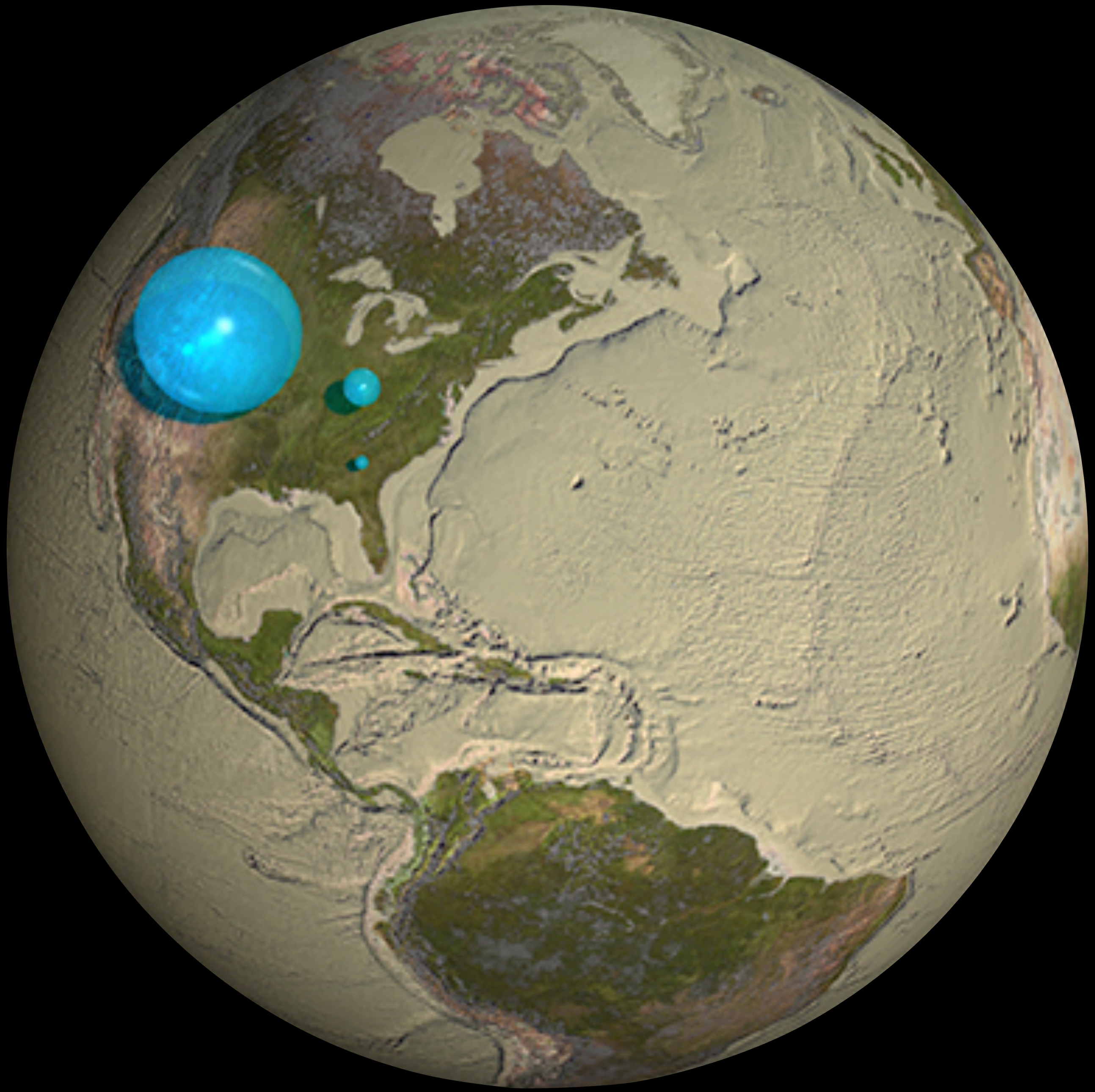
# Dynamical water delivery: how Earth and rocky exoplanets get wet

Sean Raymond
Laboratoire d'Astrophysique de Bordeaux
with Andre Izidoro and Alessandro Morbidelli

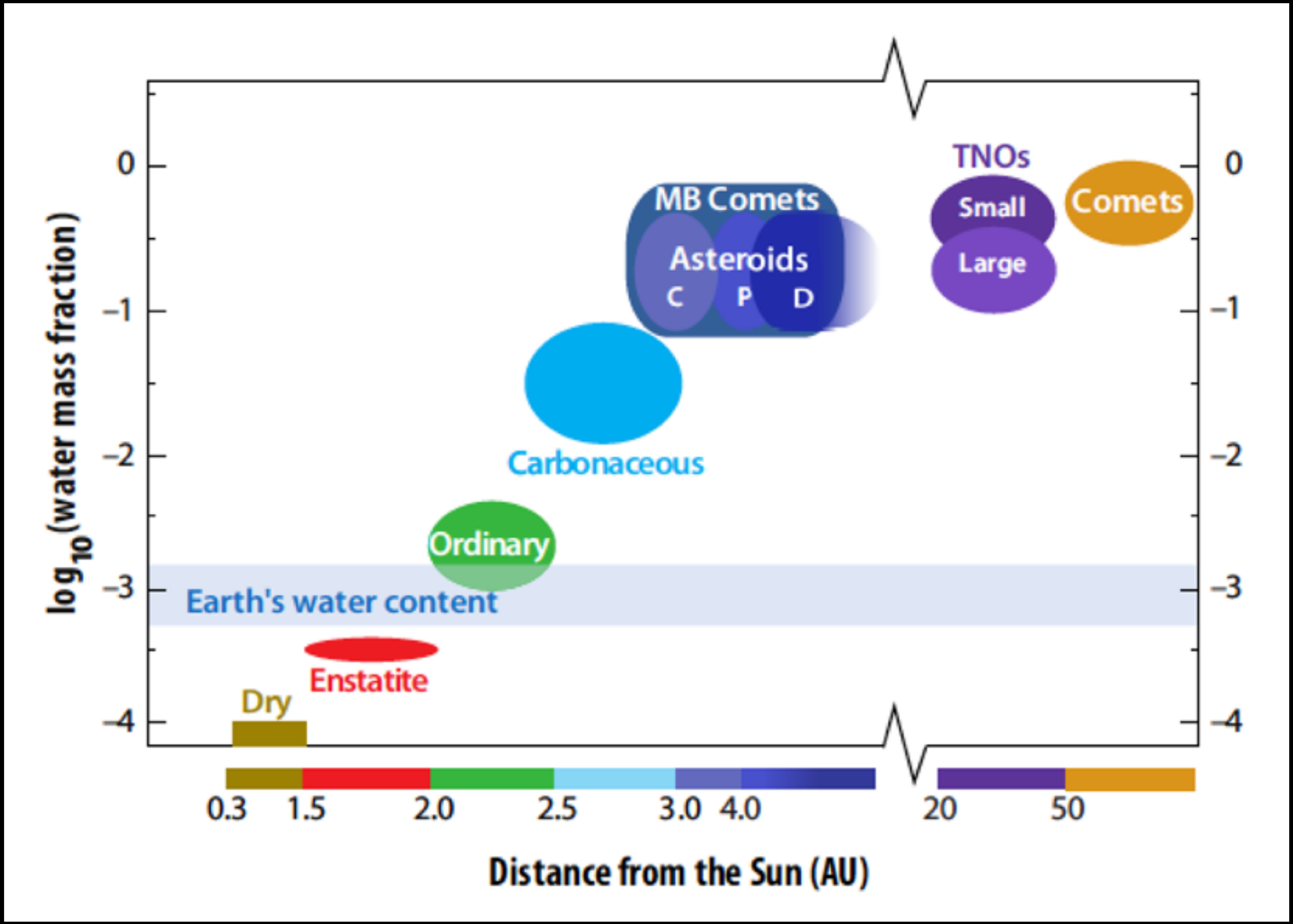
# Is Earth dry or wet?

- Surface water = 1 "ocean"
- Mantle: <0.3 to >10 oceans (Lecuyer et al 1998; Panero 2016, Marty 2012; Halliday 2013)
- Core: <0.1 to >50 oceans (Badro et al 2014, Nomura et al 2014)

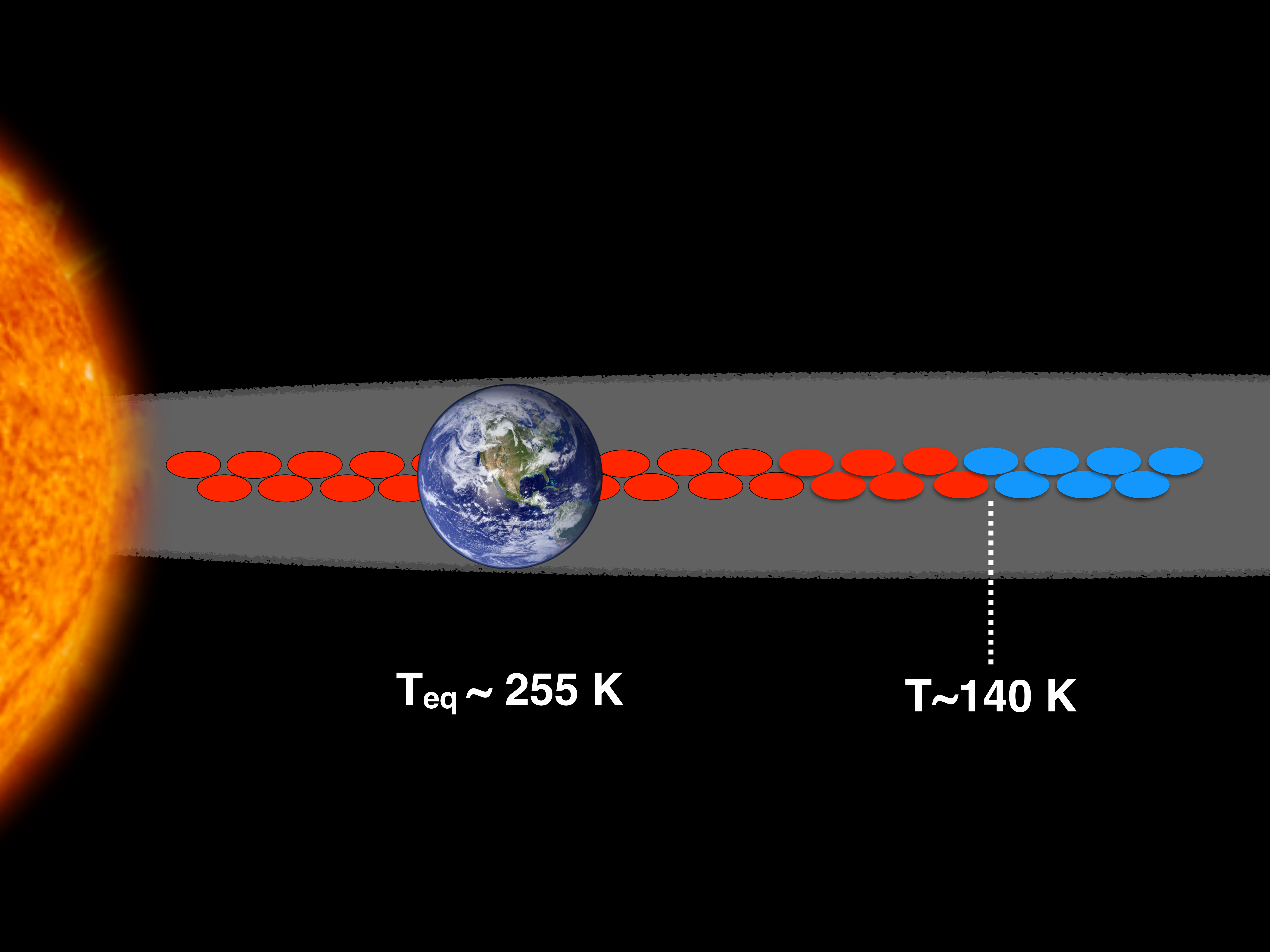


Total: $M_{water} \sim 0.1\% \; M_{Earth}$

# Water in small bodies




von Dishoeck et al 2014, PP6

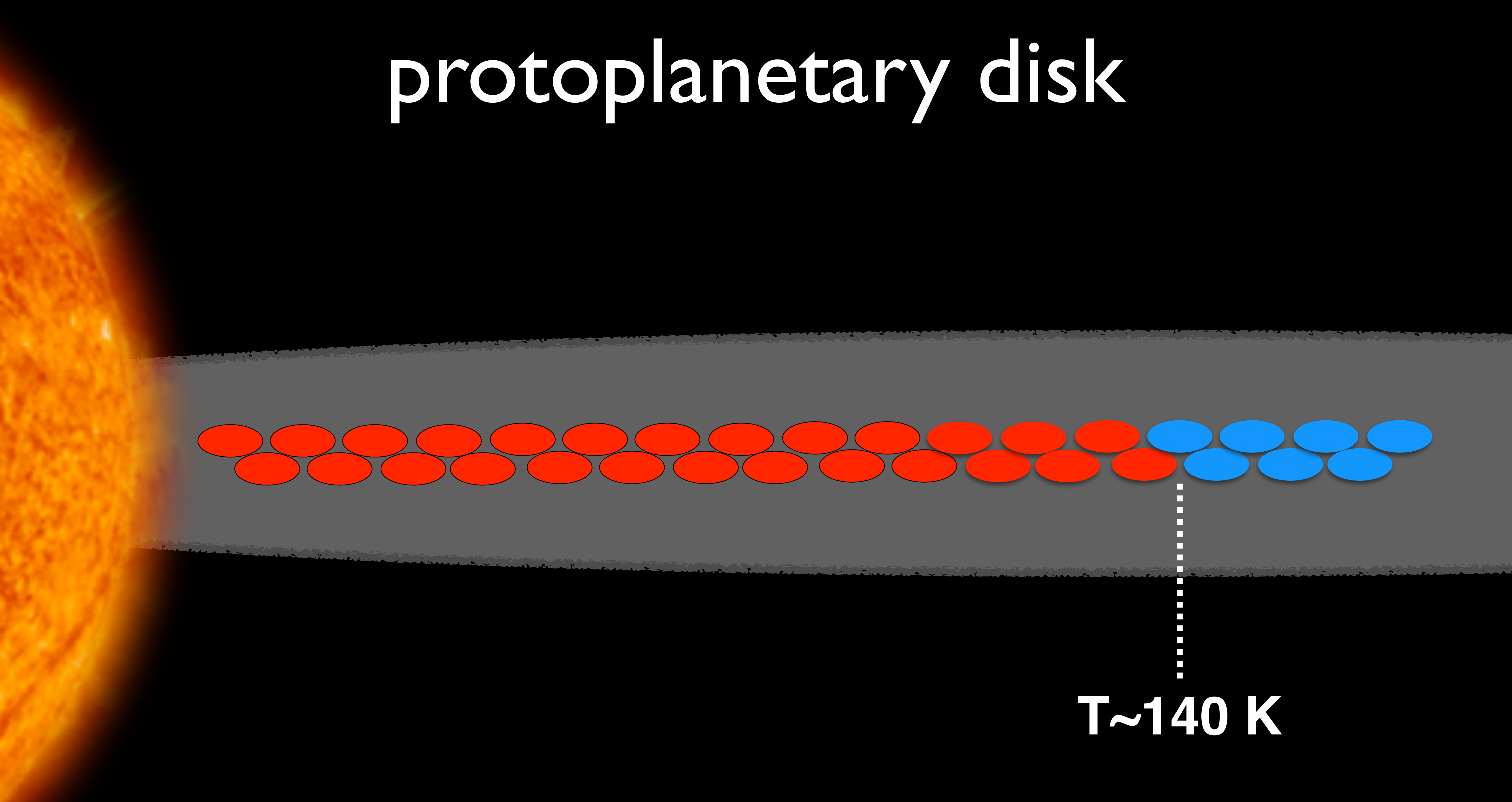

$T_{eq}$ ~ 255 K
T~140 K

# 4 mechanisms of water delivery

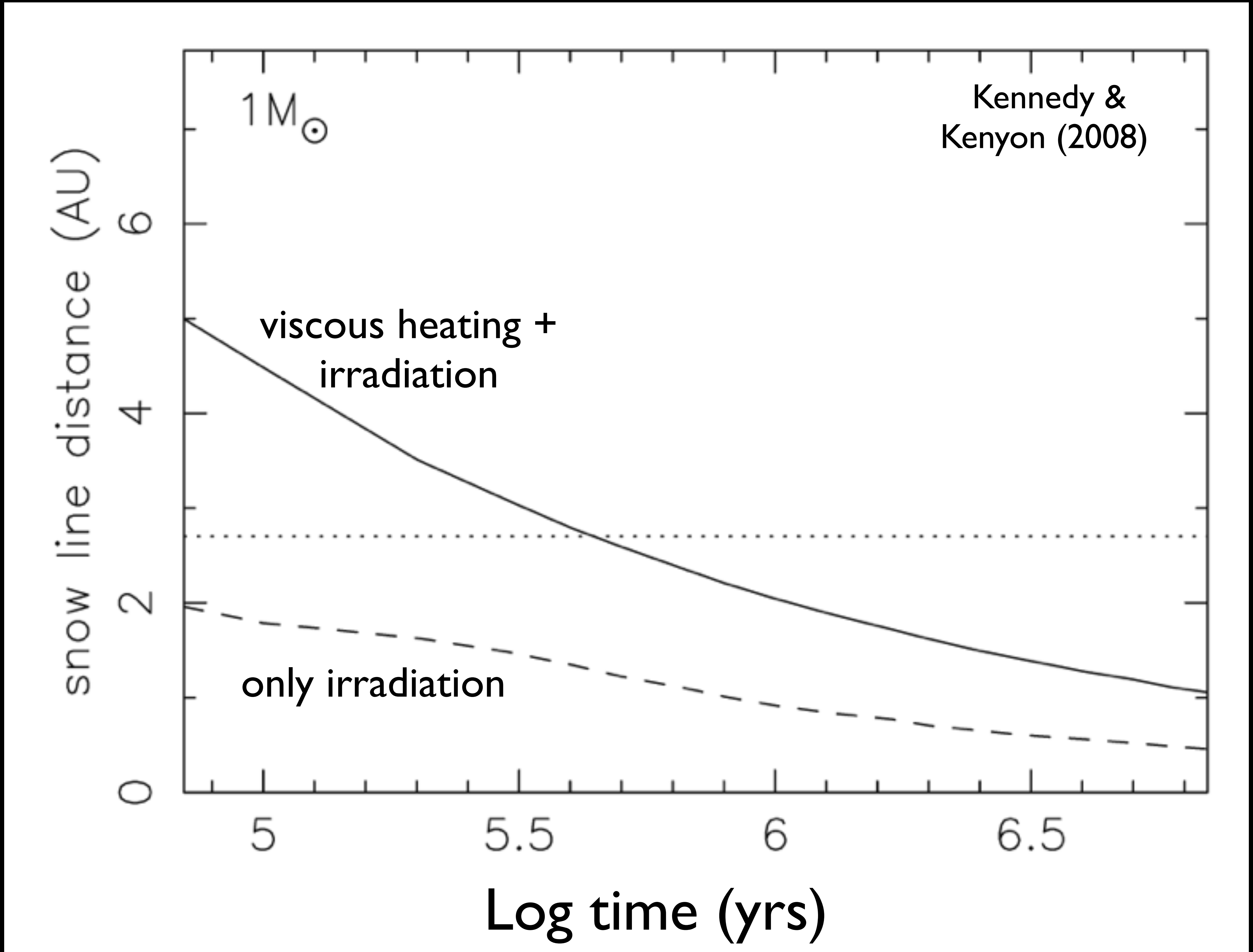
1. Pebble snow
2. Wide feeding zone
3. External pollution
4. Inward migration

# 1. Pebble snow

# Distribution of water in a protoplanetary disk

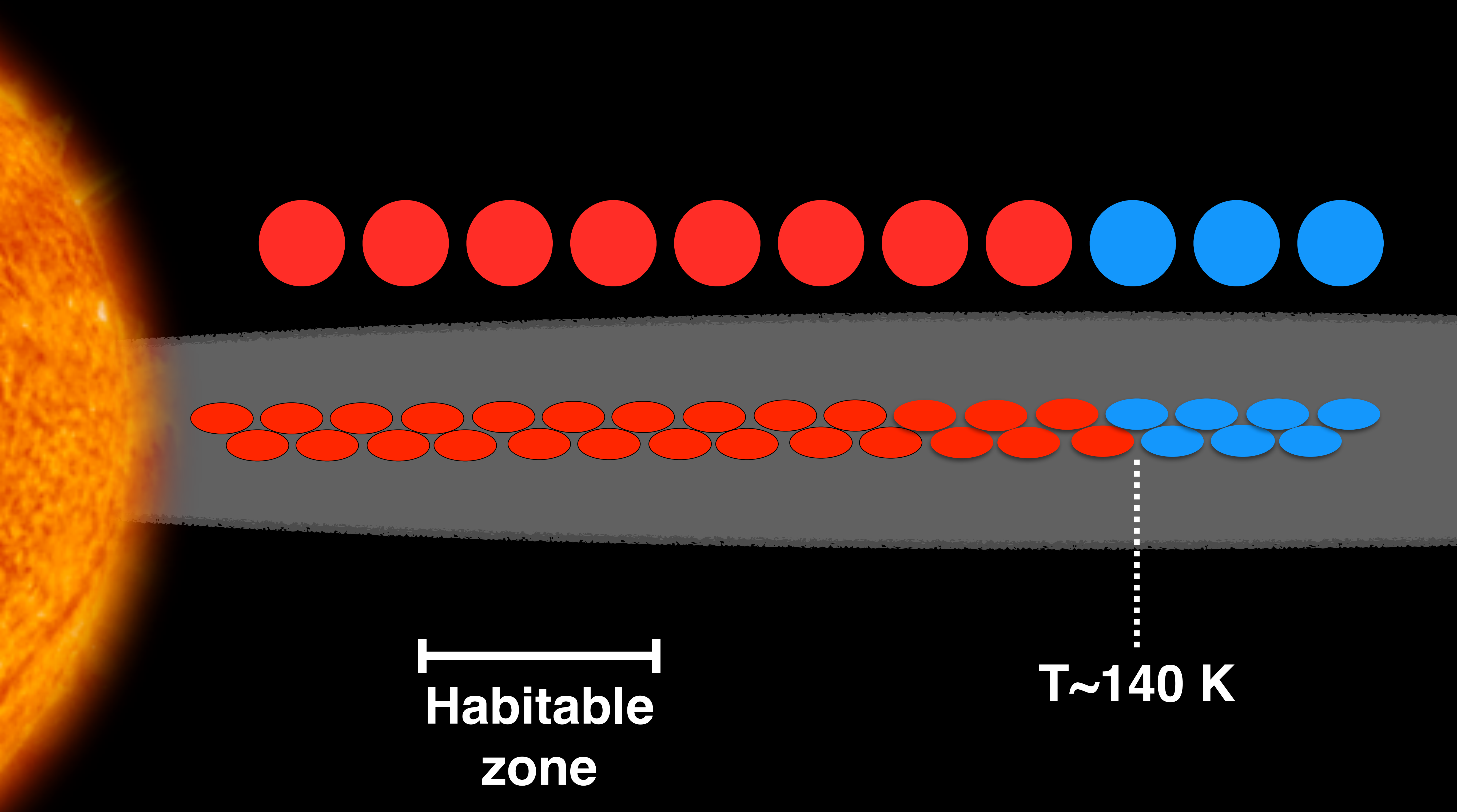



Temperature determined by viscous heating, irradiation (e.g., Chiang & Goldreich 1997; Ciesla & Cuzzi 2006)

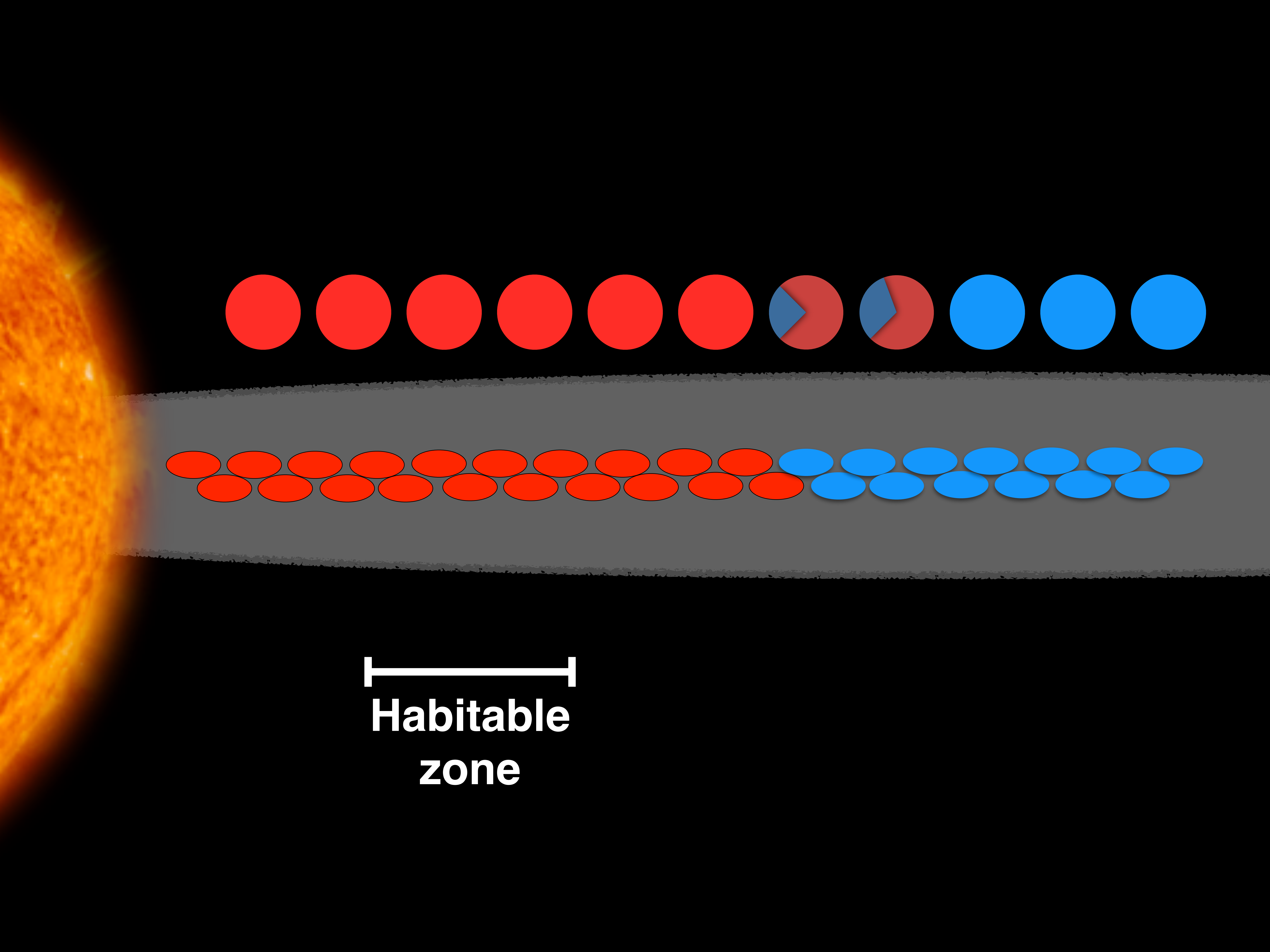


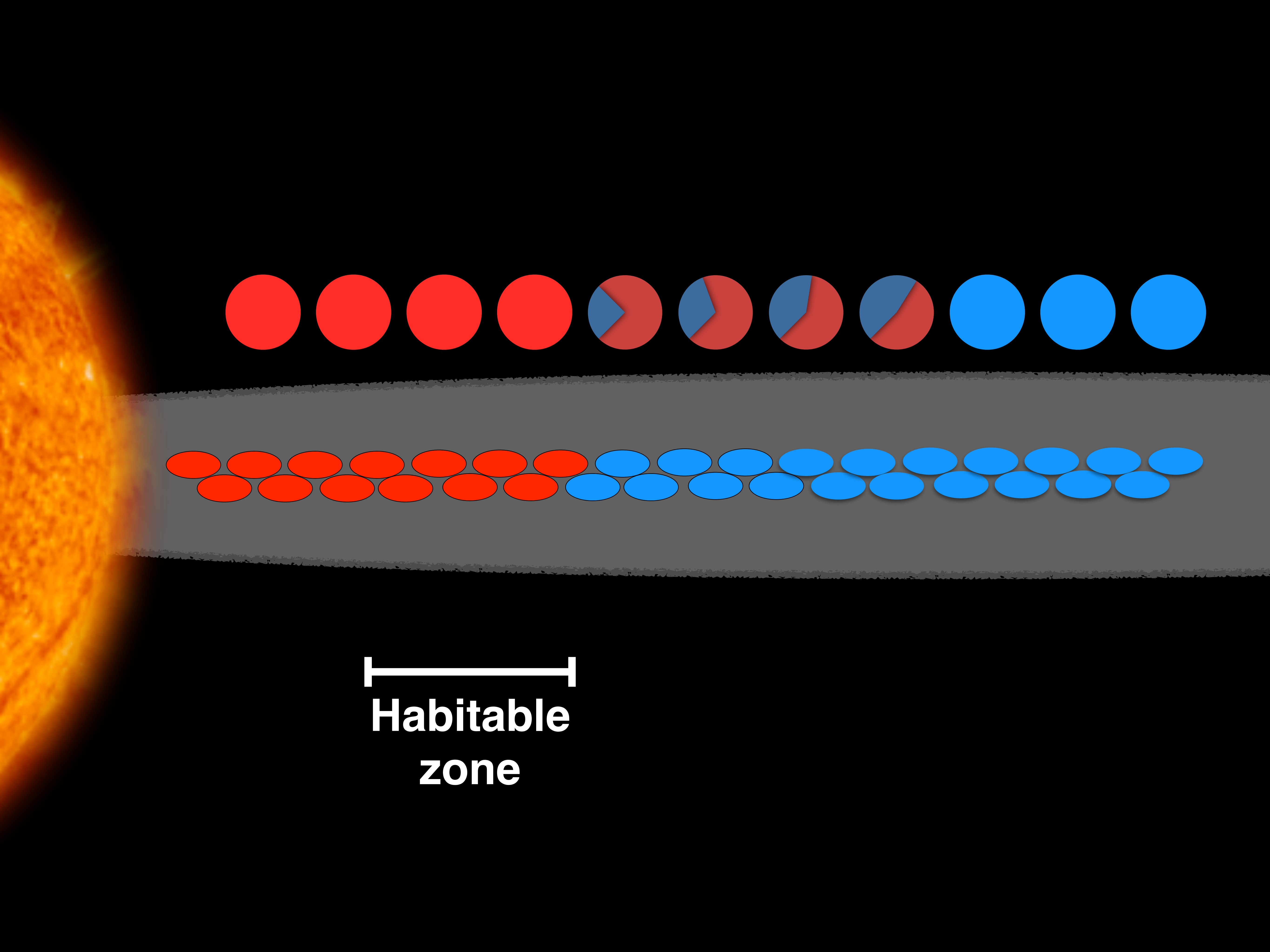

As disk cools, snow line moves inward

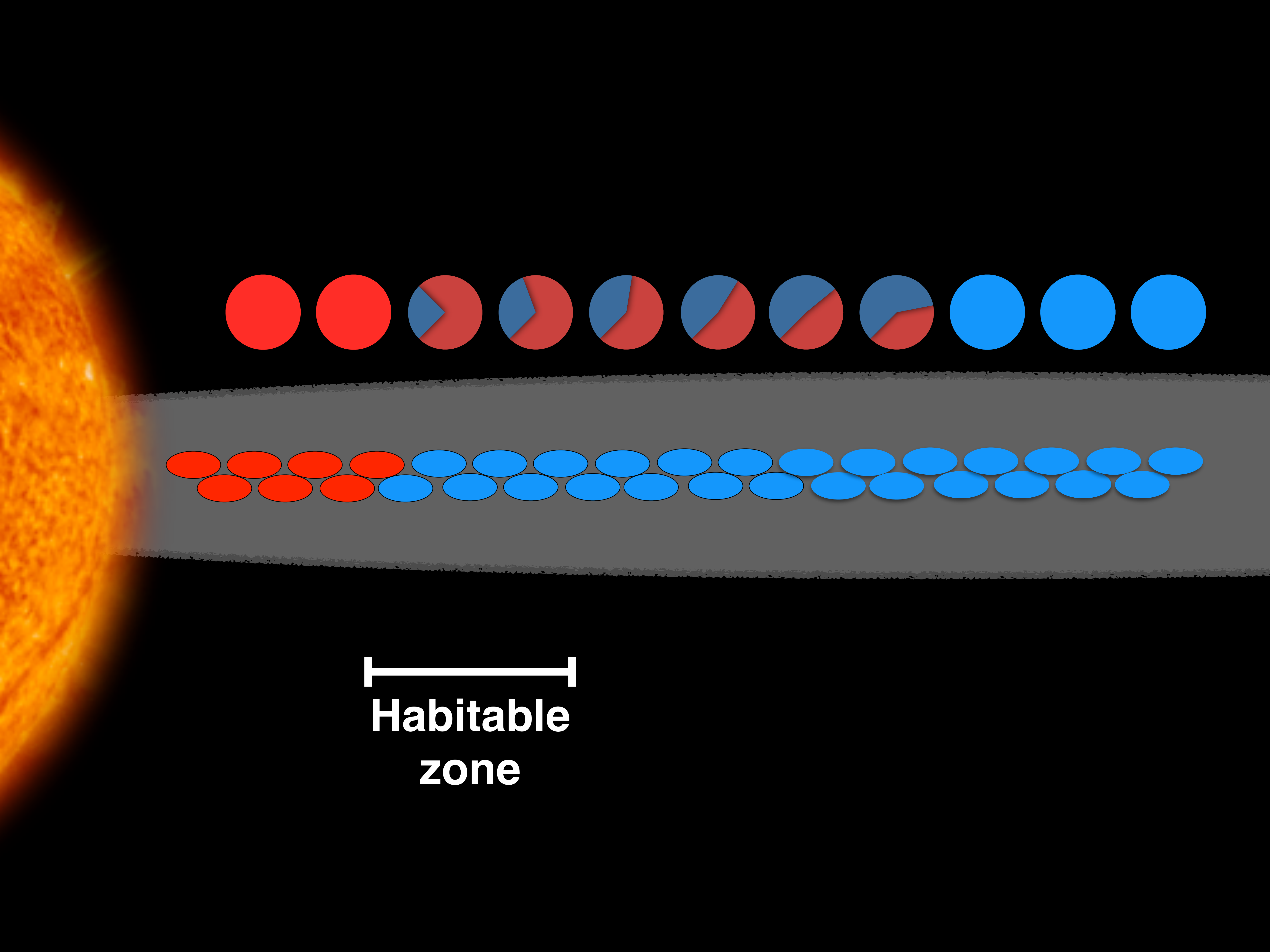
(e.g., Sasselov & Lecar 2000; Dodson-Robinson et al 2009; Martin & Livio 2012; Ciesla et al 2015)

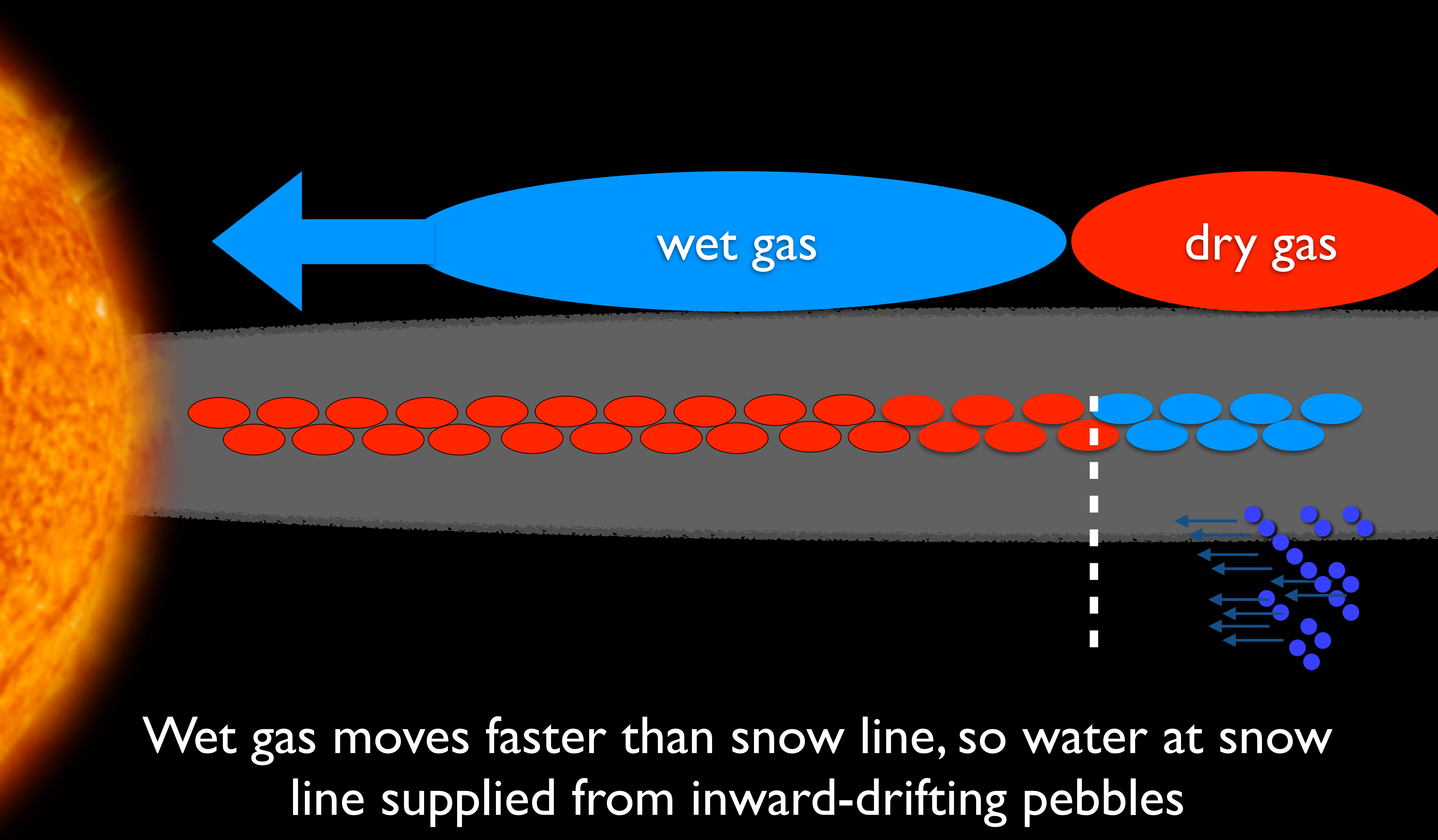


Habitable
zone
T~140 K

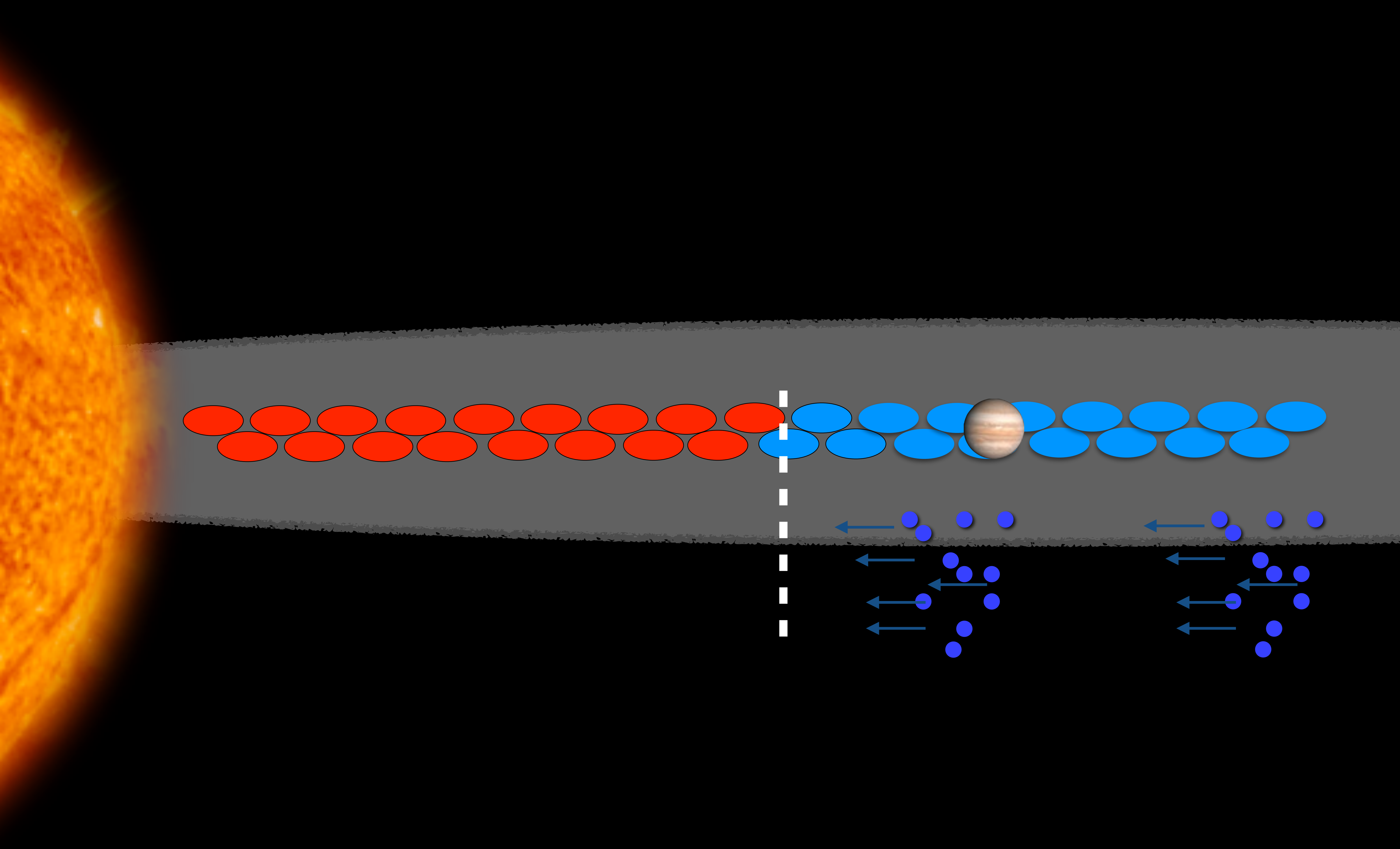

Habitable
zone

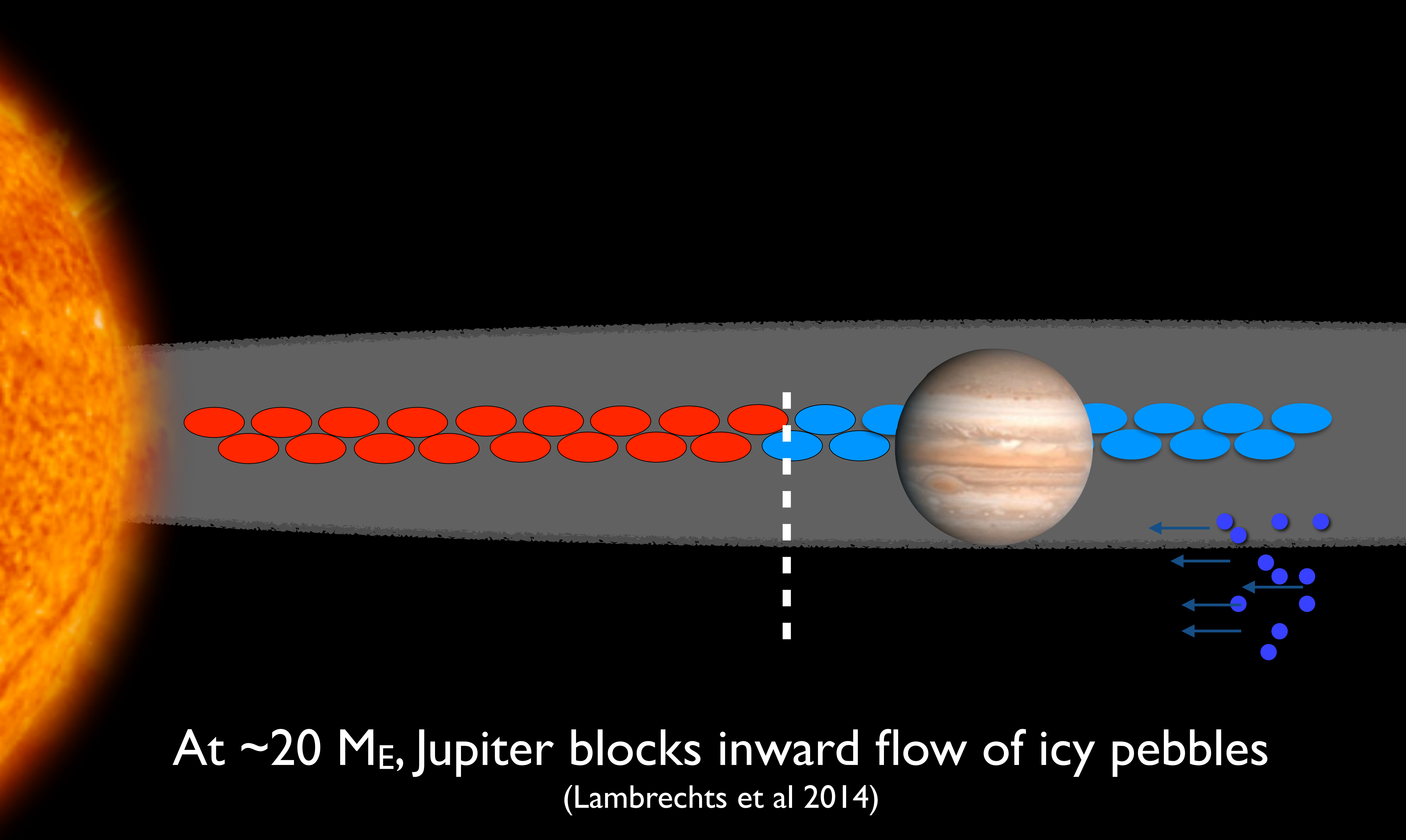

Habitable
zone


Habitable
zone



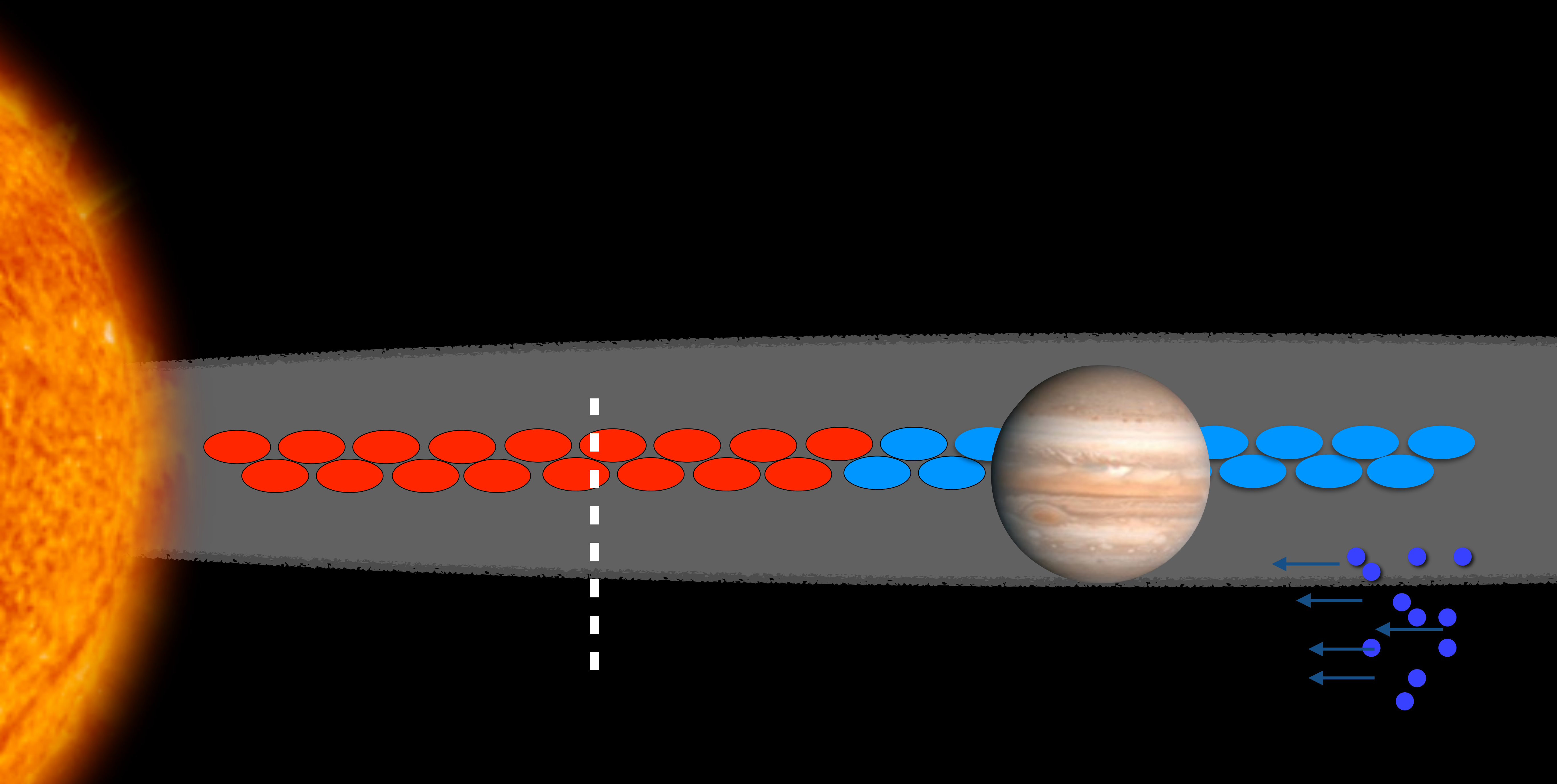

Wet gas moves faster than snow line, so water at snow line supplied from inward-drifting pebbles





At ~20 $M_E$, Jupiter blocks inward flow of icy pebbles

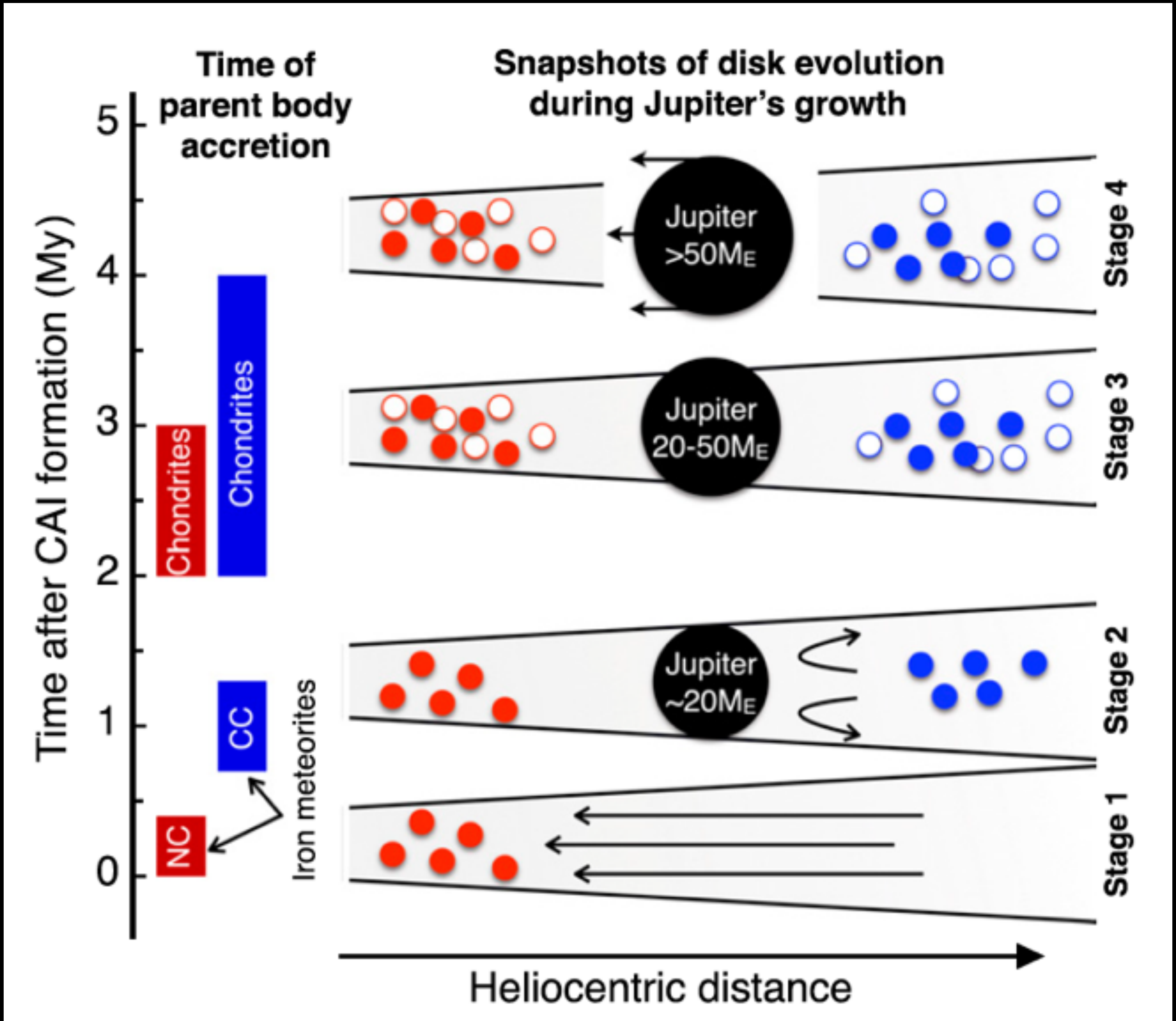
(Lambrechts et al 2014)



# Disk cools but snow line is “fossilized”

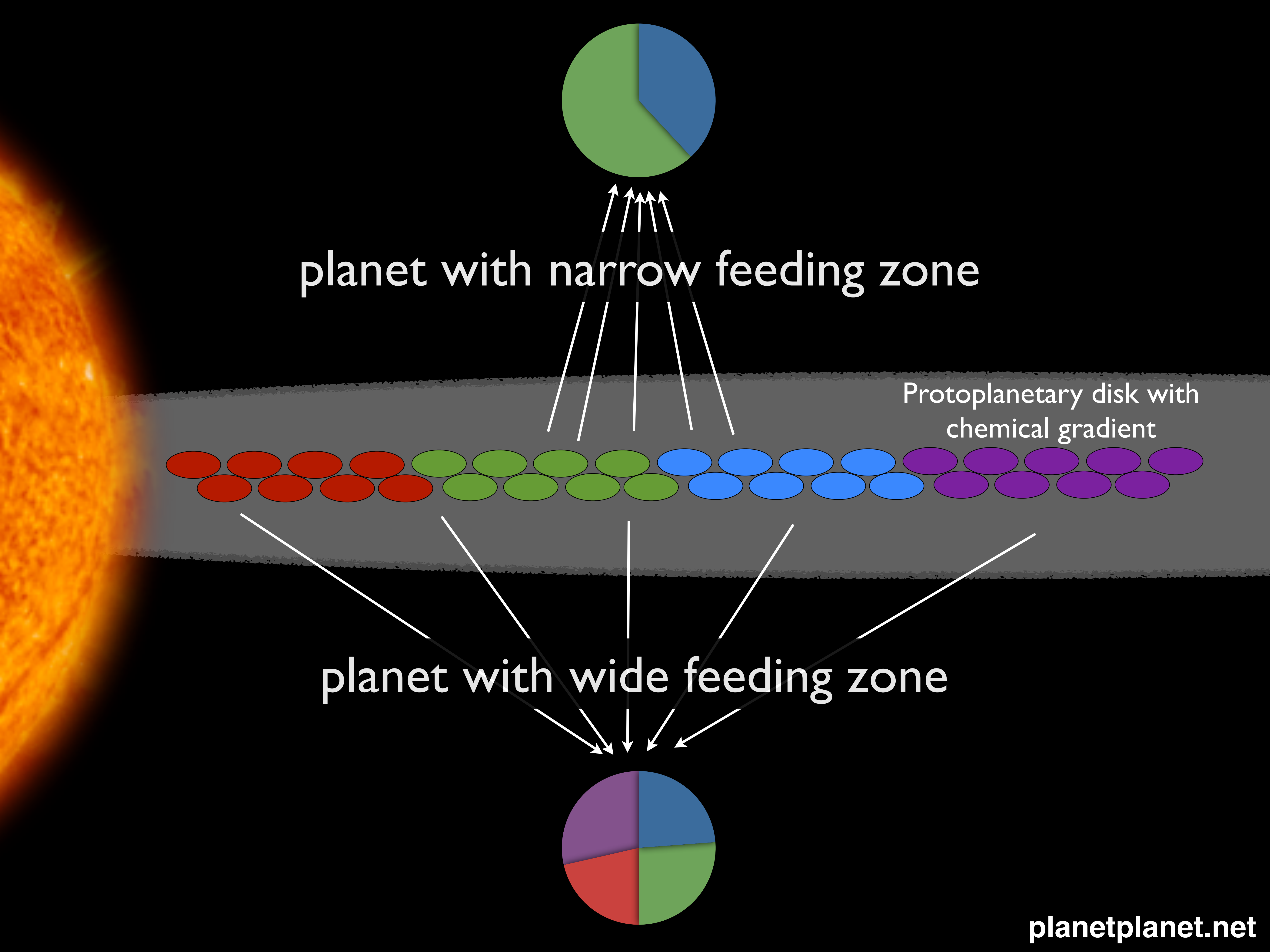
(Morbidelli et al 2016)

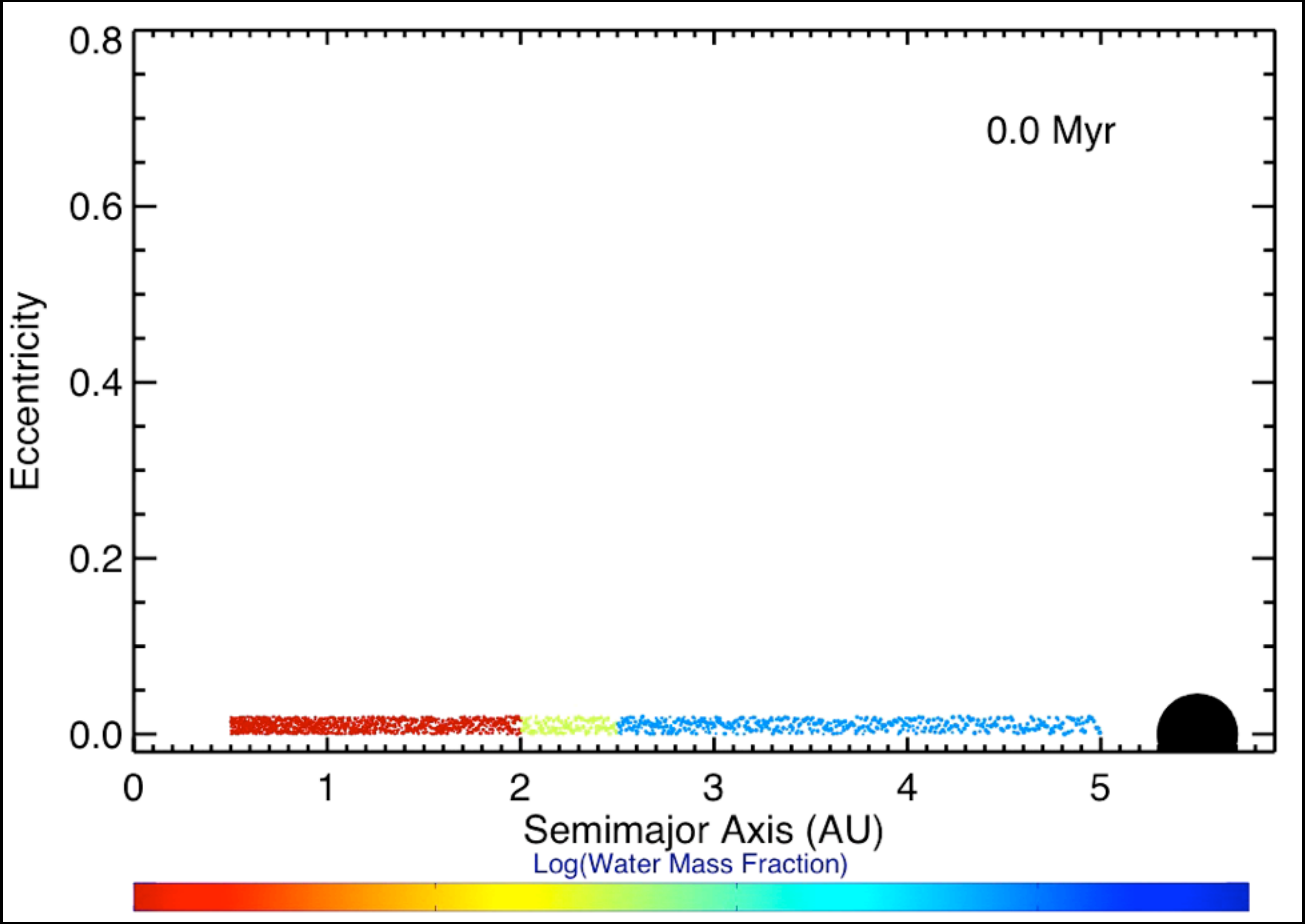
# Jupiter prevented pebbles from delivering Earth's water



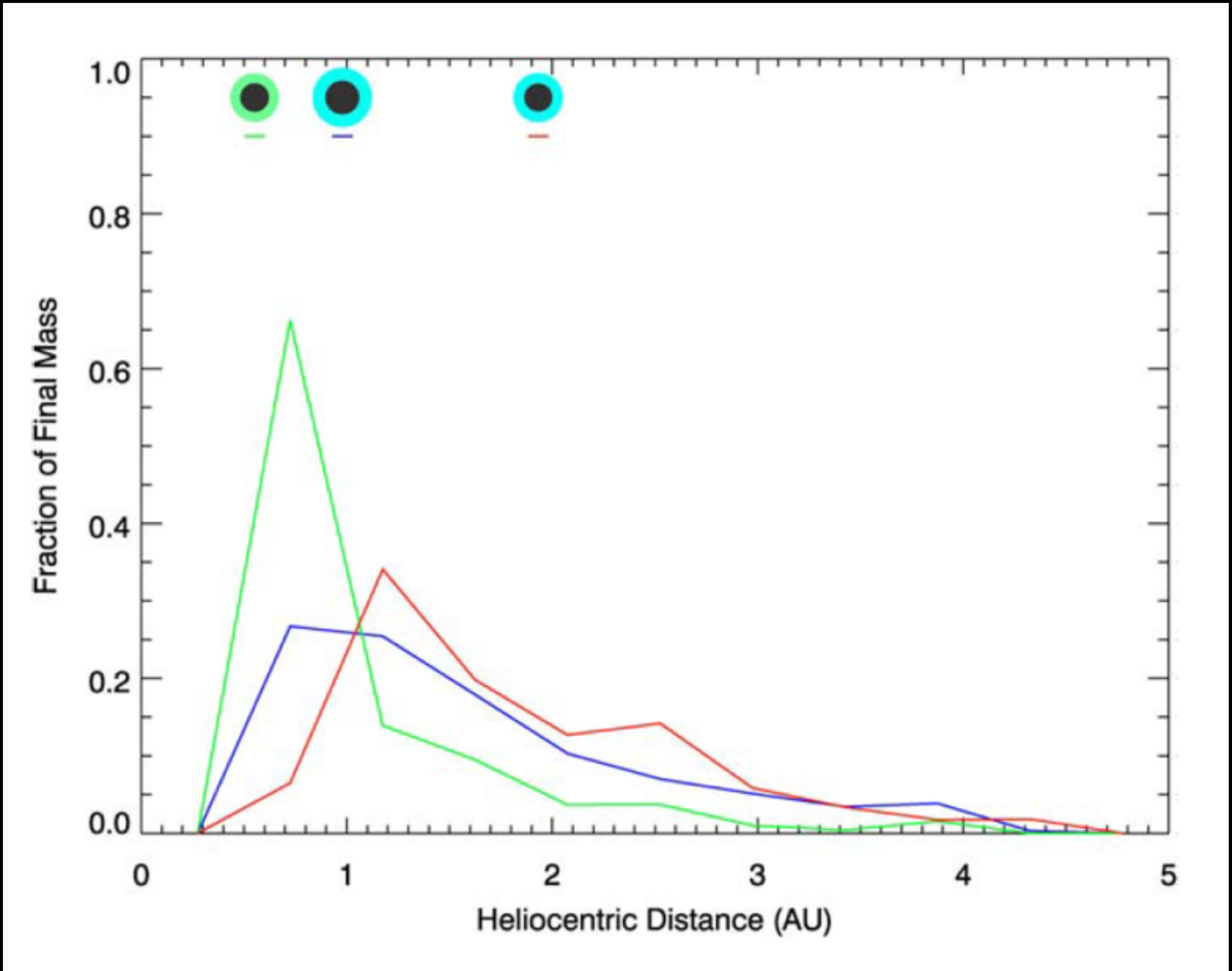

Kruijer et al 2017

# 2. Wide feeding zone


planet with narrow feeding zone
Protoplanetary disk with
chemical gradient
planet with wide feeding zone
planetplanet.net



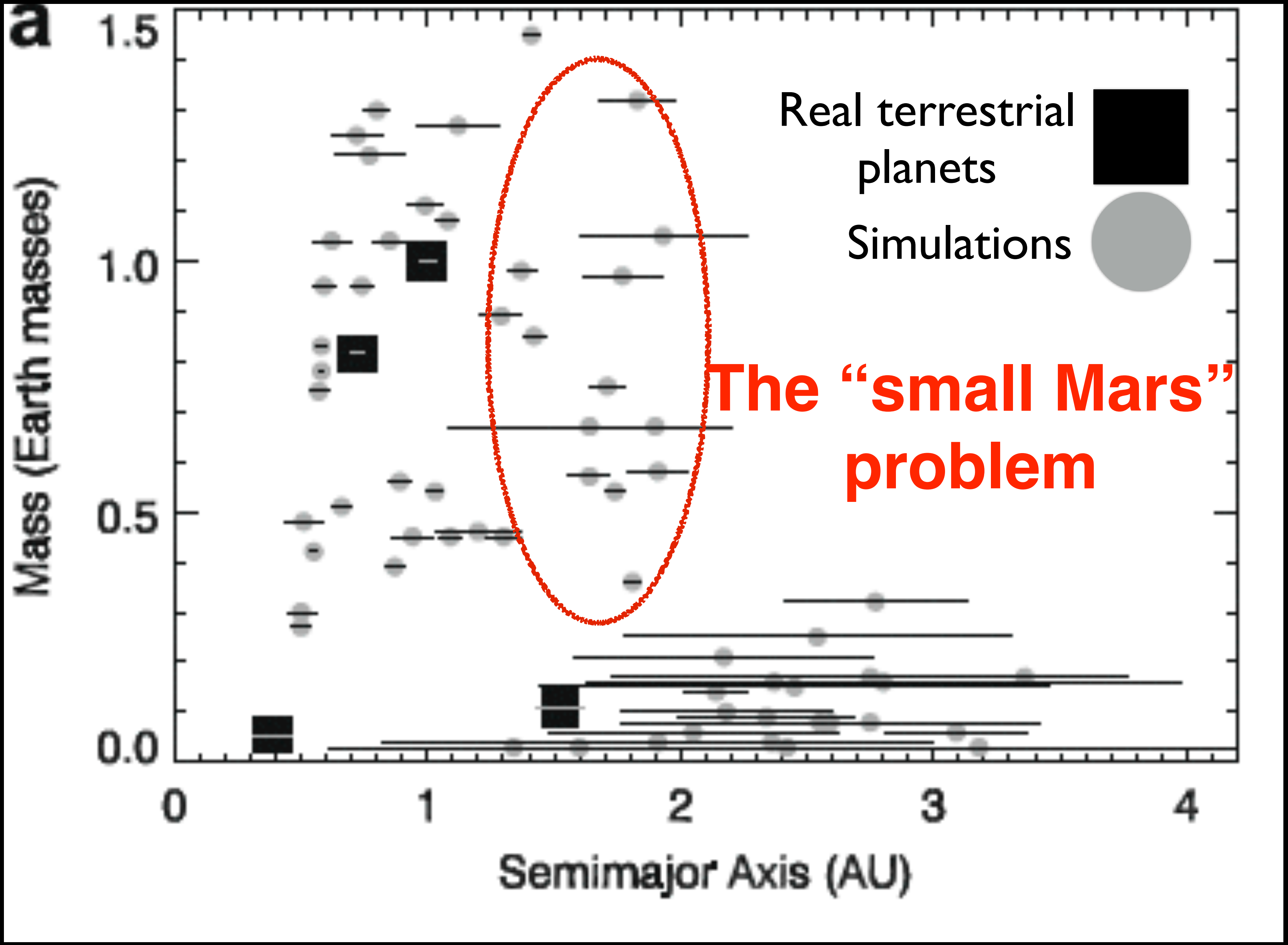

Raymond, Quinn & Lunine 2006




Feeding zones are several AU wide (in this case)

(Raymond et al 2006)

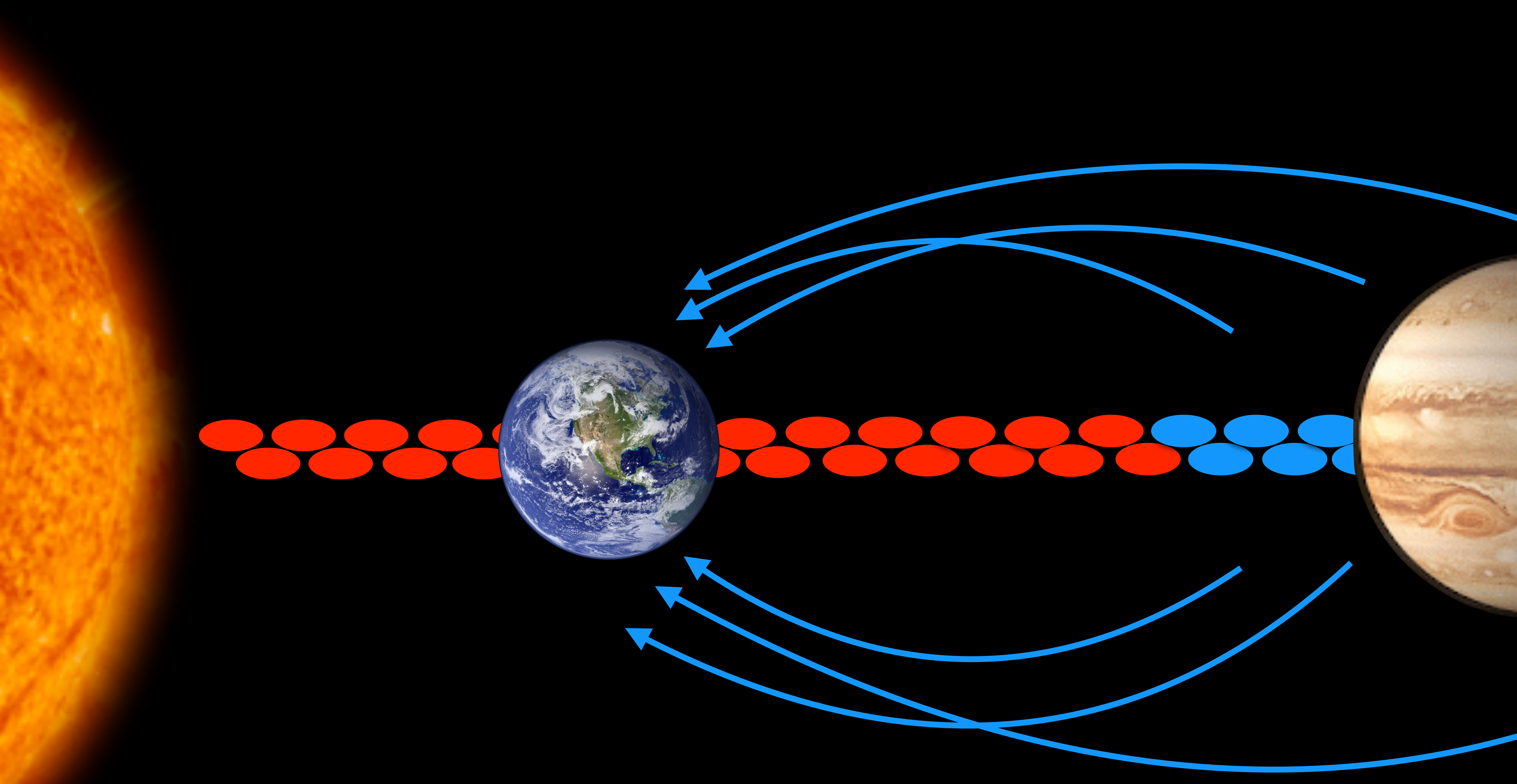
# The classical model




Raymond et al 2009

Wetherill 1991; Chambers 2001; O'Brien et al 2006; Raymond et al 2006, 2009, Morishima et al 2008, 2010; Nagasawa et al 2005, 2007; Thommes et al 2008; Fischer & Ciesla 2014; Izidoro et al 2014, 2015

# 3. External pollution

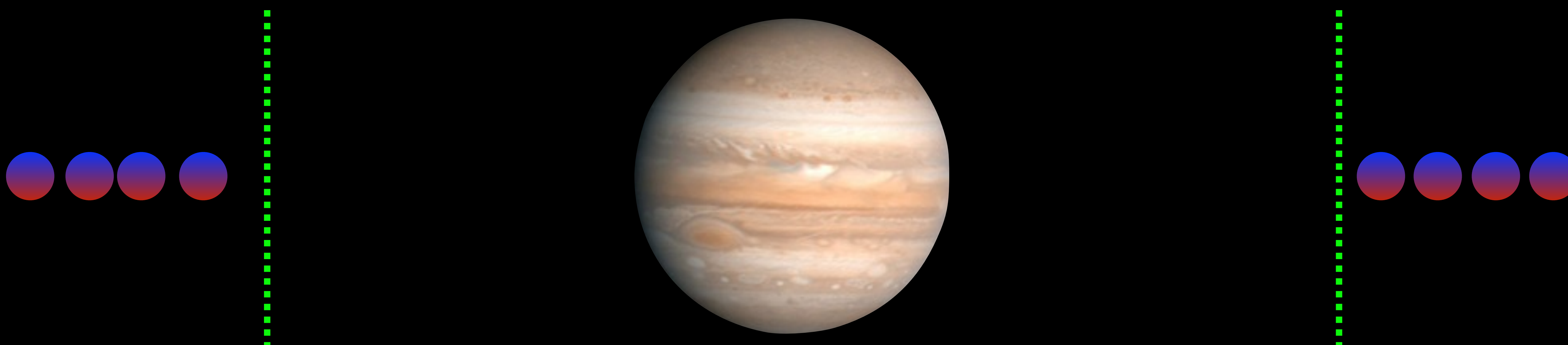


Narrow feeding zone + pollution from scattered planetesimals

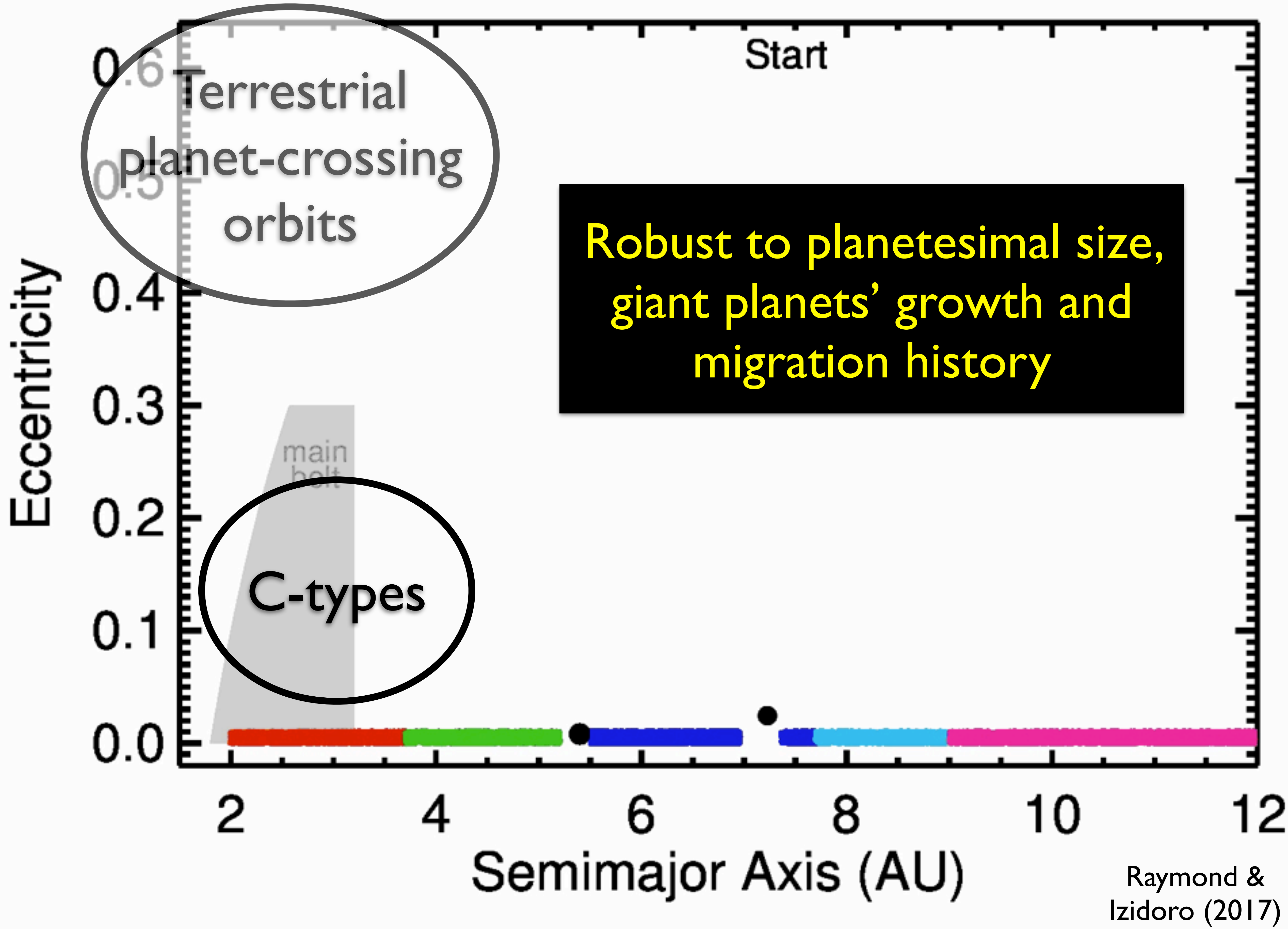
# Jupiter's growth affected nearby planetesimals

Stability limit for nearby orbits (~3.5 $R_{Hill}$ ~$M^{1/3}$)

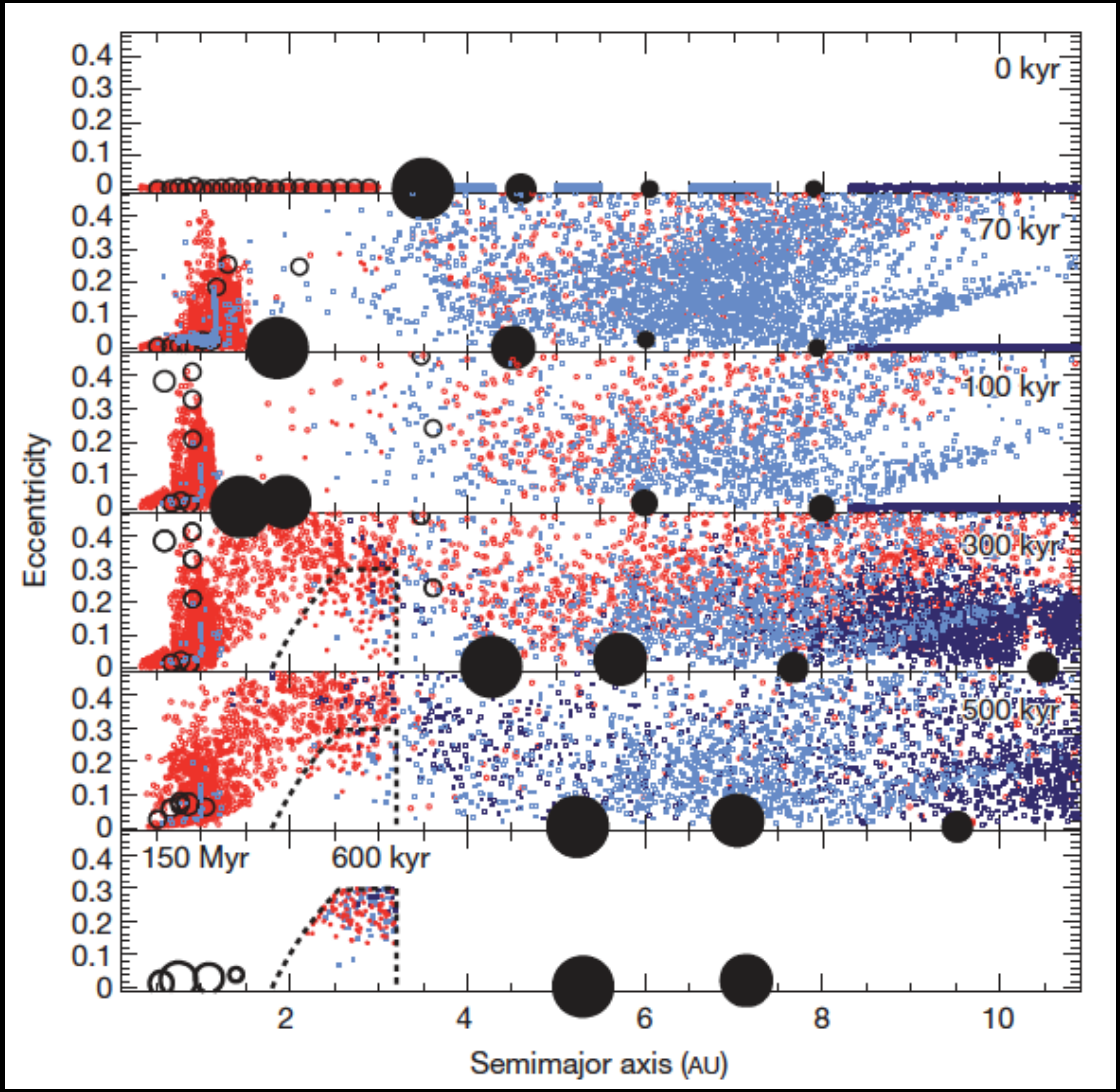
# Jupiter's growth affected nearby planetesimals



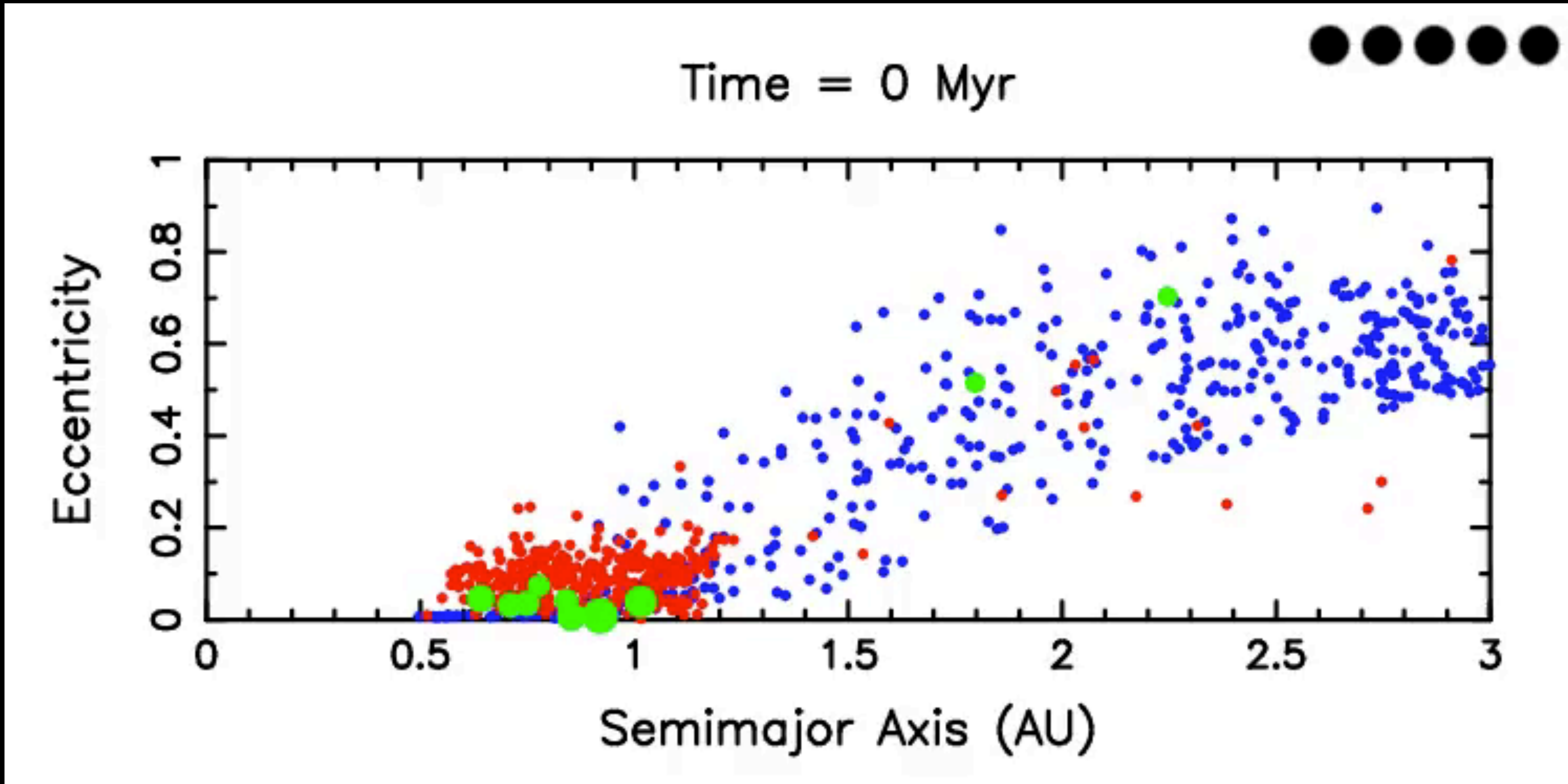
Stability limit for nearby orbits (~3.5 $R_{Hill}$ ~$M^{1/3}$)


Start
Terrestrial planet-crossing orbits
Robust to planetesimal size, giant planets' growth and migration history
main belt
C-types
Eccentricity
0.0
0.1
0.2
0.3
0.4
0.5
0.6
2
4
6
8
10
12
Semimajor Axis (AU)
Raymond & Izidoro (2017)

# The Grand Tack model




Walsh et al 2011



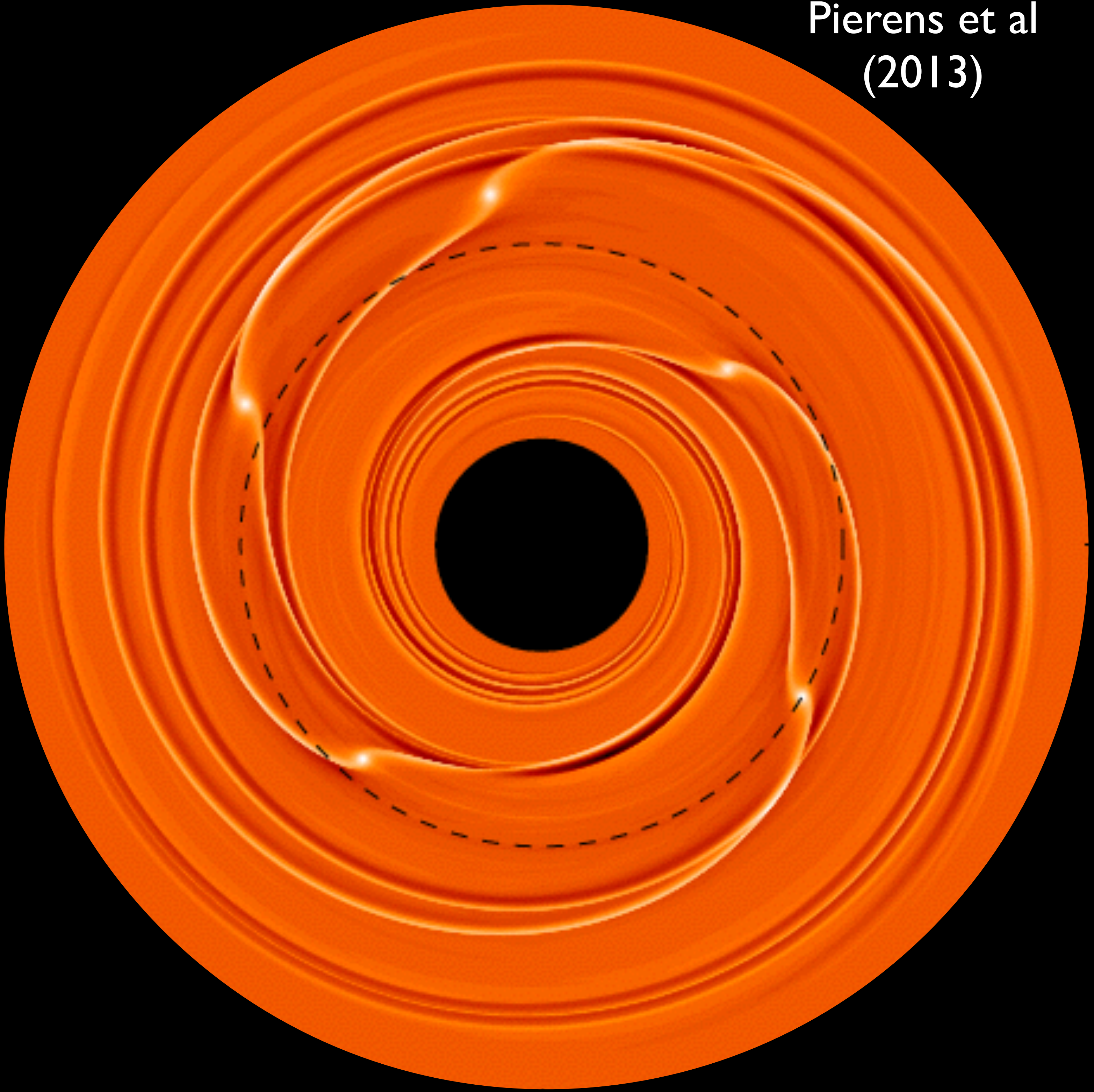

Water is delivered to Earth by same population that was implanted into asteroid belt as C types

(Walsh et al 2011; O'Brien et al 2014; Raymond & Izidoro 2017)

# 4. Migration

# Type 1 migration

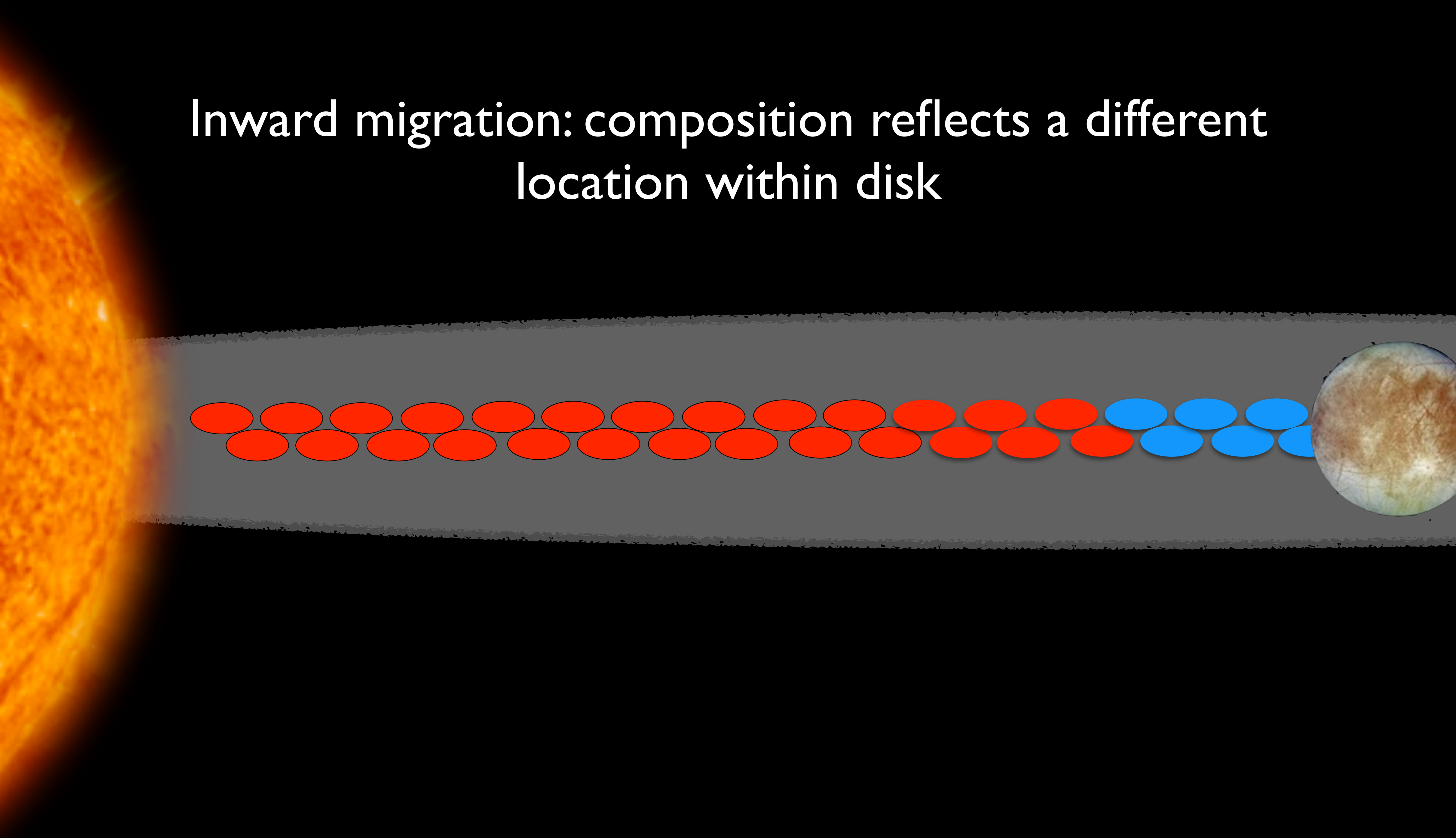
- Inward or outward
- Timescale ~10-100 kyr (bigger=faster)



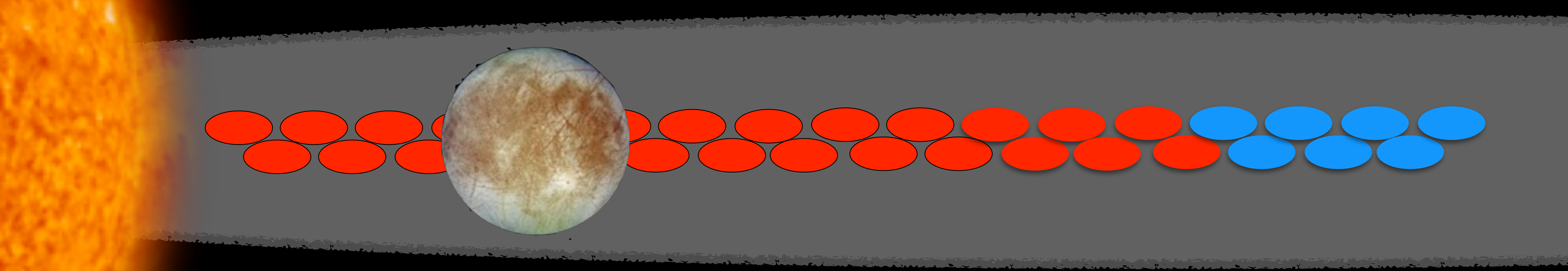
Pierens et al (2013)

Golreich & Tremaine 1980; Ward 1986, 1997; Kley & Crida 2008; Paardekooper et al 2010, 2011; Pierens et al 2013; Lega et al 2014; Bitsch et al 2014; Kley & Nelson 2014

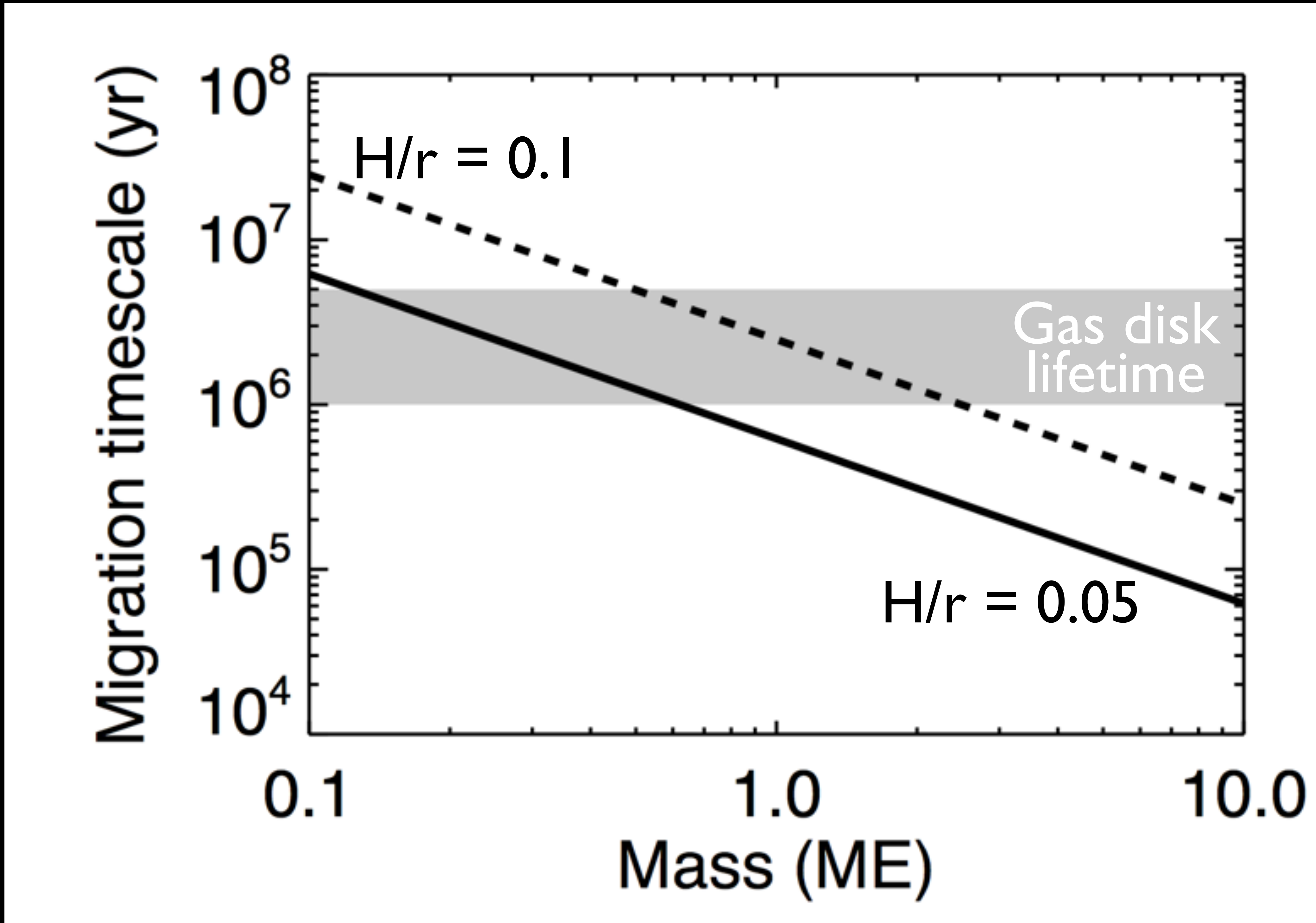
Inward migration: composition reflects a different location within disk



Inward migration: composition reflects a different location within disk



Key unknown: formation zone of migrating bodies (e.g., rocky vs. icy)

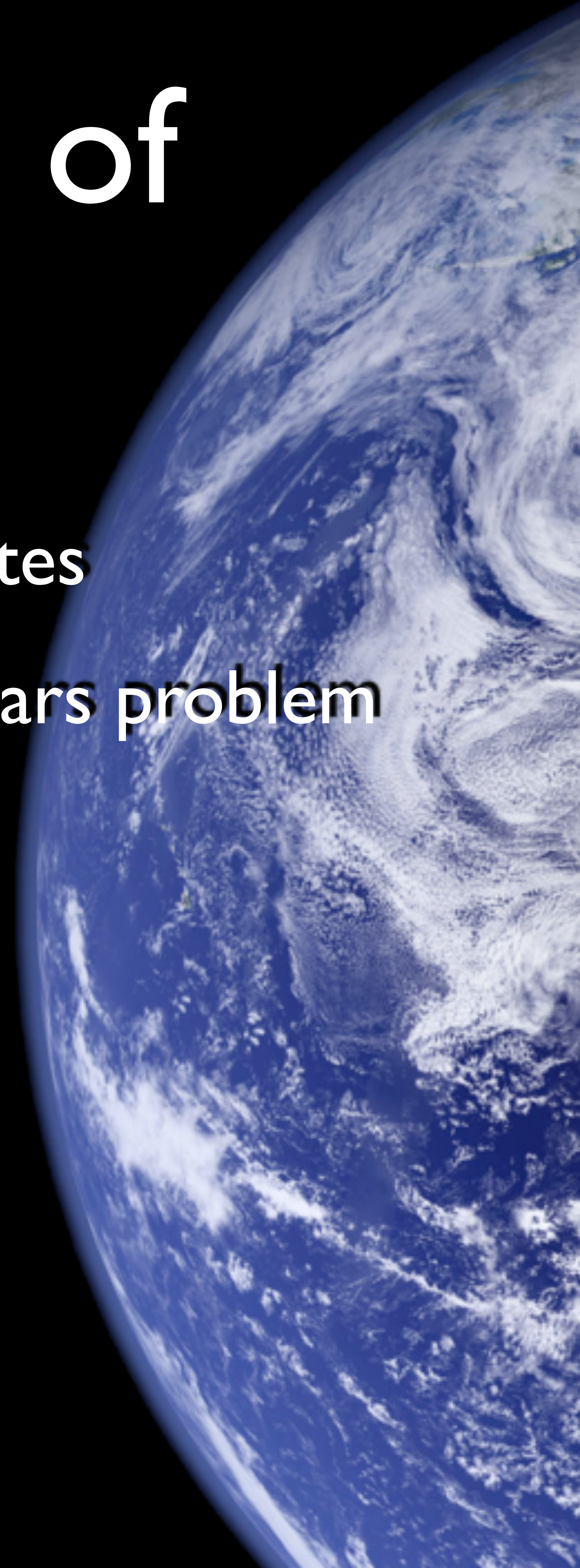



The ~Mars-mass building blocks of the terrestrial planets were too small for long-range migration

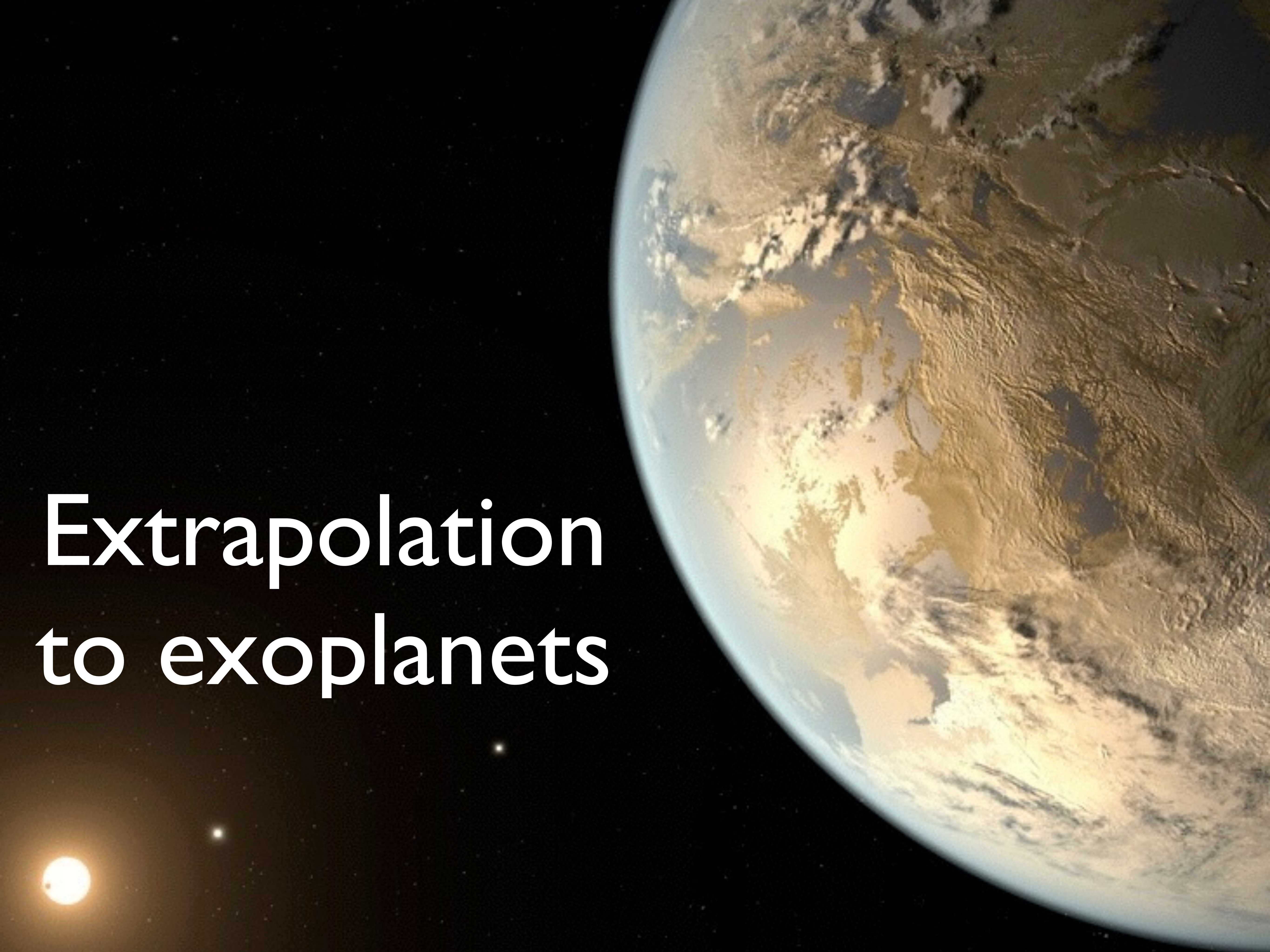
# Possible sources of Earth's water

- Pebble "snow": too many dry meteorites
- Wide feeding zone: Classical model Mars problem
- External pollution

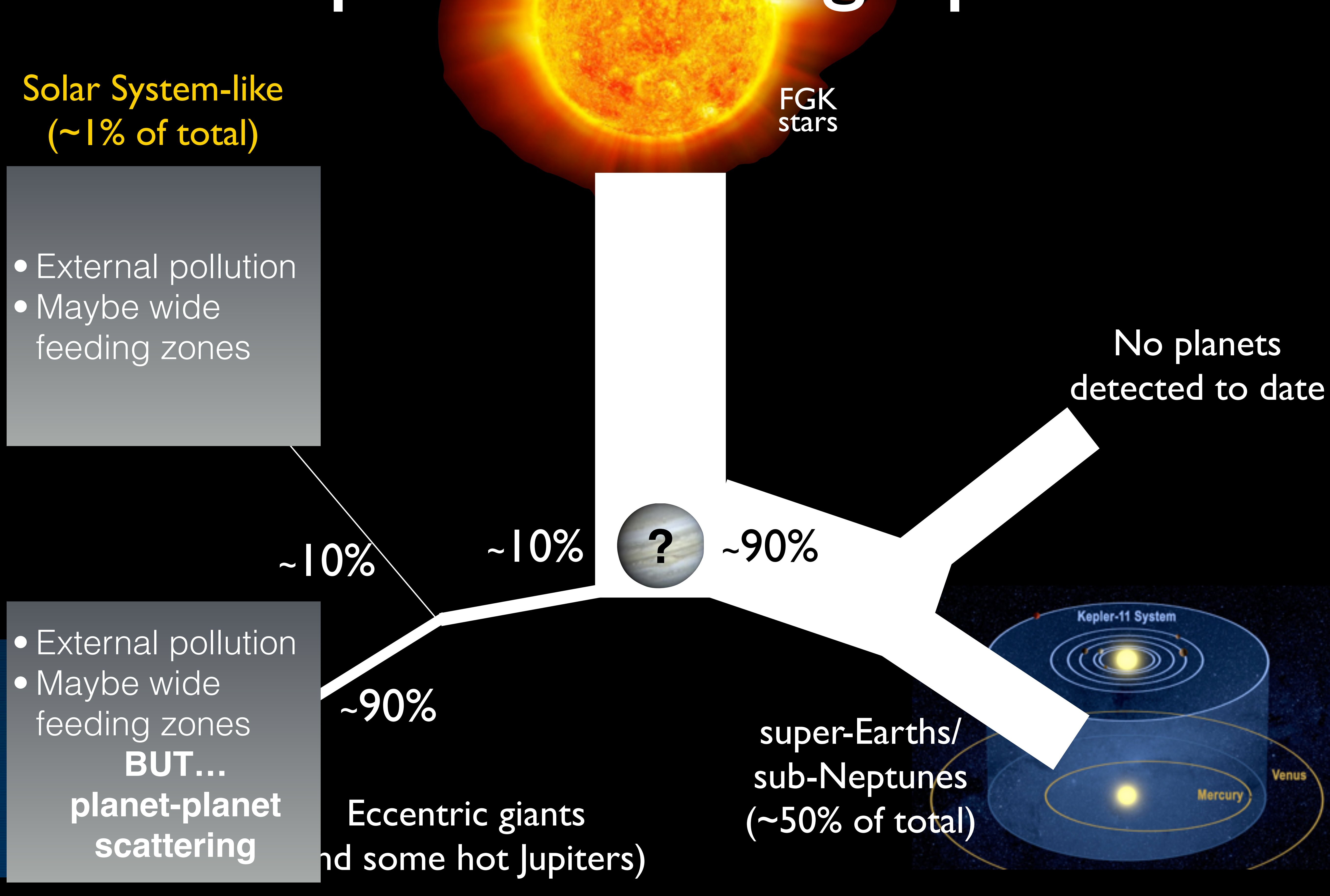
  - Giant planets' growth
  - Grand Tack
- Inward migration: Earth too dry

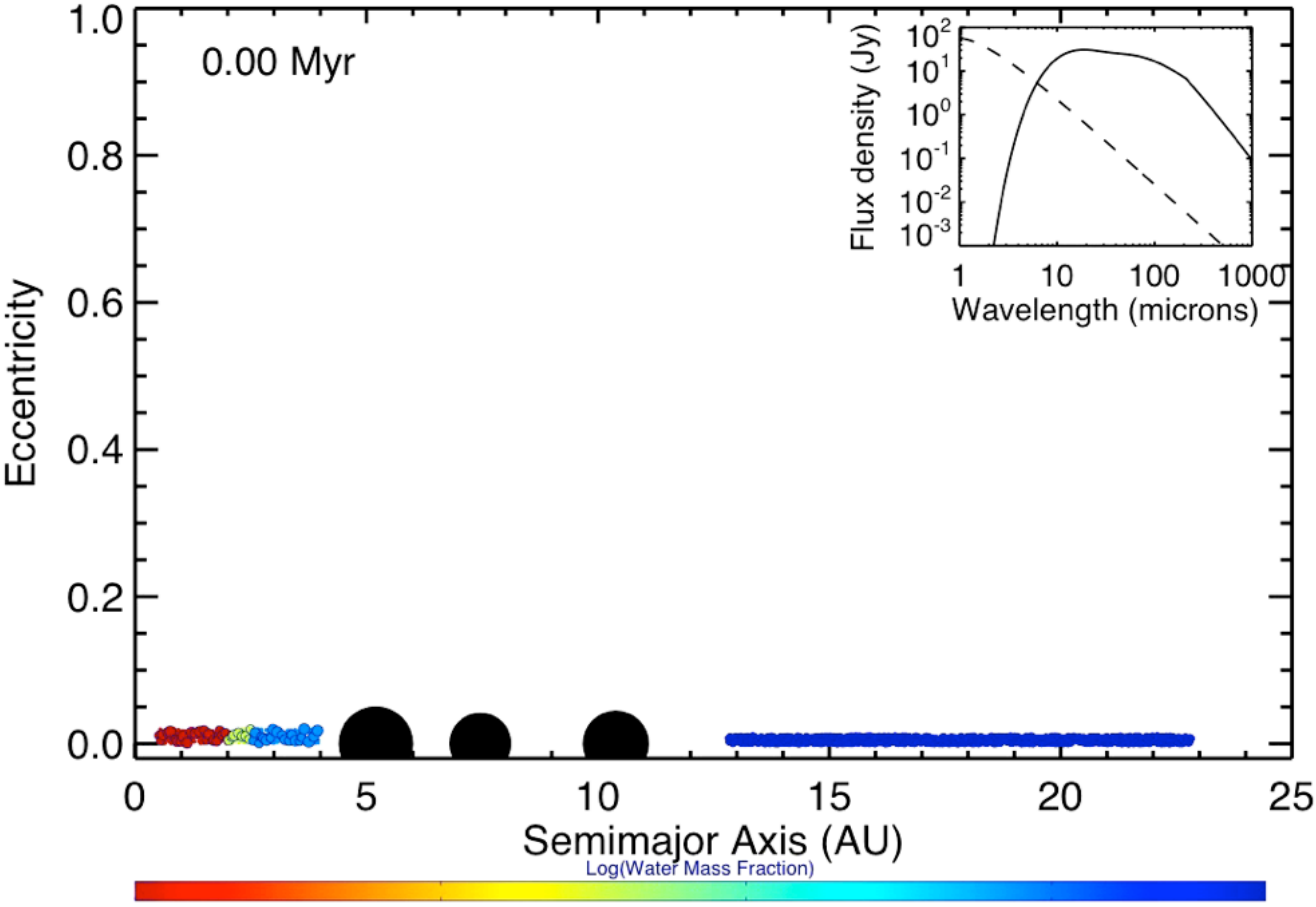


# Extrapolation to exoplanets

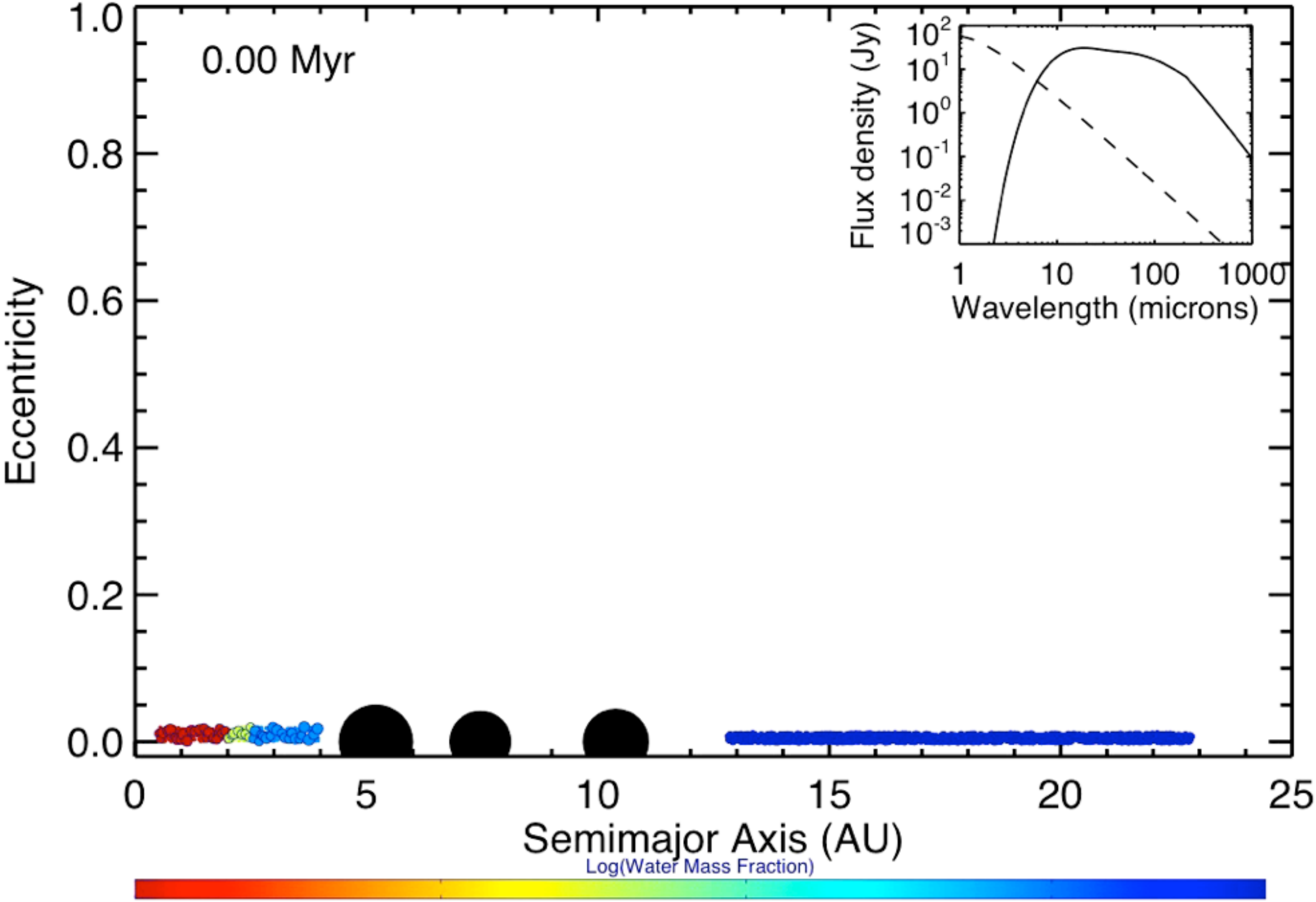


# Exoplanet demographics



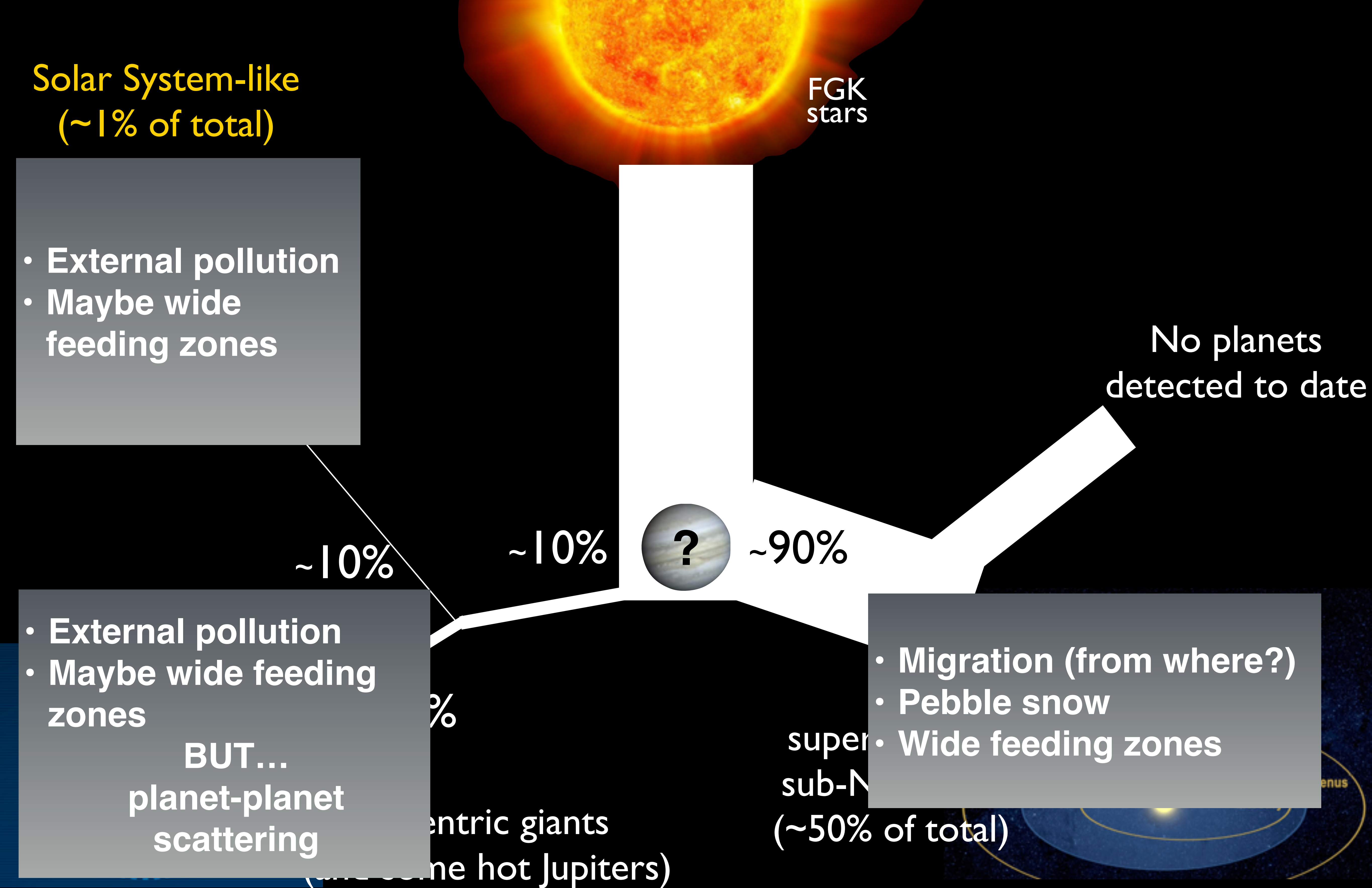



Raymond et al 2012



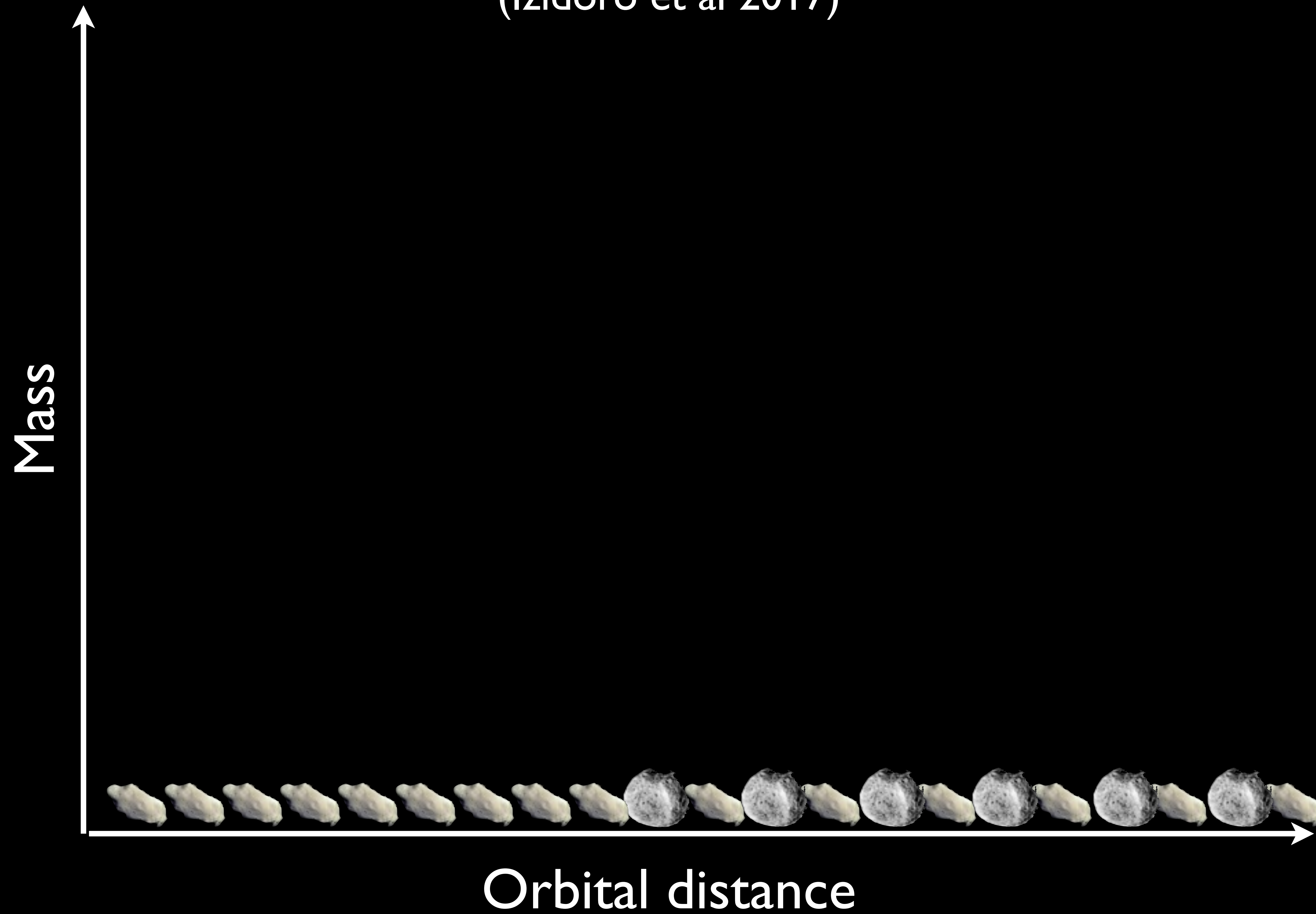

Raymond et al 2012

# Exoplanet demographics



# Forming hot super-Earths by type 1 migration

(Izidoro et al 2017)

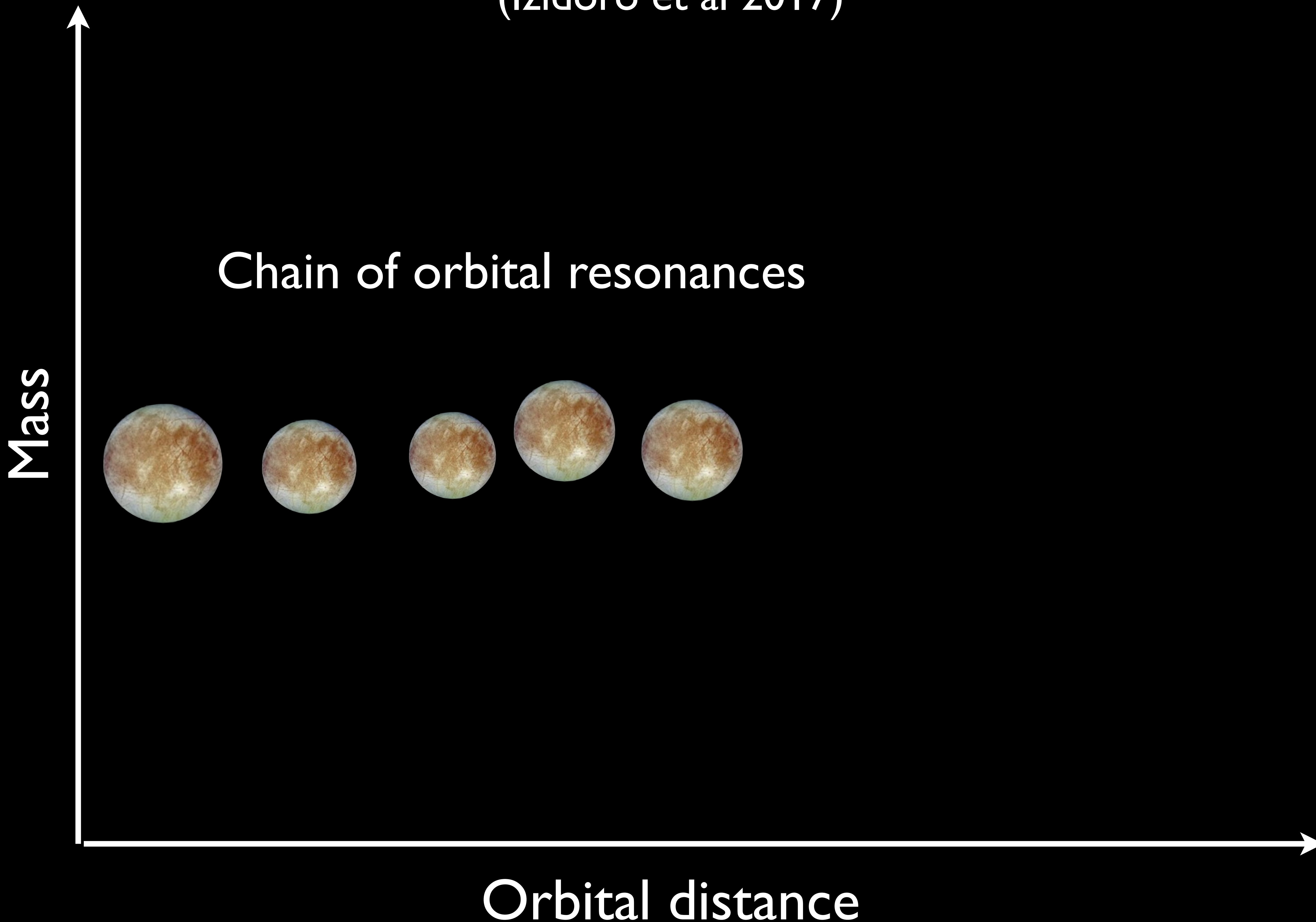


# Forming hot super-Earths by type 1 migration

(Izidoro et al 2017)

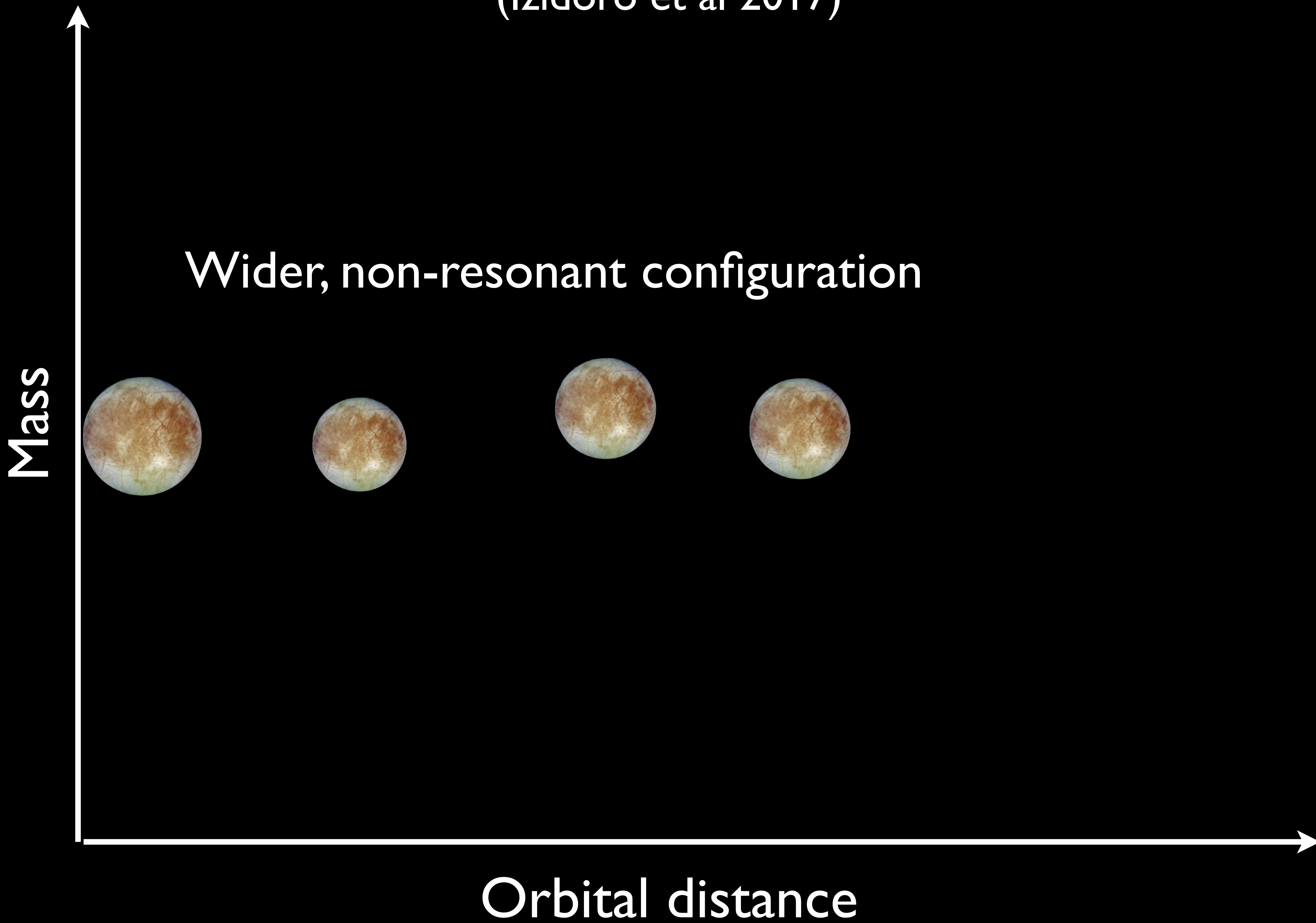
# Forming hot super-Earths by type 1 migration

(Izidoro et al 2017)

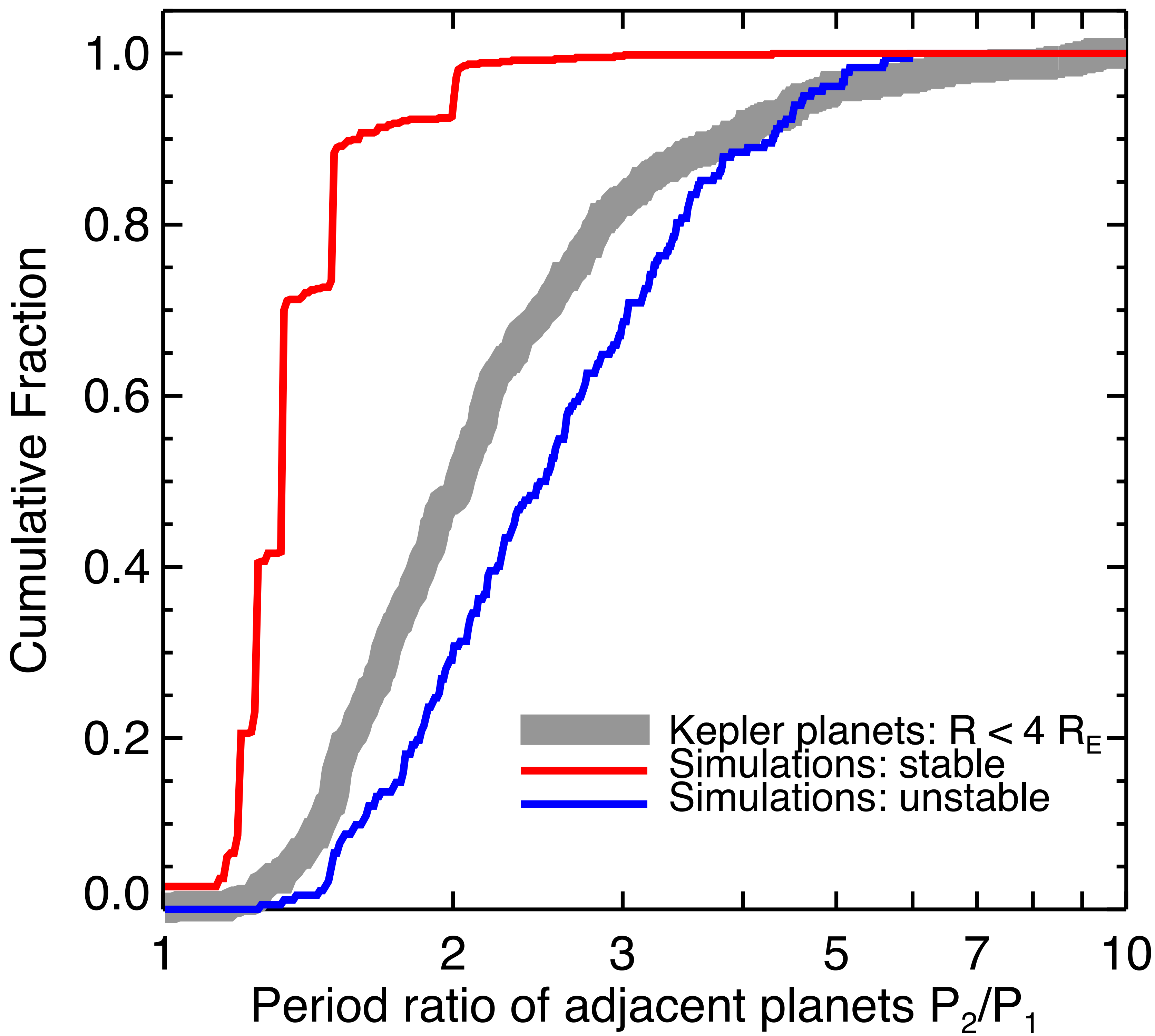


# Forming hot super-Earths by type 1 migration

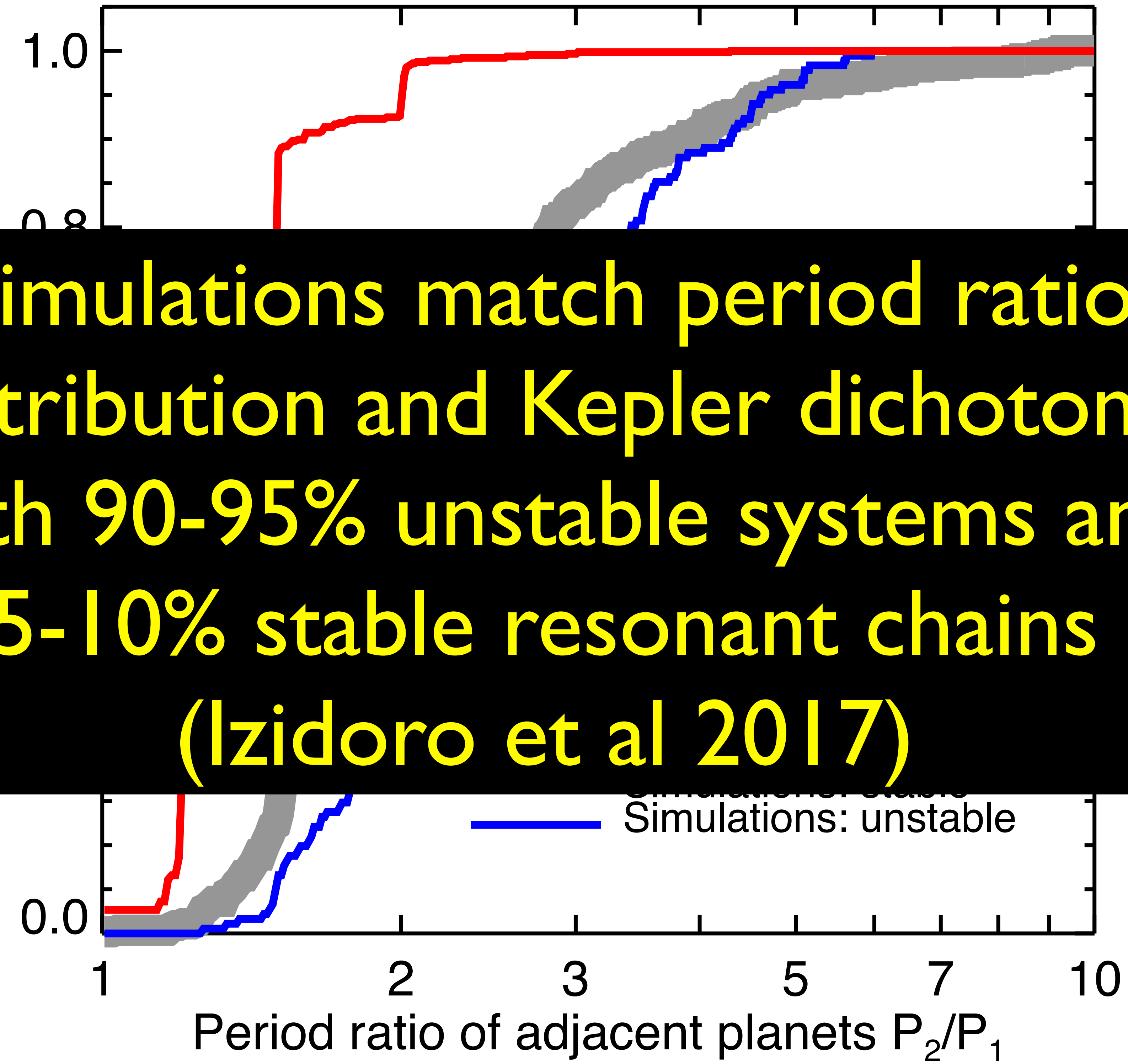
(Izidoro et al 2017)



# The period ratio distribution

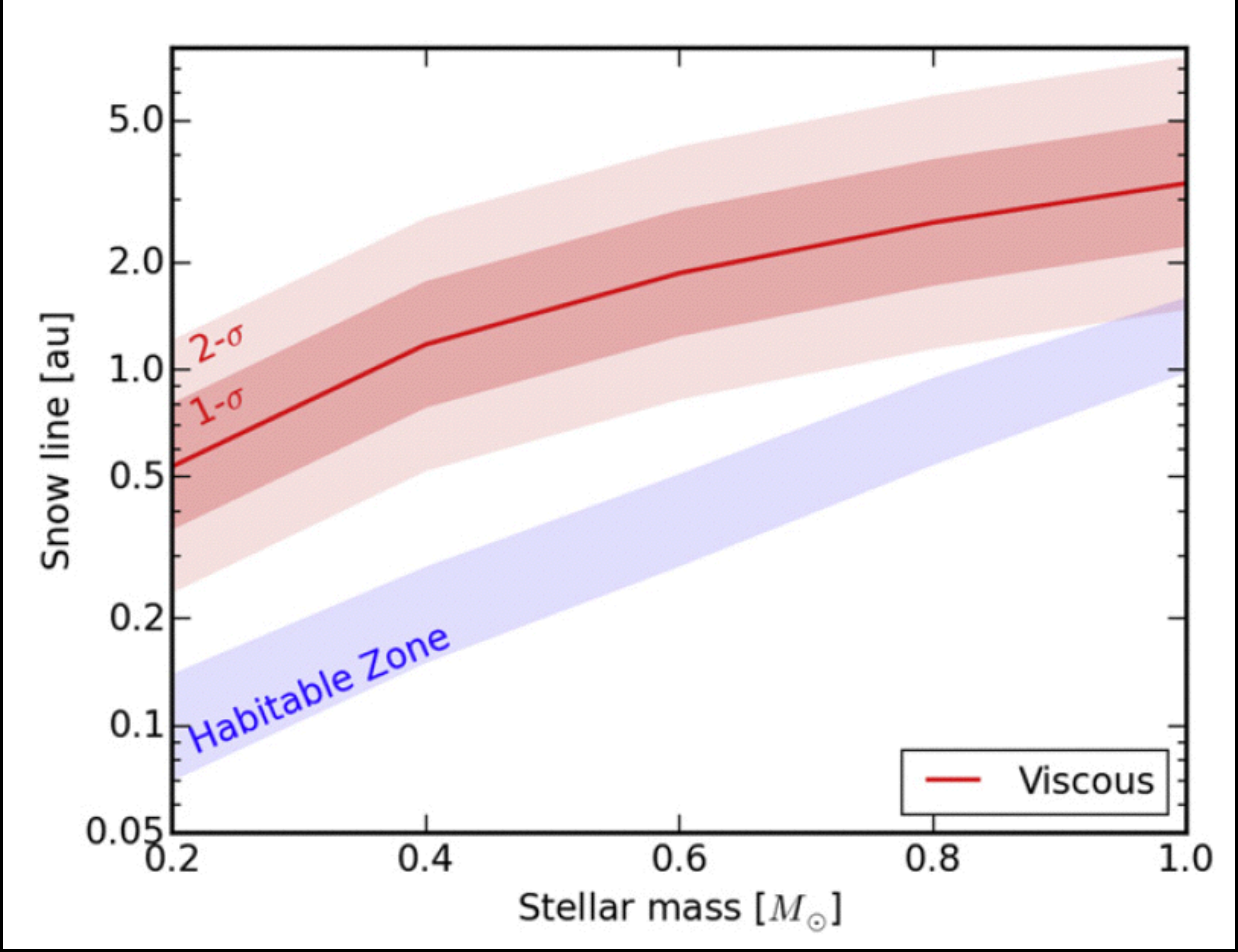


# The period ratio distribution



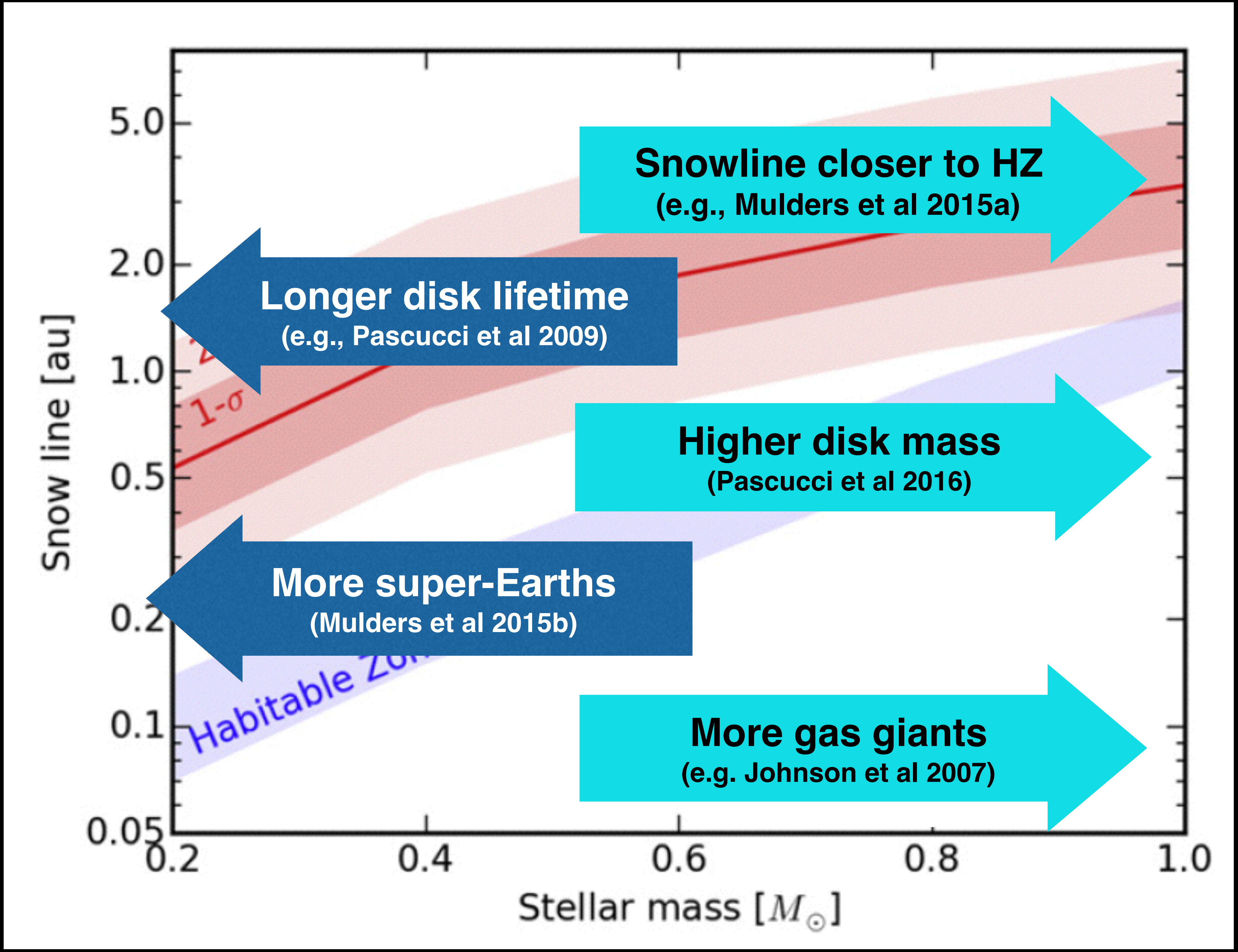

Simulations match period ratio distribution and Kepler dichotomy with 90-95% unstable systems and 5-10% stable resonant chains (Izidoro et al 2017)

# The snow line vs stellar mass




Mulders et al 2015

# Stellar-mass dependent factors




Mulders et al 2015

# Summary

- Four mechanisms of water delivery
  - Pebble "snow" (Sato et al 2016)
  - Wide feeding zones (Morbidelli et al 2000; Raymond et al 2007)
  - External pollution (Raymond & Izidoro 2017; Walsh et al 2011)
  - Migration (Izidoro et al 2017)

- Exoplanets
  - Planet-planet scattering bad for terrestrials (Raymond et al 2011, 2012)
  - Super-Earths: migration model matches observations (Izidoro et al 2017)
  - Stellar mass trends: it's complicated…