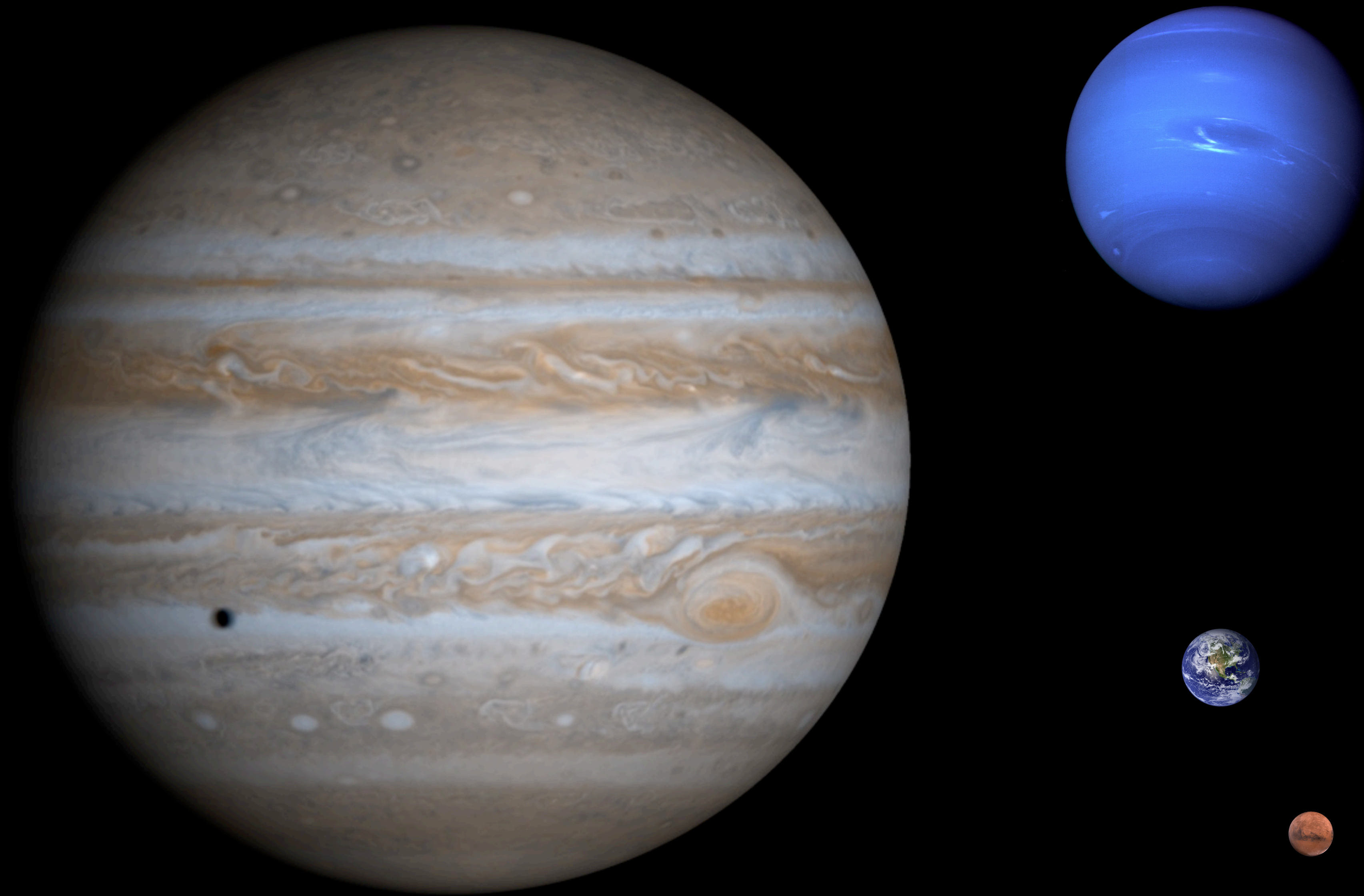


Theory of Planet Formation and Planetary System Architectures

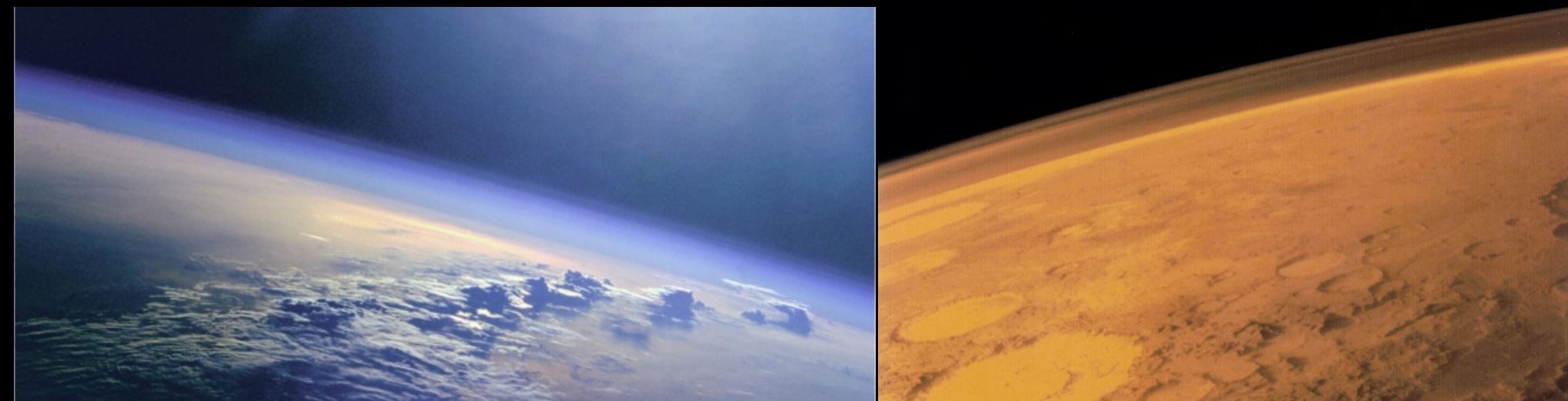
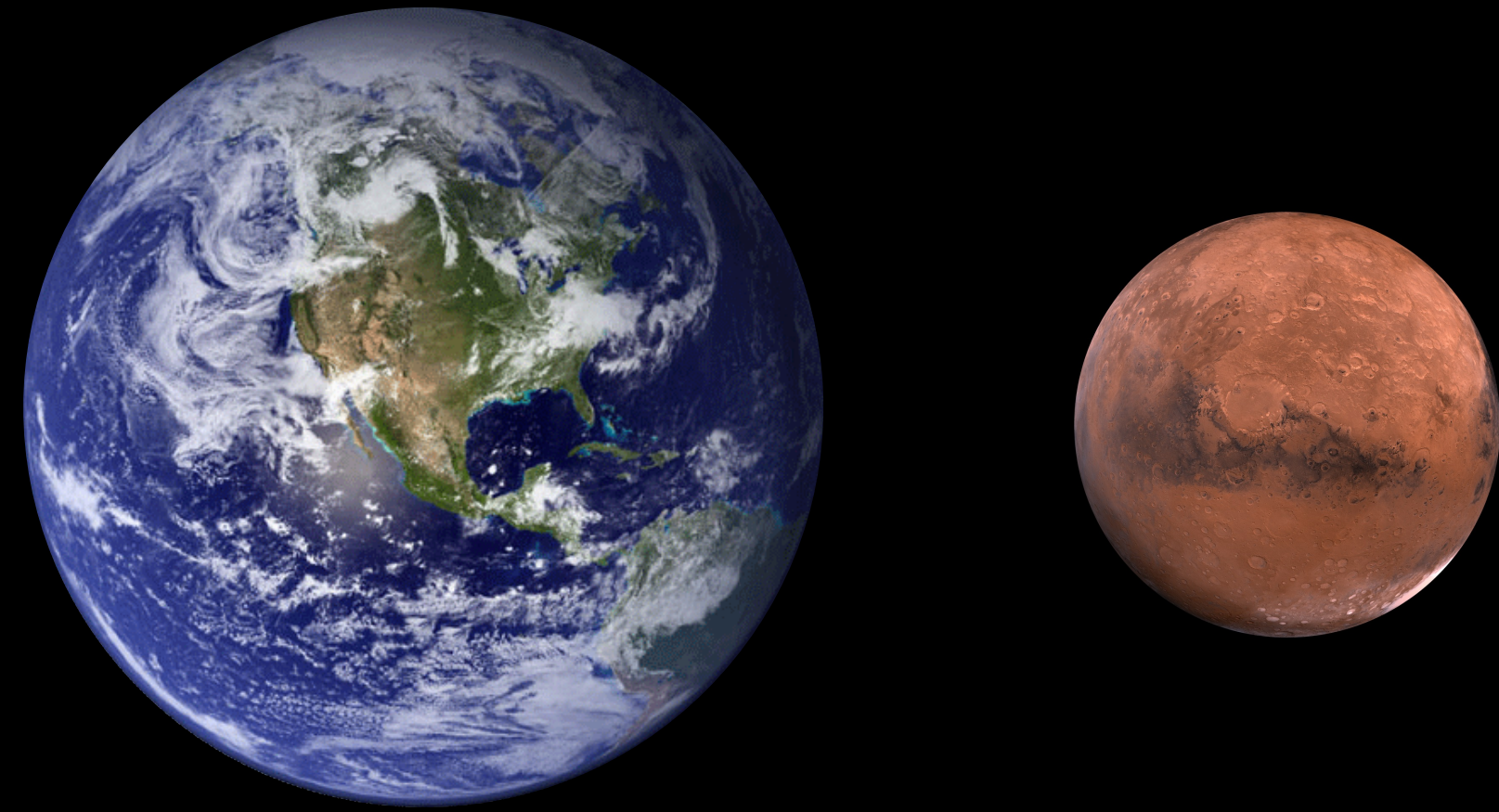
Ruth Murray-Clay
UC Santa Cruz



Image Credit: NASA



terrestrial planets



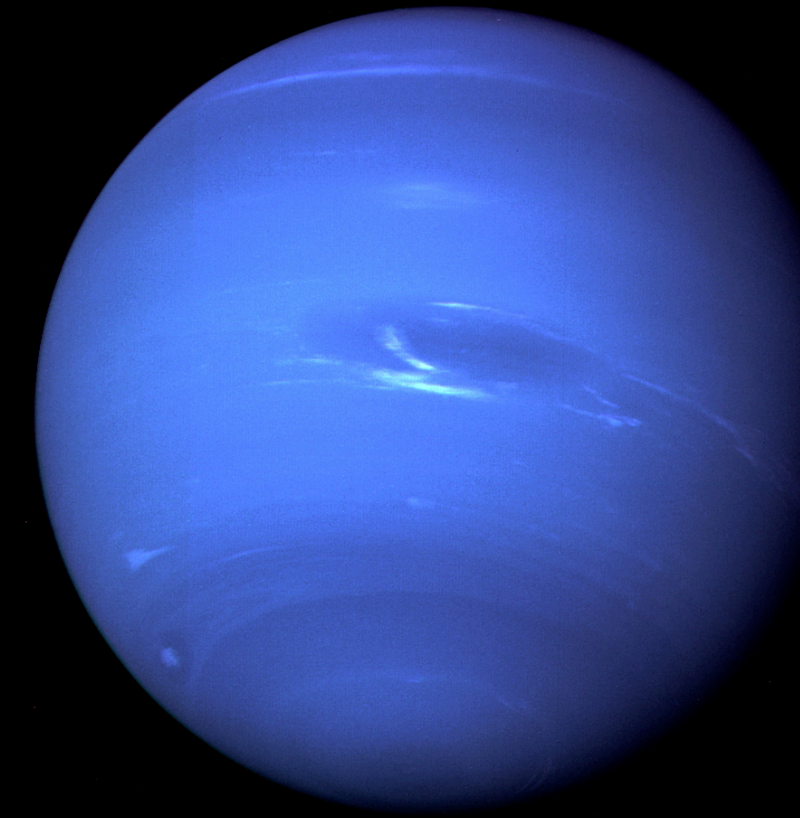
atmosphere

~ 0.0001%

~ 0.000003%

of the planet's mass

ice giants



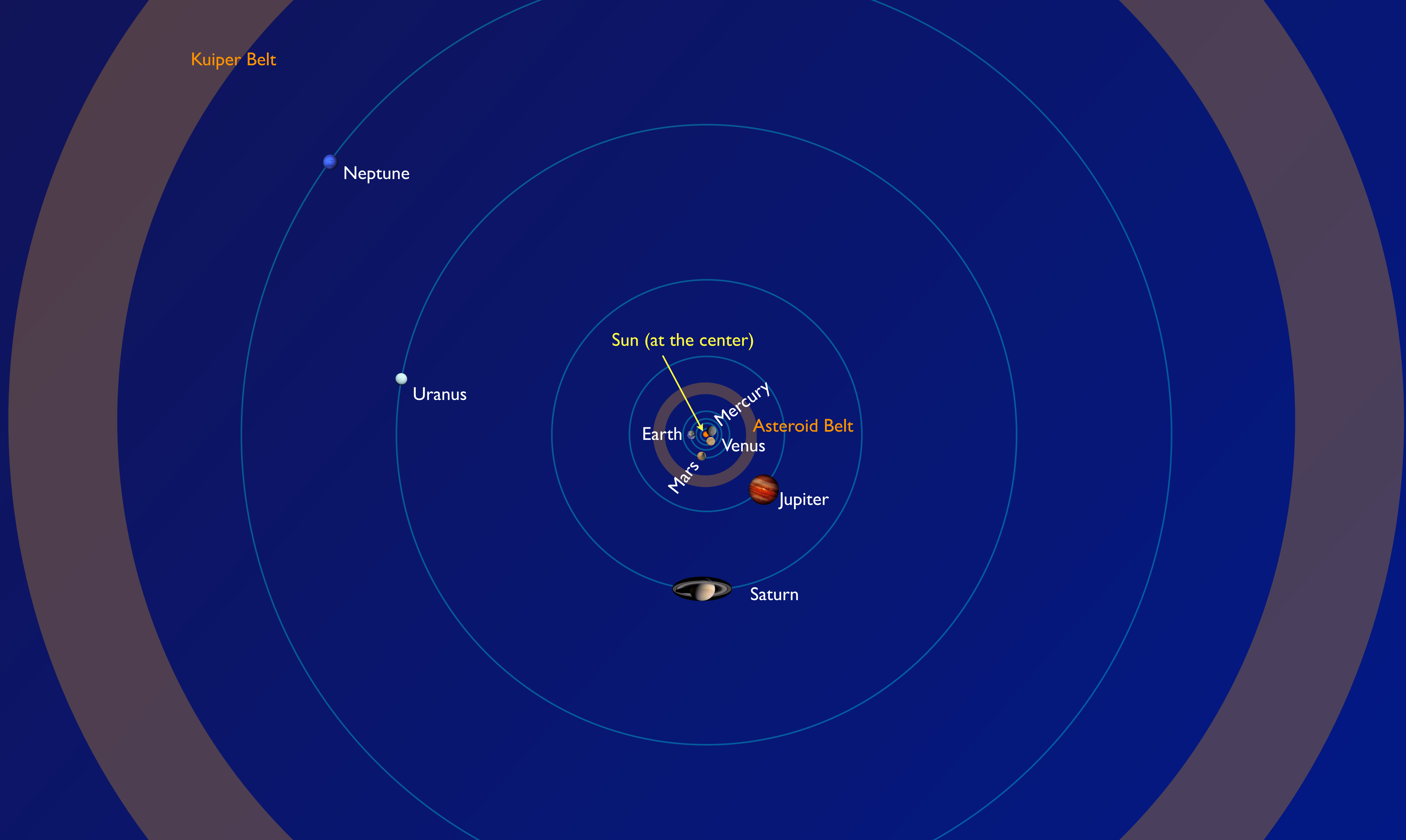
~10% hydrogen &
helium atmosphere

gas giants

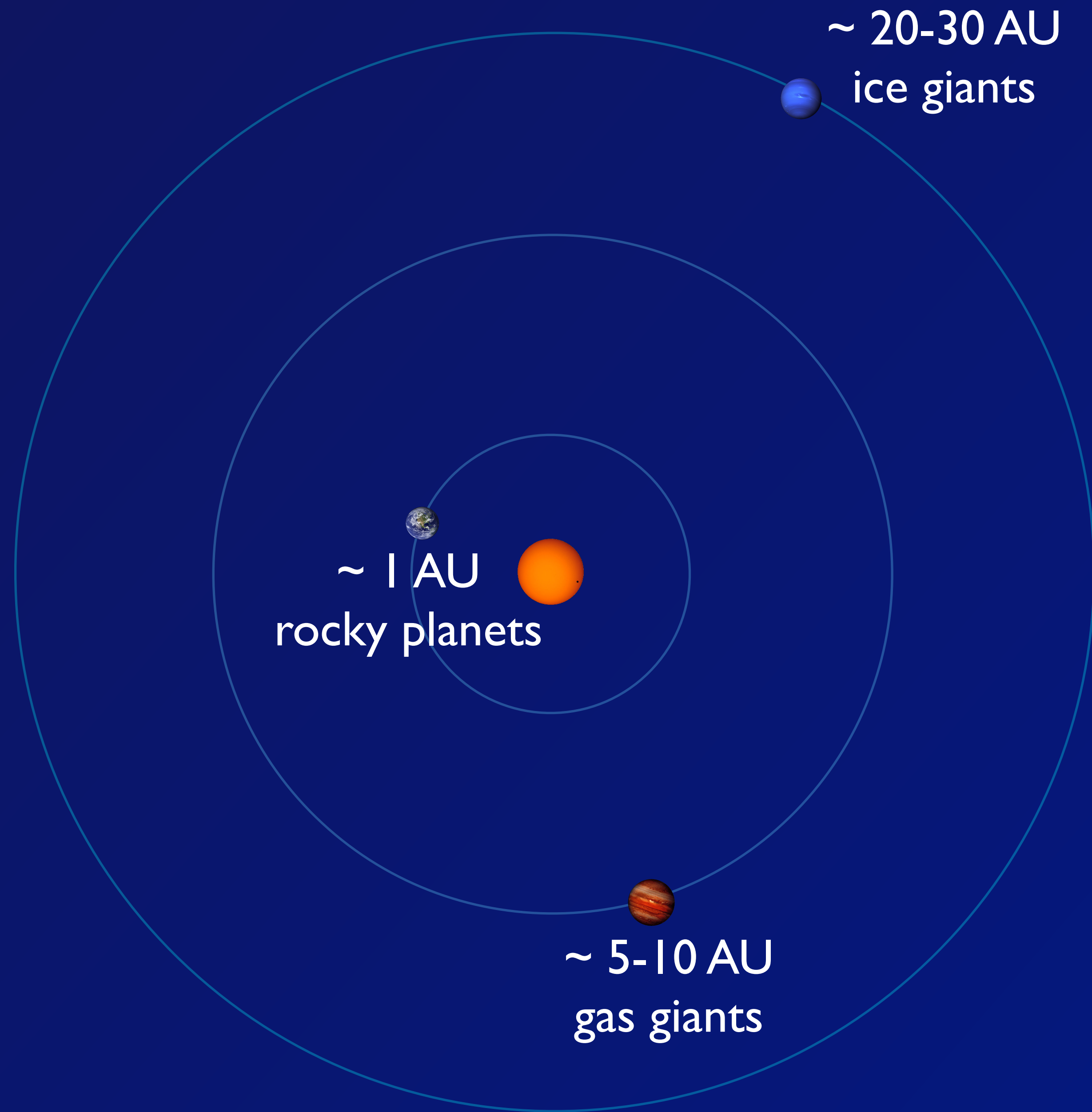


massive hydrogen &
helium atmosphere

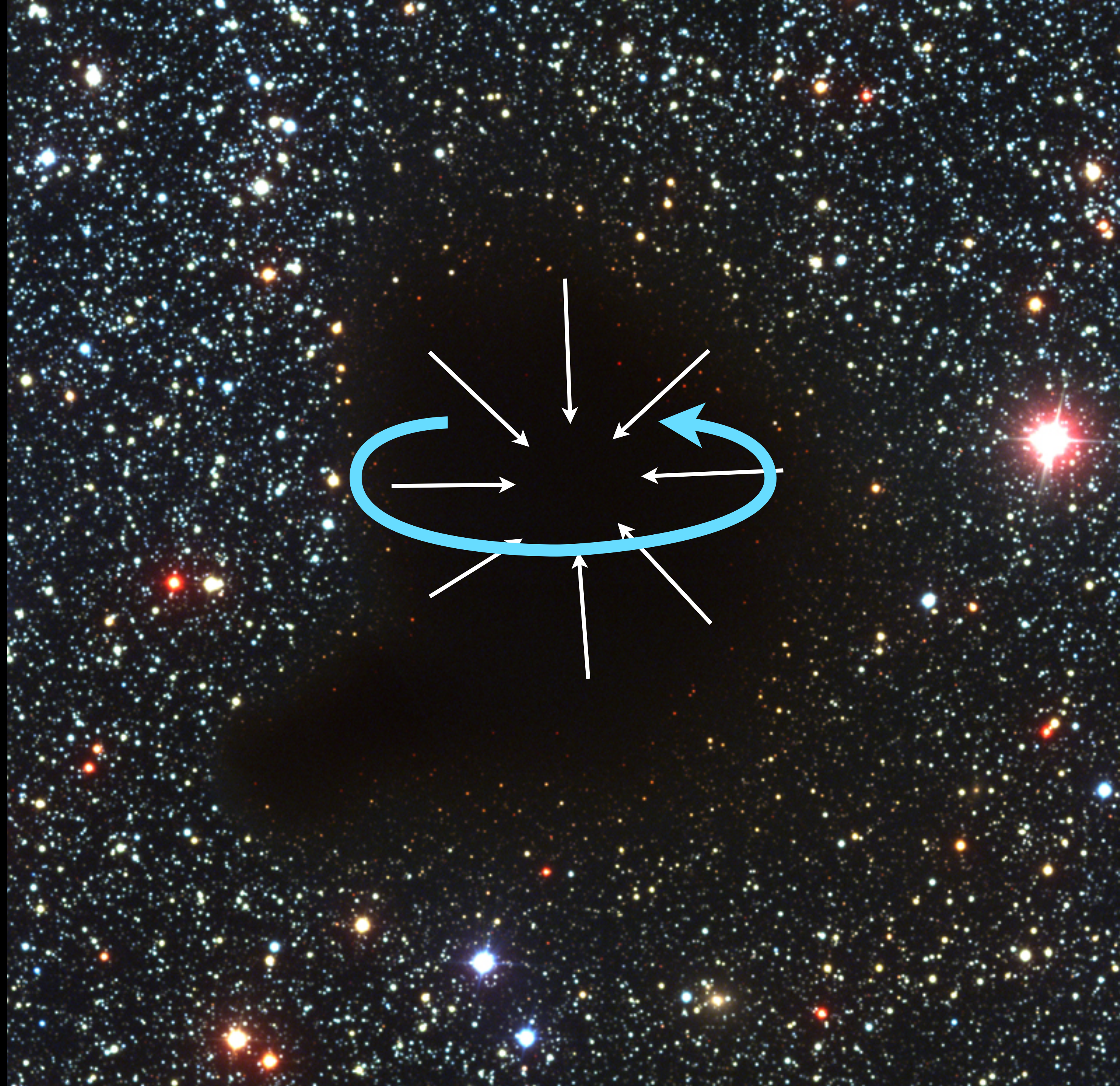
>95% of the planet's
mass

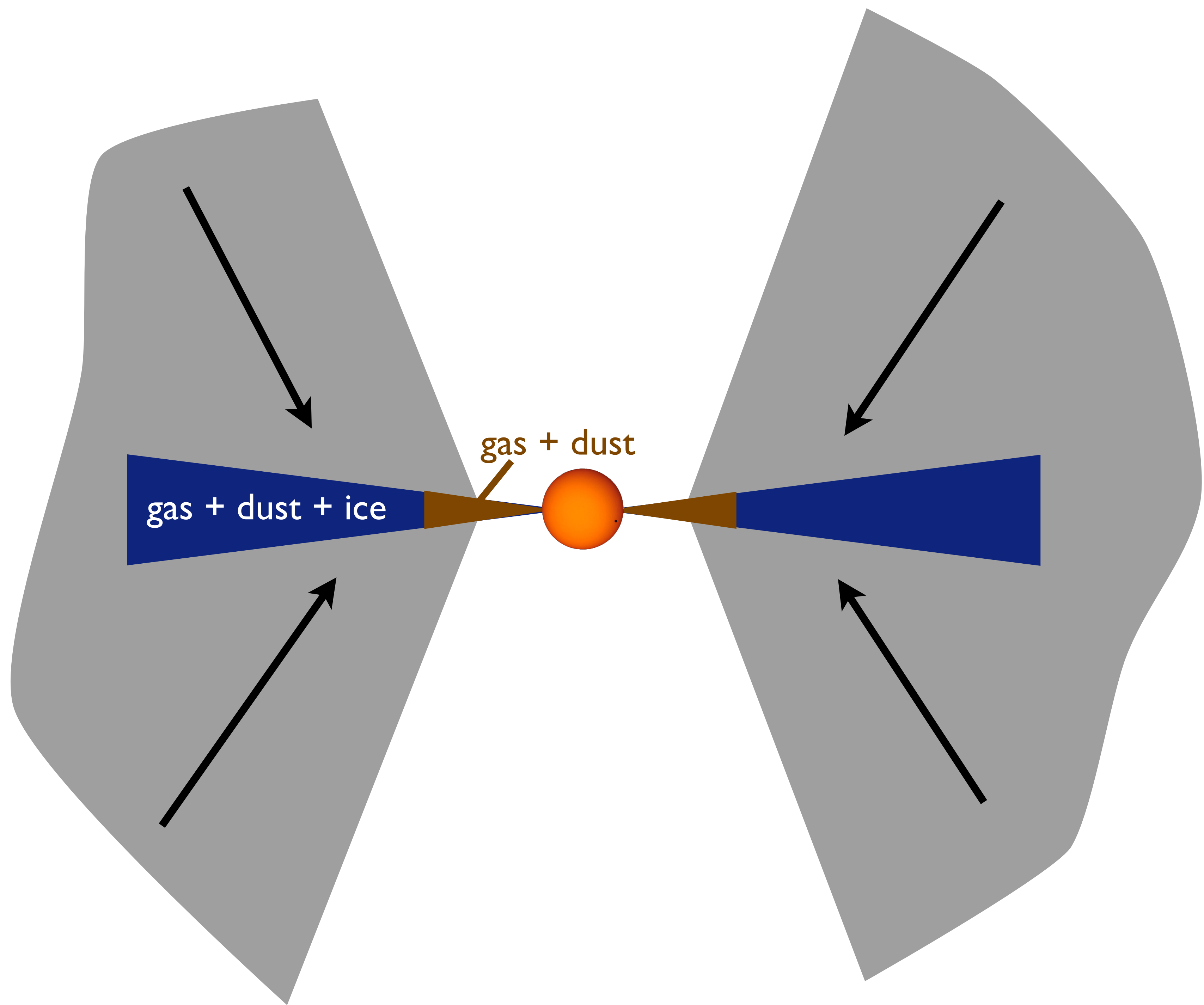


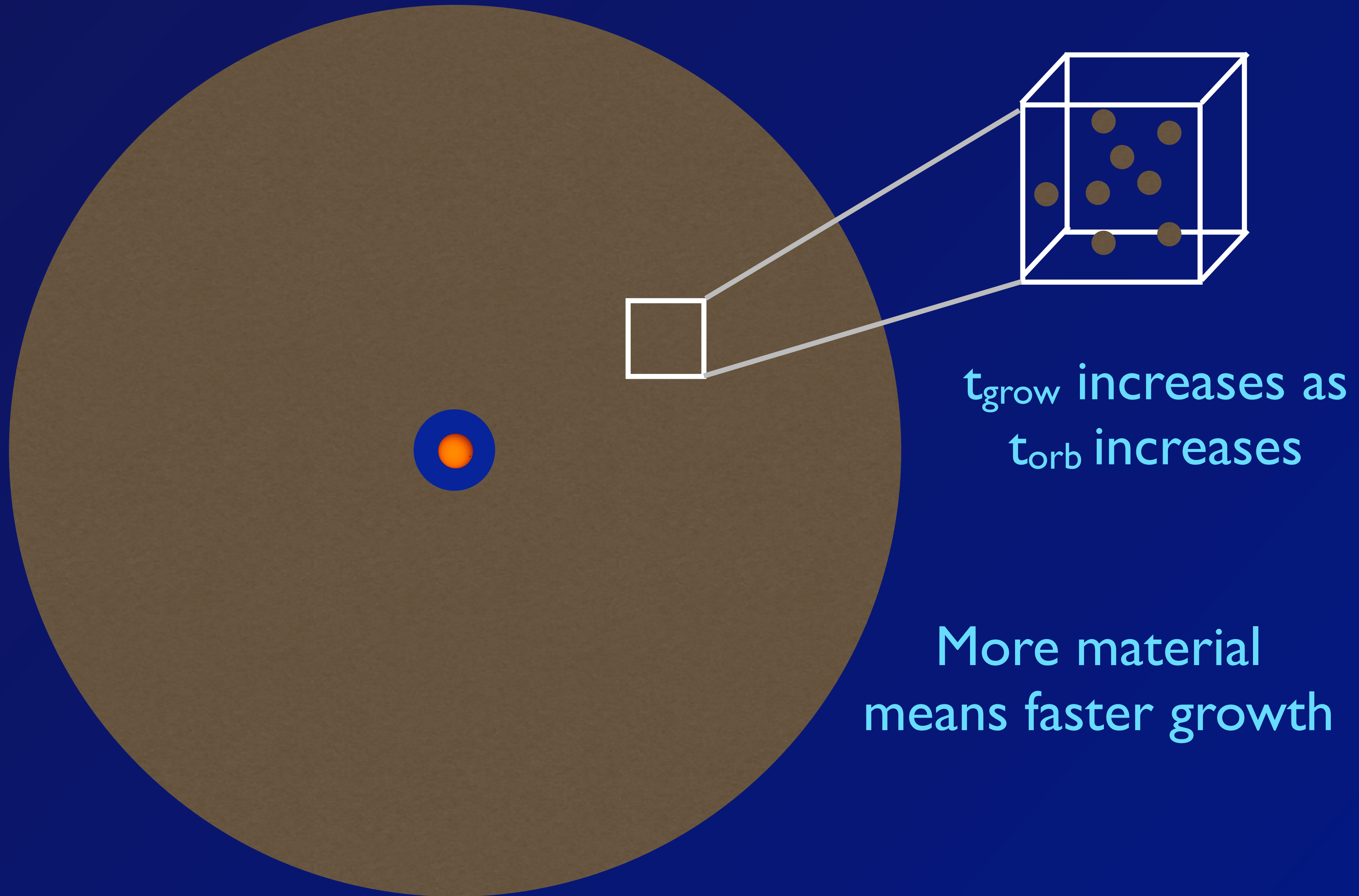
Pre-exoplanets:









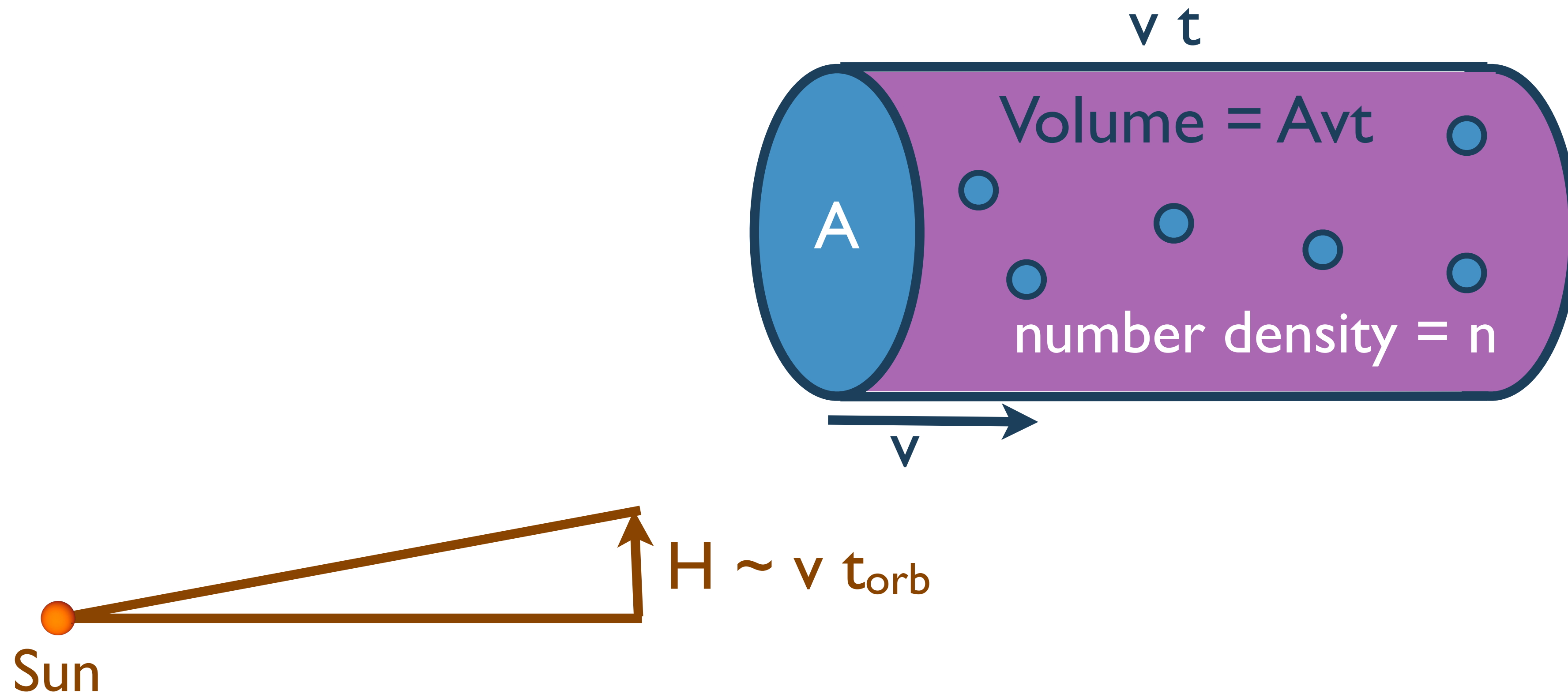


Growth timescale is set by:

A: cross-section for collisions

v: relative velocities of colliding bodies

n: density of bodies available to accrete



$$\# \text{ collisions in time } t \sim n A v t \sim (n H) A (t/t_{\text{orb}})$$

mass of object
trying to grow

orbital time:
longer farther
from the star

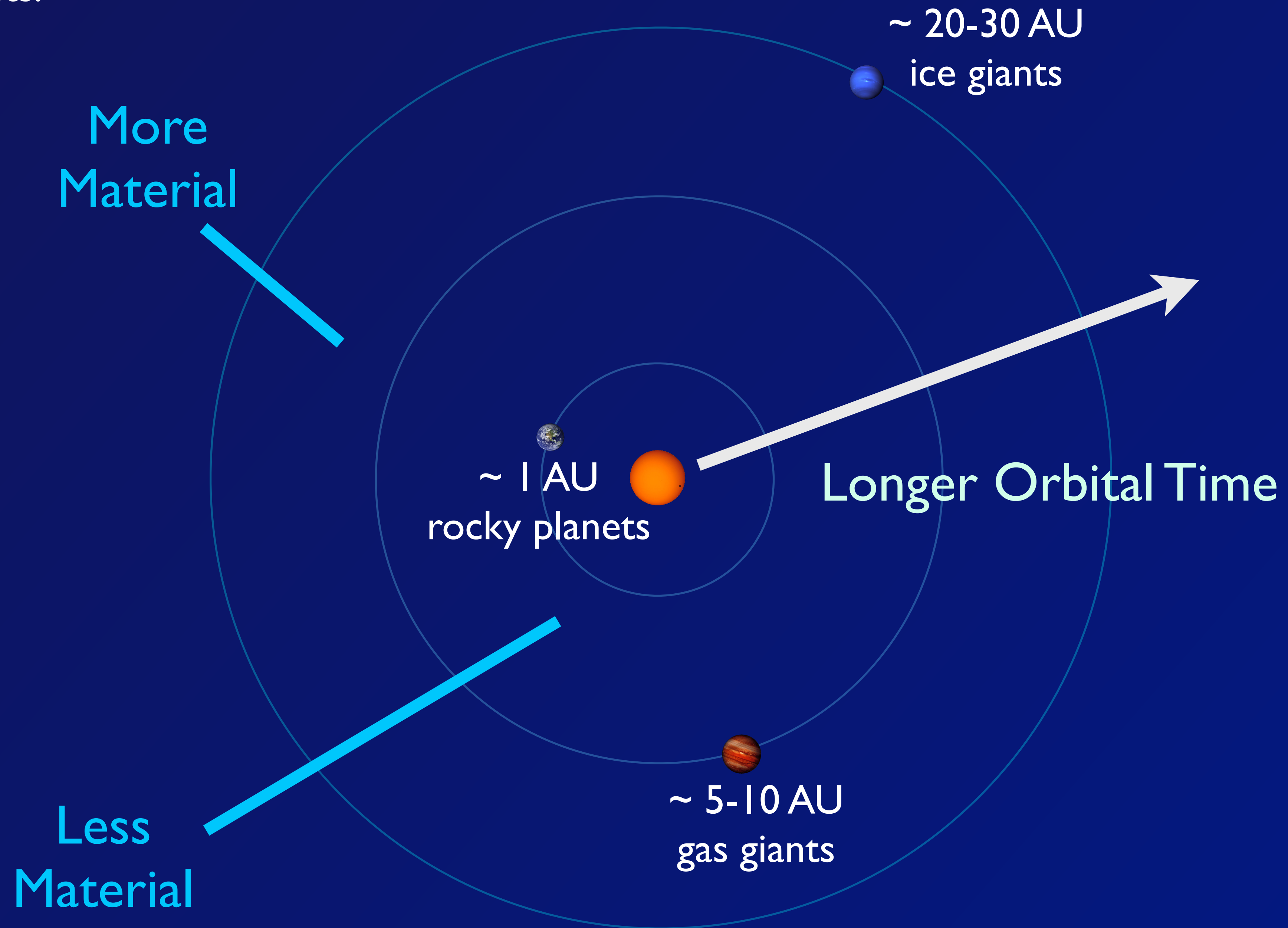
$$t_{\text{grow}} = \frac{M}{\dot{M}} \sim \frac{M}{\Sigma A} t_{\text{orb}}$$

disk surface
density in solids

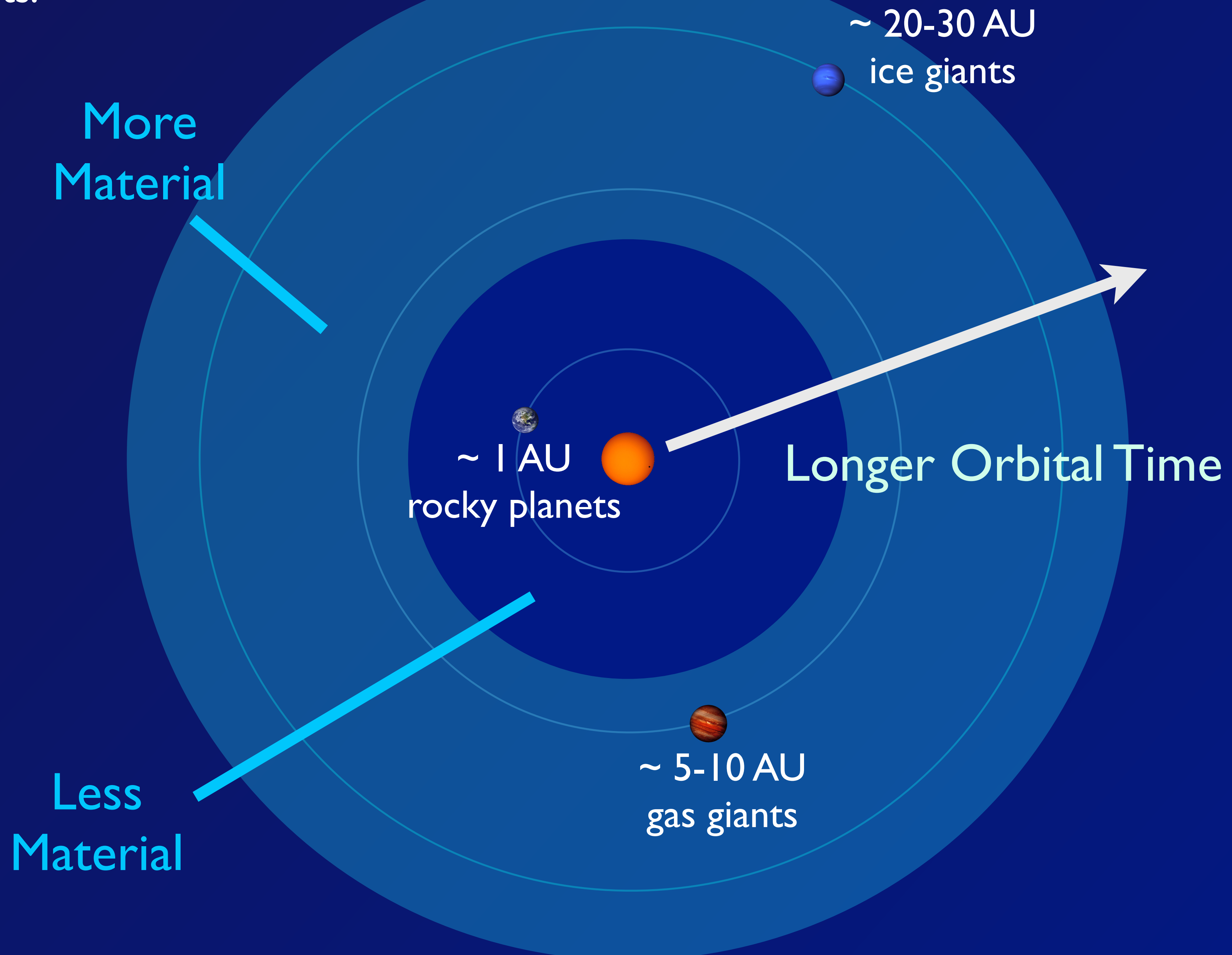
cross-section
for collisions

The diagram illustrates the equation for the growth time of a planet, $t_{\text{grow}} = \frac{M}{\dot{M}} \sim \frac{M}{\Sigma A} t_{\text{orb}}$. Each term in the equation is highlighted with a colored circle and connected to a descriptive text label. The mass M is circled in blue and labeled 'mass of object trying to grow'. The orbital time t_{orb} is circled in red and labeled 'orbital time: longer farther from the star'. The disk surface density Σ is circled in green and labeled 'disk surface density in solids'. The cross-section A is circled in purple and labeled 'cross-section for collisions', with the label enclosed in a black rectangular box.

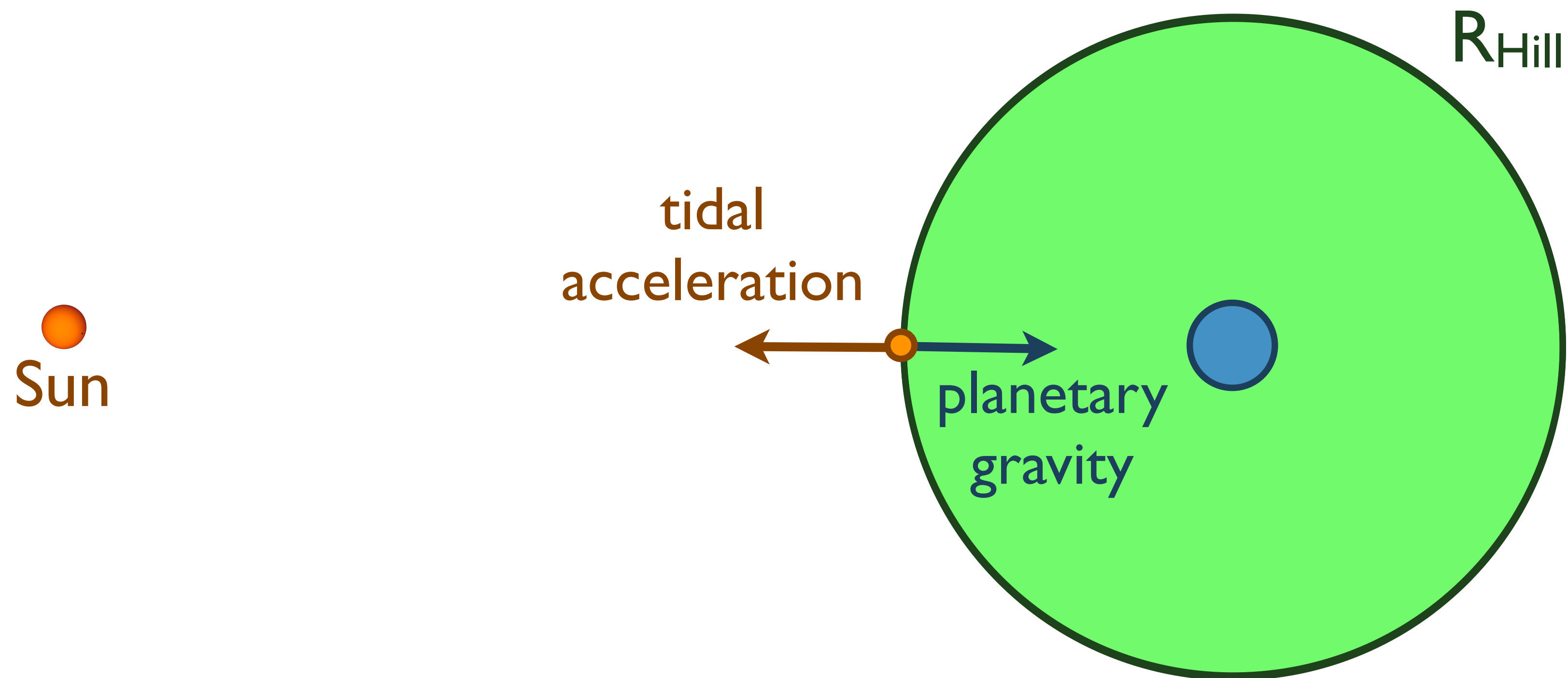
Pre-exoplanets:



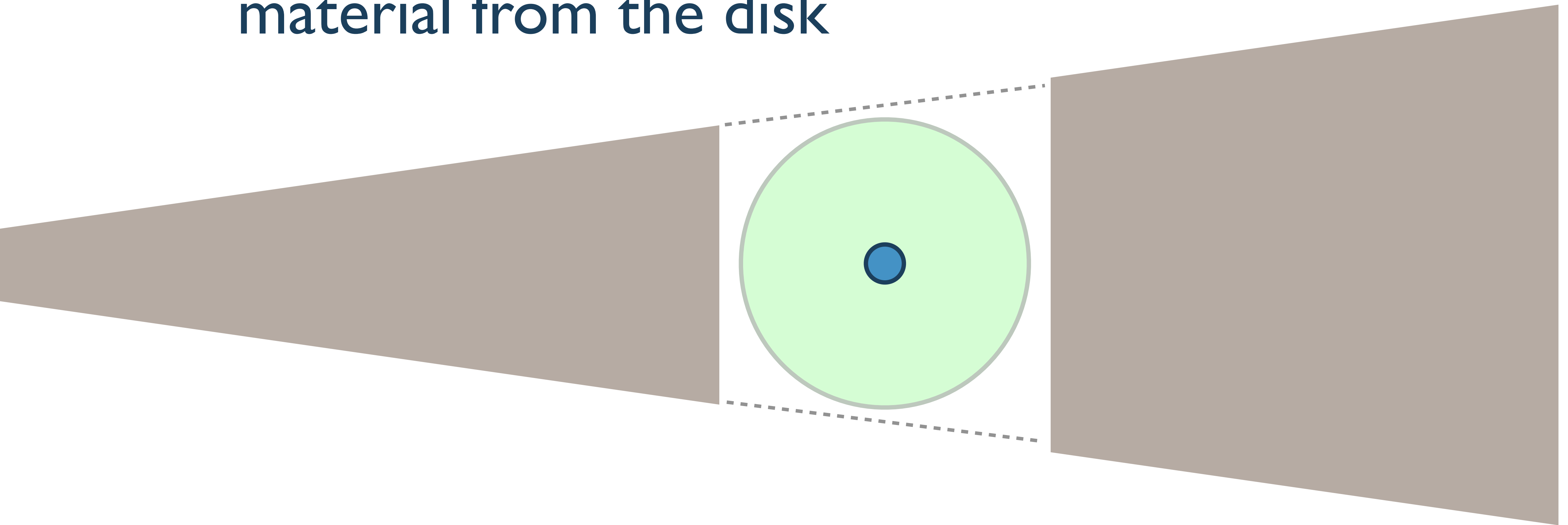
Pre-exoplanets:



The planet's gravity dominates within
the **Hill radius**

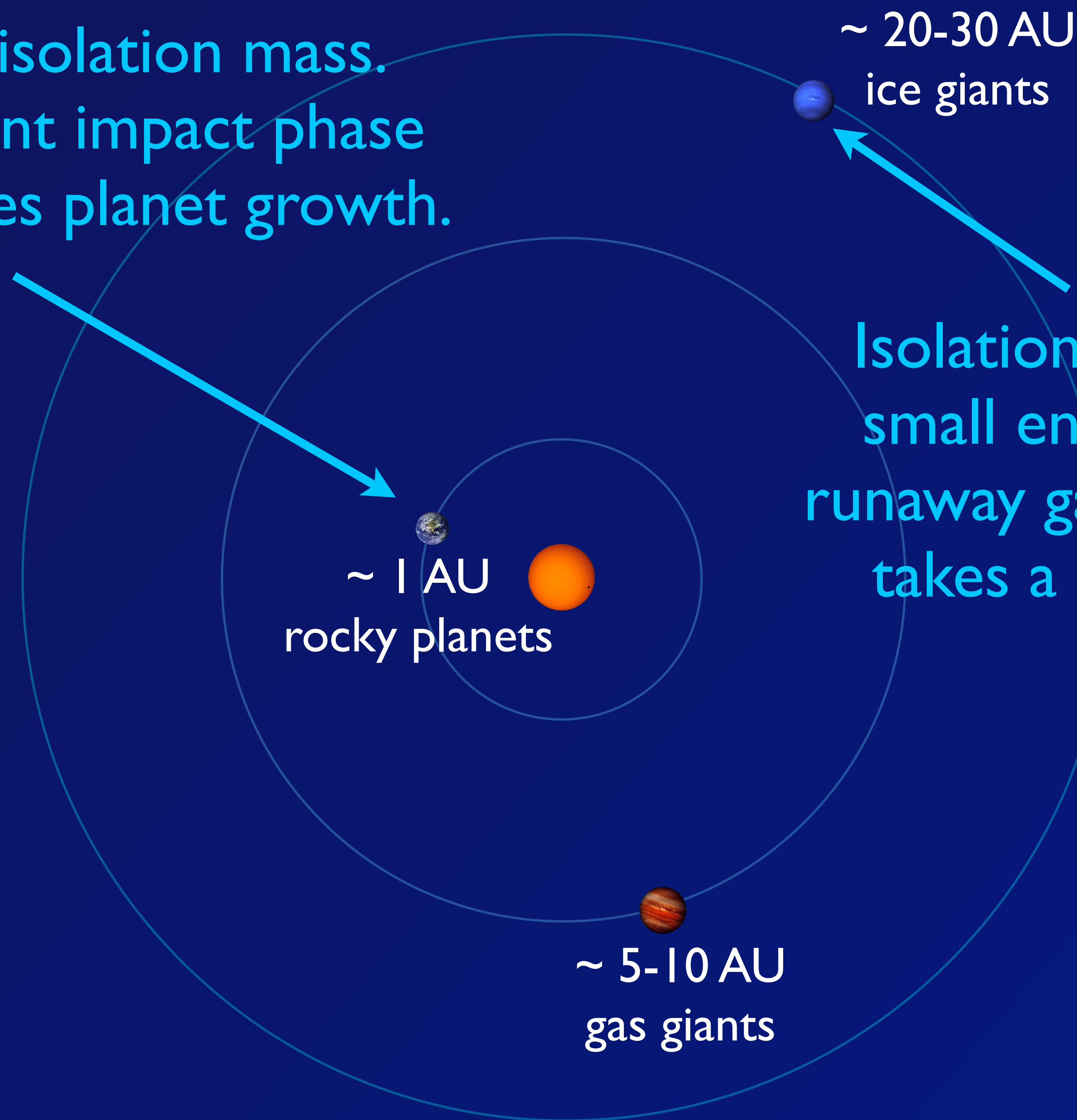


An **Isolation Mass** planet has accreted all gravitationally accessible material from the disk



Without replenishment, material
can be accreted from within
several Hill radii

Small isolation mass.
Late giant impact phase
completes planet growth.



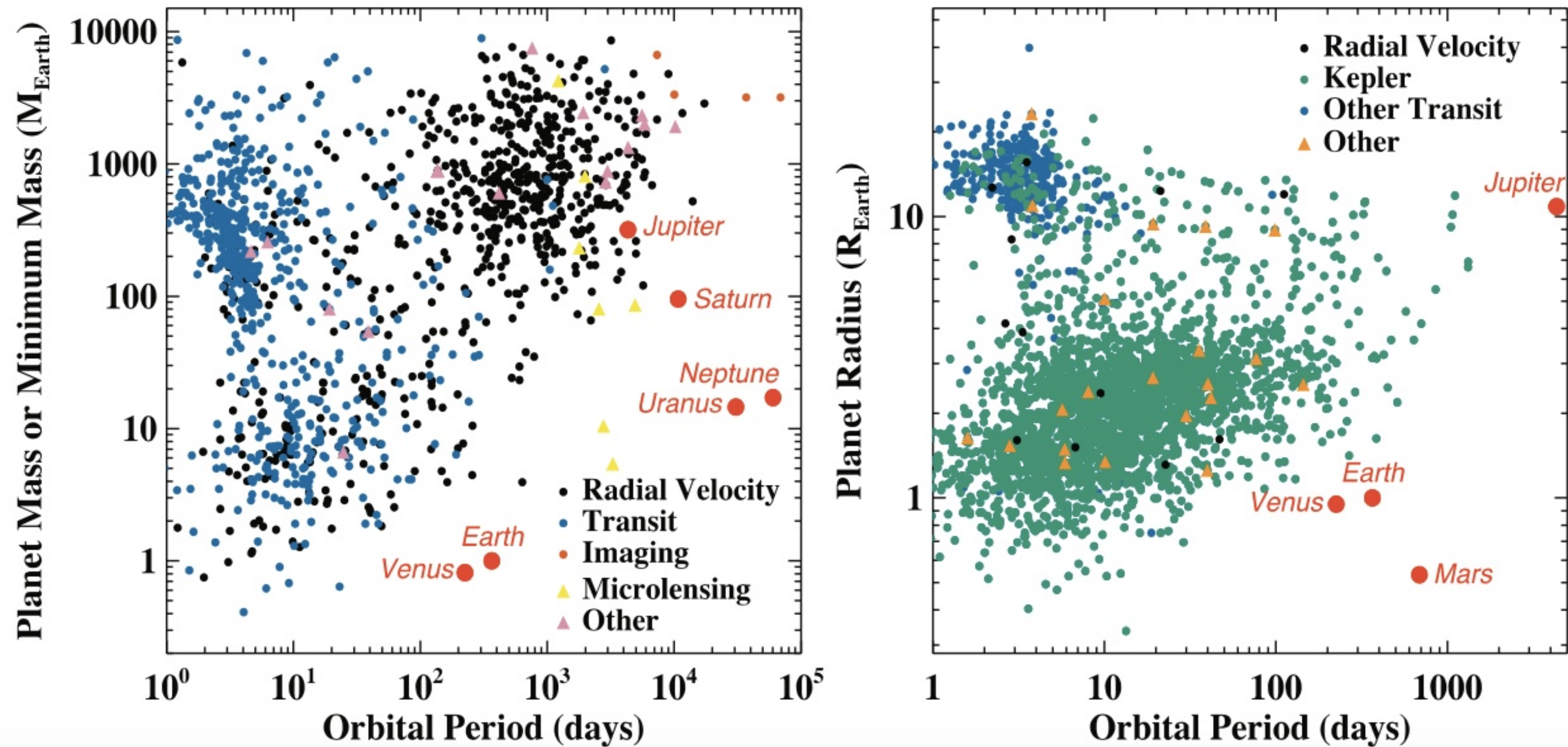
~ 1 AU
rocky planets

~ 5-10 AU
gas giants

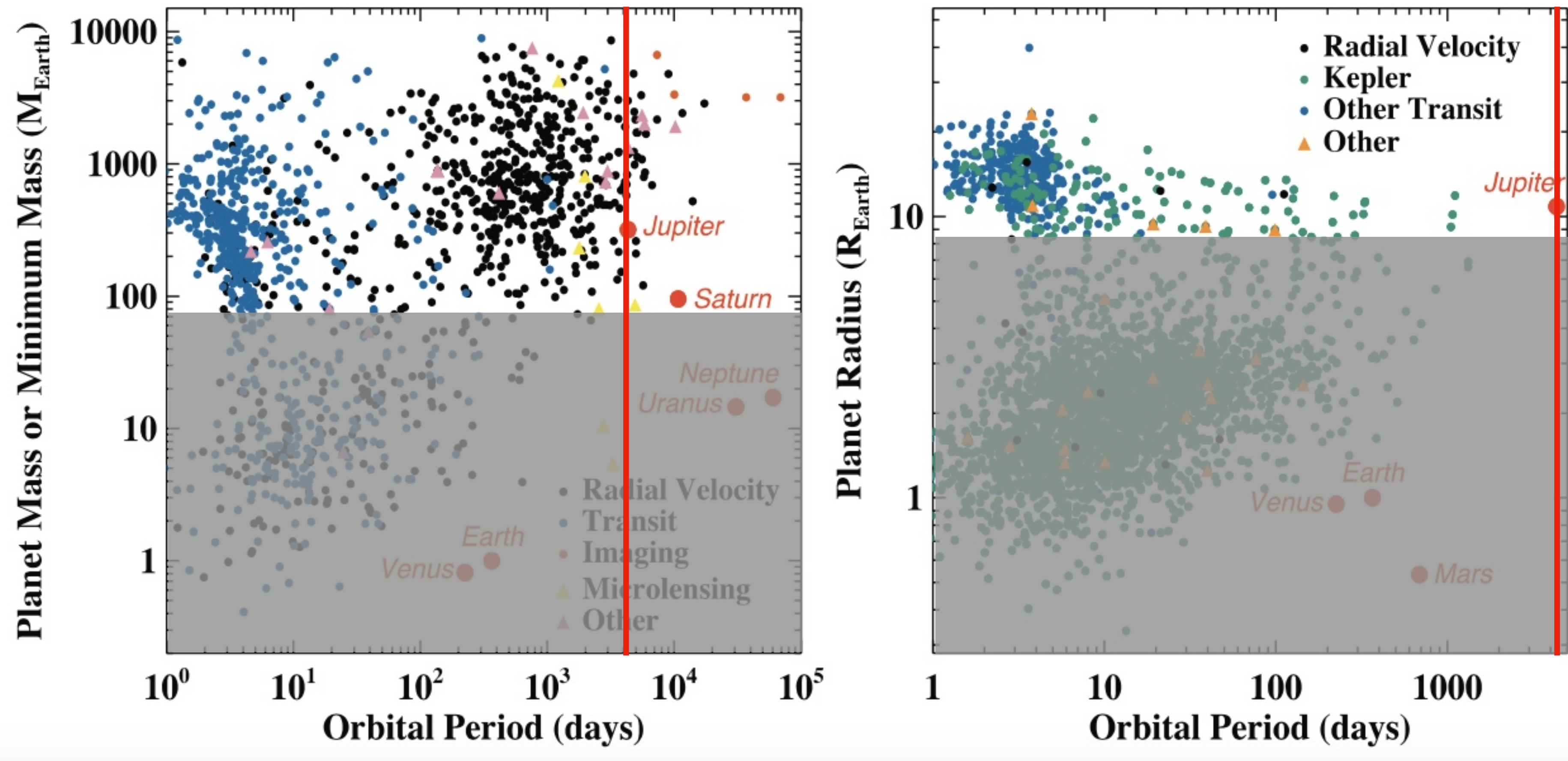
~ 20-30 AU
ice giants

Isolation mass just
small enough that
runaway gas accretion
takes a long time

Known Planets

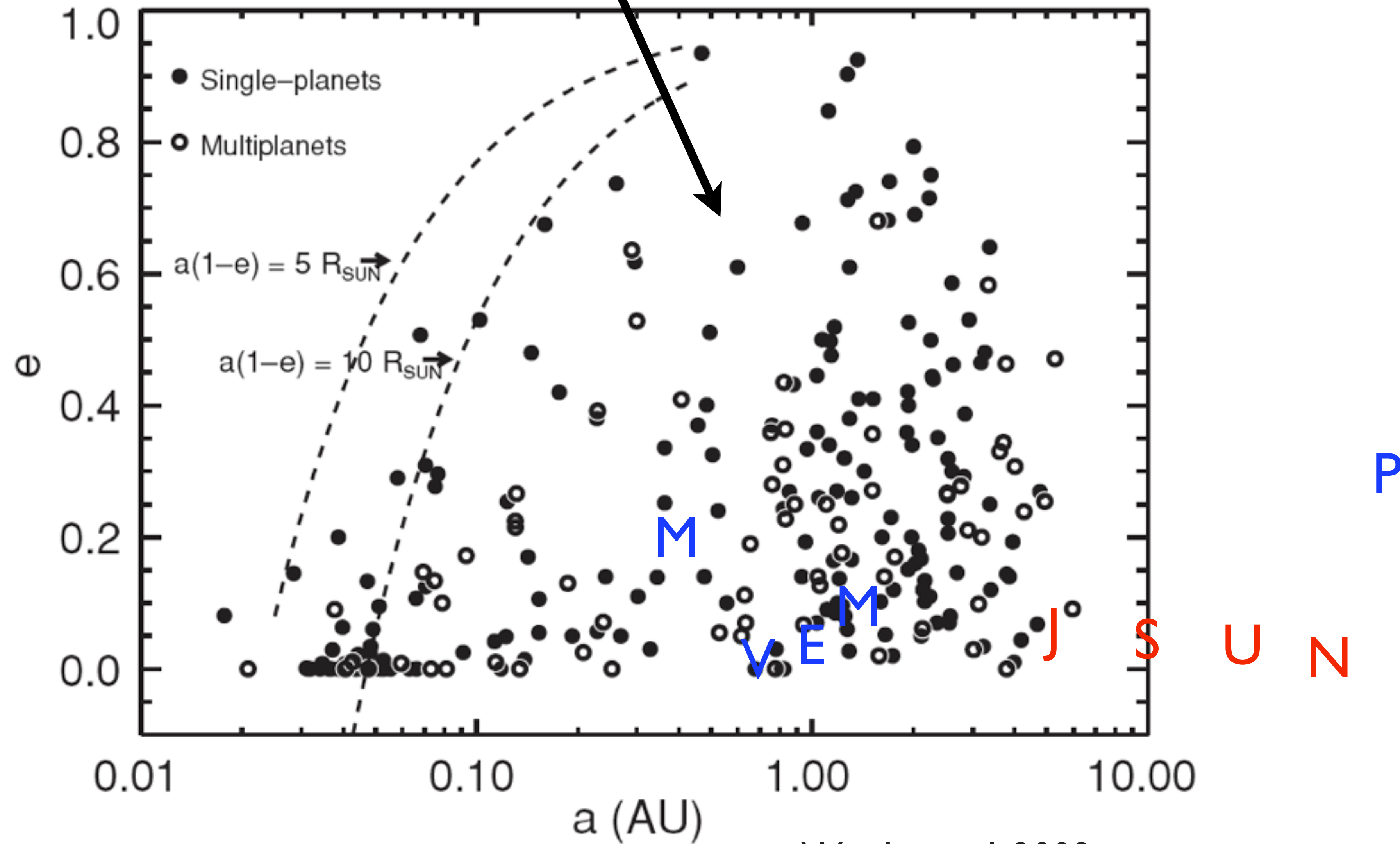


Gas Giant Planets



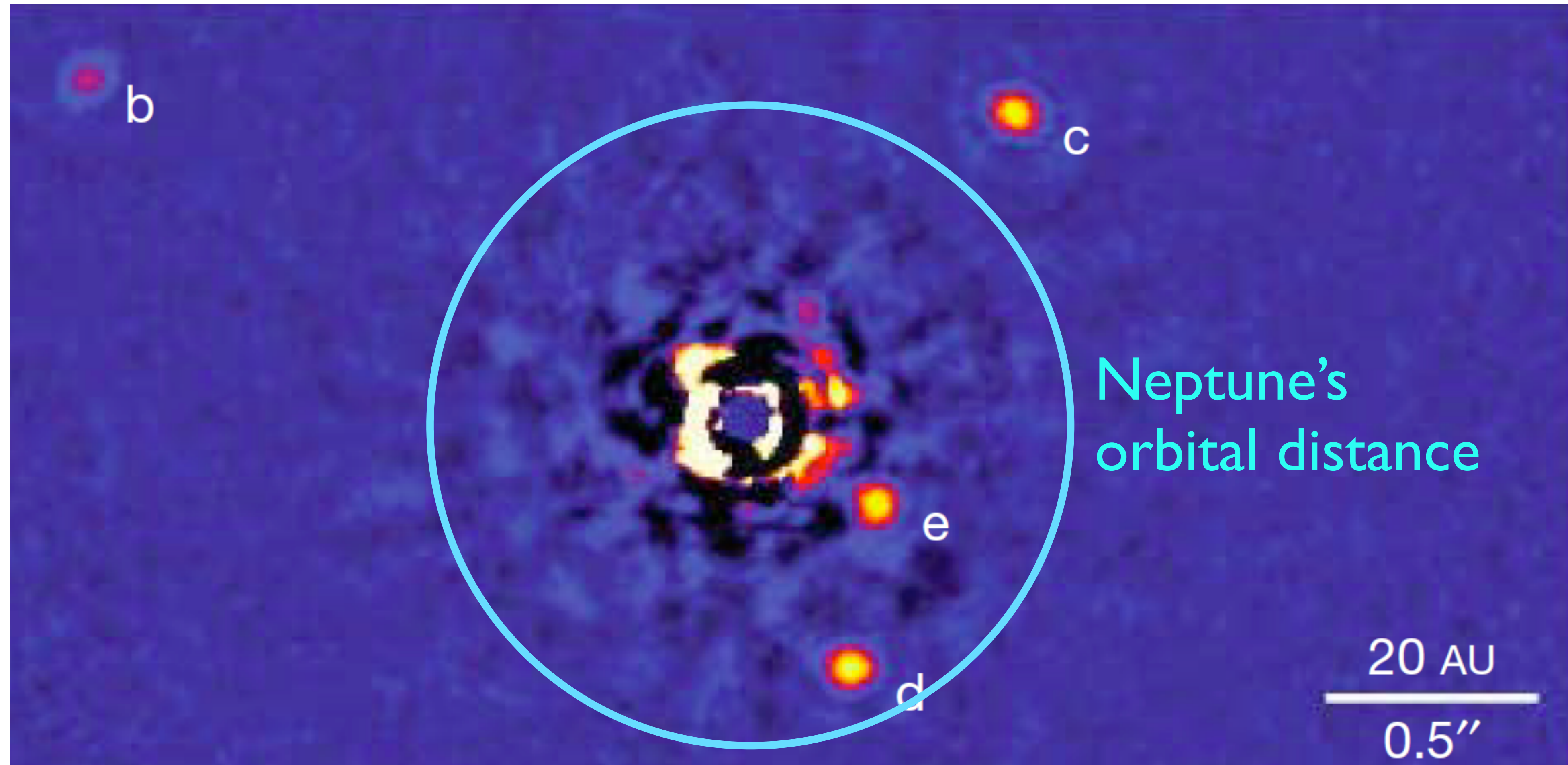
high-eccentricity giant planets

Radial Velocity planets



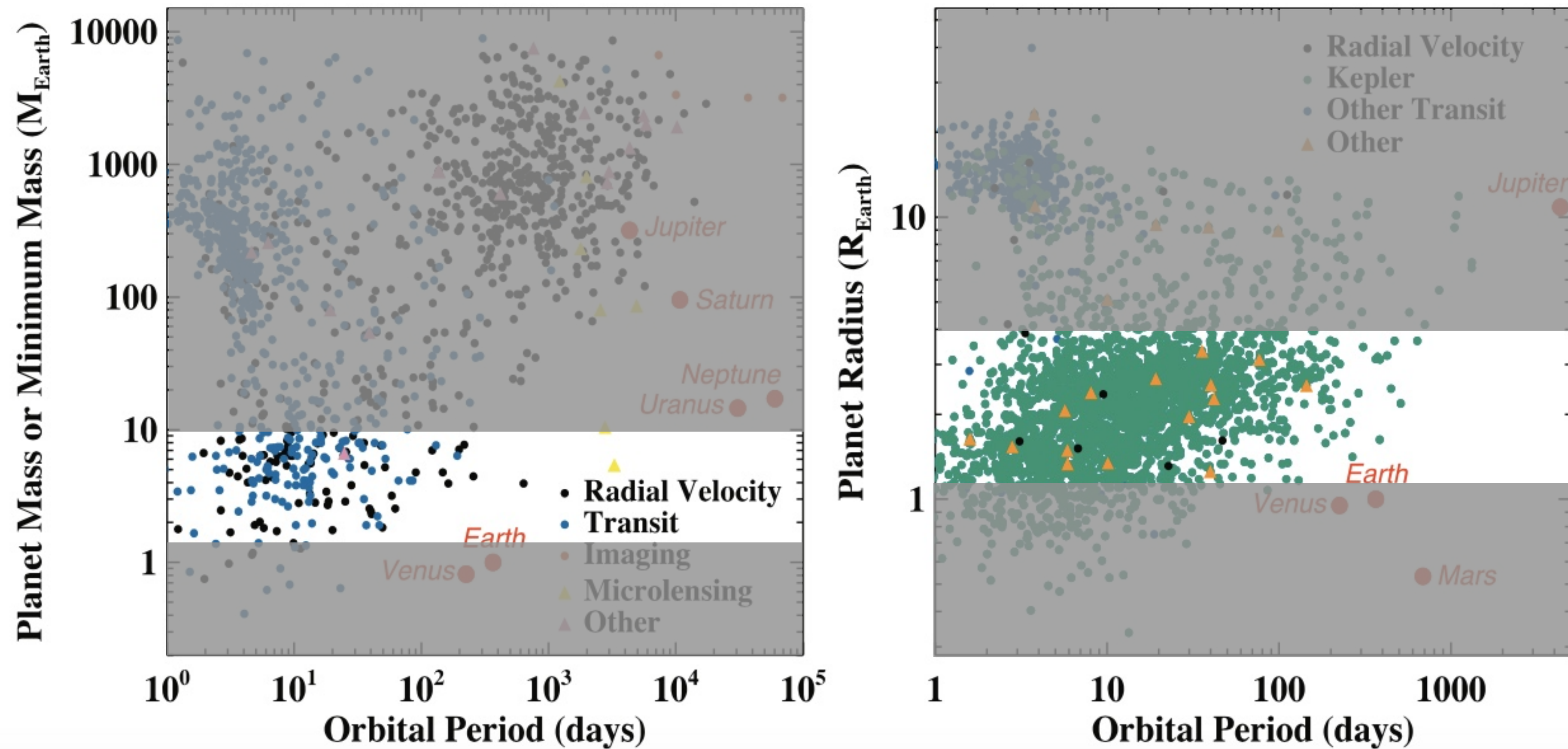
Wright et al. 2009

HR 8799: wide-separation giants

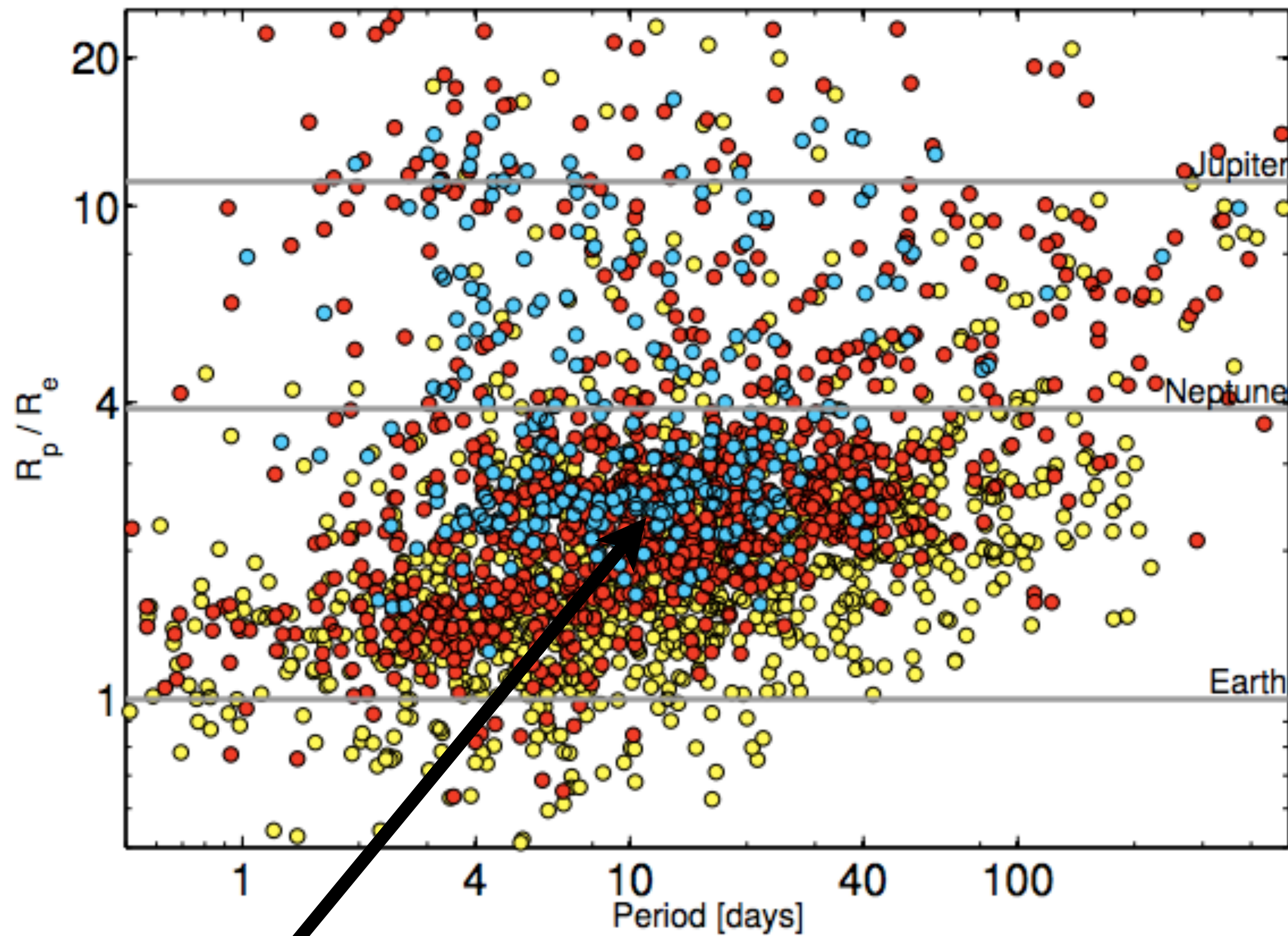


Marois et al. 2010

Super-Earths



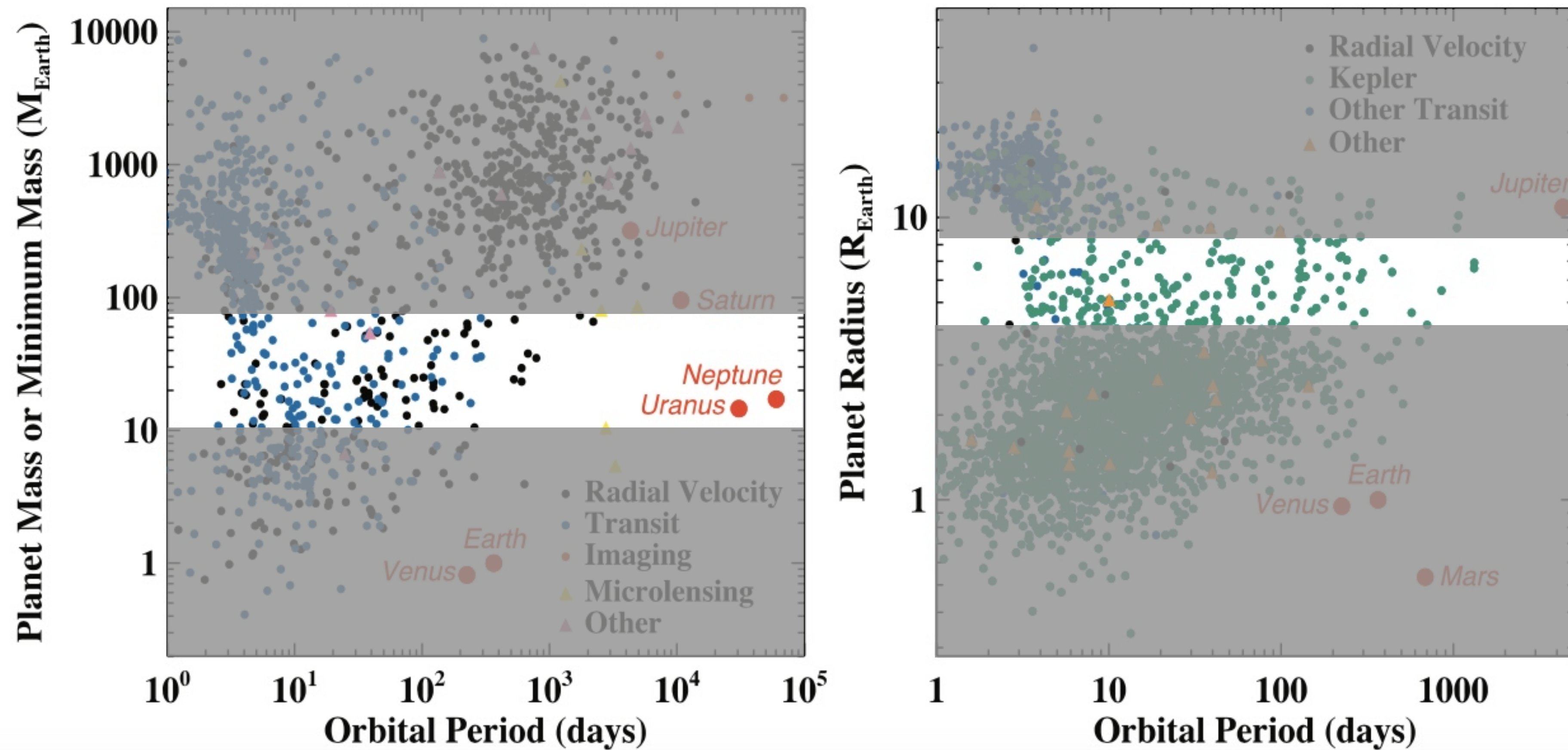
Kepler planets



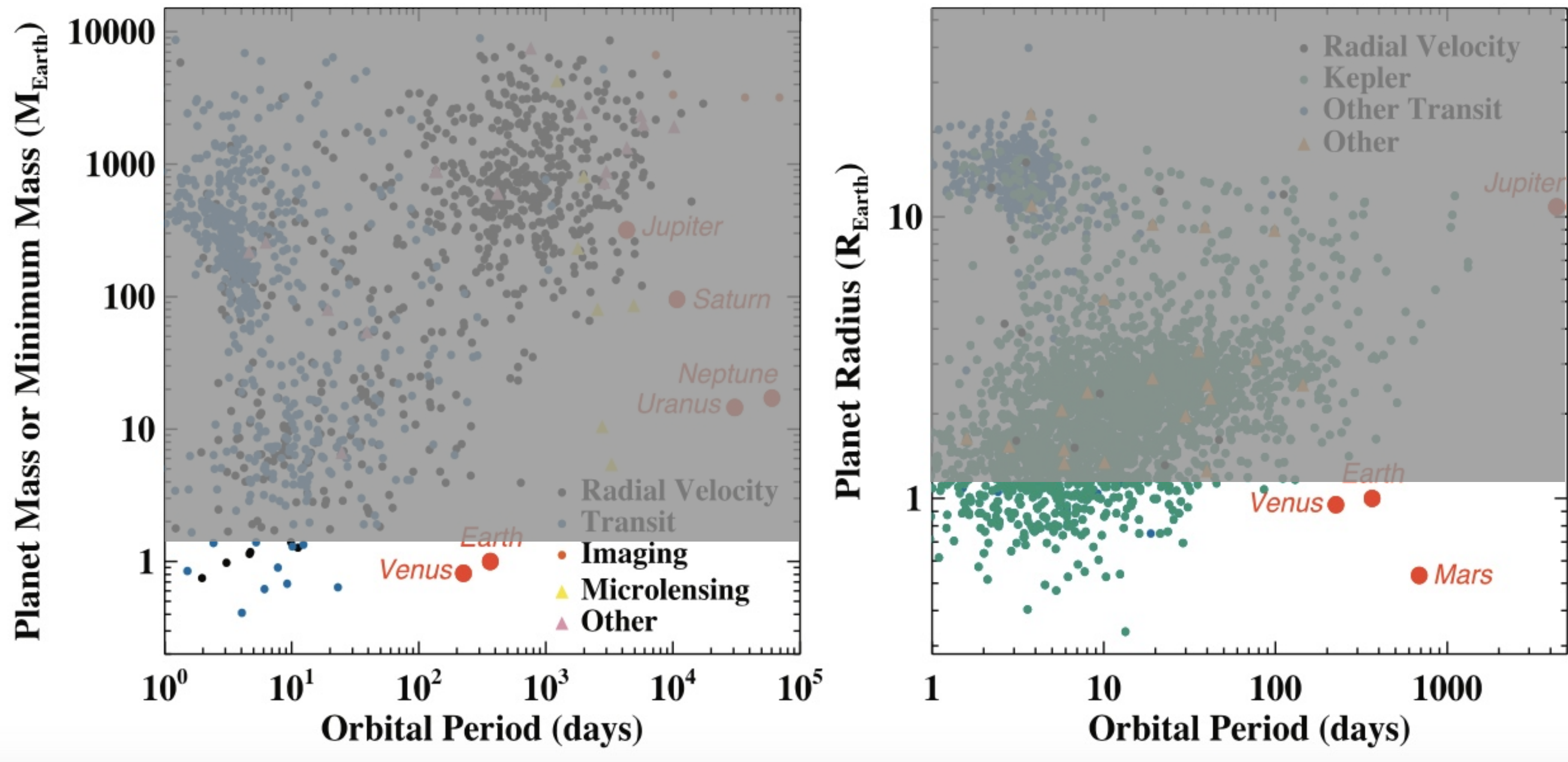
“super-Earths” are common

Batalha et al. (2012)

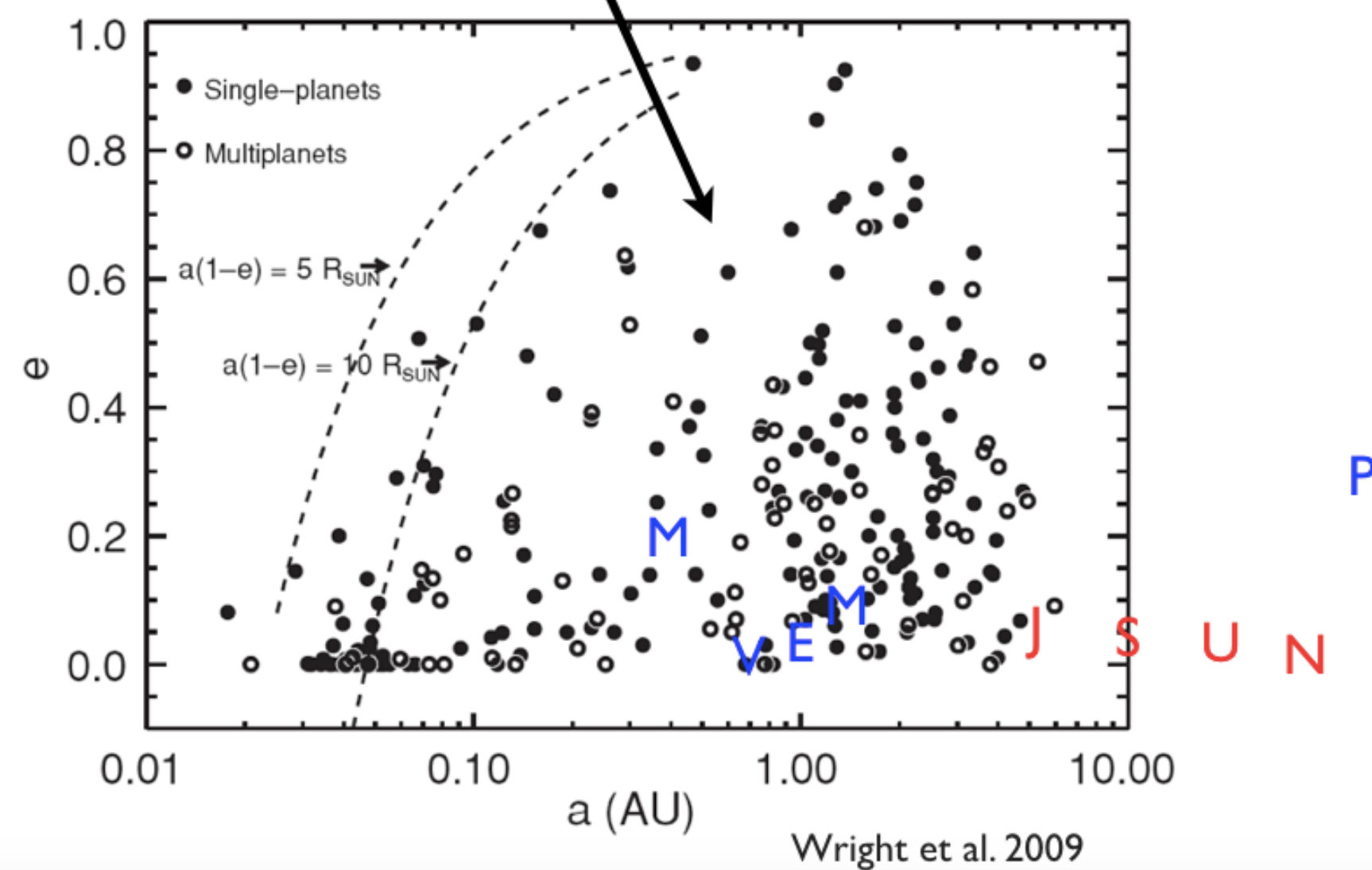
Neptunes?



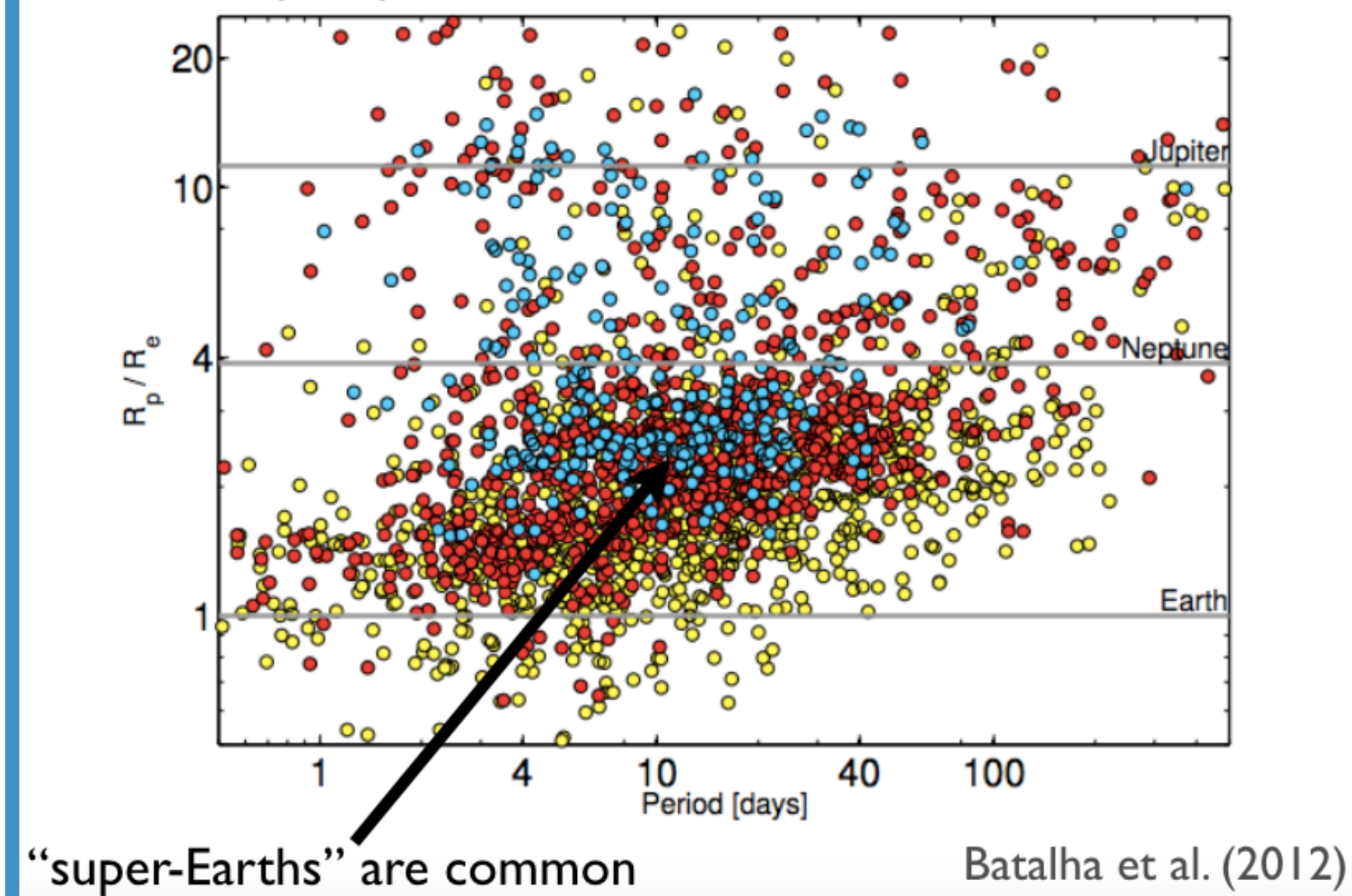
Terrestrial Planets



Radial Velocity planets

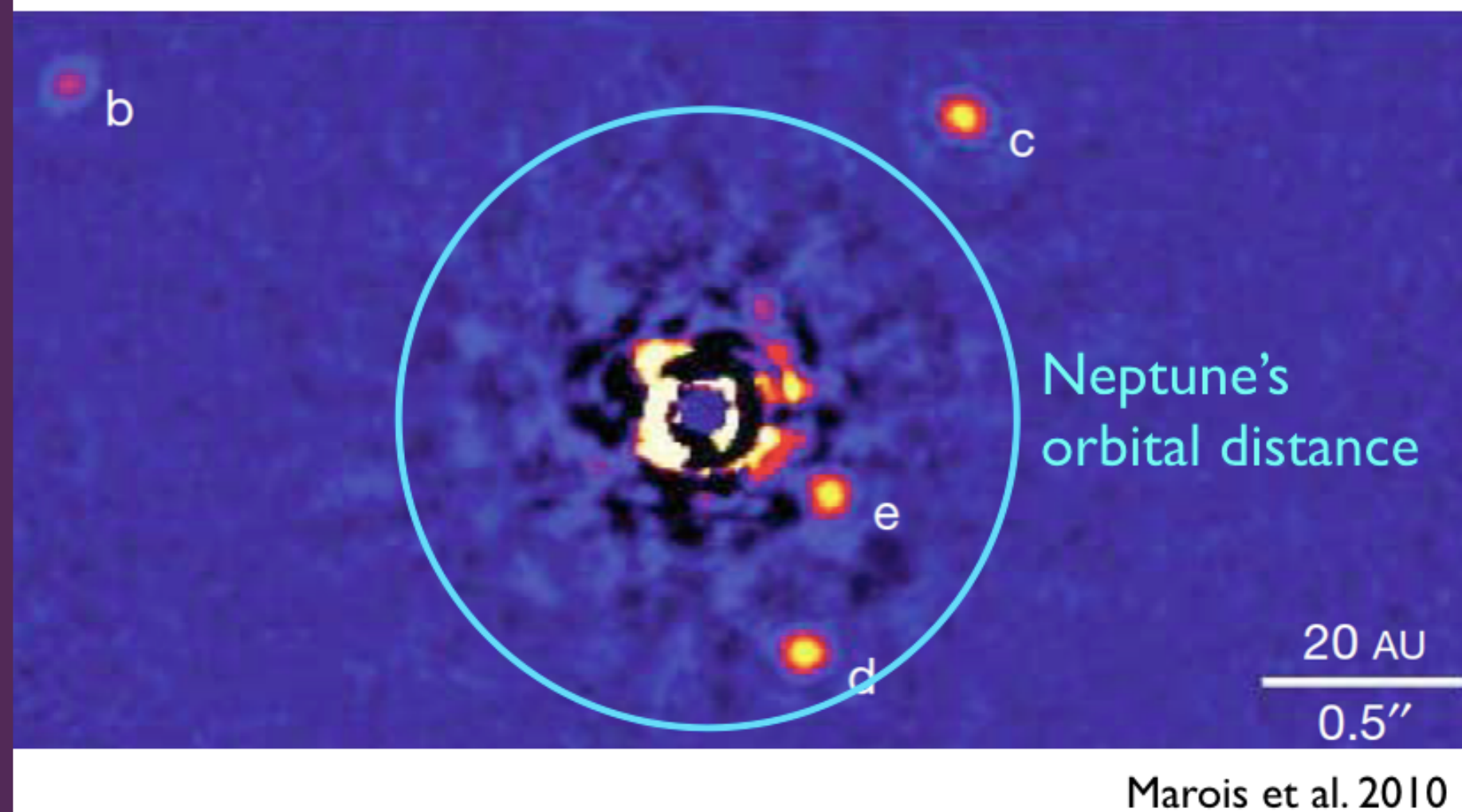


Kepler planets



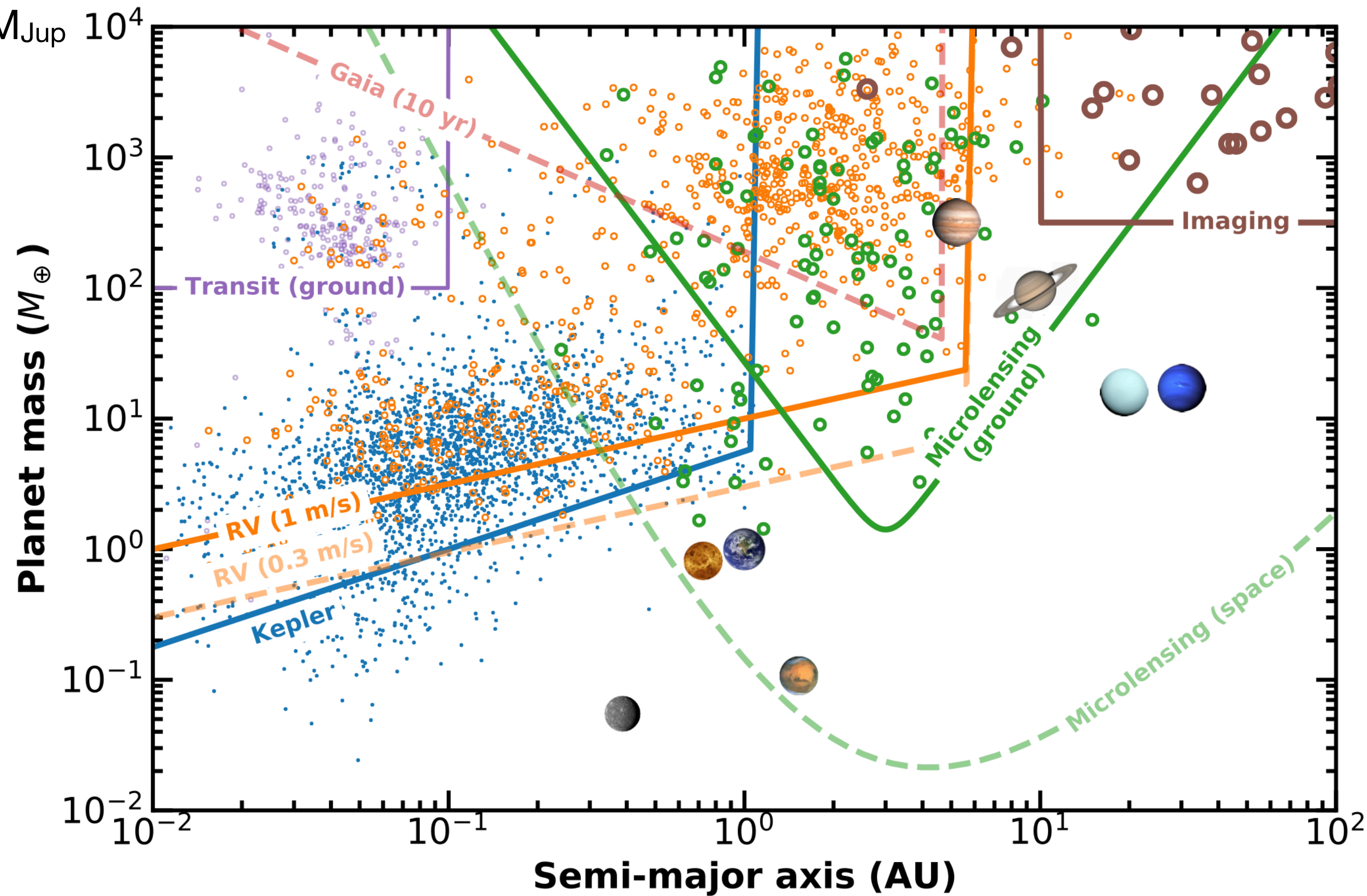
The data show that more is going on

HR 8799: wide-separation giants

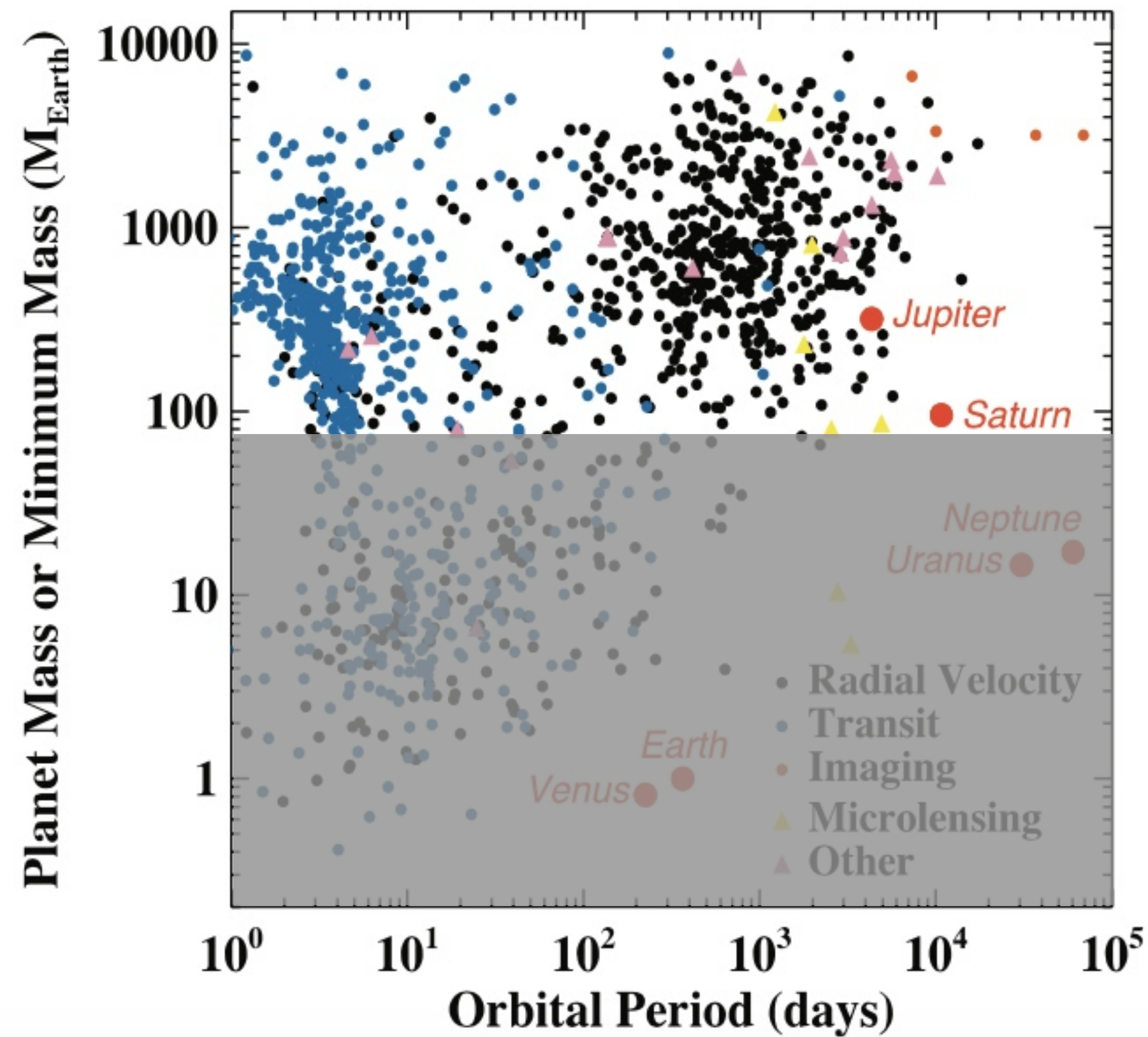


But we don't have observational grounding in the parts of planetary systems where most mass is “supposed to” end up in planets

33 M_{Jup}



Gas Giant Planets

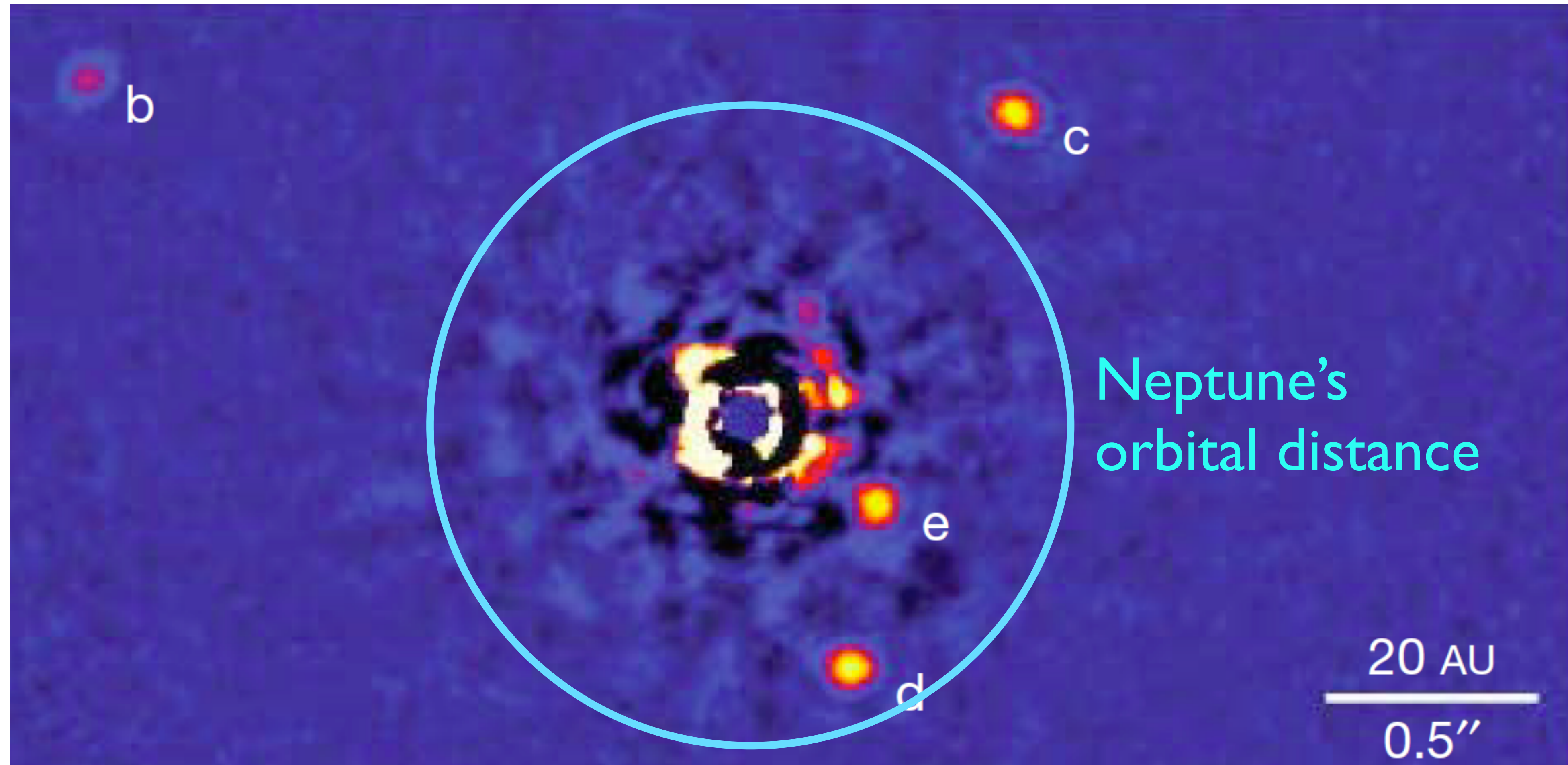


too far

too close

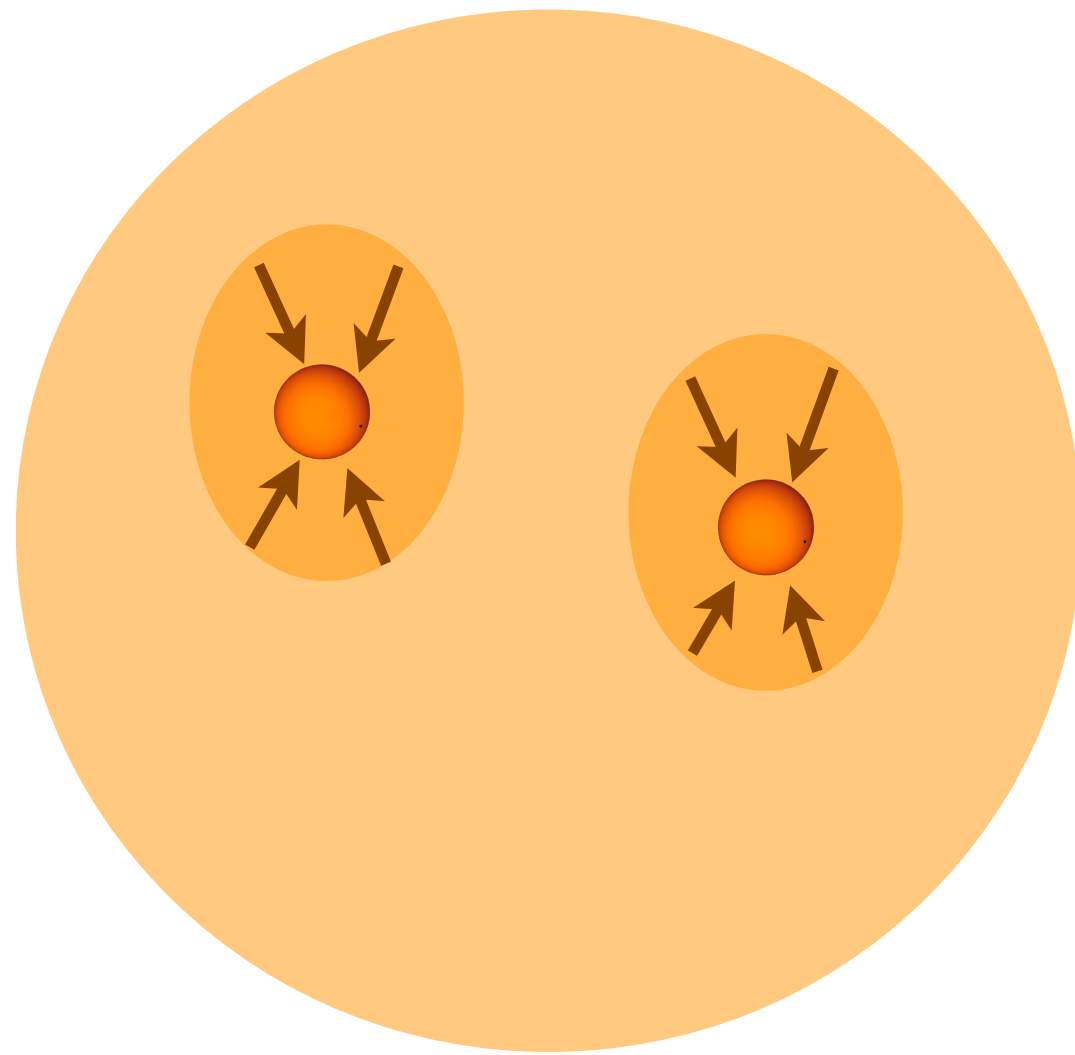
too eccentric

HR 8799: wide-separation giants (too far)

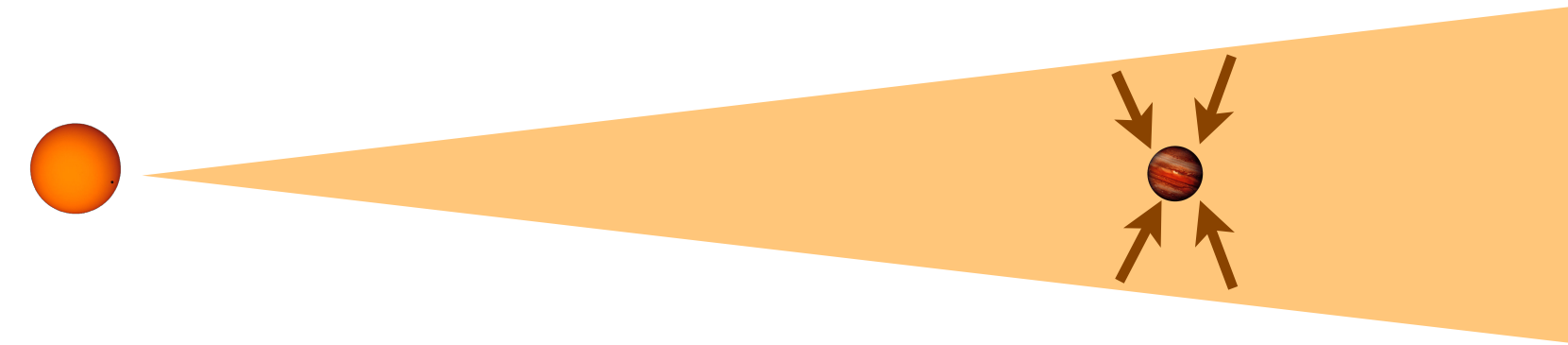


Marois et al. 2010

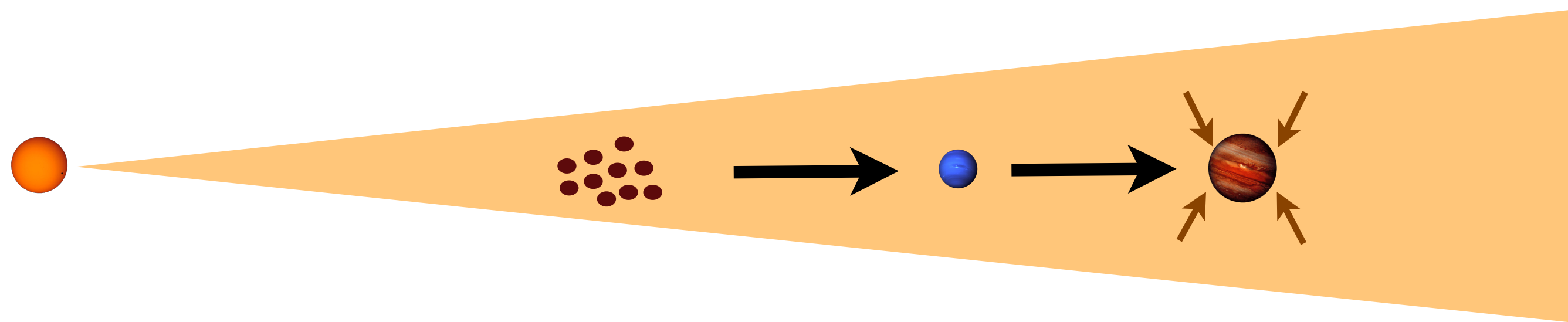
Three ways to form giant companions



turbulent fragmentation

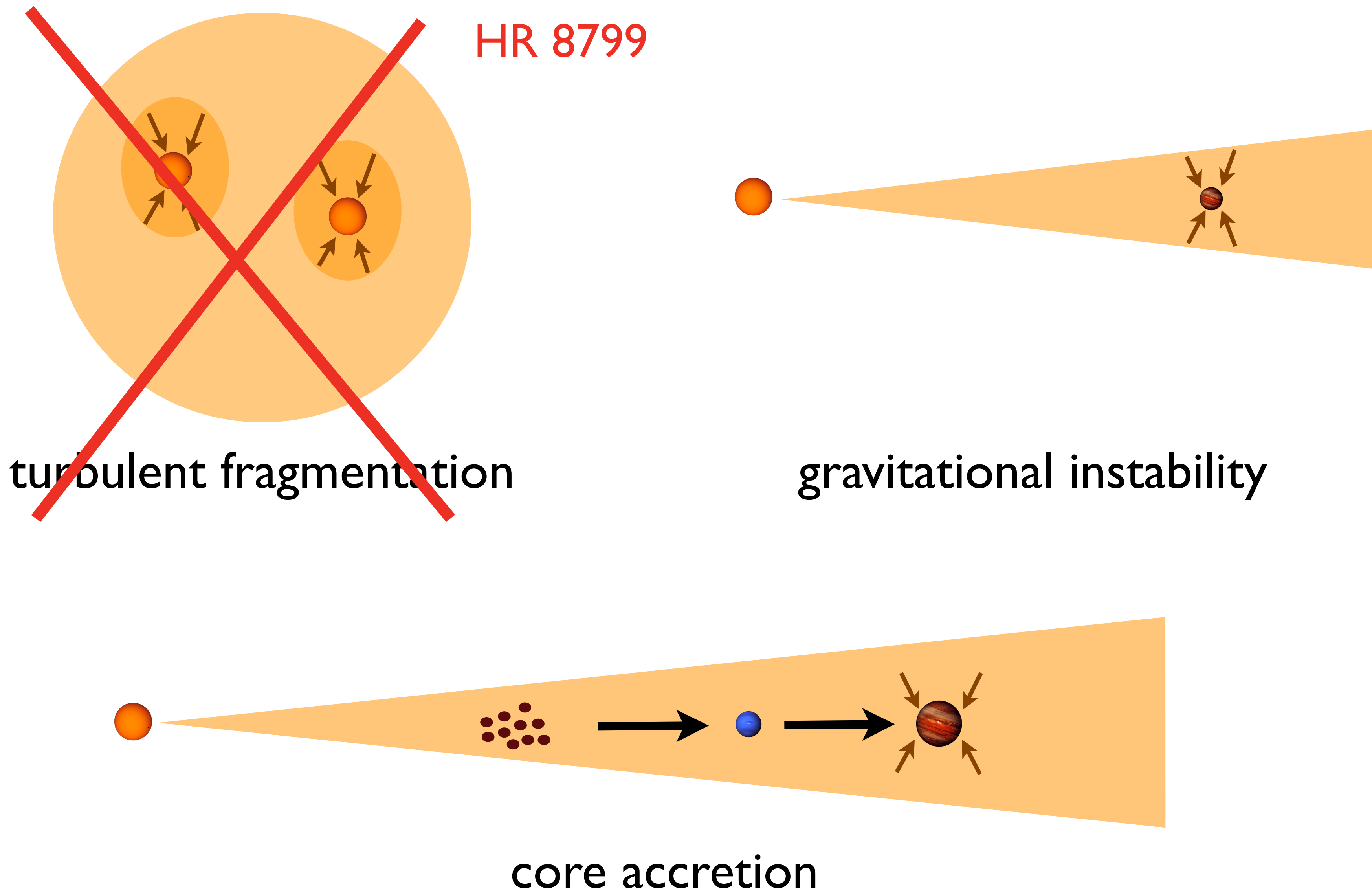


gravitational instability

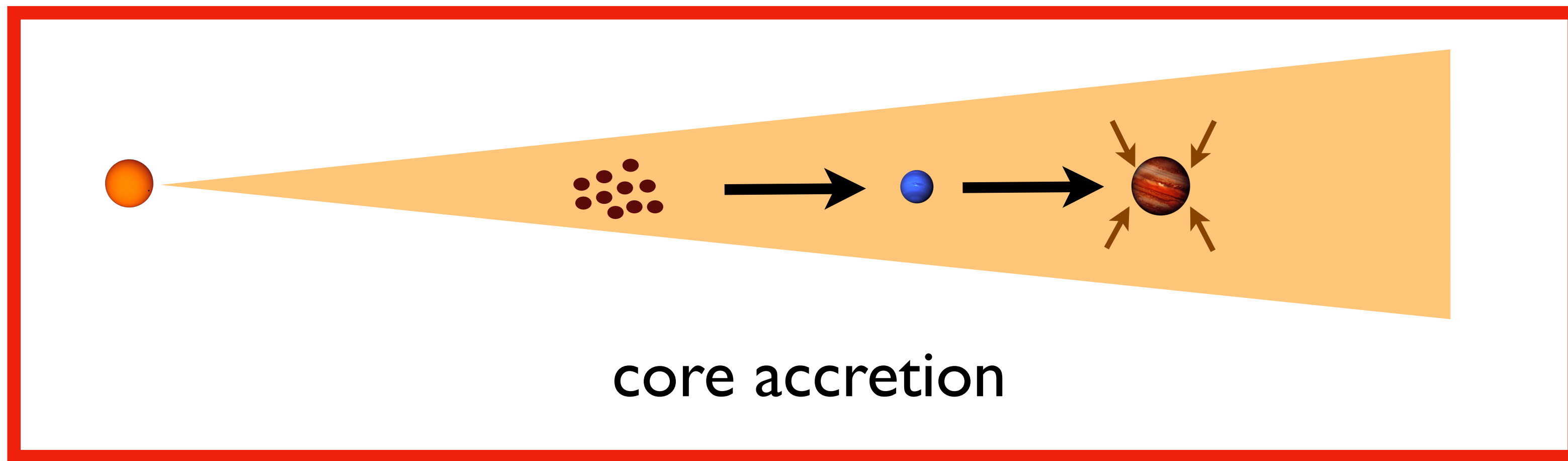
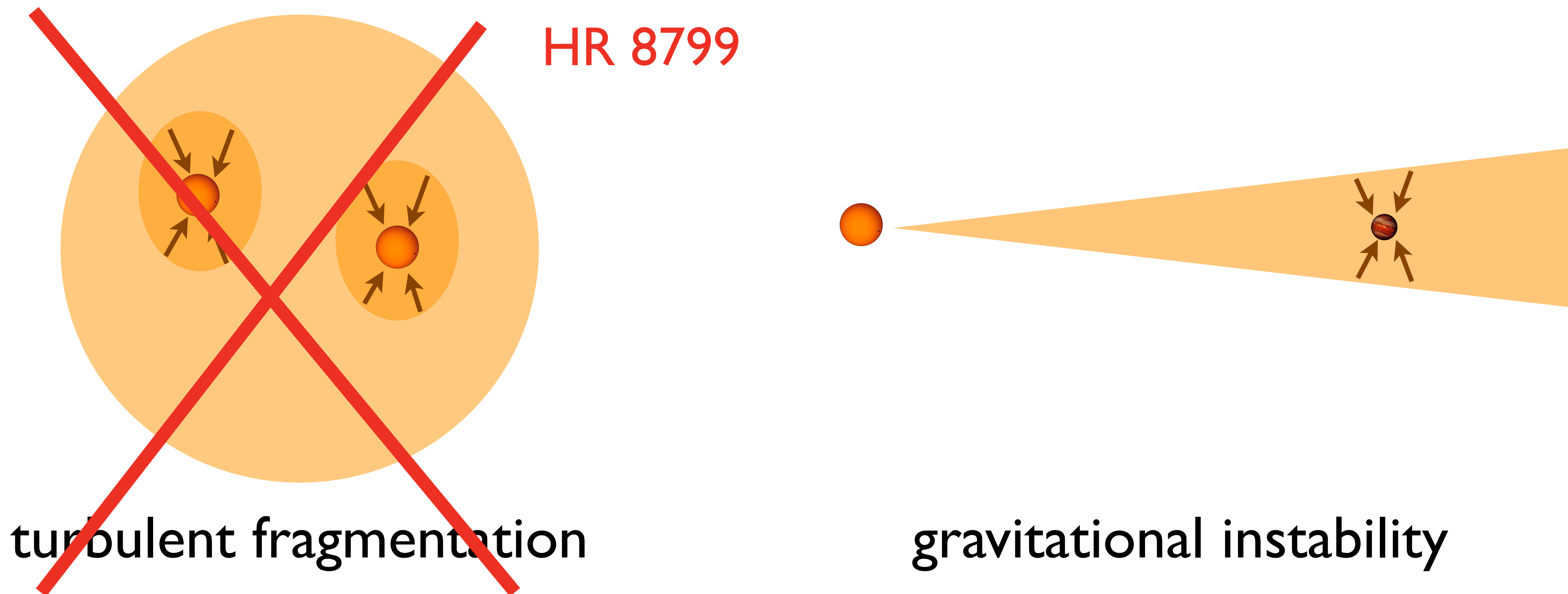


core accretion

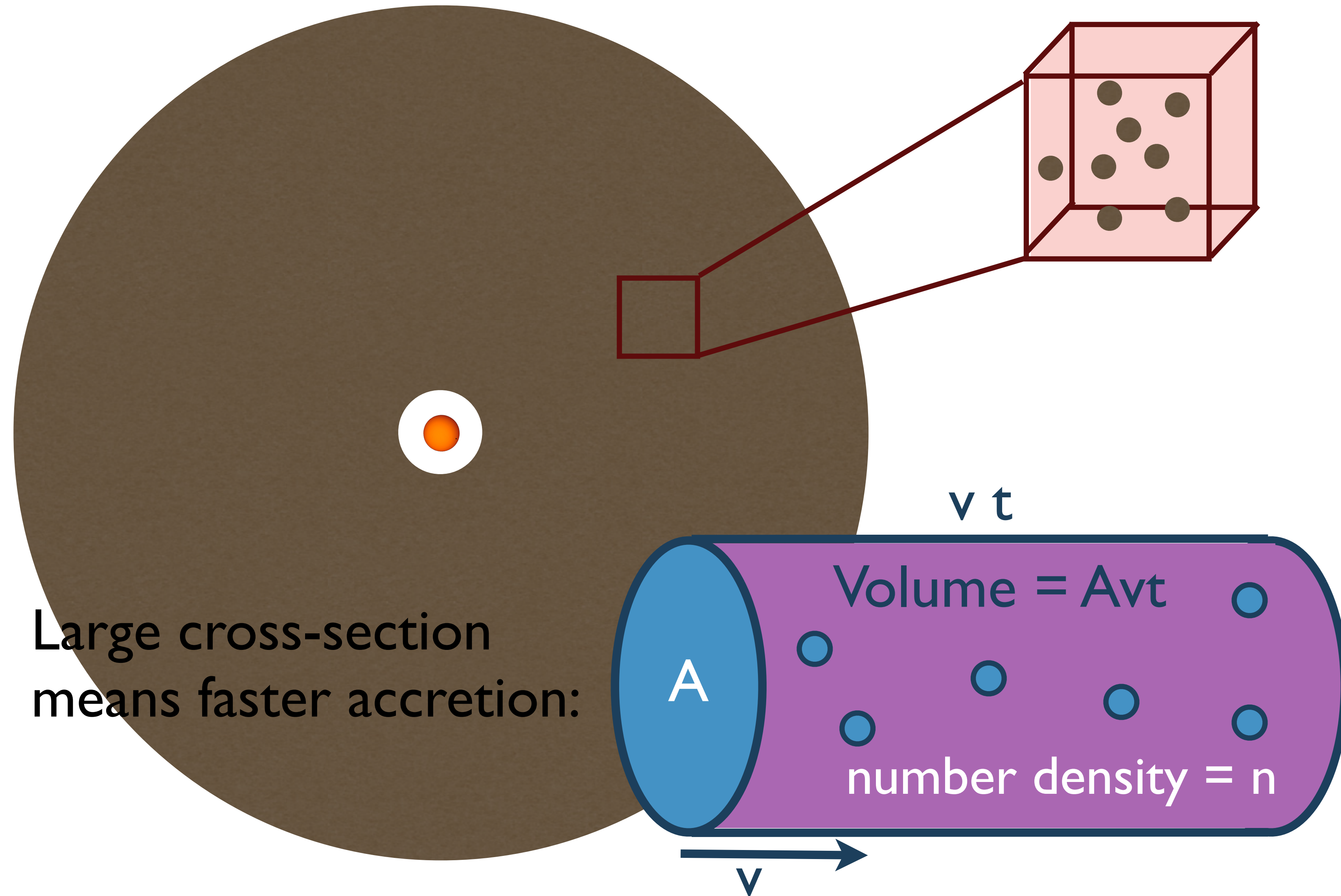
Three ways to form giant companions



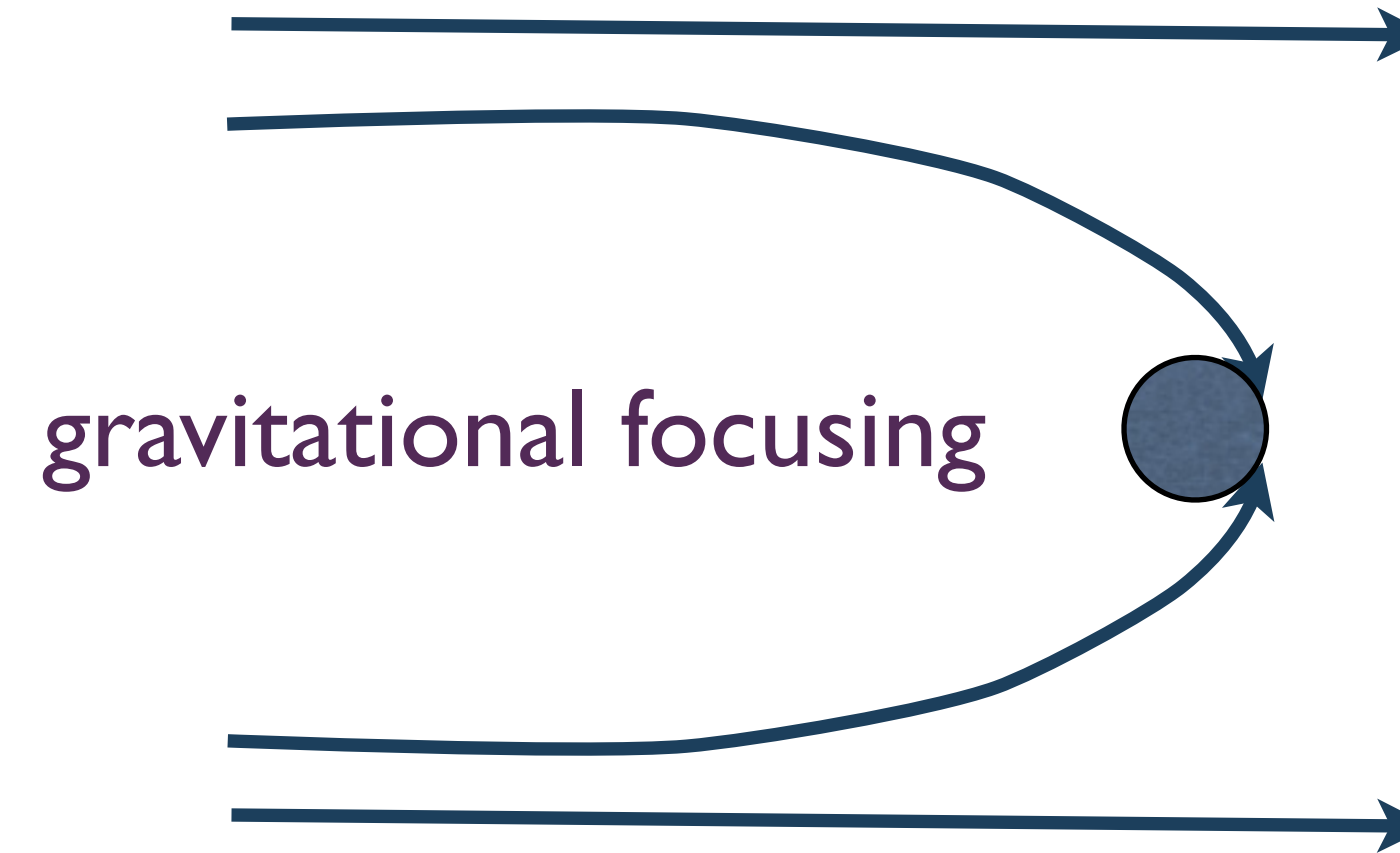
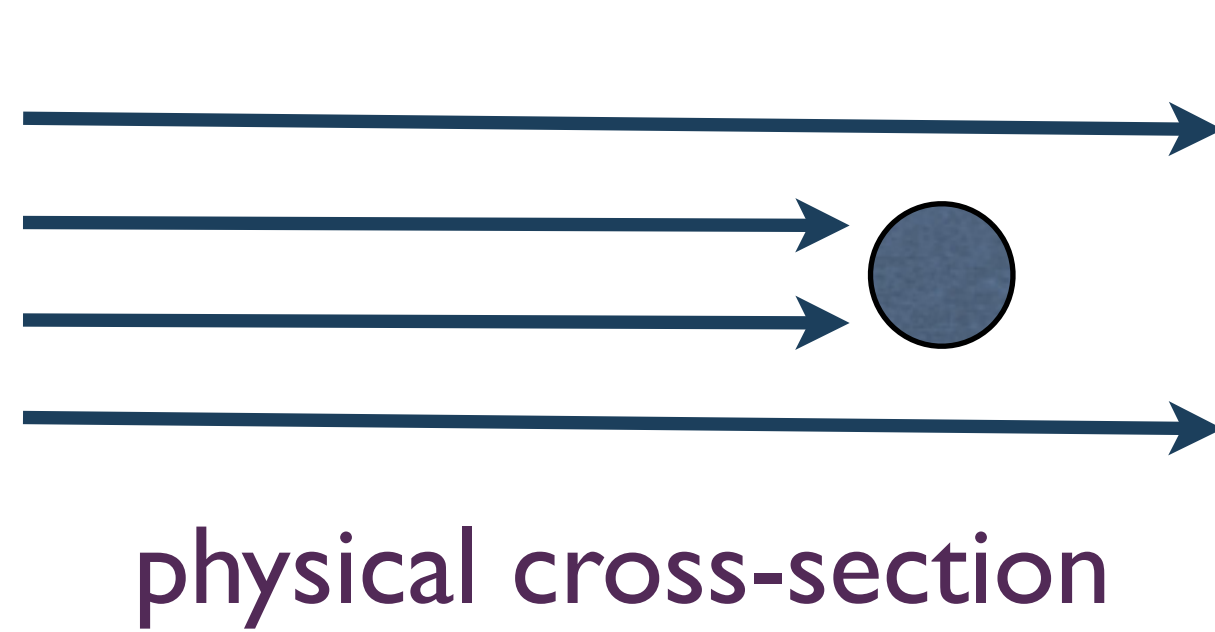
Three ways to form giant companions



Core accretion: Need to grow a massive solid core through collisions
Longstanding problem at wide separation: The last doubling time.



Cross-section regimes:



Final stage of core growth too slow at distance of HR 8799 outer planet without gas-assisted capture

Pebble accretion:

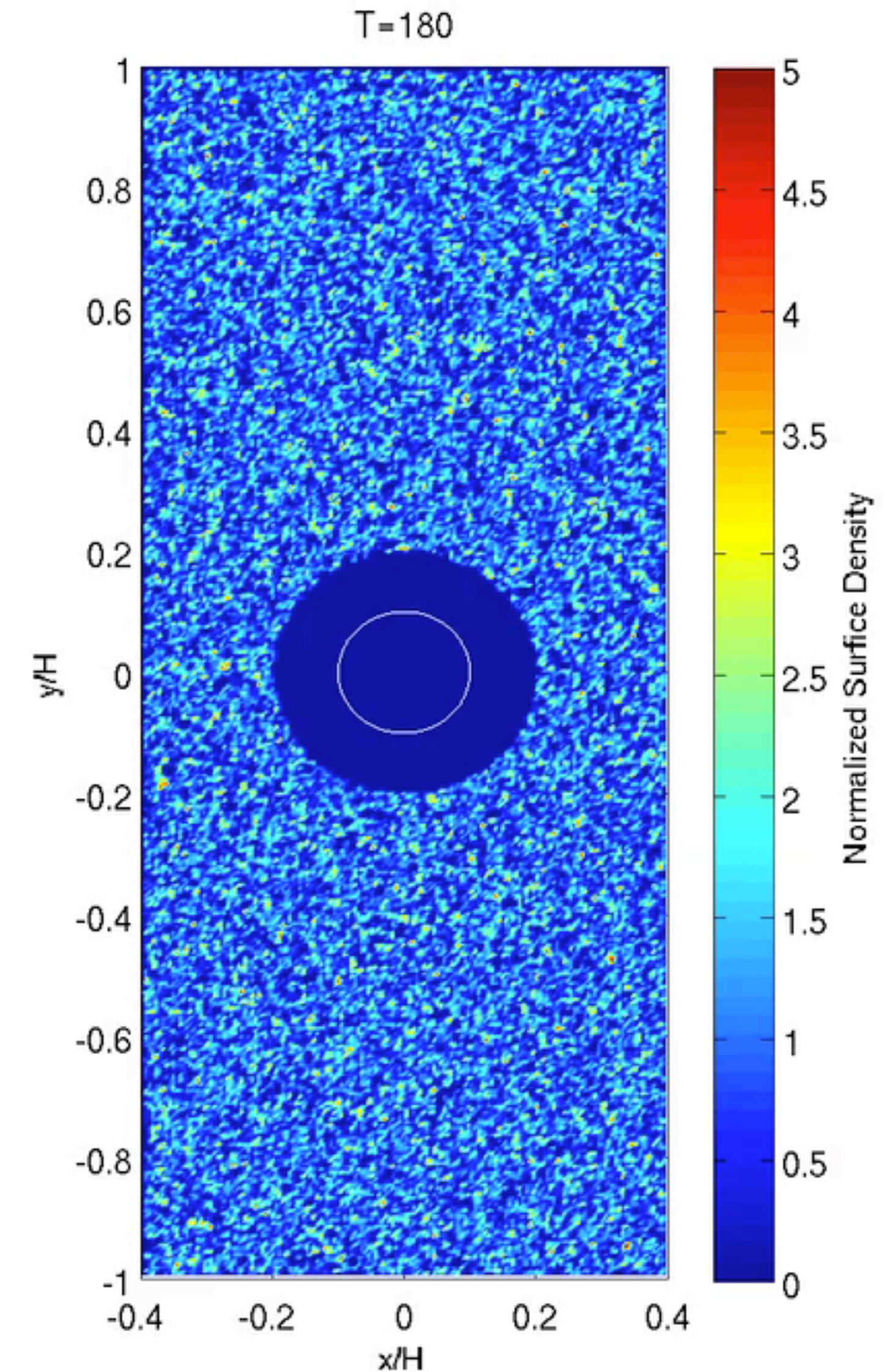
Capture by gas drag allows fast growth of planets


Sun

region of
gravitational
dominance

growing solid planet

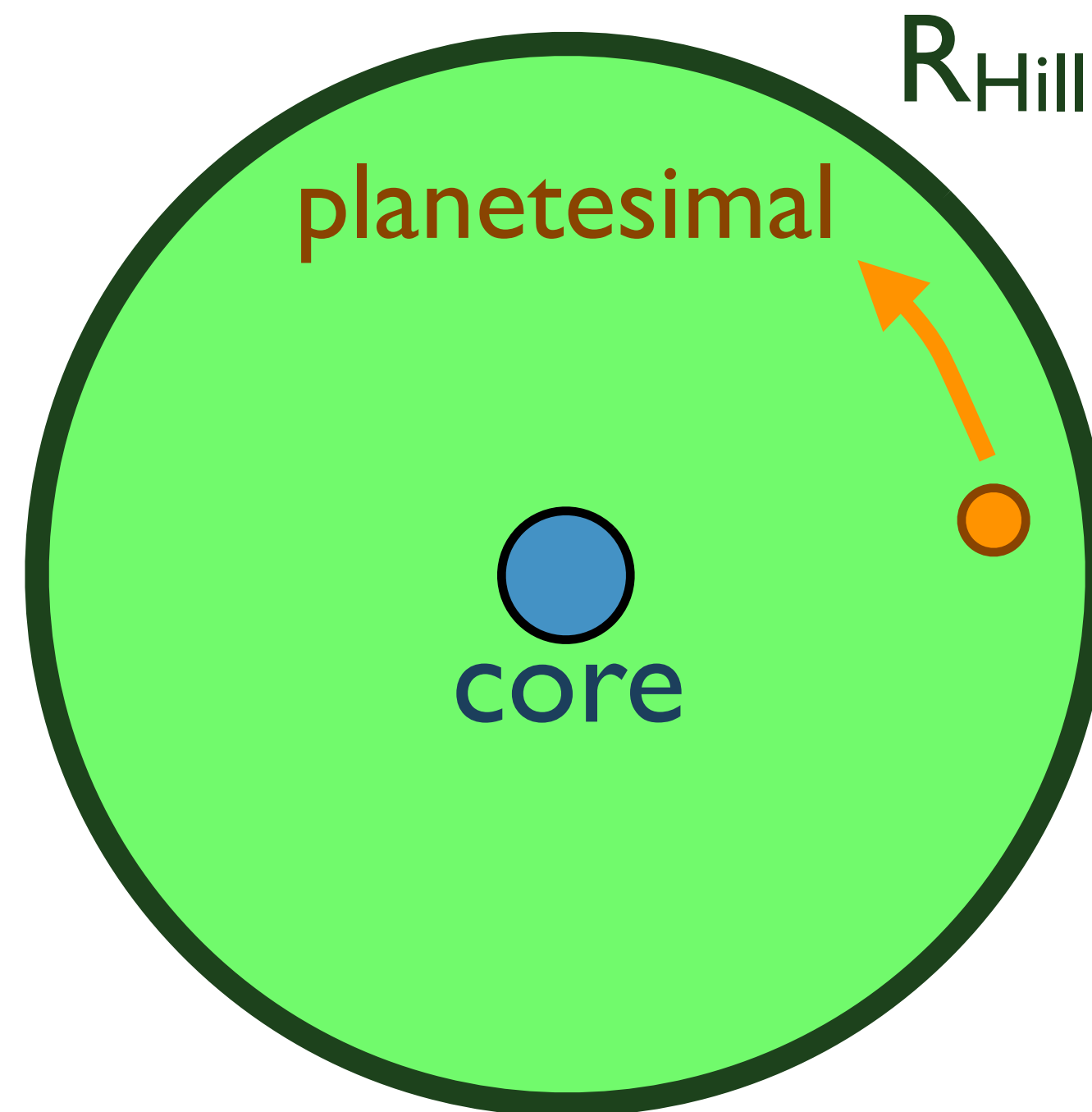
planetesimal



Ormel & Klahr 2010, Lambrechts & Johansen 2012,
Rosenthal et al. 2018, Xu et al. 2017

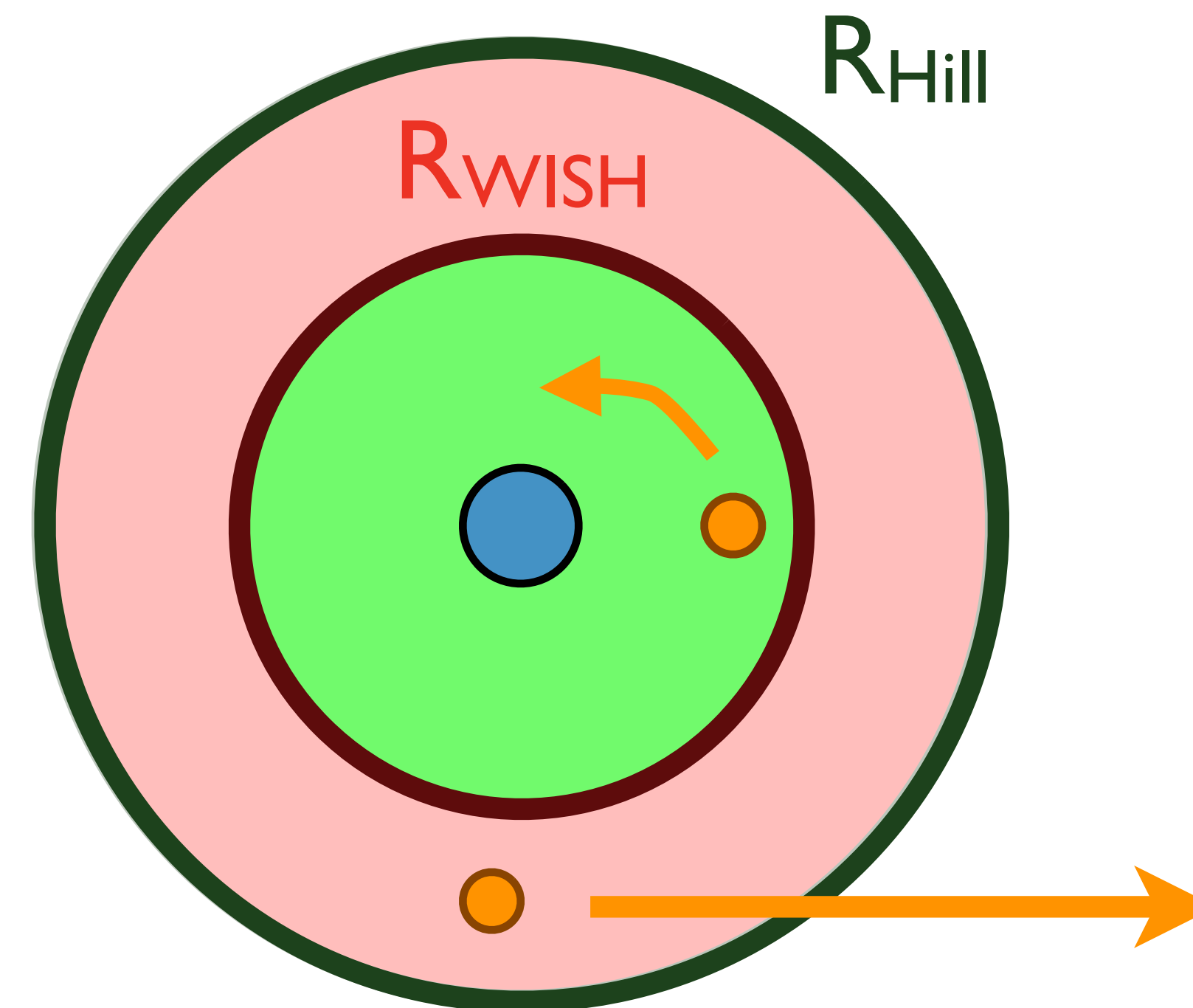
No gas:

Satellites can orbit
within the “Hill radius”



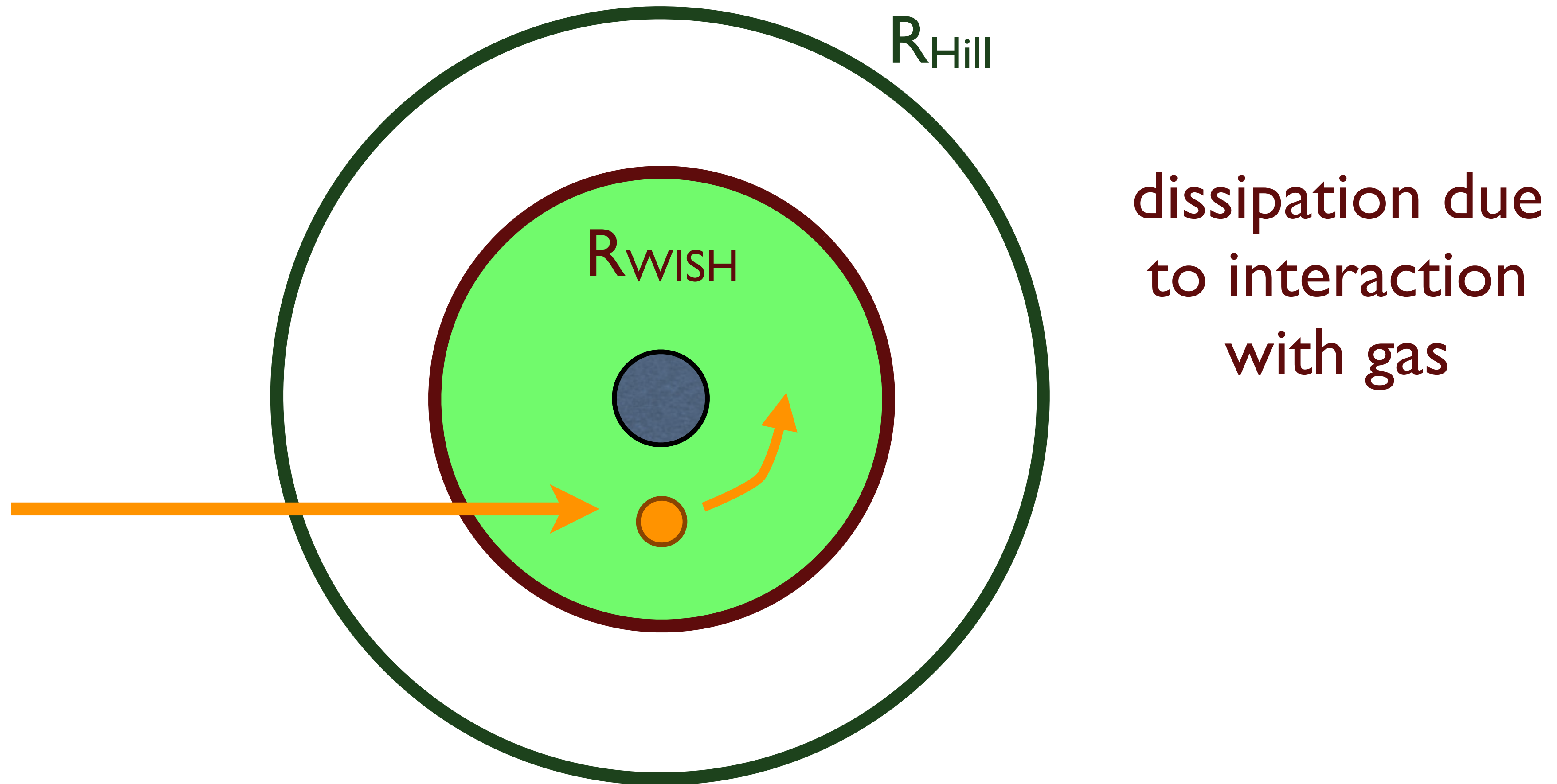
Gas:

Wind Shearing (WISH)



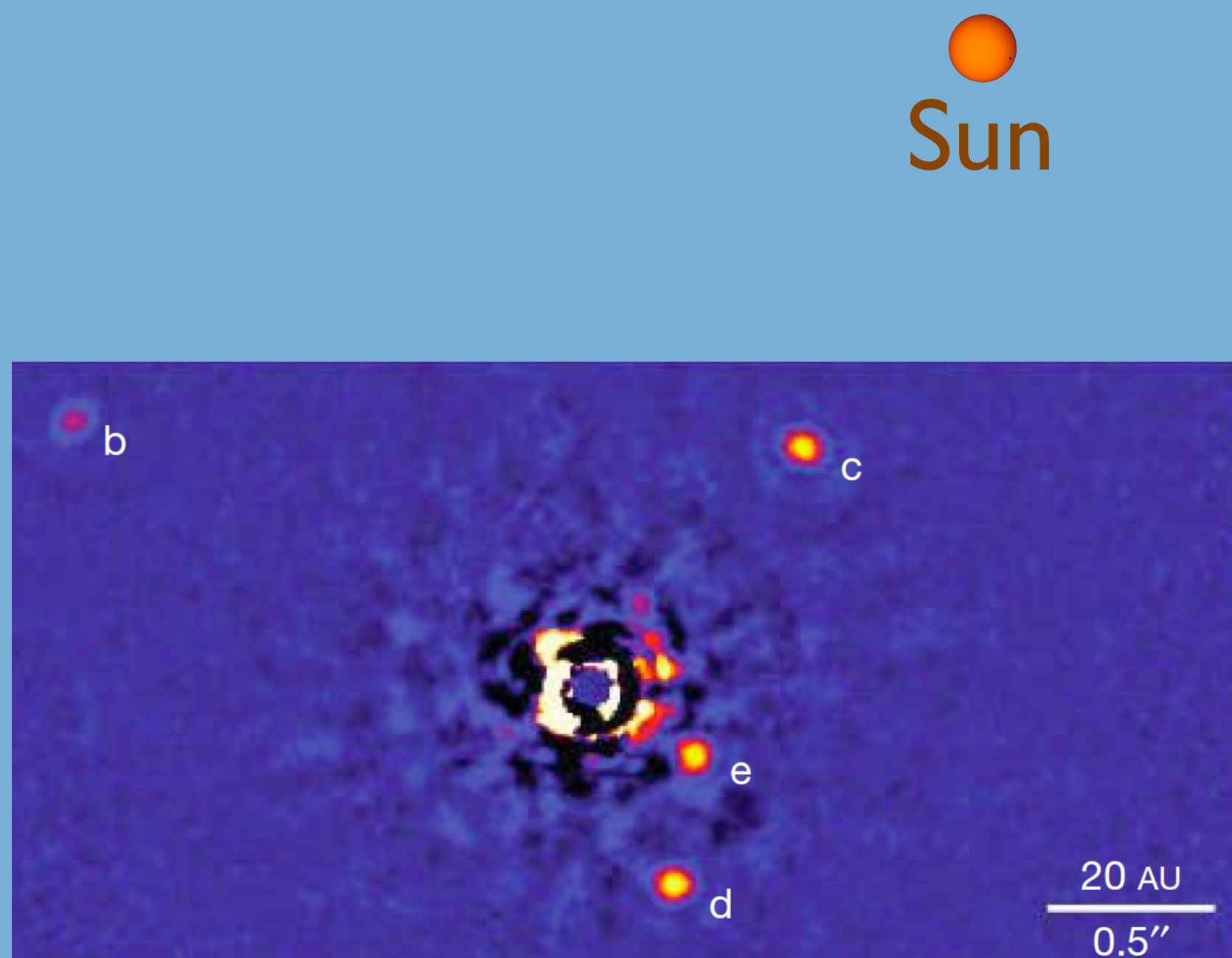
gas drag pulls off small
particles more effectively

“Binary Capture”



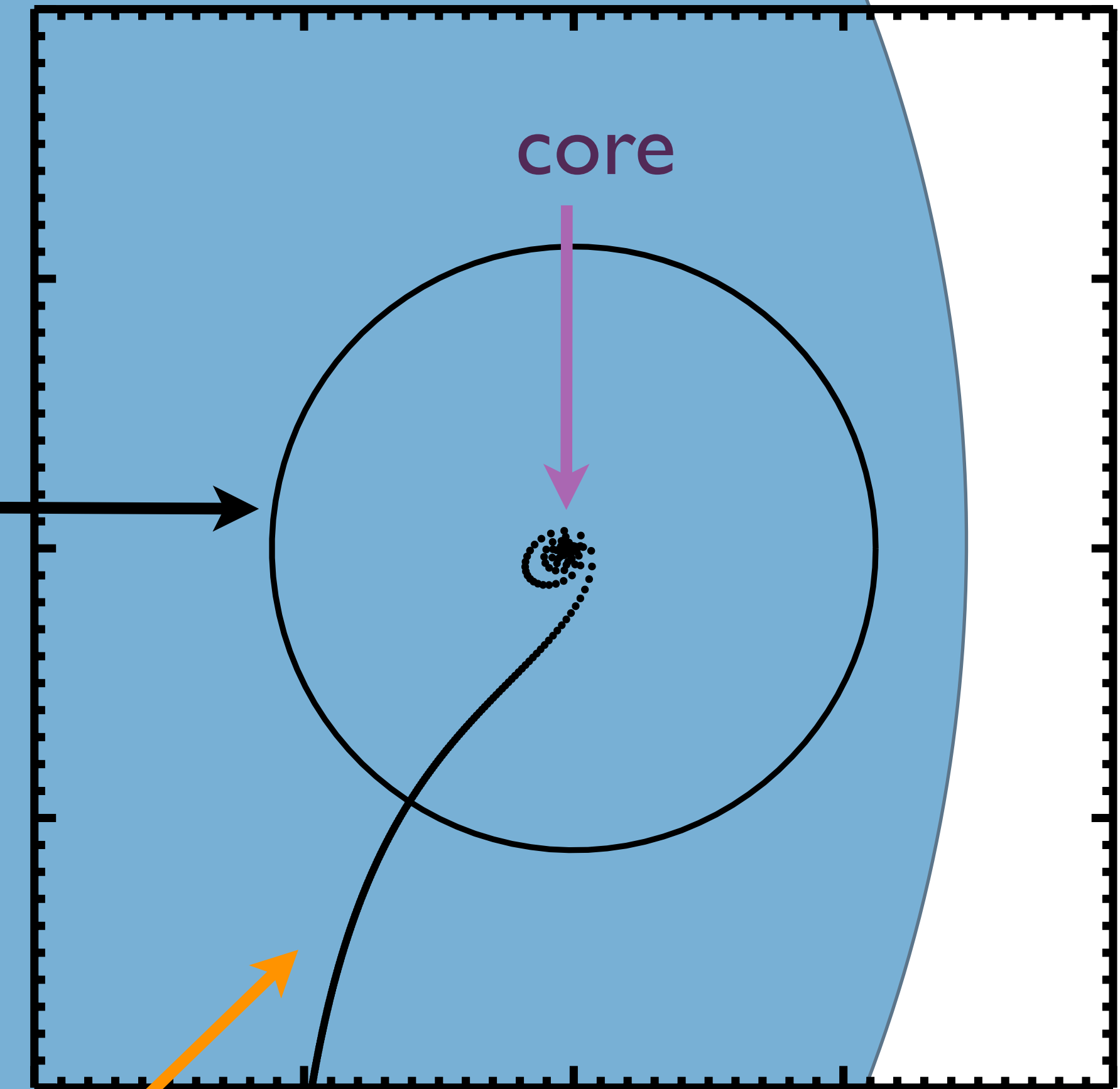
Ormel & Klahr 2010;
Lambrechts & Johansen 2012;
Rosenthal, Murray-Clay, Perets, & Wolansky 2018

Pebble accretion makes core accretion feasible at wide separations



increased
cross-section

planetesimal

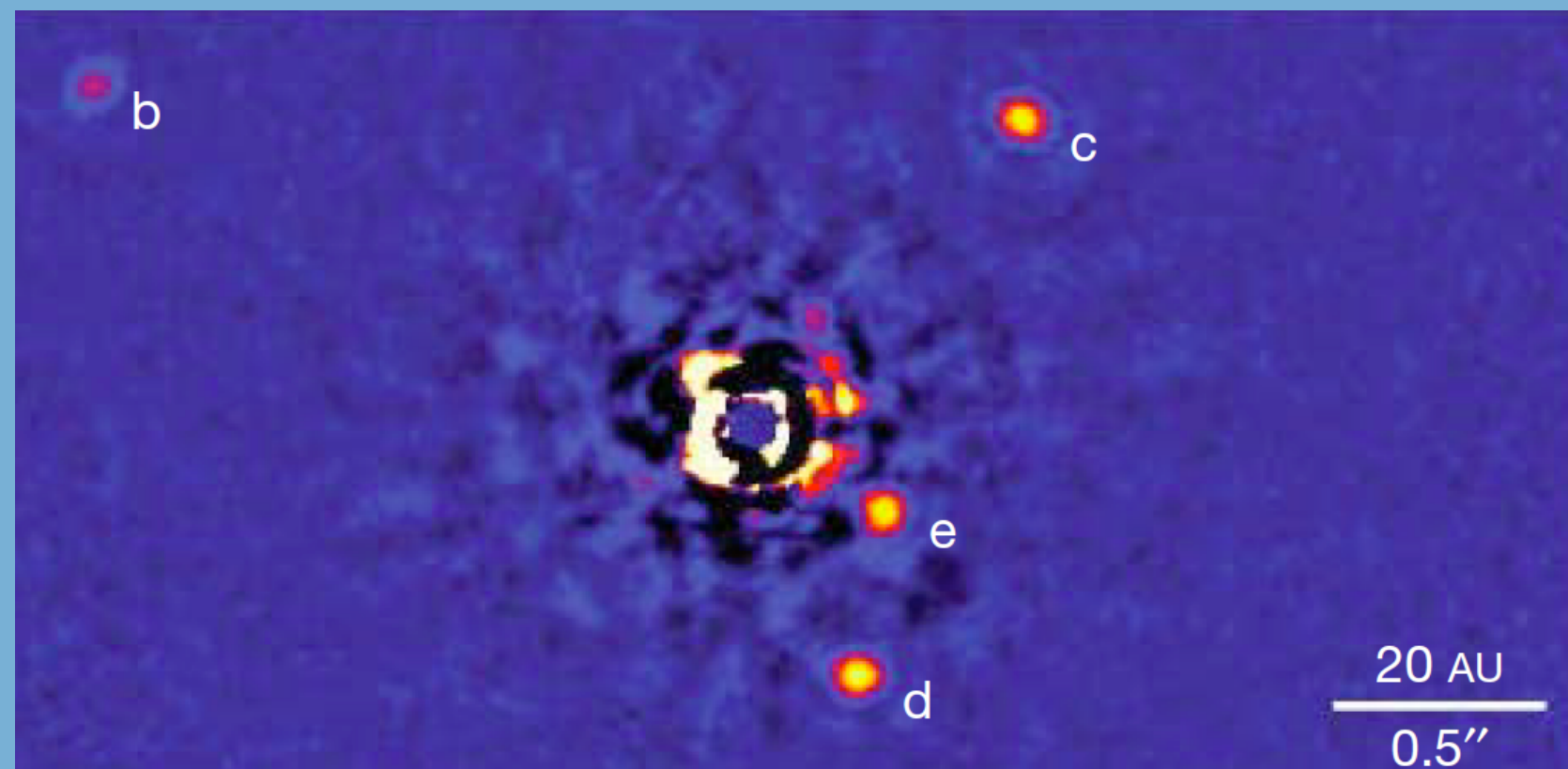


Ormel & Klahr 2010,
Lambrechts & Johansen 2012
Rosenthal, Murray-Clay, Perets,
& Wolansky 2018

Pebble accretion makes core accretion feasible at wide separations

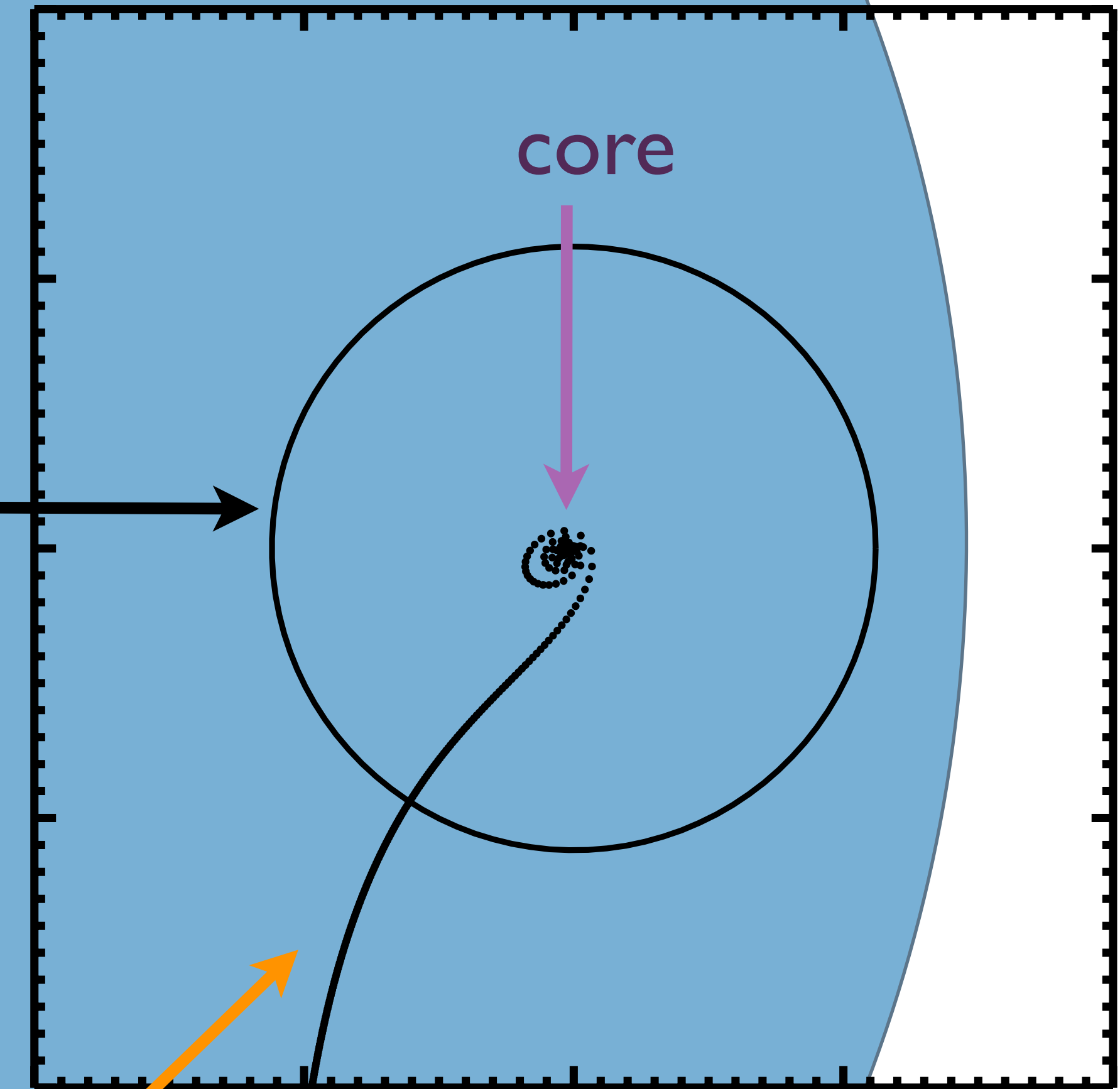
The same gas causes pebbles to drift through the disk (more later)

Sun



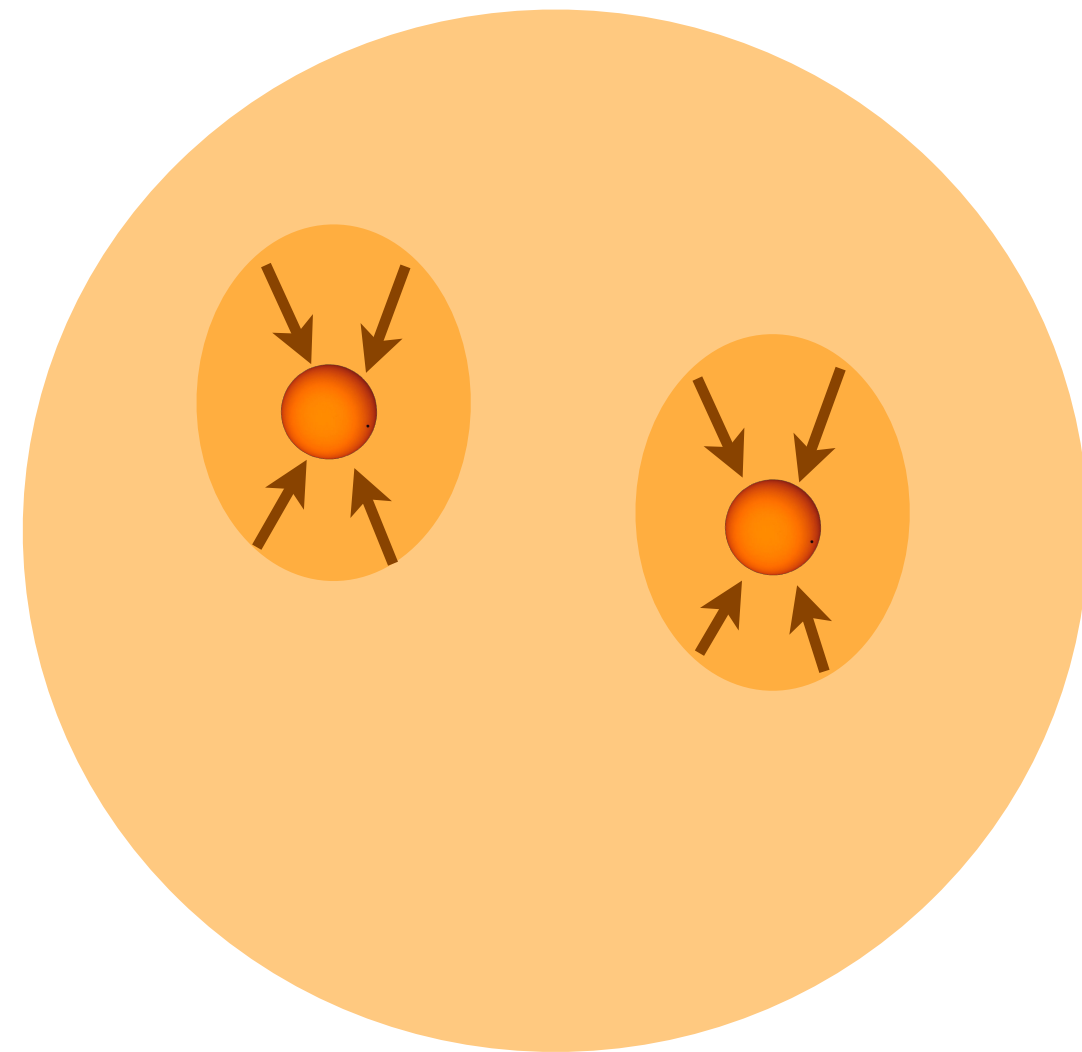
increased cross-section

planetesimal

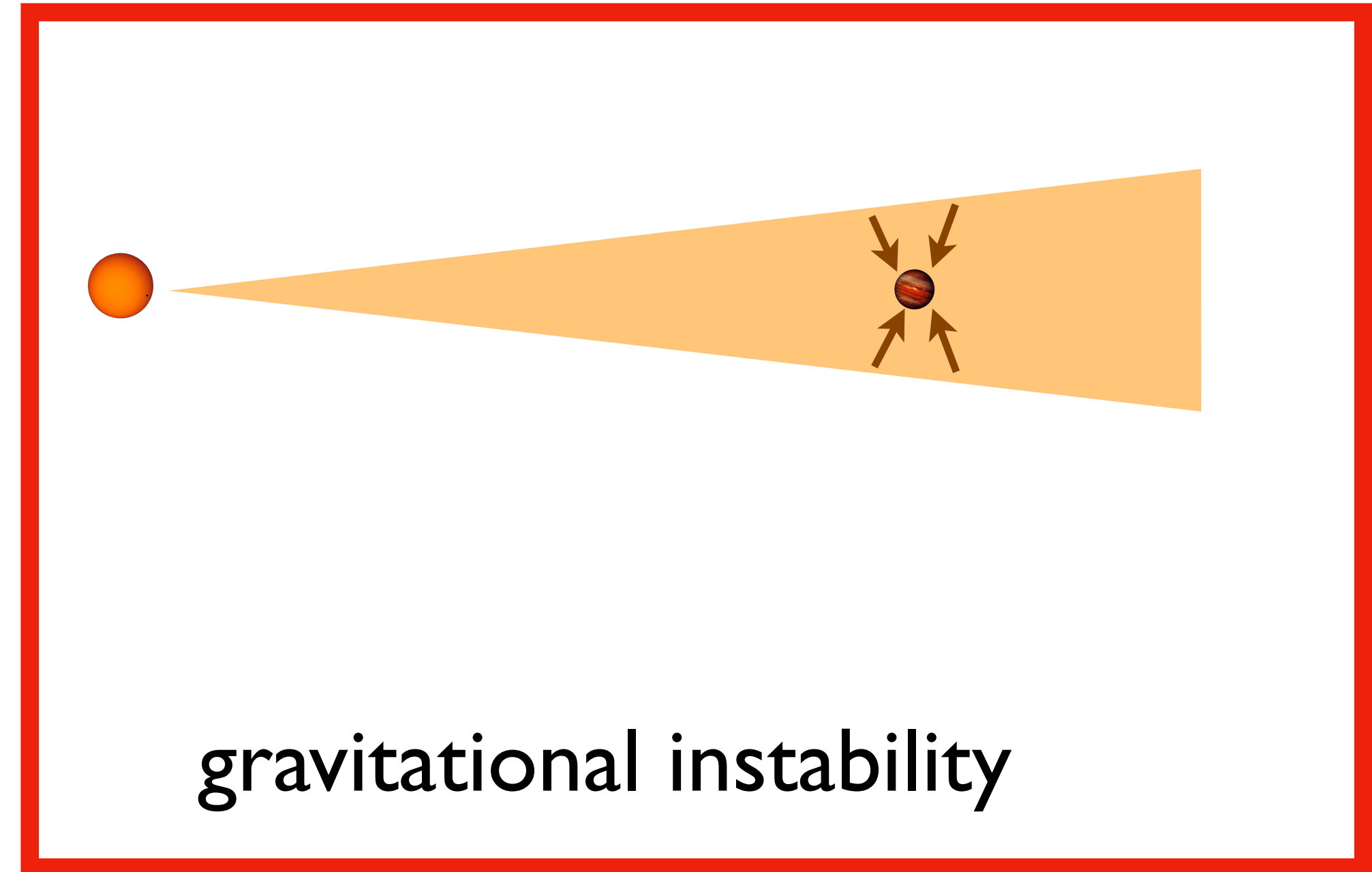


Ormel & Klahr 2010,
Lambrechts & Johansen 2012
Rosenthal, Murray-Clay, Perets,
& Wolansky 2018

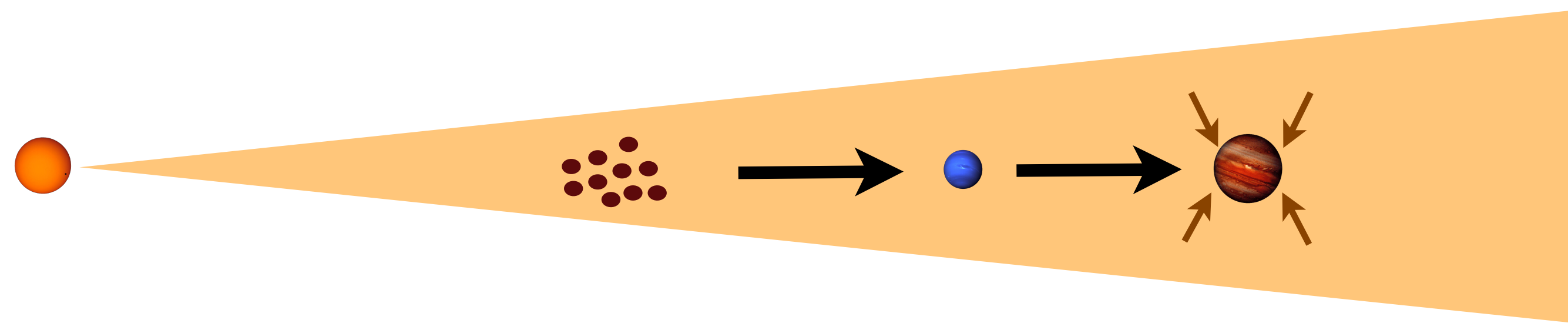
Three ways to form companions



turbulent fragmentation

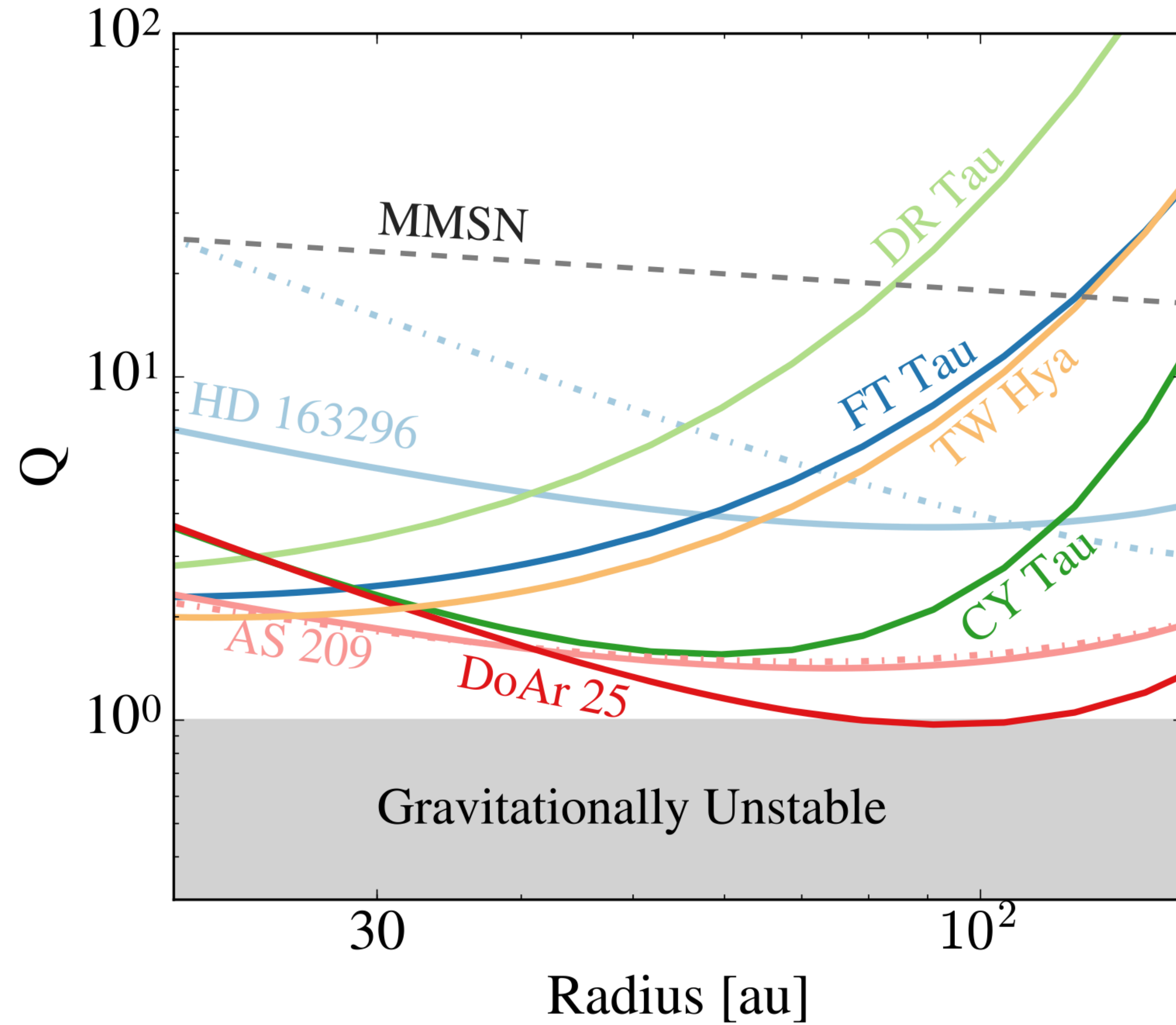


gravitational instability

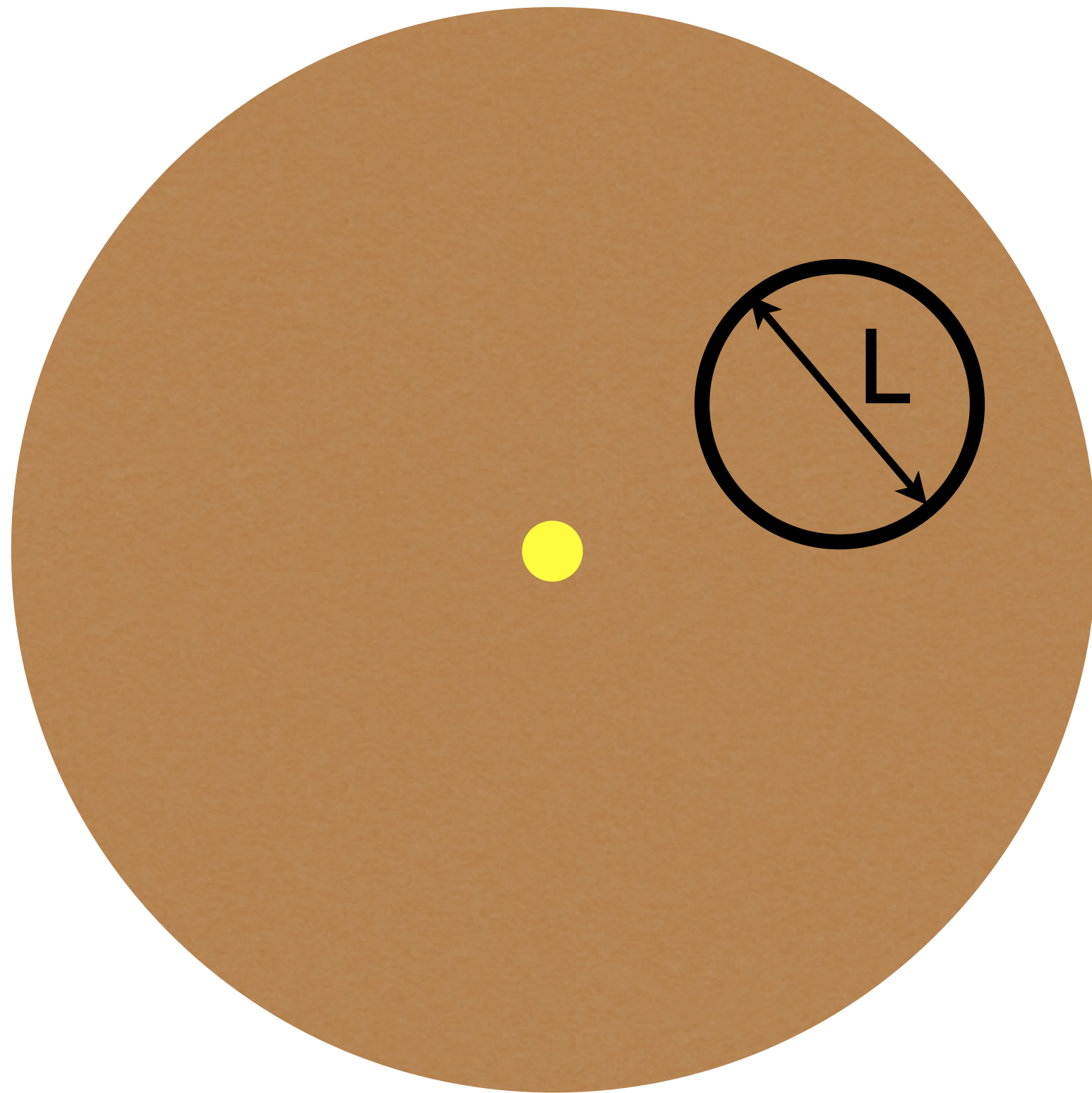


core accretion

Several techniques
are revising disk
masses upward



Gravitational instability



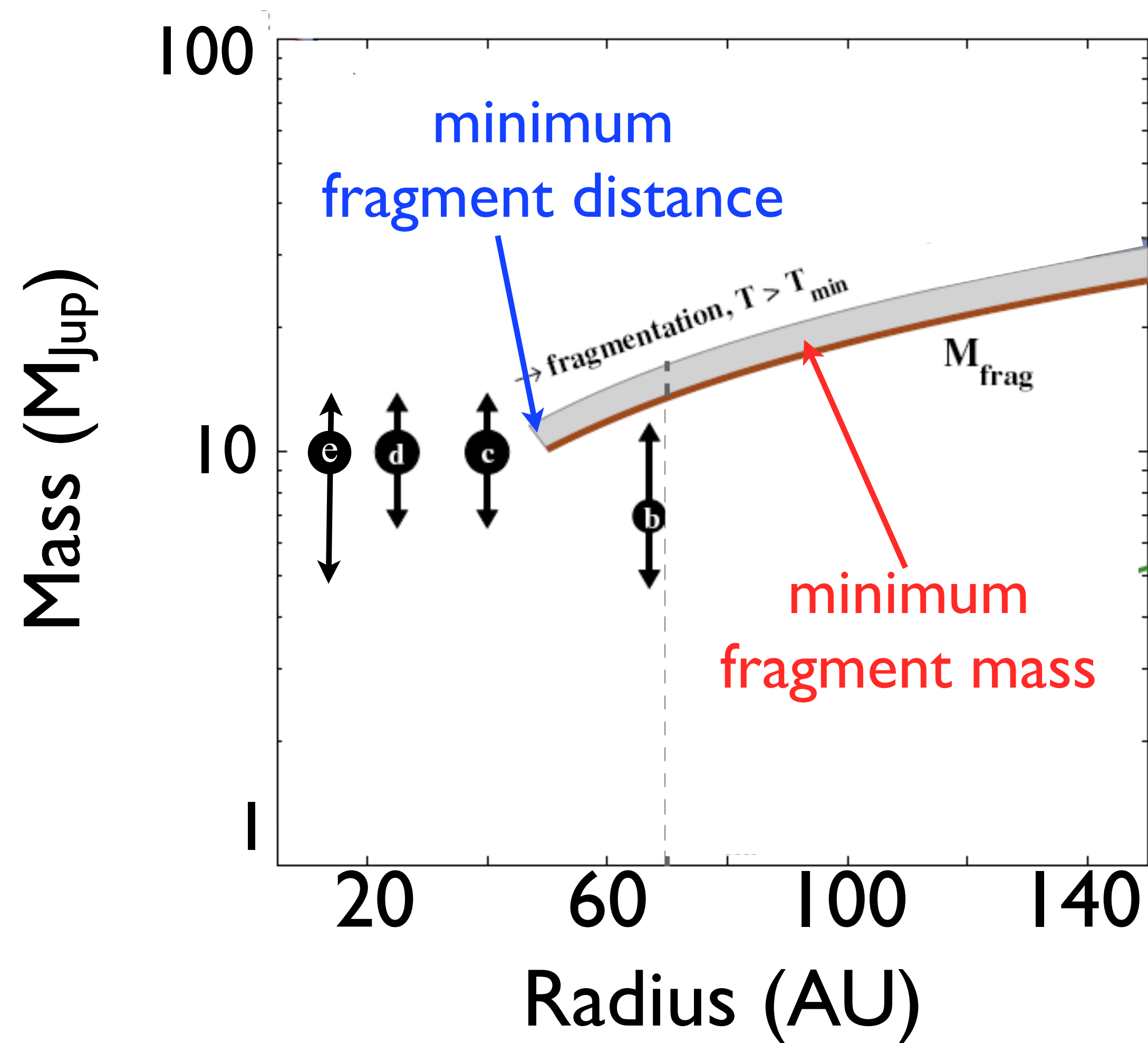
self-gravity overcomes
pressure and Keplerian shear

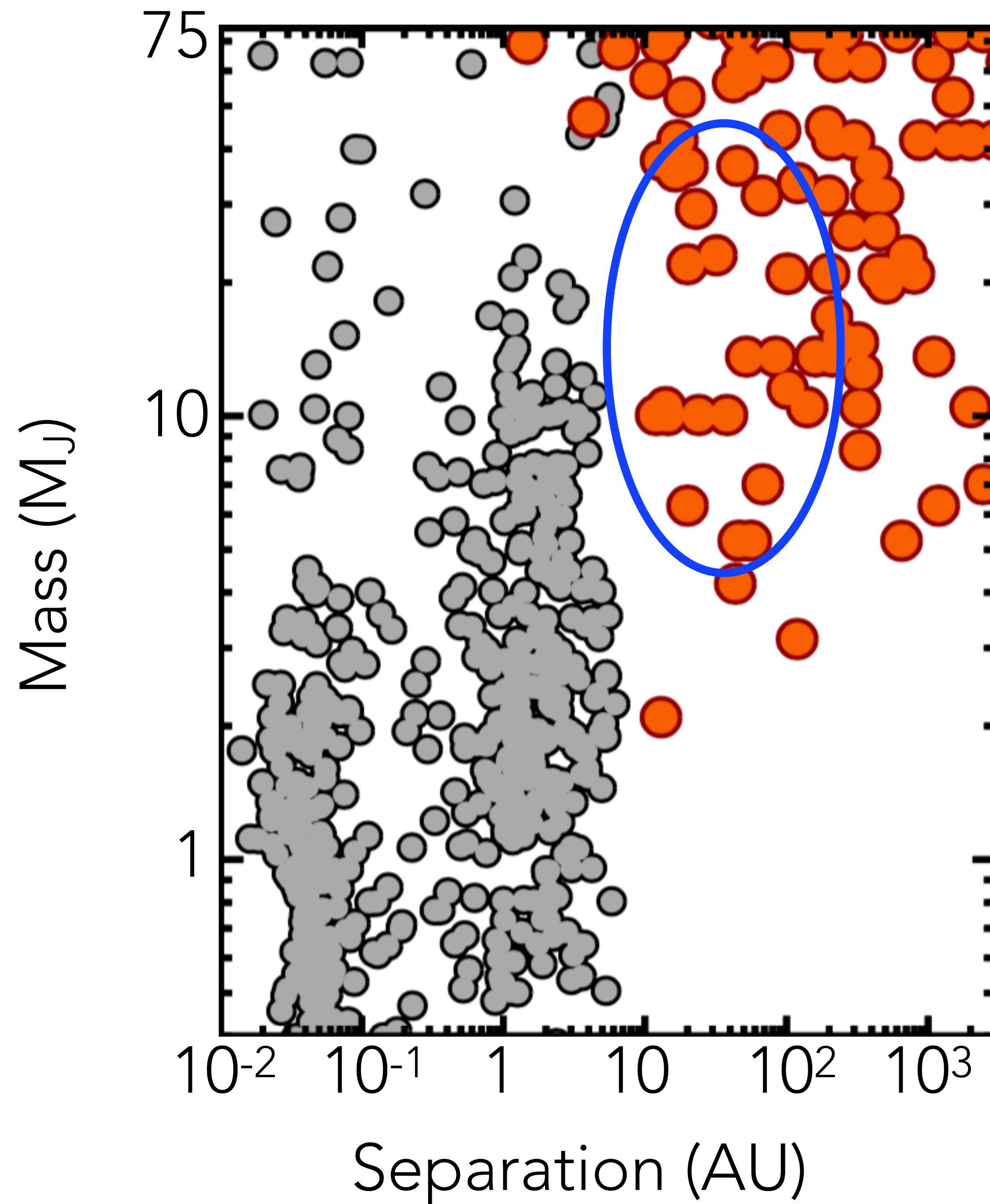
most unstable scale: $L \sim H$

$$M_{frag} \sim \Sigma (2\pi H)^2 \sim 4\pi \left(\frac{H}{a} \right)^3 M_*$$

Gravitational Instability?

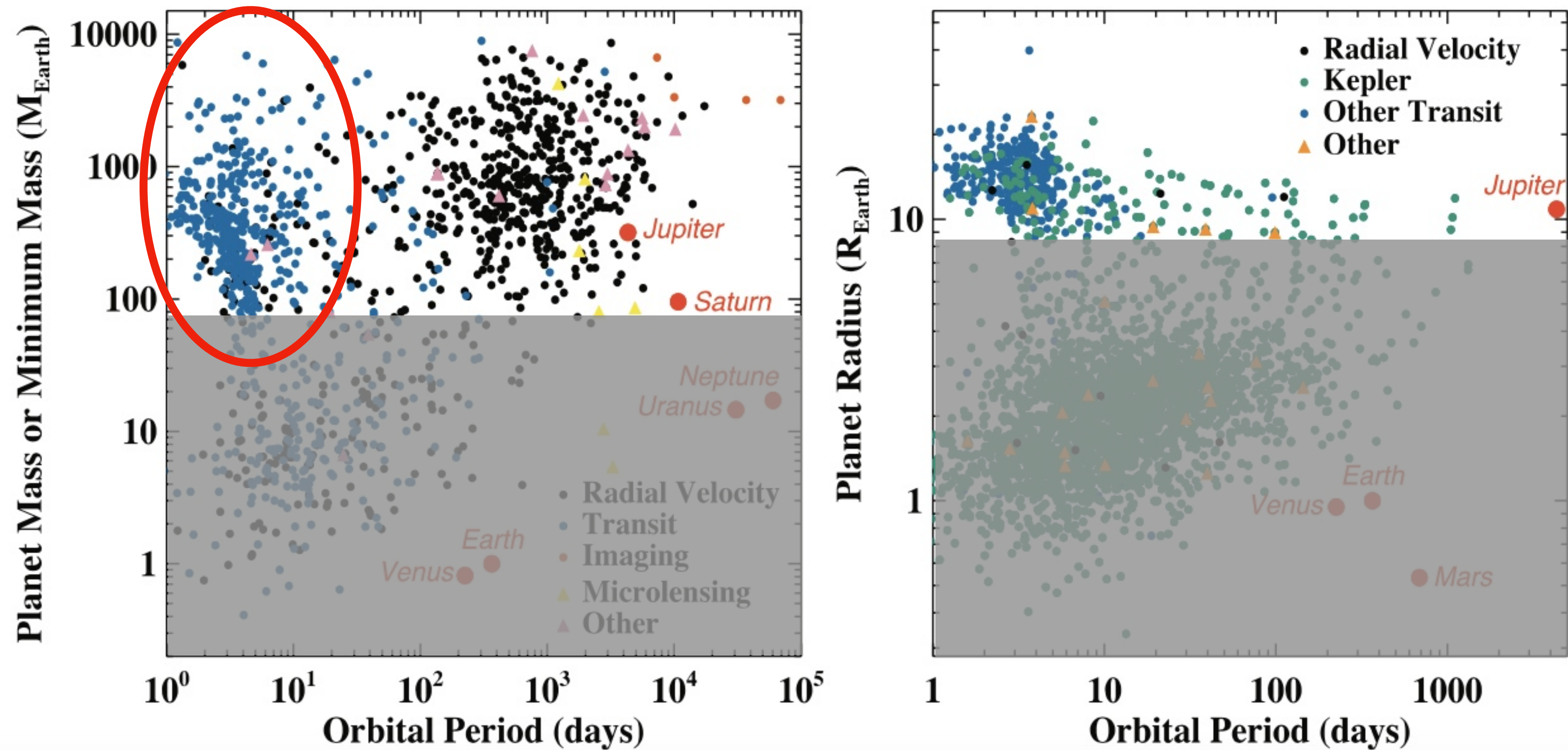
HR 8799 planets cannot grow after fragmentation and they must migrate in

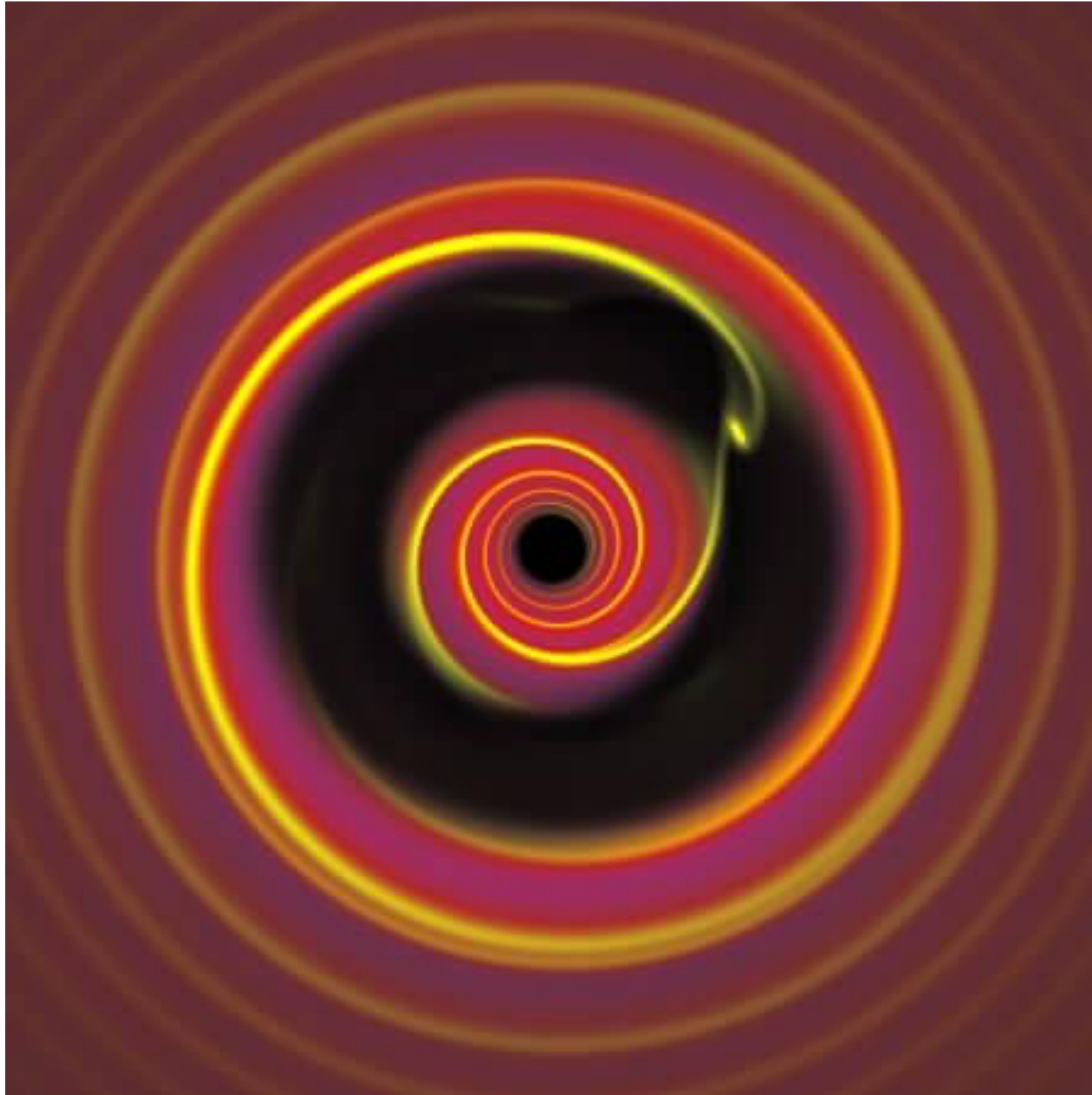




Could be
gravitational
instability
fragments

Hot Jupiters: too close





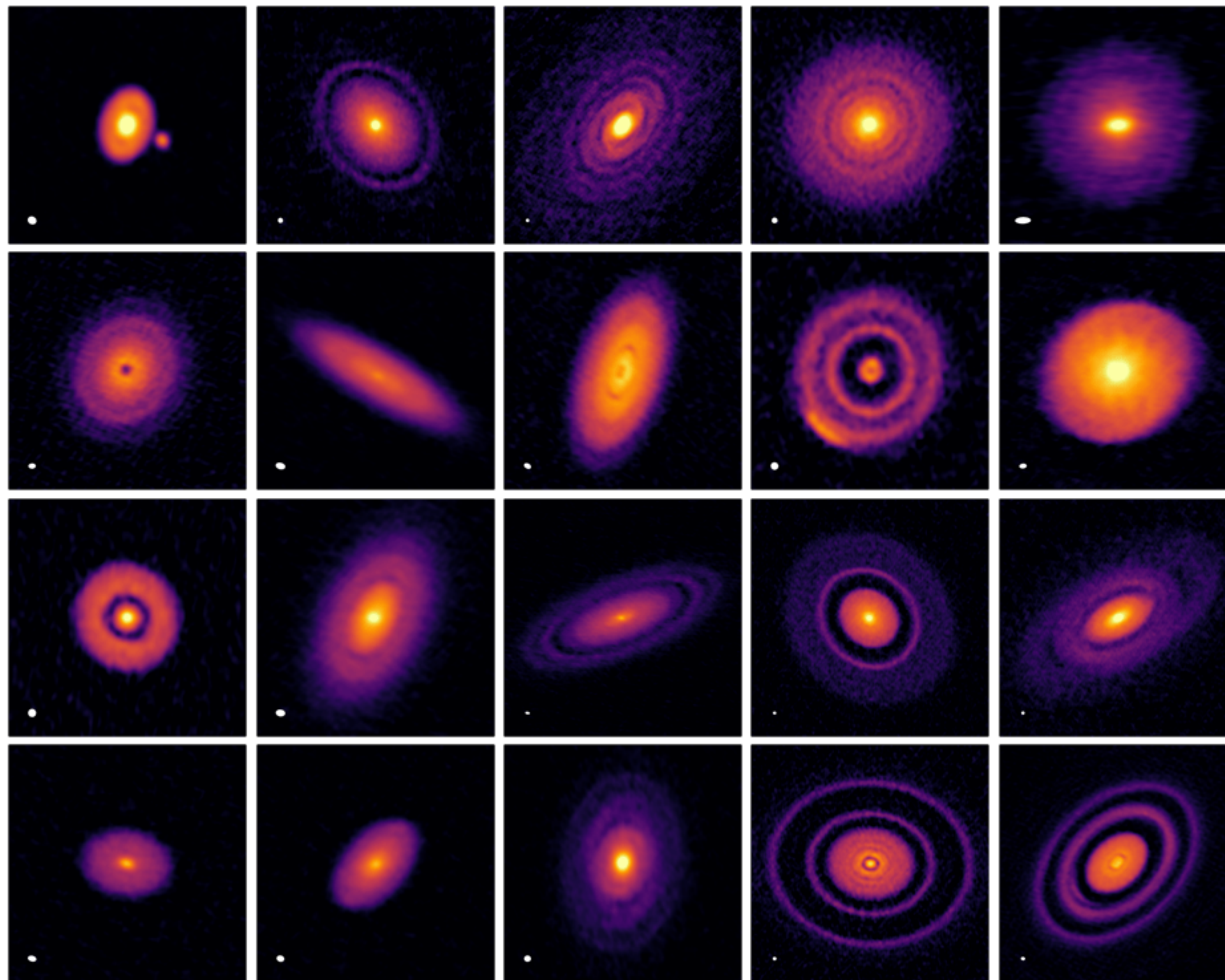
Disk Migration

May produce hot Jupiters

Outcomes very uncertain due to uncertainties in disk properties

Atacama Large Millimeter Array (ALMA)

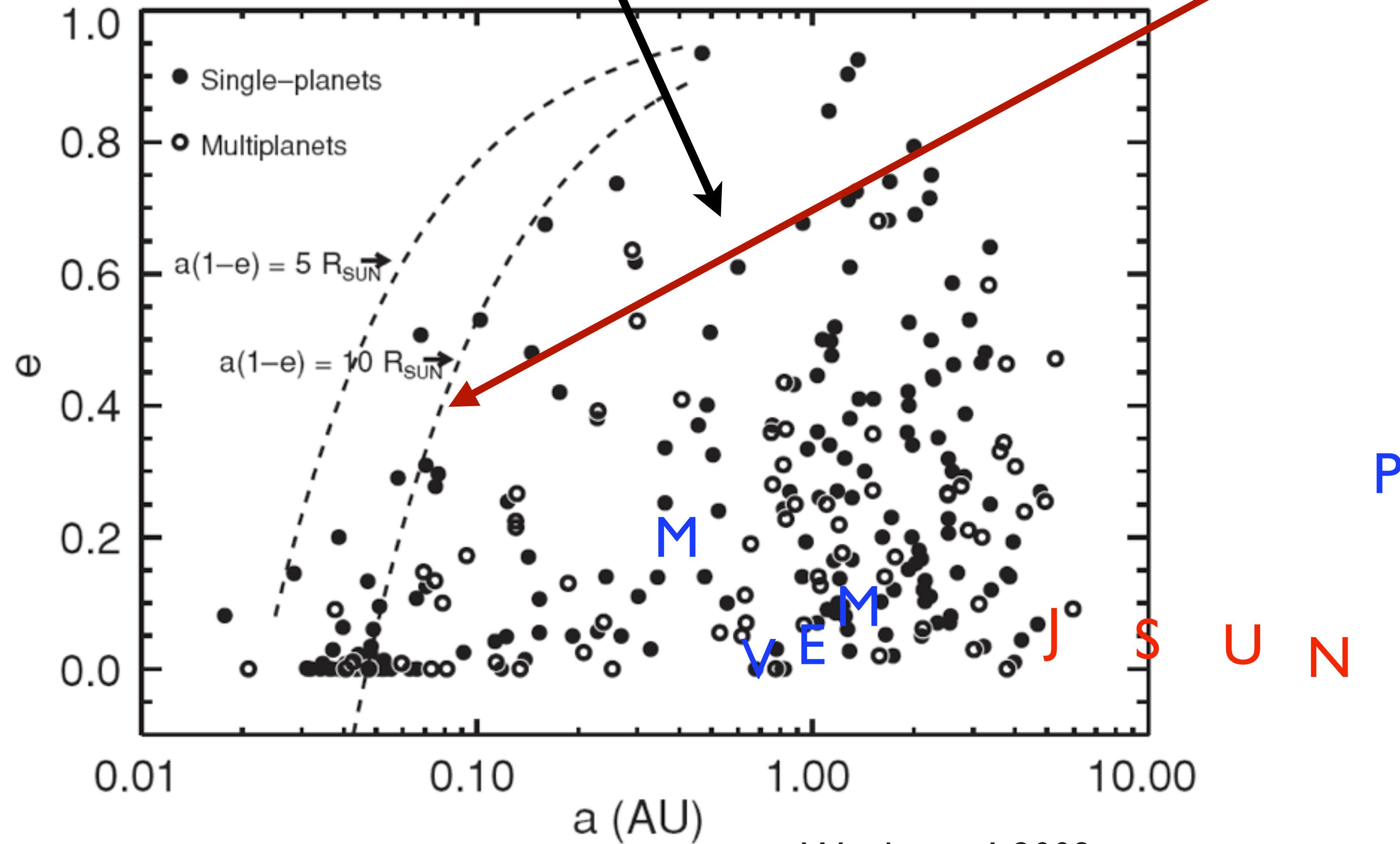




ALMA (DSHARP, Andrews+ 2018)

high-eccentricity giant planets

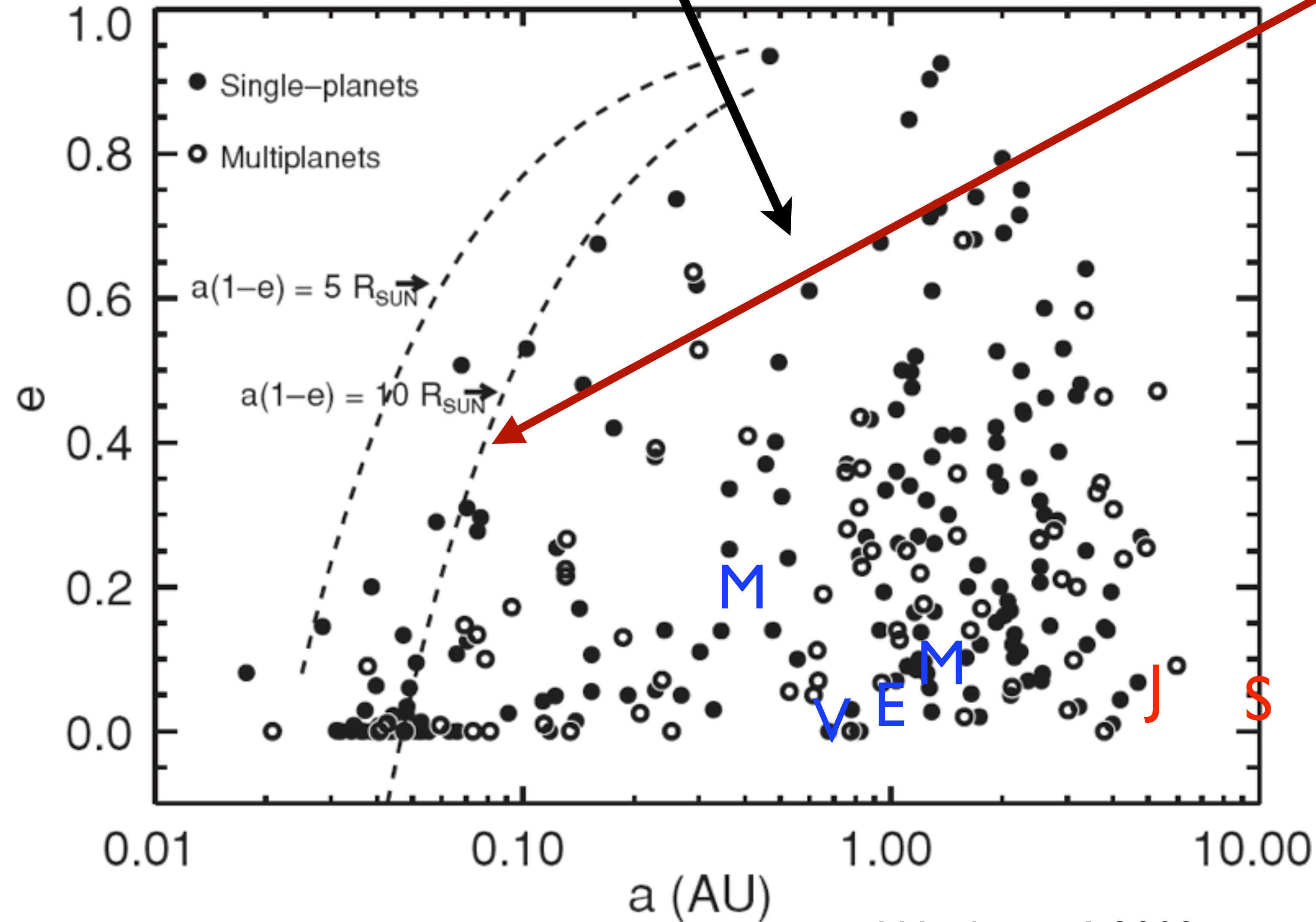
High eccentricity migration



Wright et al. 2009

high-eccentricity giant planets

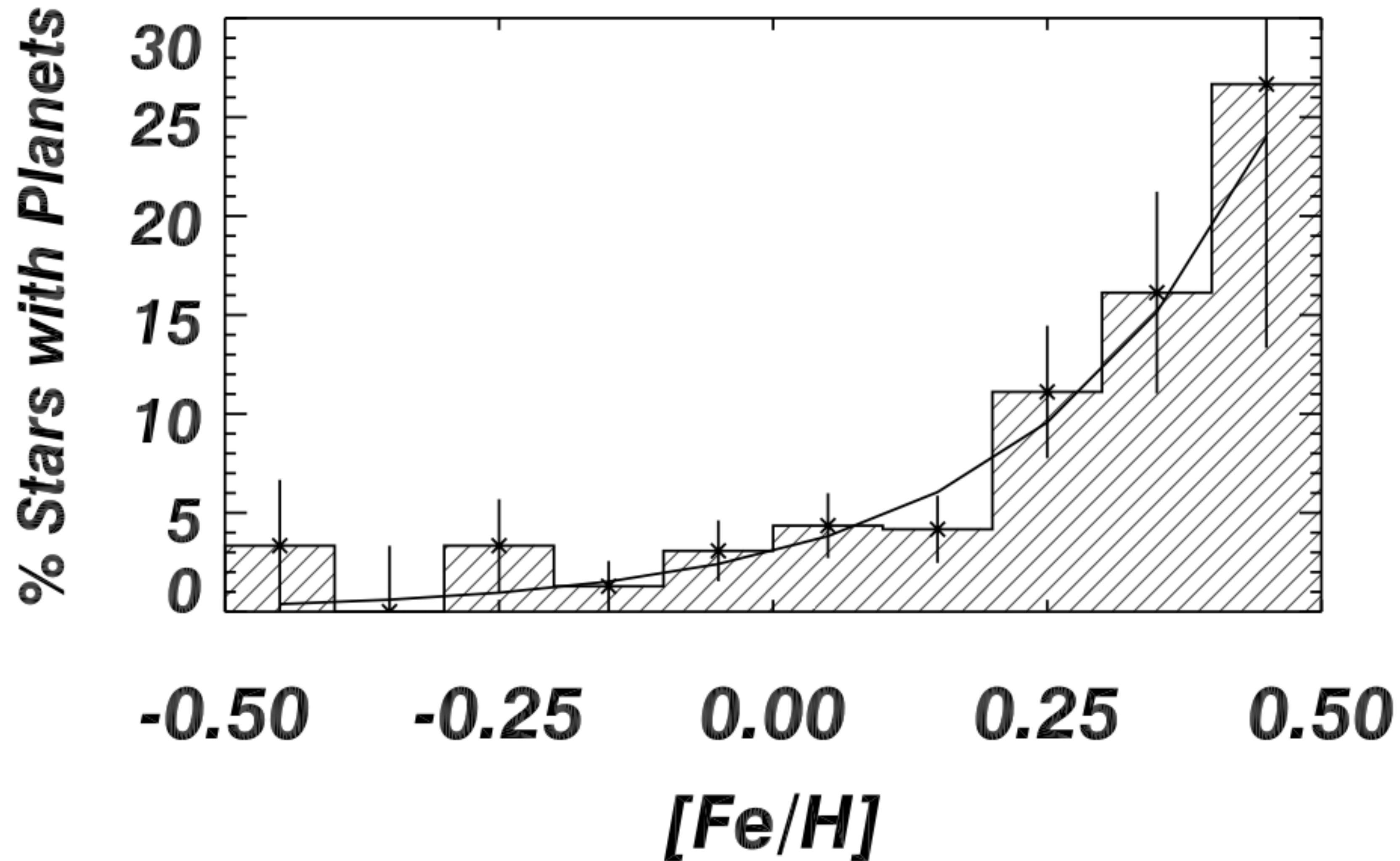
High eccentricity migration



- **Secular chaos** (Wu & Lithwick 2011)
- **The Kozai-Lidov mechanism** (e.g. Lidov 1962; Kozai 1962; Takeda & Rasio 2005; Naoz et al. 2011; Dawson & Chiang 2014)
- **Secular oscillations due to an outer planetary companion** (Petrovich & Tremaine 2016)
- **Resonant interactions with a gas disk** (Chiang & Murray 2002)
- **Planet-planet scattering** (e.g. Rasio & Ford 1996; Ford et al. 2001; Ford & Rasio 2008; Chatterjee et al. 2008; Juric & Tremaine 2008; Petrovich et al. 2014; Freikh et al. 2019, Anderson et al. 2019)

Wright et al. 2009

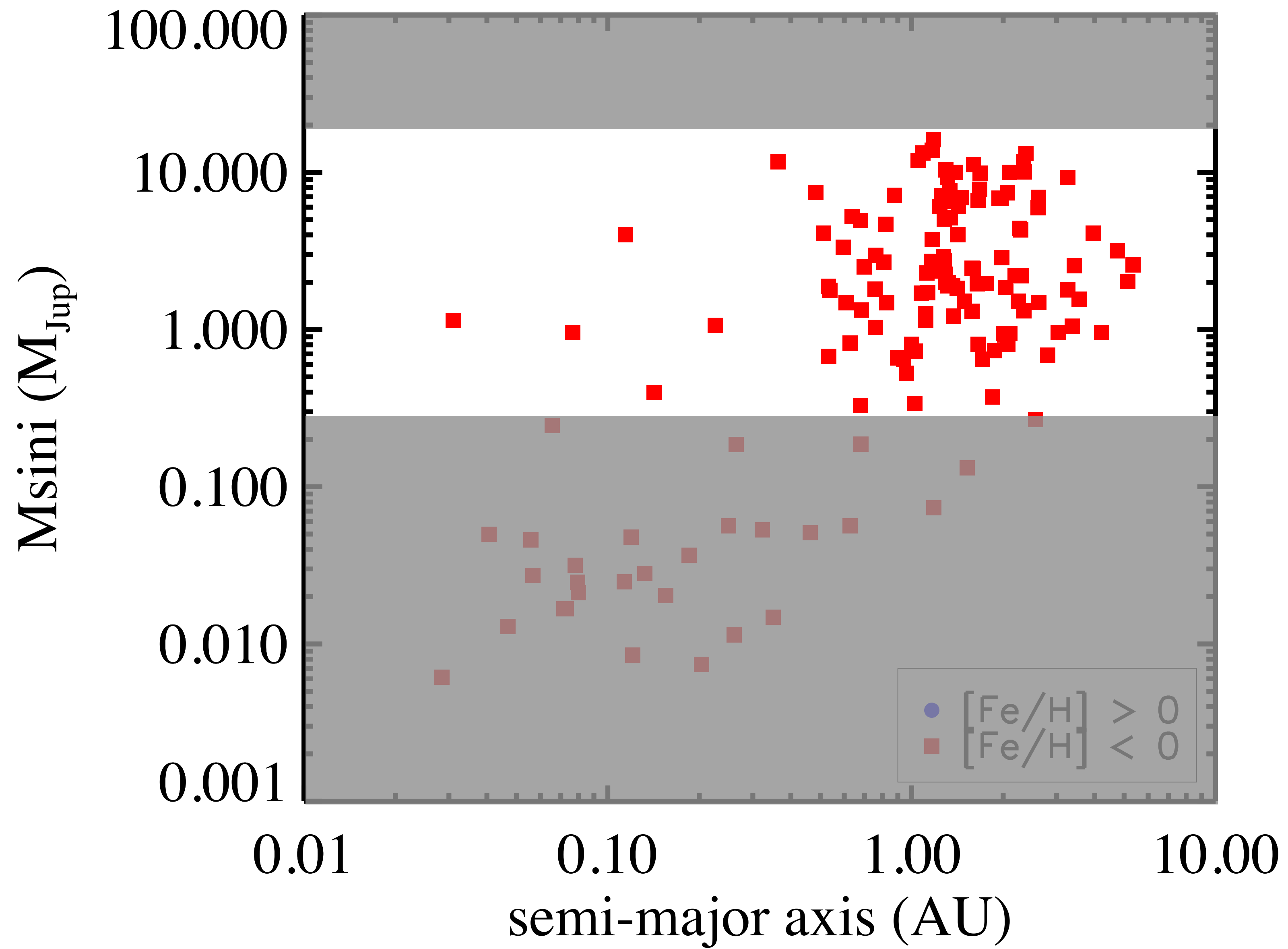
The frequency of hot Jupiters increases with stellar metallicity.



Fischer & Valenti (2005)

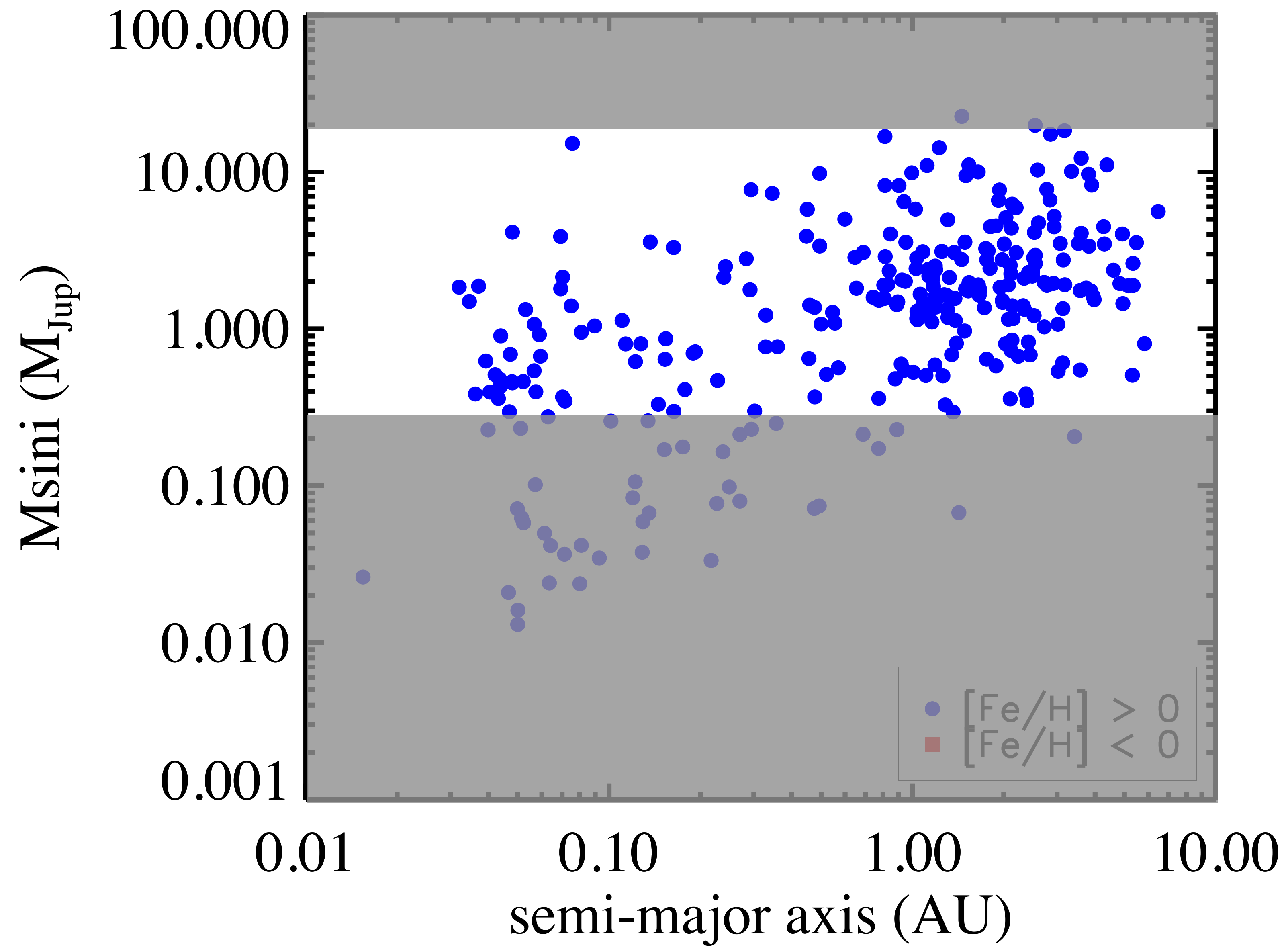
RV discoveries

Low metallicity stars

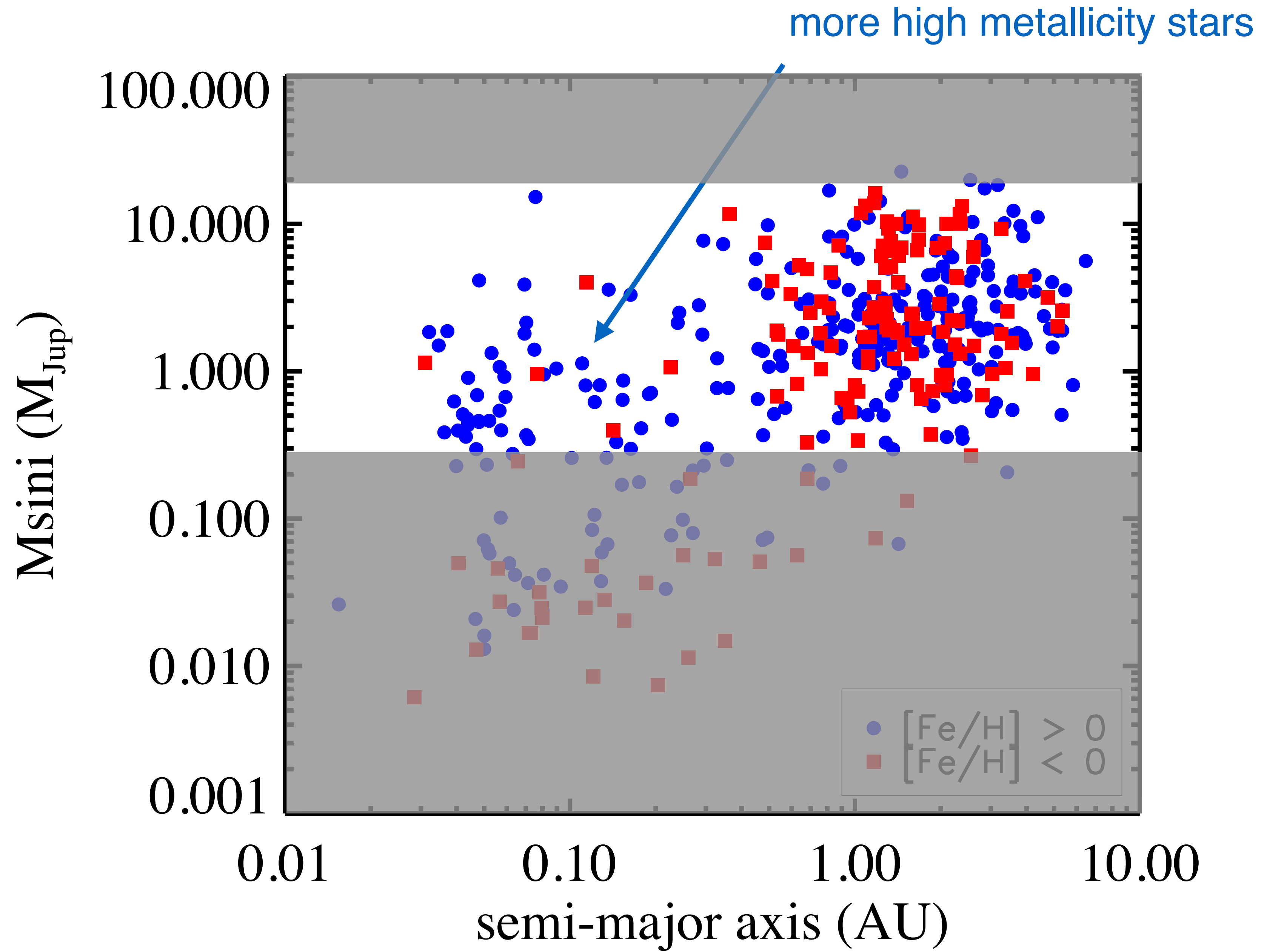


RV discoveries

High metallicity stars

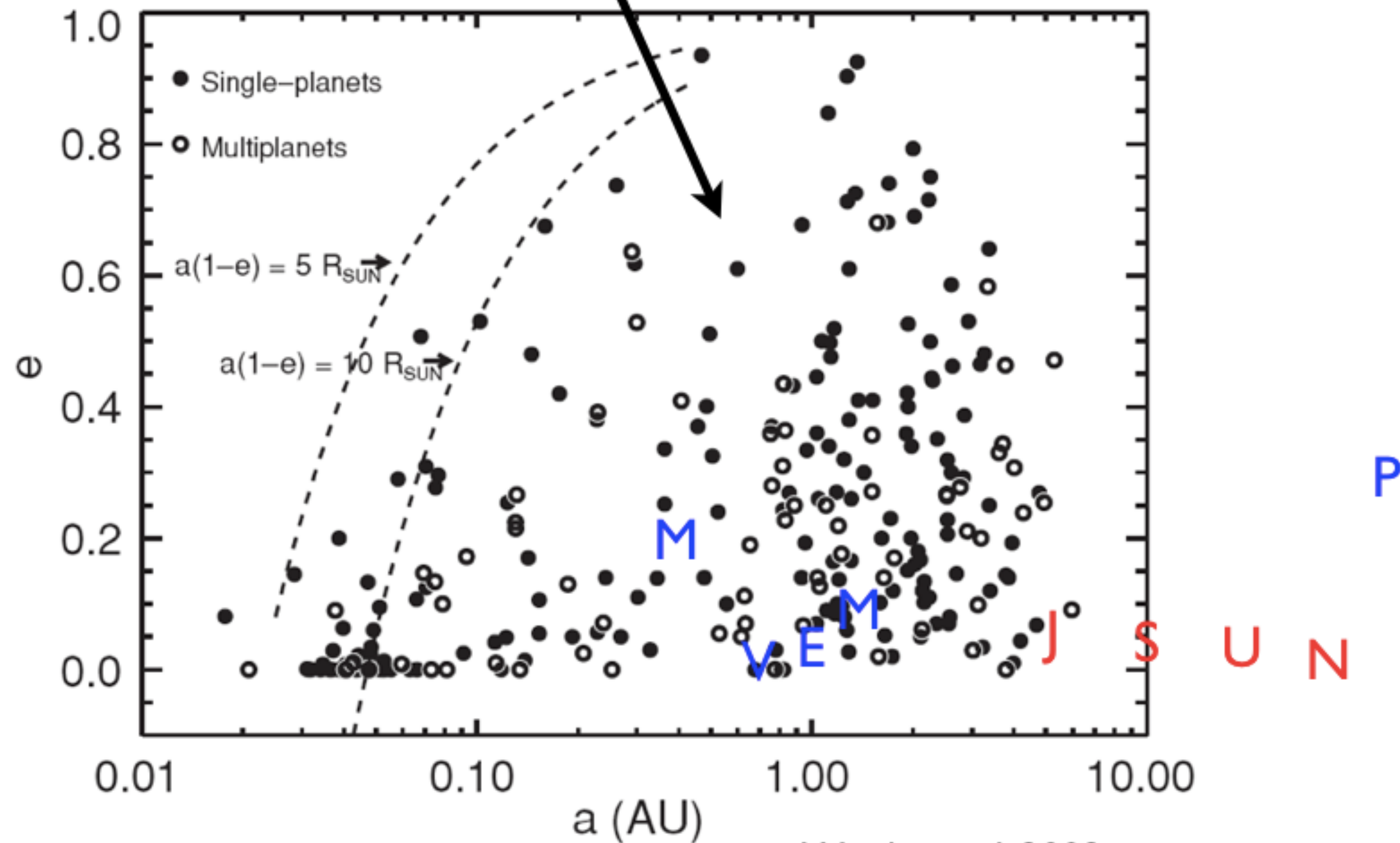


RV discoveries



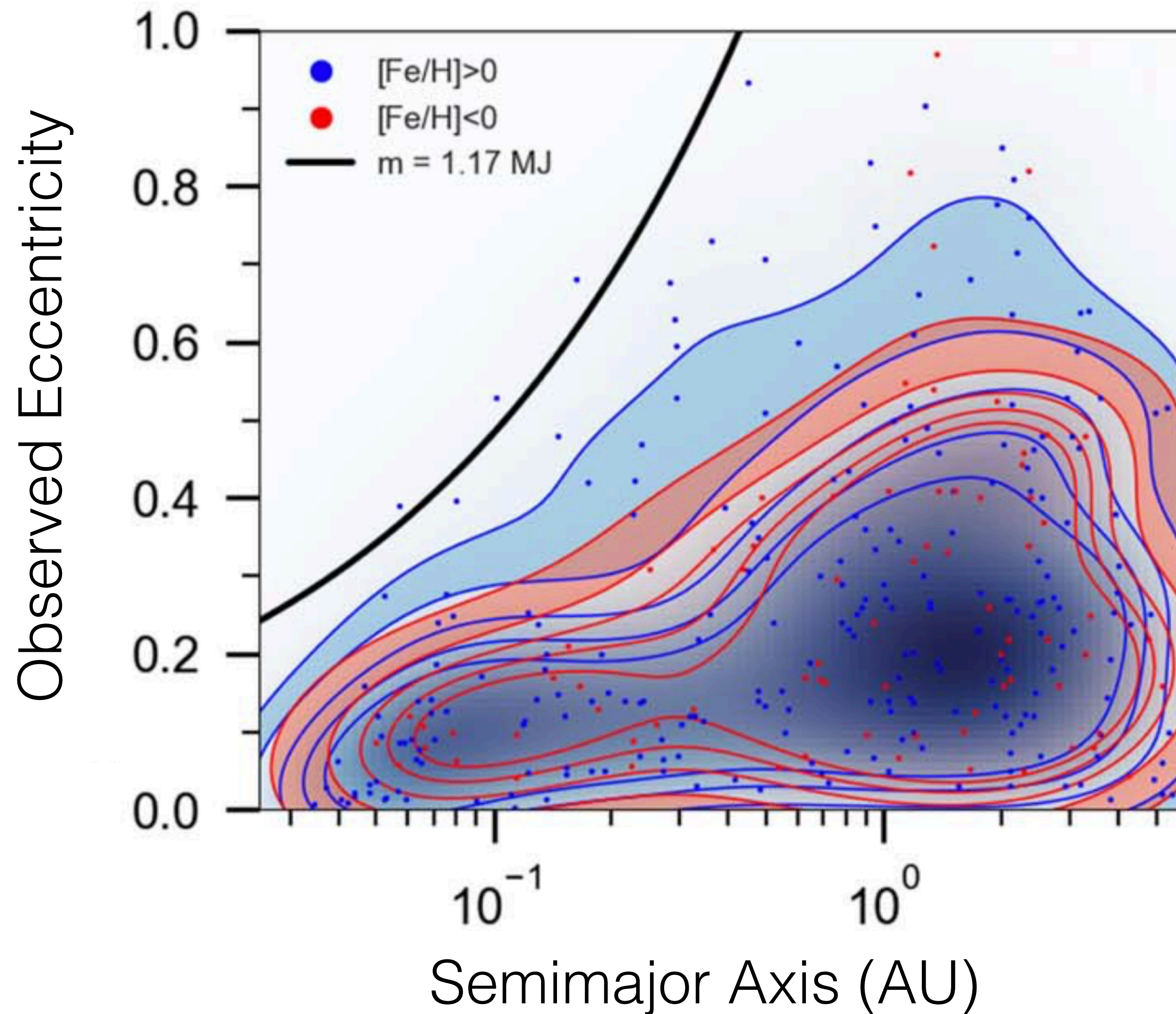
high-eccentricity giant planets

I don't want to live here

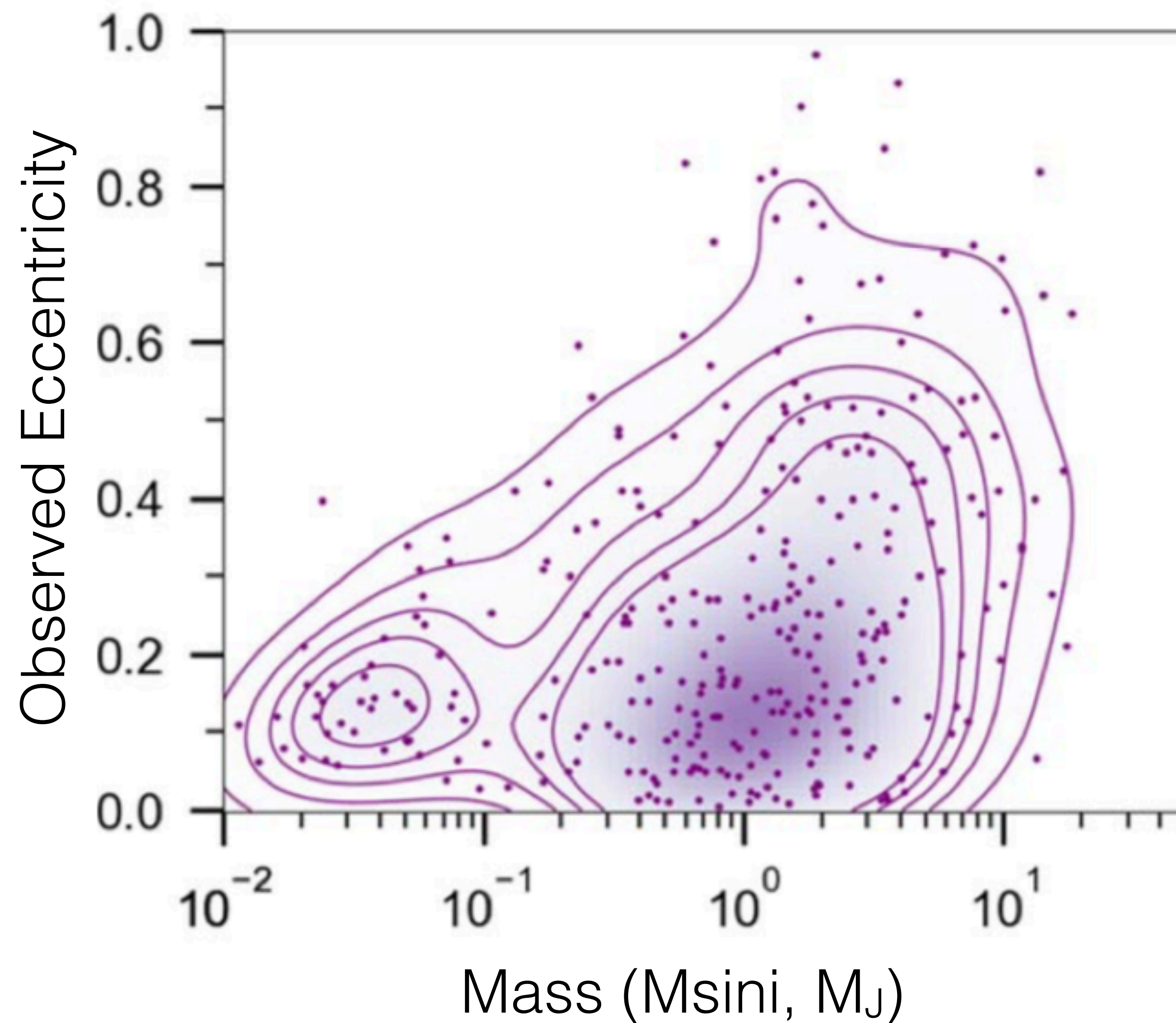


Wright et al. 2009

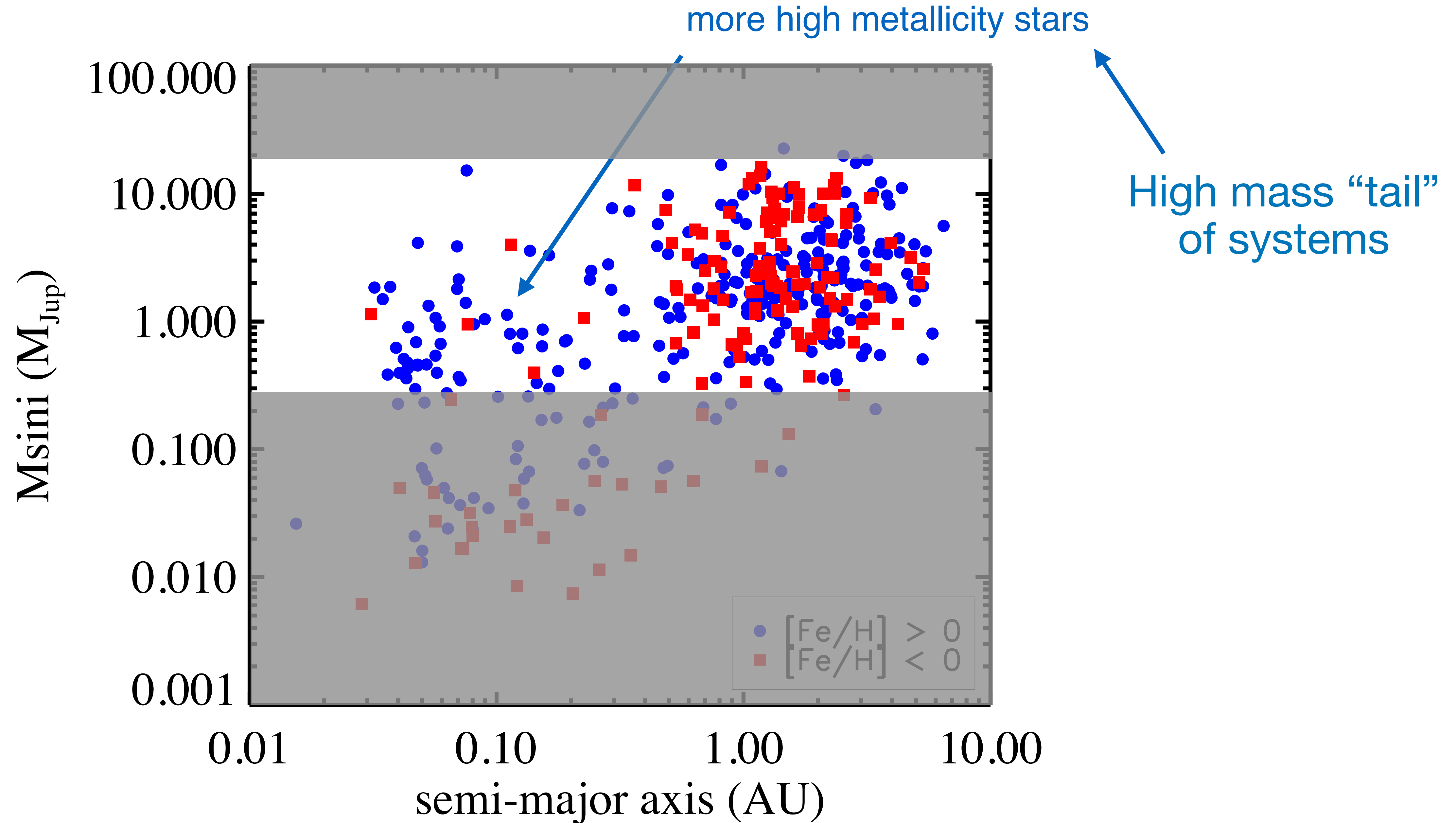
Warm Jupiters with $e > 0.4$ orbit $[\text{Fe}/\text{H}] > 0$ stars

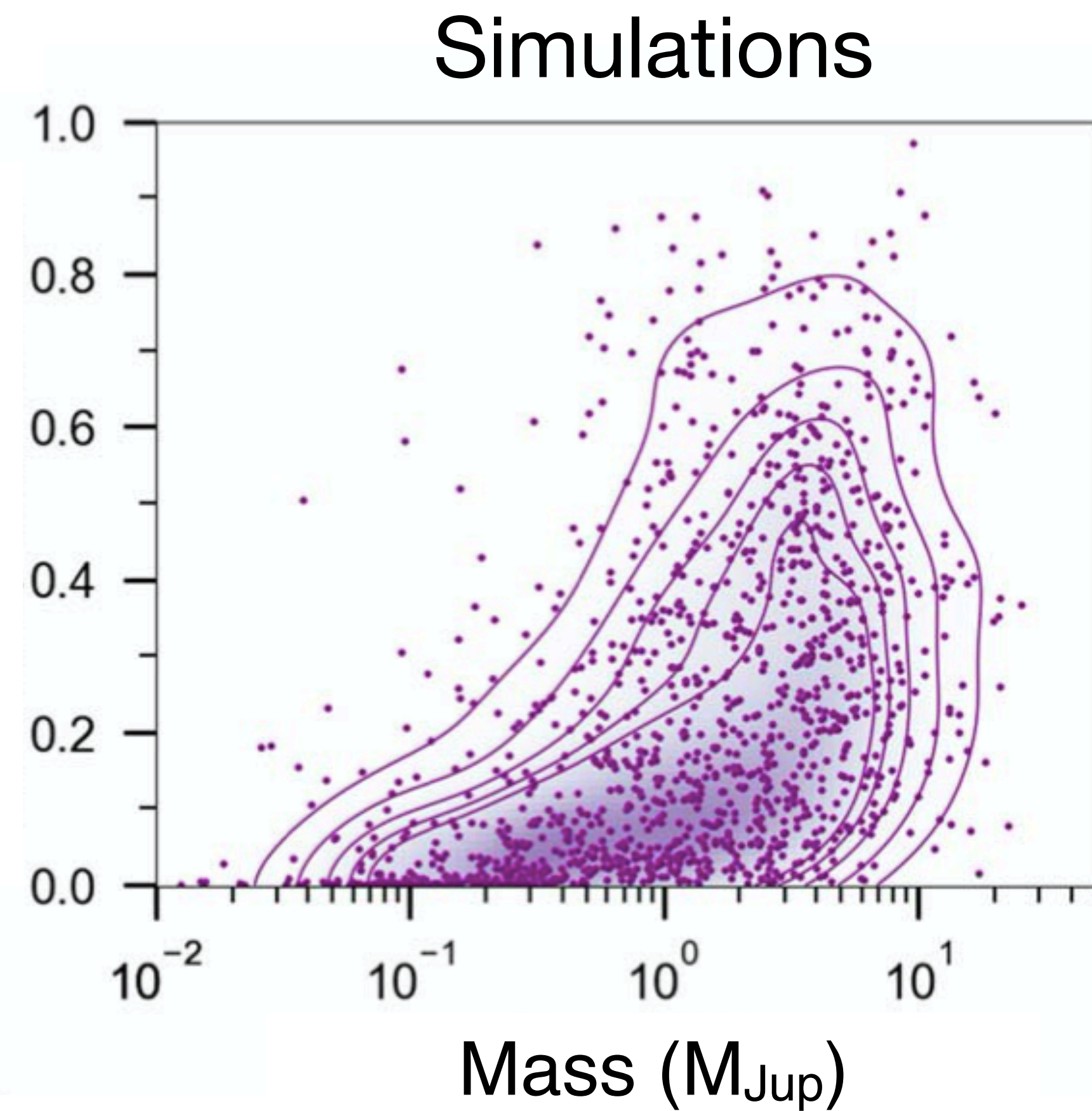
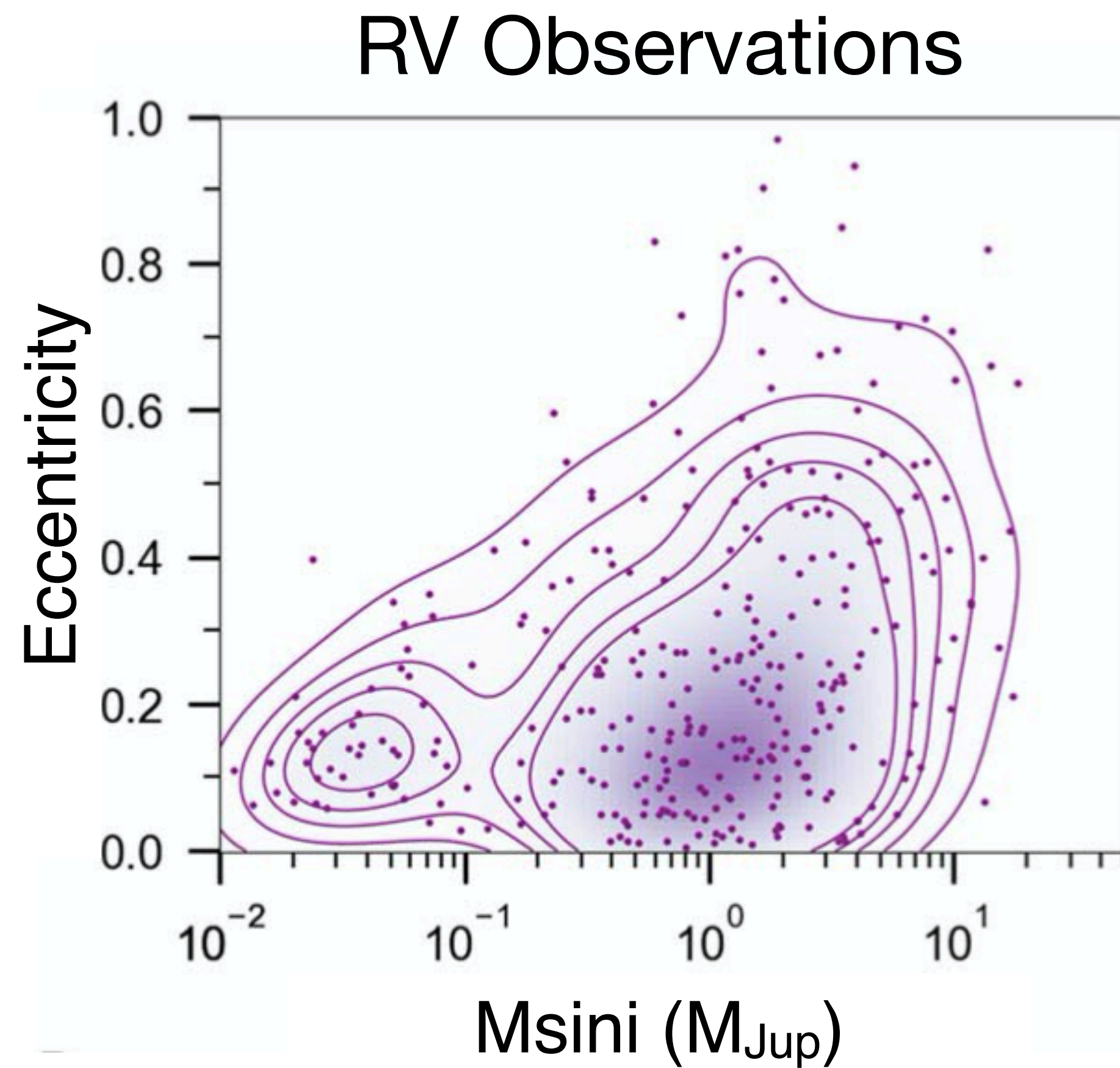


High-eccentricity giants are also higher-mass!



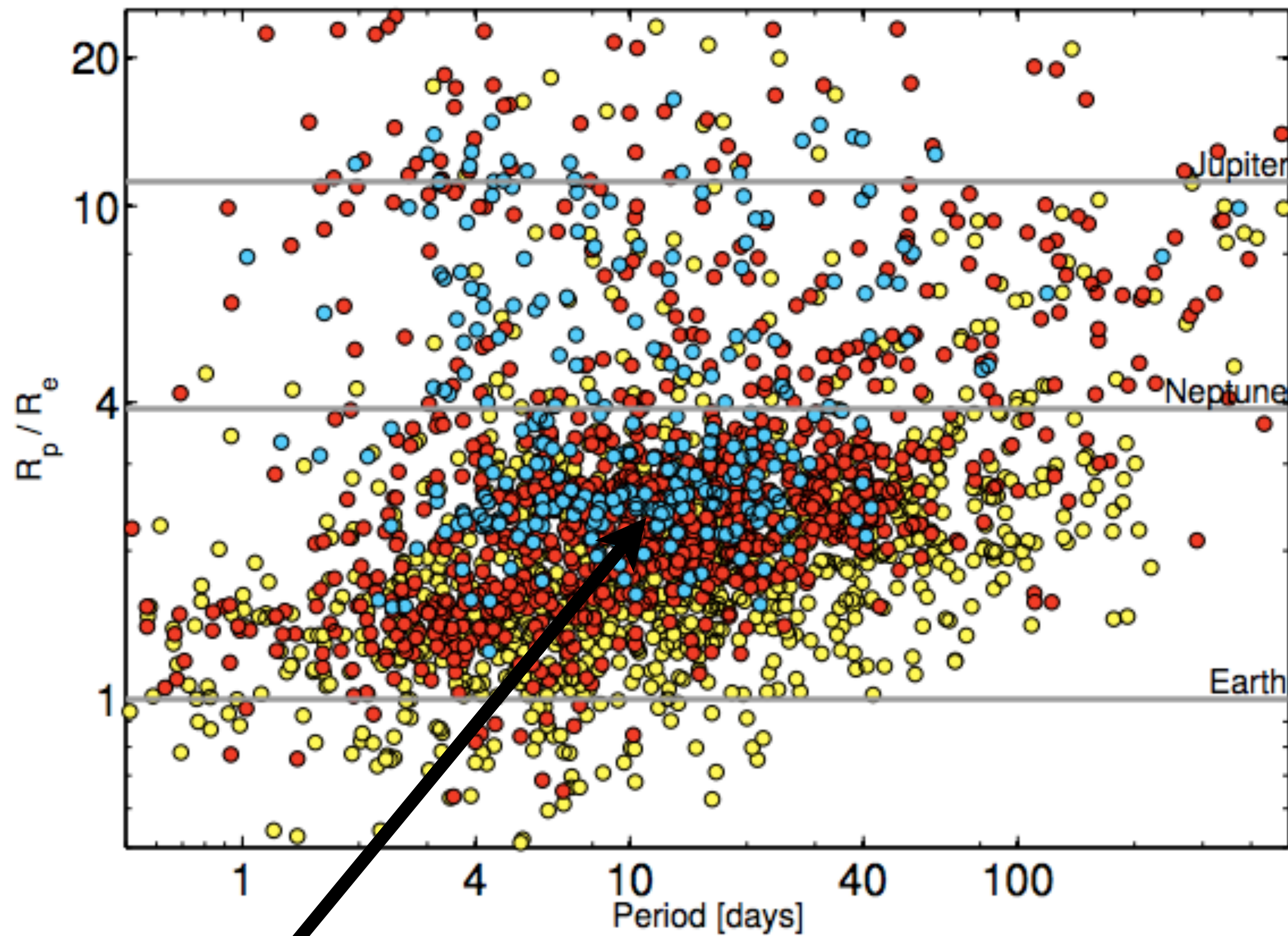
RV discoveries





disks with more (mass in) gas giants →
more giant impacts →
more massive planets →
more excitation to high eccentricity

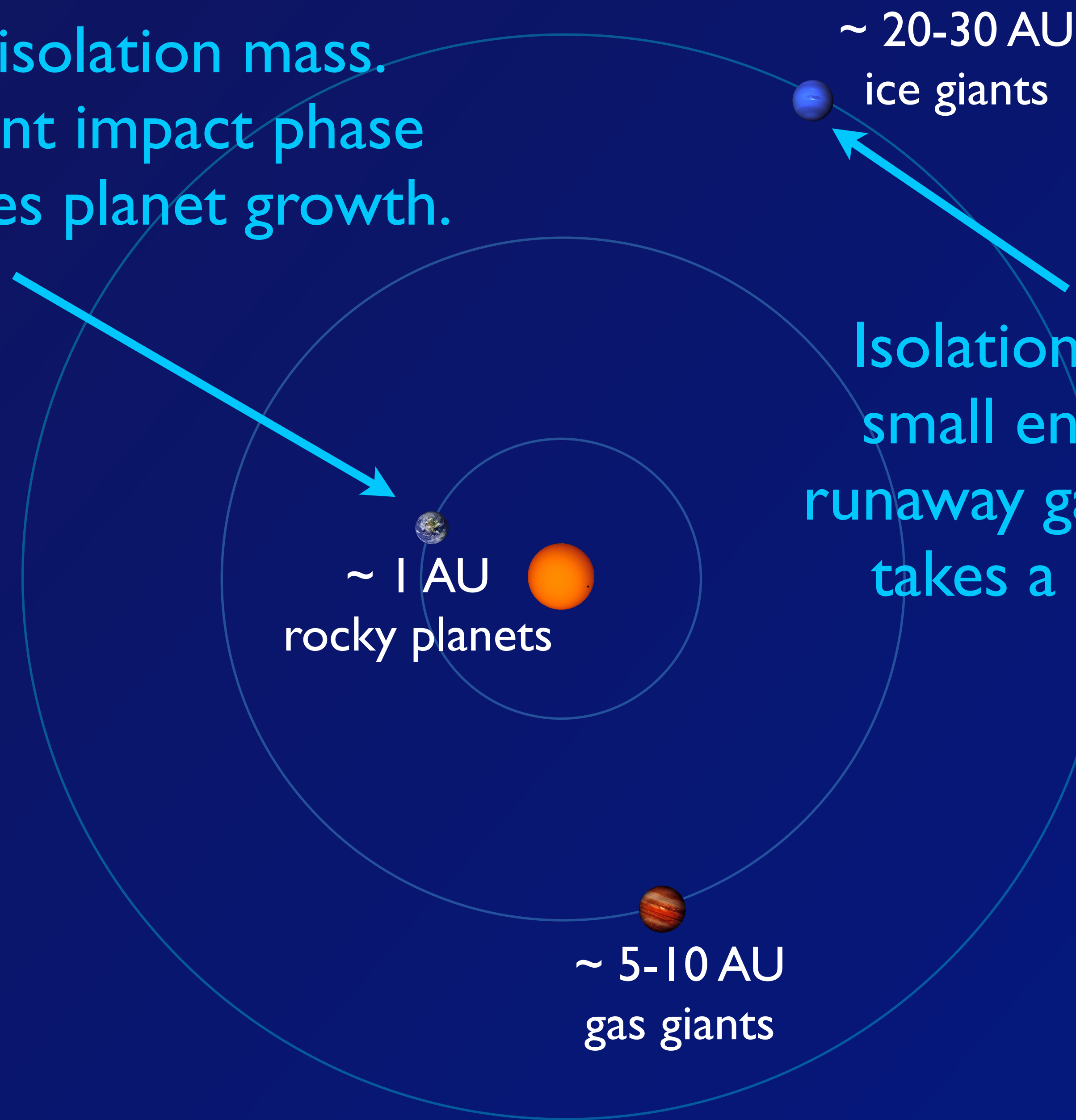
Kepler planets



“super-Earths” are common

Batalha et al. (2012)

Small isolation mass.
Late giant impact phase
completes planet growth.



~ 1 AU
rocky planets

~ 5-10 AU
gas giants

~ 20-30 AU
ice giants

Isolation mass just
small enough that
runaway gas accretion
takes a long time

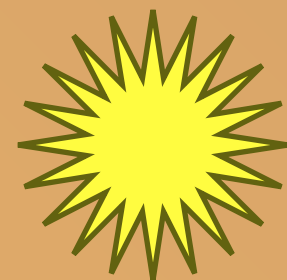
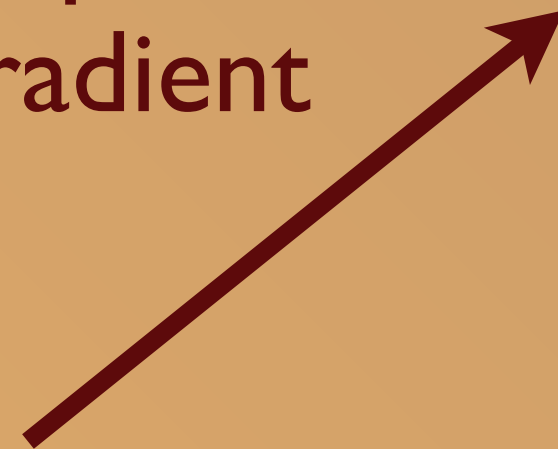
“Isolation” is Suspect

Gas drag causes drift

planetesimal
wants to orbit
star at v_{Kep}

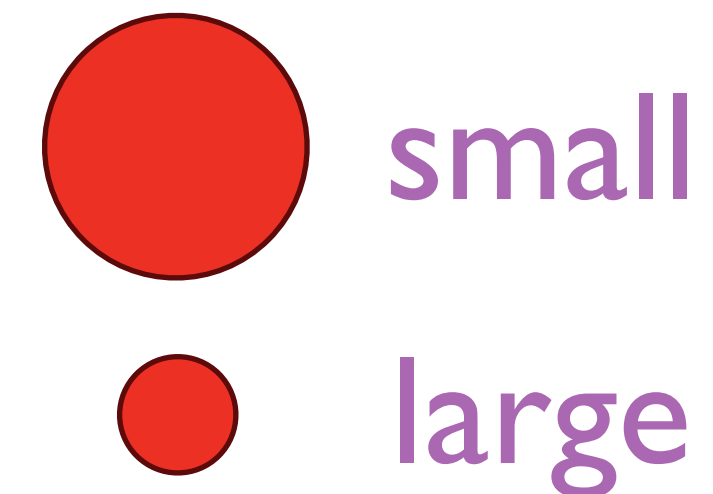


radial pressure
gradient

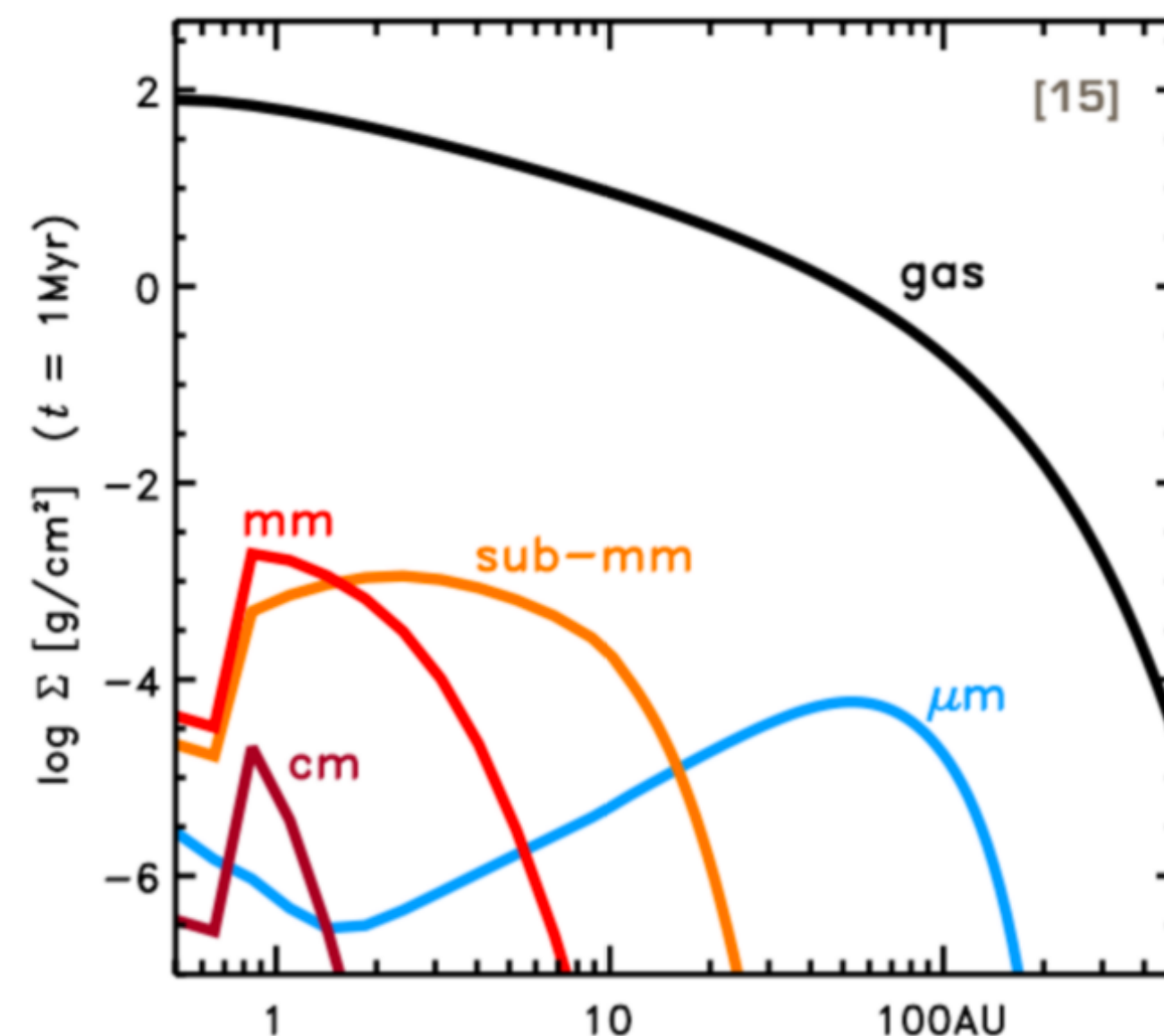
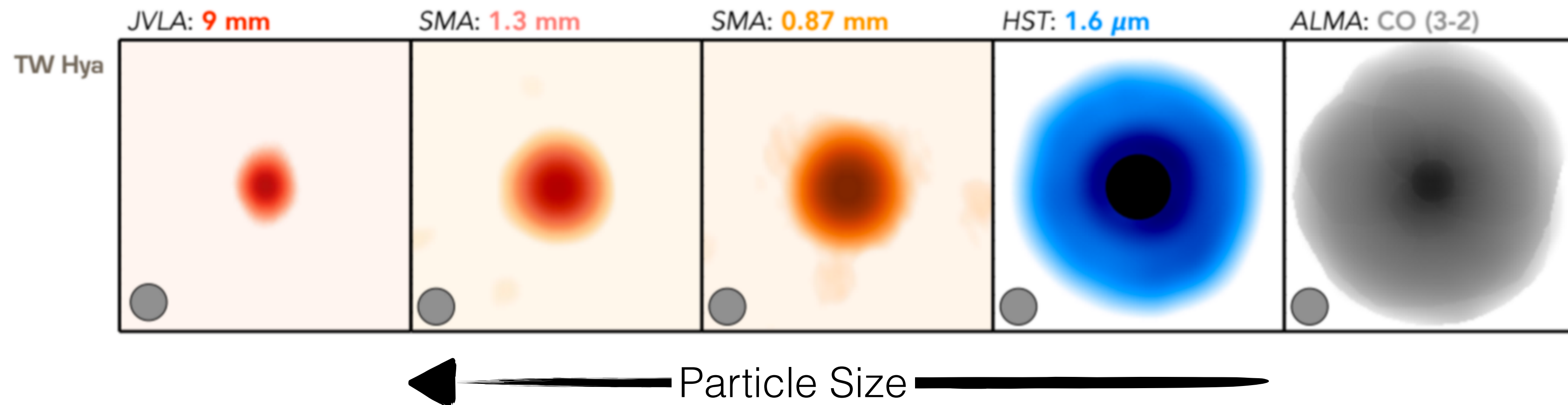


but gas orbits
more slowly
 $v_{orb} < v_{Kep}$

The resulting $\frac{F_D}{m}$ is



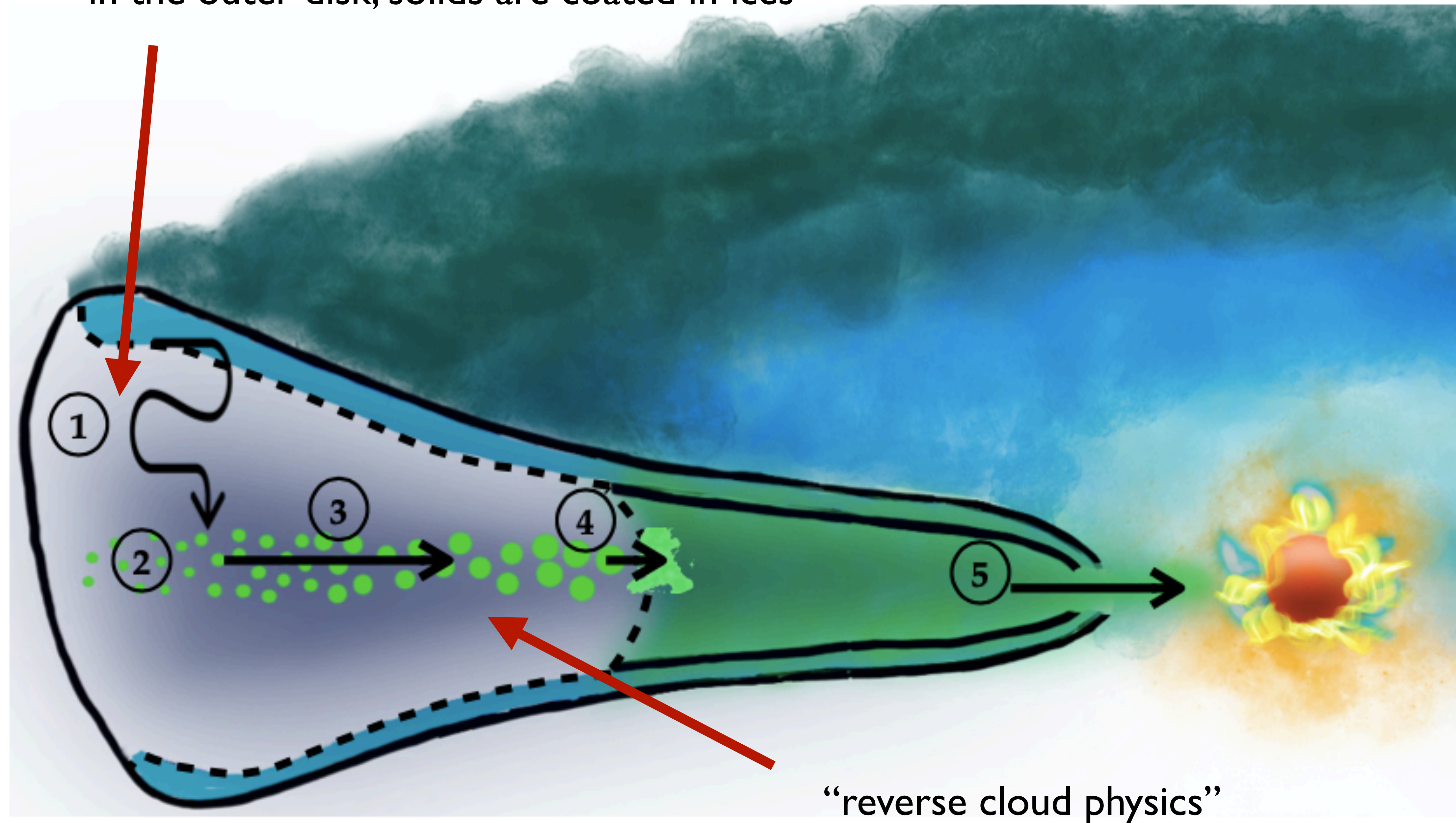
Protoplanetary disks appear smaller at longer wavelengths



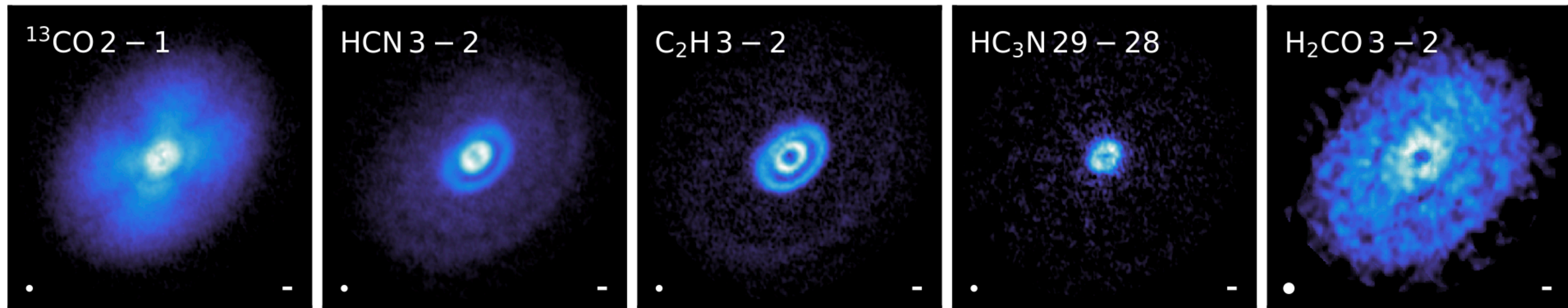
for well-coupled dust,
larger particles drift inward
more quickly

Birnstiel & Andrews 2015, Menu et al. 2014, L.I. Cleeves,
Andrews et al. 2012, Debes et al. 2013,
images from presentation by
Sean Andrews May 2016

in the outer disk, solids are coated in ices



Five molecular faces of one disk (HD 163296)



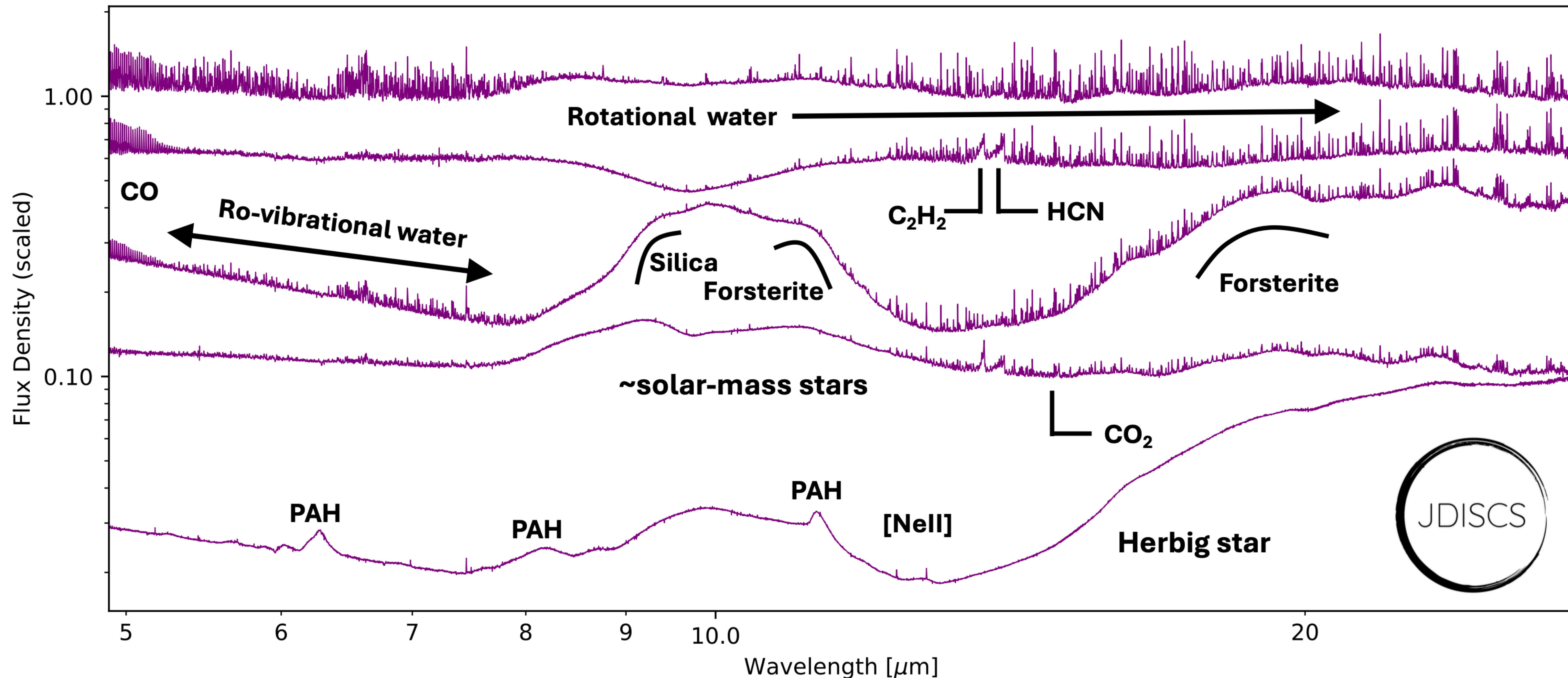
James Webb Space Telescope (JWST)

artist's conception

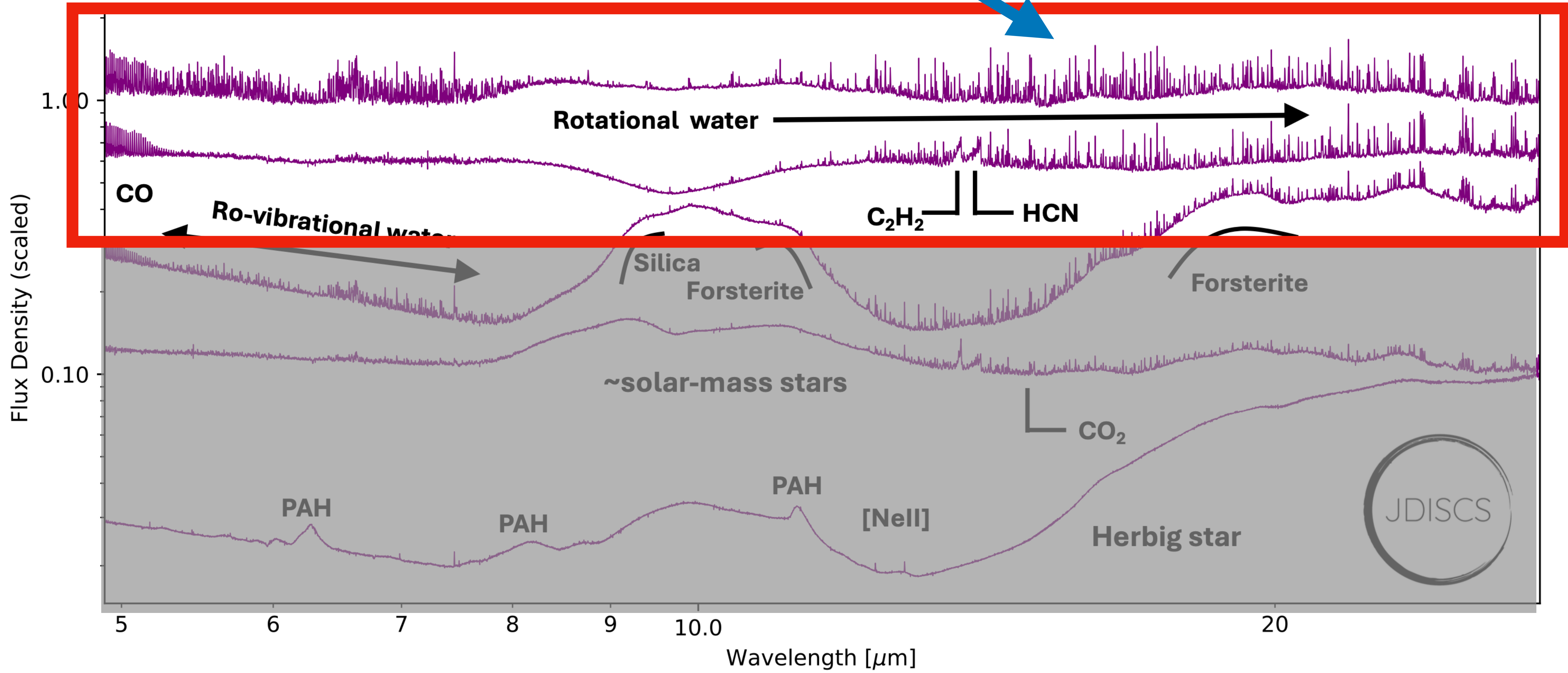


NASA

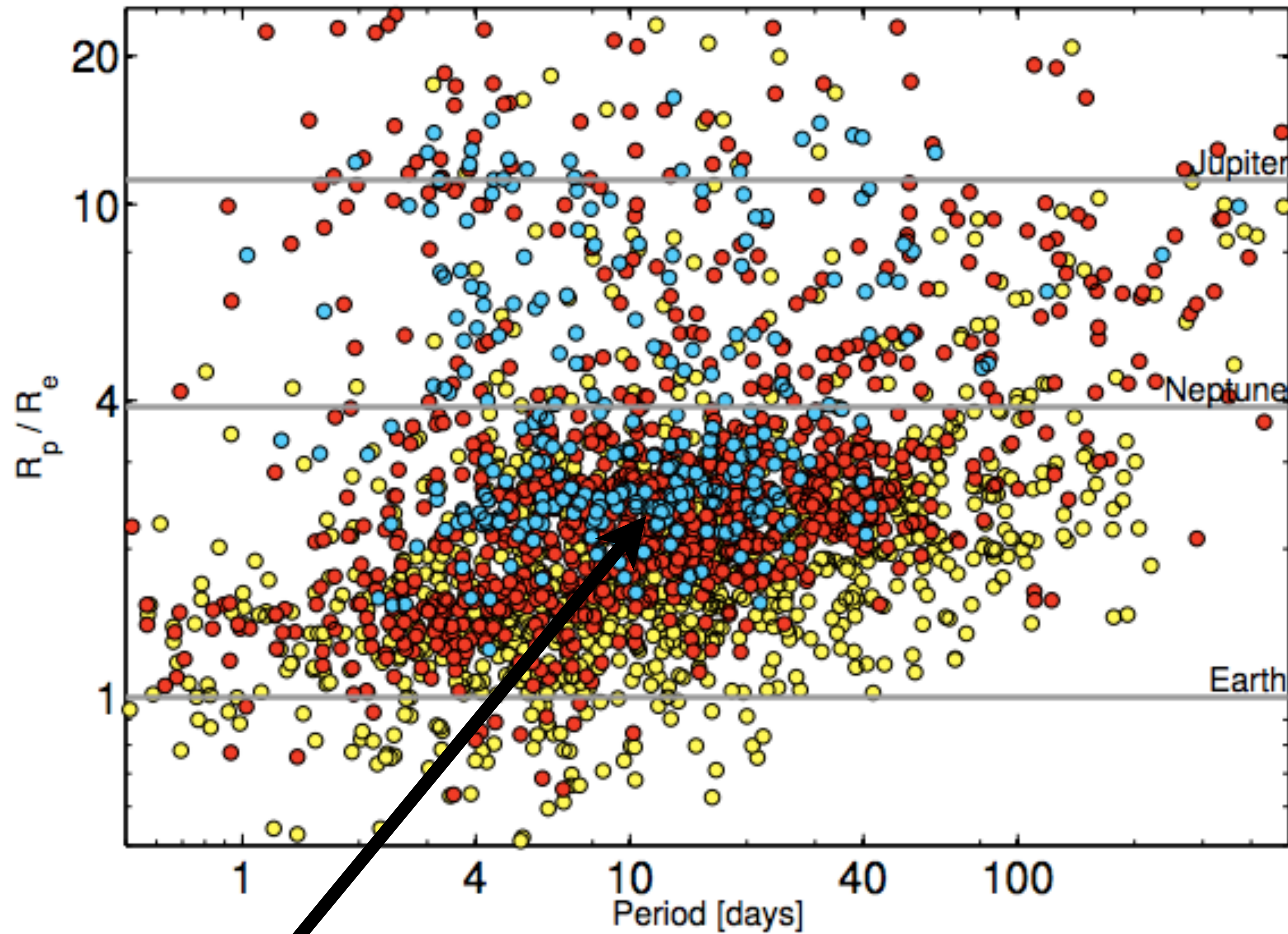
These spectra probe the **inner disk**, near where Earth formed!



Each of these is a water line

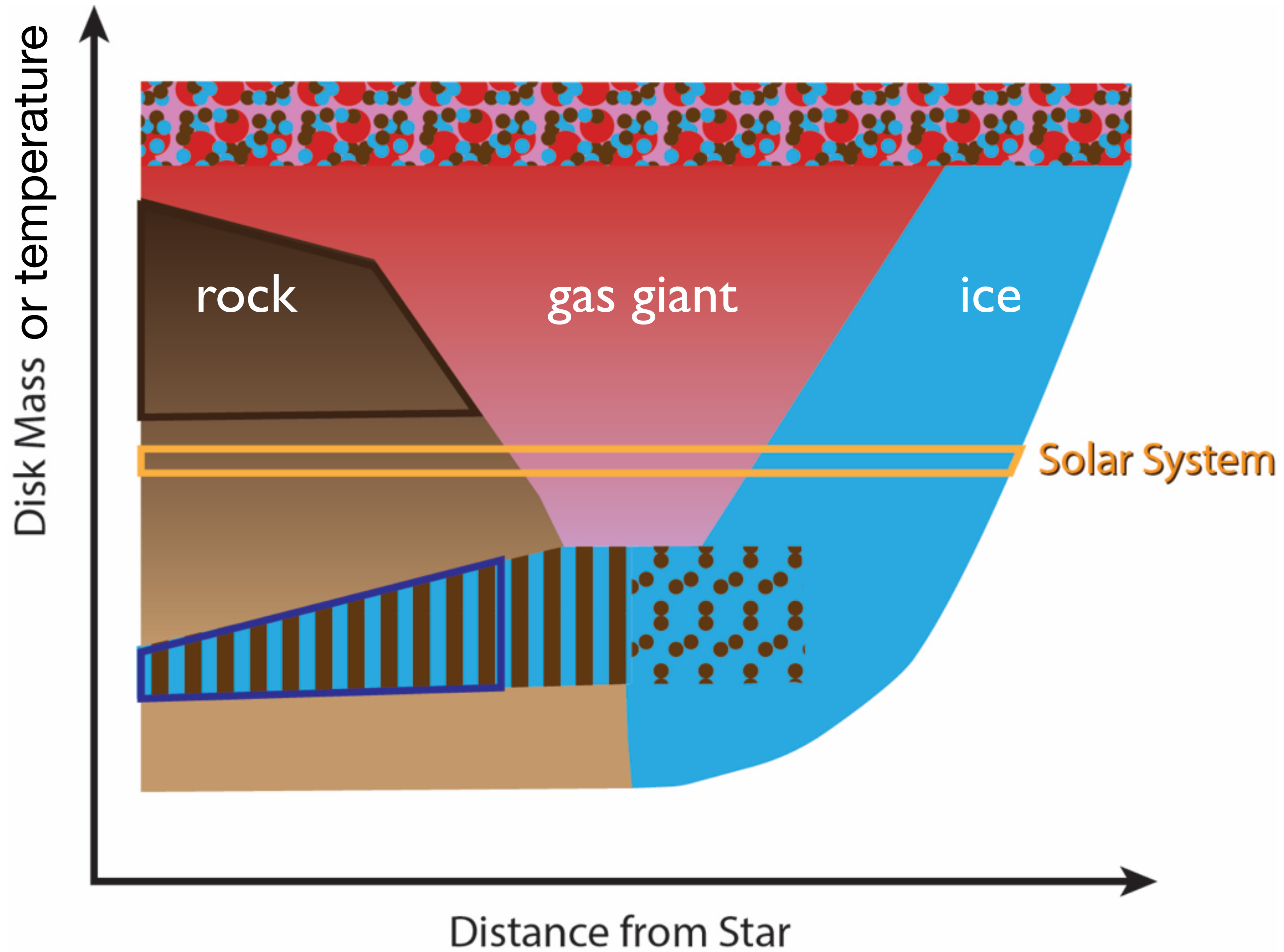


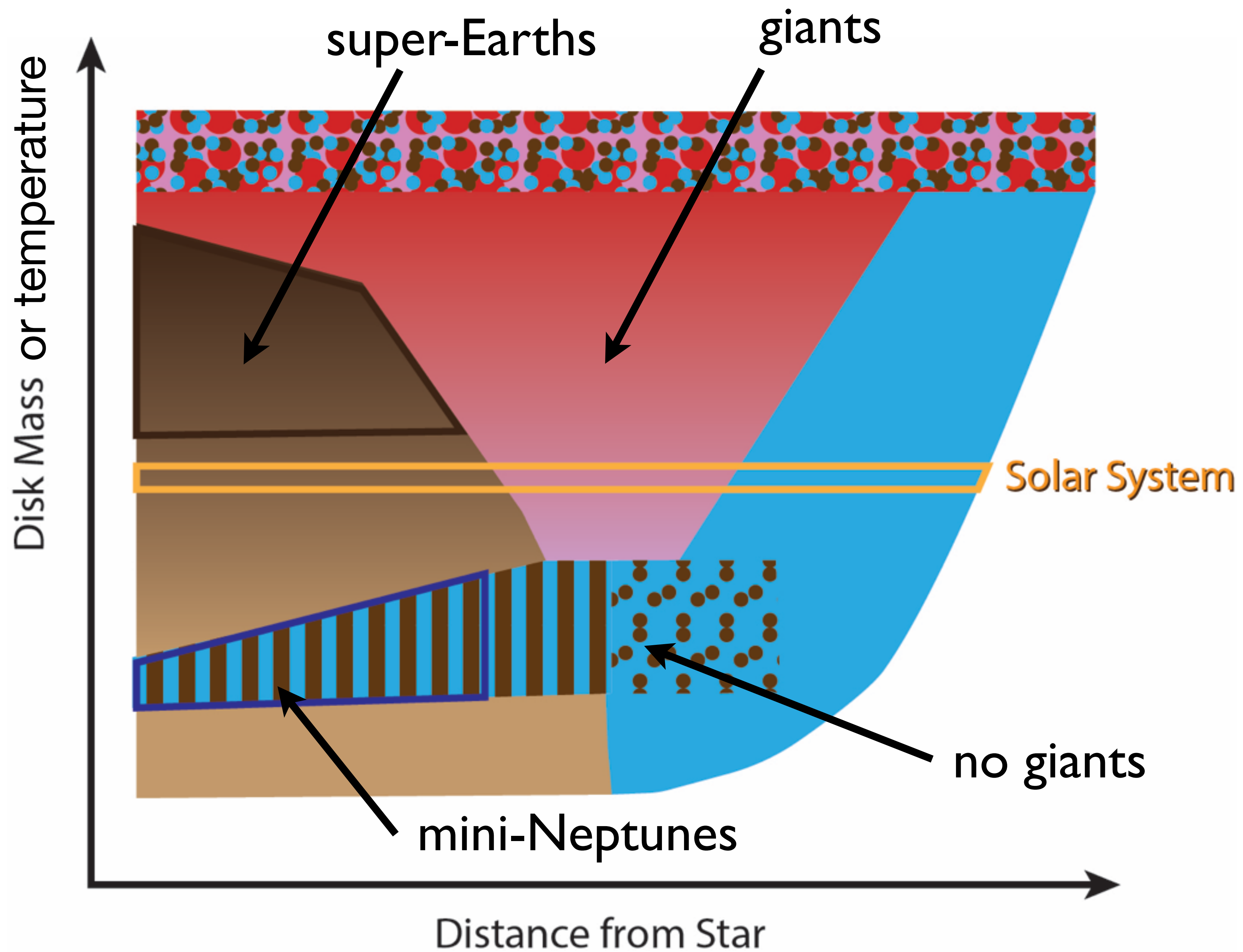
Kepler planets



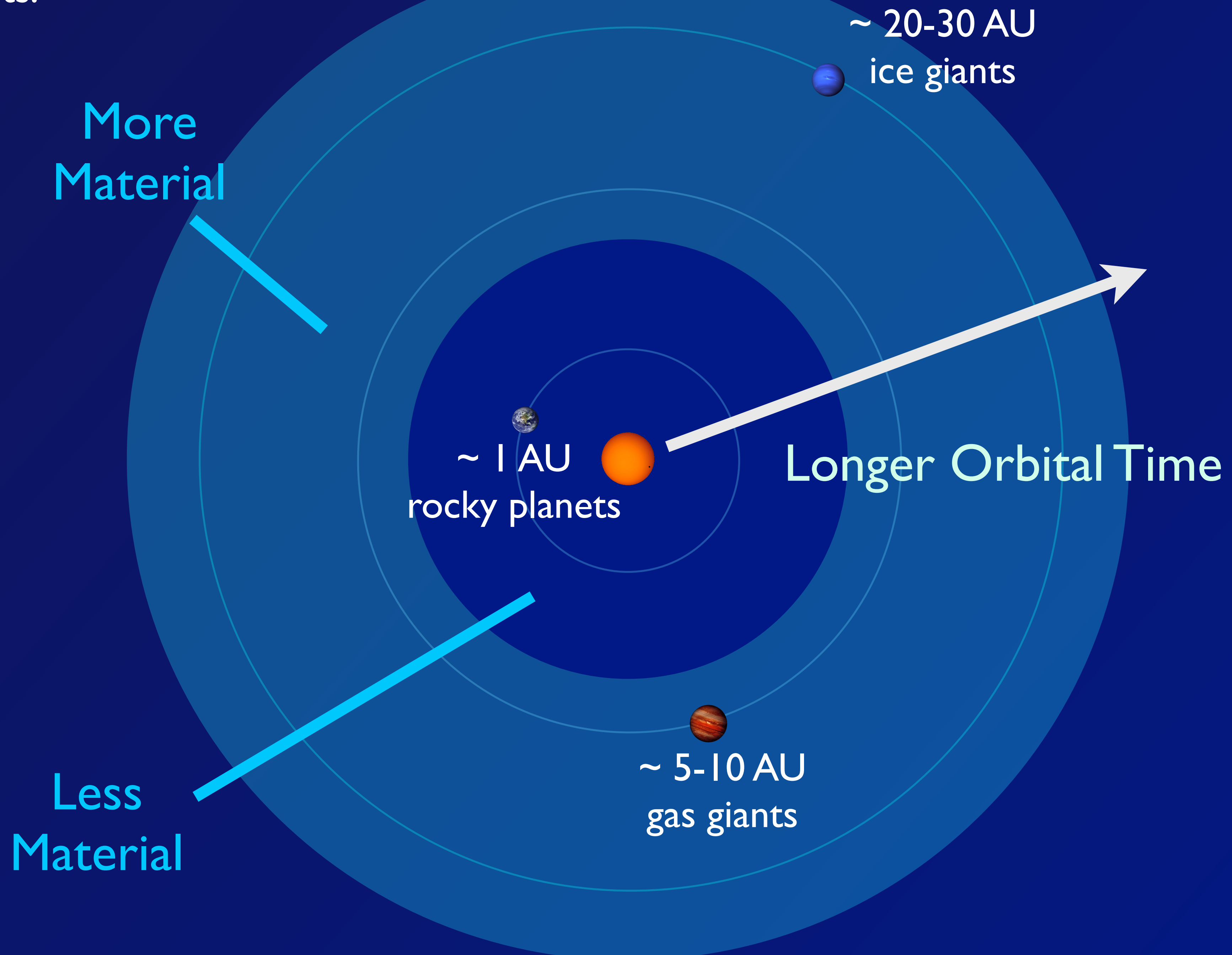
“super-Earths” are common

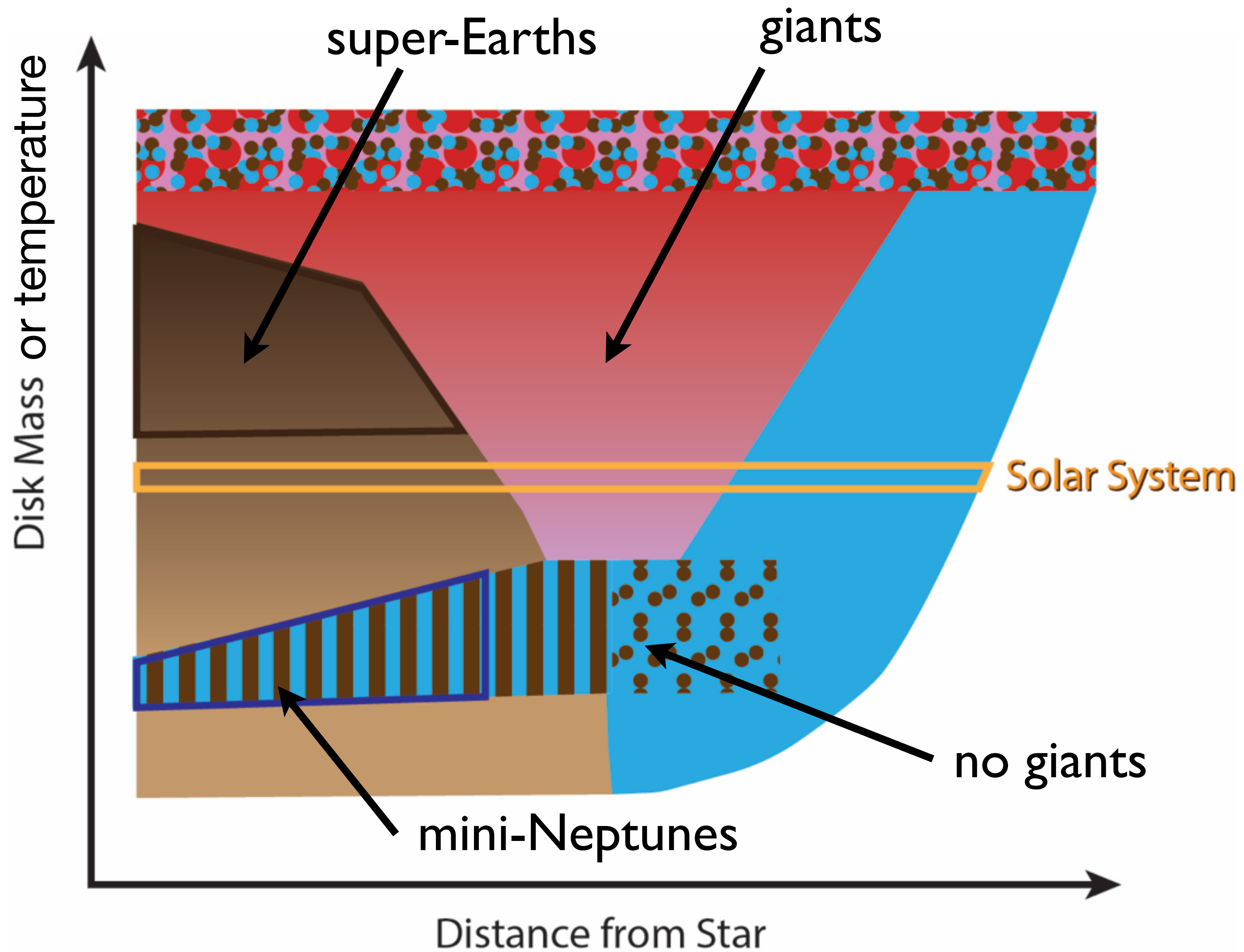
Batalha et al. (2012)



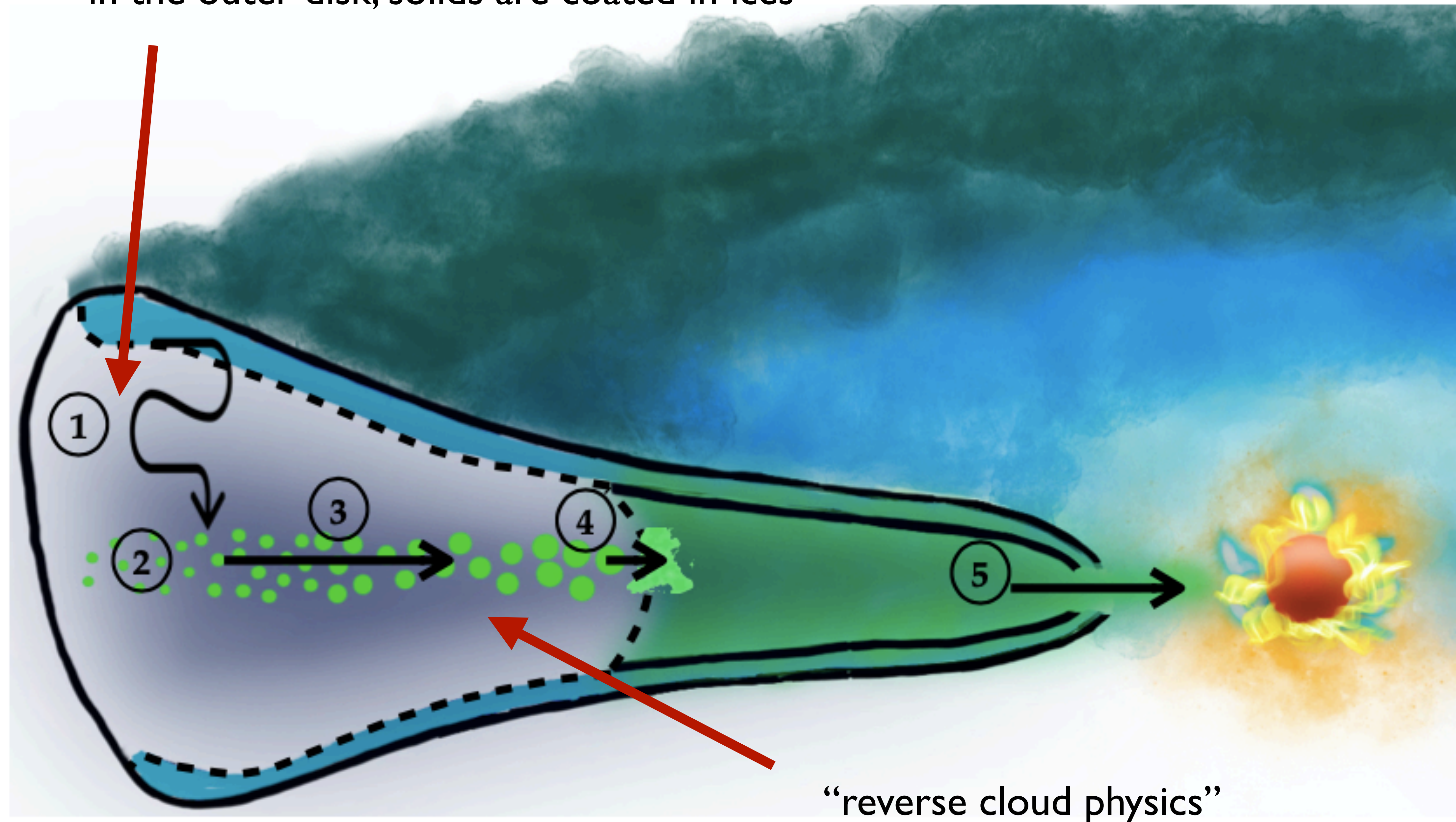


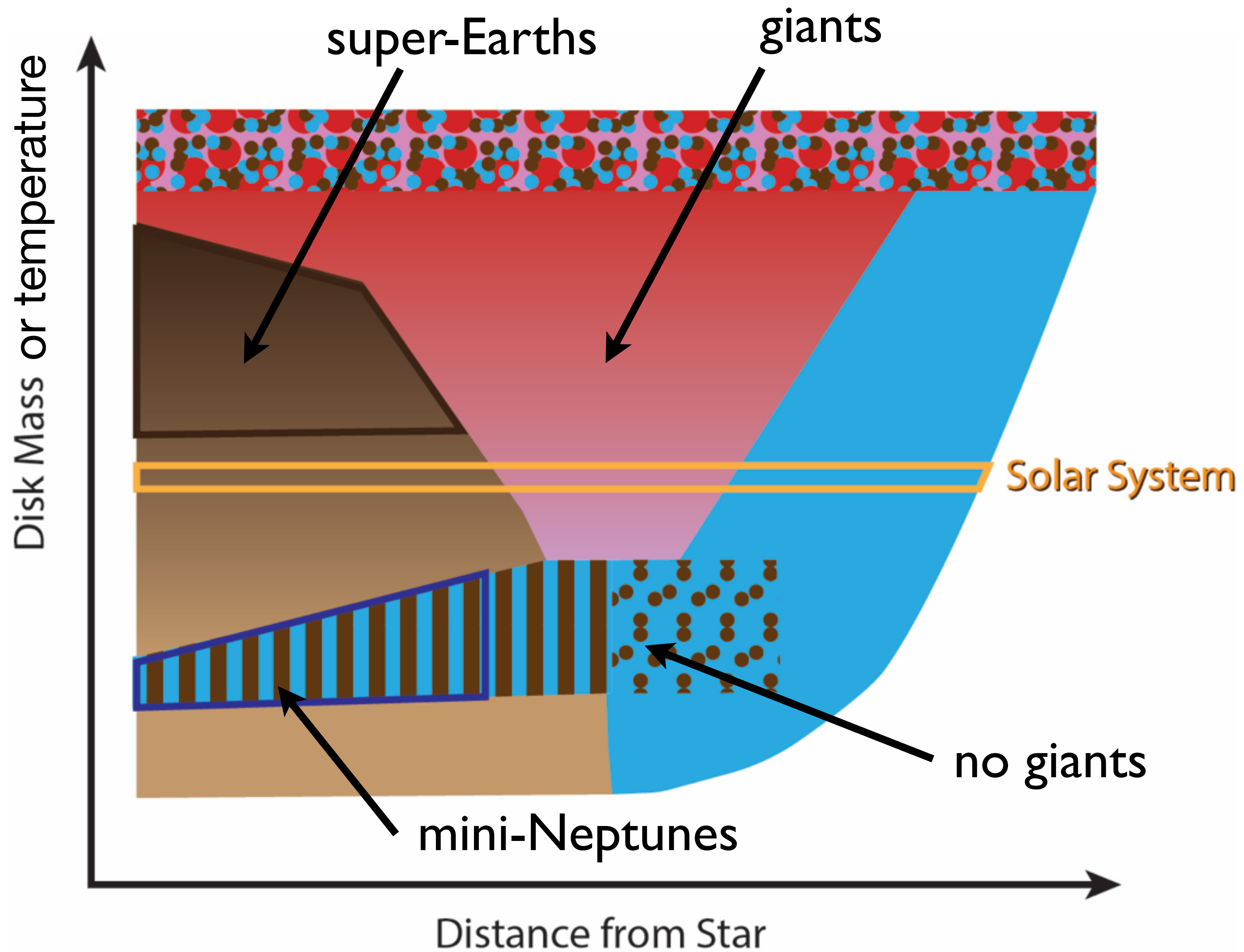
Pre-exoplanets:

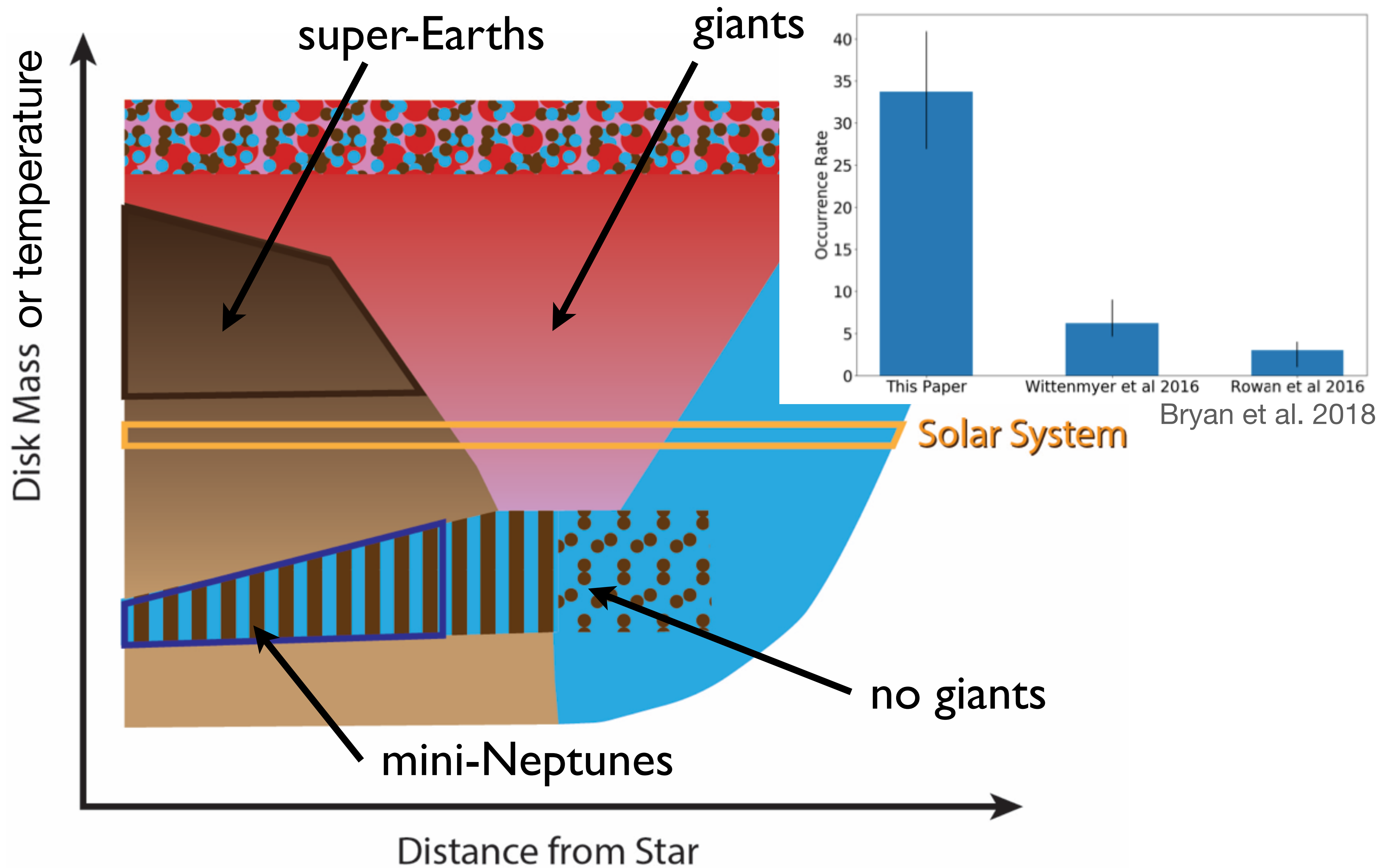


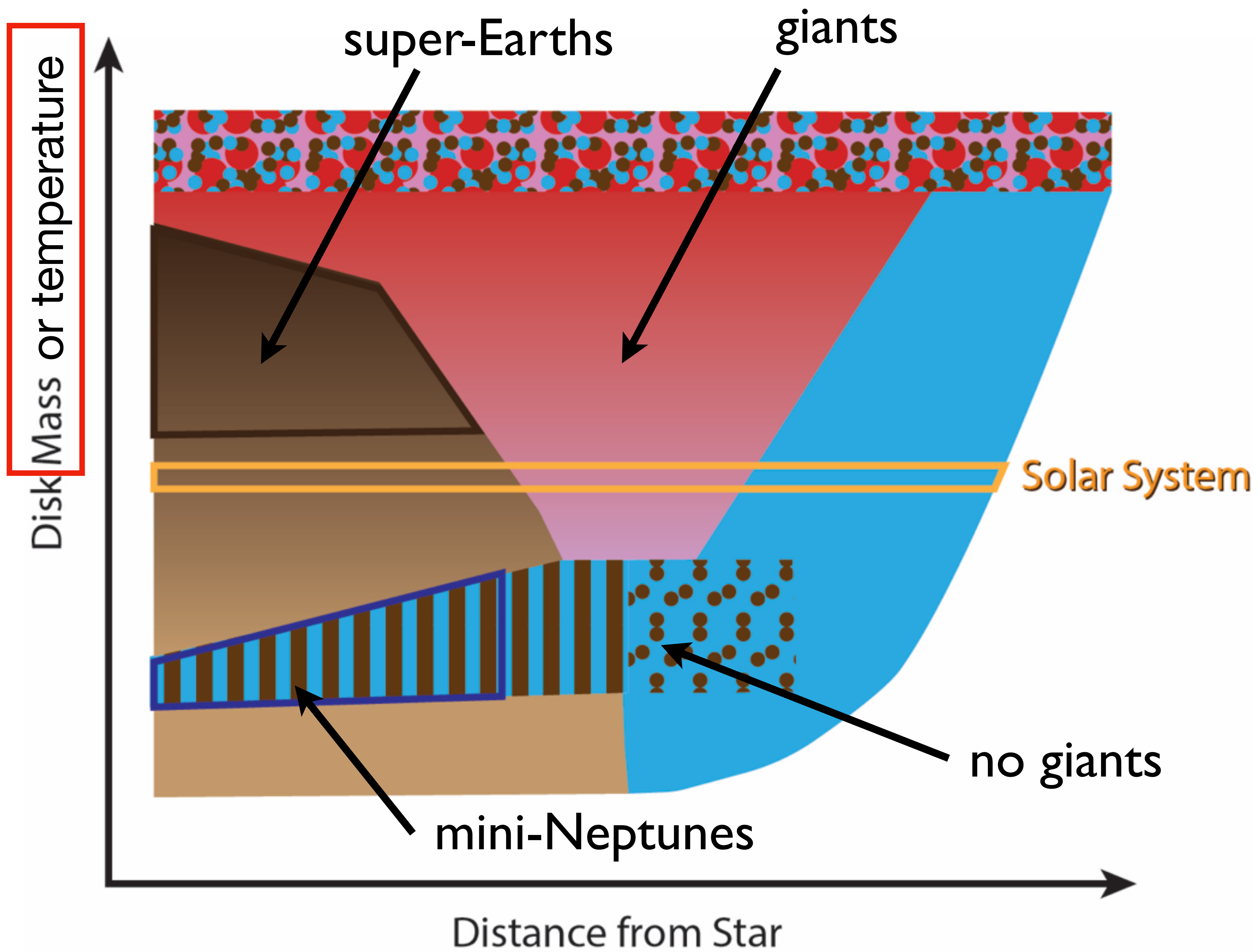


in the outer disk, solids are coated in ices









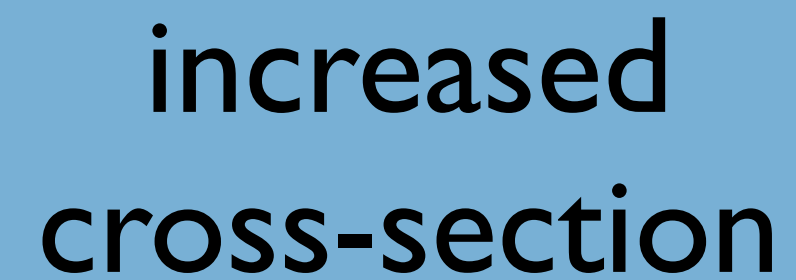
Pebble accretion:

Capture by gas drag allows (embarrassingly) fast growth, but only for certain sizes of particles

Sun

A small orange circle representing the Sun.

increased
cross-section

A black arrow pointing from the text 'increased cross-section' to the growing solid planet.

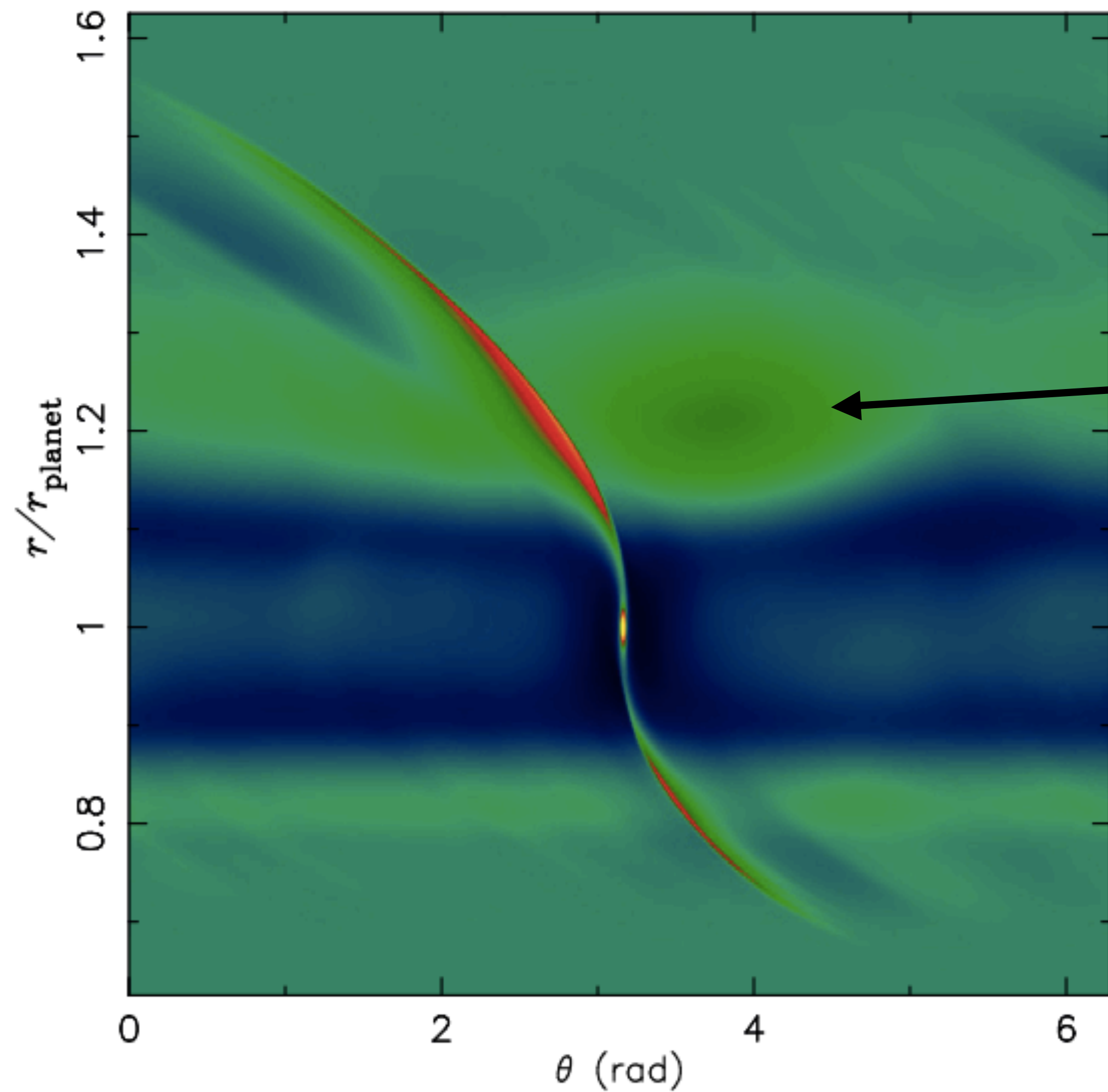
growing solid planet

A purple arrow pointing from the text 'growing solid planet' to the growing solid planet.

planetesimal

An orange arrow pointing from the text 'planetesimal' to the planetesimal.

Ormel & Klahr 2010,
Lambrechts & Johansen 2012
Rosenthal et al. 2018



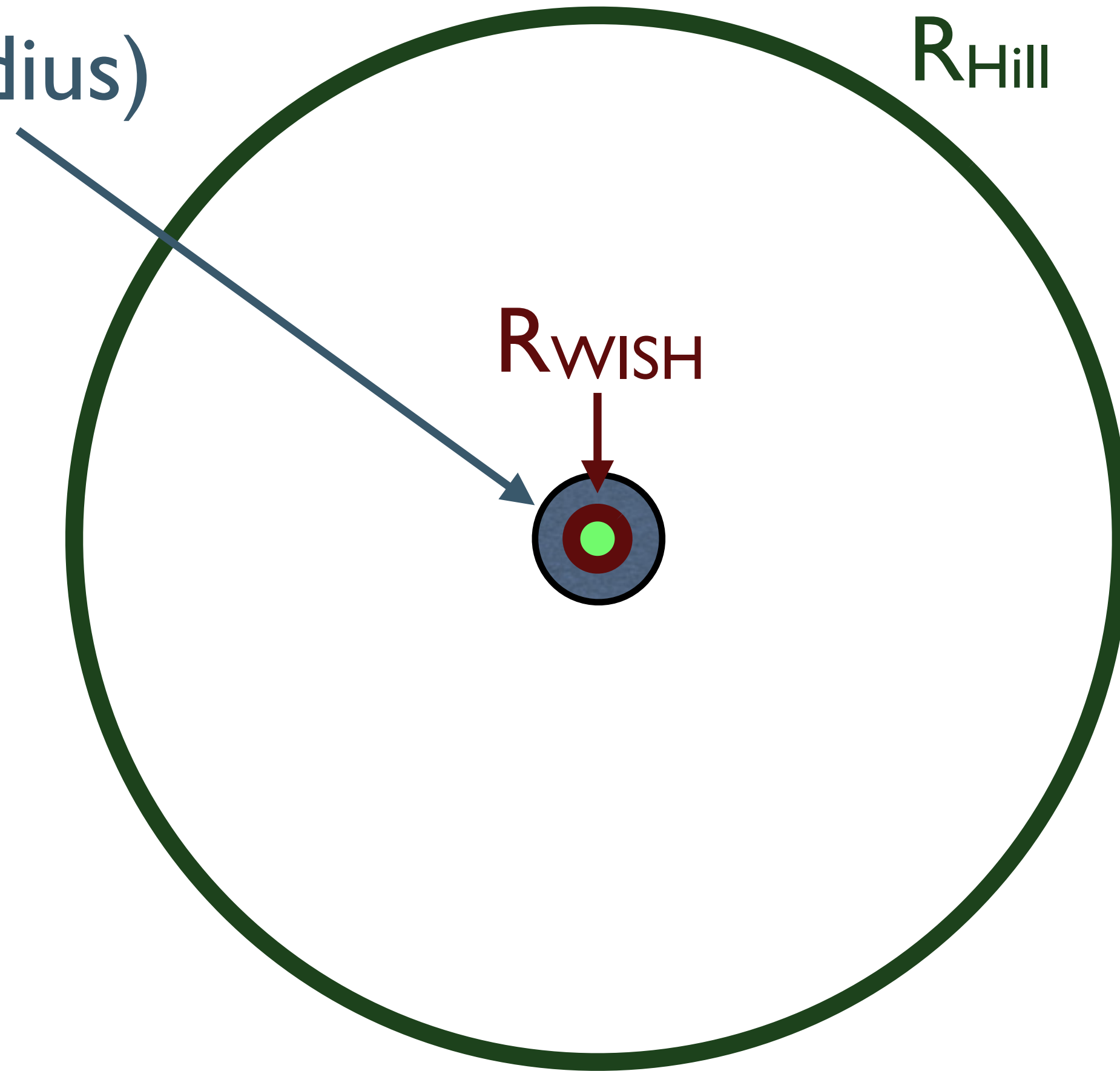
“Pebble isolation”:

overdensity in disk gas
prevents pebbles from
flowing in to the planet

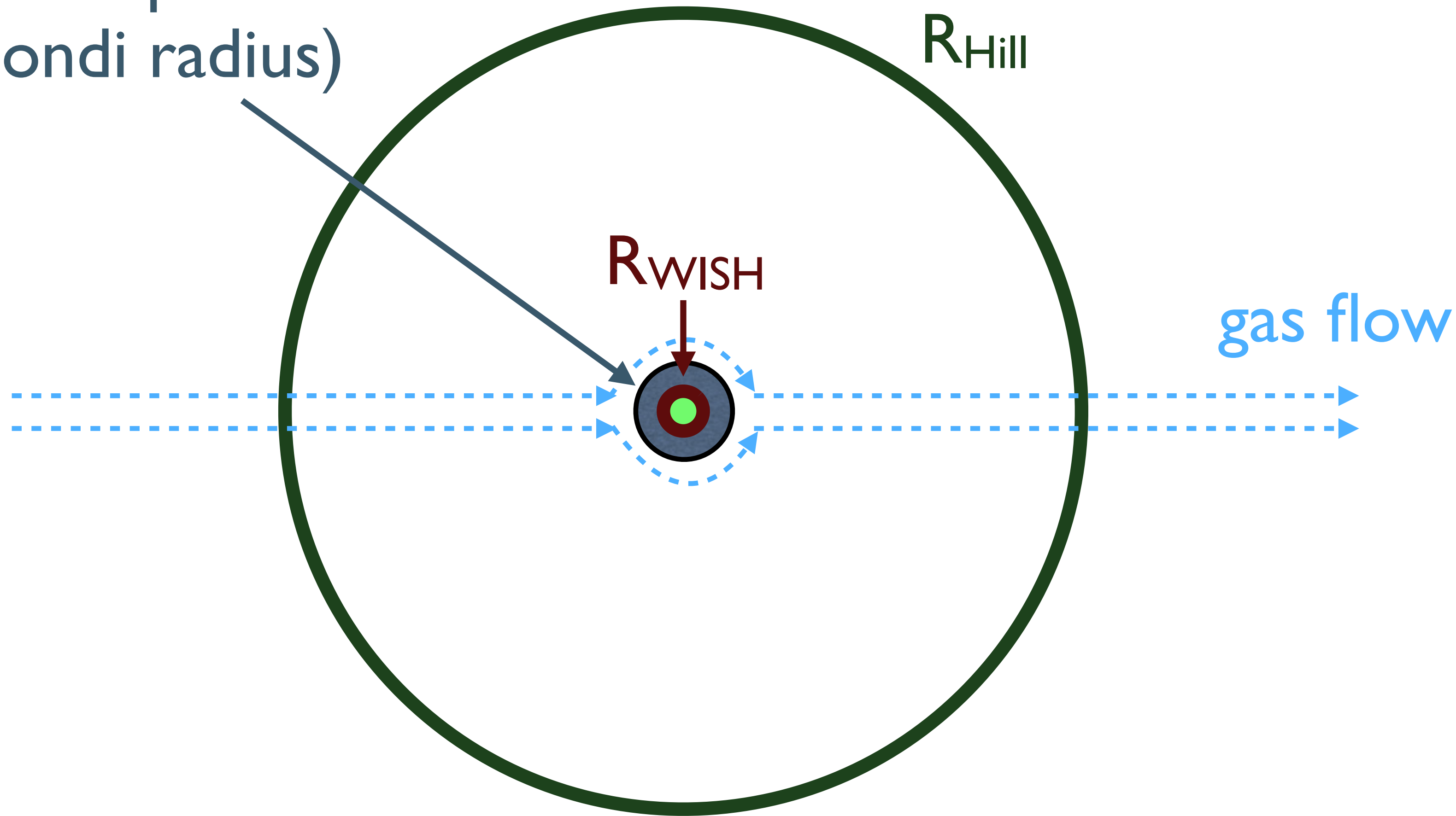
Lambrechts et al. 2014

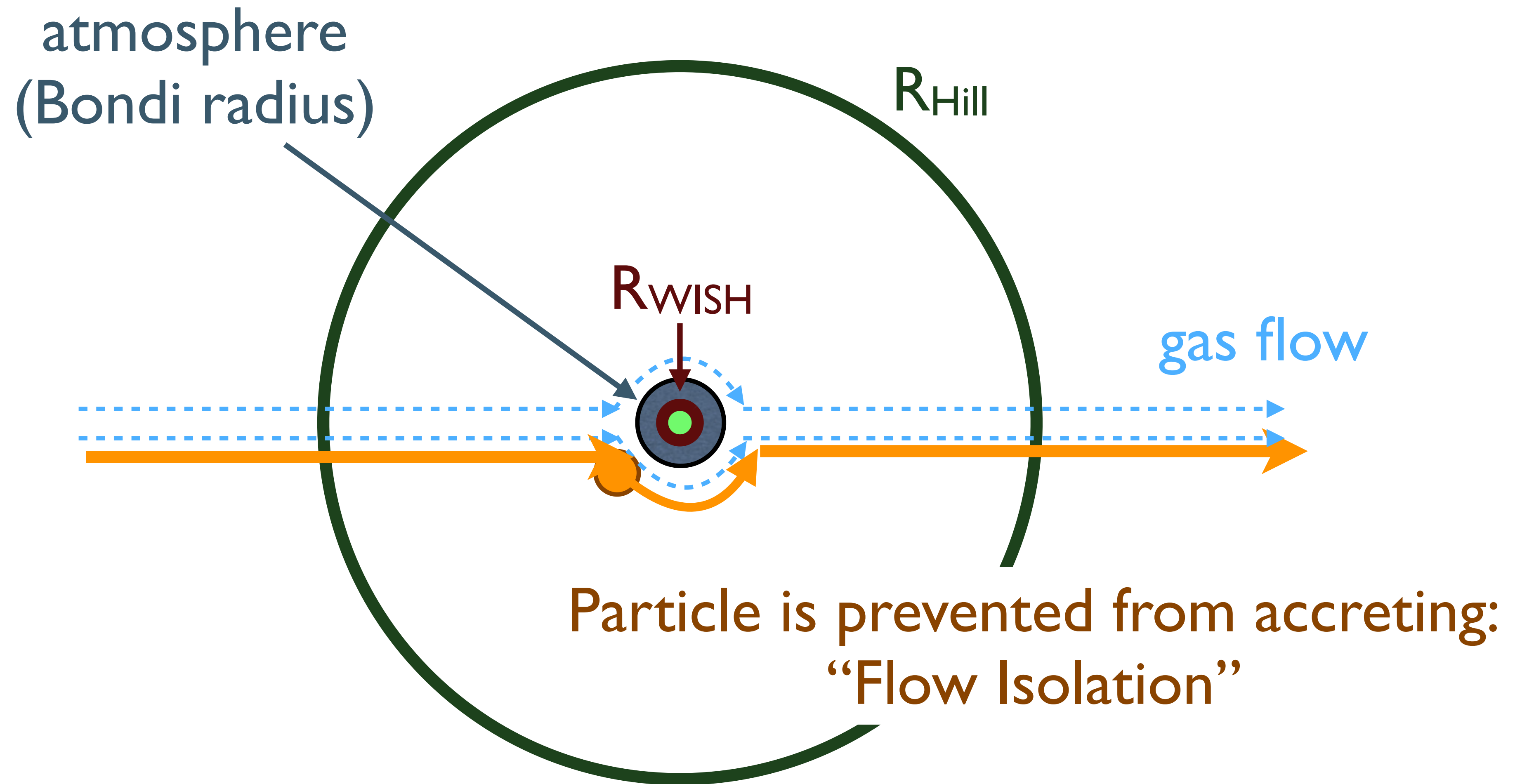
Lambrechts et al. 2014
Lambrechts & Johansen 2014
Bitsch et al. 2018

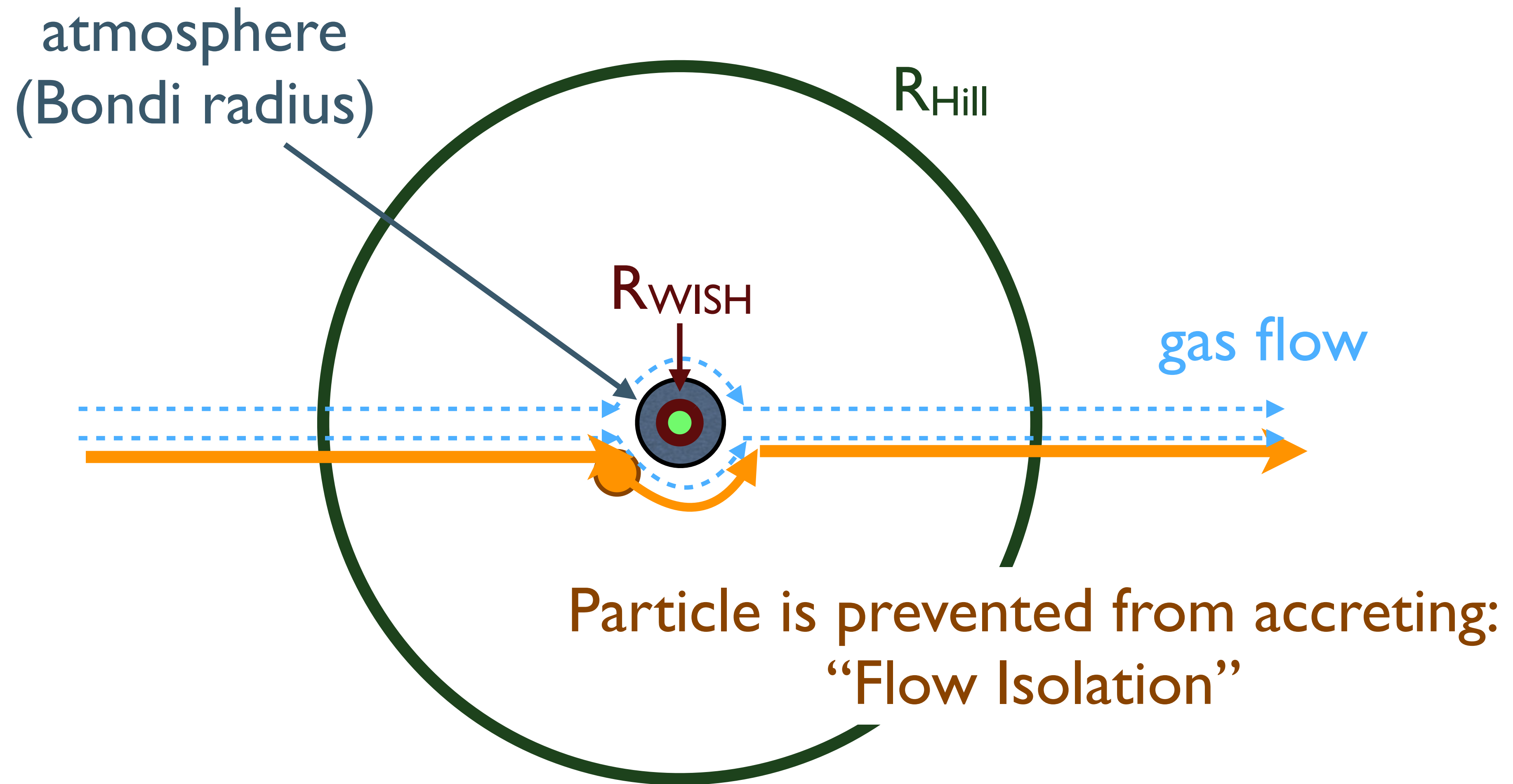
atmosphere
(Bondi radius)



atmosphere
(Bondi radius)



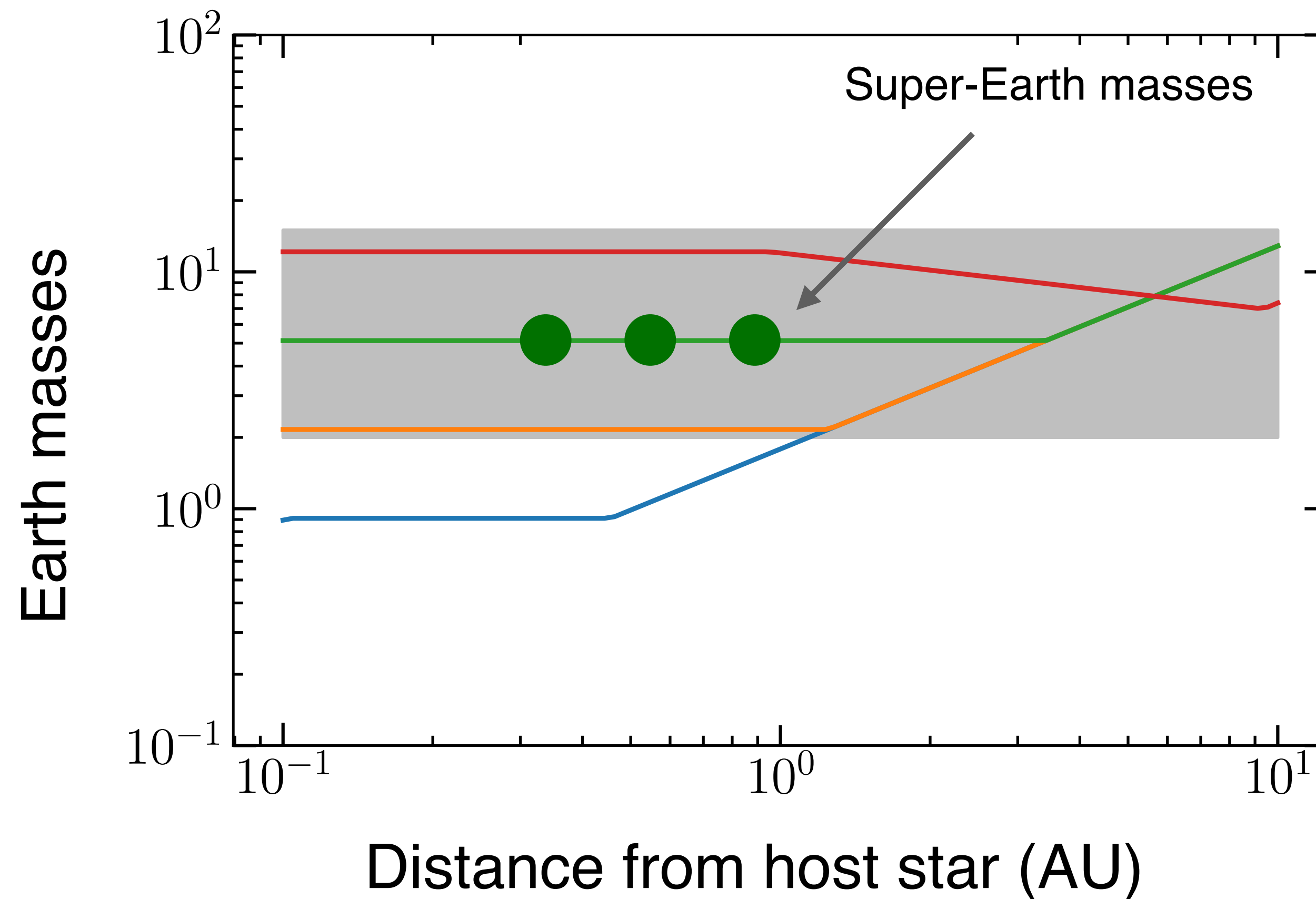




Similar mass scale to pebble isolation close in; smaller farther out

Rosenthal & Murray-Clay 2020

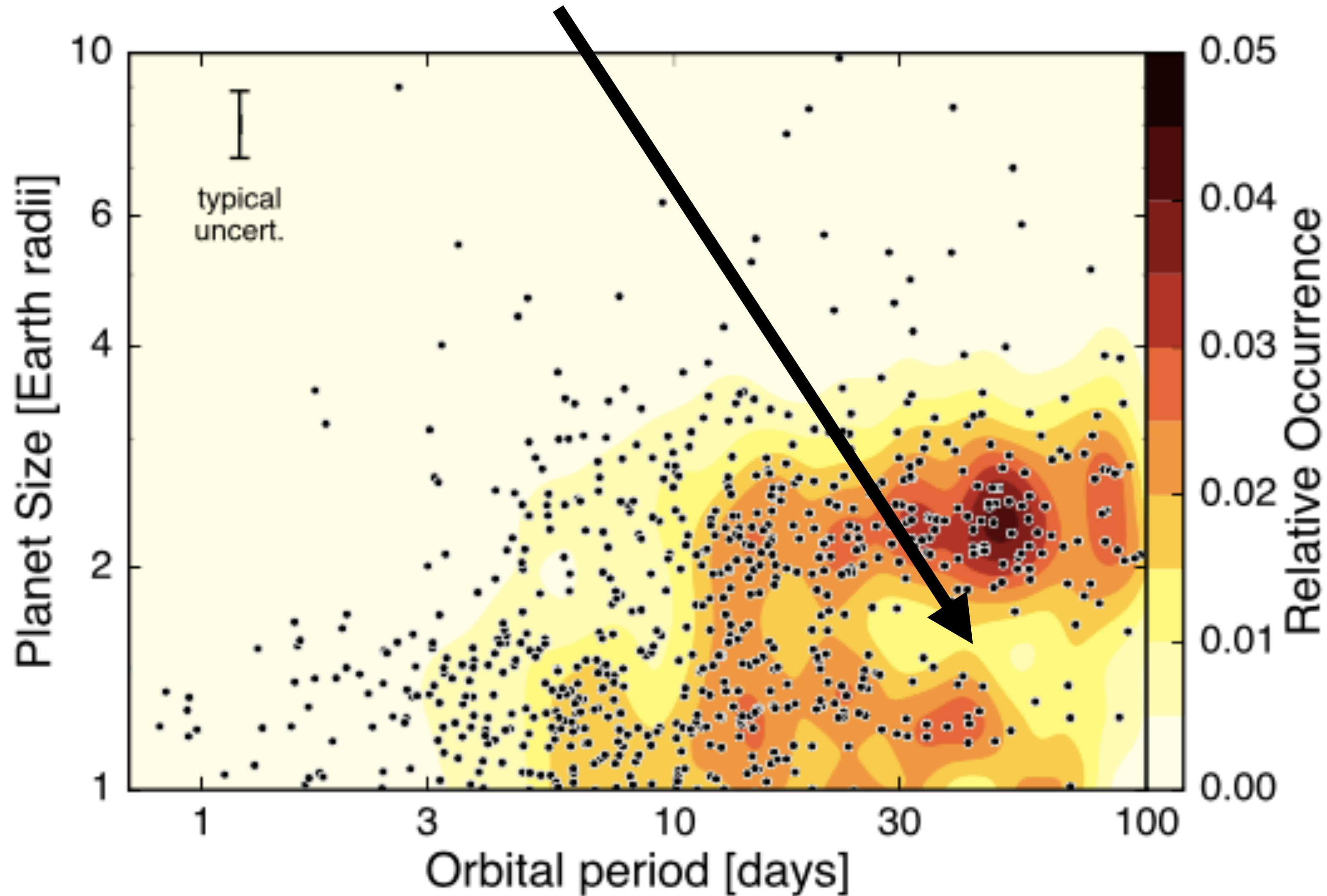
Pebble accretion could explain why super-Earths often have similar-sized siblings



but Hafnium-Tungsten dating tells us Earth's differentiation happened late

Nimmo & Kleine 2015

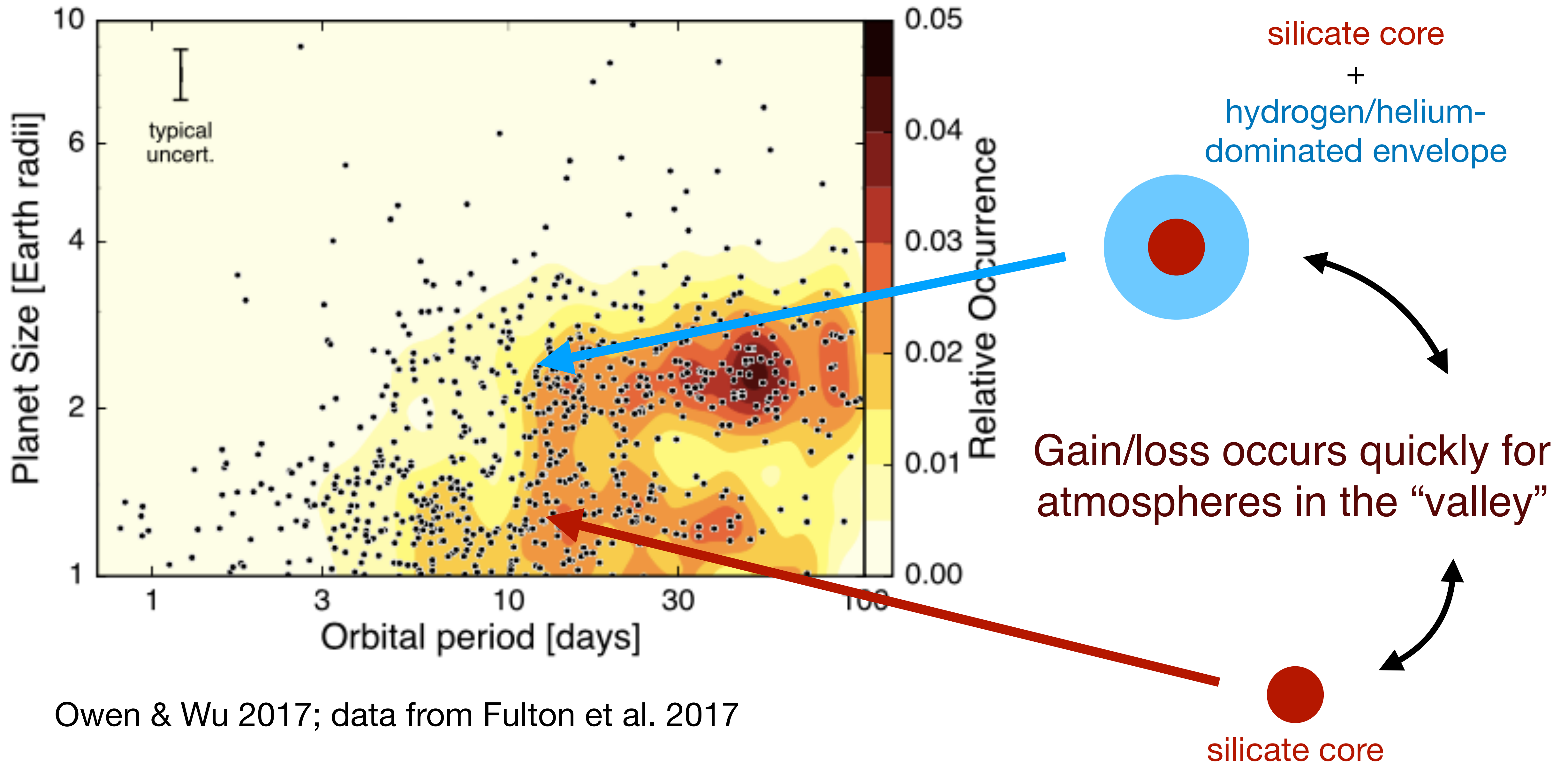
The period-radius valley suggests atmospheric escape



Predicted:
Lopez et al. 2012,
Owen & Wu 2013,
Lopez & Fortney 2013

Owen & Wu 2017; data from Fulton et al. 2017

Gap because a small amount of atmospheric mass produces a lot of puffing

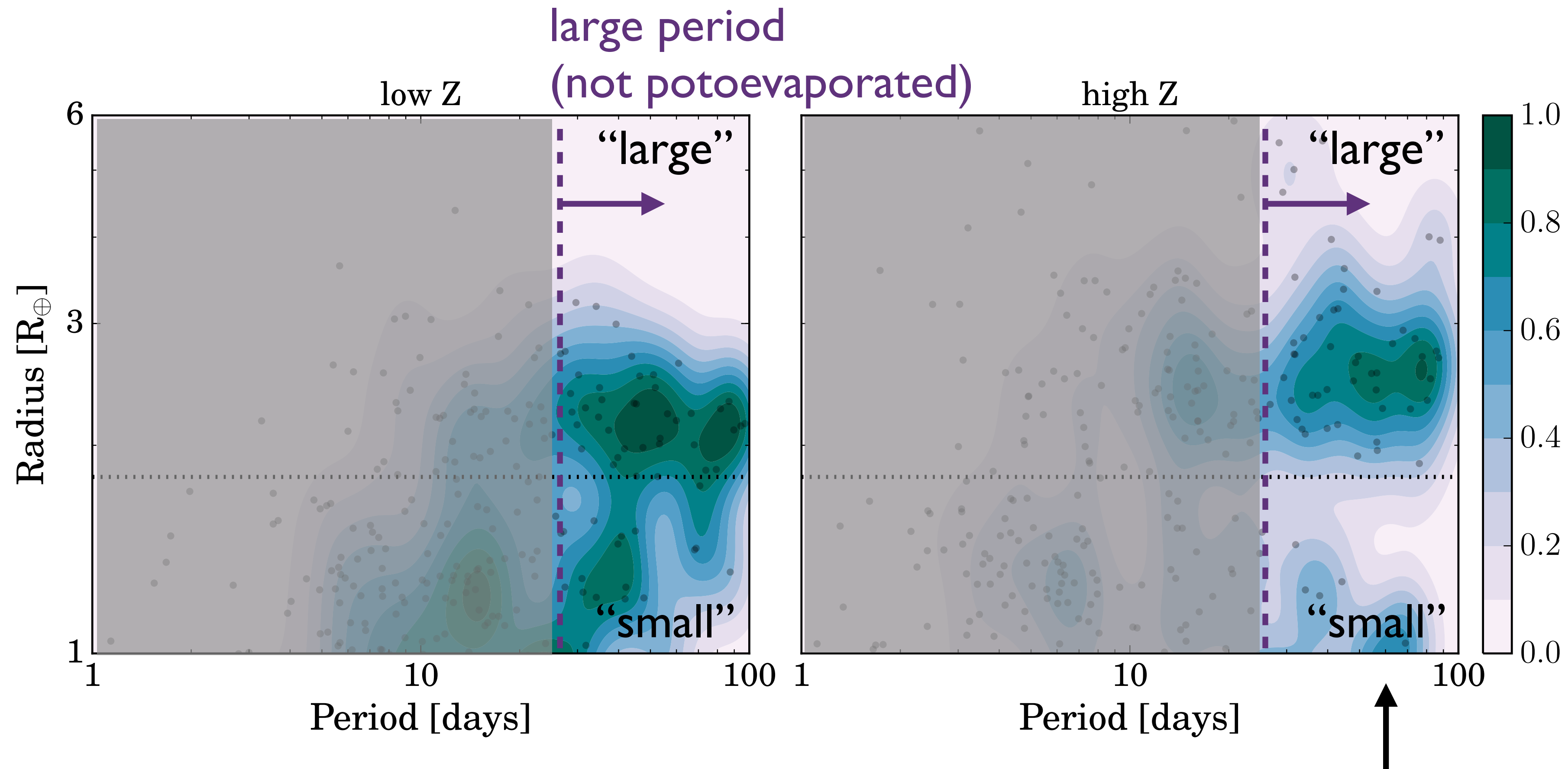


Owen & Wu 2017; data from Fulton et al. 2017

Three types of models can fit the valley

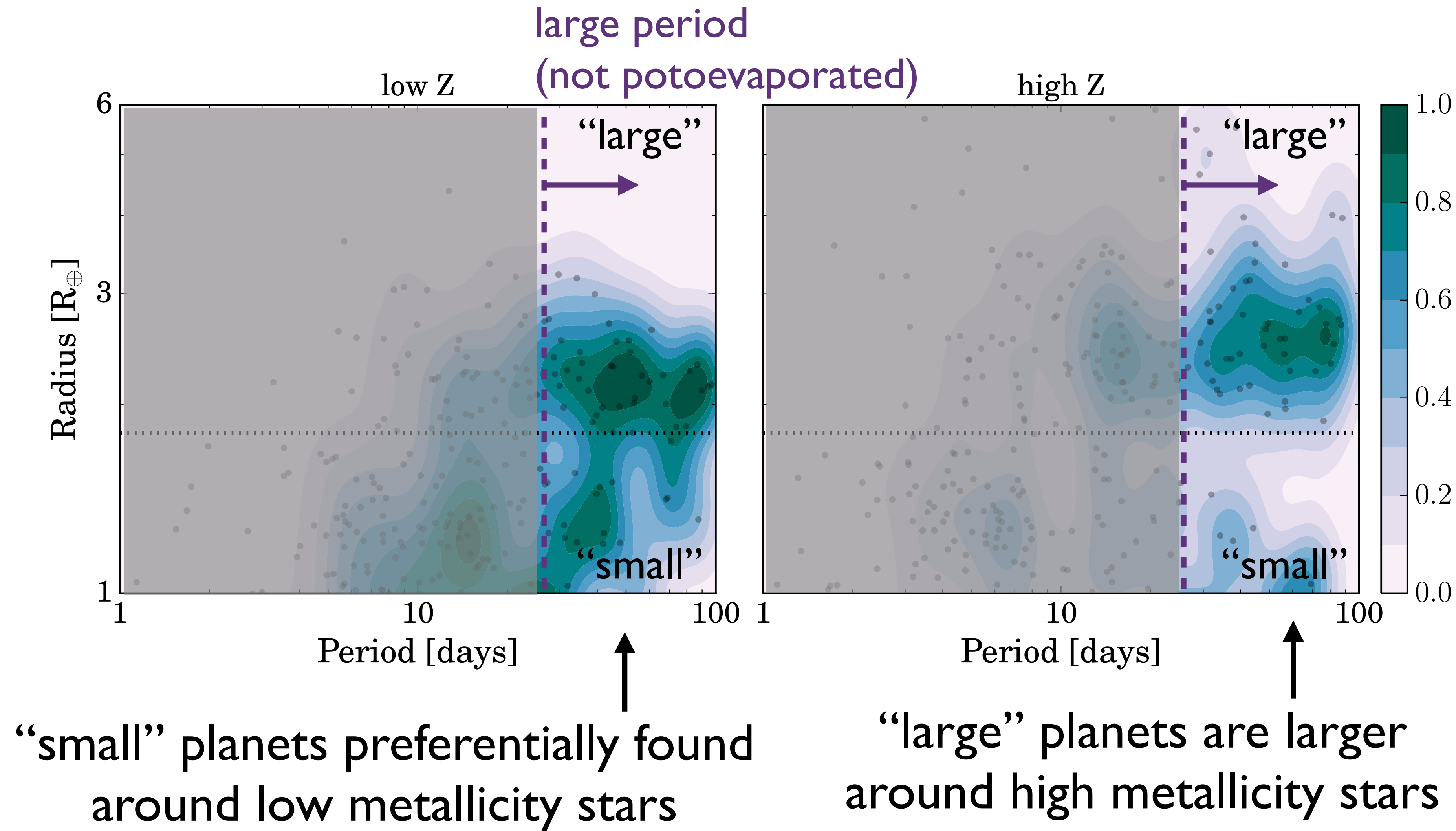
Largely because not enough masses are measured

At large periods, we do not expect atmospheric escape to dominate



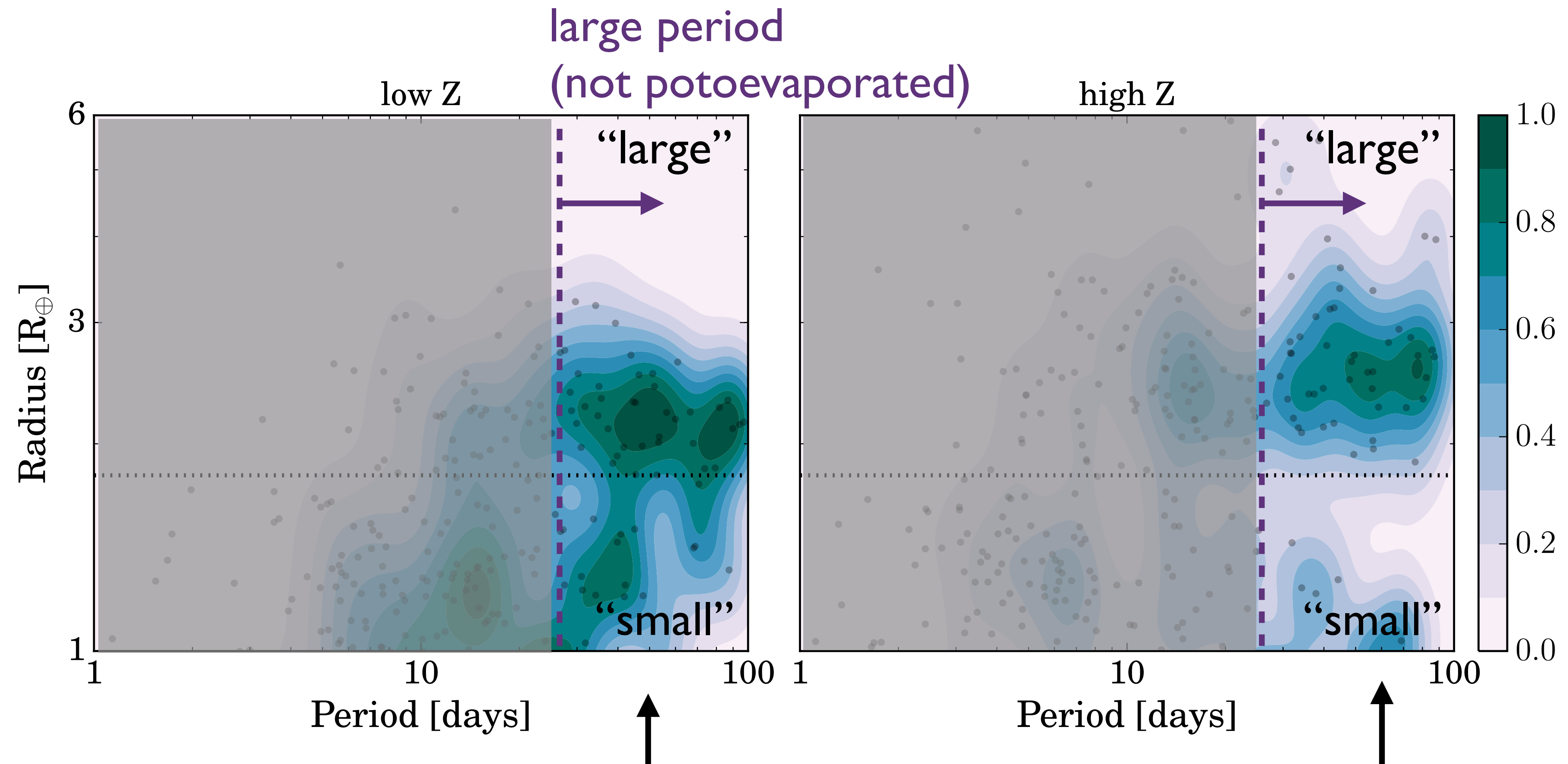
Owen & Murray-Clay (2018); CKS sample (Fulton et al. 2017)

At large periods, we do not expect atmospheric escape to dominate



See Kutra et al. (2021) who argue stellar mass correlation instead; Chen et al. (2022) find metallicity correlation using LAMOST-Gaia-Kepler catalog

Owen & Murray-Clay (2018); CKS sample (Fulton et al. 2017)



“small” planets preferentially found
around low metallicity stars

“large” planets are larger
around high metallicity stars

Prediction (Roman):

Terrestrial planets at wide separations will have a different mass
distribution than close-in stripped planets.

planet

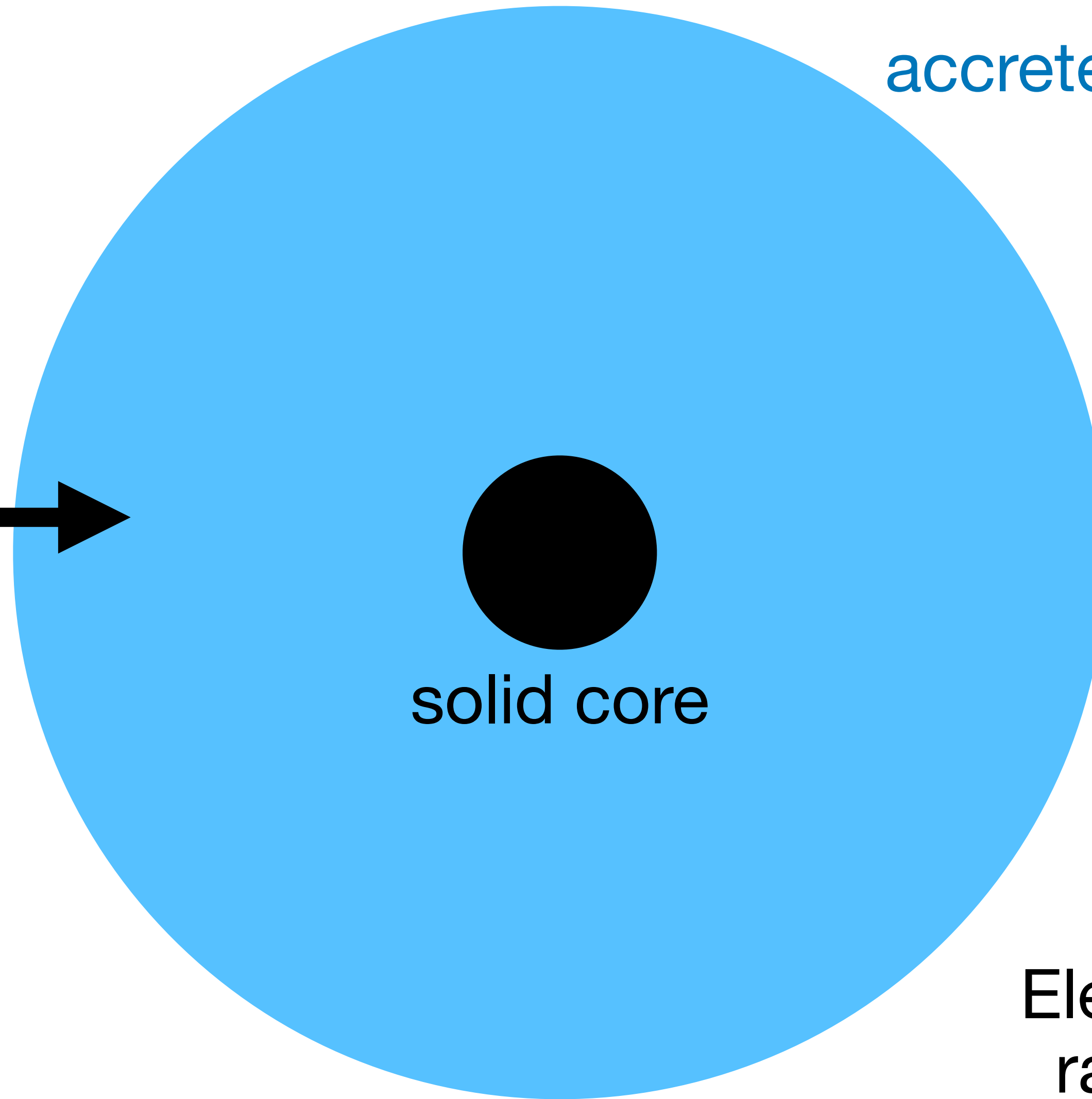
accreted gas

●
extra
accreted
solids

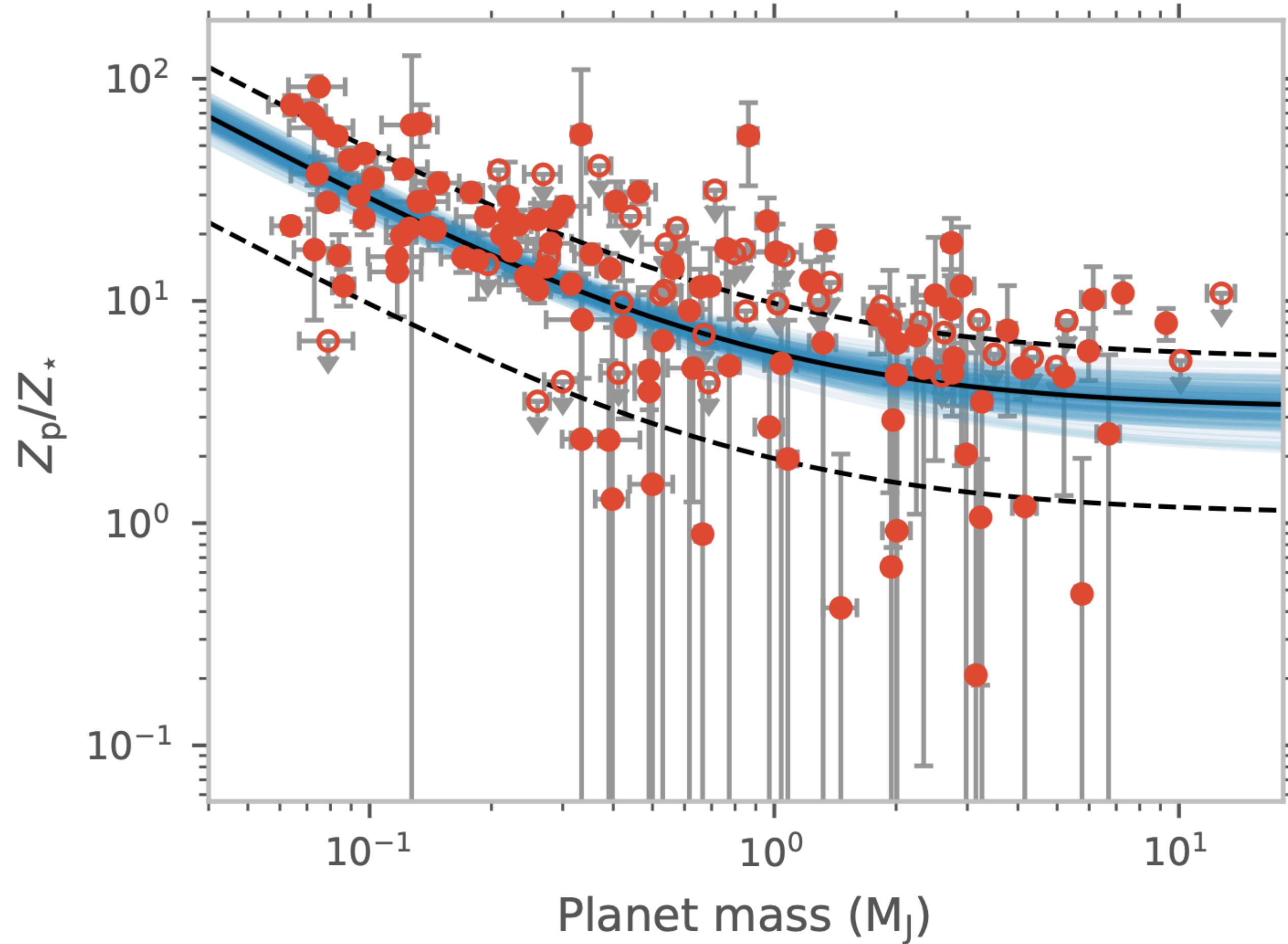


solid core

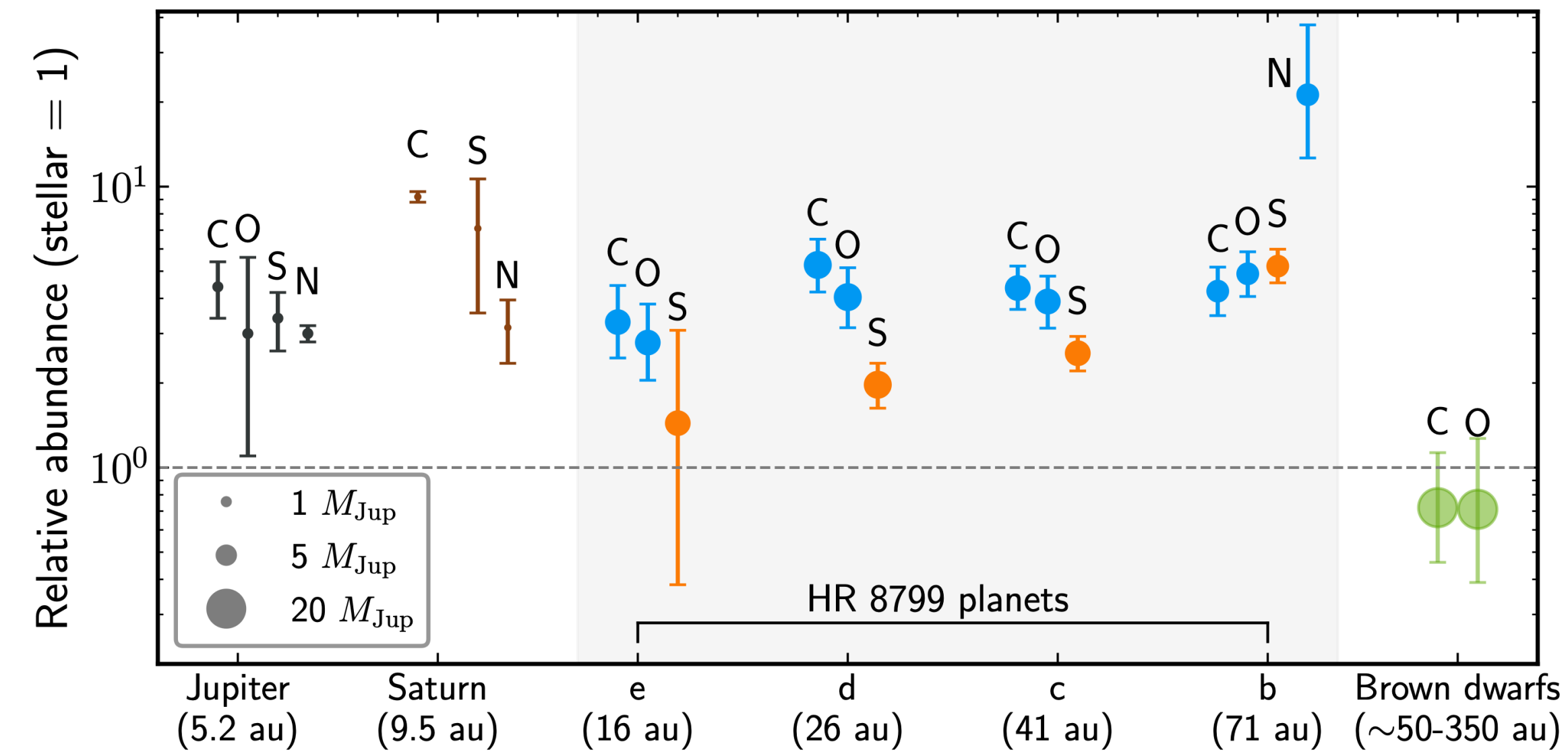
Elemental abundance
ratios not expected
to match those of the
star



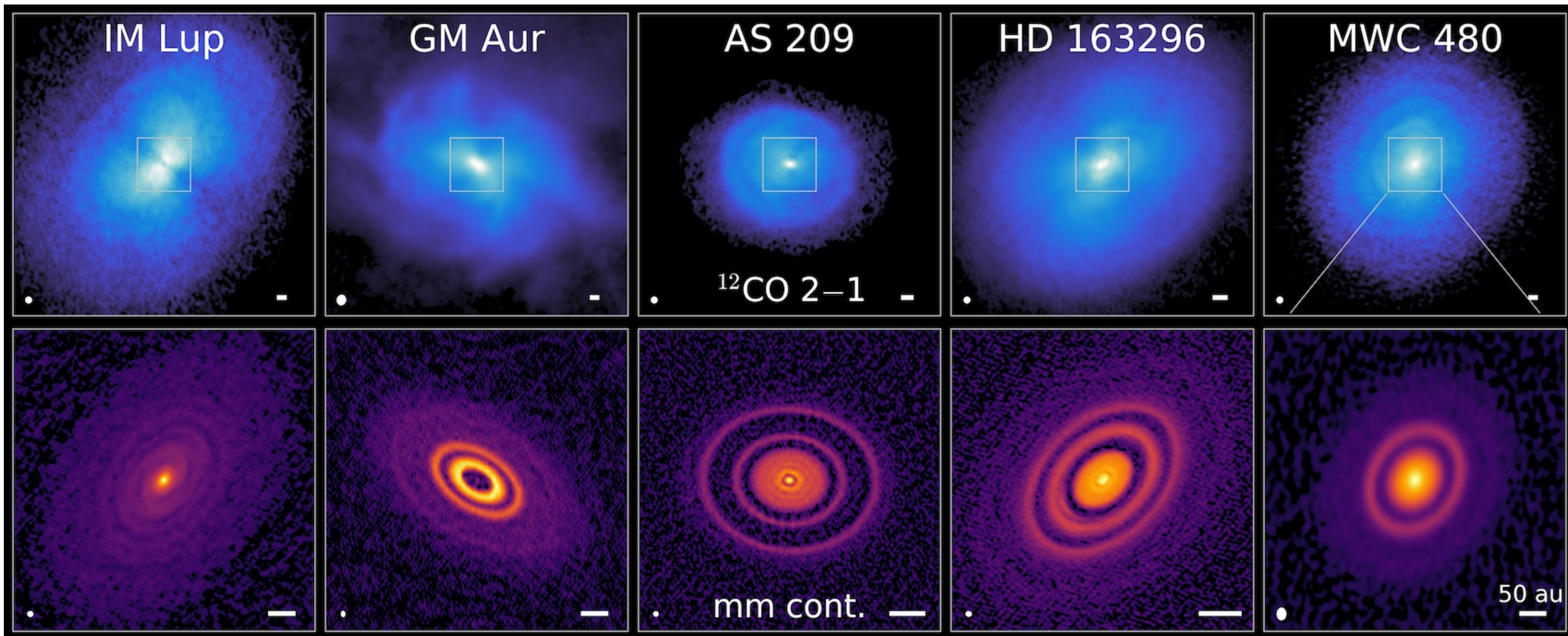
Even hydrogen-helium-dominated atmospheres have substantial metallicity

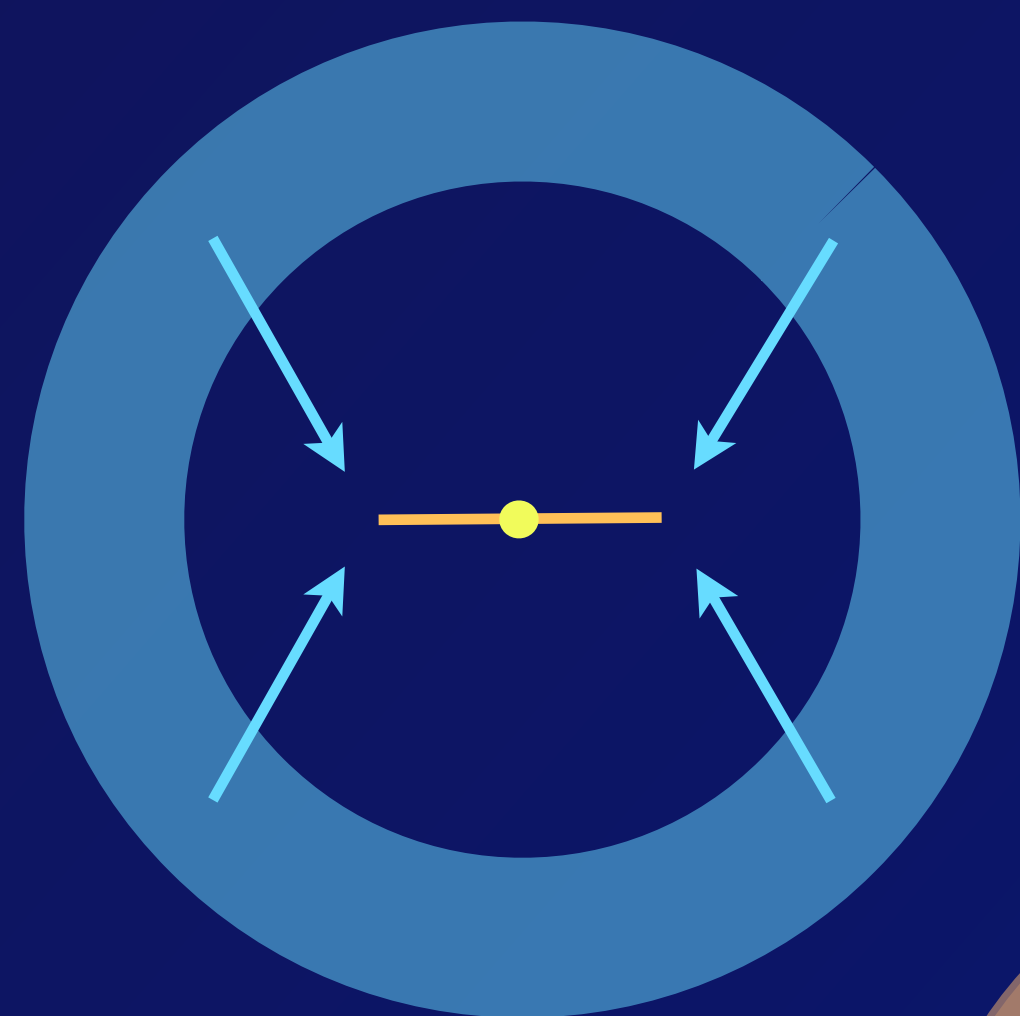


Chachan et al. 2025;
Thorngren et al. 2016

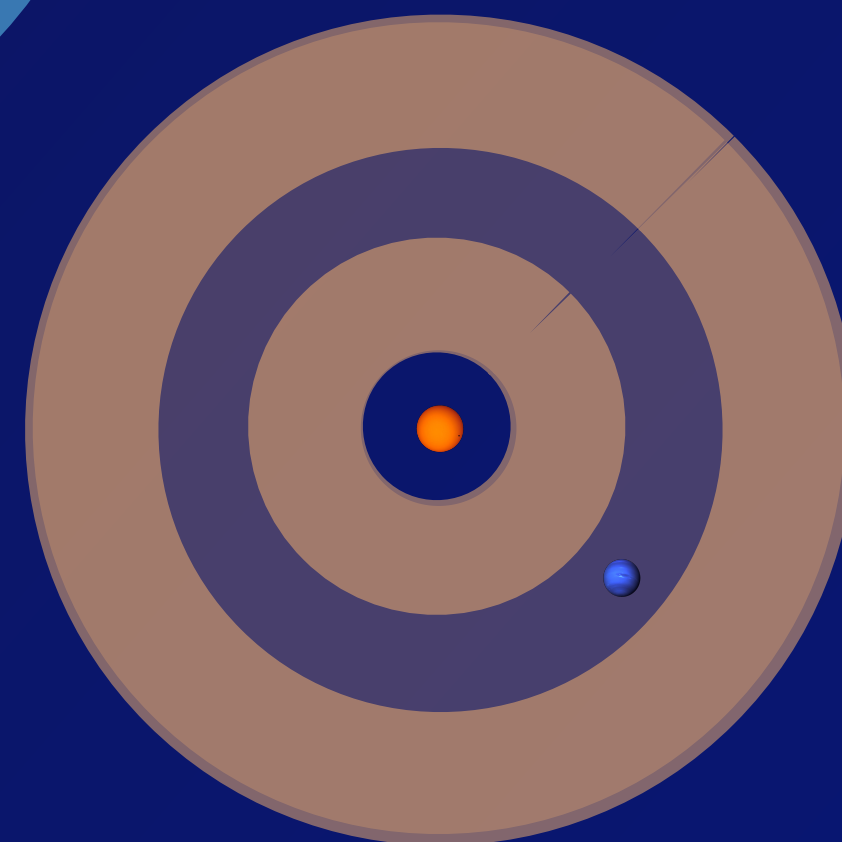


Xuan et al. 2026

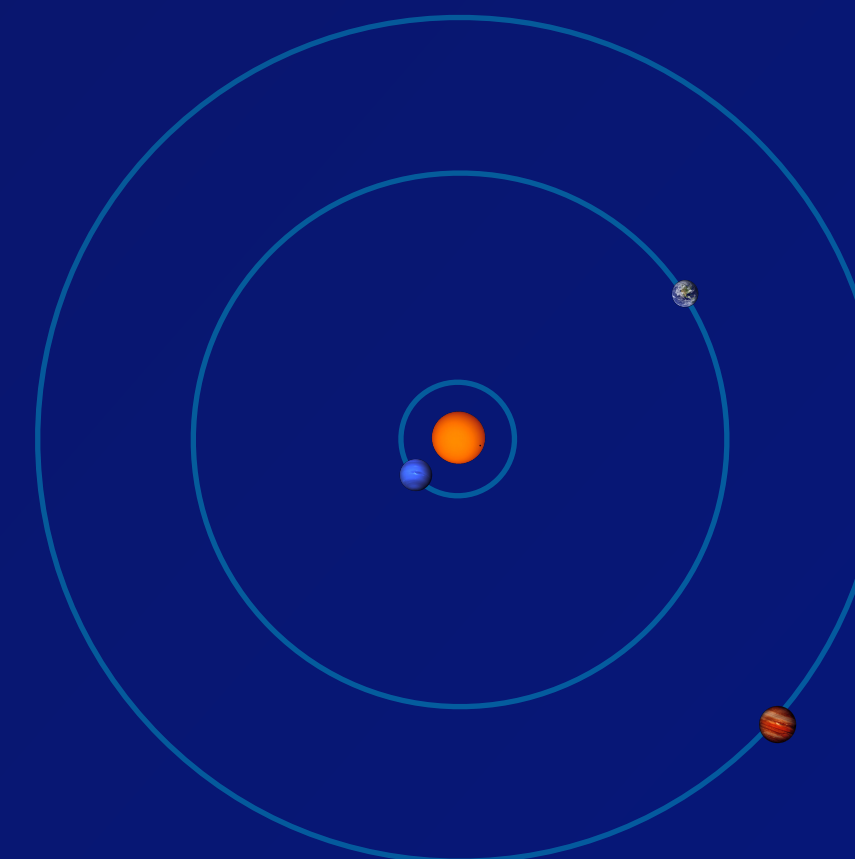




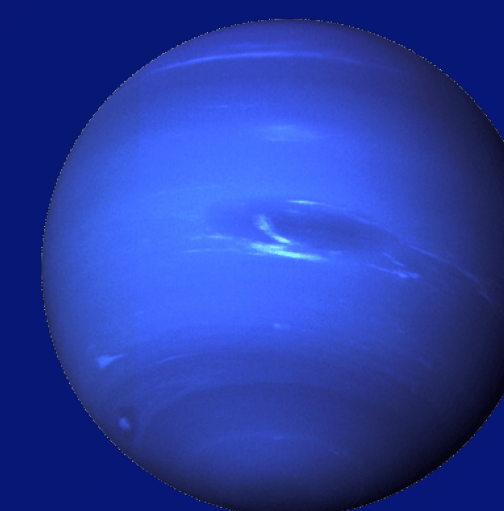
disk
formation



planet
formation

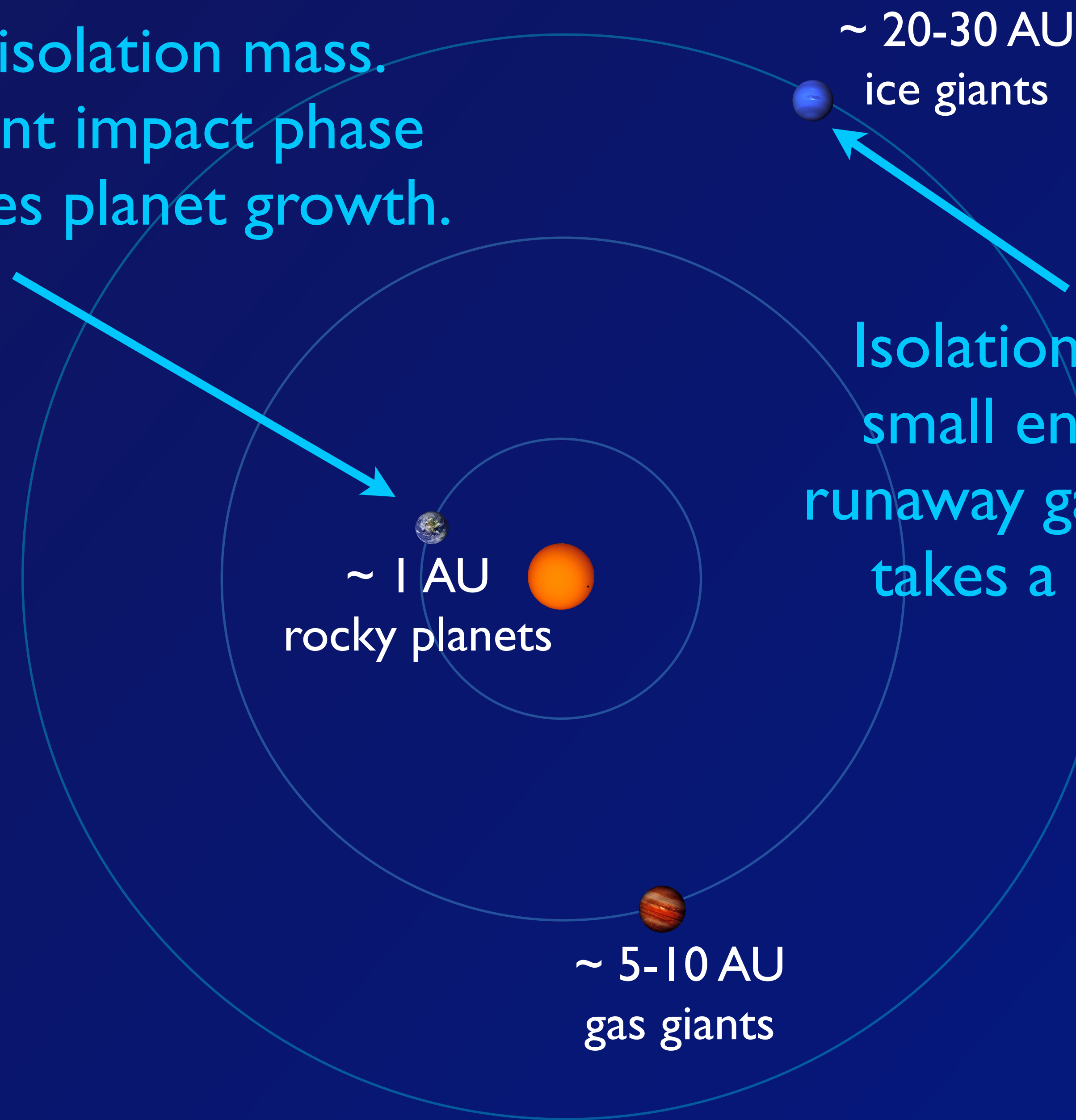


dynamical
evolution



atmospheres

Small isolation mass.
Late giant impact phase
completes planet growth.



~ 1 AU
rocky planets

~ 5-10 AU
gas giants

~ 20-30 AU
ice giants

Isolation mass just
small enough that
runaway gas accretion
takes a long time

Roman will constrain a critical new parameter space!

Even a “boring” confirmation of our general
understanding would be exciting
(though as always we should expect surprises)