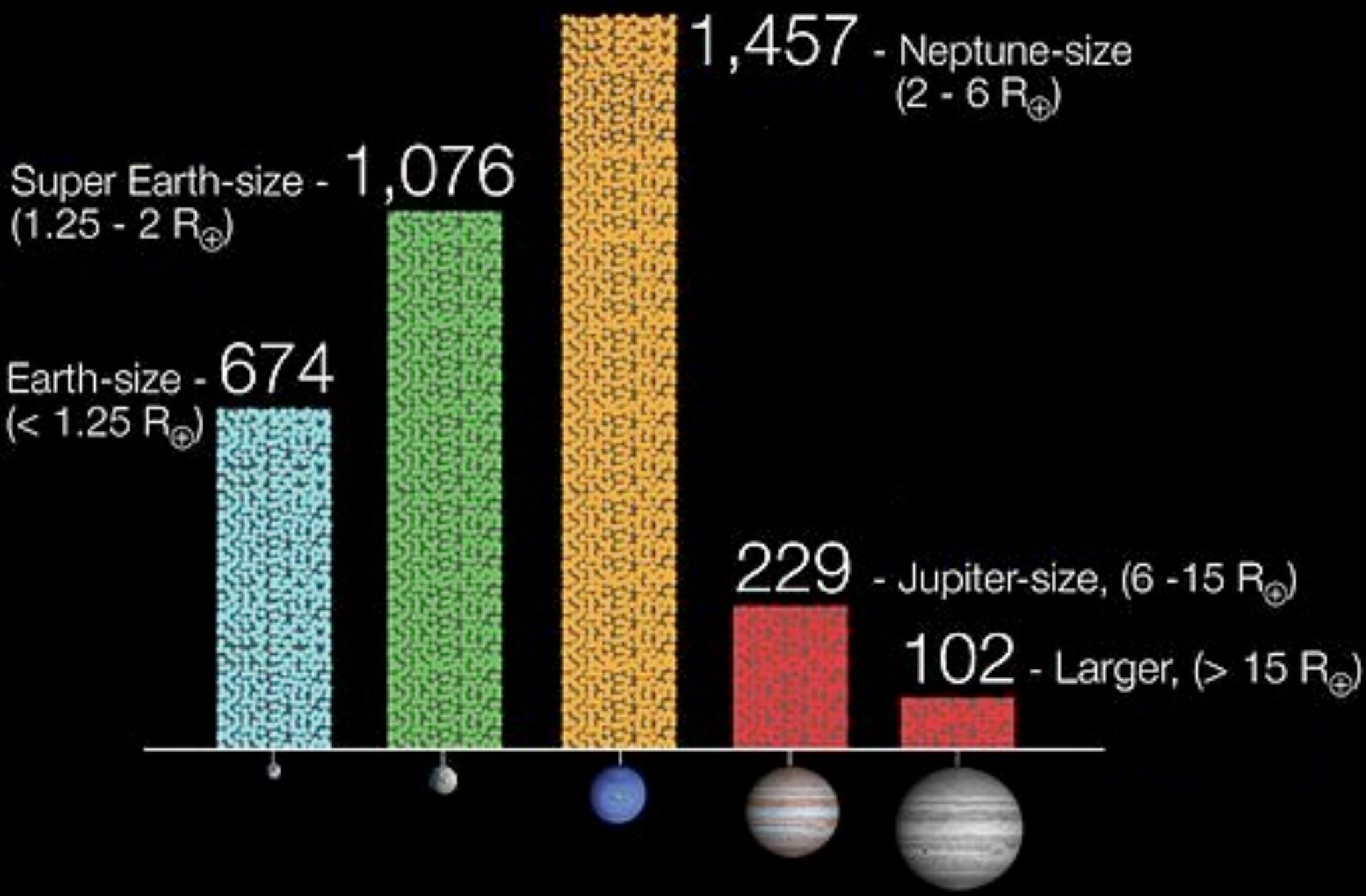
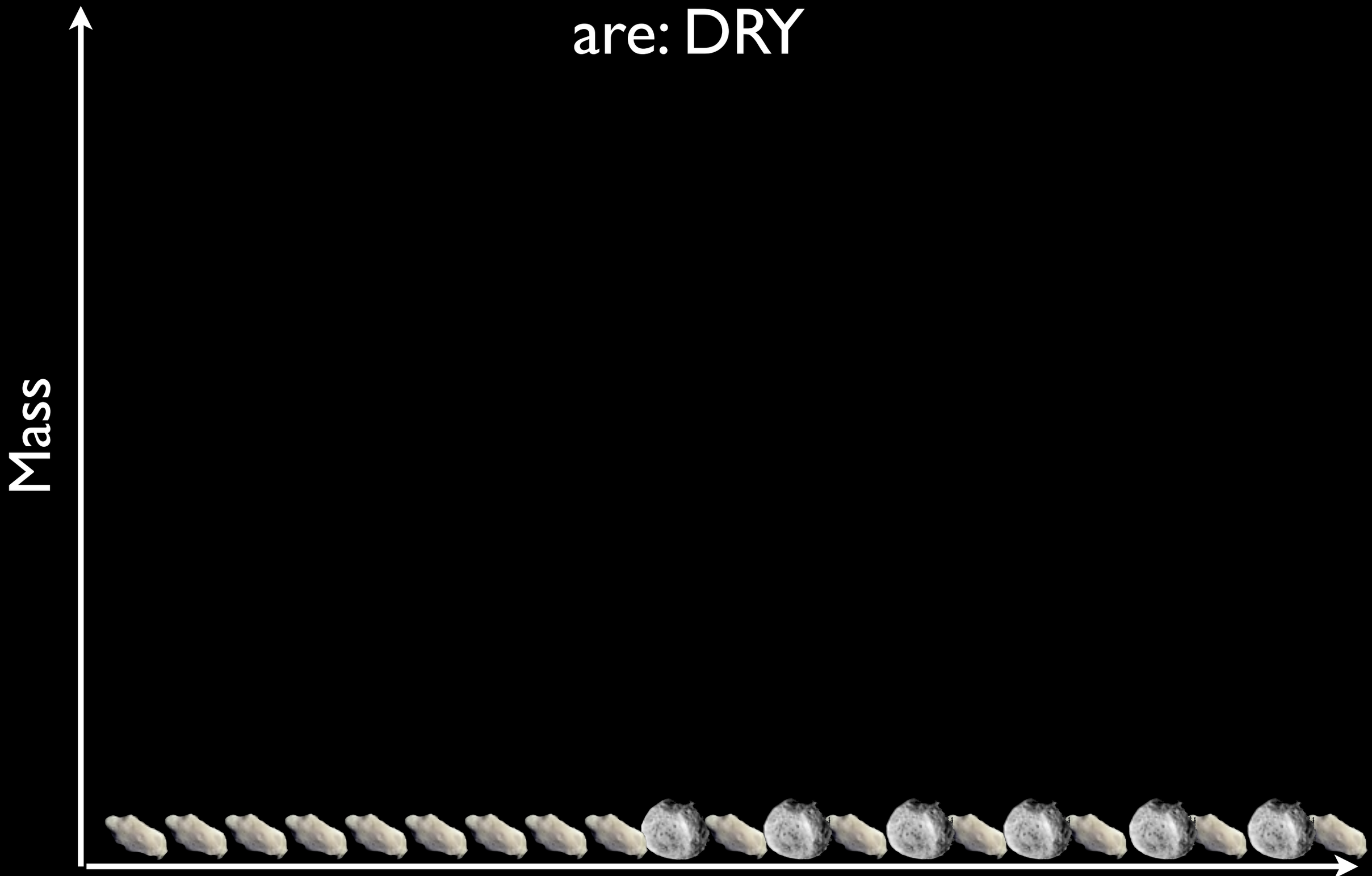
9000
8000
7000
6000
5000
4000
3000
T eff [Kelvin]

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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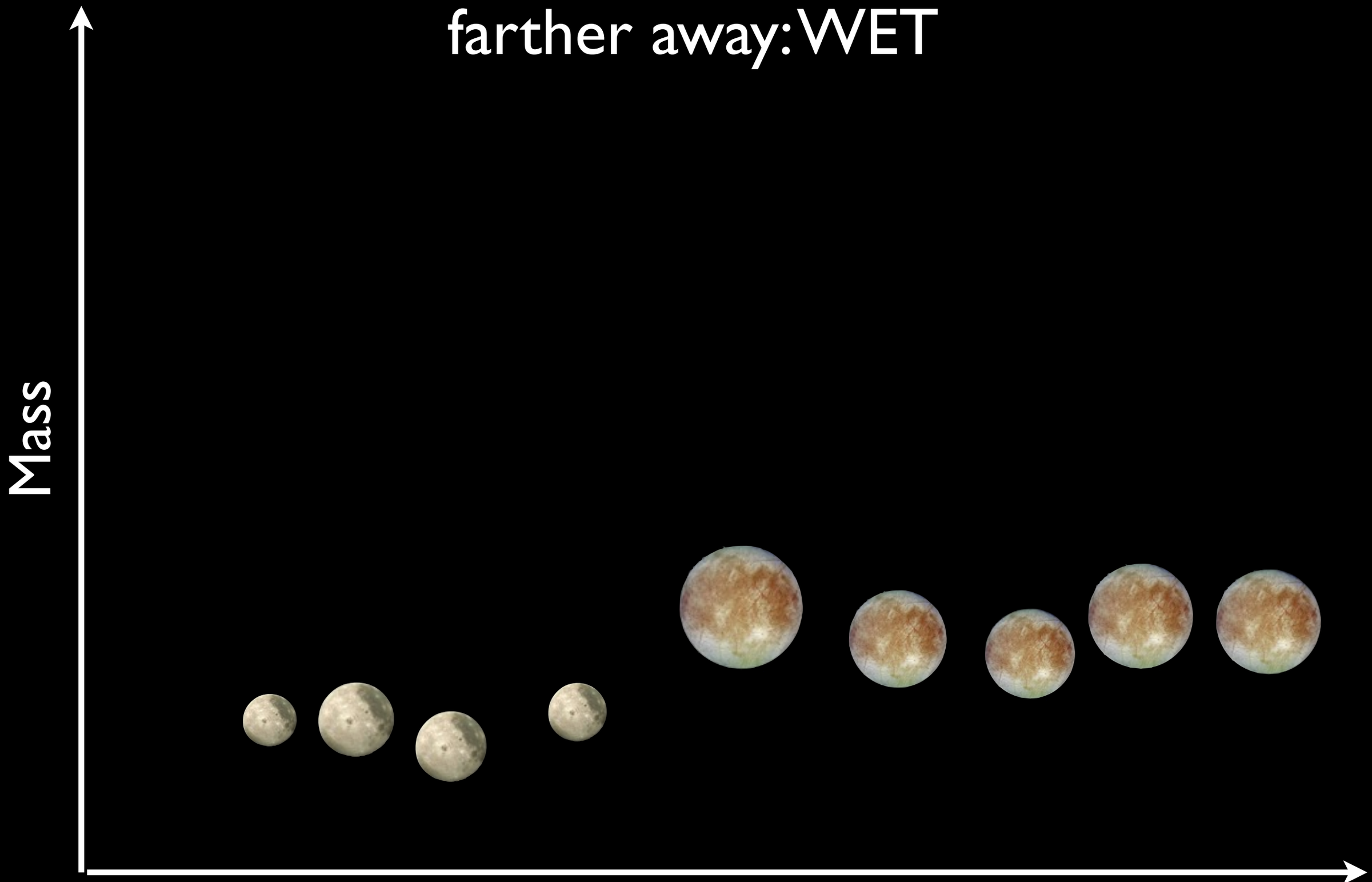
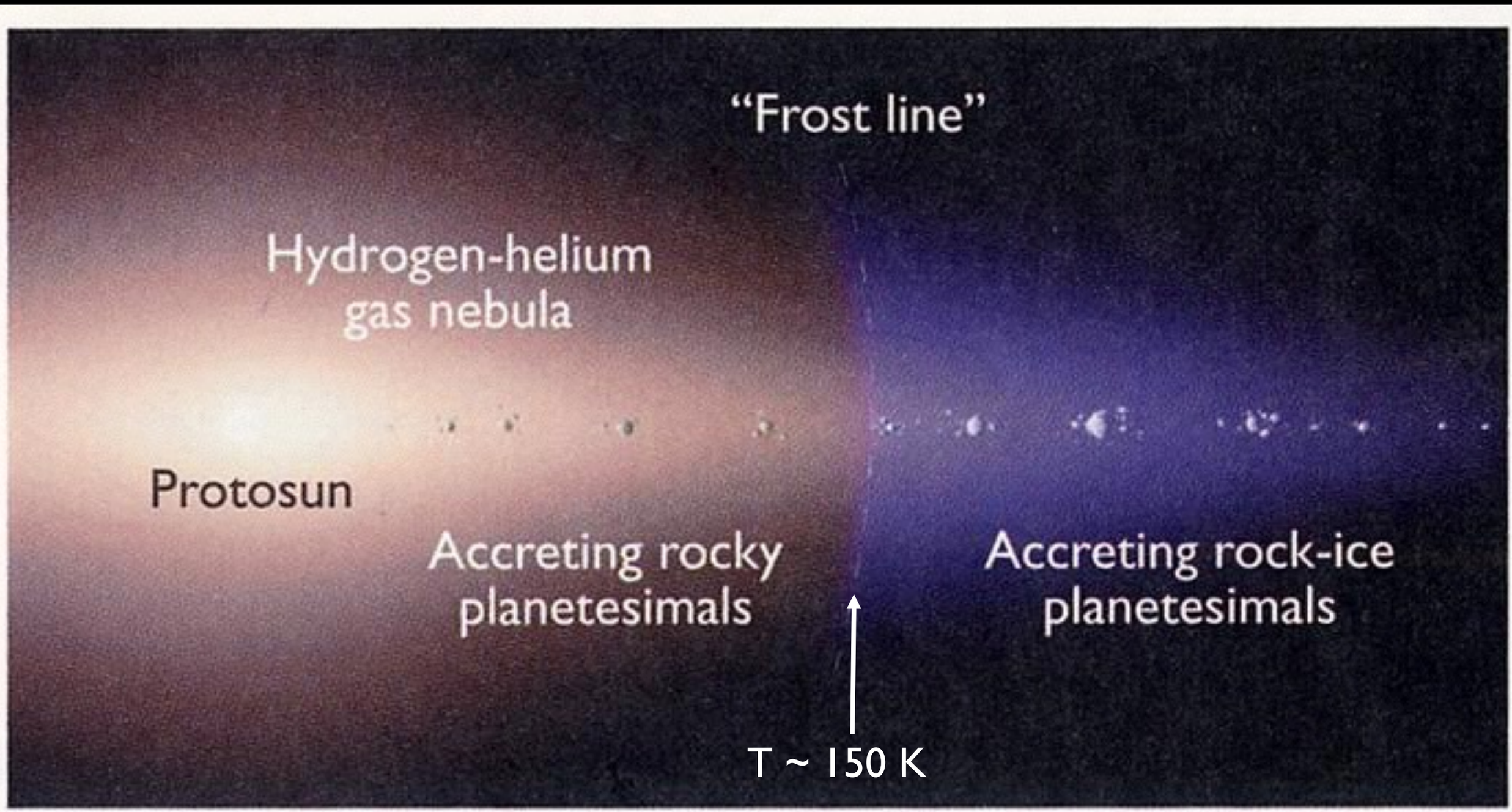


Model 2. Hot super-Earths migrate inward from farther away: WET

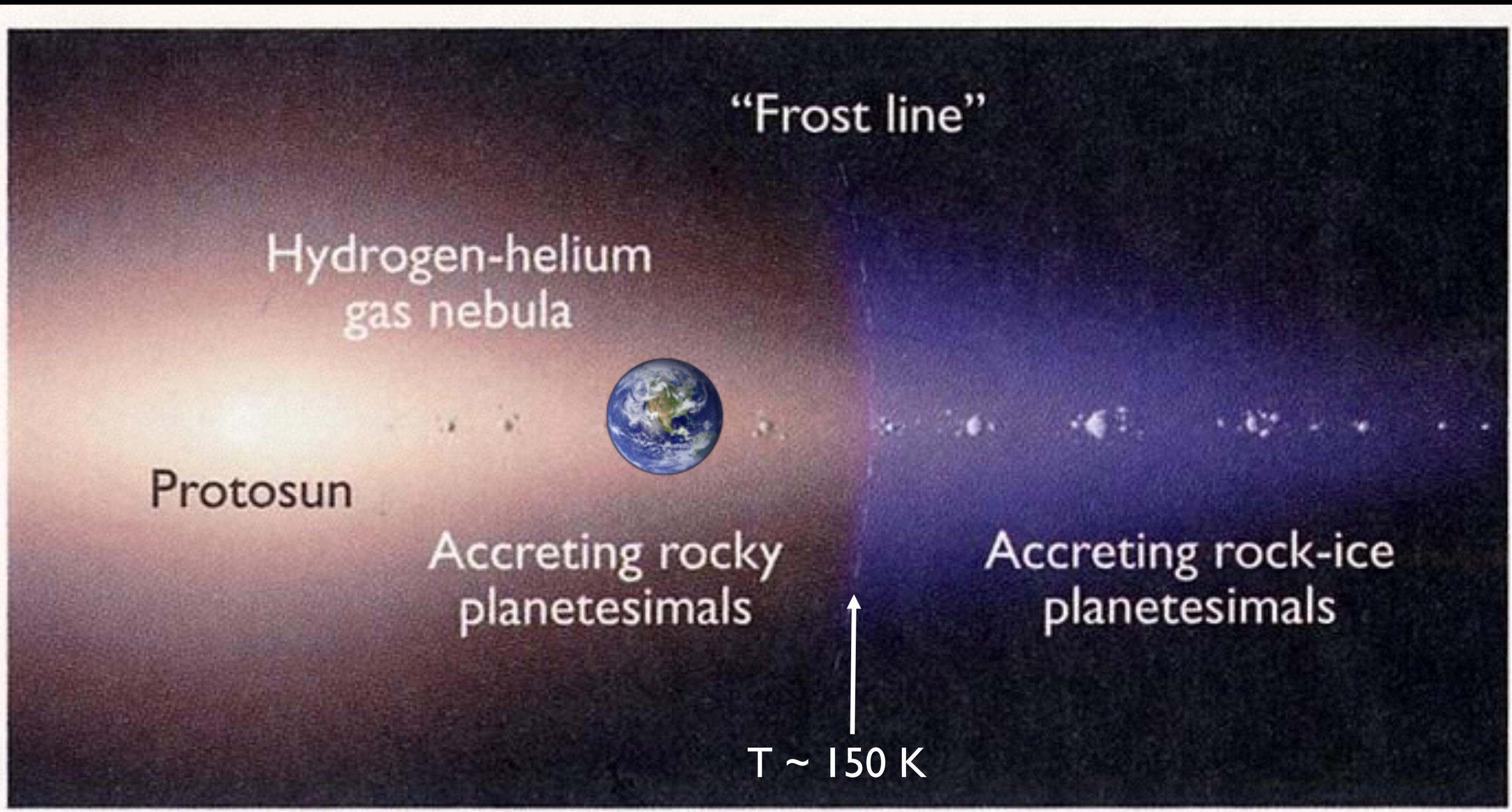
Mass

Orbital distance

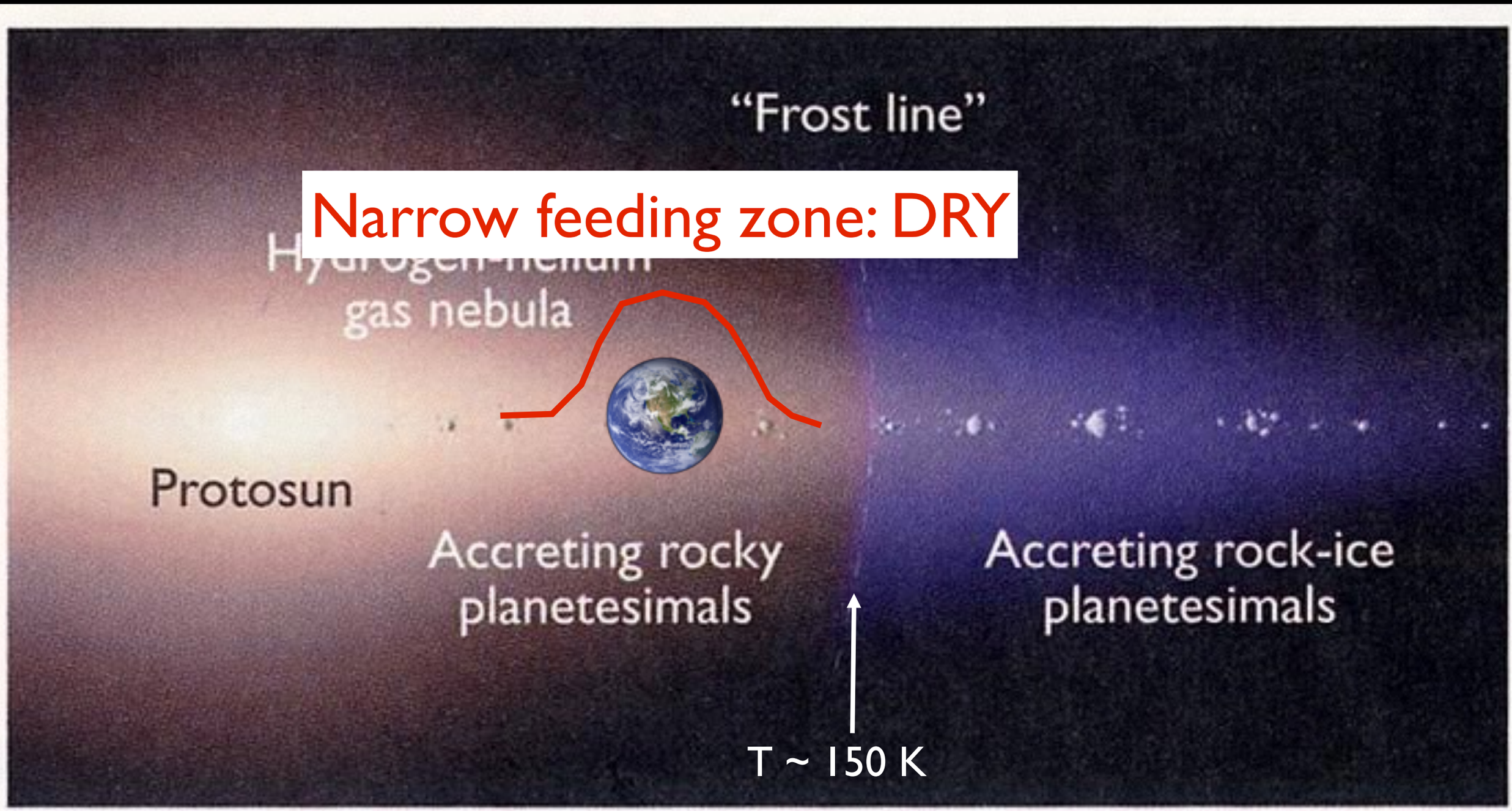
Water delivery



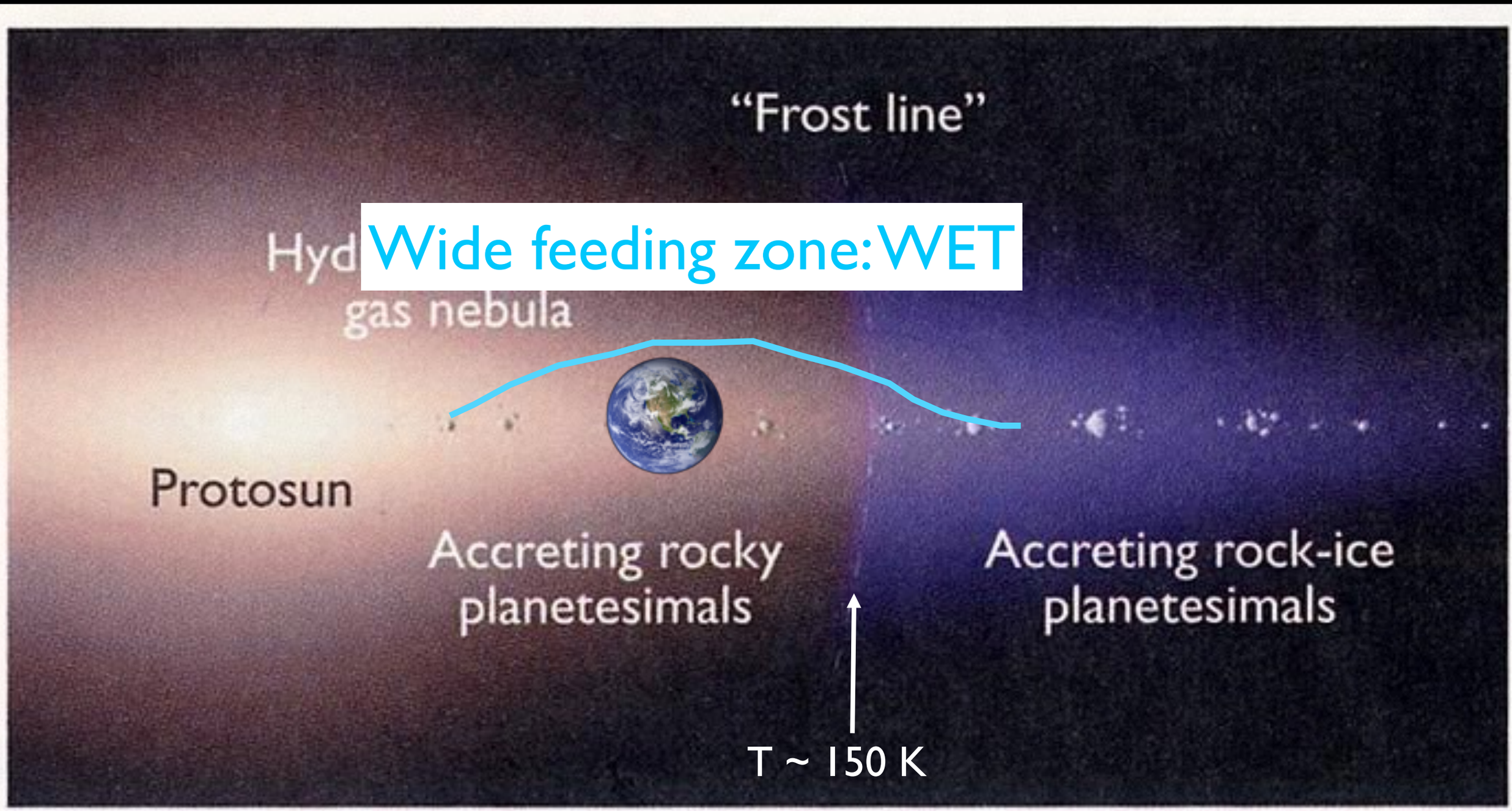
Water delivery



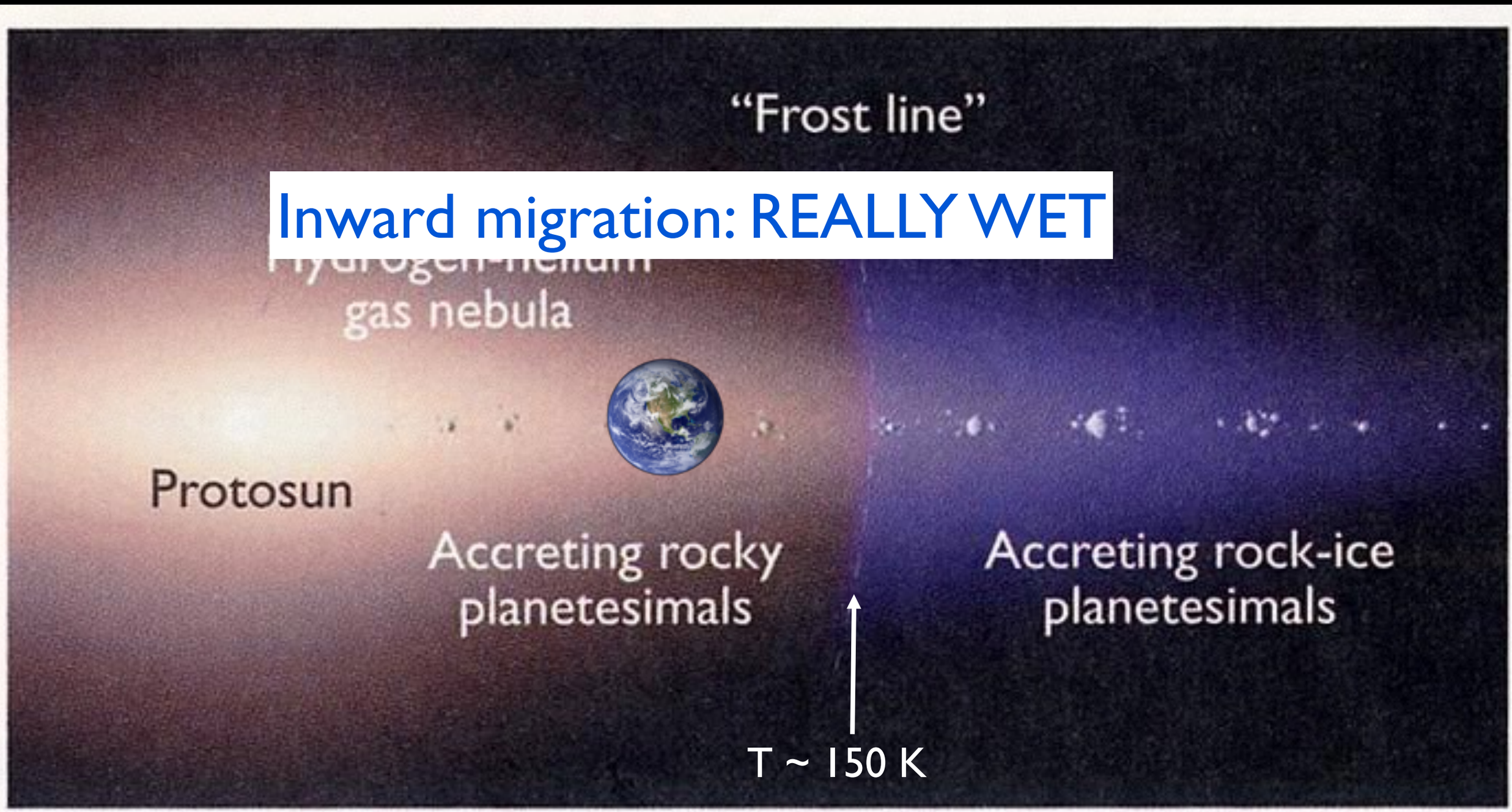
Water delivery

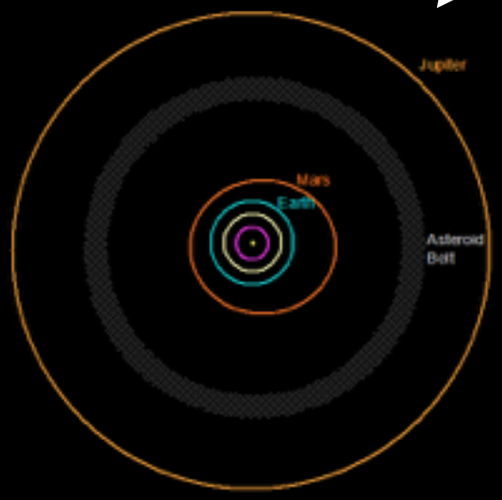


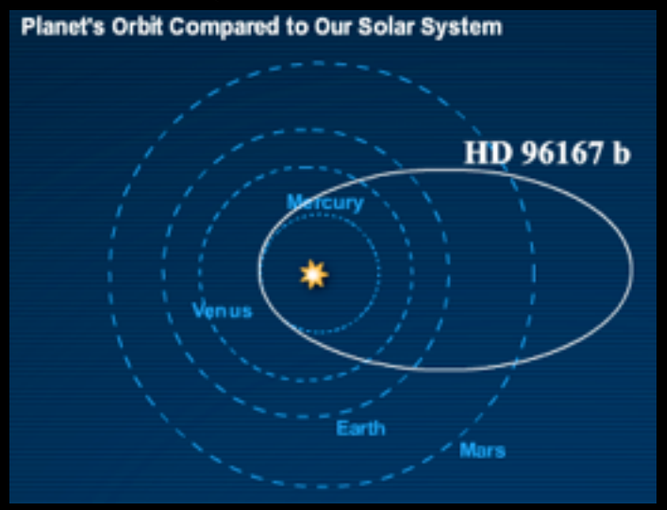
Water delivery

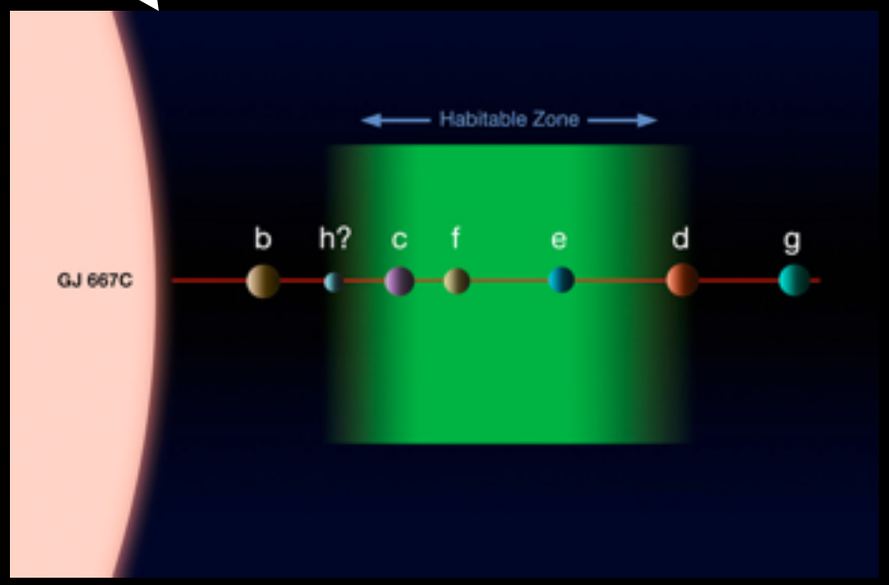


Water delivery

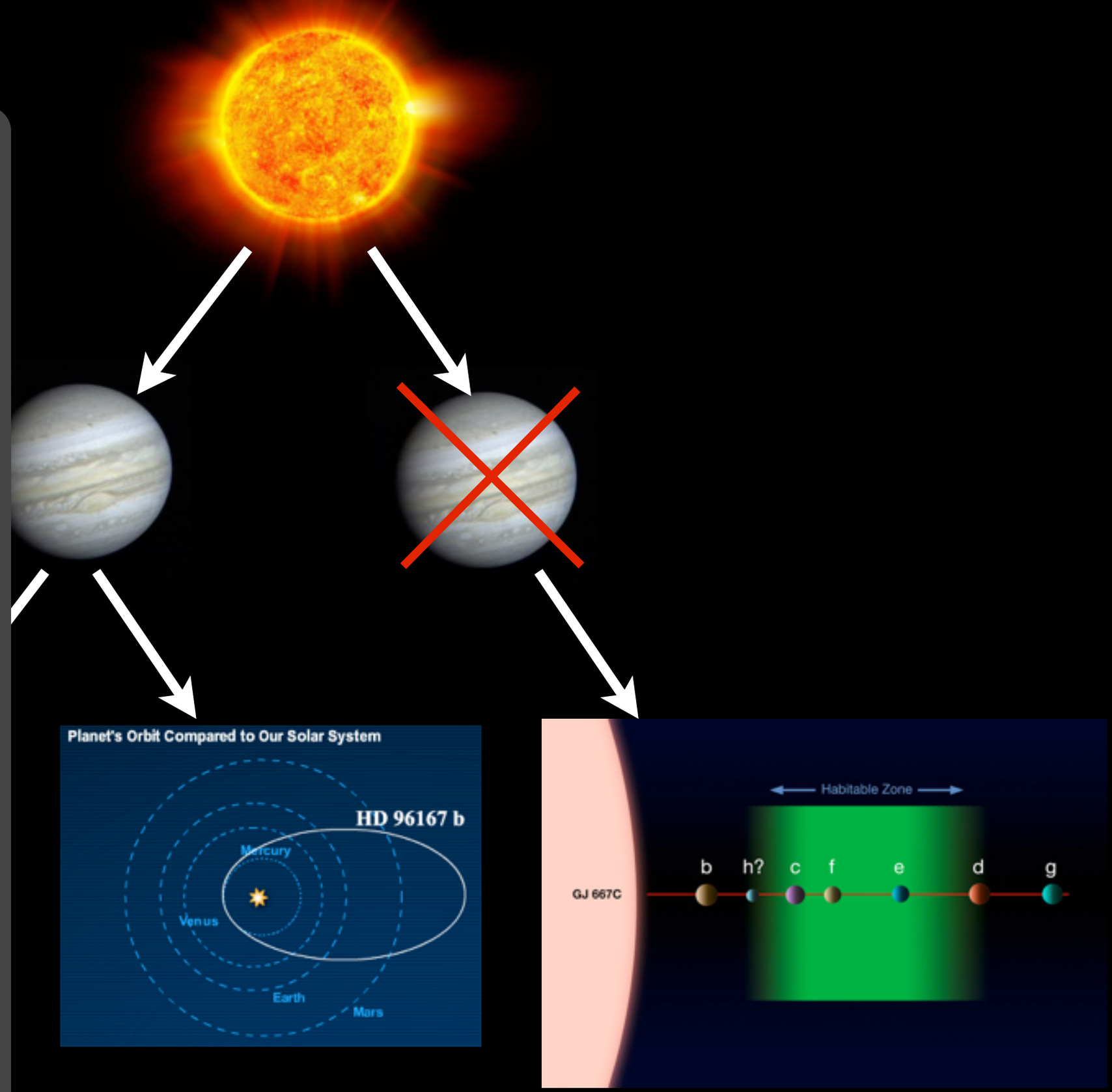



Jupiter
Mars
Earth
Asteroid
Belt

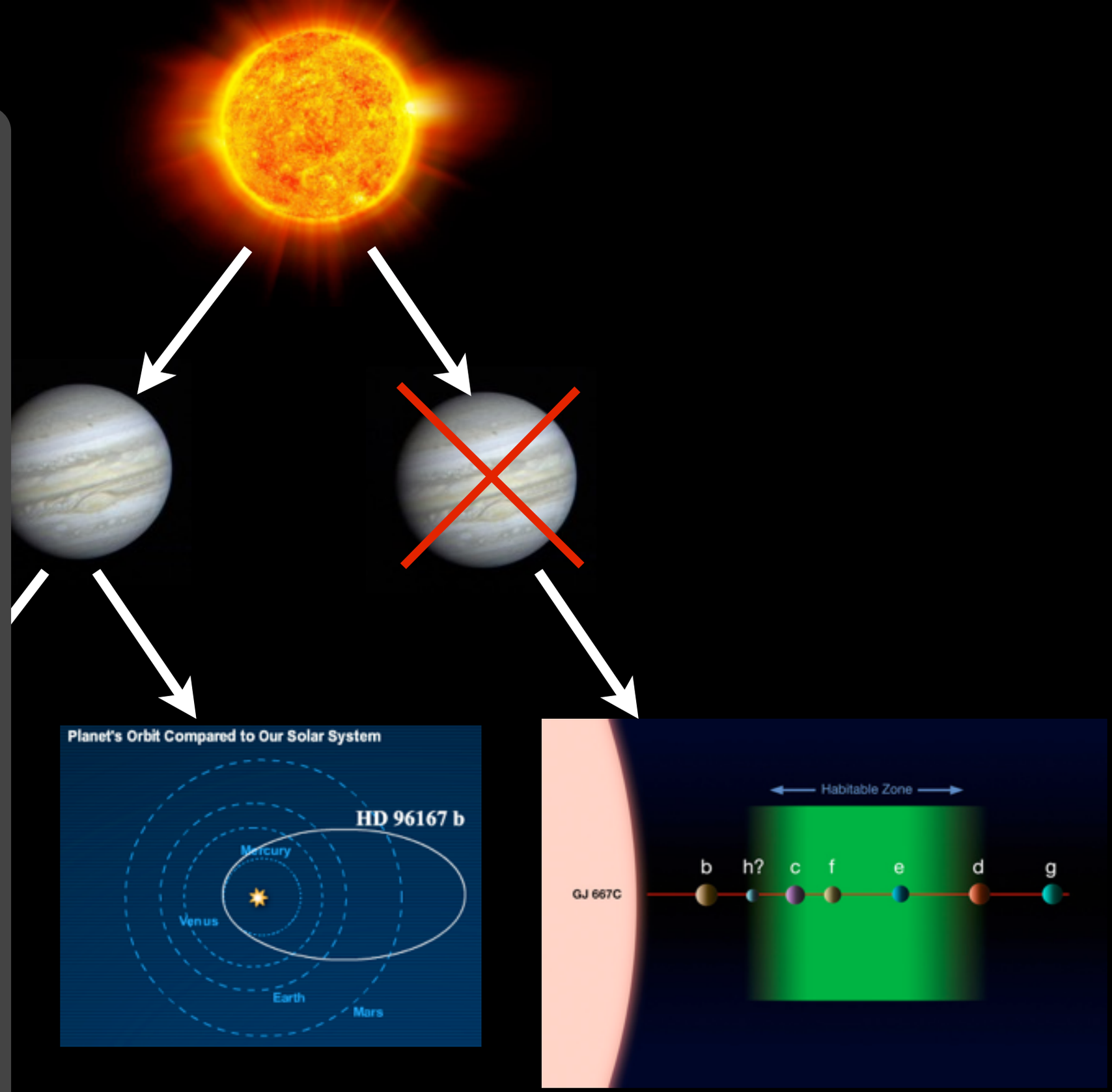

Planet's Orbit Compared to Our Solar System
HD 96167 b
Mercury
Venus
Earth
Mars


Habitable Zone
GJ 667C
b
h?
c
f
e
d
g

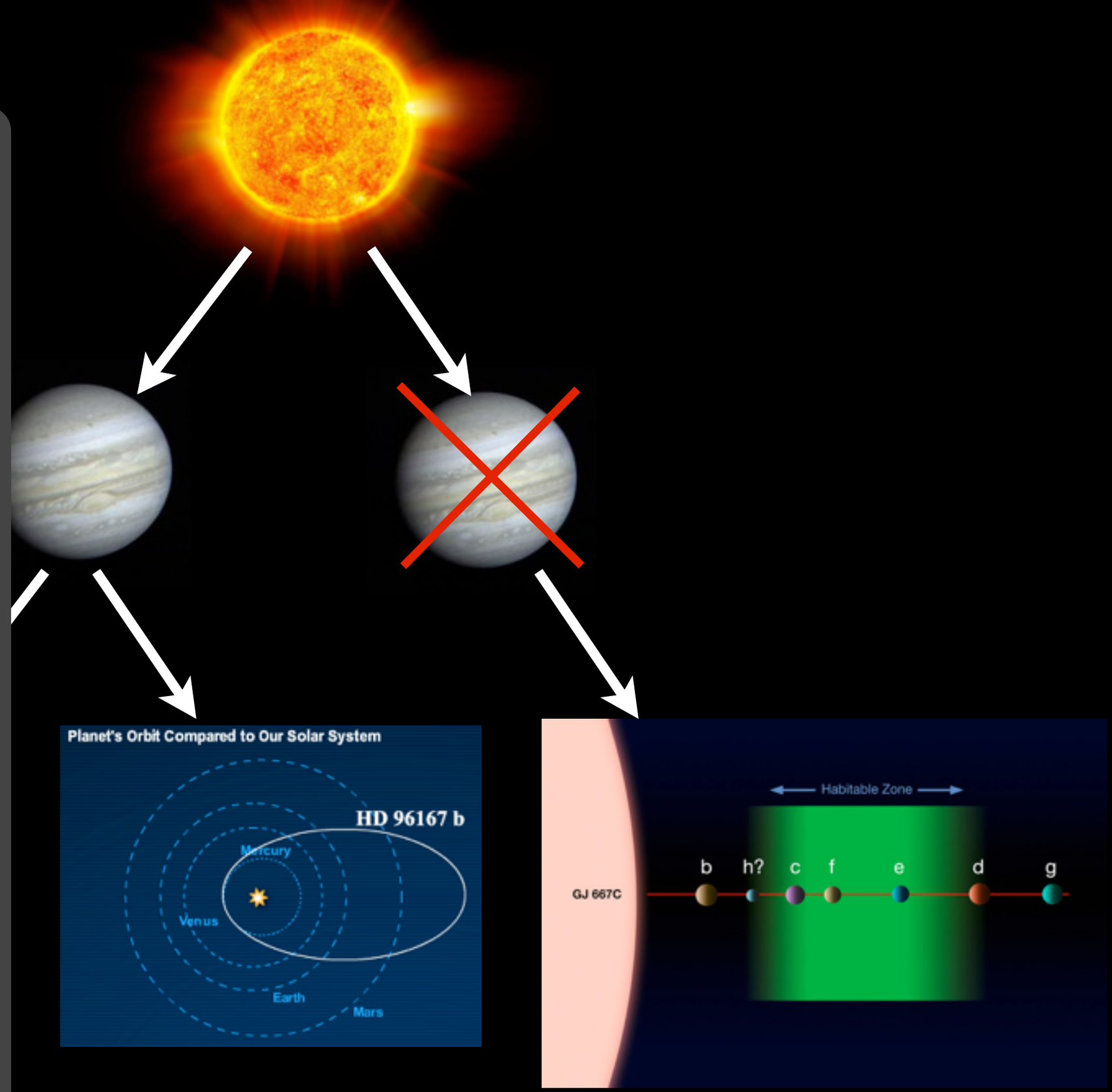
Solar System



Solar System

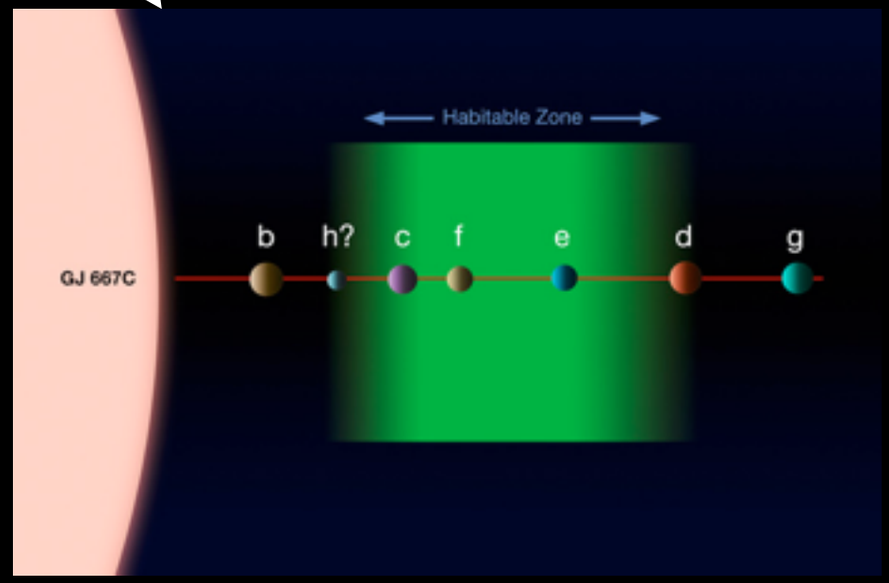


Solar System



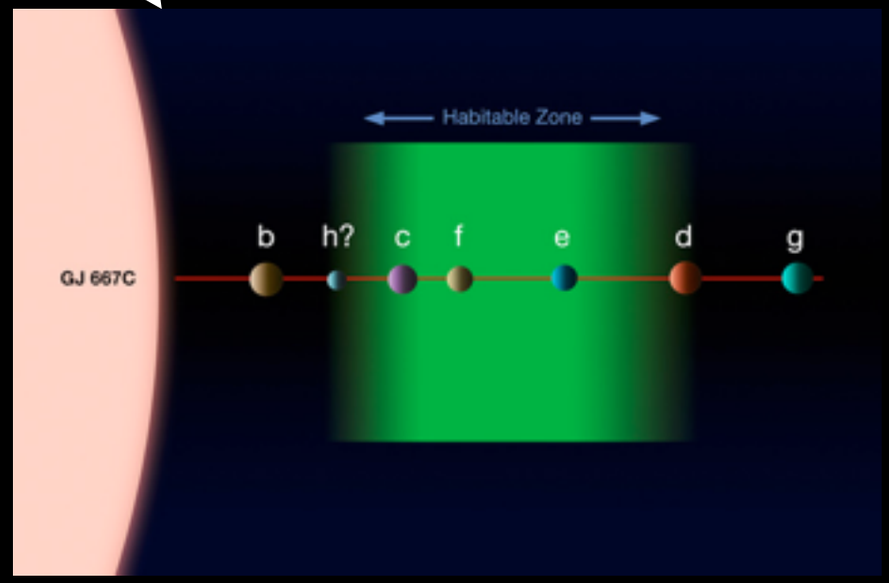
Solar System

Angry gas giants



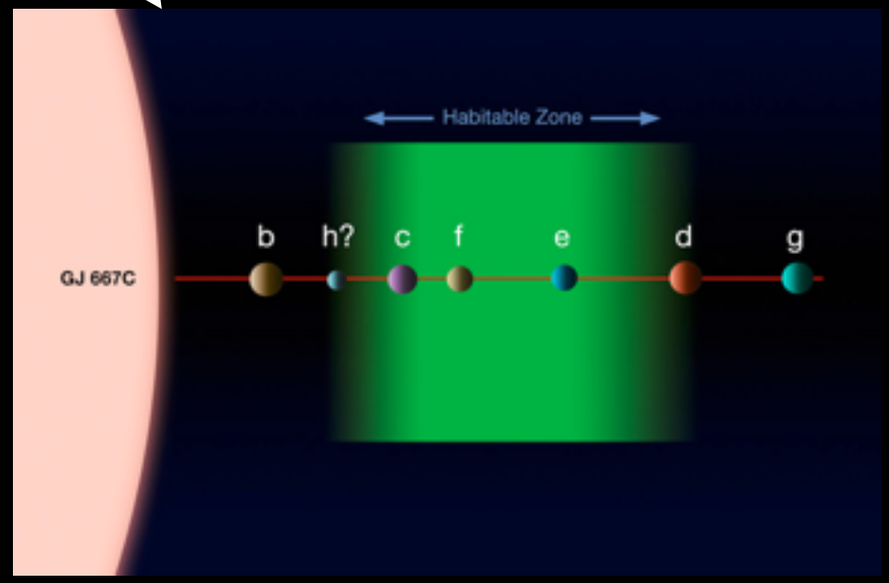
Solar System

Angry gas giants



Solar System

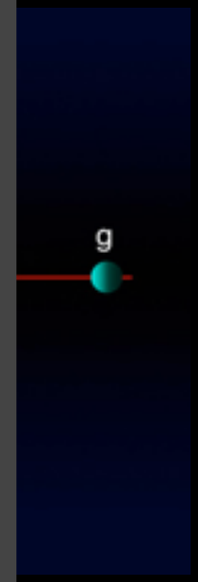
Angry gas giants



Solar System

Angry gas giants

Hot super-Earths



Solar System

Angry gas giants

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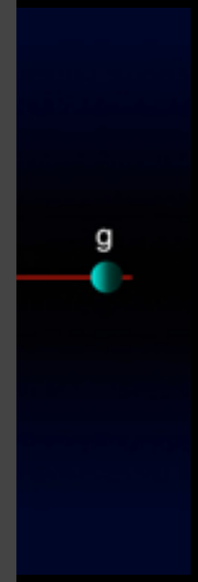

Solar System

Angry gas giants

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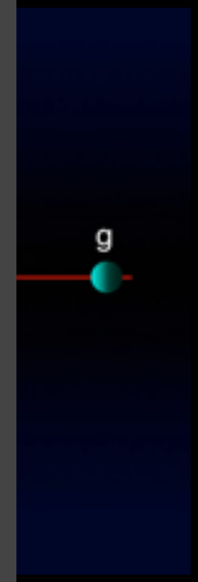
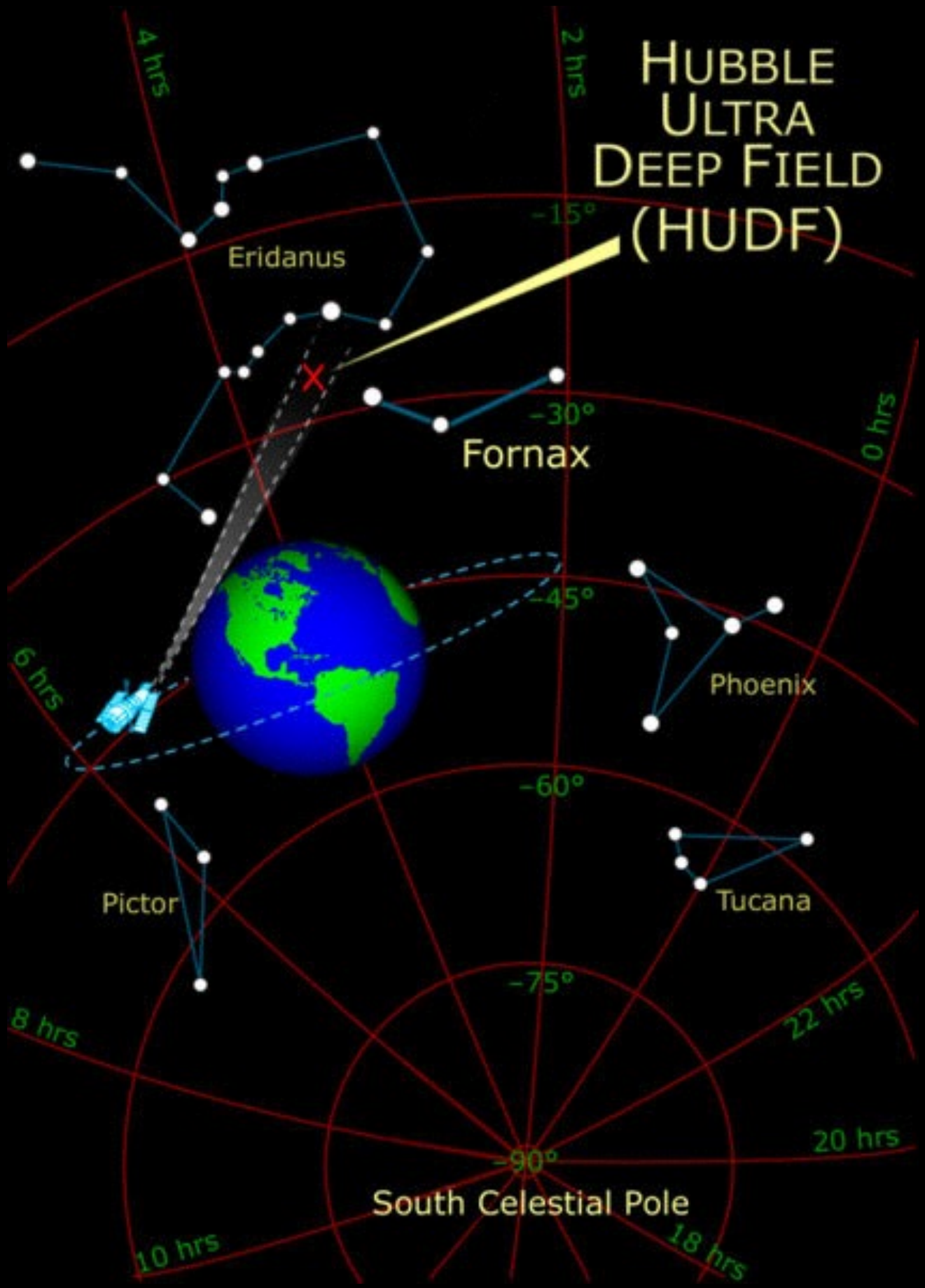


Extra slides

How many planets are out there?



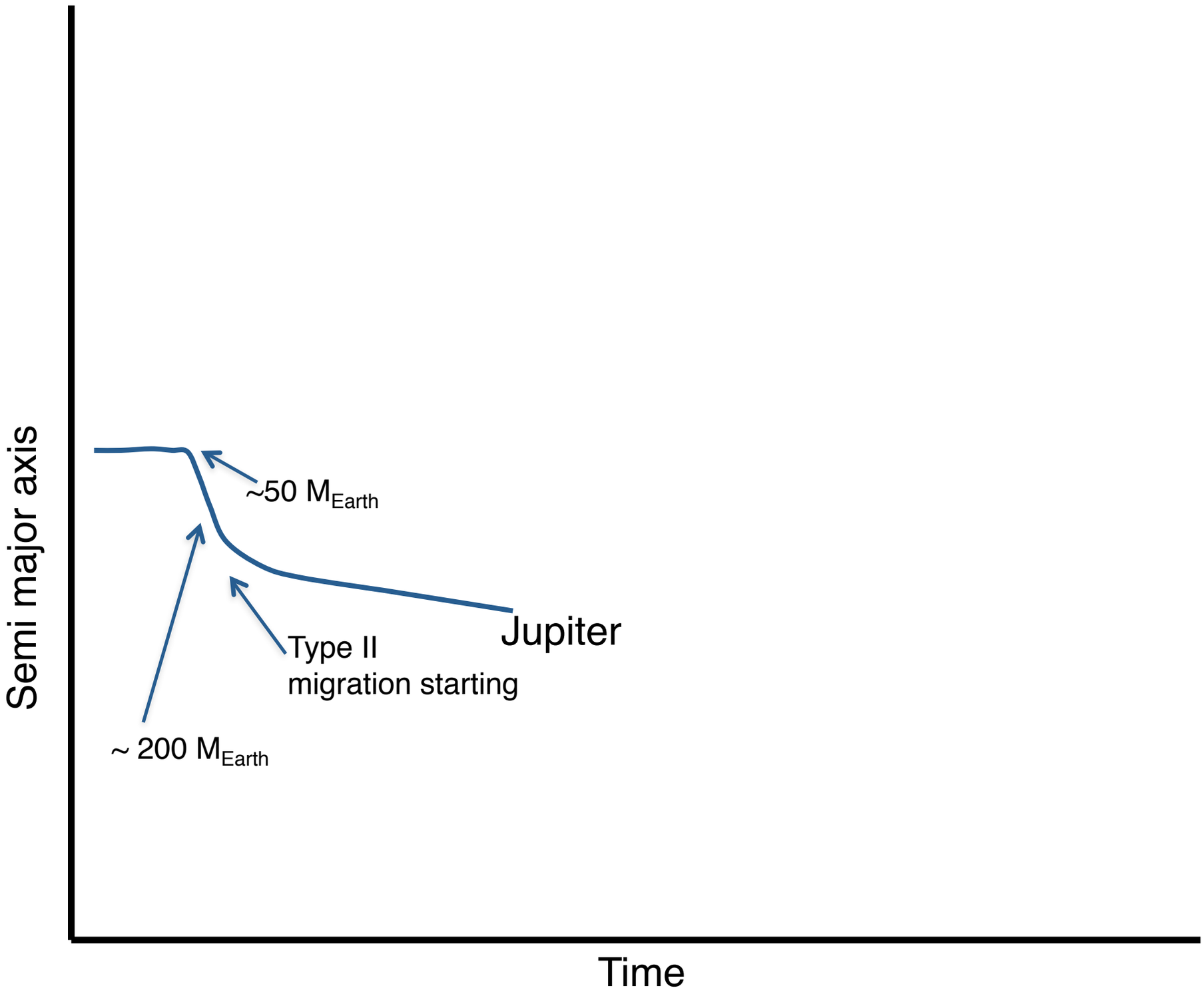
The Hubble Space Telescope stared at a dark patch of sky for 15 days straight

- 100s of billions stars in our galaxy

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

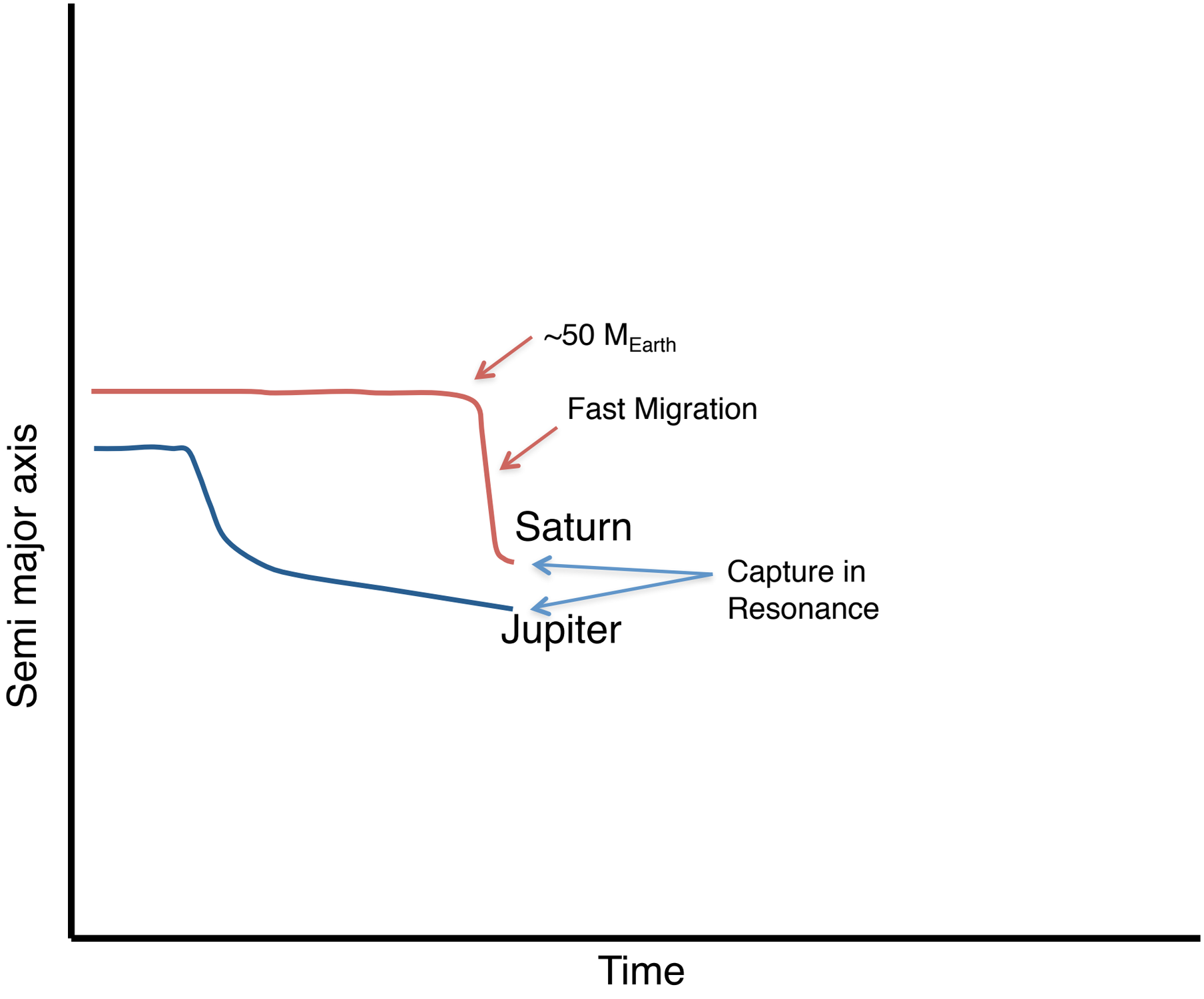
- 100s of billions stars in our galaxy
- 100s of billions of galaxies in the Universe
- Probably quintillions of planets (1,000,000,000,000,000,000)

Jupiter in the gaseous disk



slide by Kevin Walsh

Jupiter and Saturn in the gaseous disk



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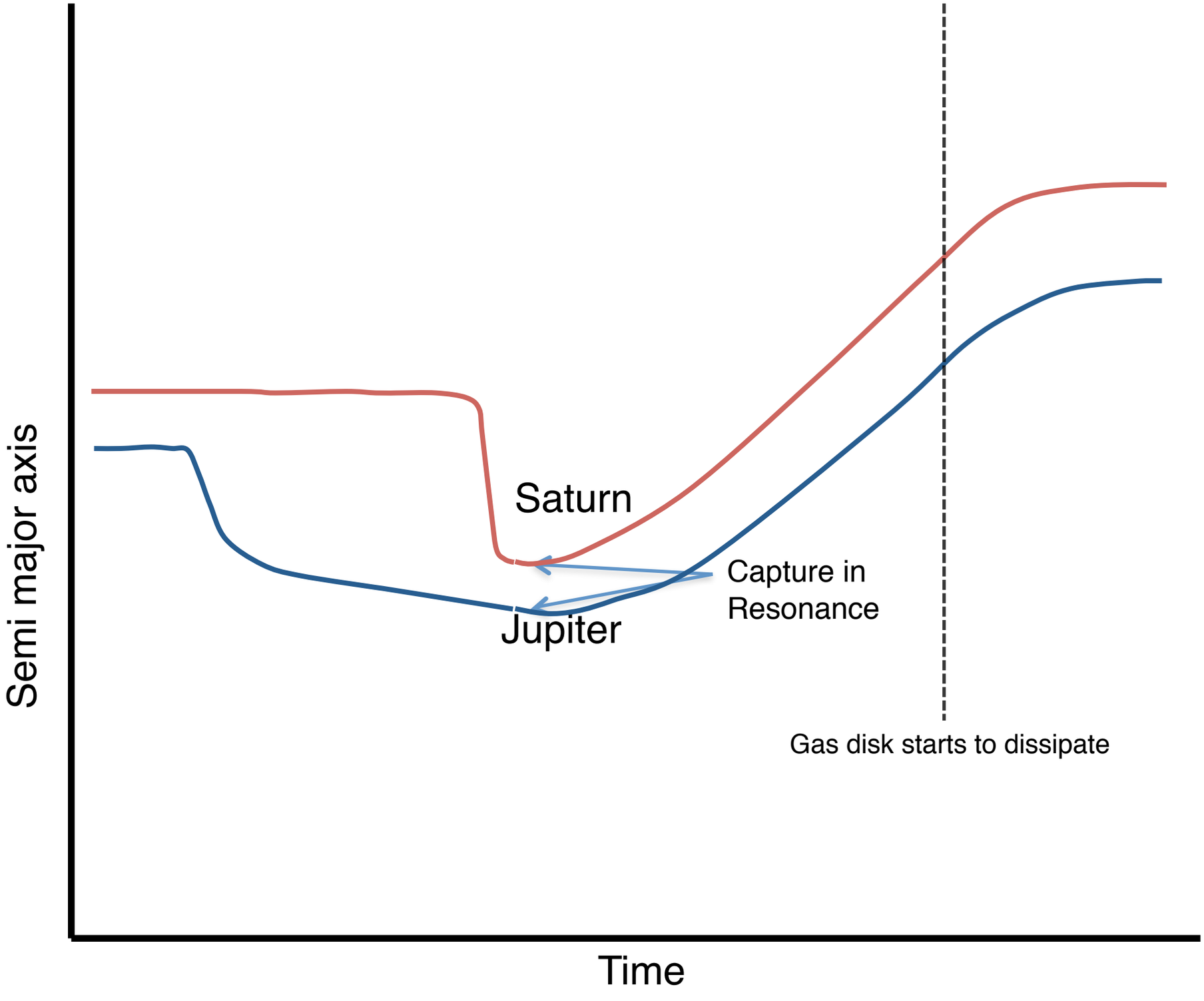
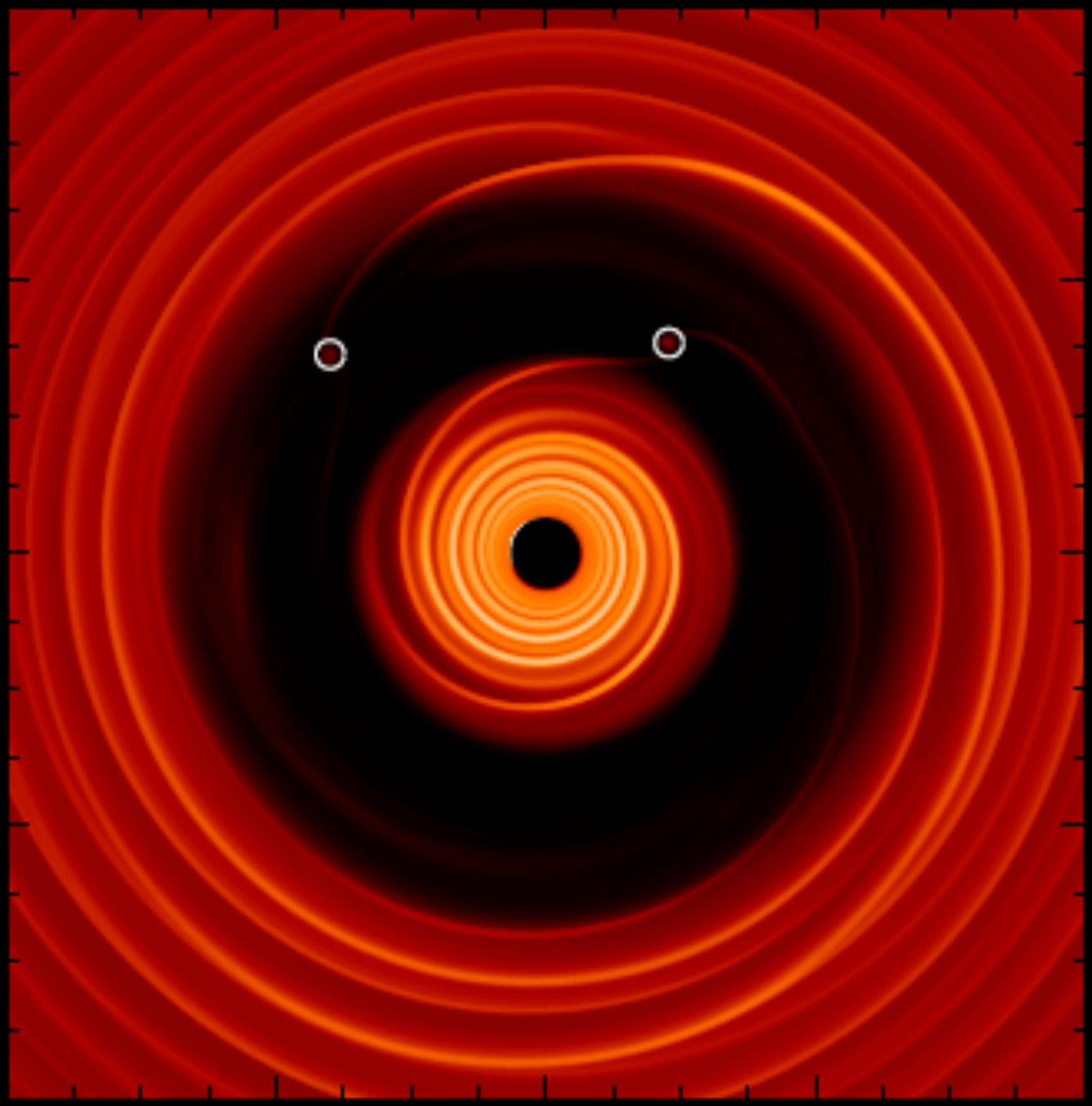
Jupiter and Saturn in the gaseous disk

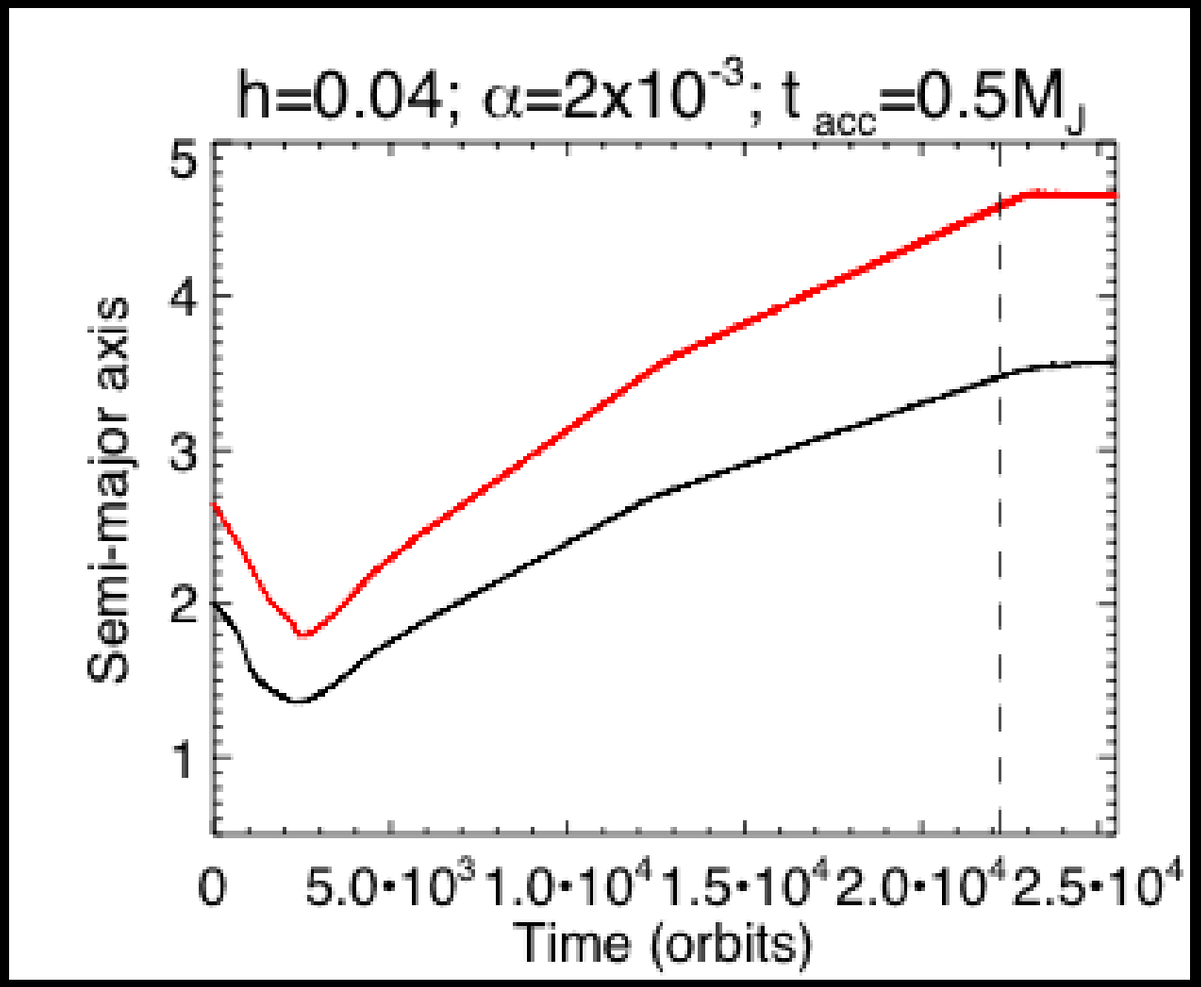


Masset & Snellgrove 2001;
Morbidelli & Crida 2007;
Pierens & Nelson 2008;
Crida et al 2009;
Pierens & Raymond 2011;
Pierens et al 2014

slide by Kevin Walsh

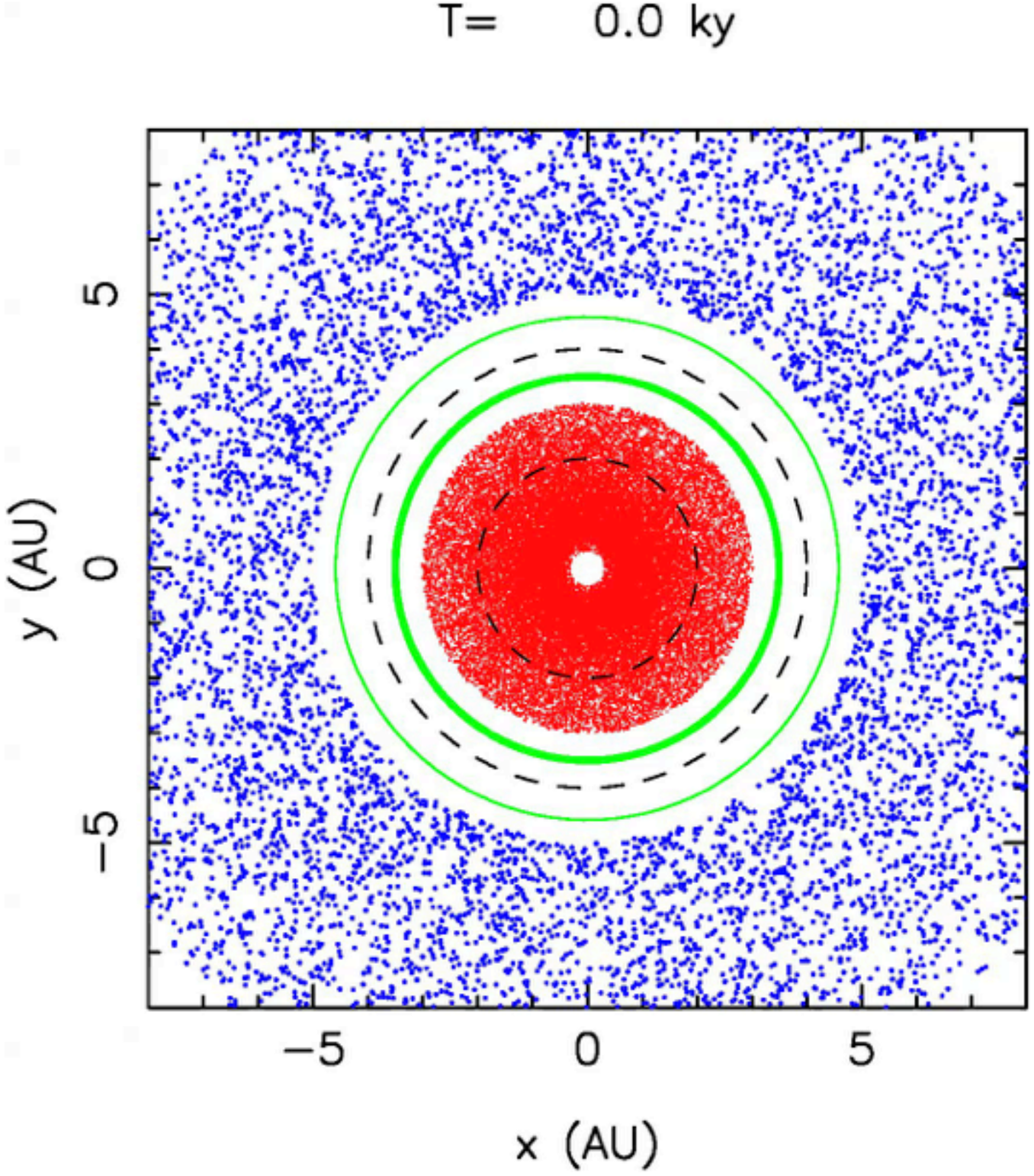


Hydrodynamical simulation with Jup, Sat accreting gas from disk (Pierens & Raymond 2011)



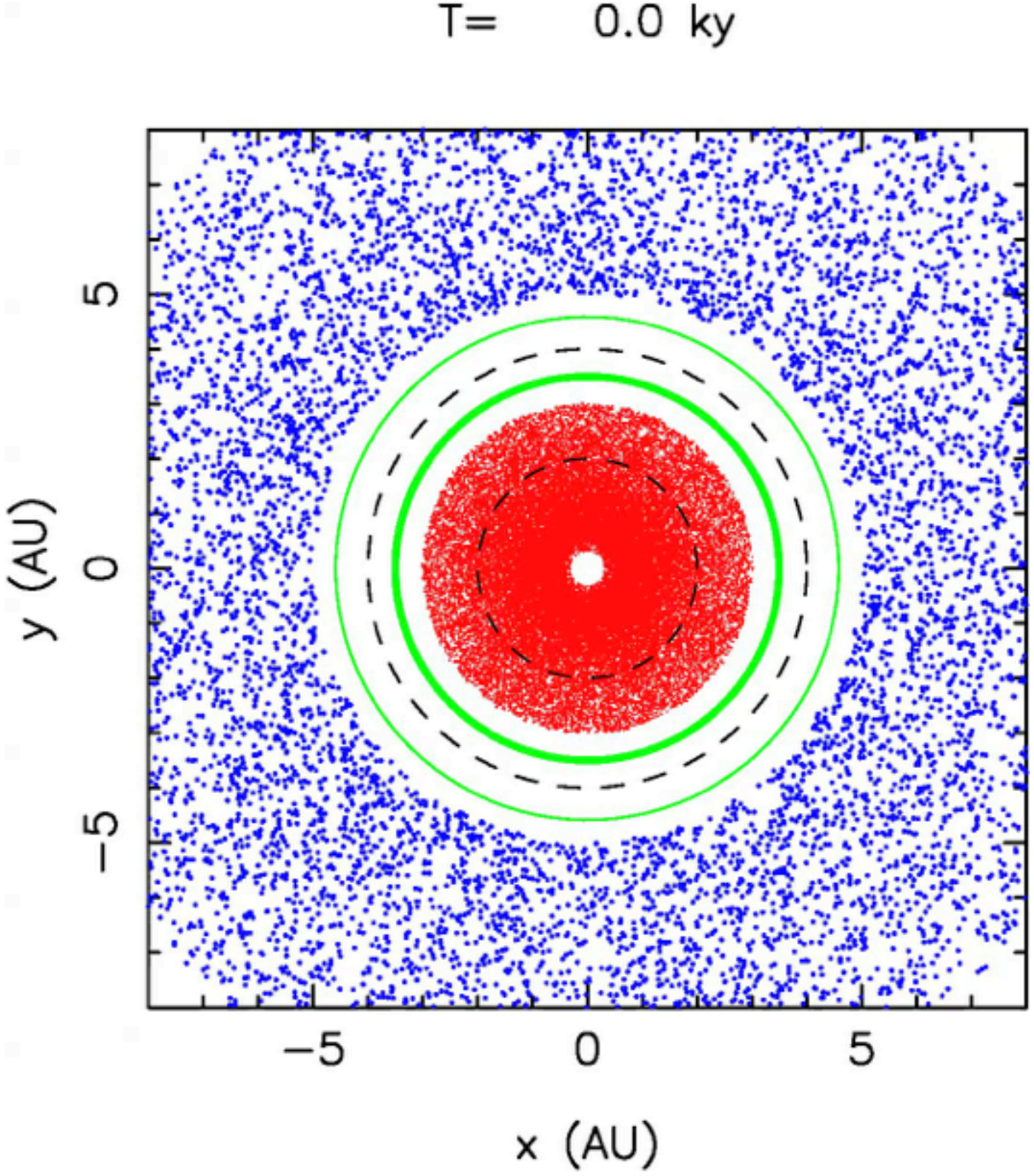
Hydrodynamical simulation with Jup, Sat accreting gas from disk (Pierens & Raymond 2011)

The Grand Tack model



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

The Grand Tack model



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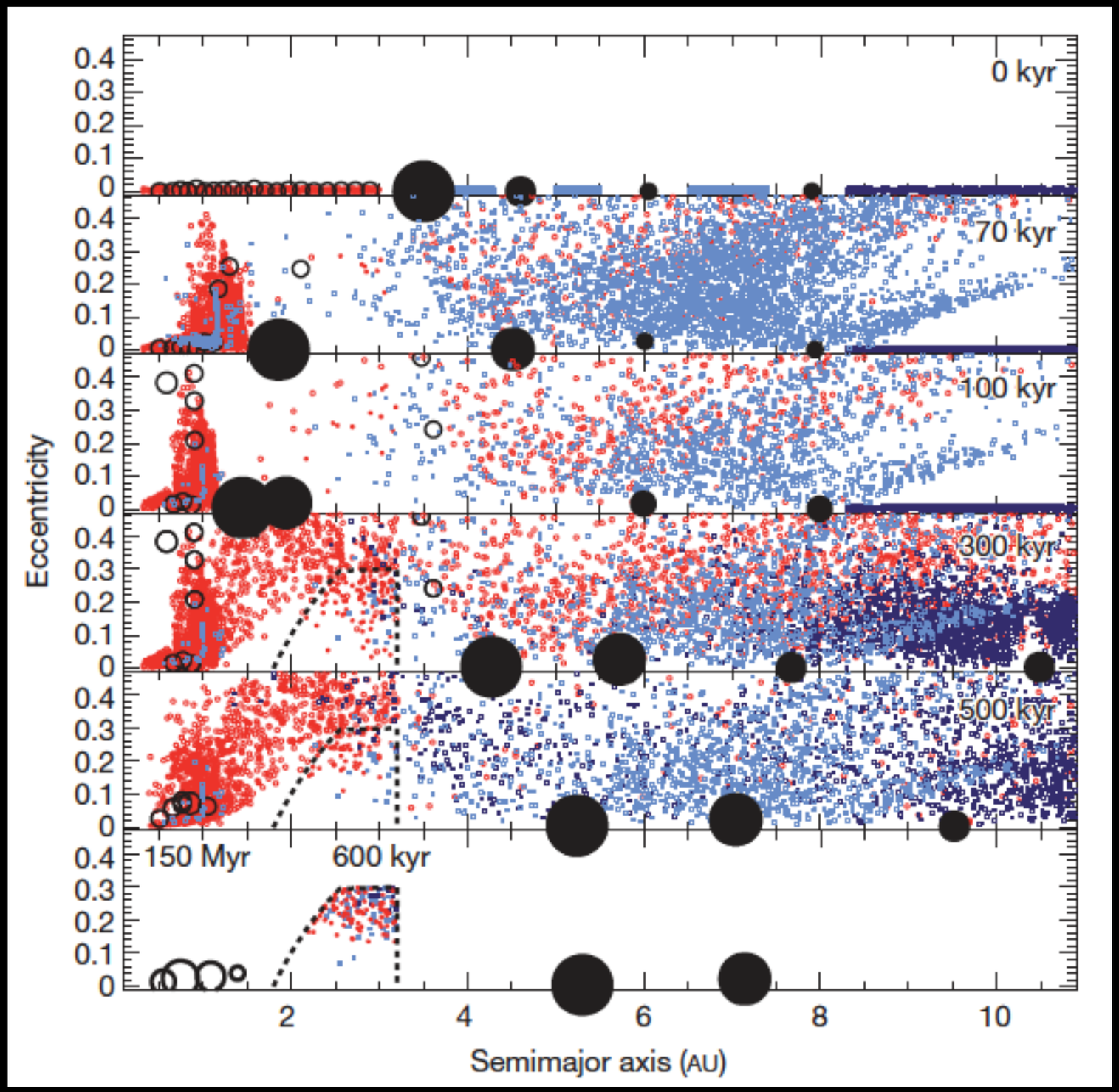
The Grand Tack



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