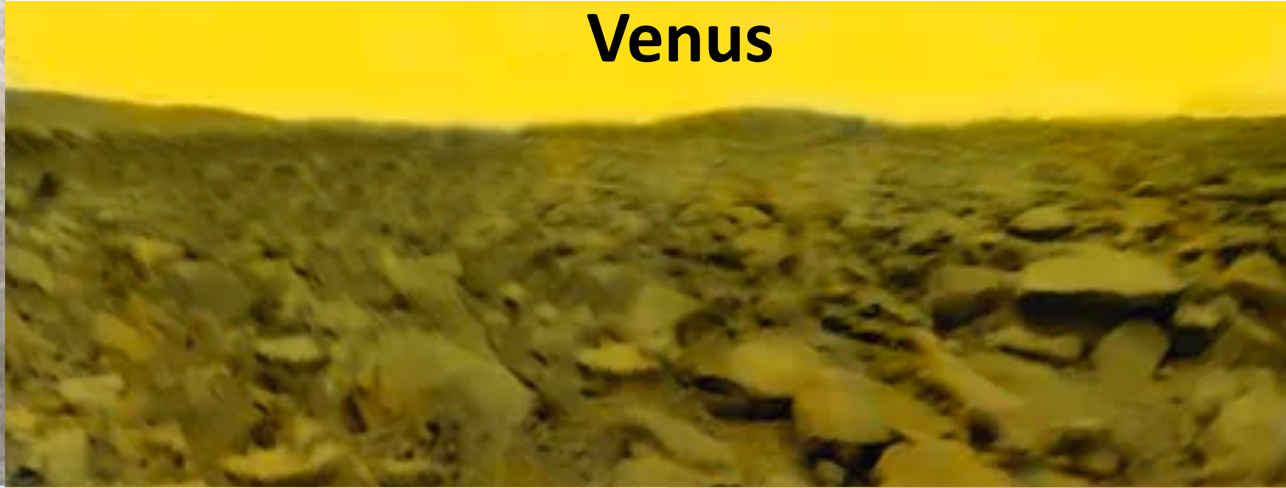
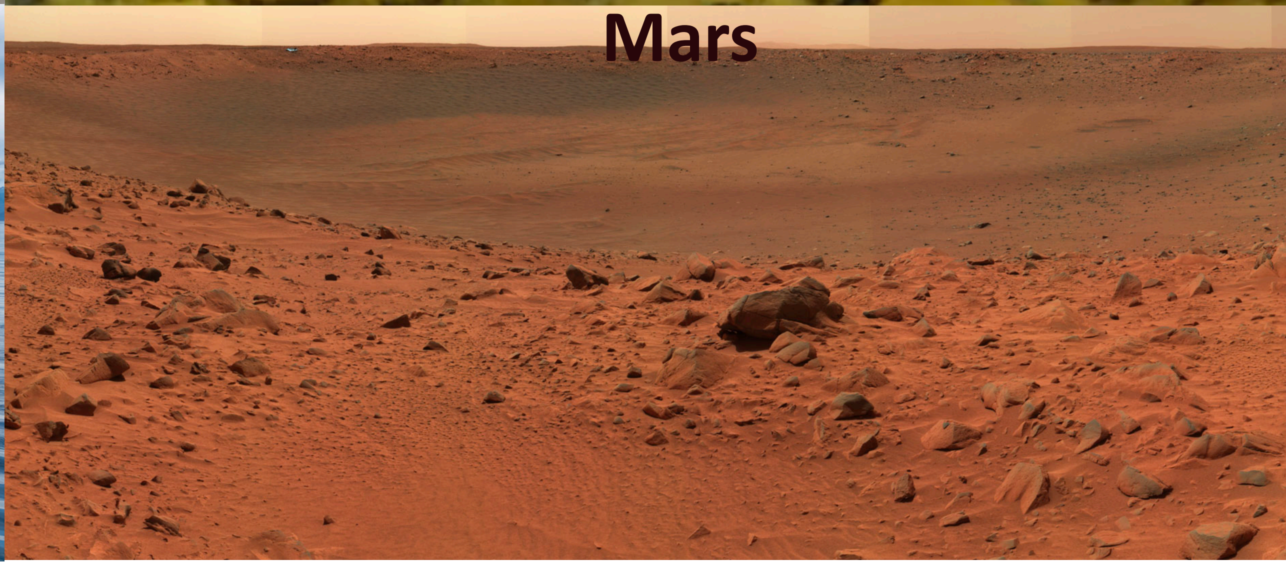
Solar and Exo-Solar terrestrial planet formation:
The bleak prospects for habitability around the smallest stars





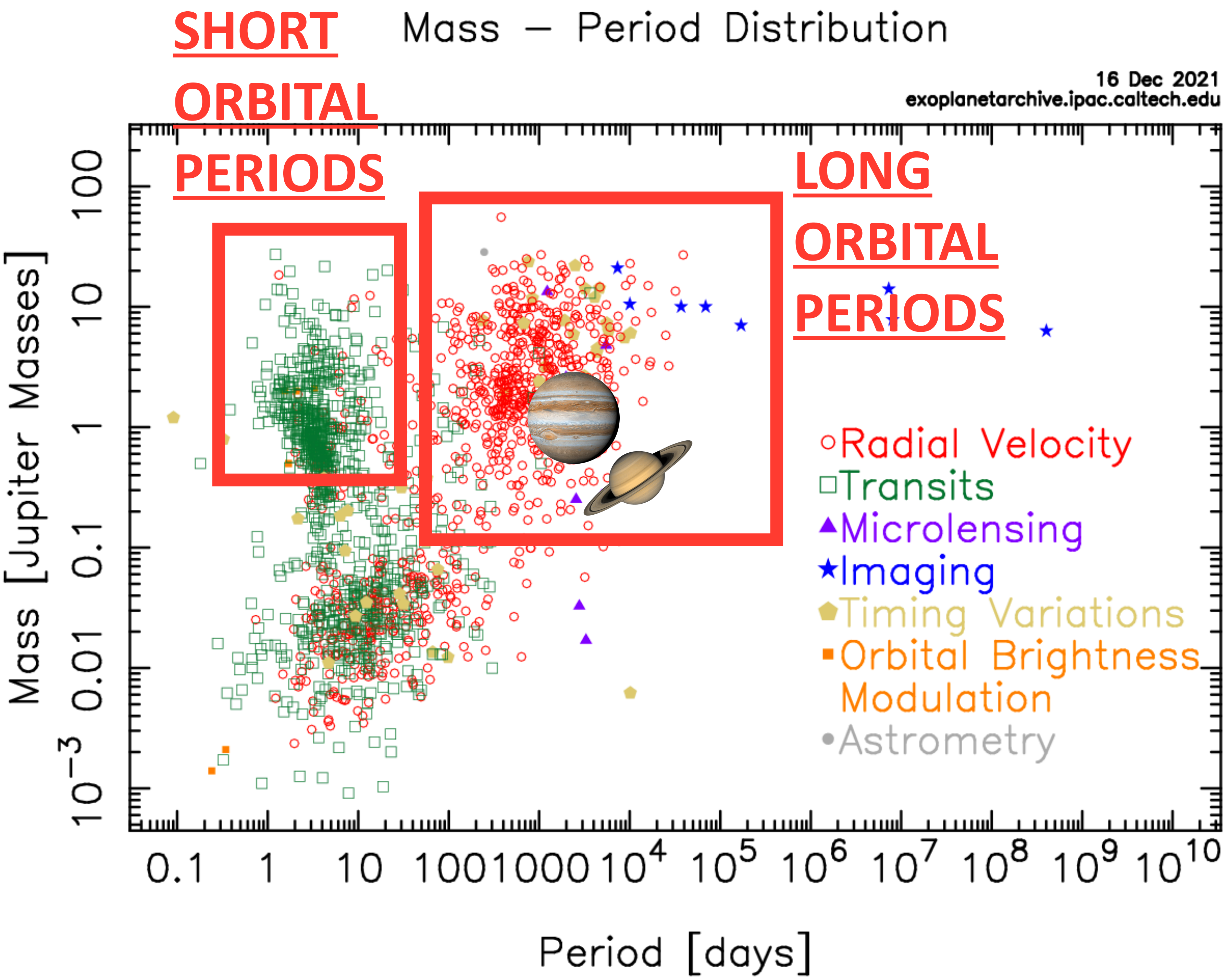
Matt Clement

Carnegie Institution for Science: Earth and Planets Laboratory

Collaborators: Elisa Quintana, John Chambers, Nate Kaib, Sean Raymond, Billy Quarles, Fabo Feng, Rogerio Deienno, Andre Izidoro, Kevin Walsh, Alan Jackson, Tim Lichtenberg, Emily Gilbert

Giant planets with large a, low e, around ~1.0 $M_{\odot}$:

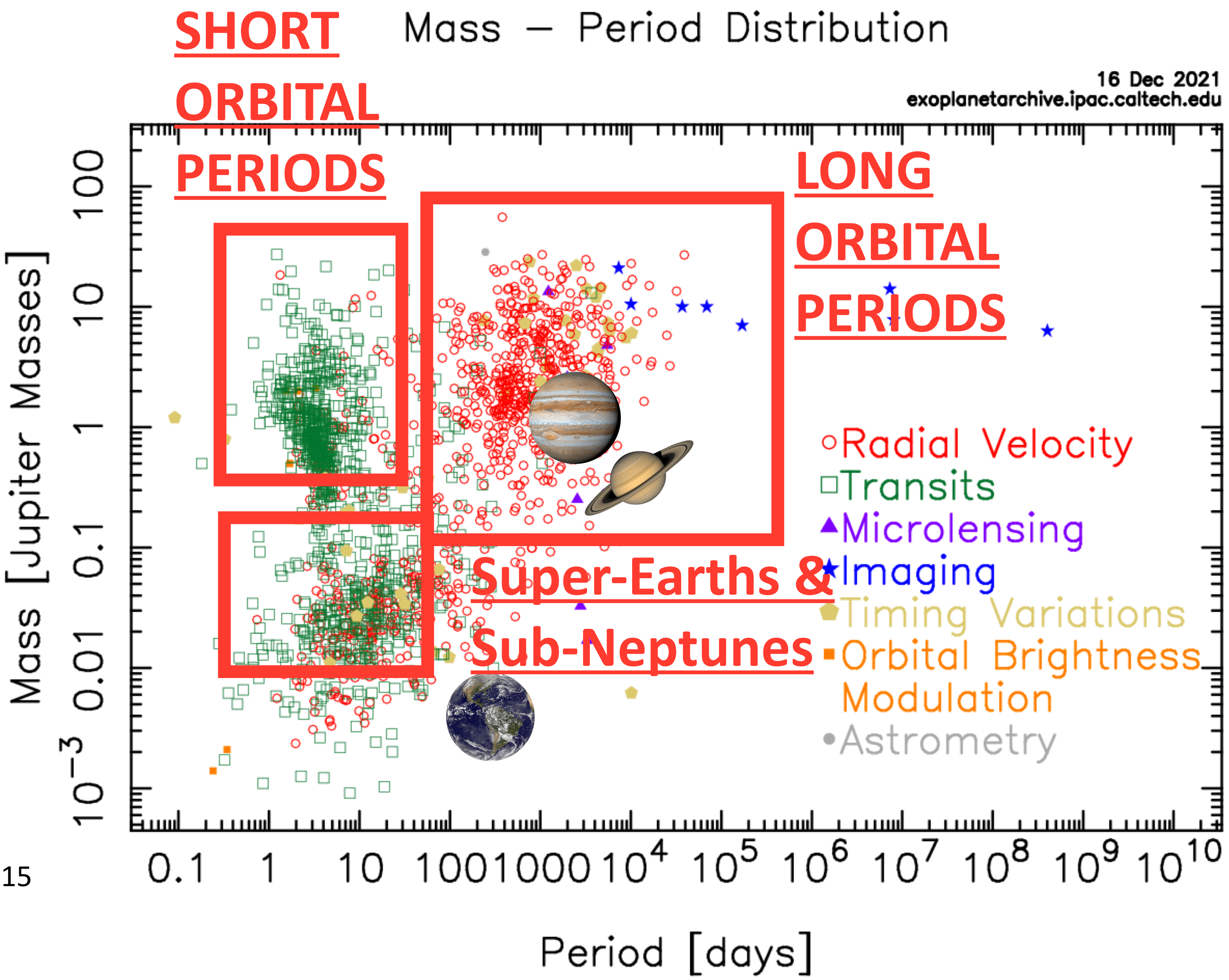
~0.1% of systems



(Chabrier 2003, Butler et al. 2006)

~1.0 $M_\odot$ without a Super-Earth:

$\lesssim$ 10-50% of systems



(Chiang & Laughlin 2013; Burke et al. 2015 Petigura et al. 2018; Zhu et al. 2018)

BIG QUESTIONS

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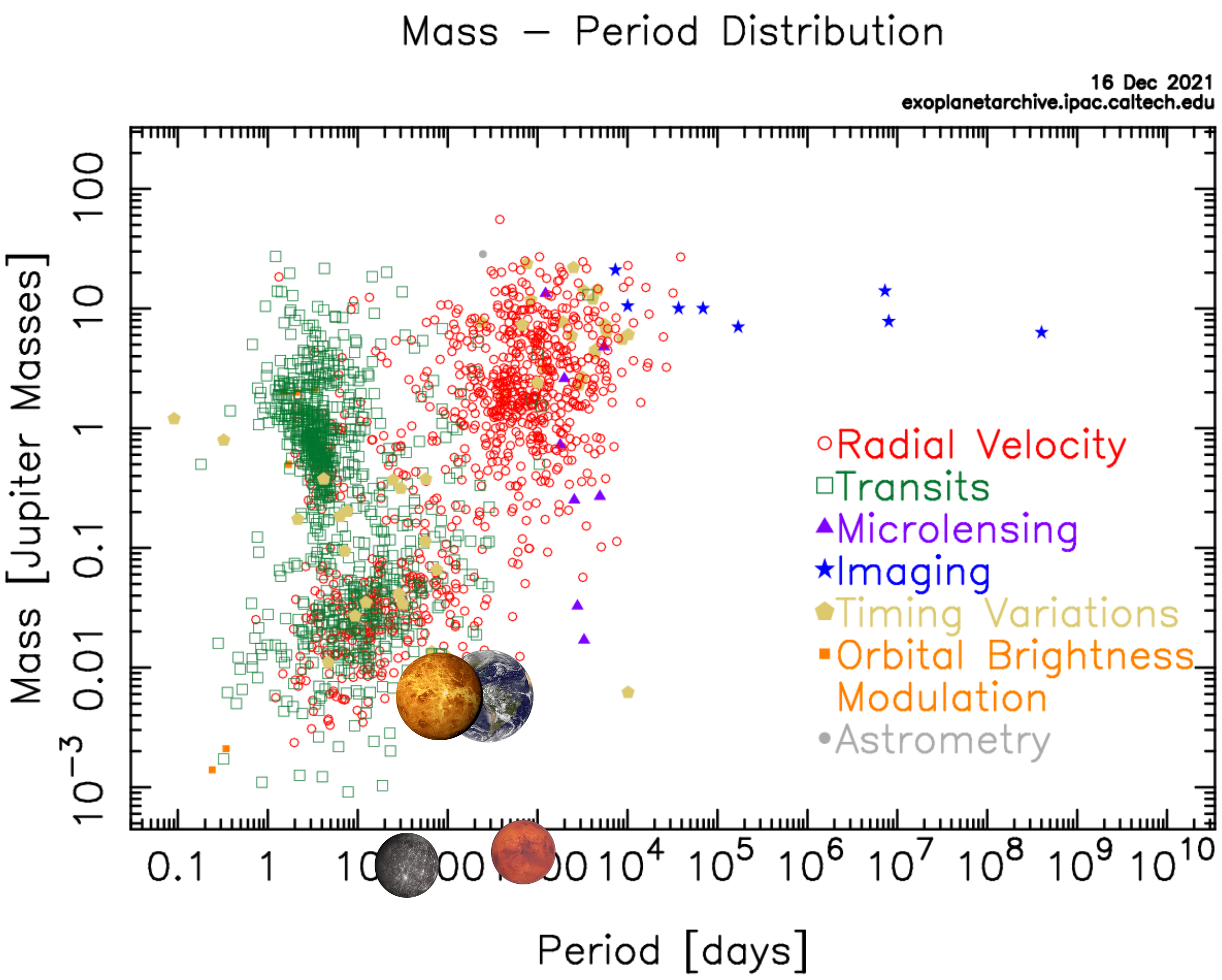
- Why doesn't the solar system have a Super-Earth or short-period planet?



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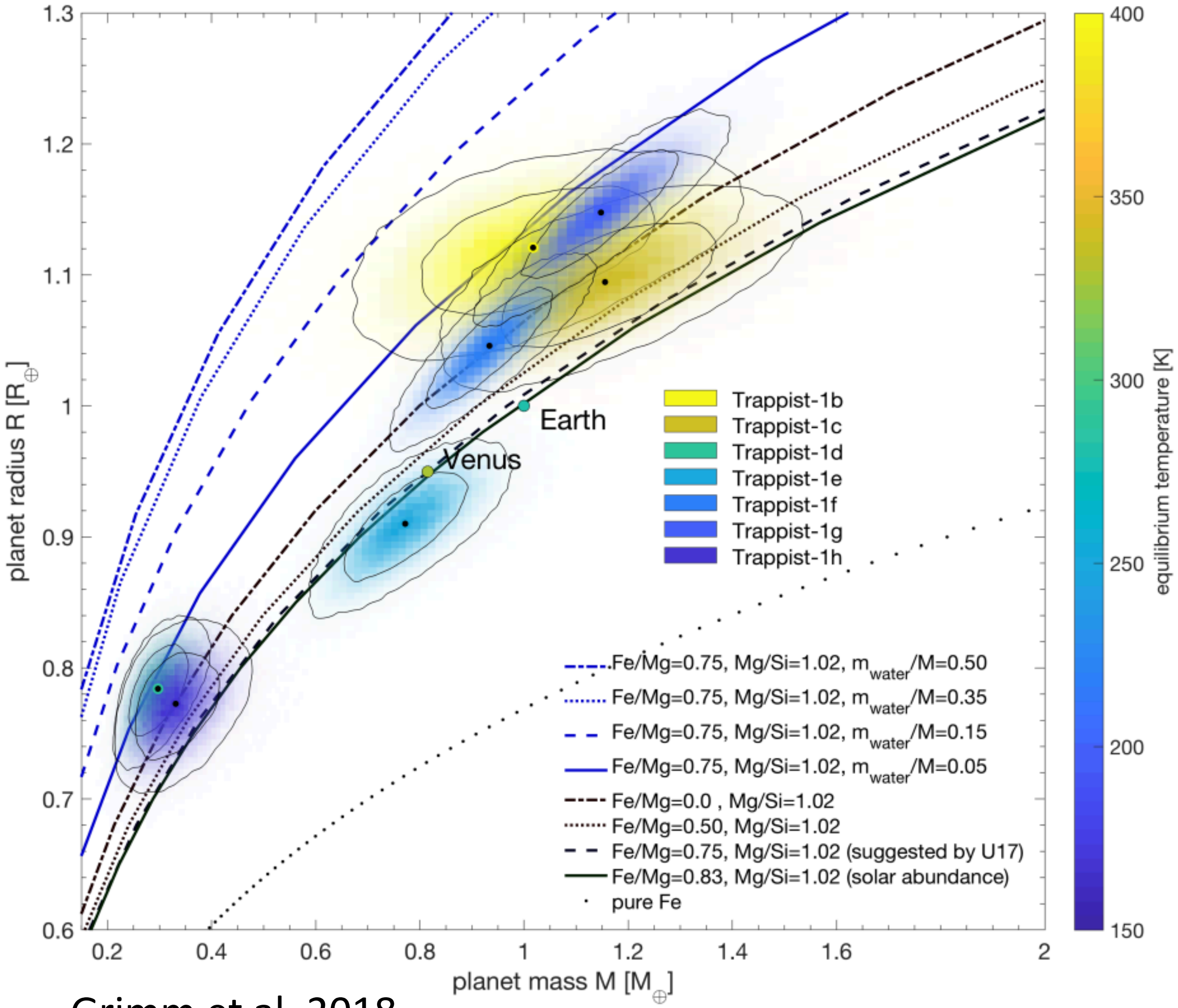

Grimm et al. 2018

BIG QUESTIONS

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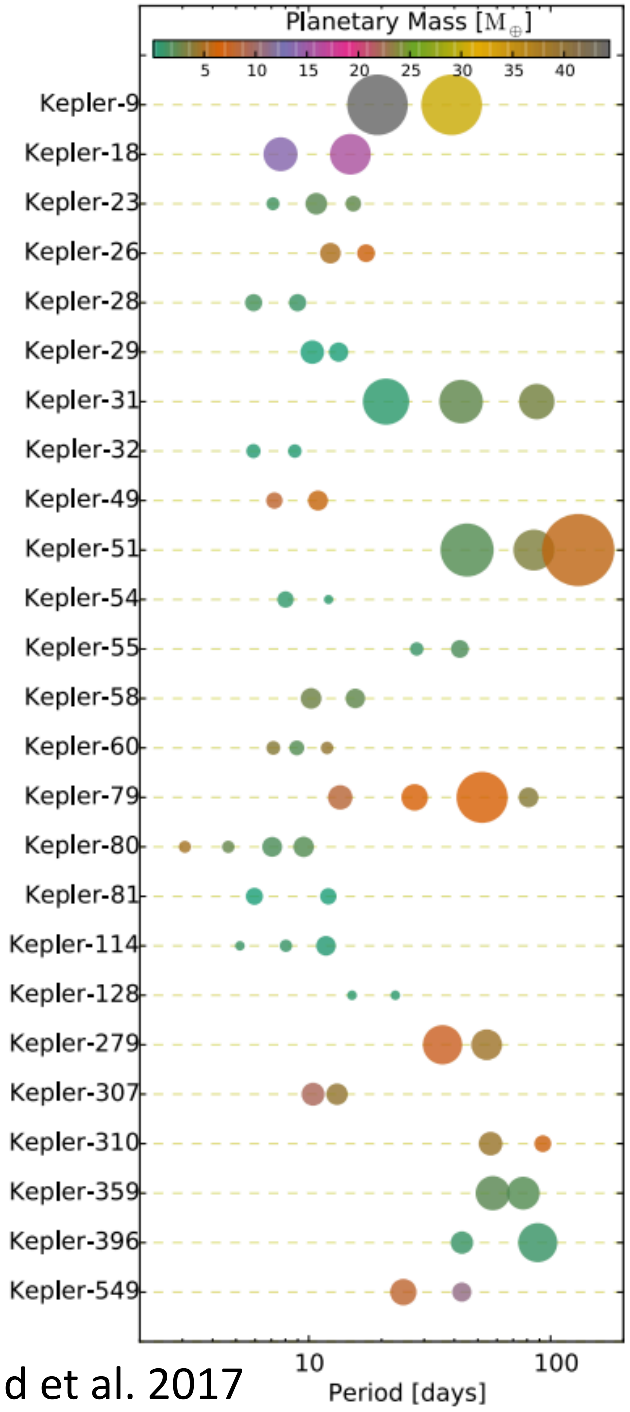


Millholland et al. 2017

BIG QUESTIONS

Studying solar and exo-solar planet formation helps us answer these

Planet Formation in one plot

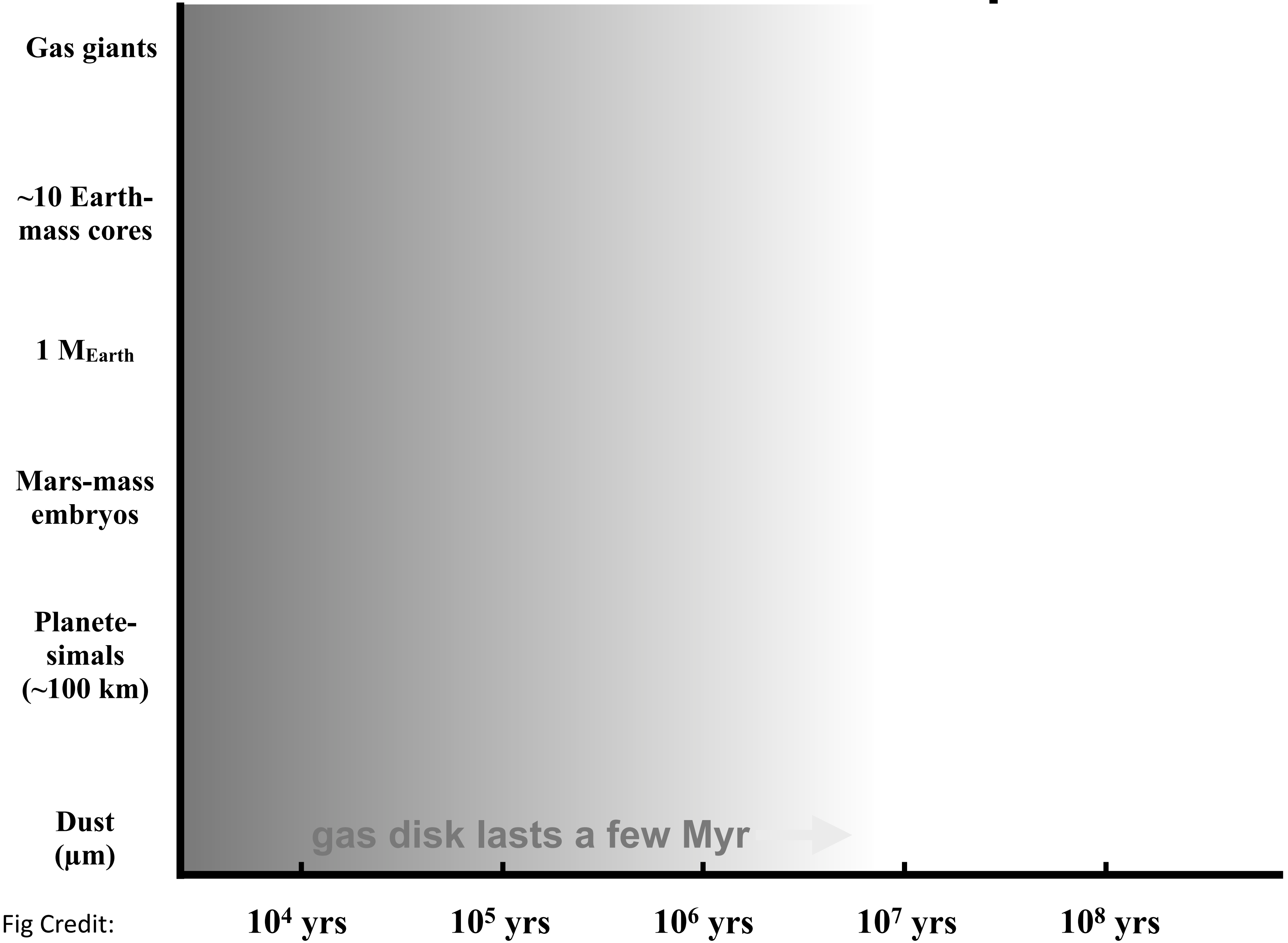
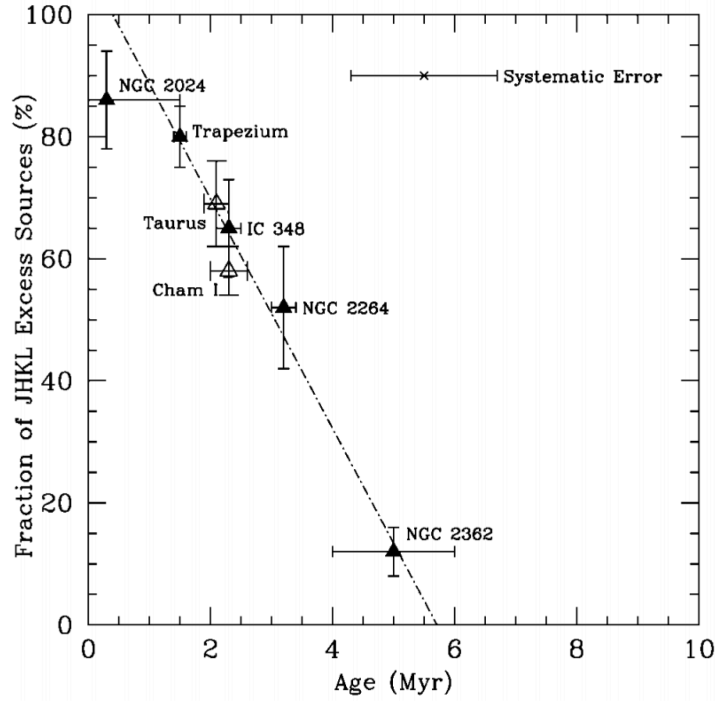


Fig Credit:
Sean Raymond



Haisch et al. 2001, also:
Briceno et al. 2001,
Hernandez et al. 2007,
Hillenbrand 2008, Mamajek 2009

Planet Formation in one plot

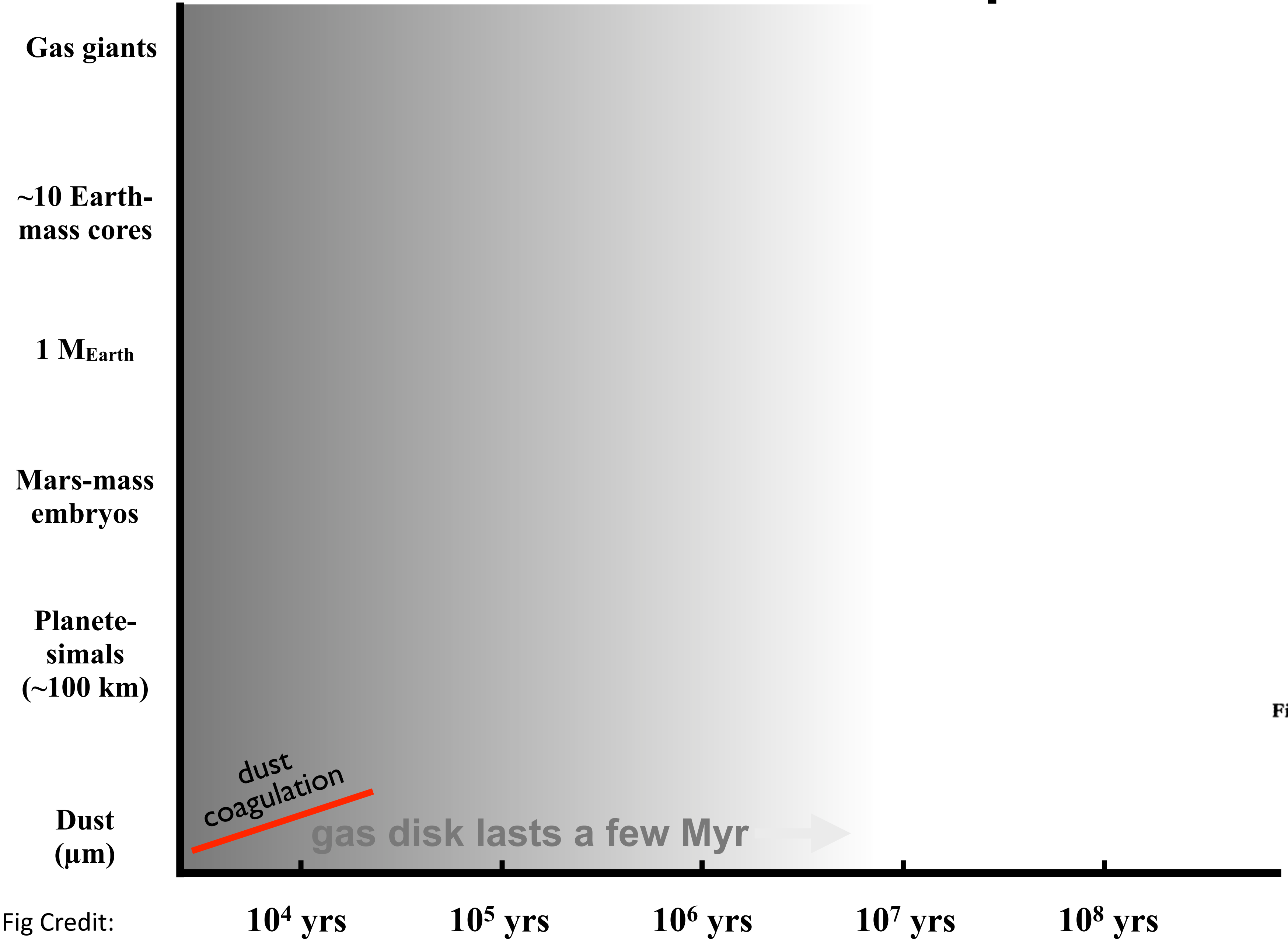


Fig Credit: Sean Raymond

~meter sized objects drift to Sun in ~100-1,000 years

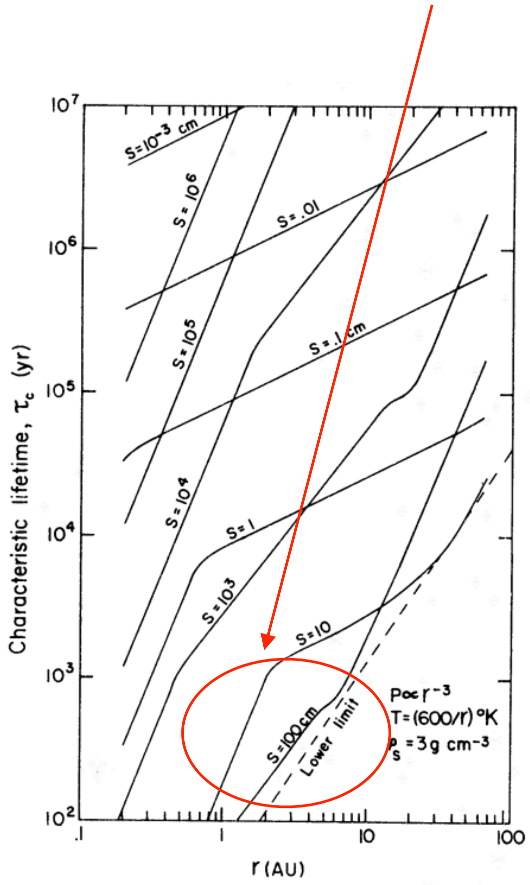


Figure 6. Characteristic lifetime against loss into the sun, $\tau_c = r/|dr/dt|$.

Weidenschilling 1977

Planet Formation in one plot

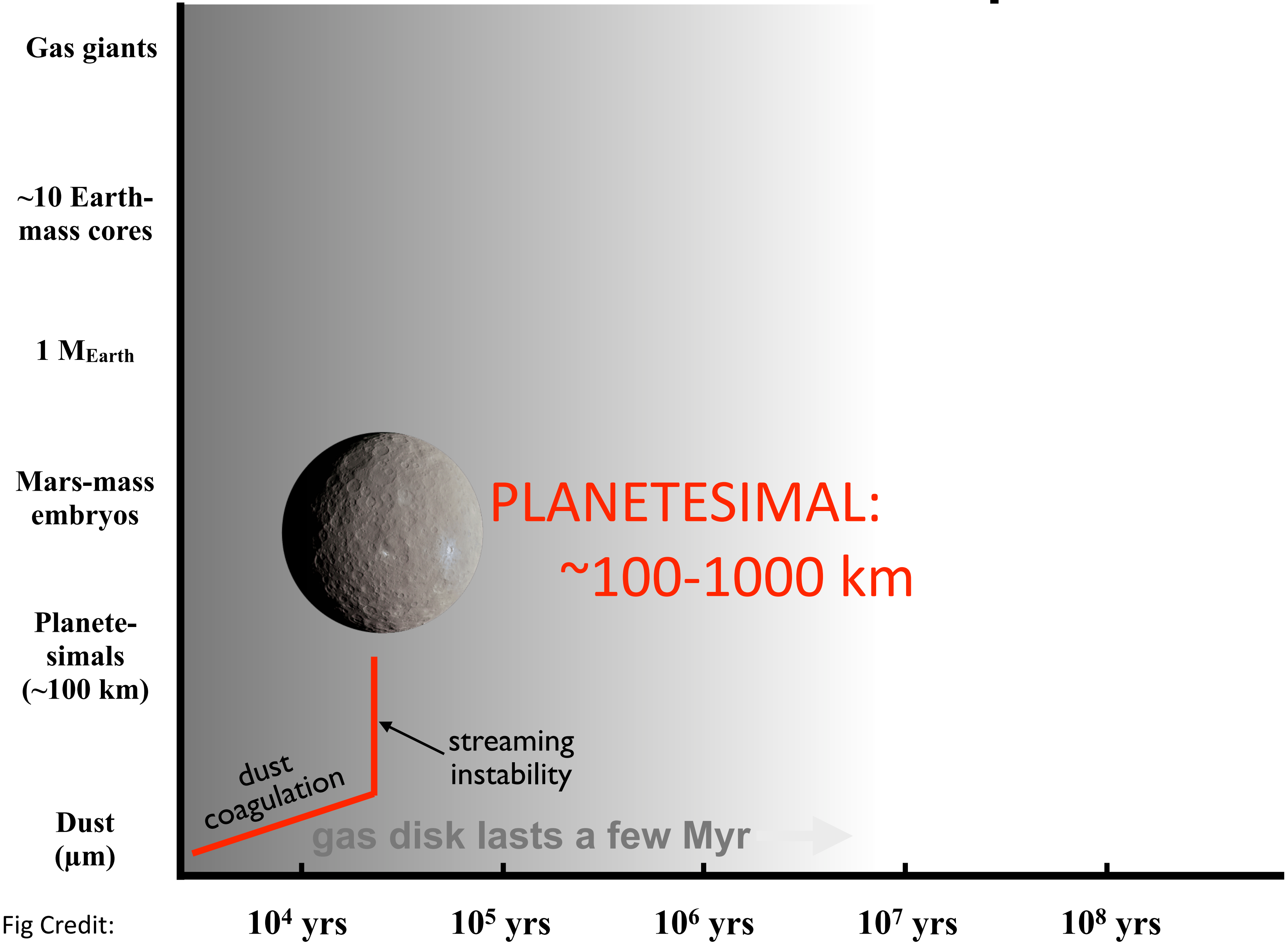
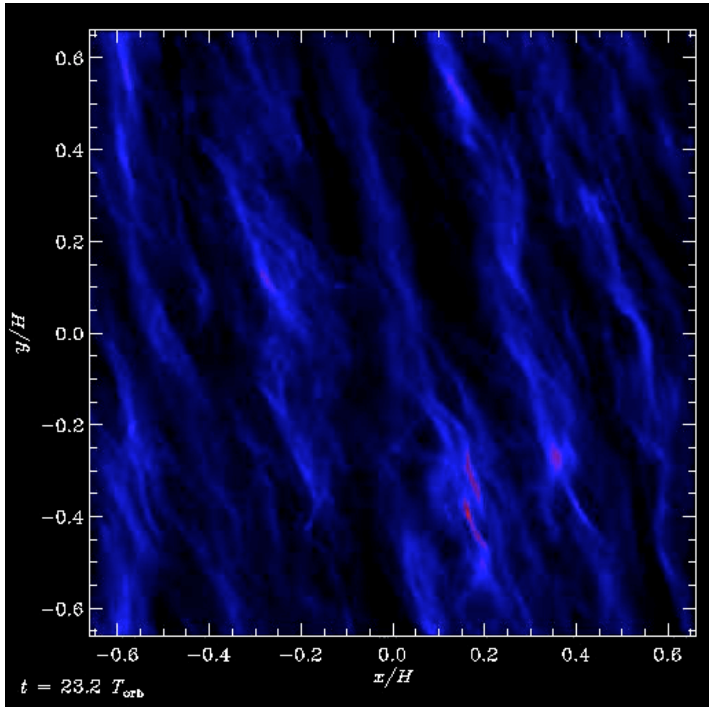


Fig Credit: Sean Raymond



Video credit: Johansen et al., 2015

Planet Formation in one plot

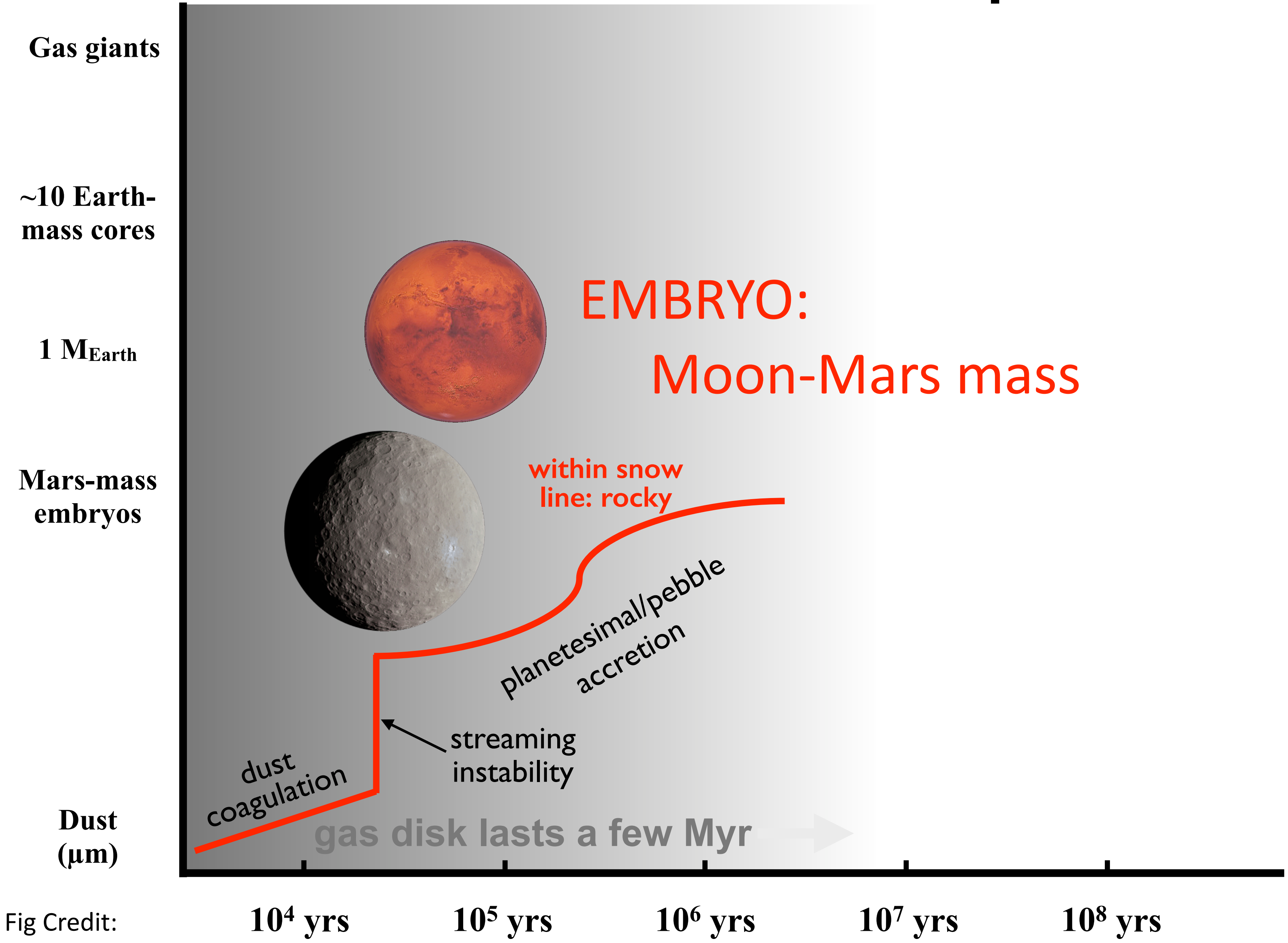
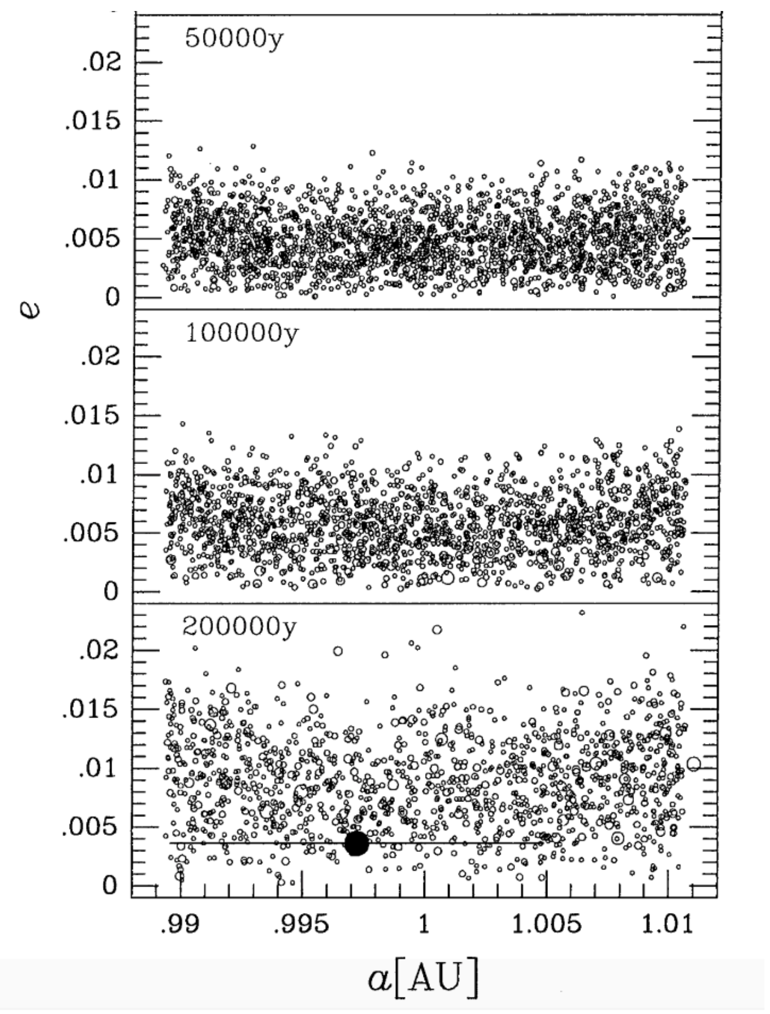


Fig Credit: Sean Raymond

Planetesimal runaway growth



Kokubo & Ida. 1998

Planet Formation in one plot

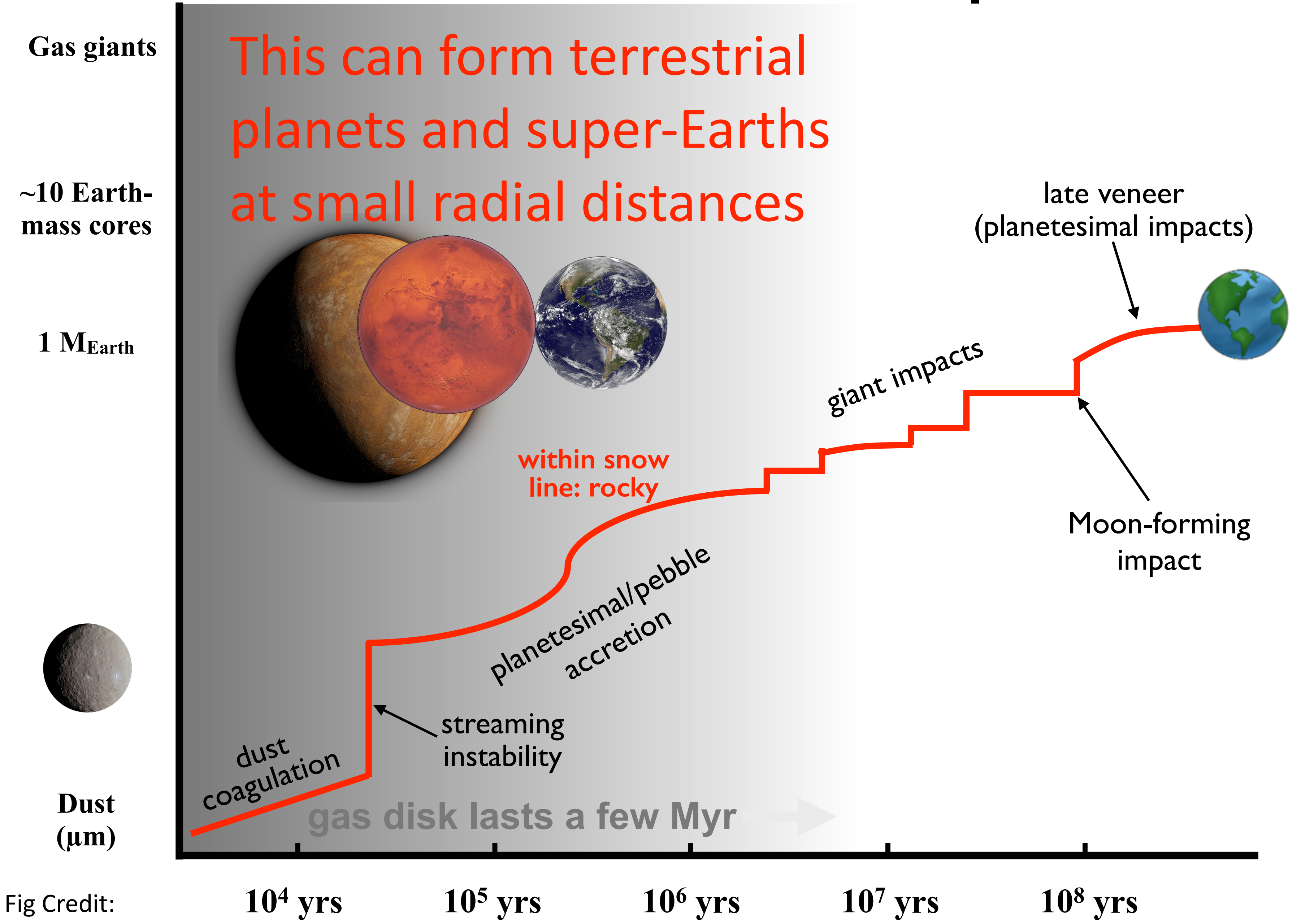
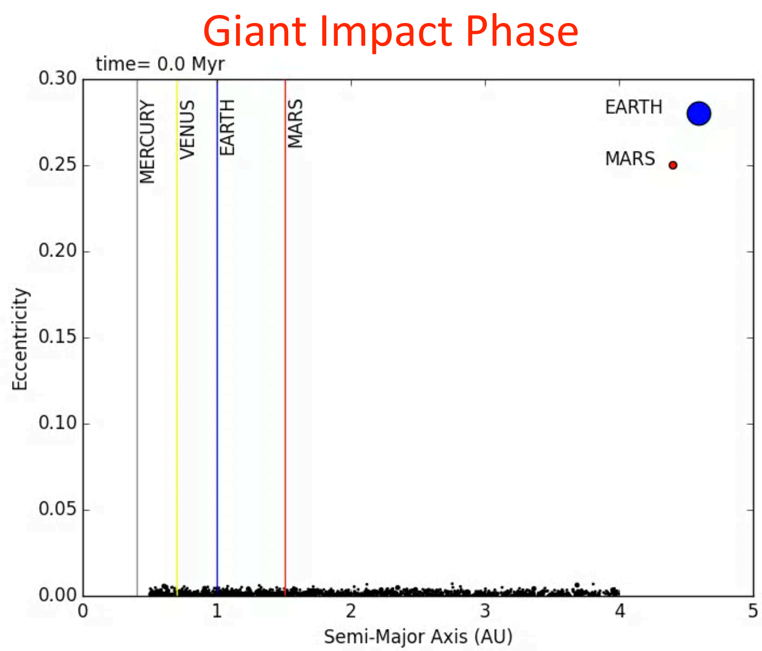


Fig Credit: Sean Raymond



Clement et al. 2018

Planet Formation in one plot

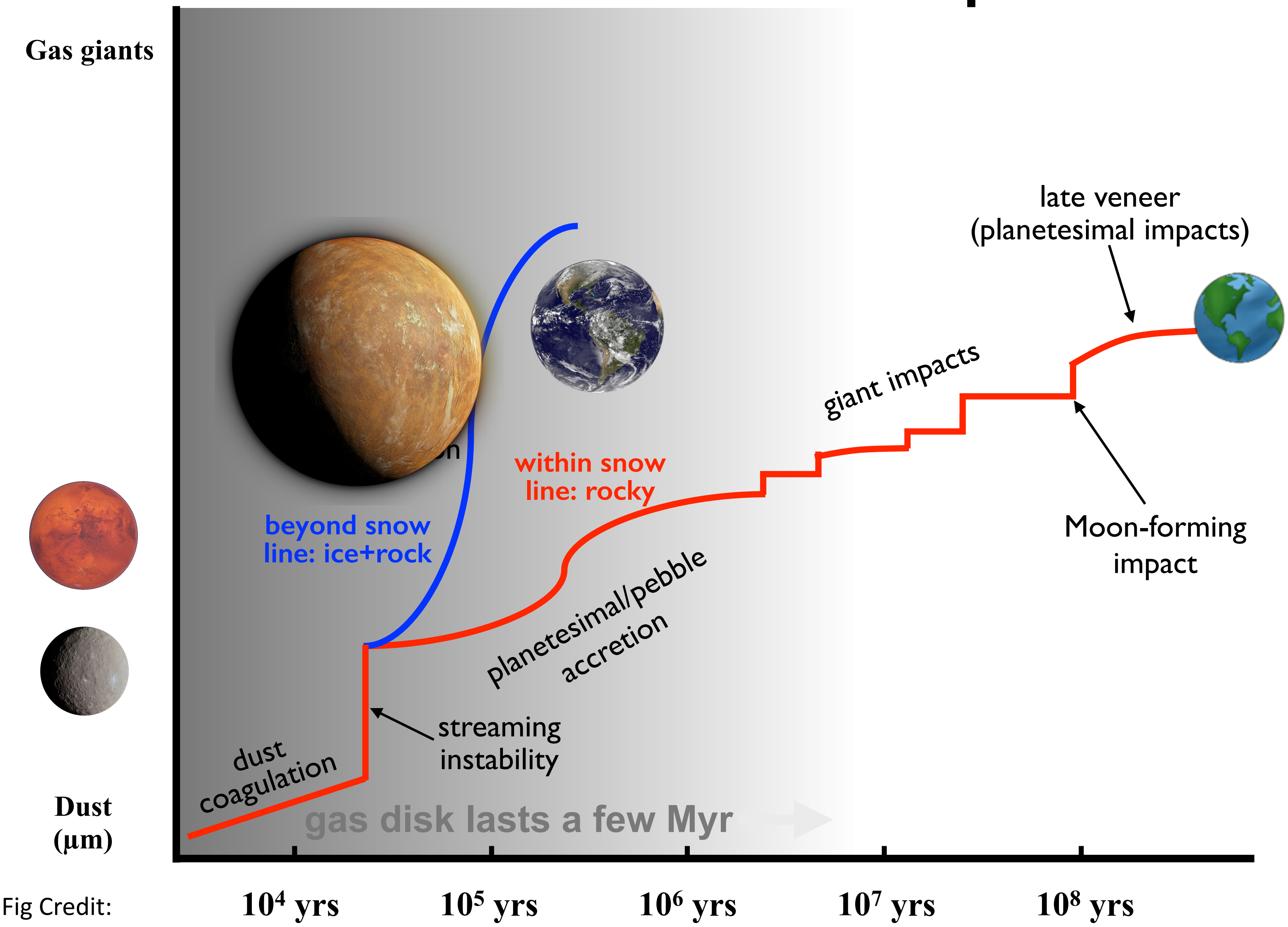
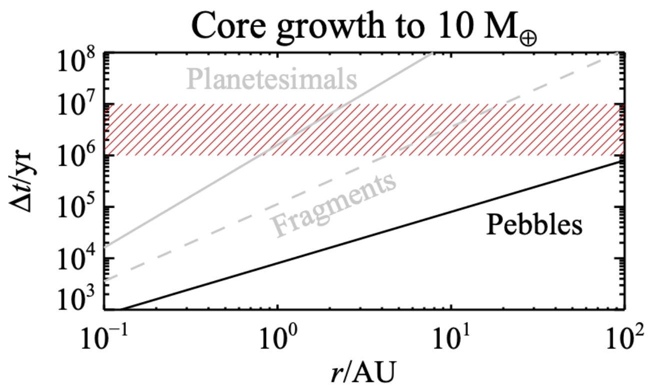


Fig Credit:
Sean Raymond

Giant planets form in the outer disk because:

-**<u>Pebble flux/sizes are larger</u>** (ice sublimation in inner disk)

-**<u>Large cores forming in inner disk form too fast and migrate:</u>**



Lambrechts & Johansen (2012)

Planet Formation in one plot

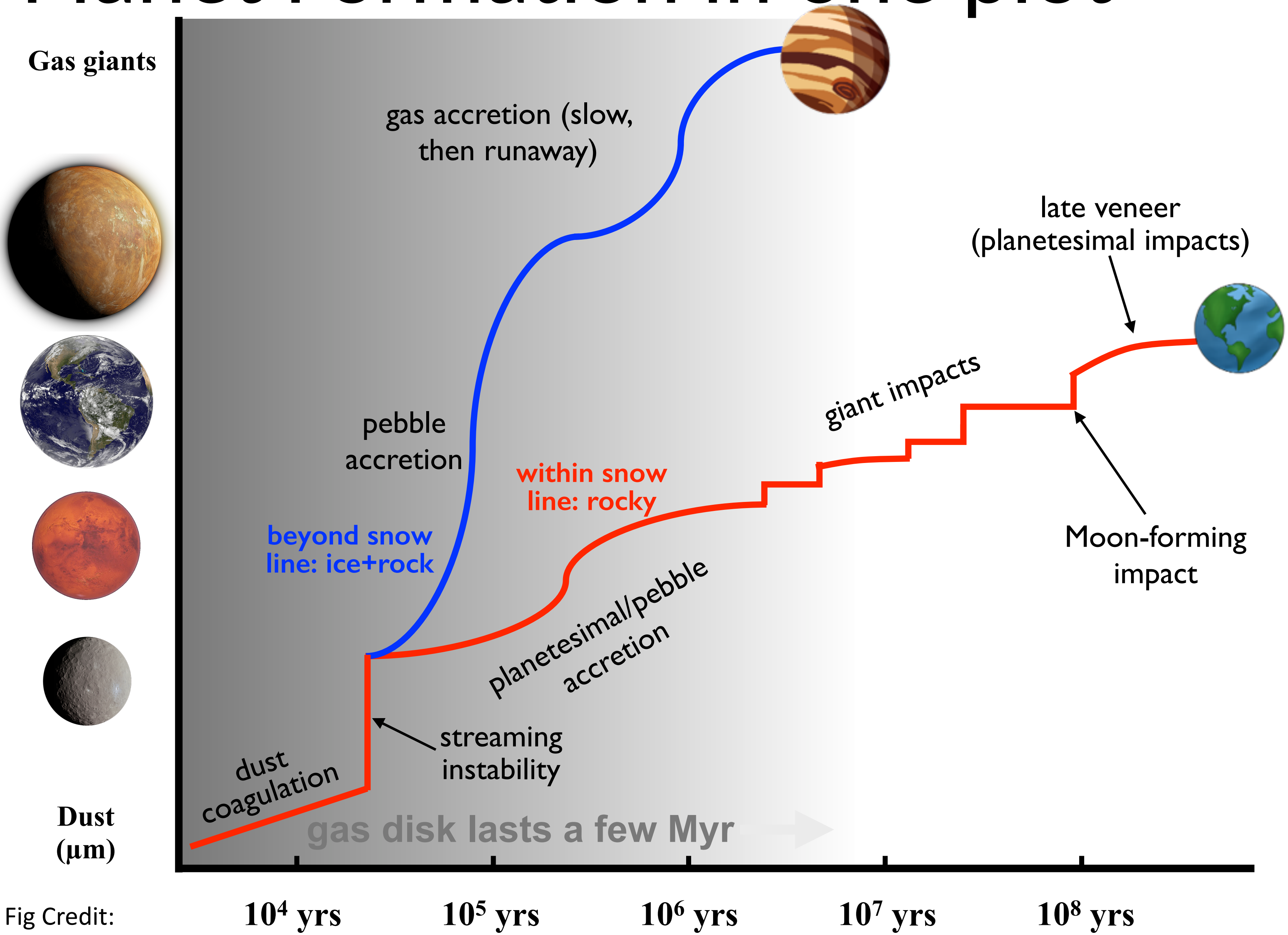


Fig Credit:
Sean Raymond

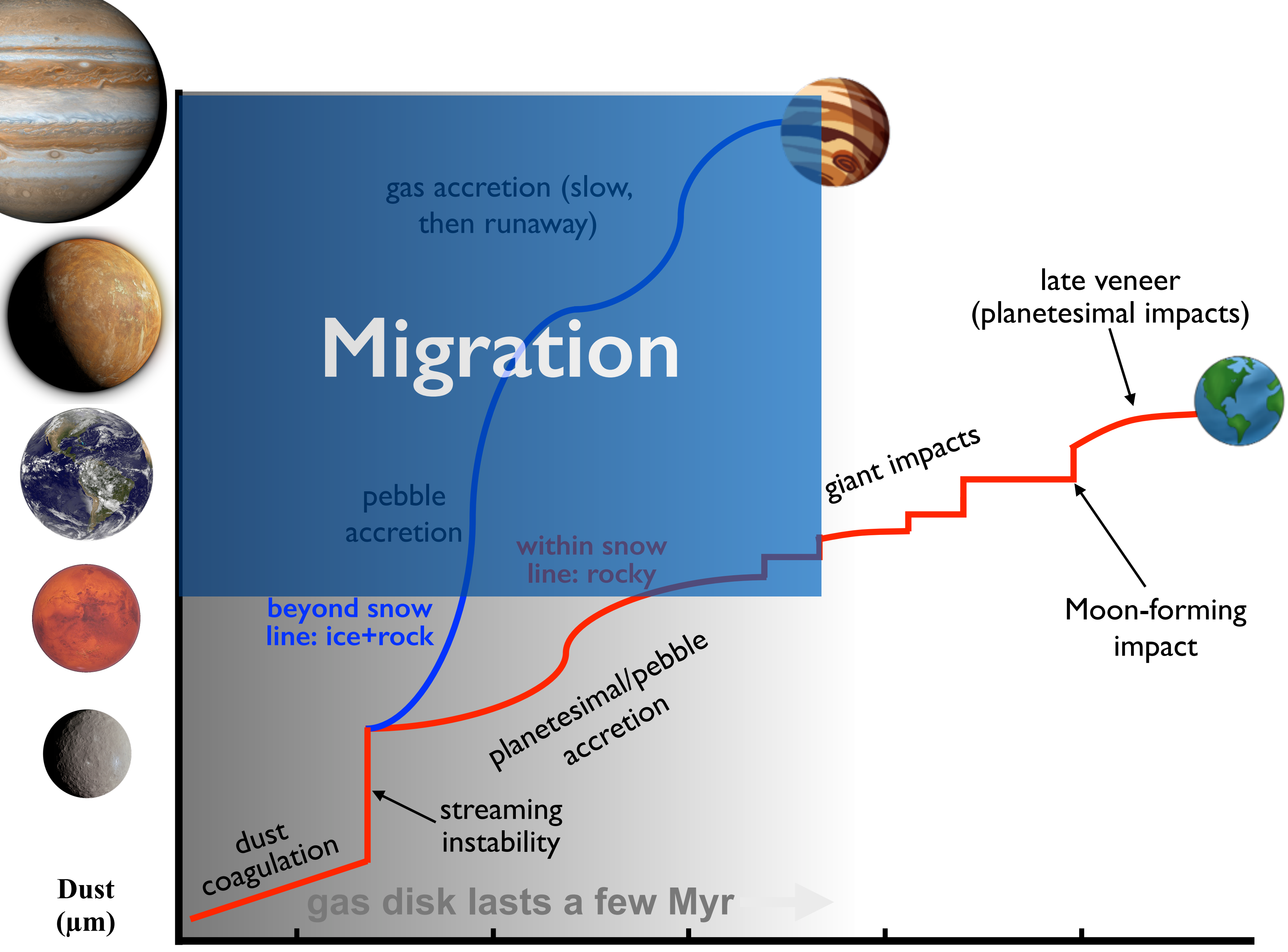


Fig Credit: Sean Raymond

This can form:

-**Super-Earths/Sub-Neptunes** (grew too slow to accrete gas before migrating)

-**Distant giant planets** (grew fast enough to accrete gas and didn't migrate)

-**Hot Jupiters** (accreted gas, and migrated in)

BIG QUESTIONS

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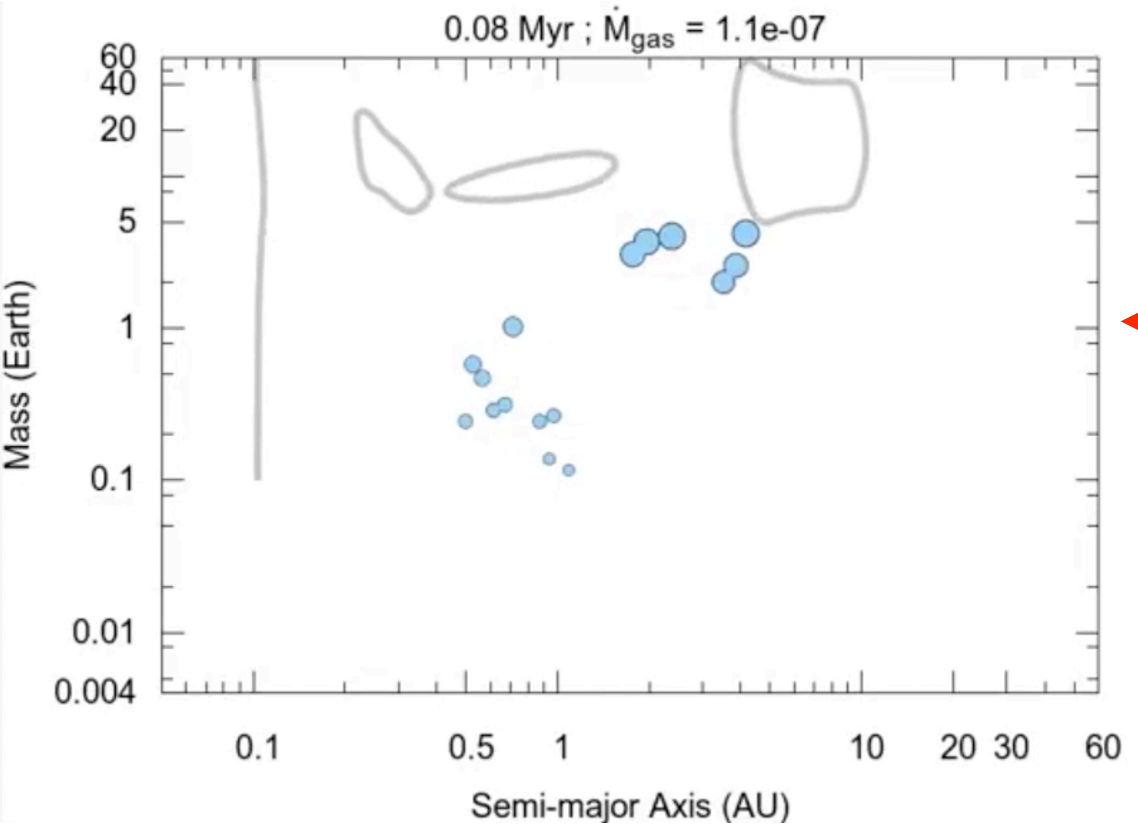
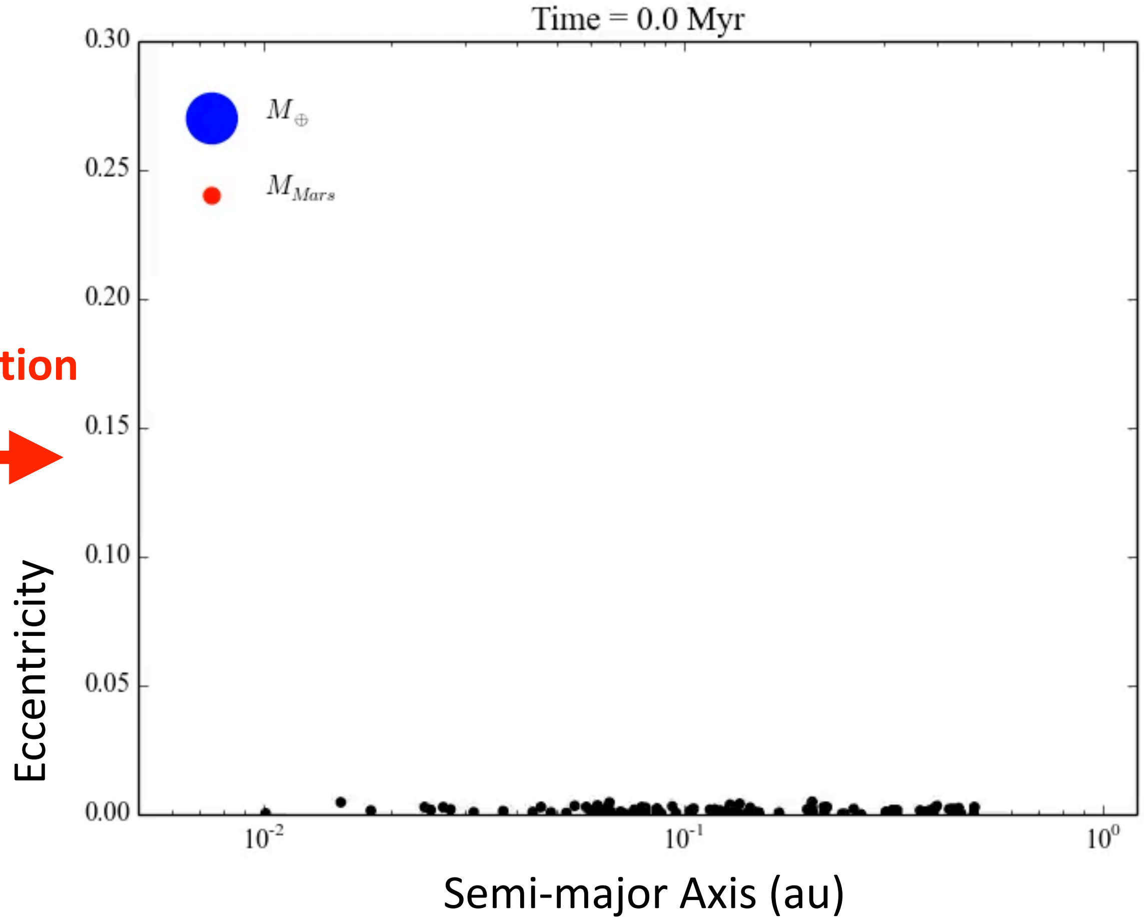
- Are Earth-analogs around M-Dwarfs habitable?
- Why are the solar system's planets so non-uniform in m/R (besides Earth and Venus)?

Recall: Super Earth's can be formed close-in, or further out:



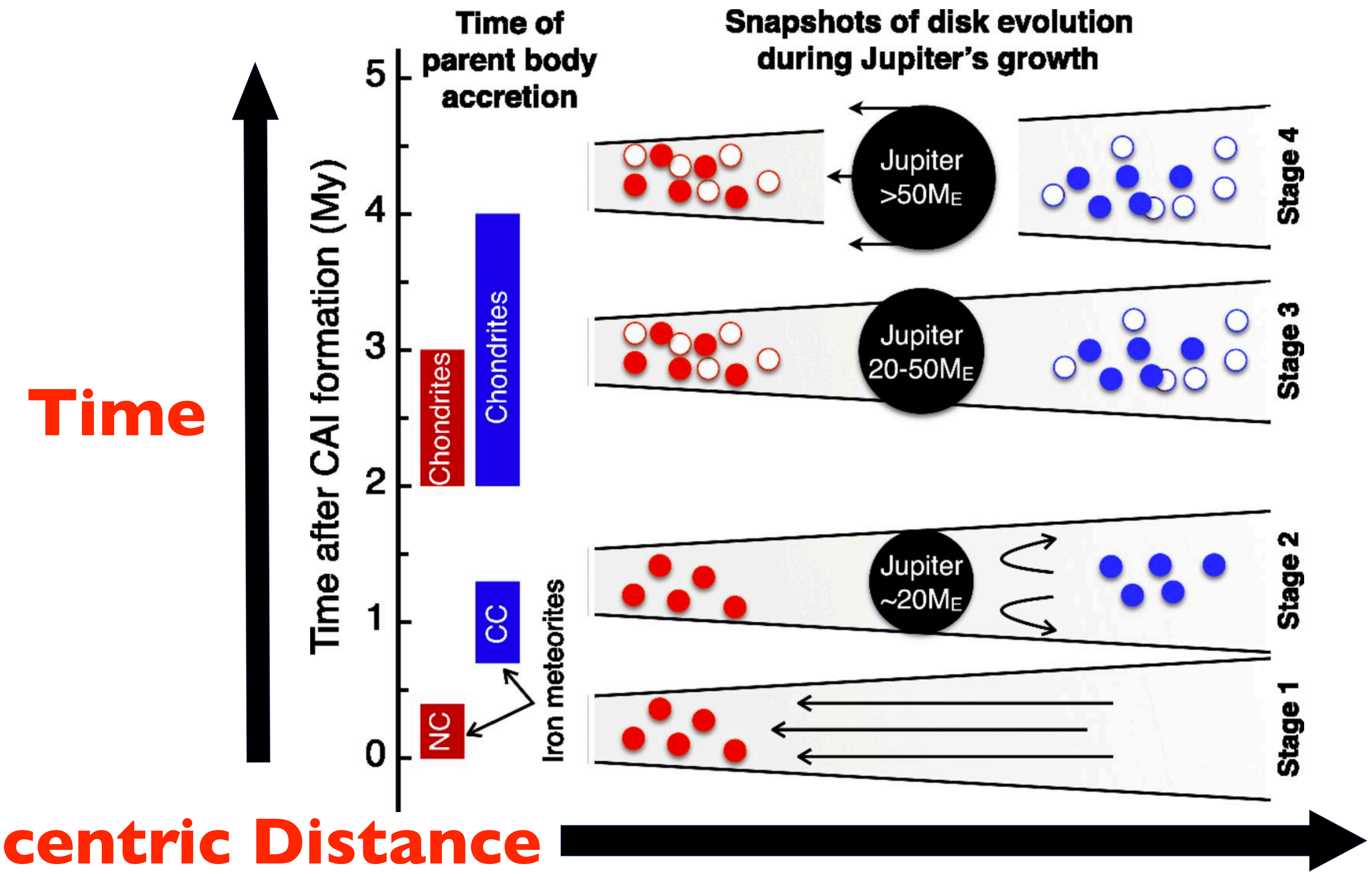
Migration

In-Situ



Video Credit: Sean Raymond, Clement, Quintana & Quarles (revision submitted)

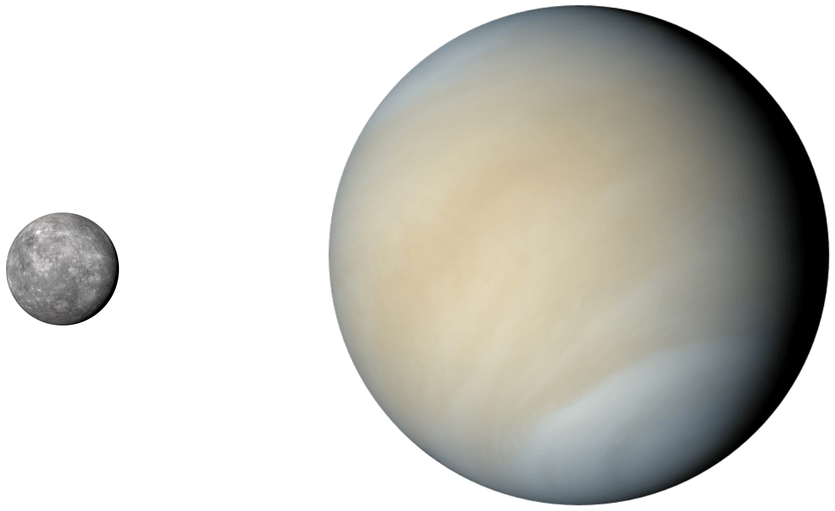
✗ Migration: Prevented by Jupiter



Kruijer et al., 2017

? In-Situ: Why Mercury and no Super-Earth?

- Small
  - $M_v/M_{M,ss} = 14.8$



Video Credit: Clement et al. 2018

In-Situ: Why Mercury and no Super-Earth?

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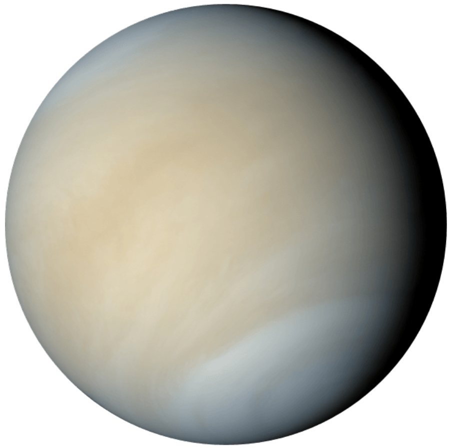
- Dynamically isolated
  - $P_v/P_{M,ss}$= 2.6



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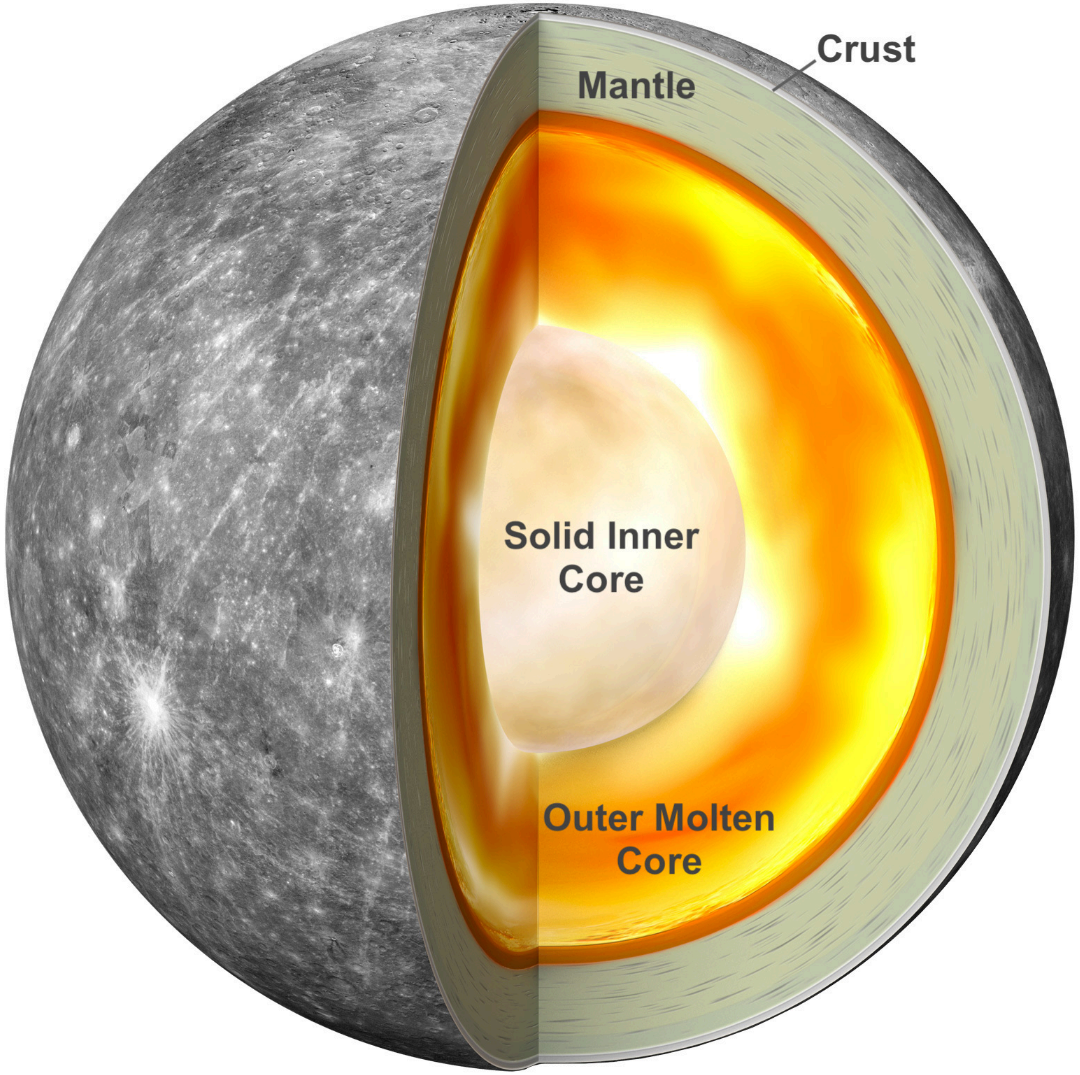
- Dynamically excited orbit (e=0.2,i=7°)



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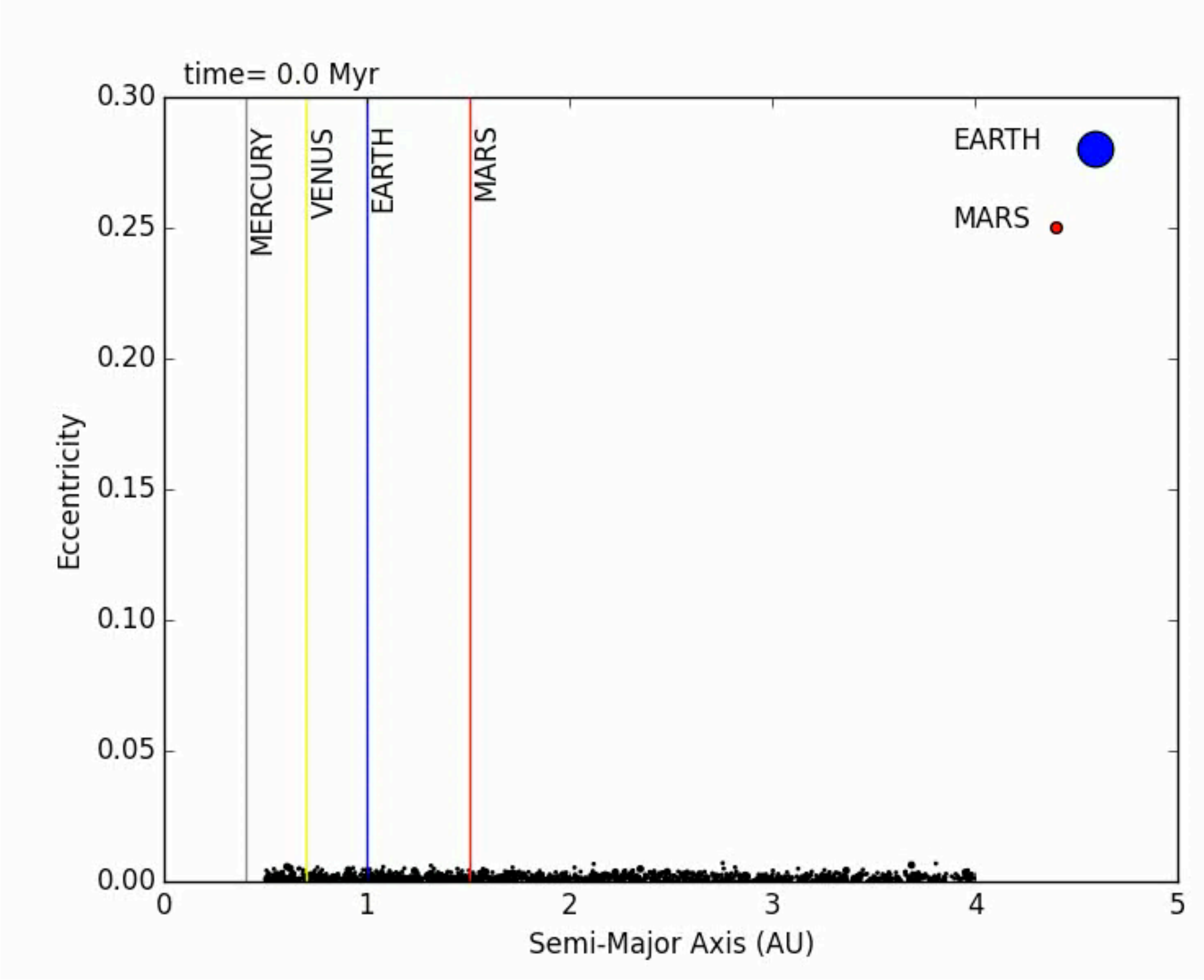
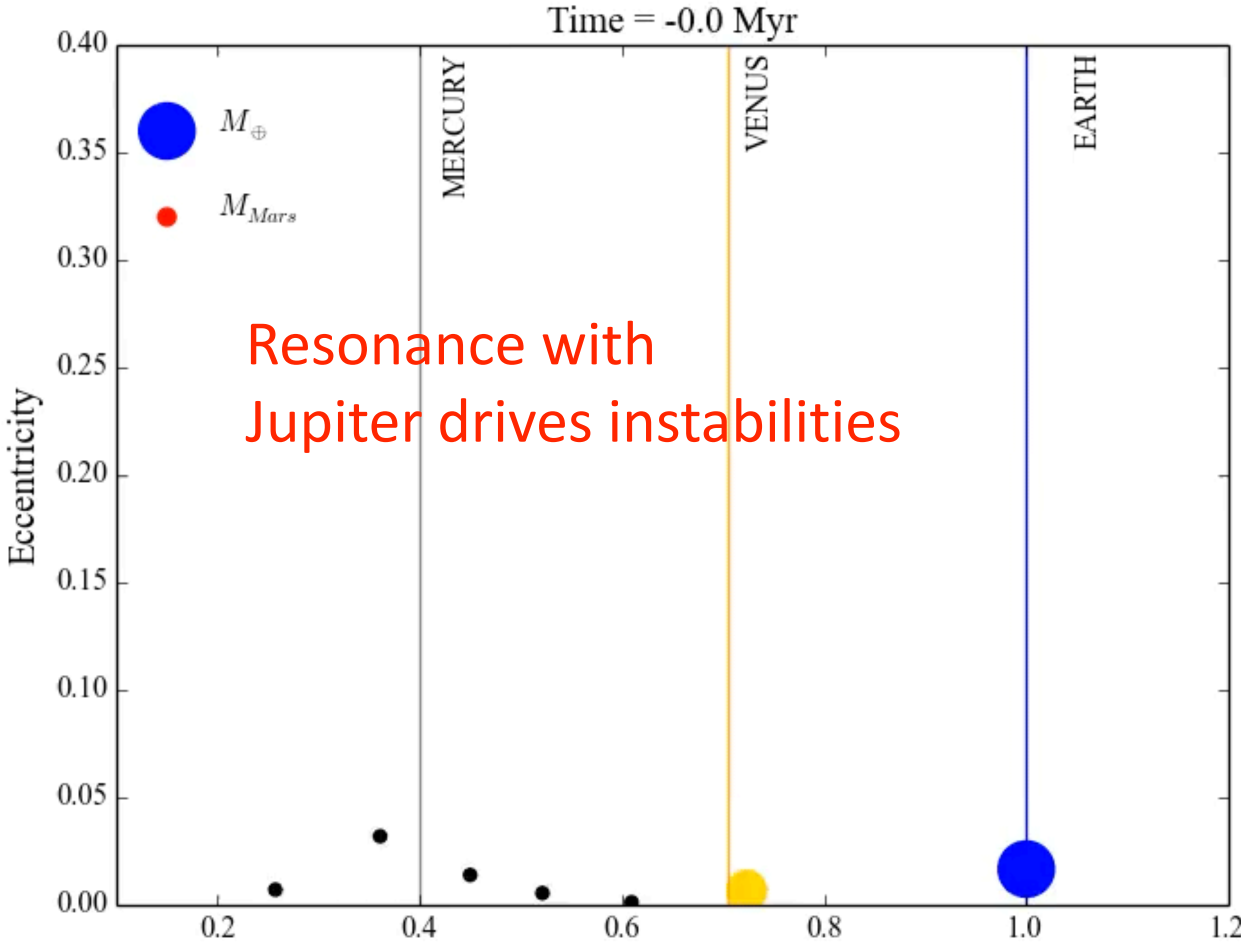
- Large Core Mass Fraction
- Dynamically excited orbit (e=0.2,i=7°)
- Classic models (e.g.: Chambers 2001) predict forming additional Earth-mass planets interior to Venus (something like TRAPPIST-1)



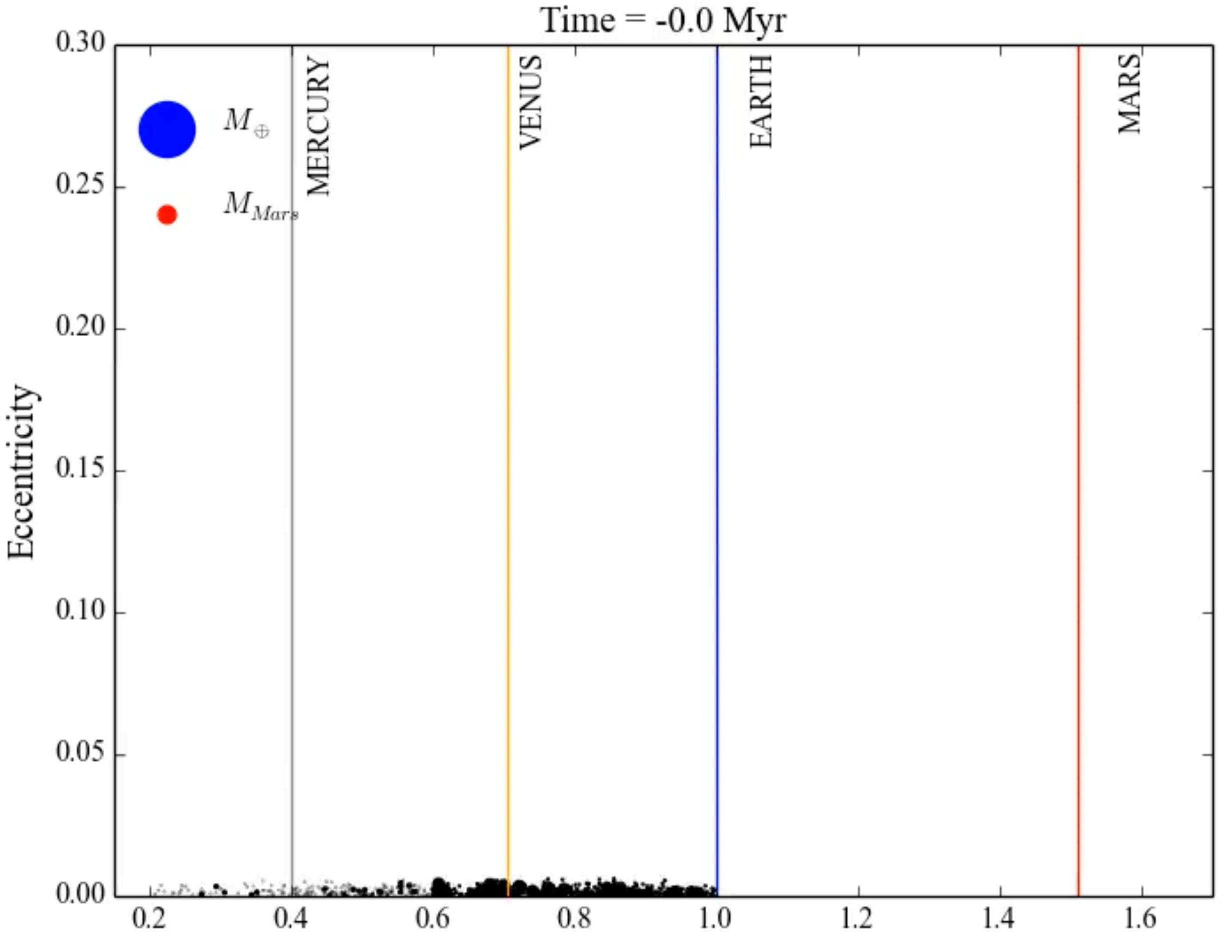
Video Credit: Clement et al. 2018

Perturbations from Jupiter and a mass deficit interior to Venus

Clement et al. 2021



Clement & Chambers 2021



Earth and Mars' disparate compositions: Implications for Mercury's formation

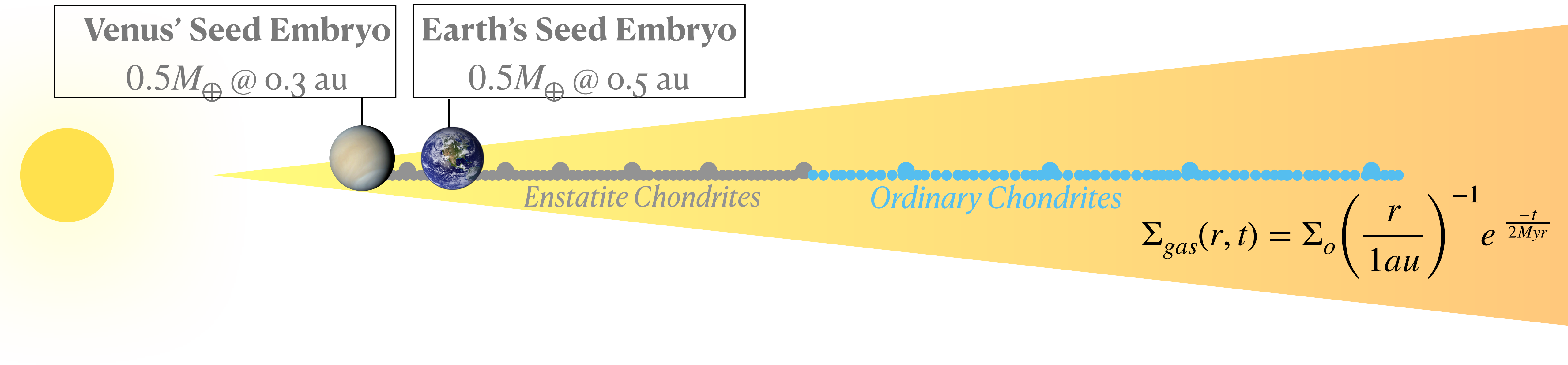


Fig credits: Clement et al. (2021e)

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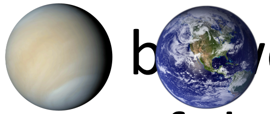

In addition to explaining the masses of each planet, this explains differences between the Earth and Mars in terms of their bulk isotopic similarities to various chondritic meteorites

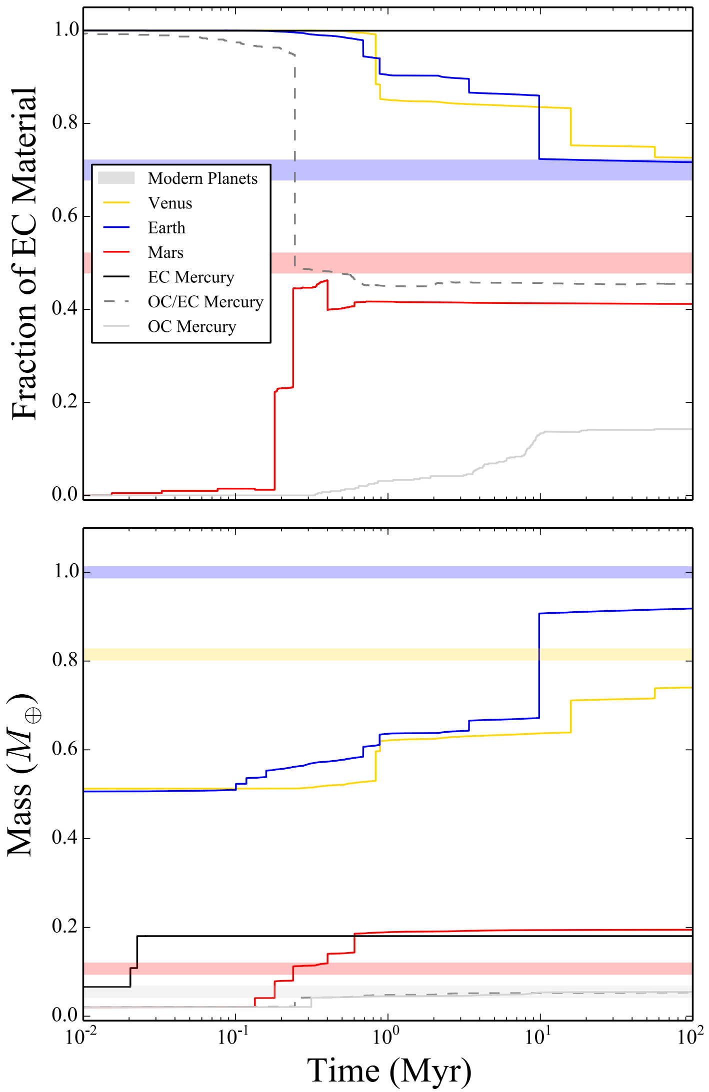

Fig credits: Clement et al. (2021e)

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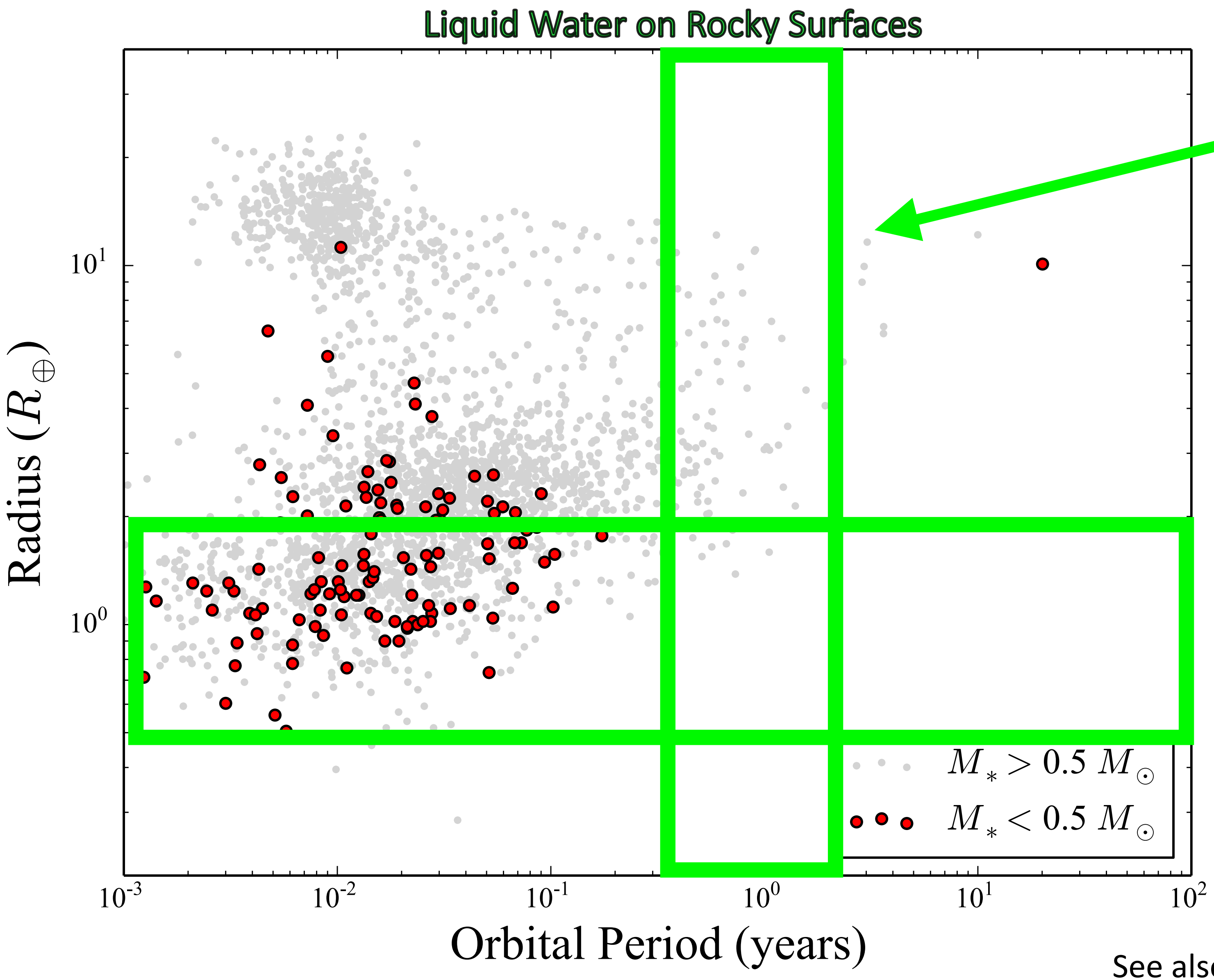
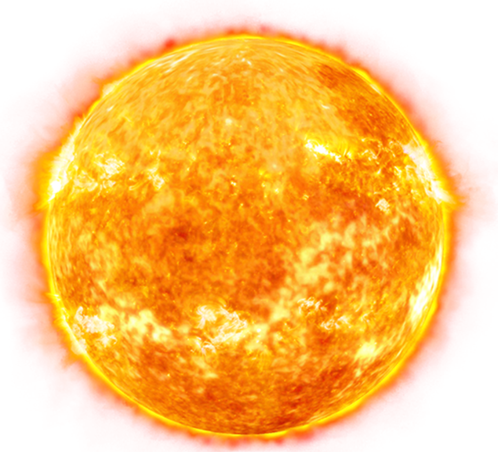
Transiting planets in HZ: M Dwarfs vs. Sun-like



Habitable Zone for Sun-like Stars



See also: Dressing & Charbonneau 2013,2015; Gaidos et al. 2016

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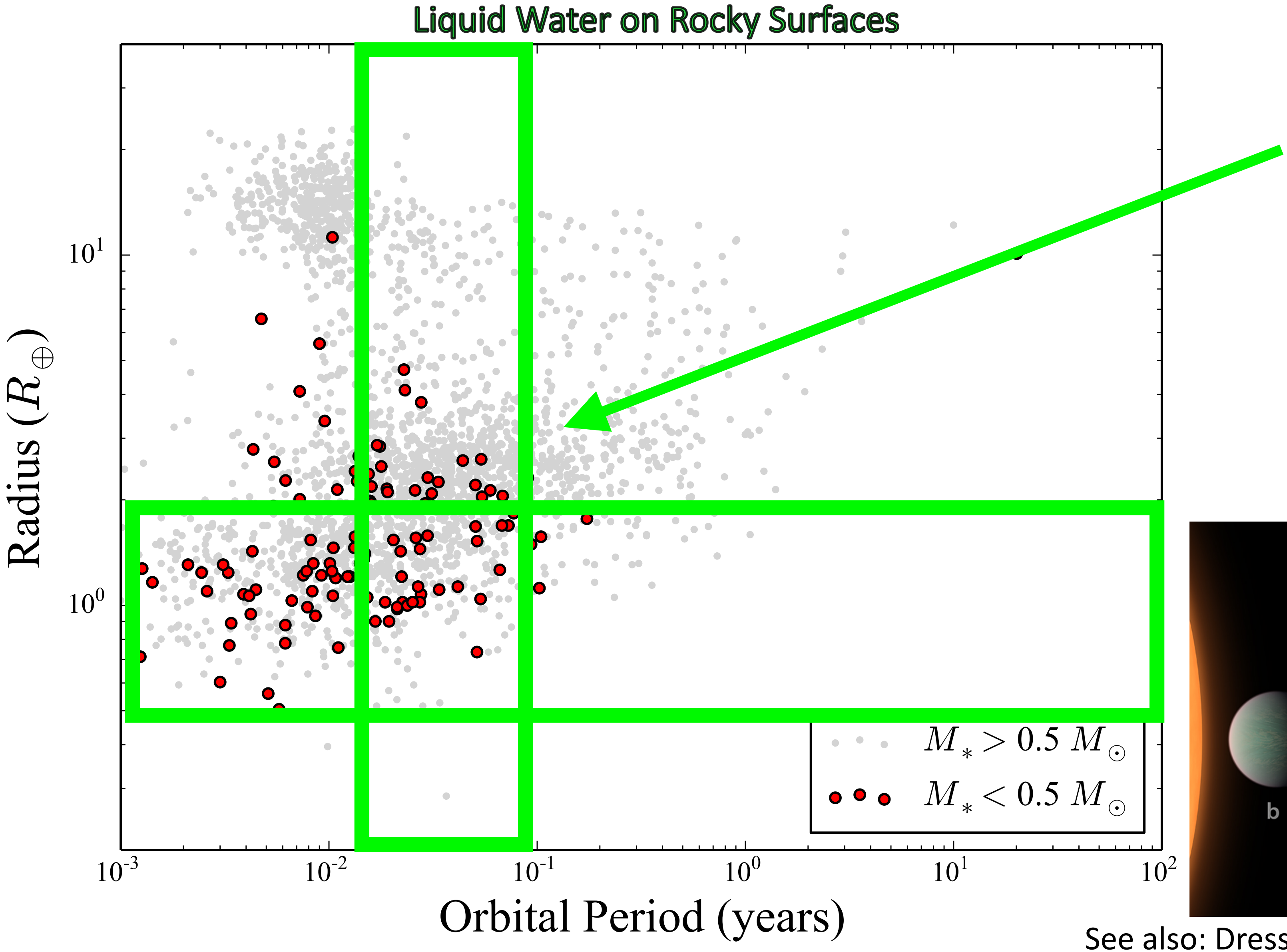
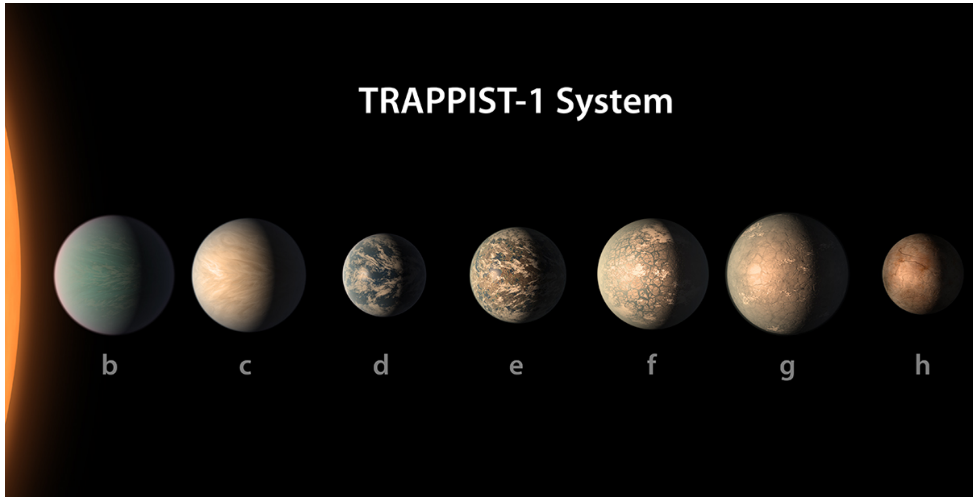


Habitable Zone for M-Dwarfs

- Most common stars
- Most common type of planet in the HZ
- Short Period and deep transits



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Hazards faced by potentially habitable planets around small stars

- Planets' and their atmospheres must overcome a myriad of challenges:
  - Flares

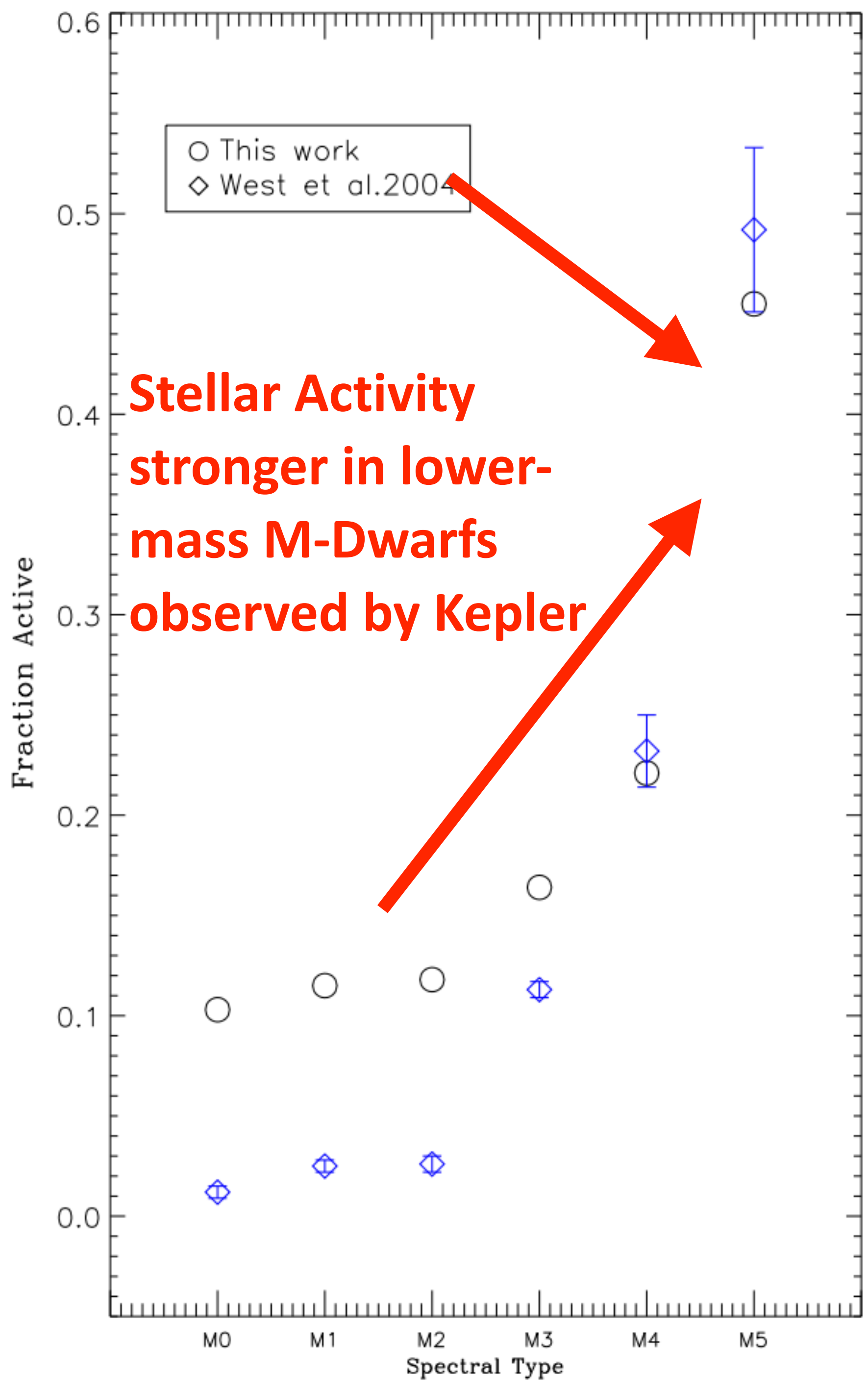

Fig Credits: Sanz-Forcata et al., 2011; Bolmont et al 2017, Yang et al. 2017

Hazards faced by potentially habitable planets around small stars

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  - Tides (locking and heating)

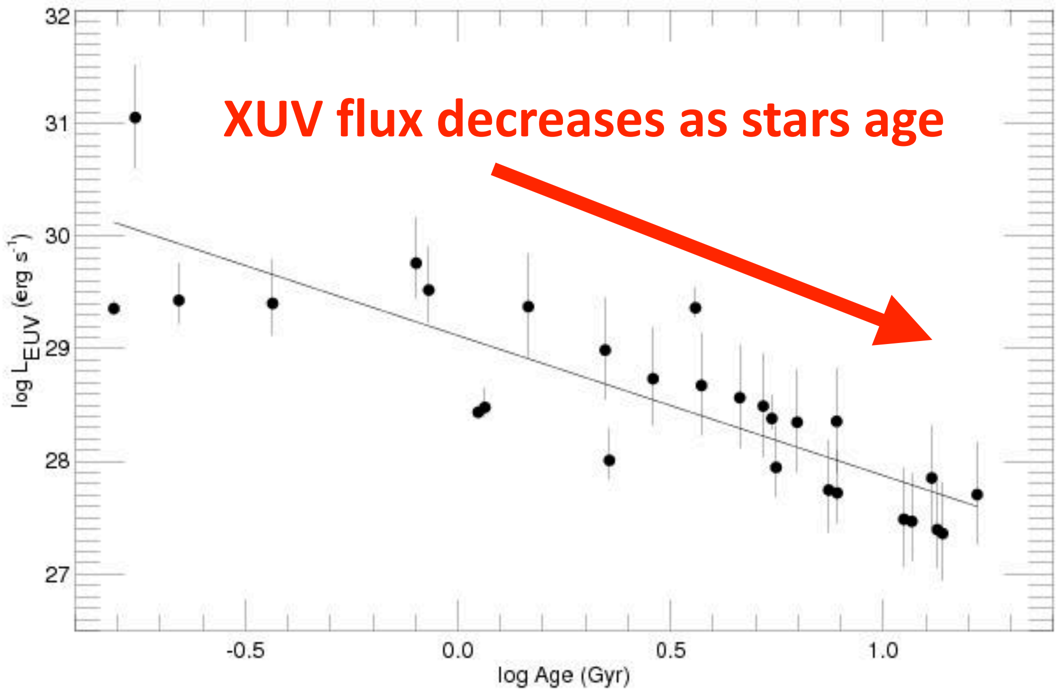


Fig Credits: Sanz-Forcata et al., 2011; Bolmont et al 2017, Yang et al. 2017

Hazards faced by potentially habitable planets around small stars

- Planets' and their atmospheres must overcome a myriad of challenges:
    - Flares
    - Tides (locking and heating)
    - XUV Radiation
- Long cooling times
    - Stars don't reach Main Sequence until after the planets form.

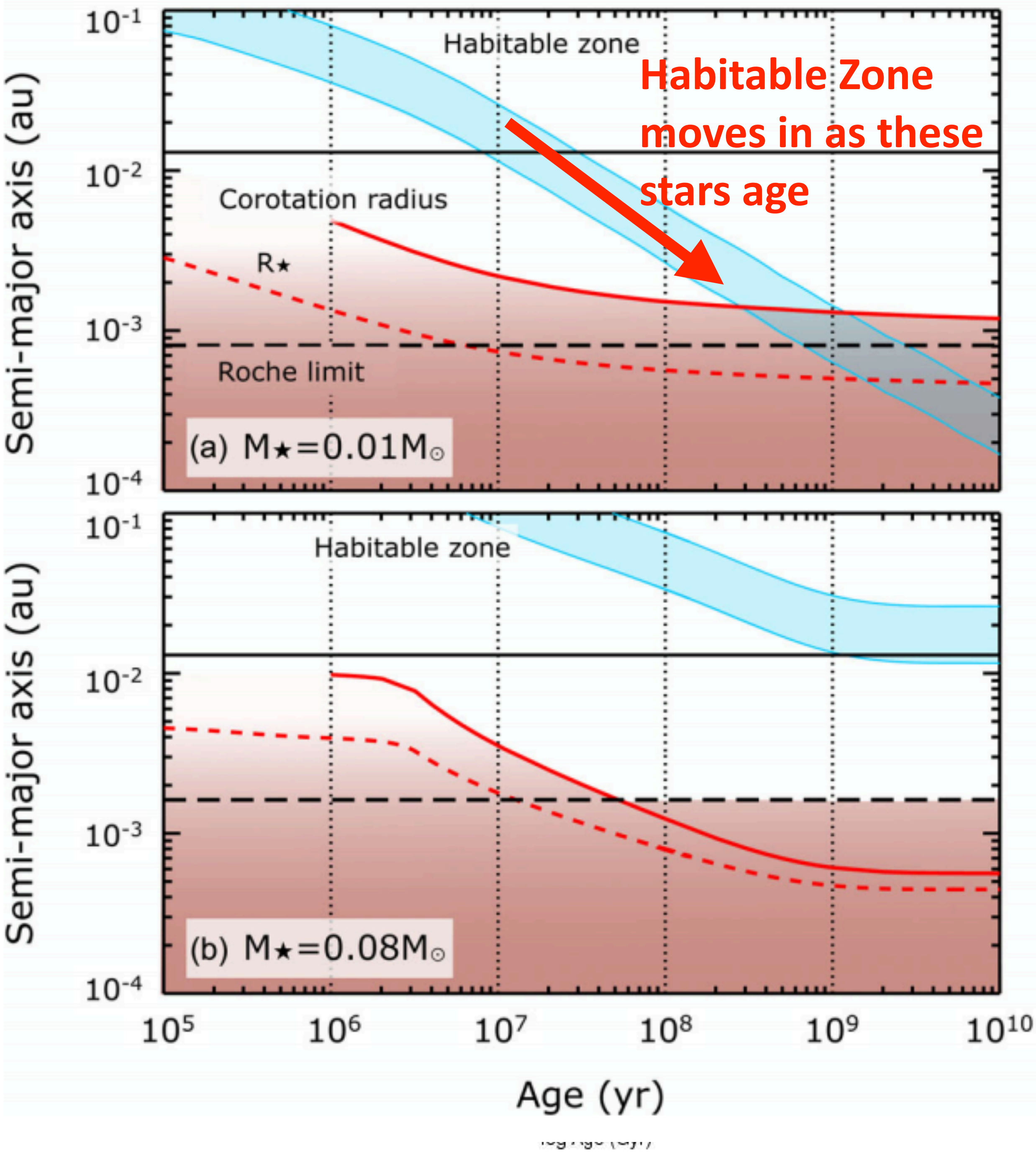
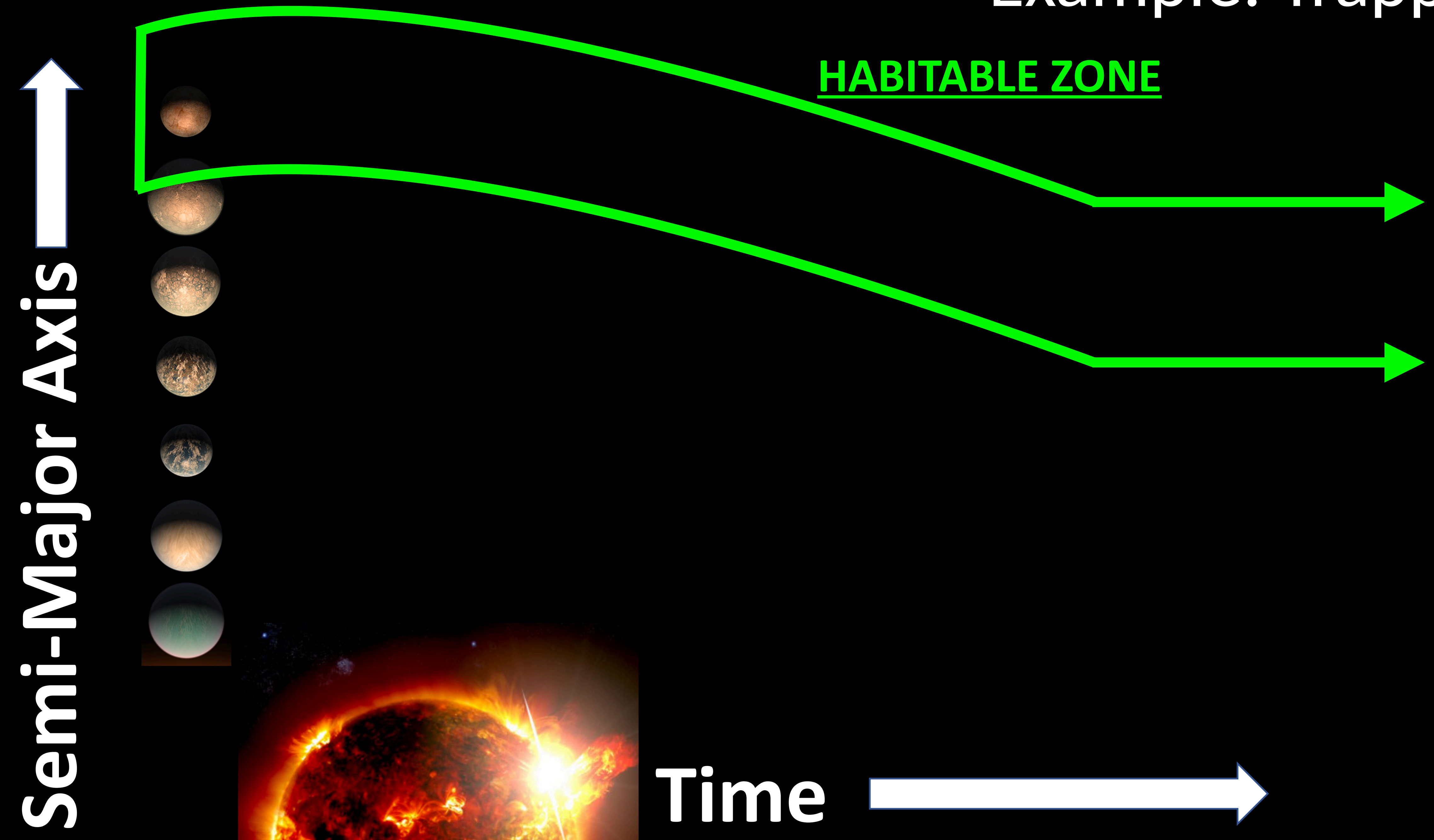


Fig Credits: Sanz-Forcata et al., 2011; Bolmont et al 2017, Yang et al. 2017

Example: Trappist 1



If atmosphere is lost, can it be replenished?

- It is thought that Earth's primordial **atmosphere was reshaped by impacts over Gyr-timescales** from:
  - Comets
  - Asteroids
  - Left-over planetesimals

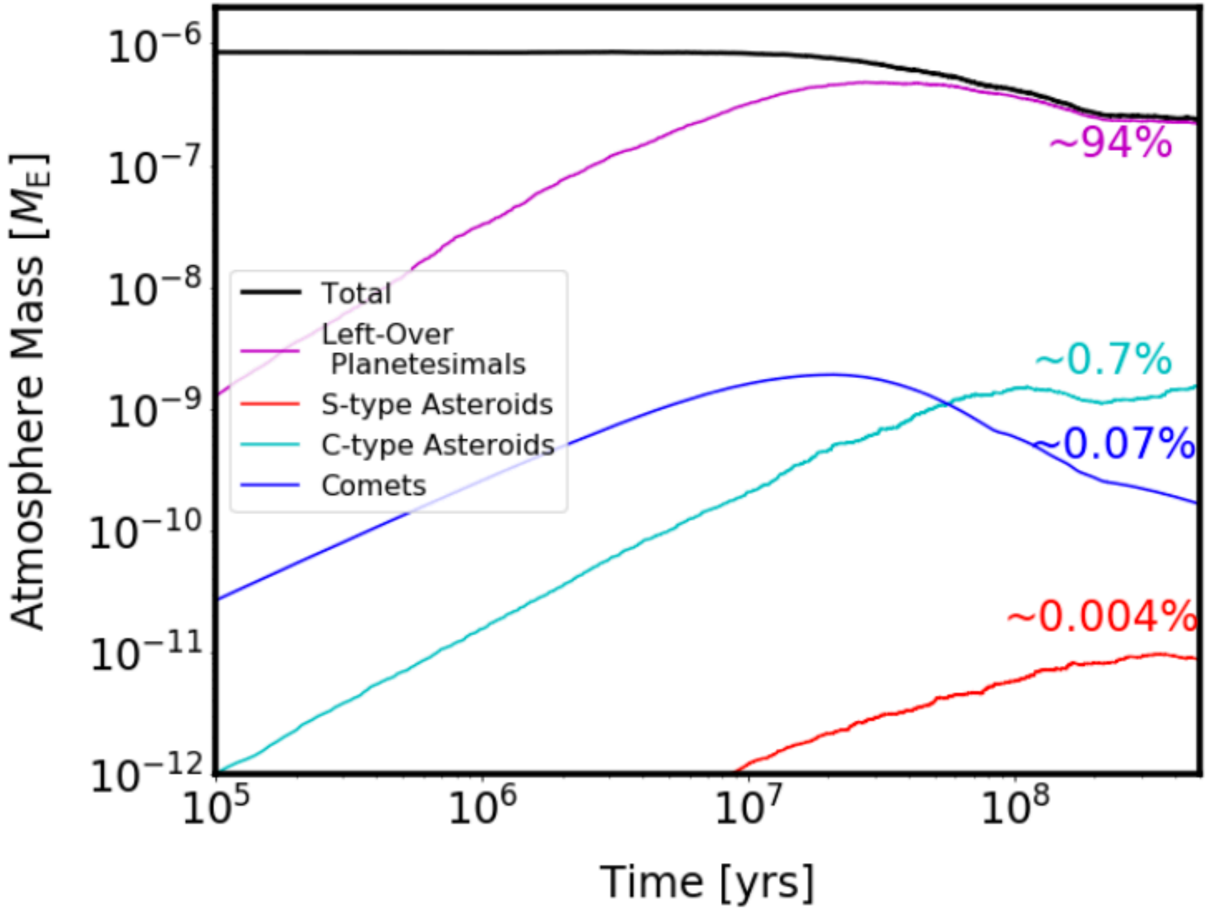


Fig Credit: Sinclair et al 2020

Probability of a late, large, wet impact

$$P \propto P(t \gtrsim 500\text{Myr}) \times P(a_o \gtrsim a_{\text{Snow}}) \times P(D \gtrsim 100\text{km})$$

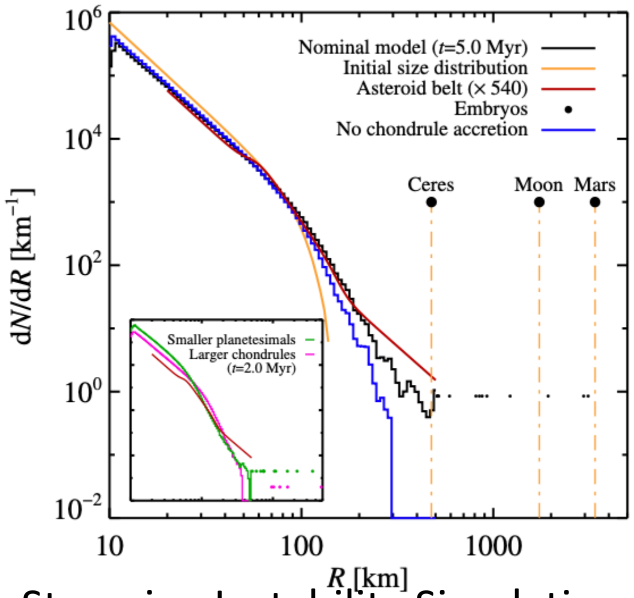
From Debris Simulations

From Planet Formation Simulations

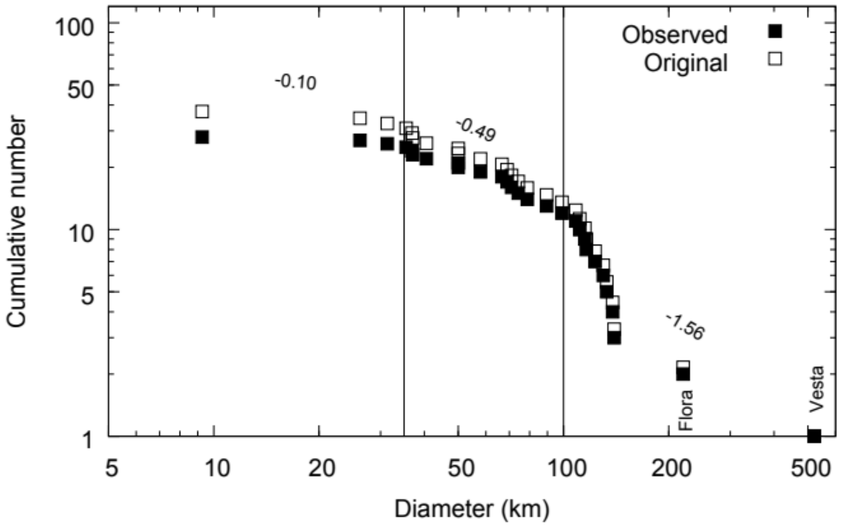
Depends on initial SFD (Size Freq. Dist.) and total leftover mass

Probability of a late, large, wet impact

- Assumptions:
  - Leftover mass ($\sim 0.10 M_{\oplus}$)
  - Leftover Size Frequency Distribution (SFD):
    - Modern asteroid belt (e.g.: Bottke et al. 2005, Morbidelli et al. 2016,2018)
    - More realistic: Modern belt with a ~100 km component

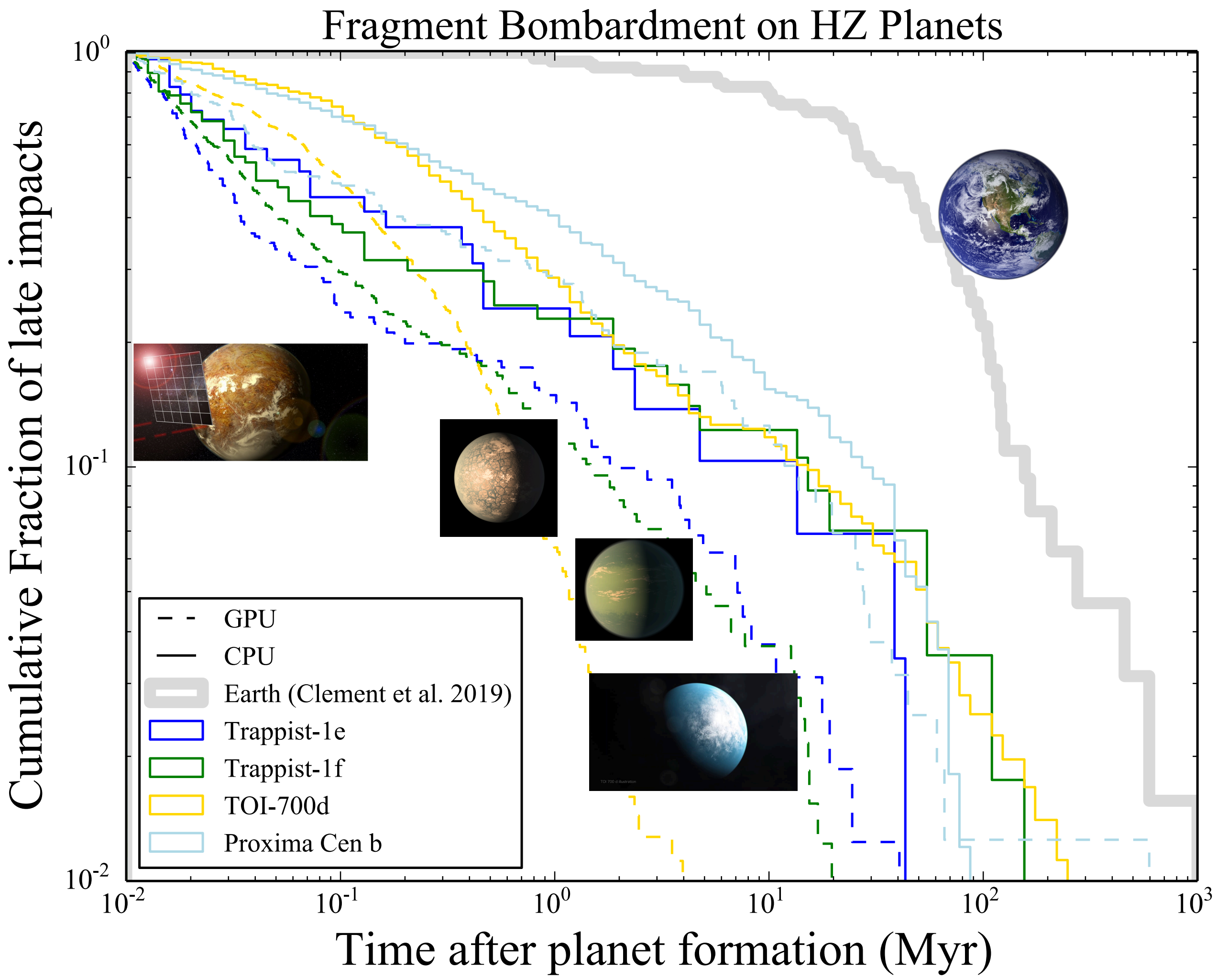


Steaming Instability Simulations
(Johansen et al. 2015)



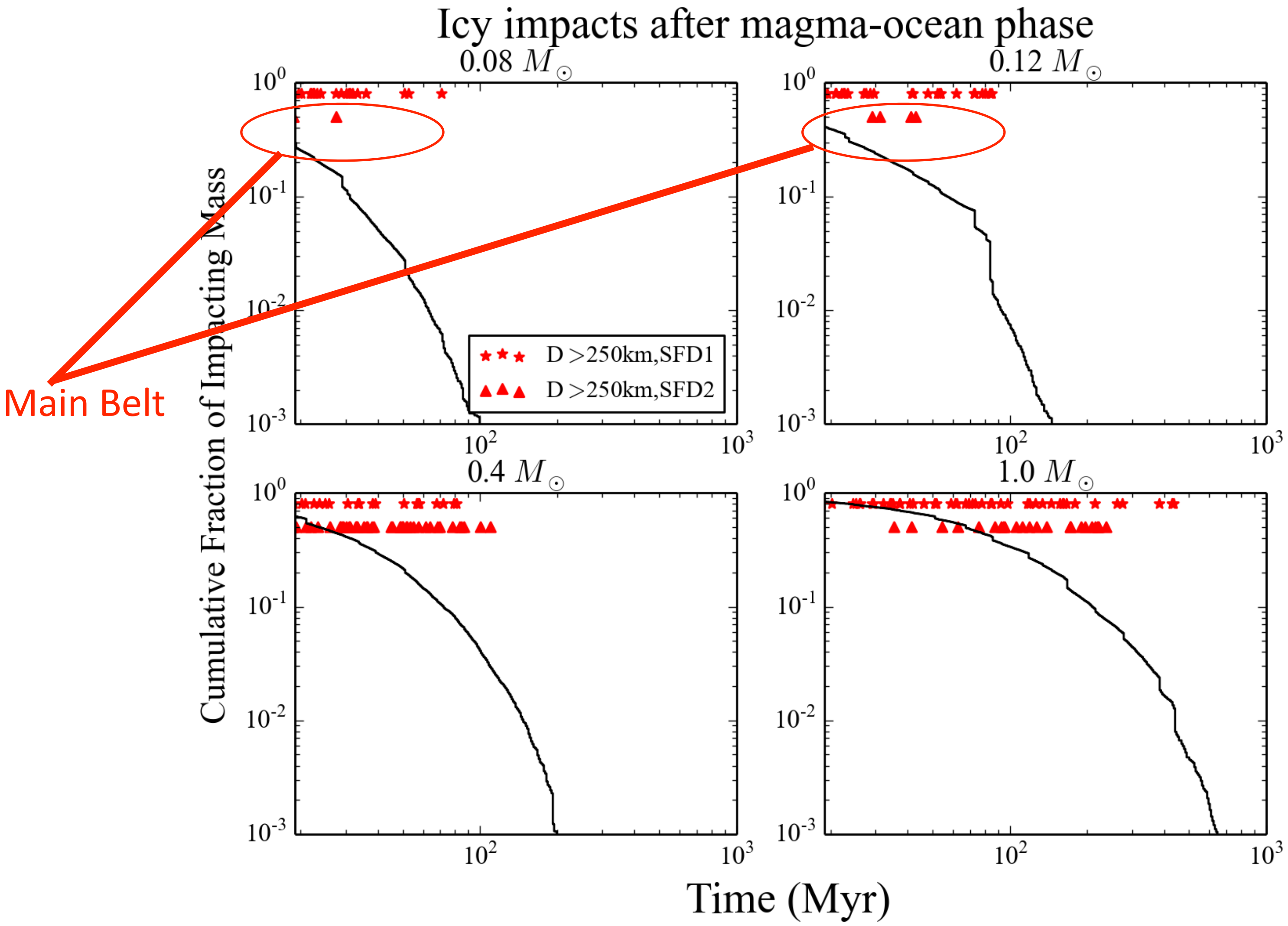
Asteroids not belonging to collisional families
Delbo et al (2019)

Quantifying late bombardment



Clement, Quintana & Quarles (revision submitted); Lichtenberg & Clement (in prep)

Quantifying late bombardment



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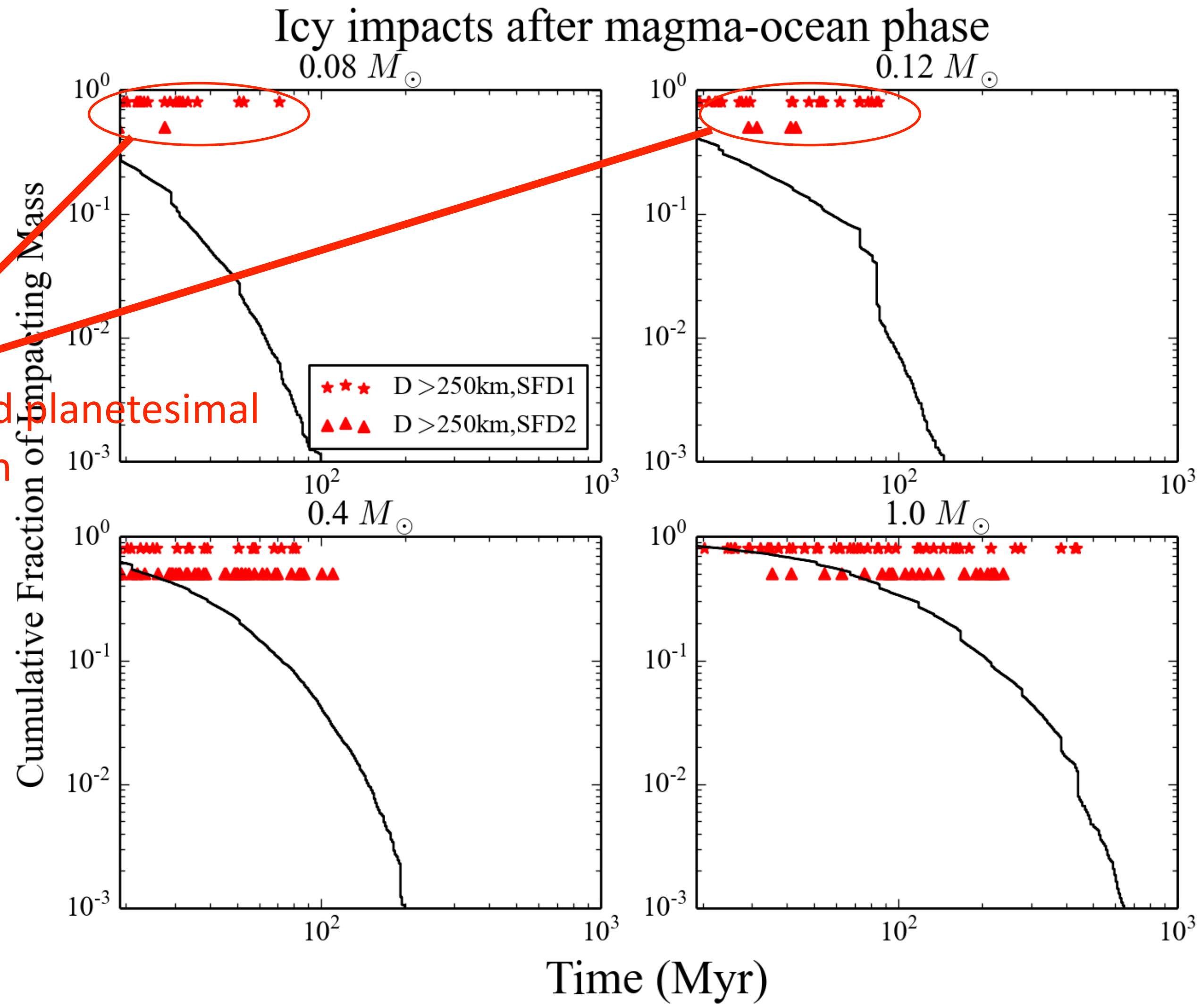
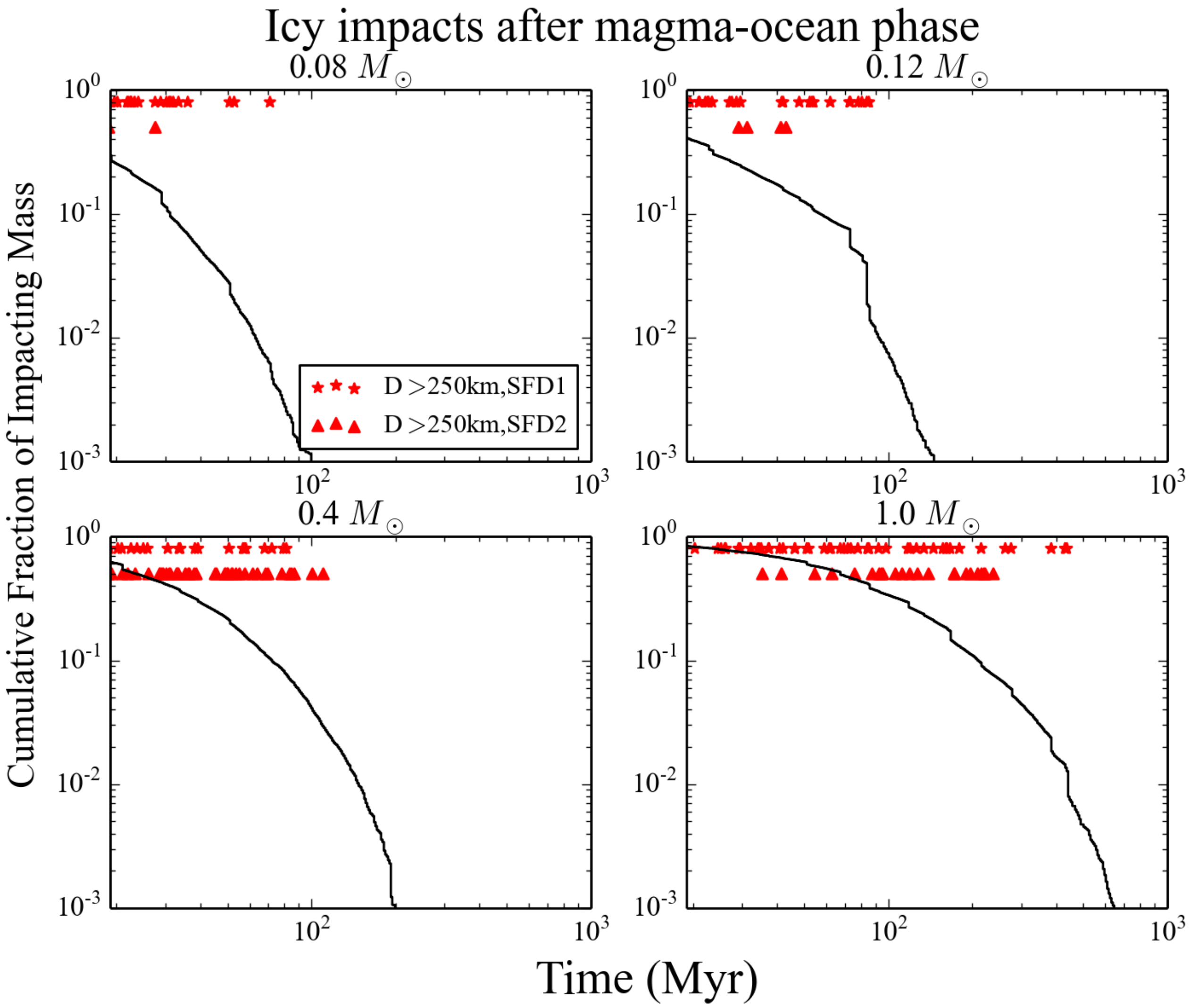


Presumed planetesimal formation

Clement, Quintana & Quarles (revision submitted); Lichtenberg & Clement (in prep)

Quantifying late bombardment

- Extremely sensitive to the system mass
- Somewhat sensitive to the SFD of the leftover material (this affects volatile retention)
- Prospects are bleak around earlier M-Dwarfs

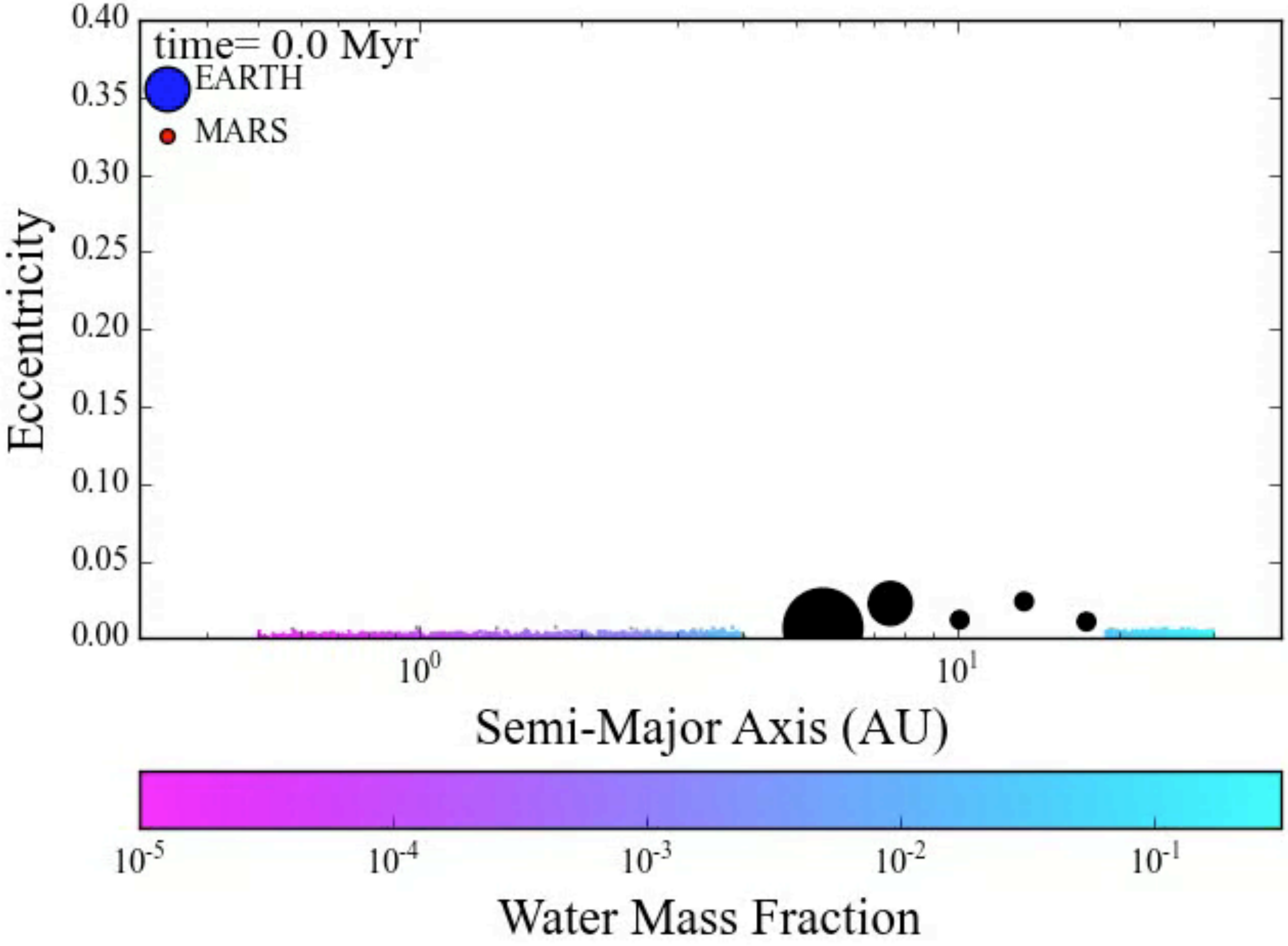


Clement, Quintana & Quarles (revision submitted); Lichtenberg & Clement (in prep)

BIG QUESTIONS

- Why doesn't the solar system have a Super-Earth or short-period planet?
  - Location of resonance with Jupiter, and possible outward migration of Earth and Venus.
- Are Earth-analogs around M-Dwarfs habitable?
  - **Possibly not in the way planets around larger stars might be**
- Why are the solar system's planets so non-uniform in m/R (besides Earth and Venus)?

Early Instability explains Mars' mass and the lack of planets in the asteroid belt



Clement et al., 2018, 2019a,b, 2021e, Nesvorny et al. 2021

Conclusions

- Understanding the formation of the solar system's ***smallest planet*** helps us understand ***major differences*** between exoplanets and our own system
- While Earth analogs around ***early M-Dwarfs*** likely face ***numerous challenges*** the Earth did not, those around ***late M-Dwarfs*** might have ***more in common*** with the Earth.
- ***Jupiter*** and ***Saturn***'s earliest evolution fundamentally changed the solar system's evolutionary trajectory.

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