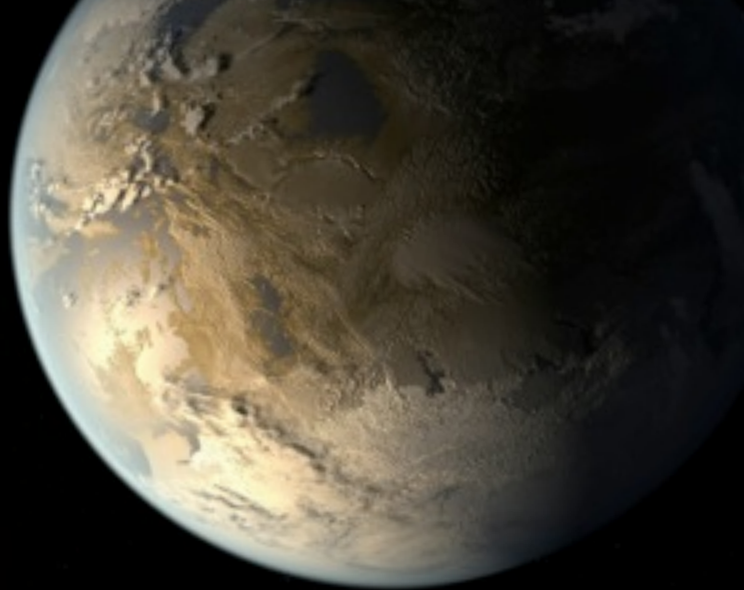
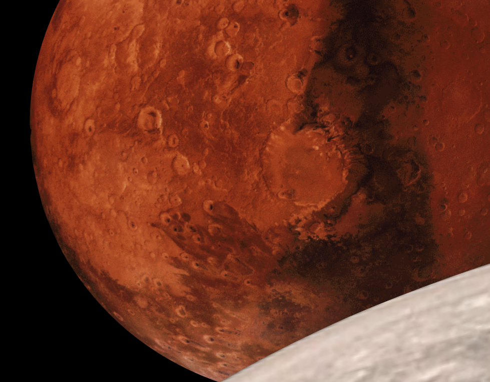




Models of Solar System formation

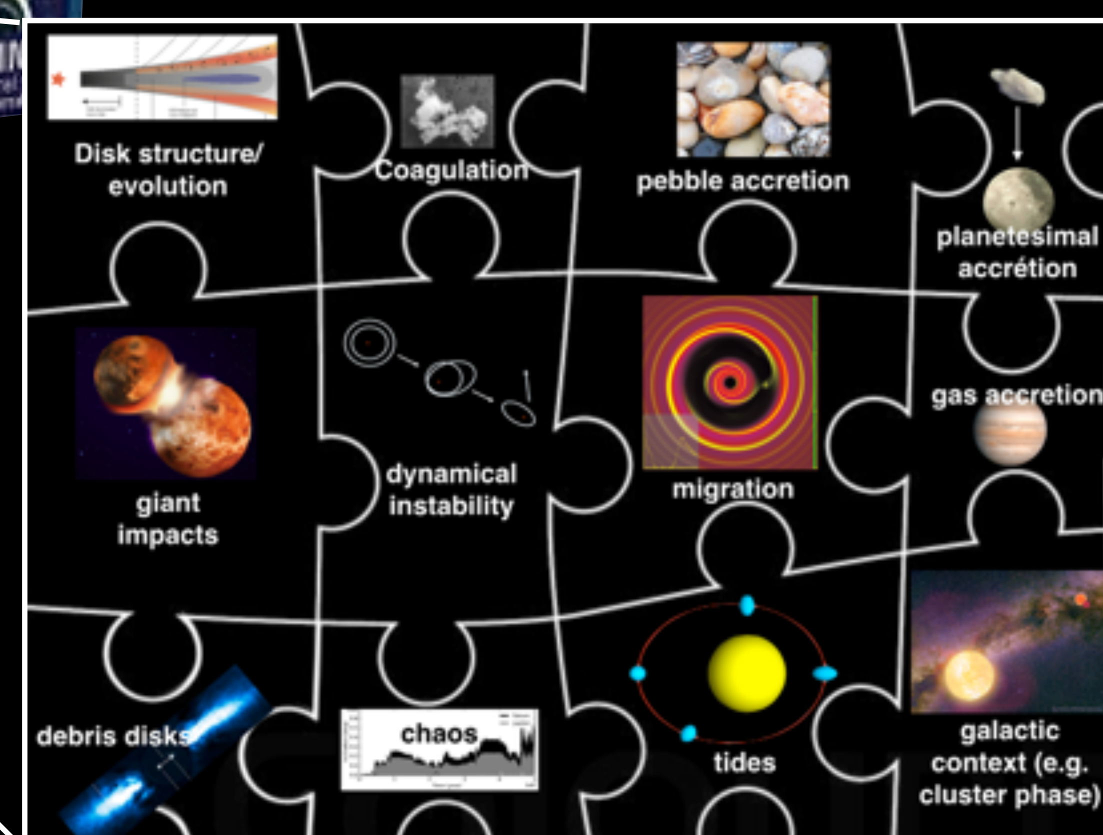
Sean Raymond

Laboratoire d'Astrophysique de Bordeaux

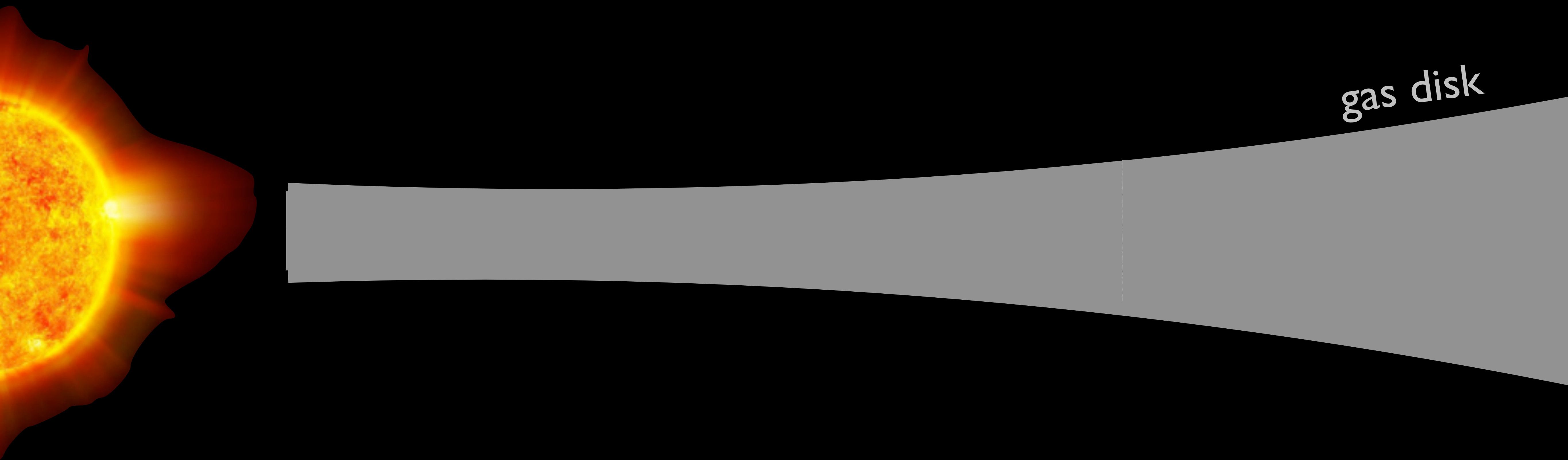
planetplanet.net

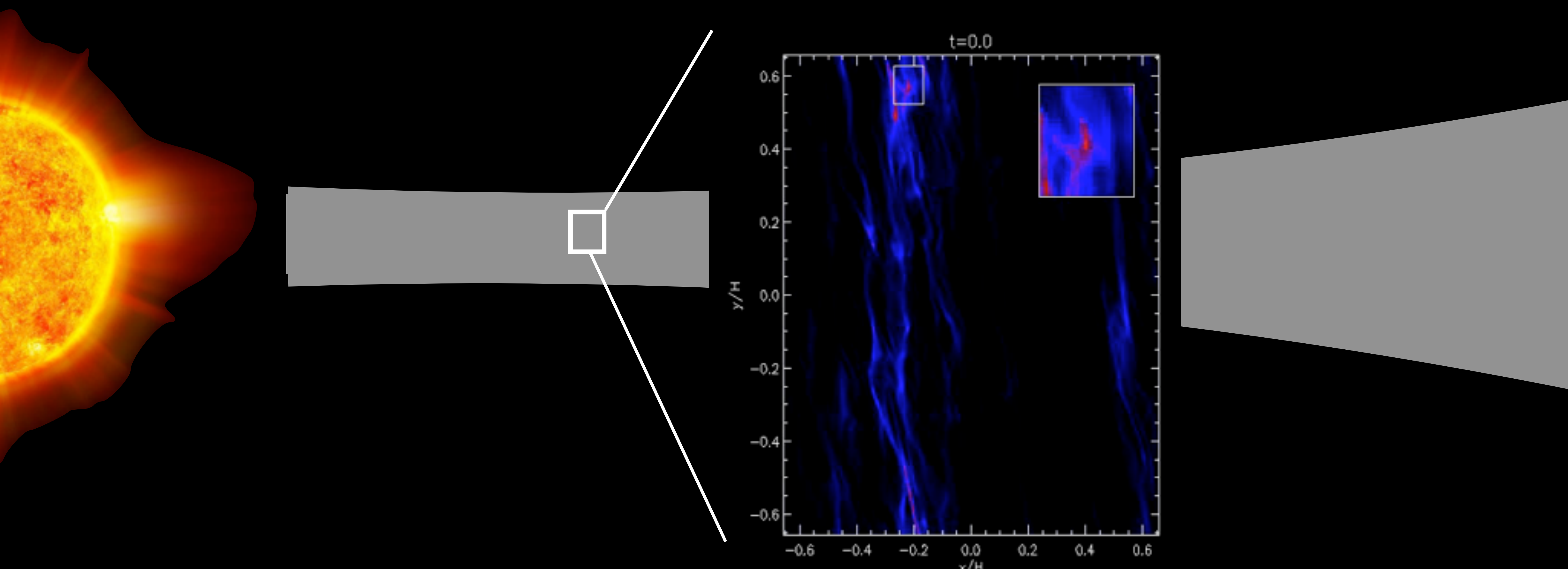
with A. Izidoro, A. Morbidelli, A. Pierens, M. Clement, K. Walsh, S. Jacobson, N. Kaib, B. Bitsch

Mudpuppy puzzles, ages 5-9

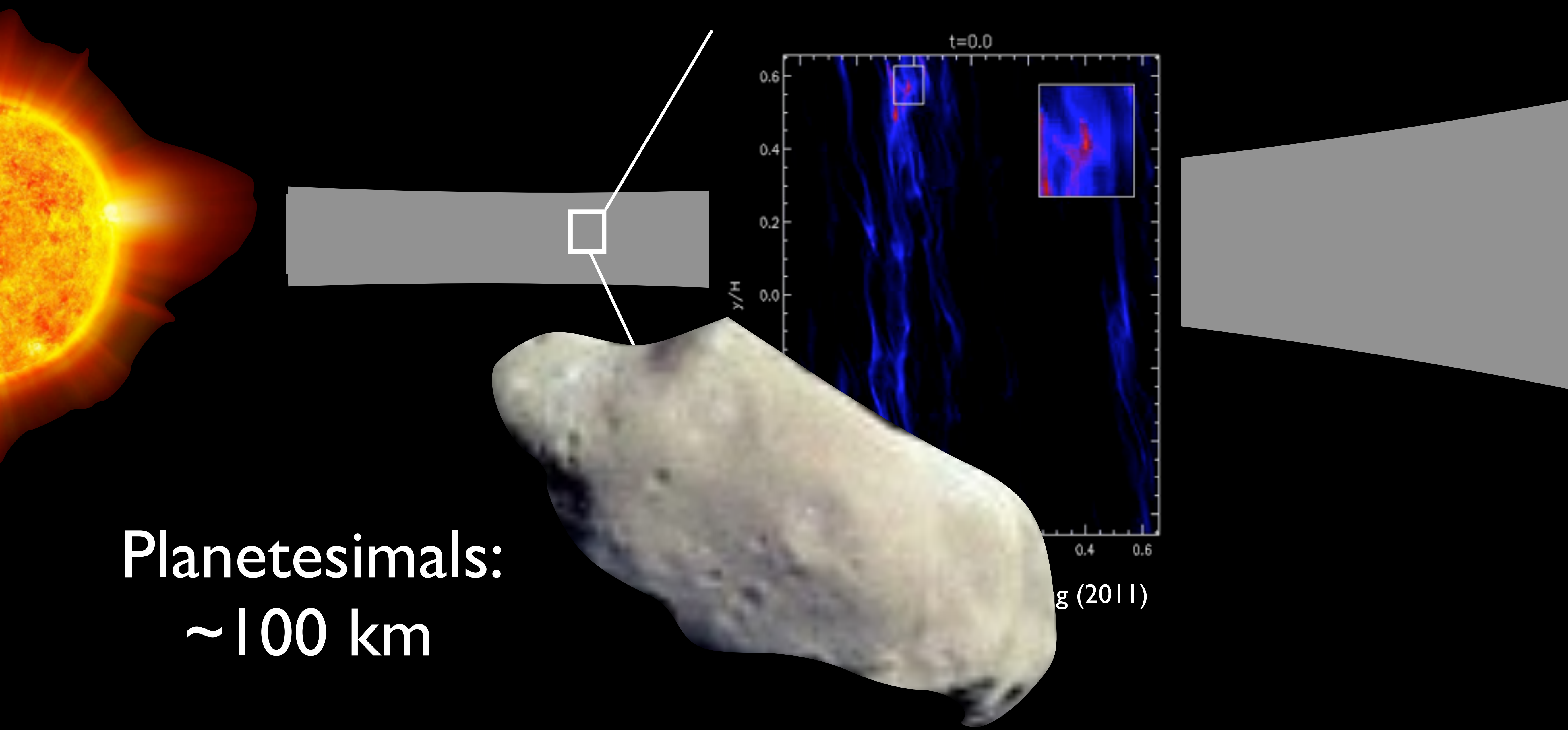


Two recent (ridiculously long) reviews: Raymond et al (2018); Raymond & Morbidelli (2020)


gas disk



Johansen, Klahr & Henning (2011)



Planetesimals:
~100 km

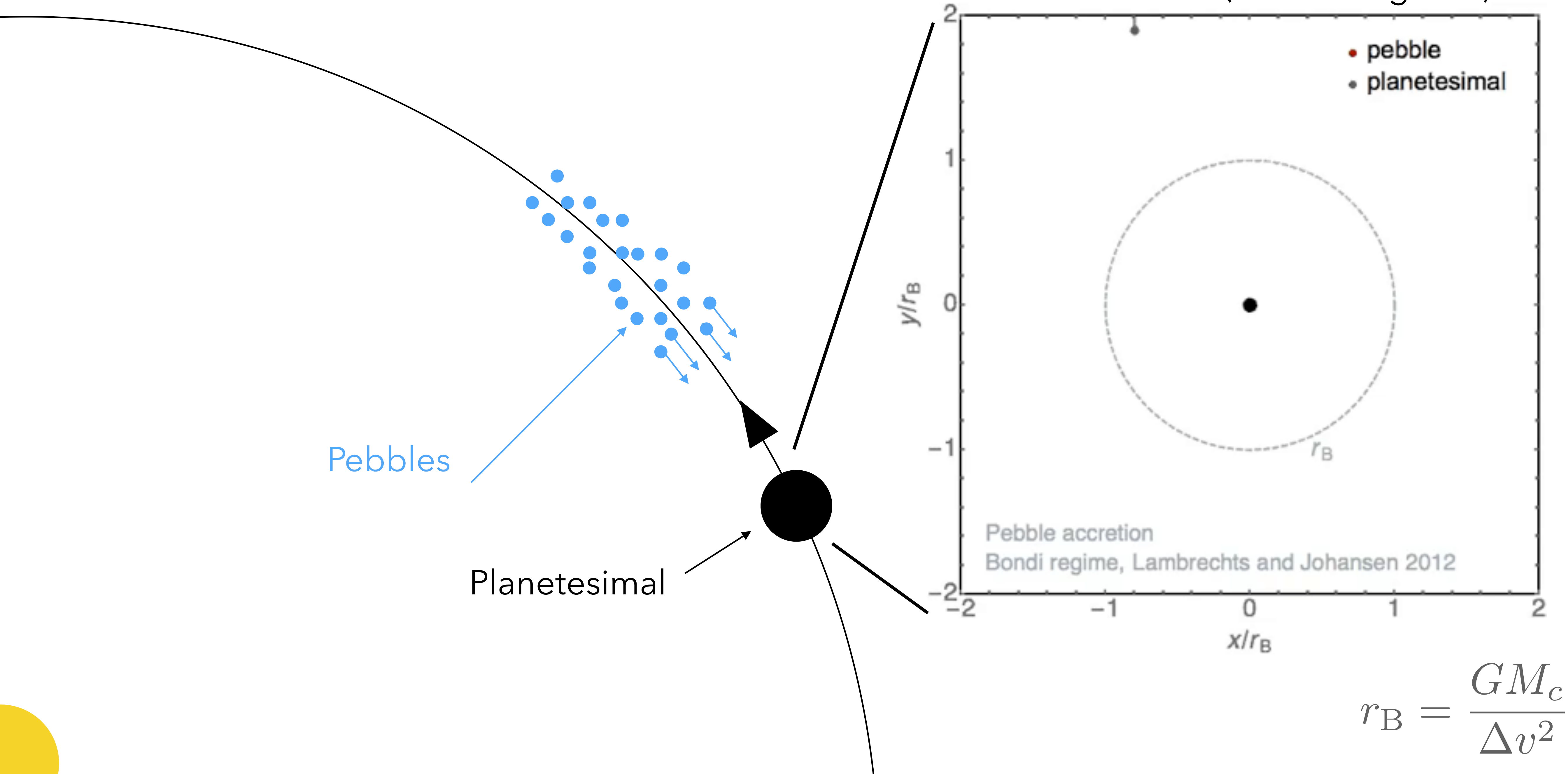
Review of planetesimal formation: Johansen et al (2014, PP6)

Pebble accretion

Slide courtesy M. Lambrechts

Johansen & Lacerda 2010; Ormel & Klahr 2010; Lambrechts & Johansen 2012, 2014; Morbidelli & Nesvorny 2012, Bitsch et al 2015, 2018; Levison et al 2015a,b; **Johansen & Lambrechts 2017; Ormel 2017**; Brouwers et al 2019; Liu et al 2019, …

Pebble accretion (“Bondi regime”)

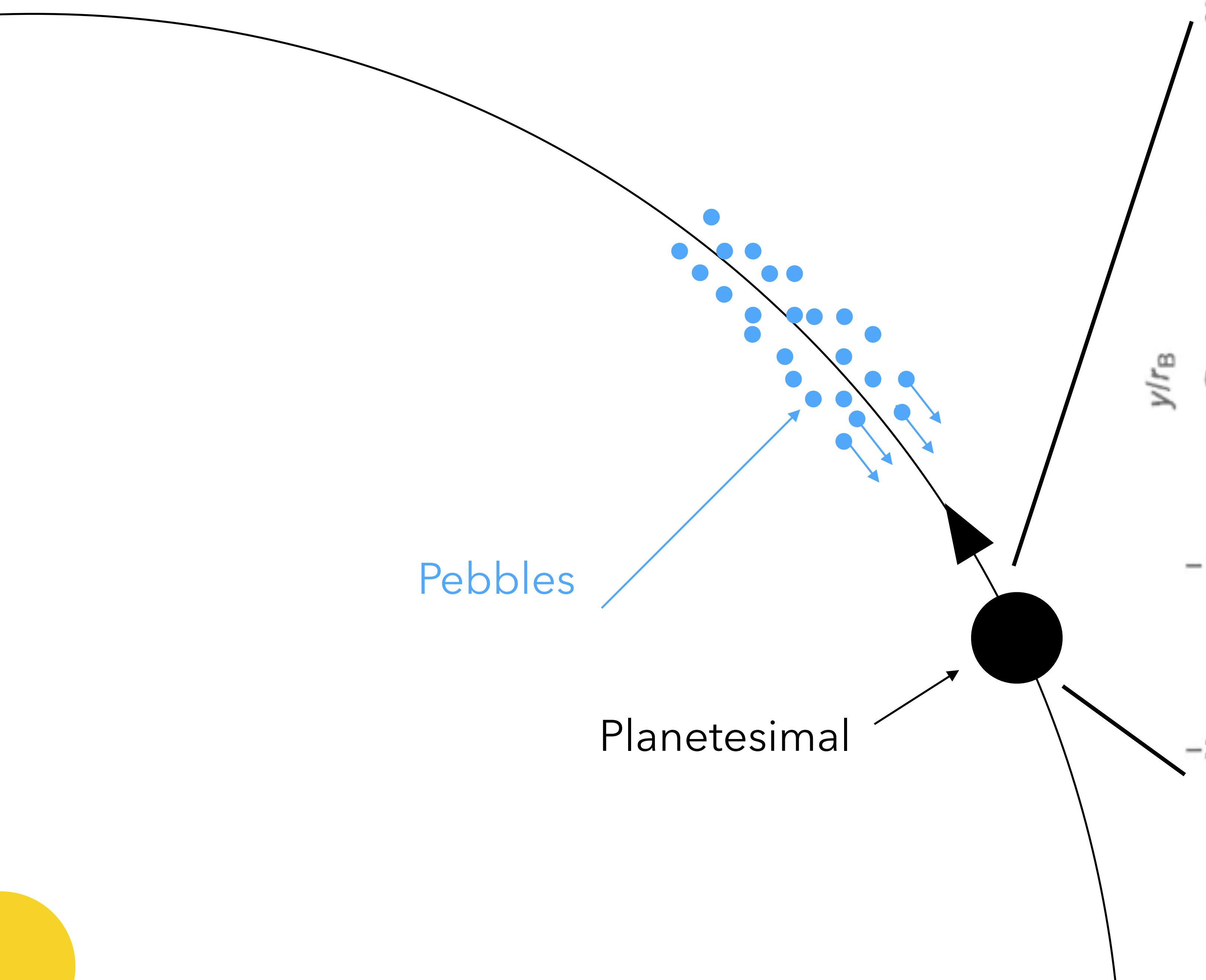


$$r_{\mathrm{B}} = \frac{GM_c}{\Delta v^2}$$

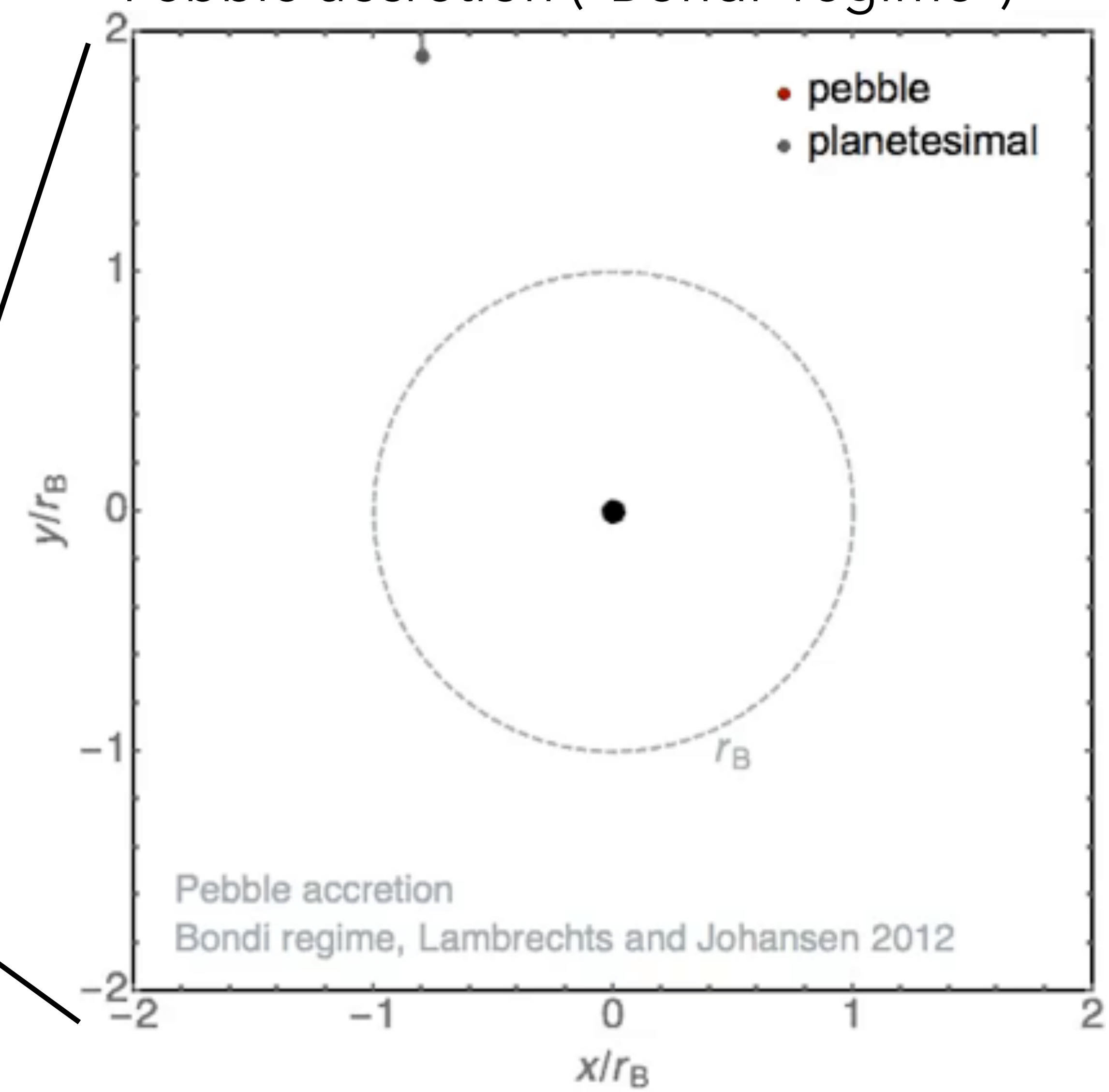
Pebble accretion

Slide courtesy M. Lambrechts

Johansen & Lacerda 2010; Ormel & Klahr 2010; Lambrechts & Johansen 2012, 2014; Morbidelli & Nesvorny 2012, Bitsch et al 2015, 2018; Levison et al 2015a,b; **Johansen & Lambrechts 2017; Ormel 2017**; Brouwers et al 2019; Liu et al 2019, …

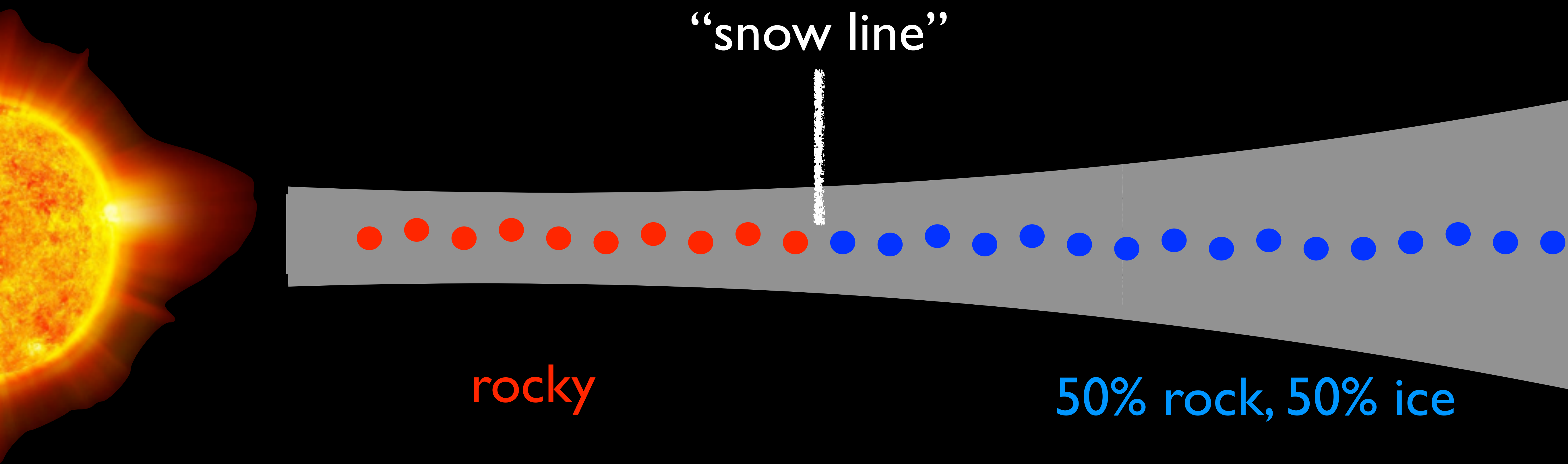


Pebble accretion (“Bondi regime”)

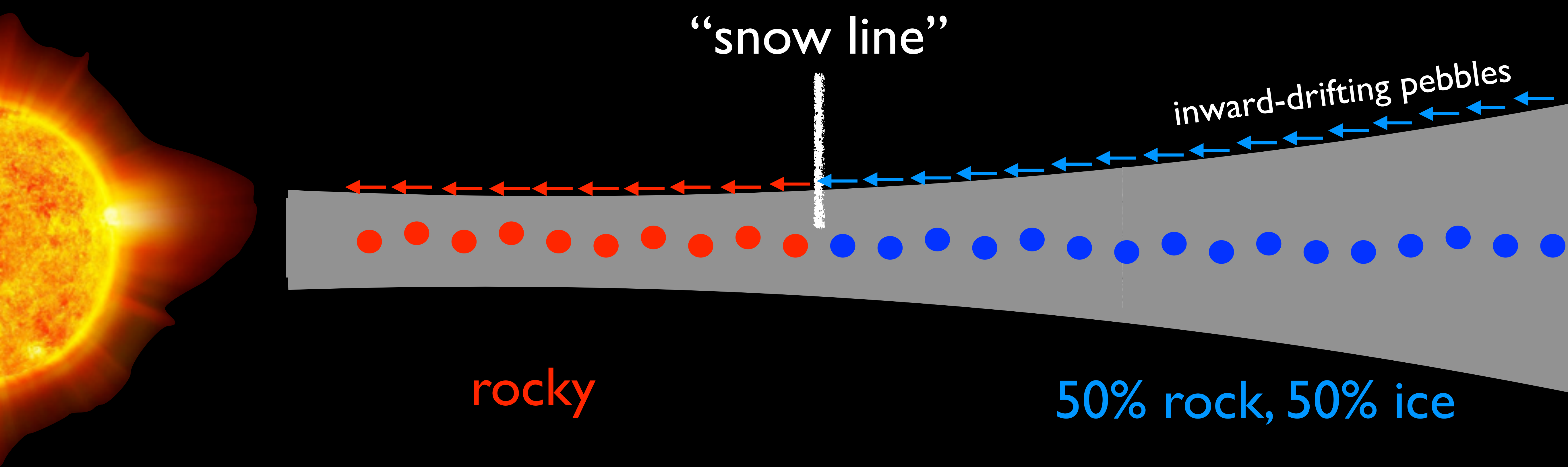


$$r_{\rm B} = \frac{GM_c}{\Delta v^2}$$

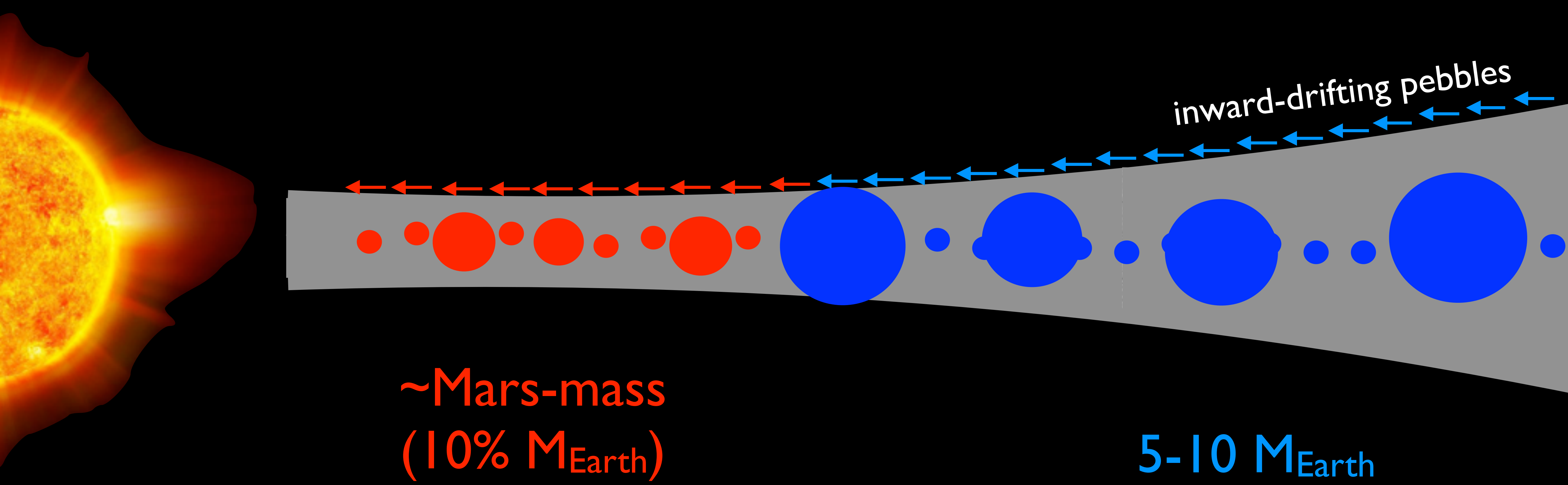
Planetesimals



Planetesimals



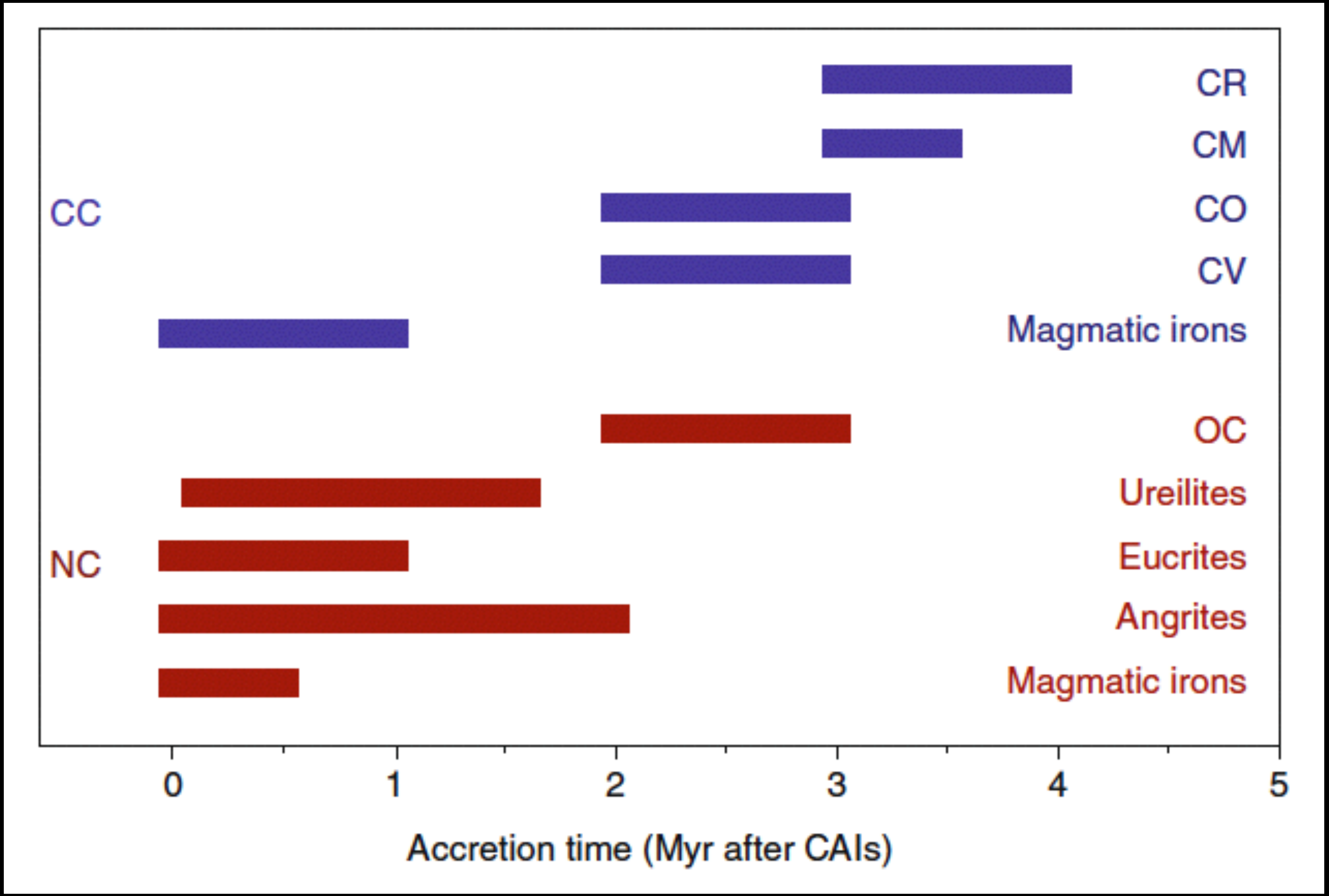
Planetary embryos



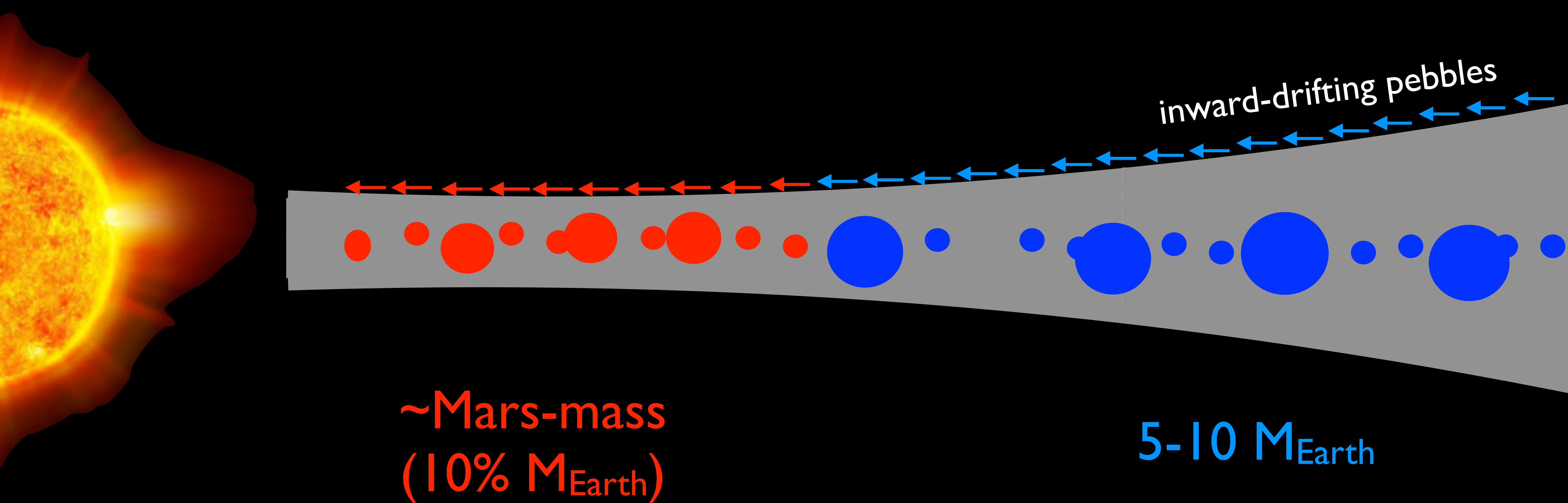
Pebble accretion is far more efficient past the snowline

(Lambrechts et al 2014; Morbidelli et al 2015; Ormel et al 2017)

Age distributions of carbonaceous and non-carbonaceous meteorites

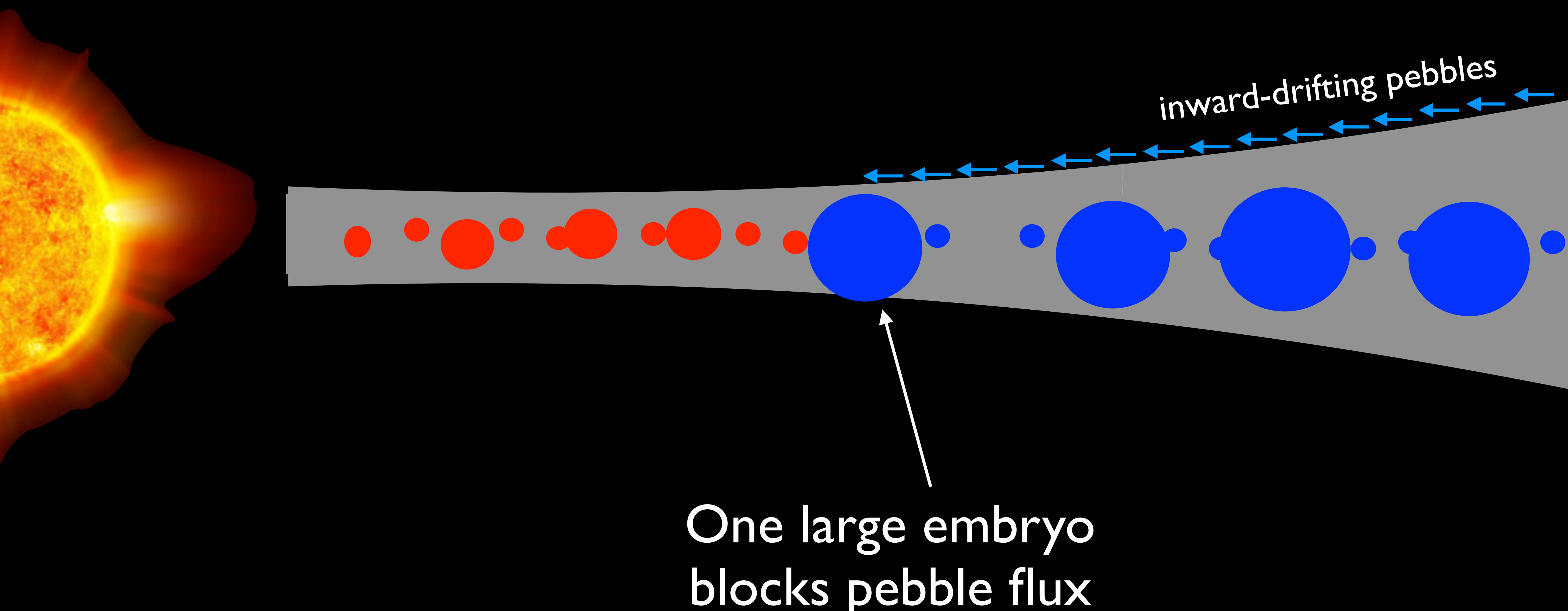


Kruijer et al (2020)



inward-drifting pebbles
~Mars-mass
(10% MEarth)
5-10 MEarth

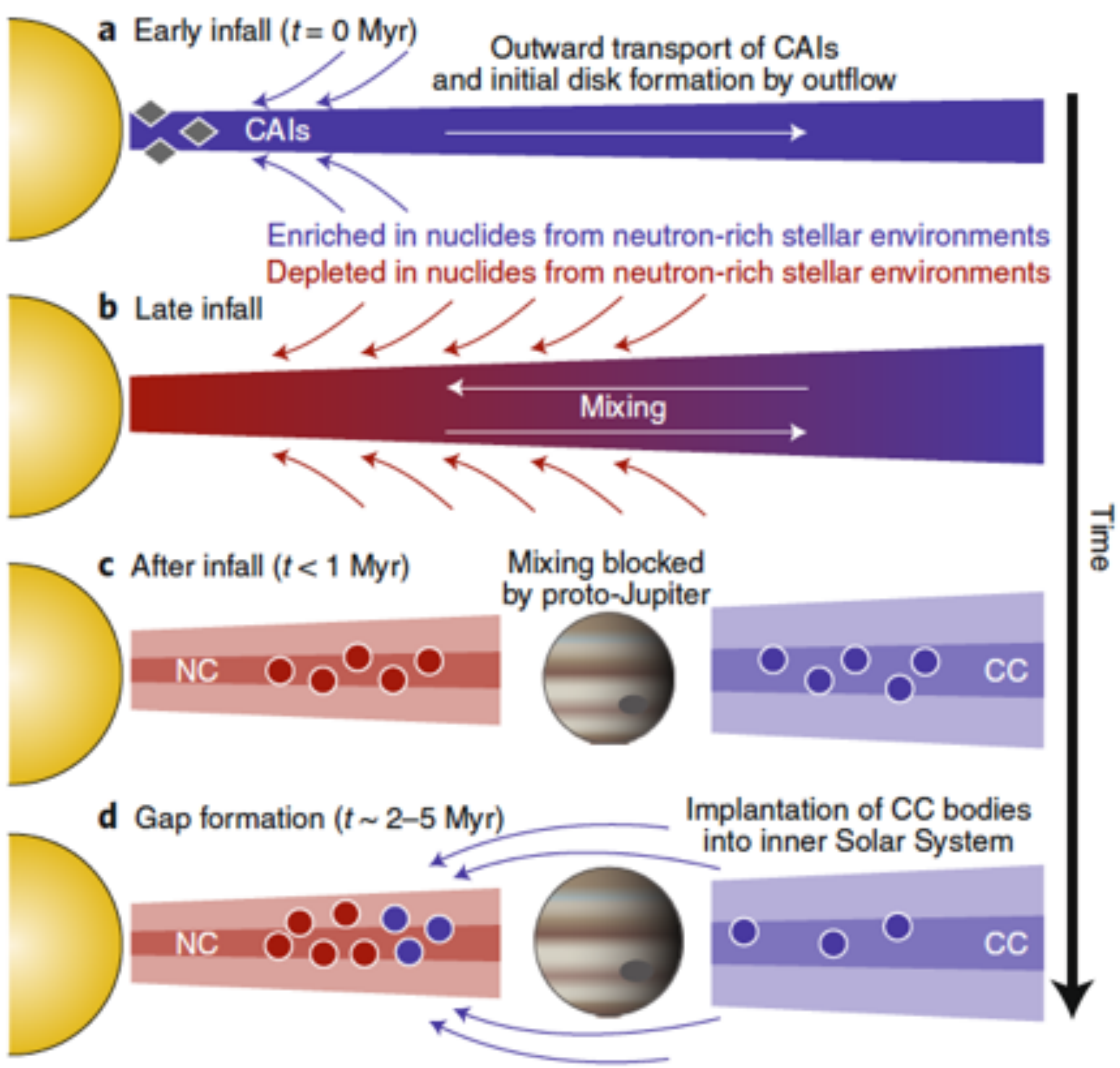
Jupiter's core blocks the inward flux of pebbles, starving the growing terrestrial planets



Morbidelli et al (2015); Lambrechts et al (2019)

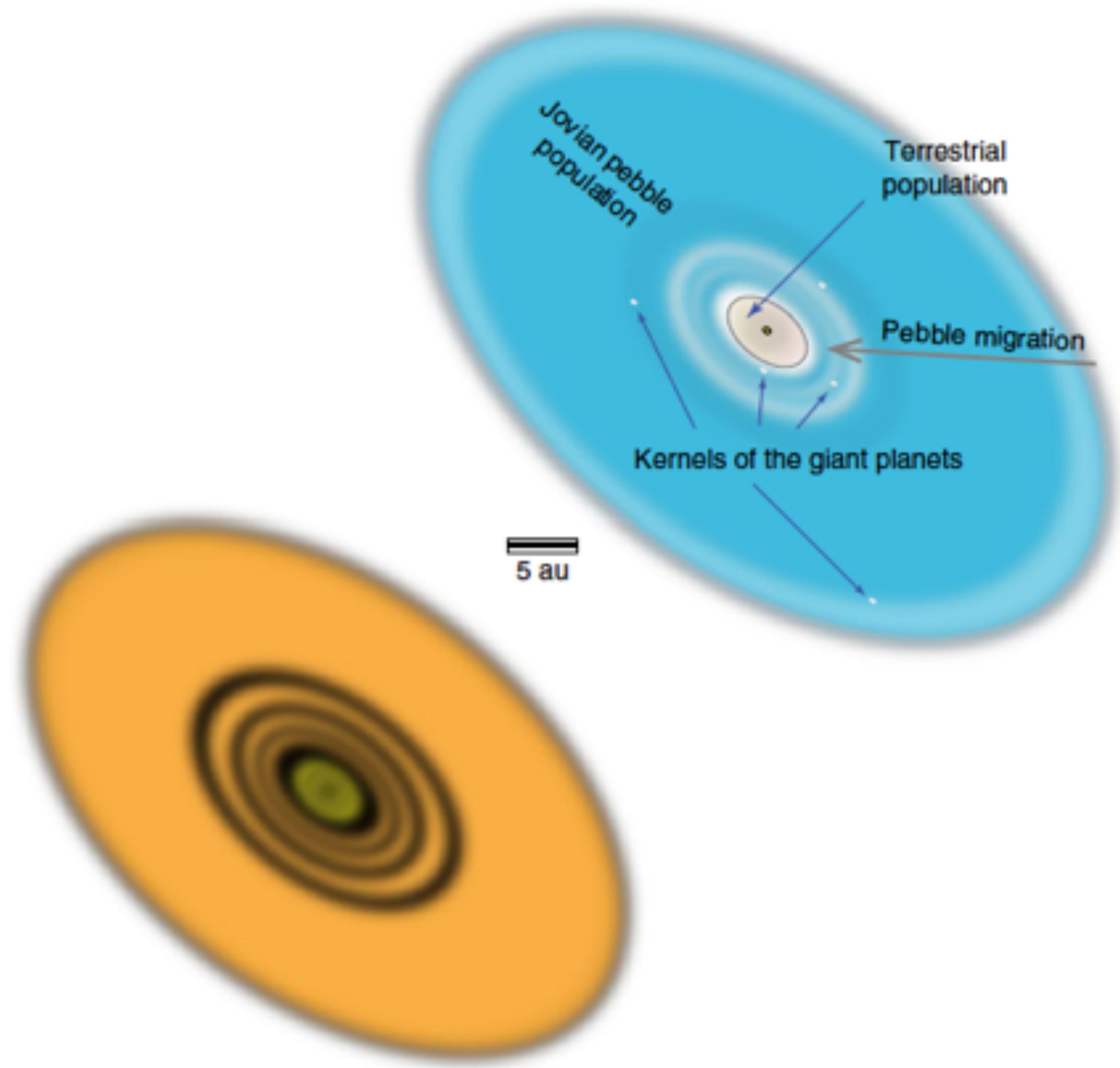
How was Solar System chopped in two?

Jupiter’s core?



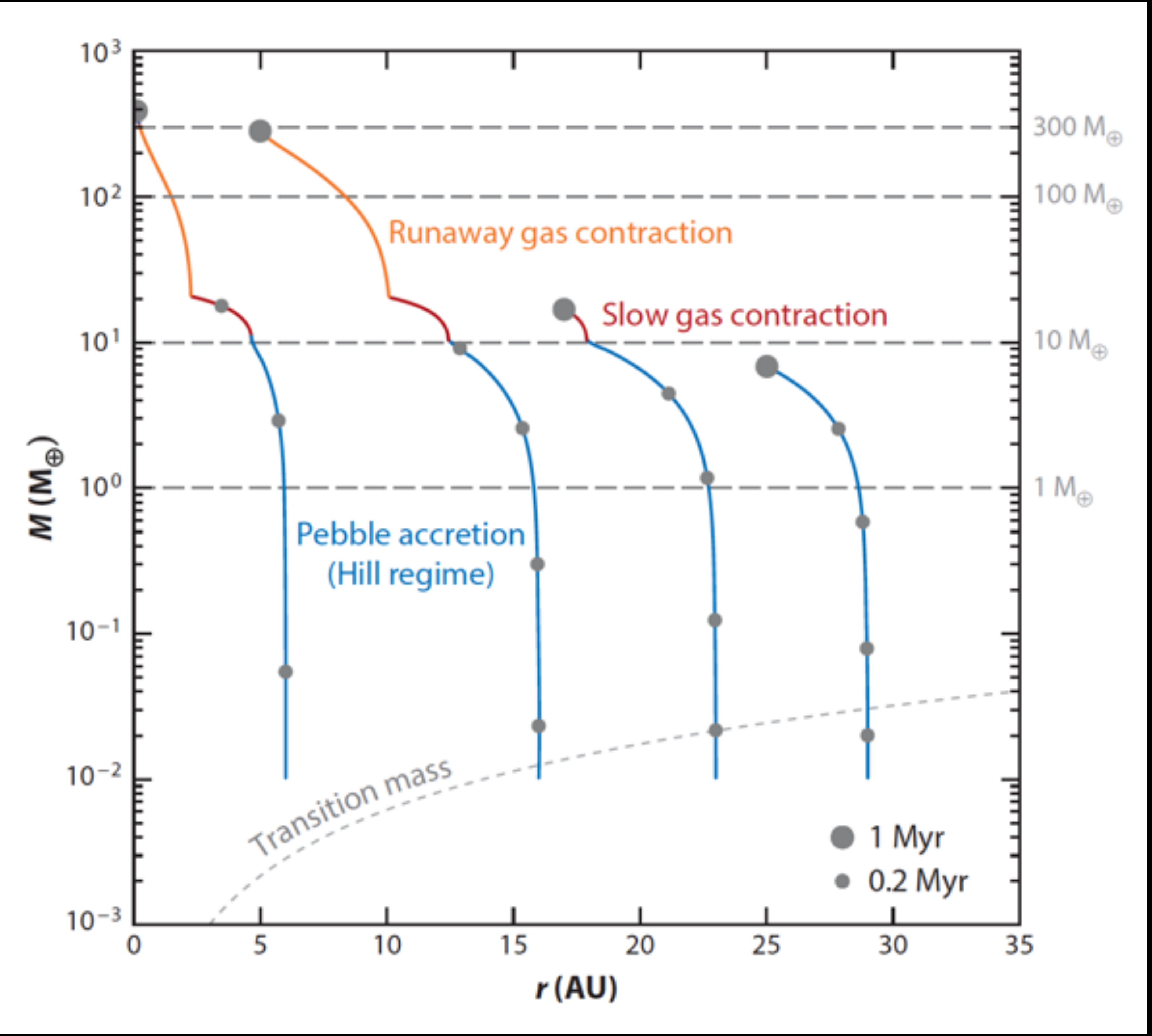
Kruijer et al (2017, 2020)

Pressure bump in the disk?



Brasser & Mojzsis (2020)

Growth+migration tracks of giant planets



Johansen & Lambrechts (2017); after Bitsch et al (2015)

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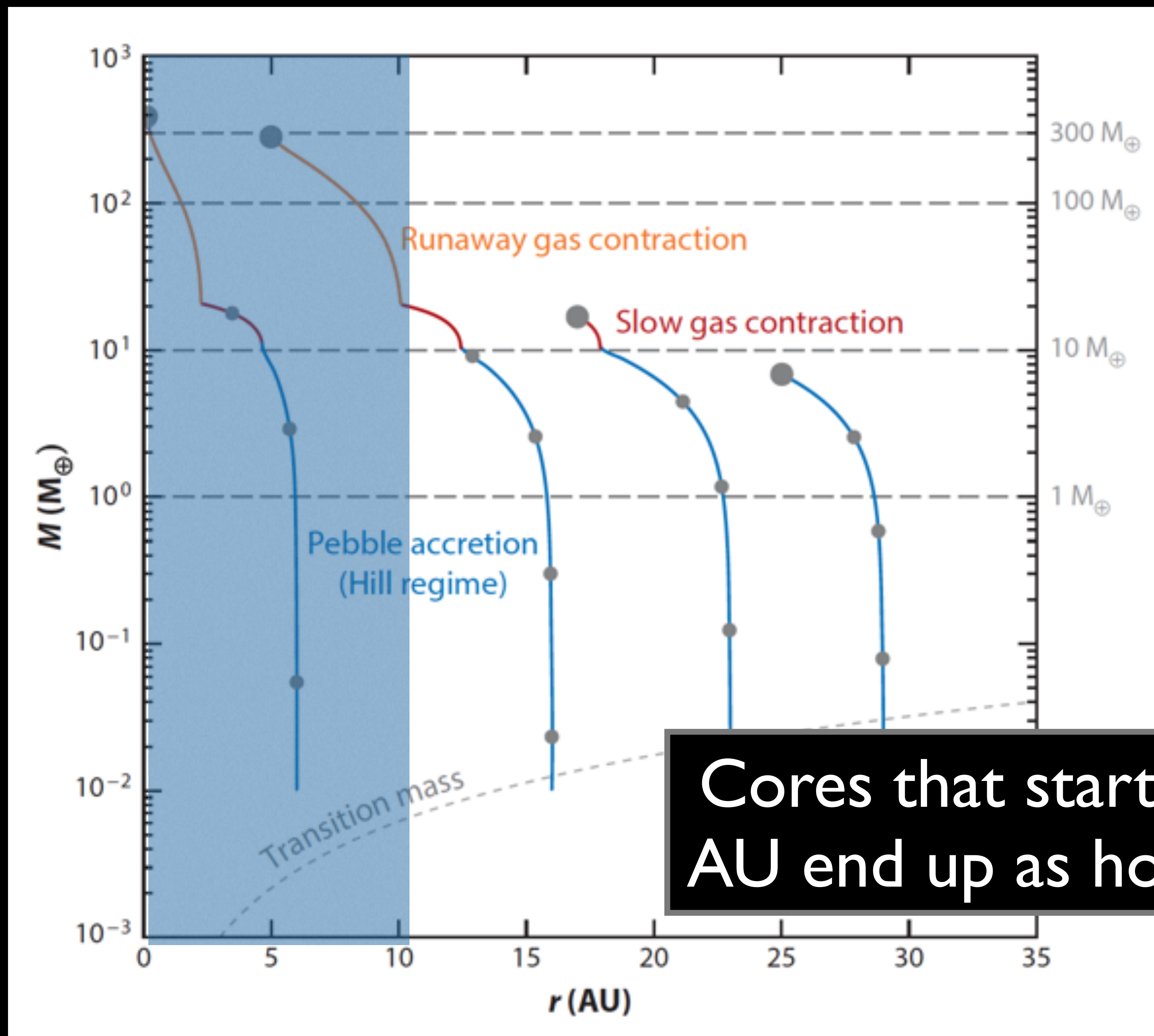
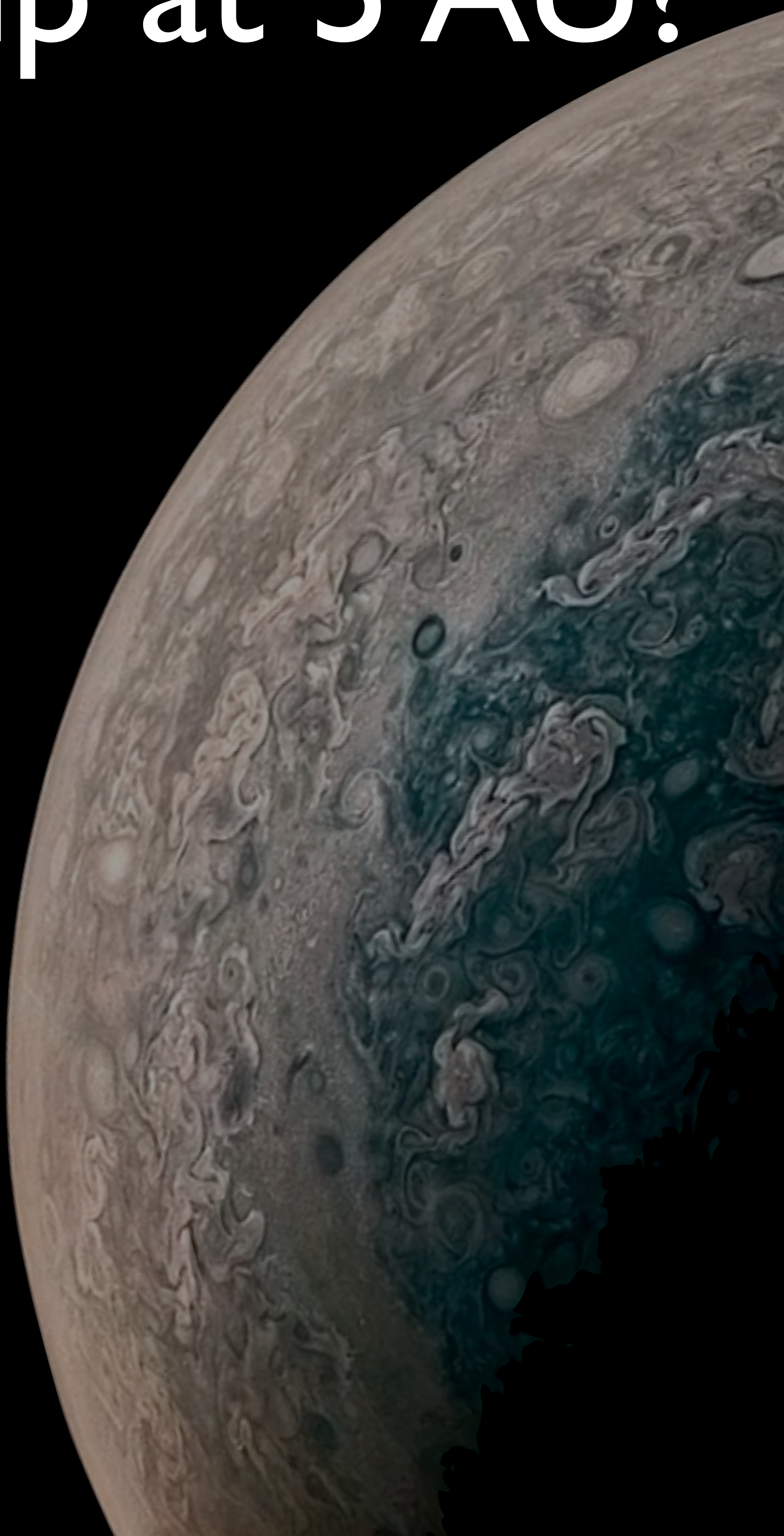


Cores that start inside 10 AU end up as hot Jupiters!

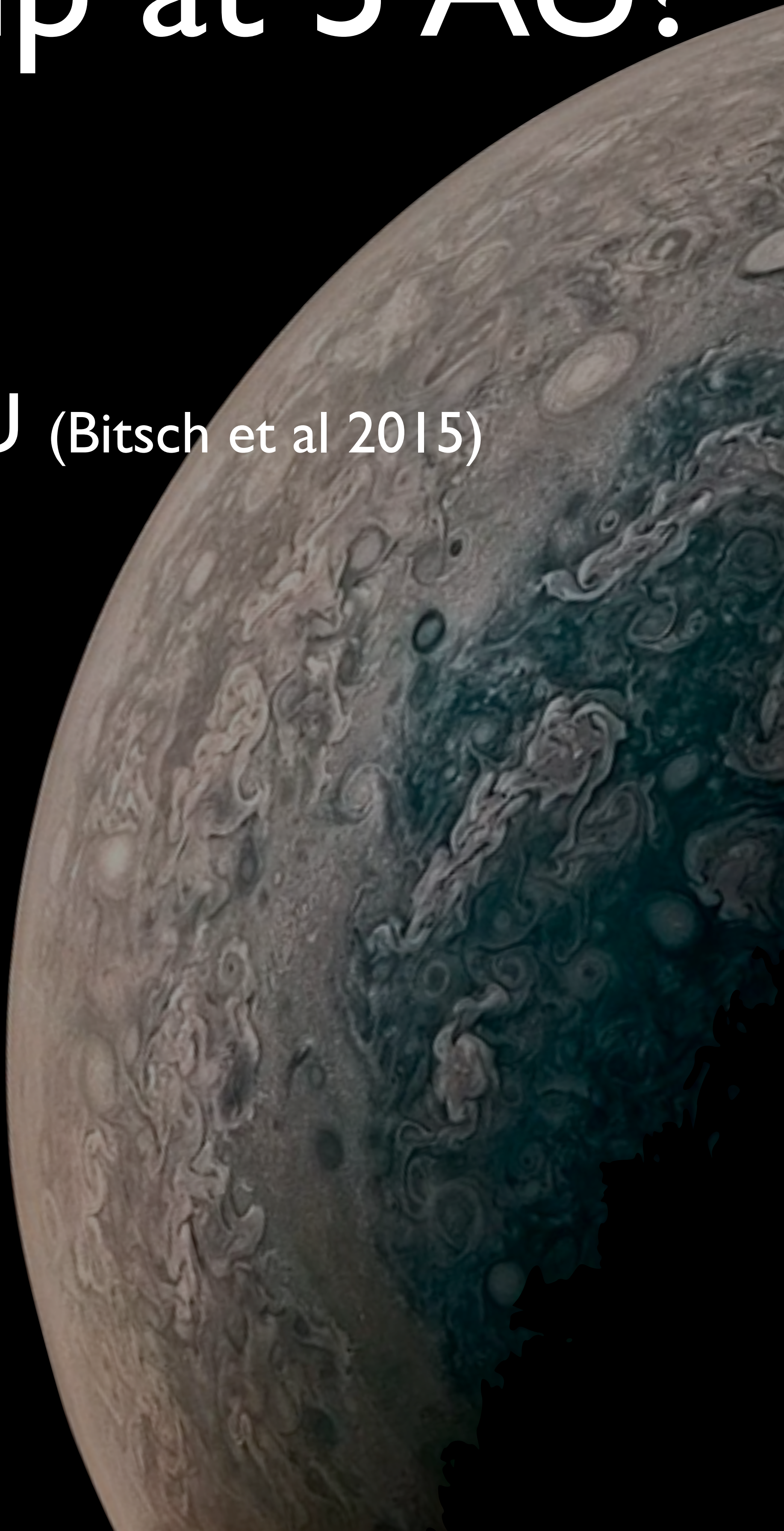
Johansen & Lambrechts (2017); after Bitsch et al (2015)

How did Jupiter end up at 5 AU?



How did Jupiter end up at 5 AU?

- Jupiter's core formed at 15-20 AU (Bitsch et al 2015)



How did Jupiter end up at 5 AU?

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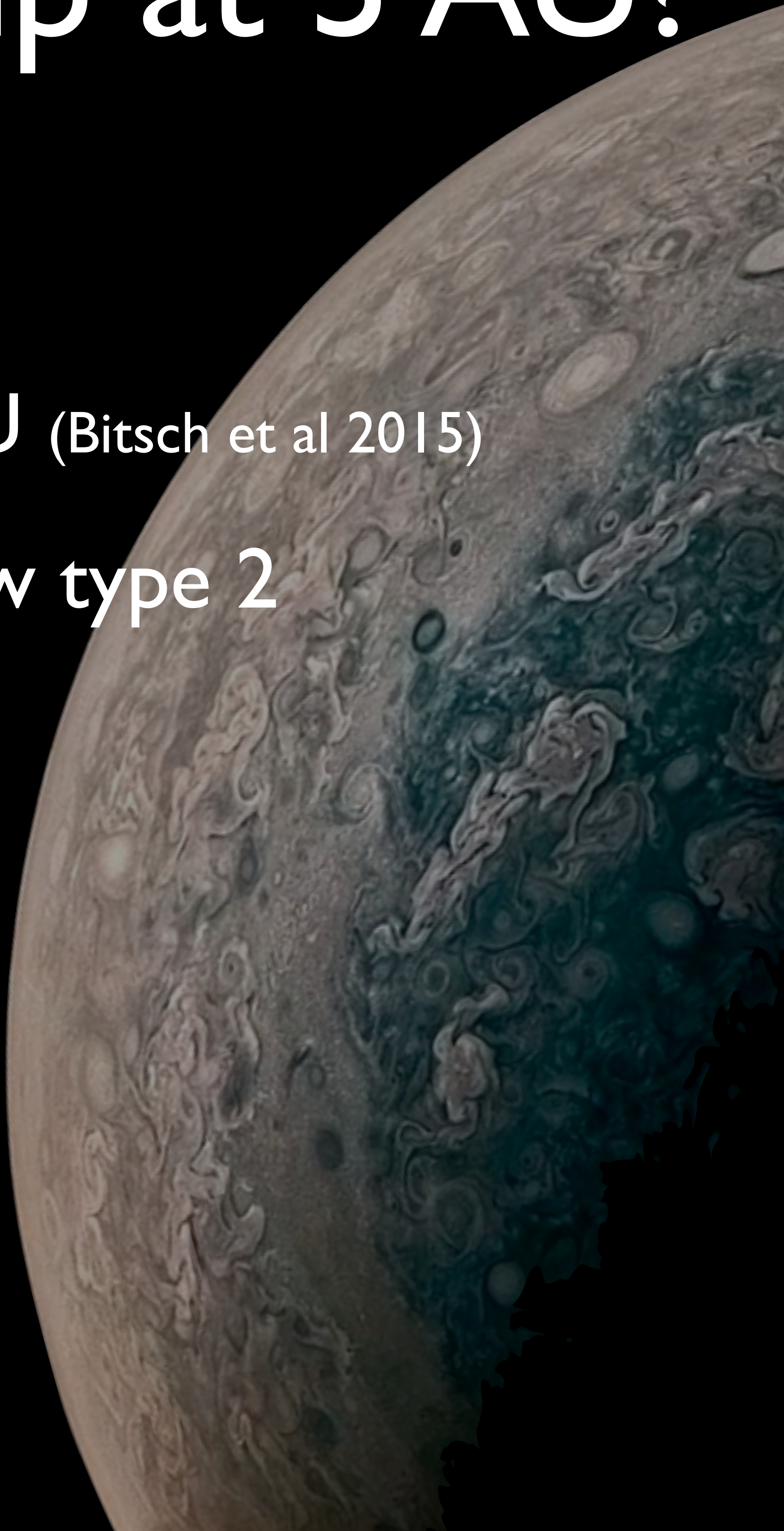
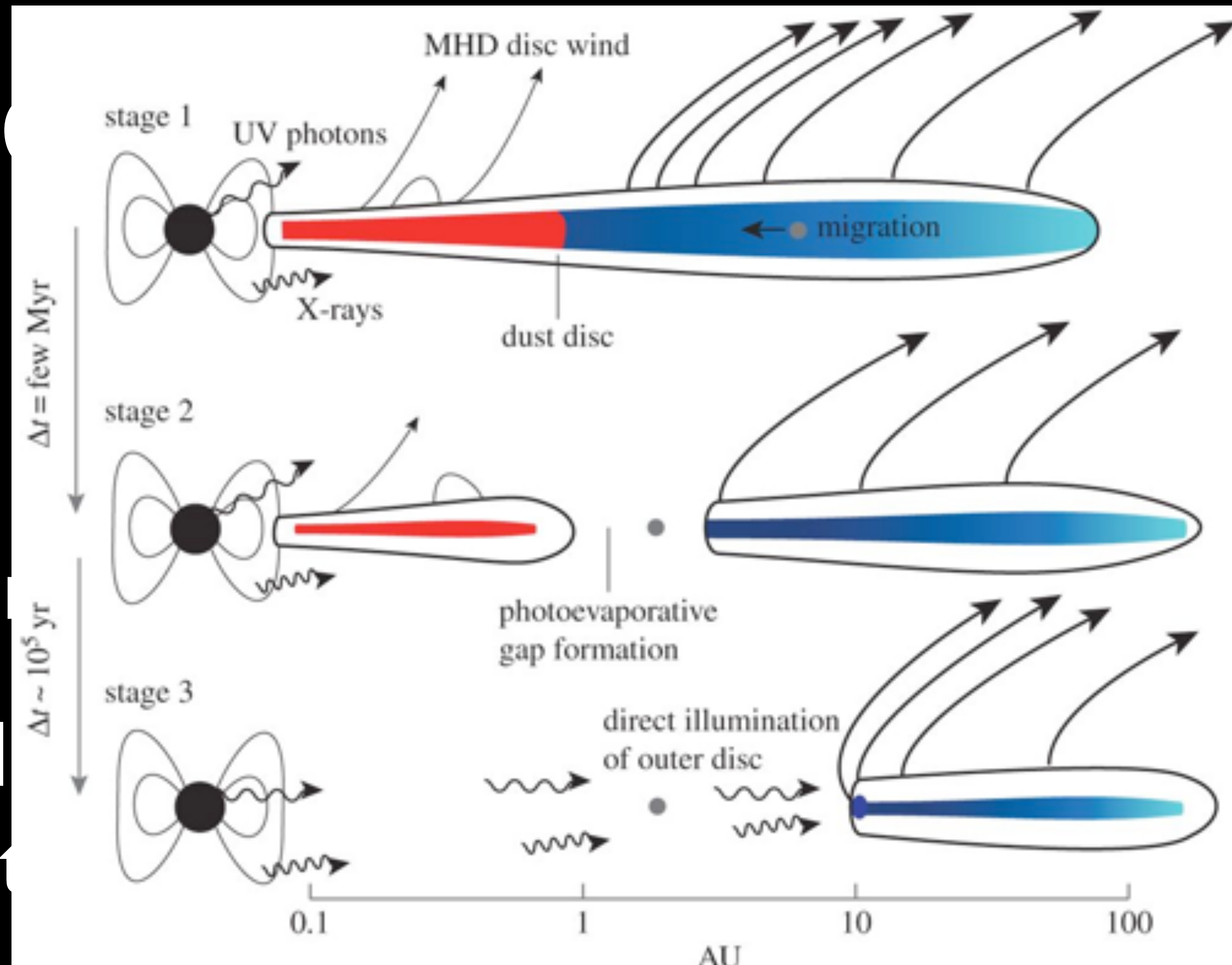
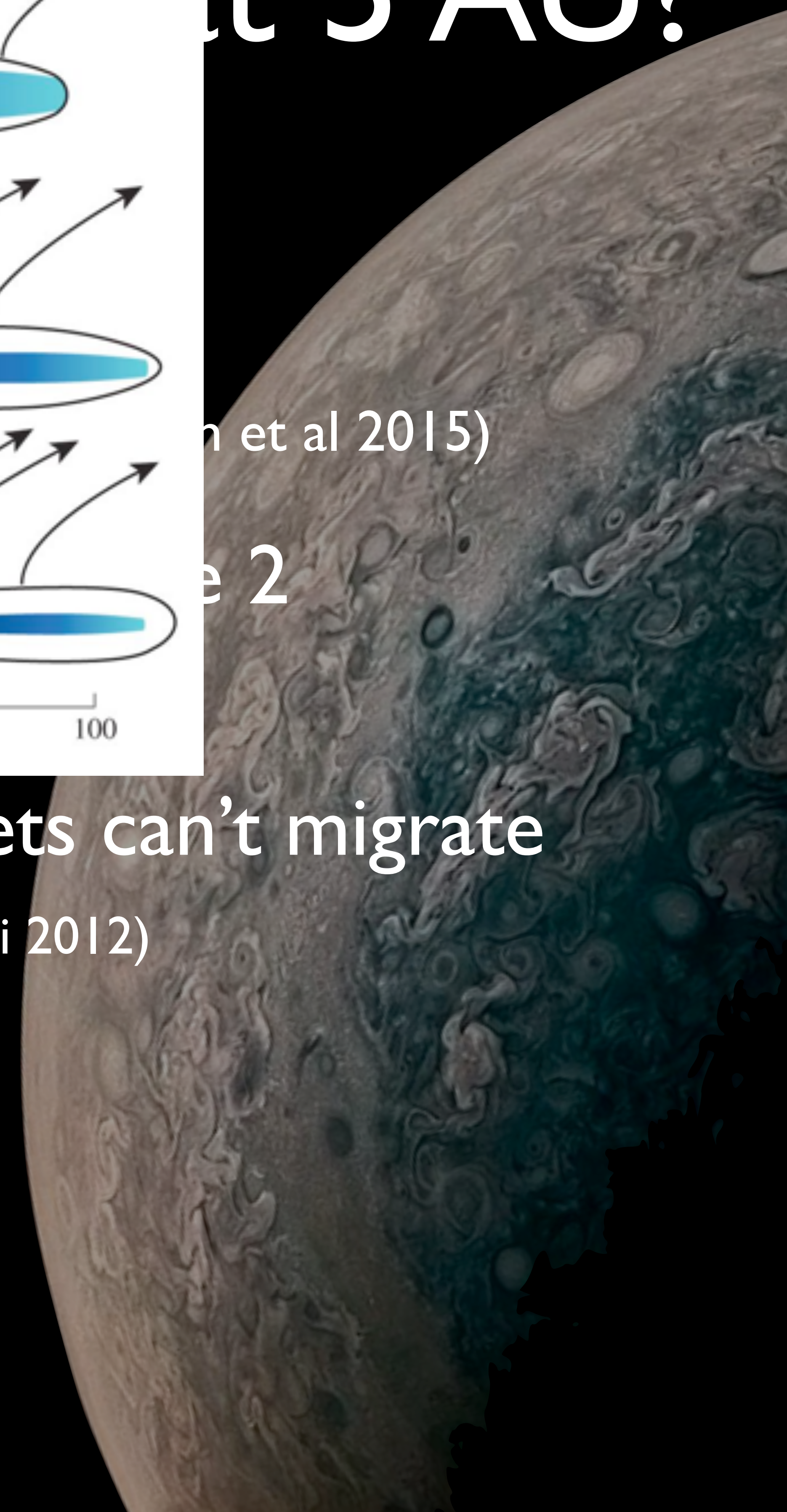
- Very low viscosity disks: very slow type 2 migration (e.g., Bitsch et al 2019)



How di … t 5 AU?



- Jupite … n et al 2015)
- Very l … e 2 migrat …
- Inner disk evaporated away, planets can't migrate closer than ~1 AU (Alexander & Pascucci 2012)



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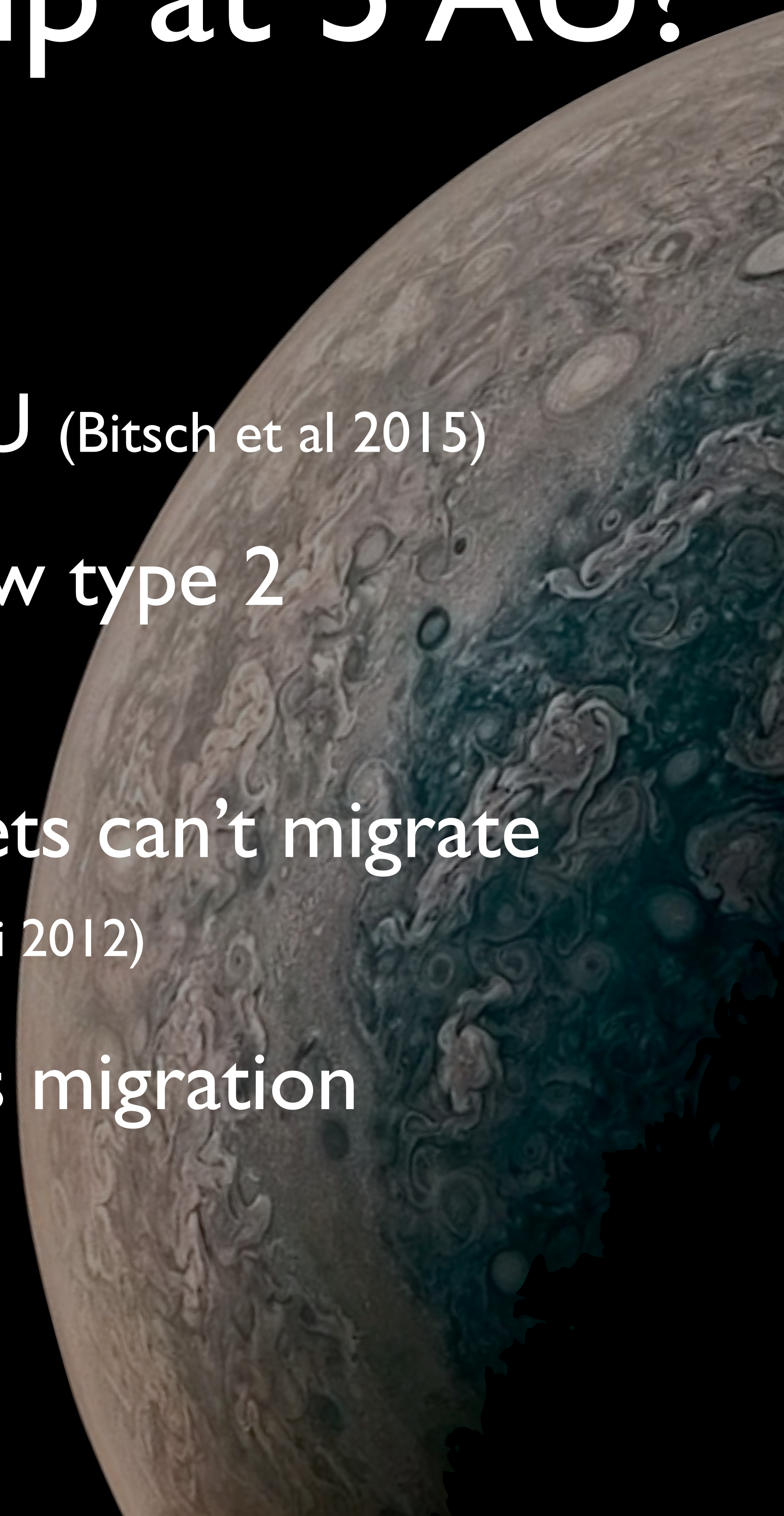

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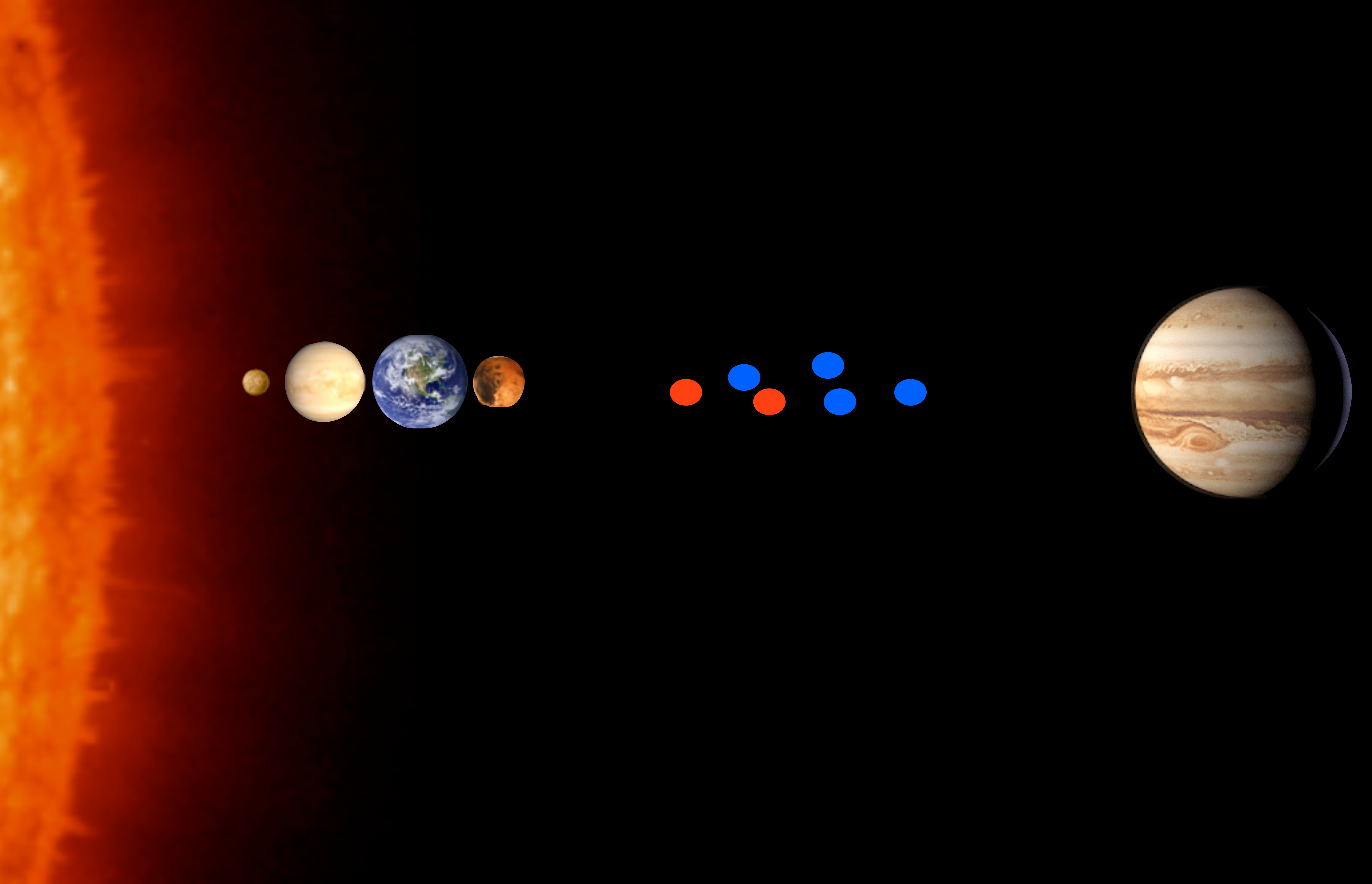
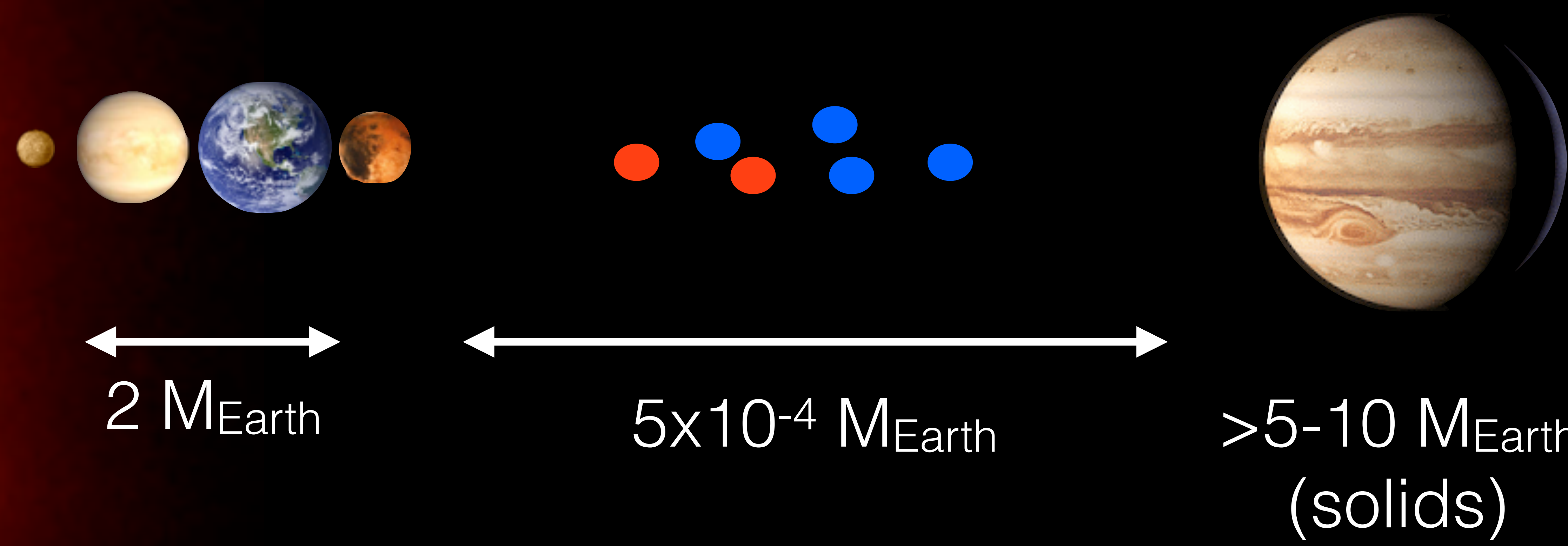
- Very low viscosity disks: very slow type 2 migration (e.g., Bitsch et al 2019)
- Inner disk evaporated away, planets can't migrate closer than ~1 AU (Alexander & Pascucci 2012)
- Saturn stops or reverses Jupiter's migration (Masset & Snellgrove 2001; Grand Tack model)

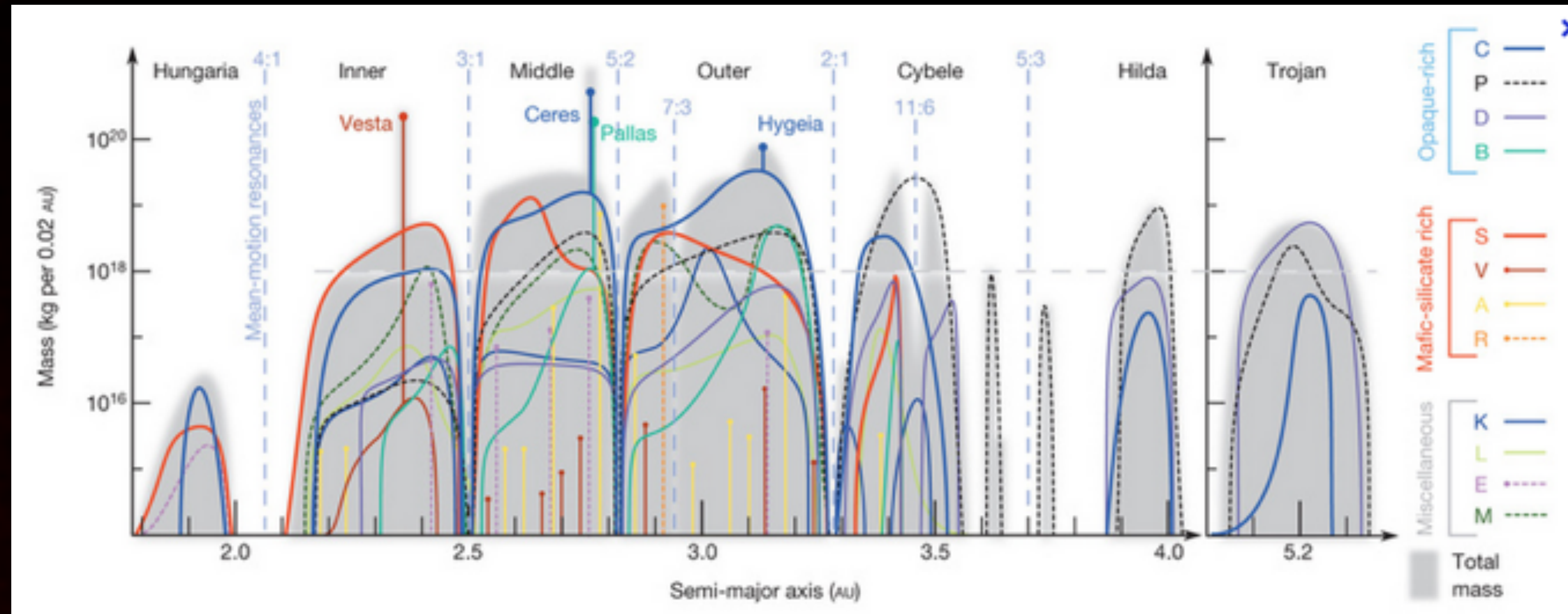
Inner Solar System constraints

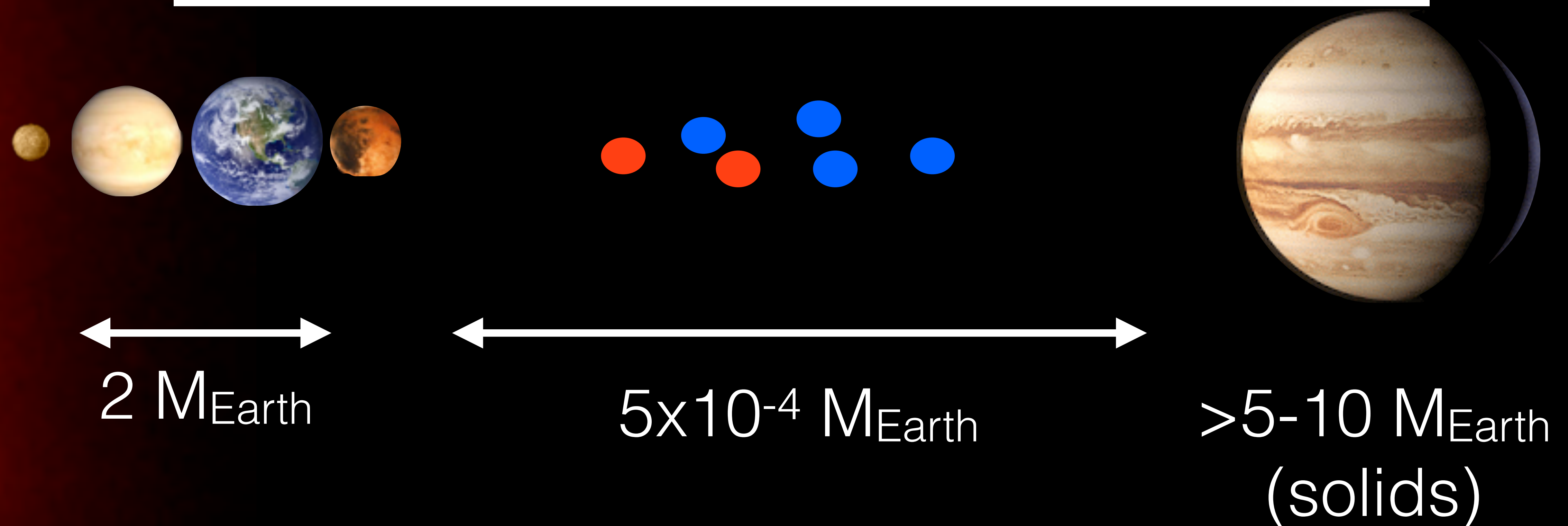


Inner Solar System constraints



Demeo & Carry 2014





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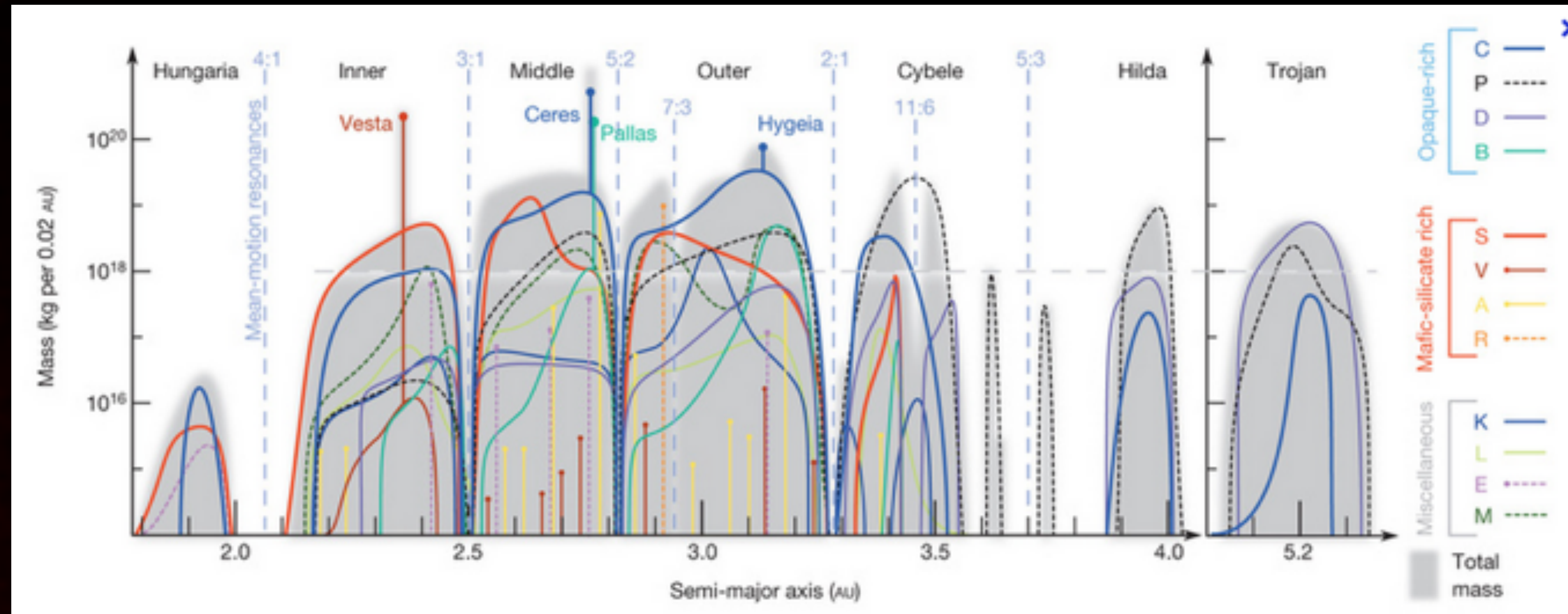
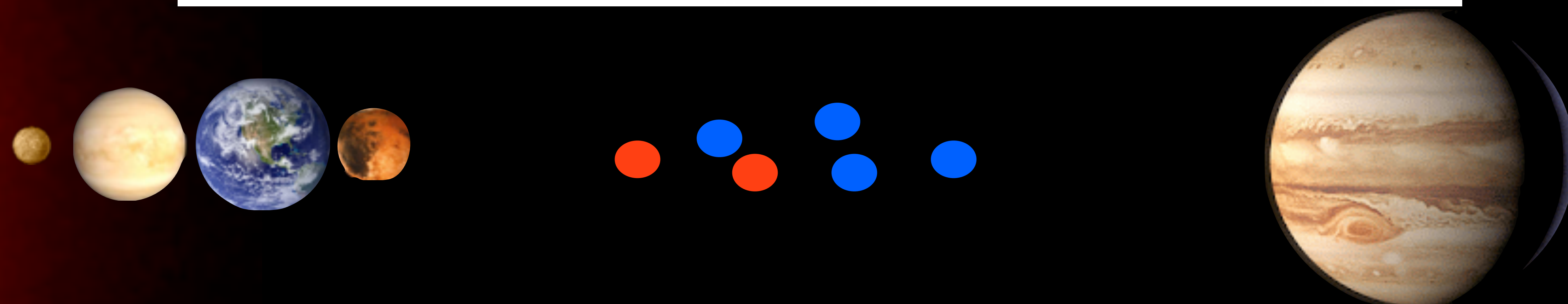




2 M_{Earth}

$5x10^{-4}$ M_{Earth}

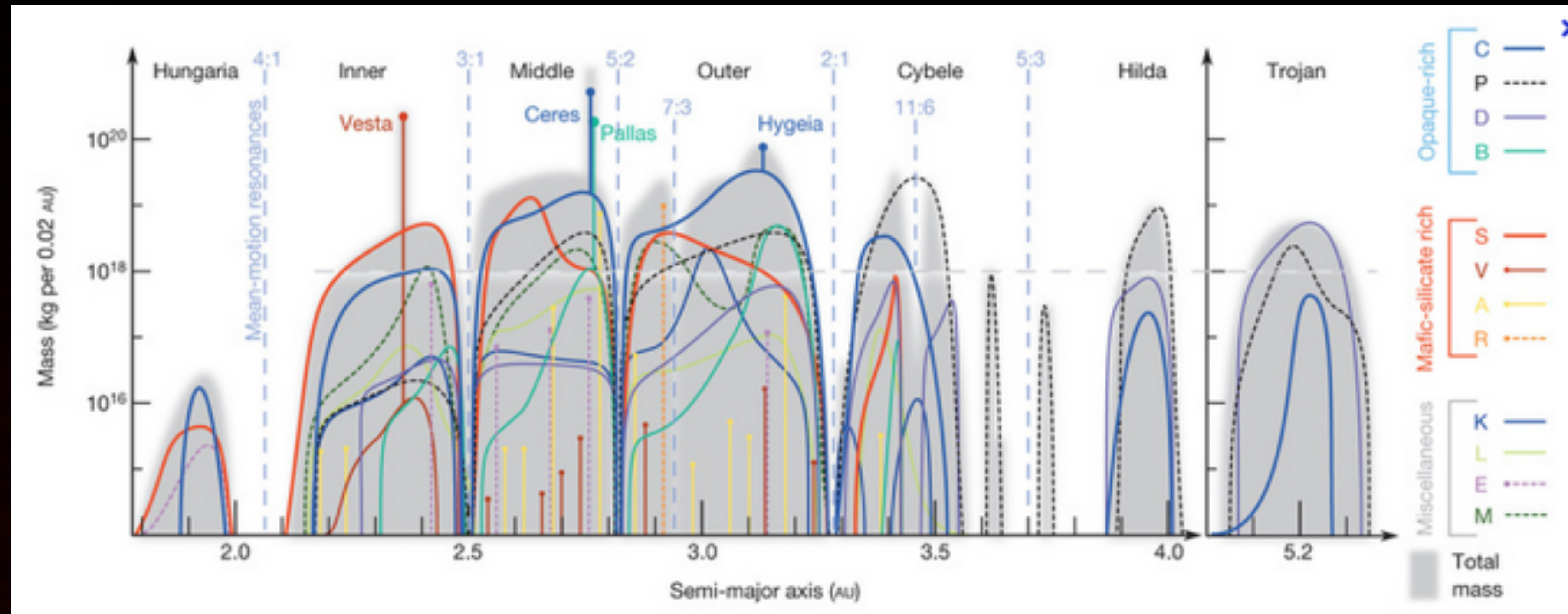
>5-10 M_{Earth} (solids)

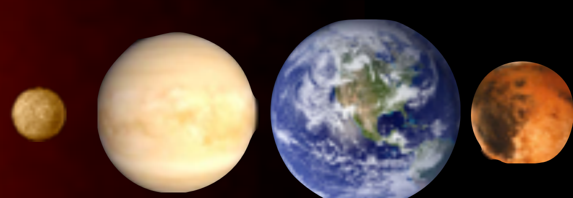
Number, masses

Angular momentum deficit

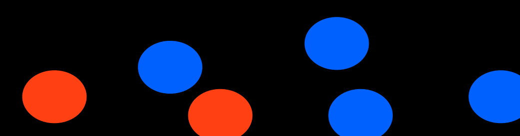
Growth timescales, compositions

Demeo & Carry 2014





Water



2 M_{Earth}

5×10^{-4} M_{Earth}

>5-10 M_{Earth} (solids)

Number, masses

Angular momentum deficit

Growth timescales, compositions

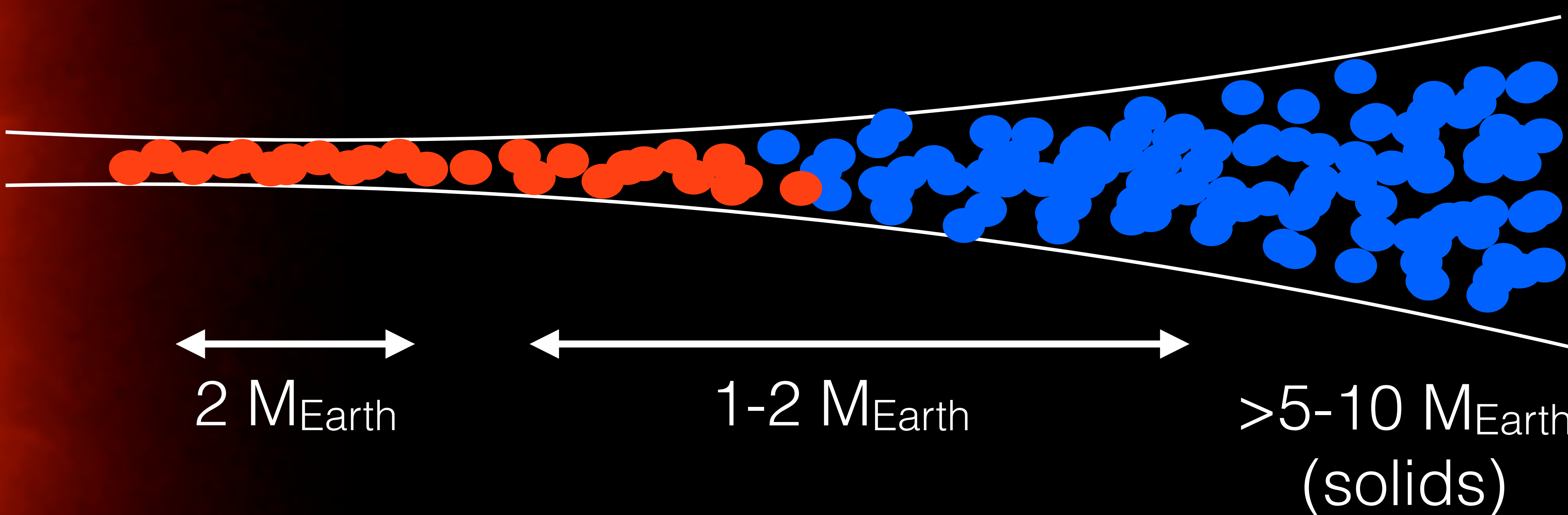
Total mass

S/C dichotomy

Orbital distribution

Simulations of the "classical model"

(Wetherill 1978-96; Chambers 2001; Raymond et al 2004, 2006, 2009, 2014; O'Brien et al 2006; Izidoro et al 2015; Morishima et al 2008, 2010; Fischer & Ciesla 2014; Kaib & Cowan 2015, …)



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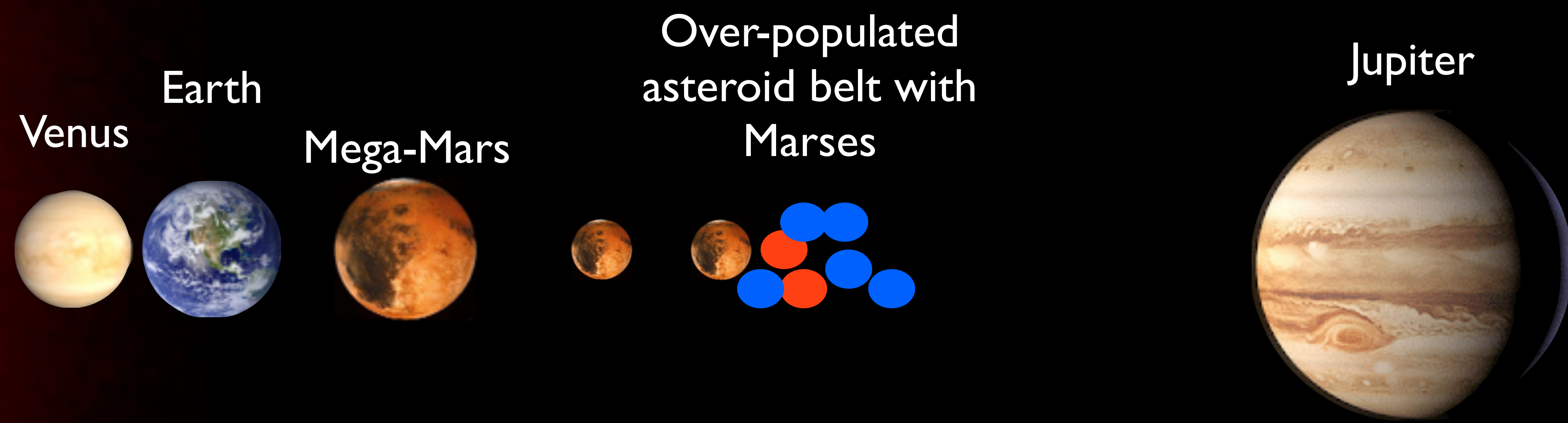

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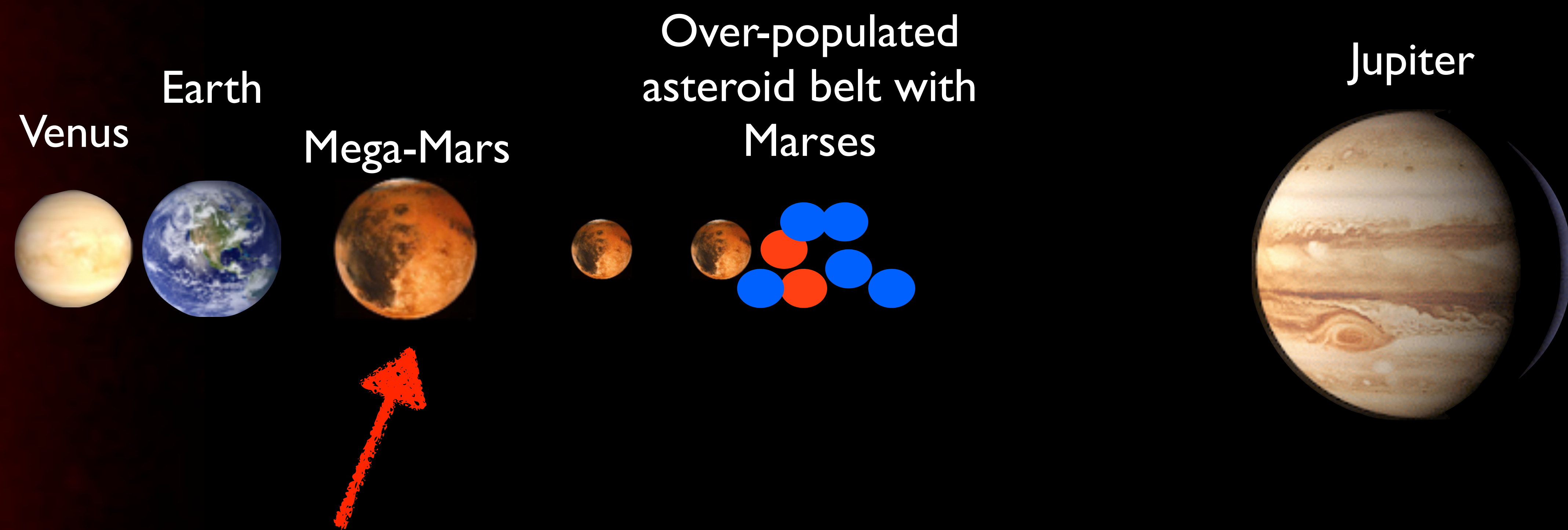

Problem 1: Mars is as big as Earth

(Wetherill 1991)

Simulations of the "classical model"

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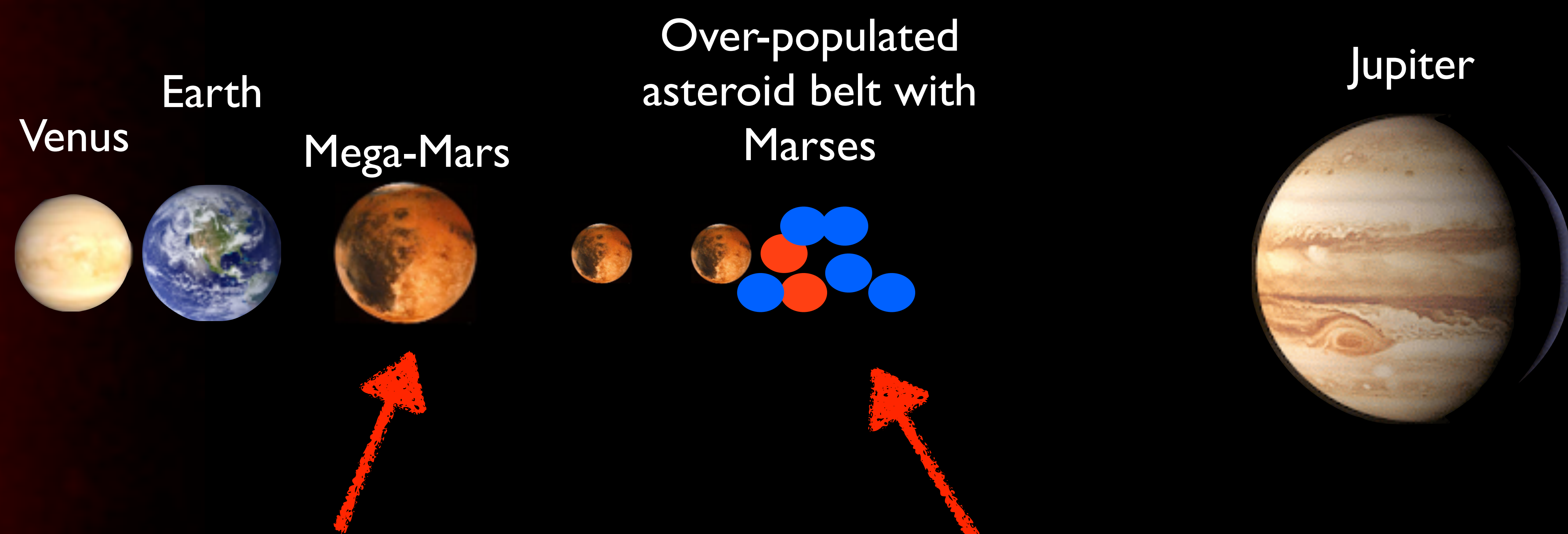


Problem 1: Mars is as big as Earth

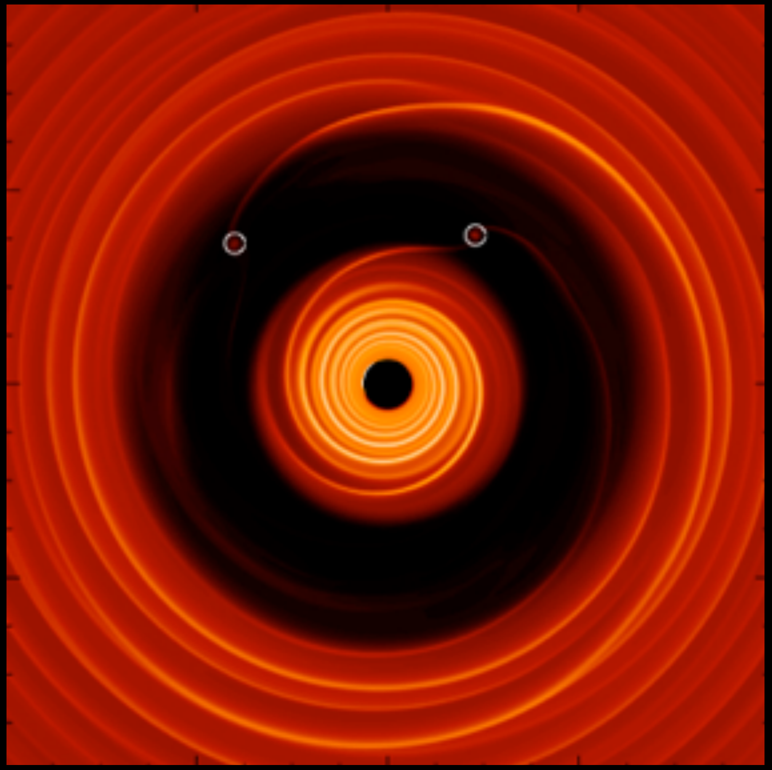
(Wetherill 1991)

Problem 2: too many asteroids (on bad orbits)

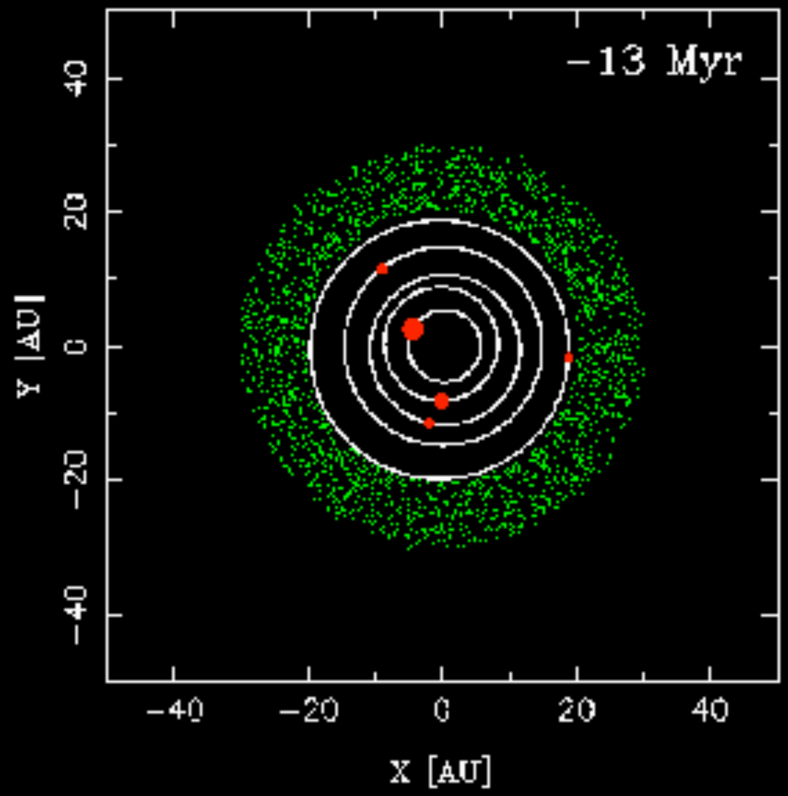
(Raymond et al 2009; Izidoro et al 2015)

3 possible solutions

"Low-mass asteroid belt"



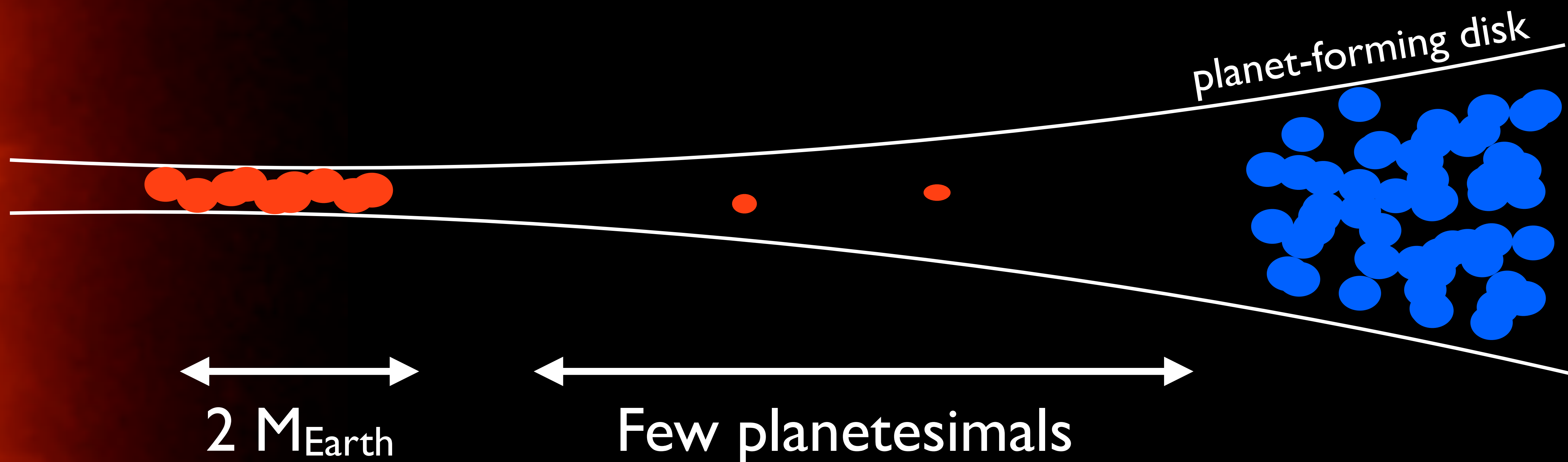
The "Grand Tack"



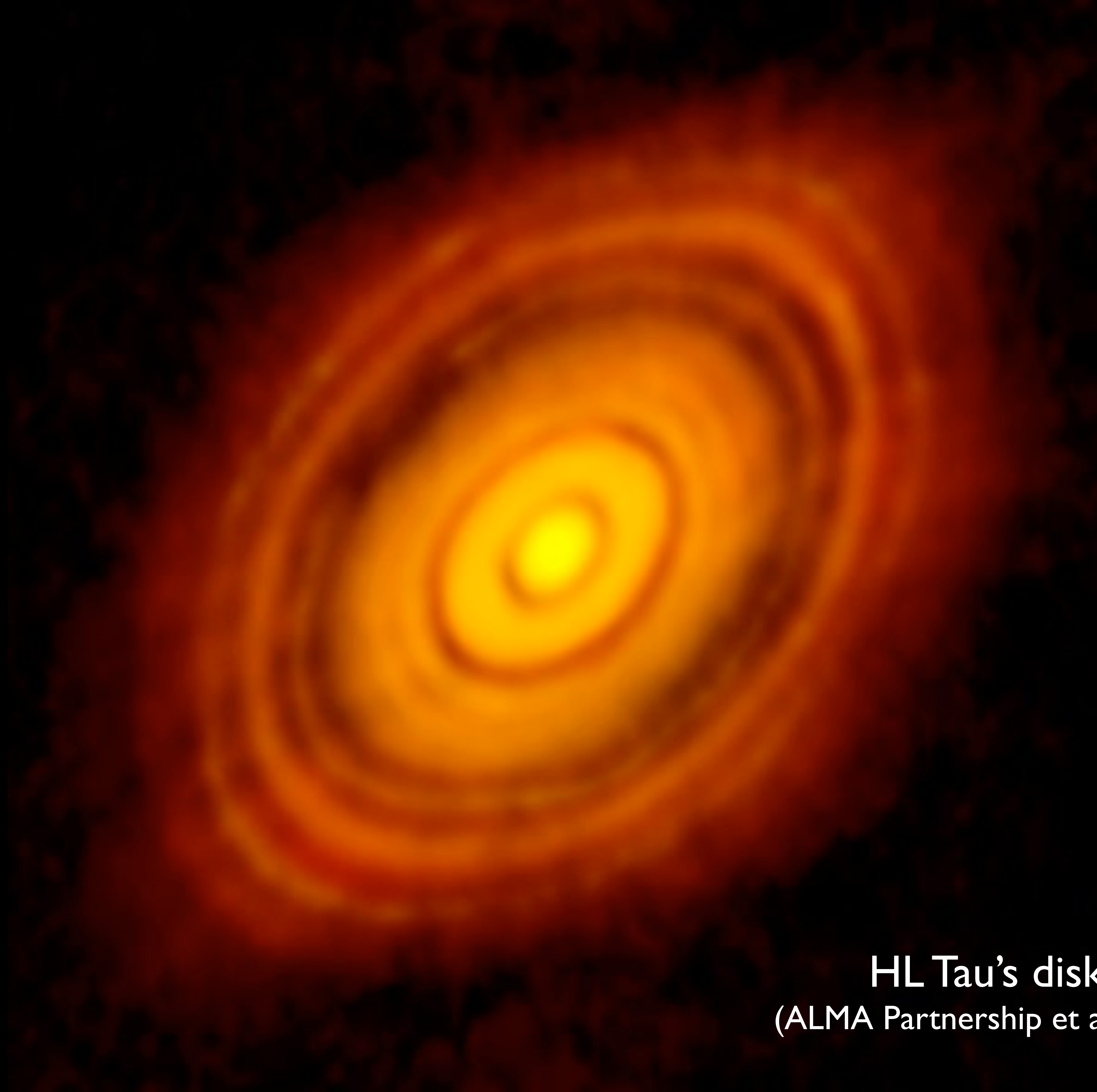
Early instability

Solution 1. planetesimal distribution

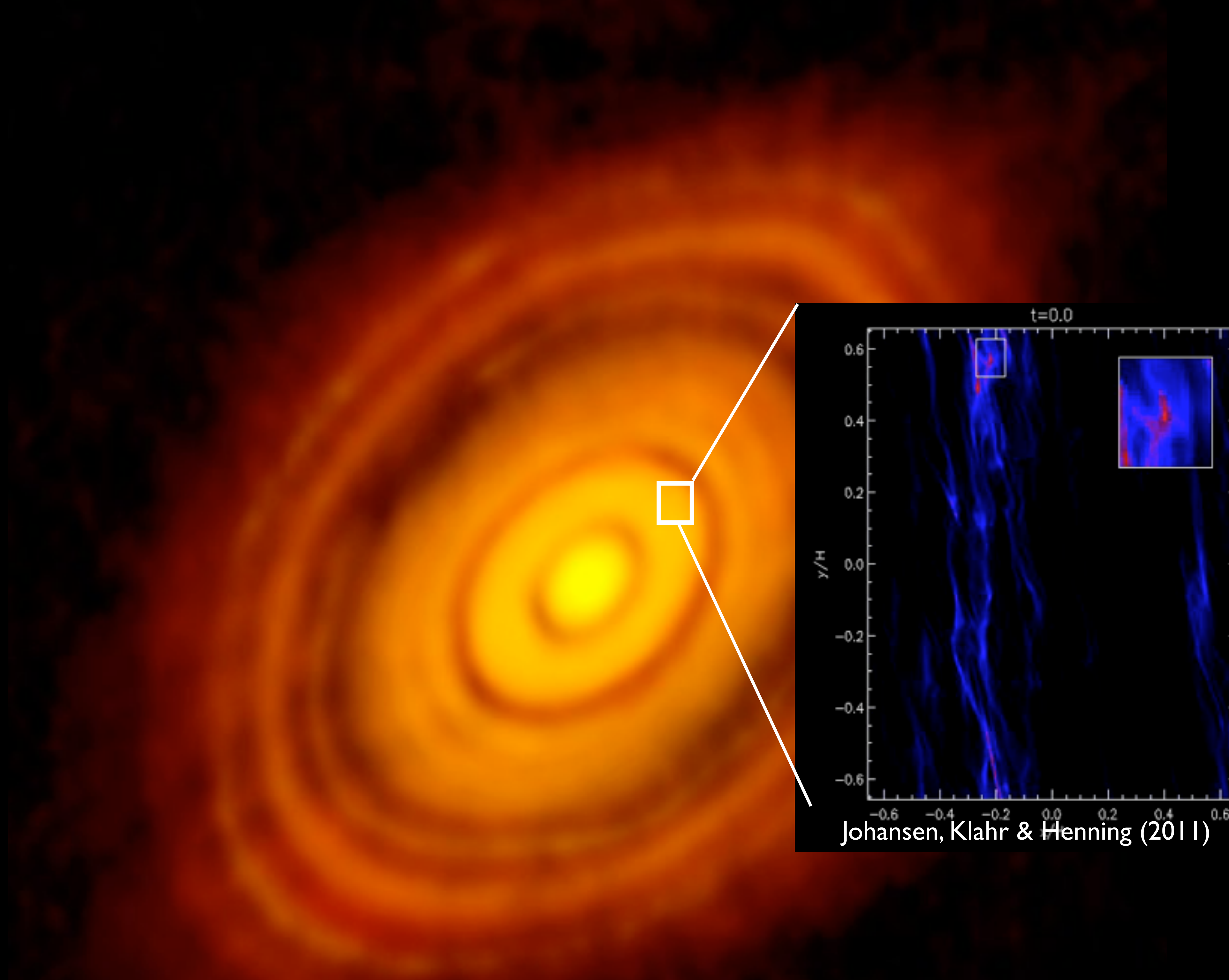
Assumption: few (if any) planetesimals formed in Mars region/asteroid belt



(Hansen 2009; Izidoro et al 2015; Walsh & Levison 2016; Drazkowska et al 2016; Raymond & Izidoro 2017b)



HL Tau’s disk
(ALMA Partnership et al 2015)



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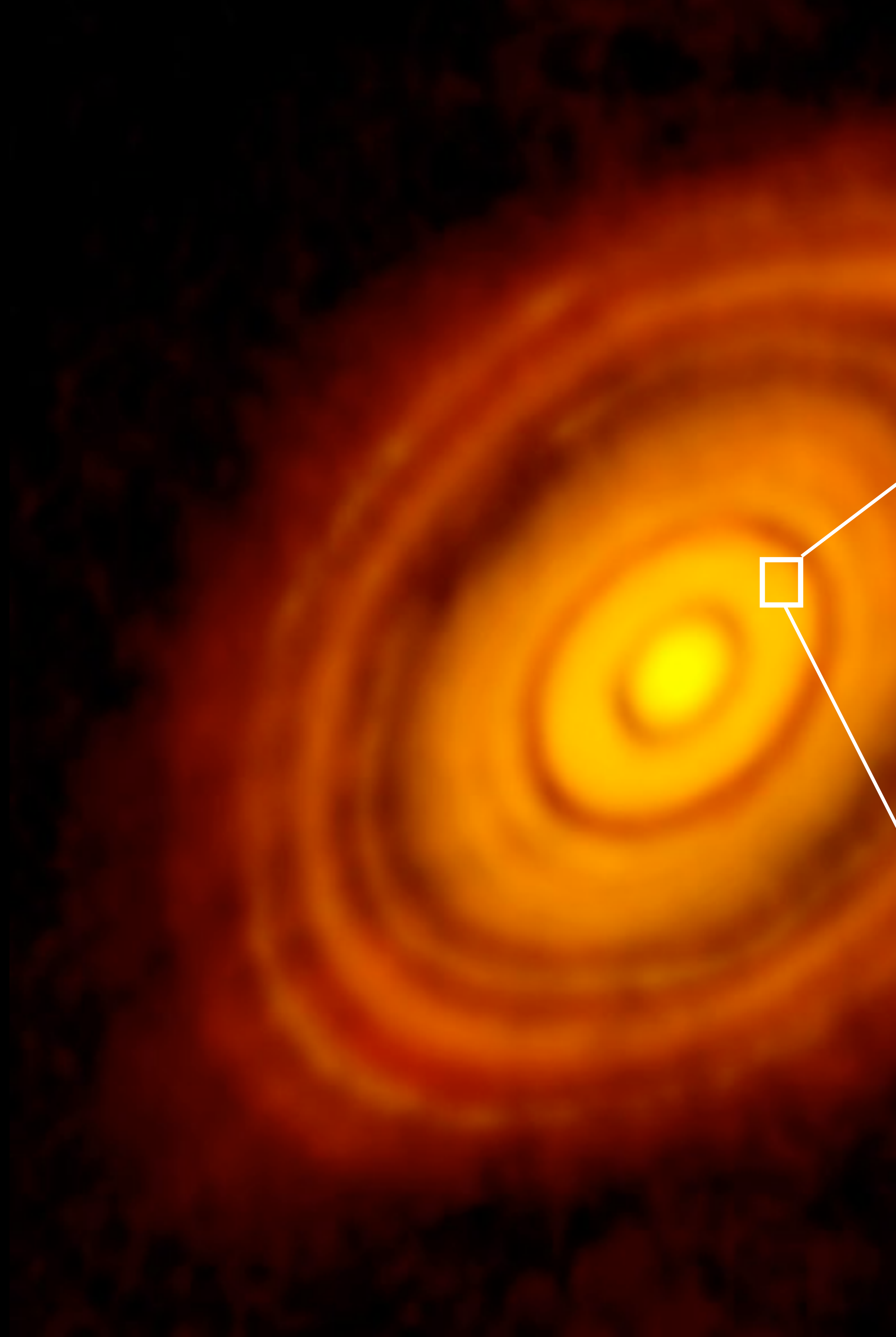
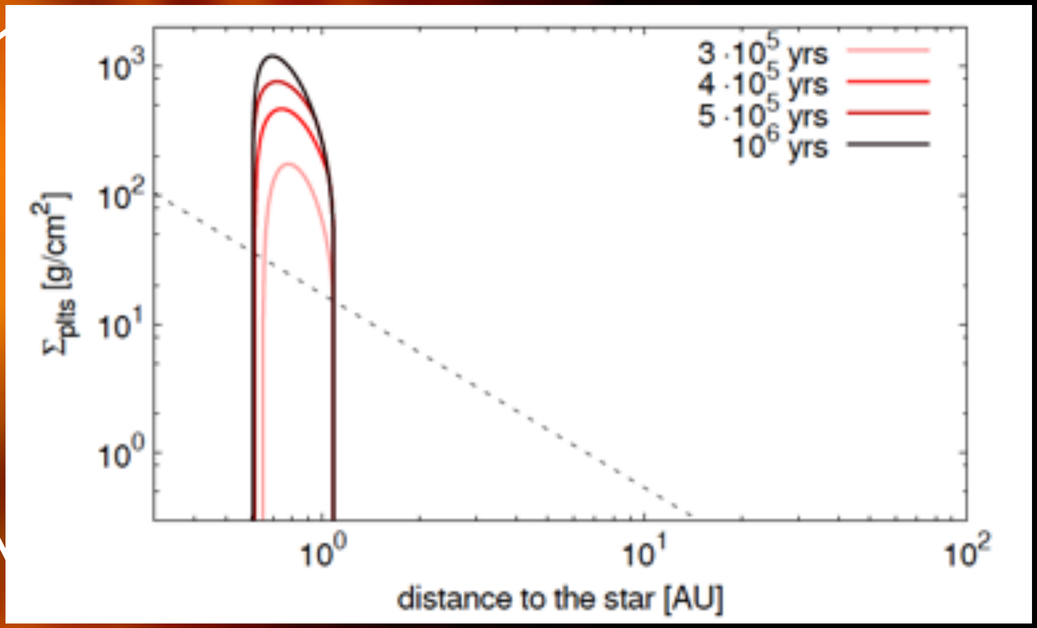
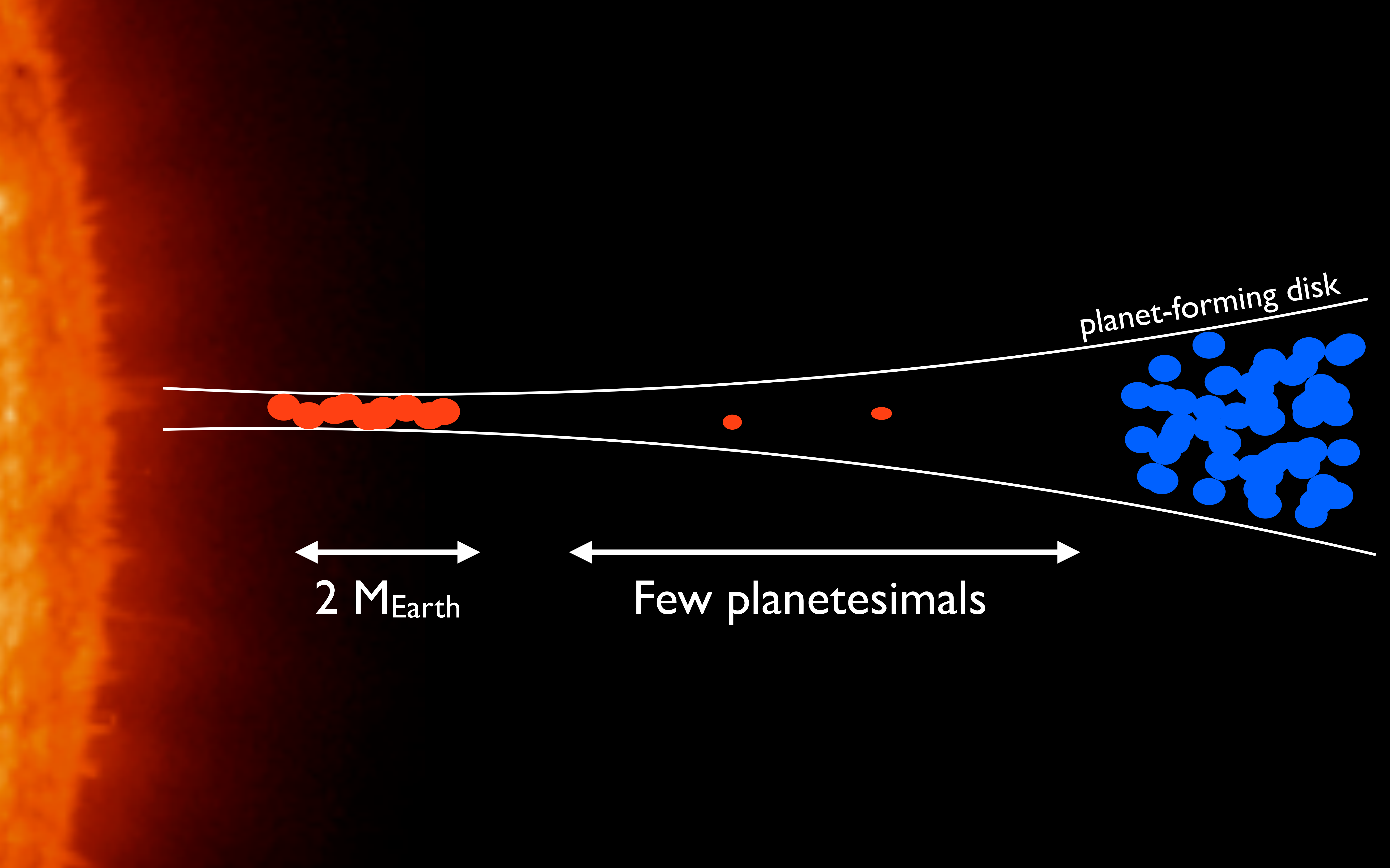




Drazkowska et al (2016)

HL Tau's disk
(ALMA Partnership et al 2015)

Solution 1. Low-mass asteroid belt



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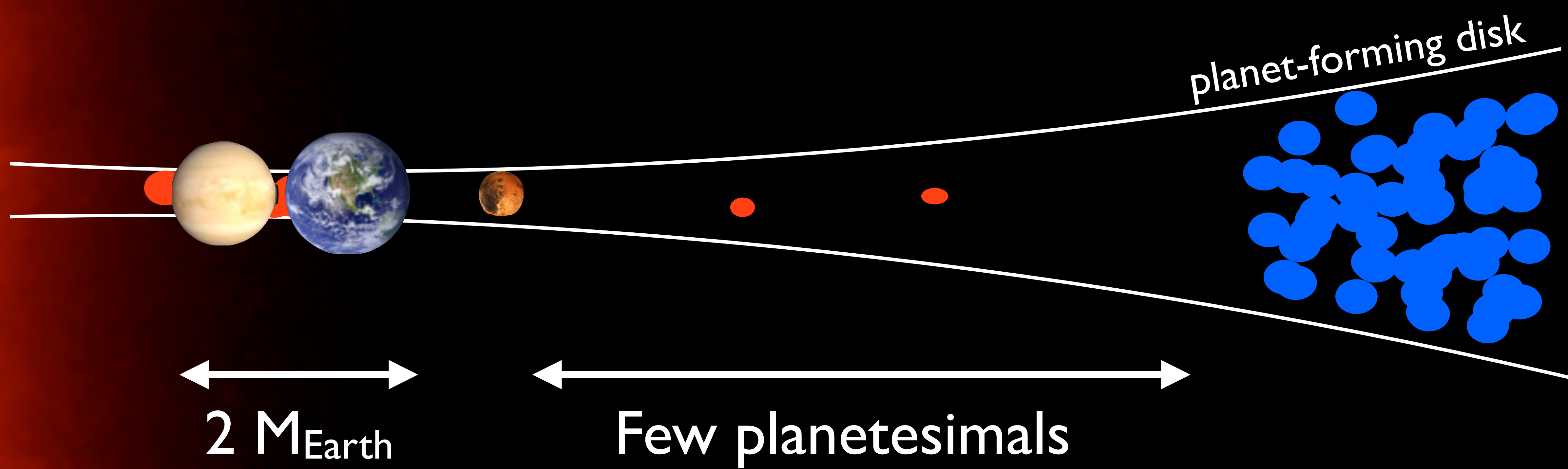

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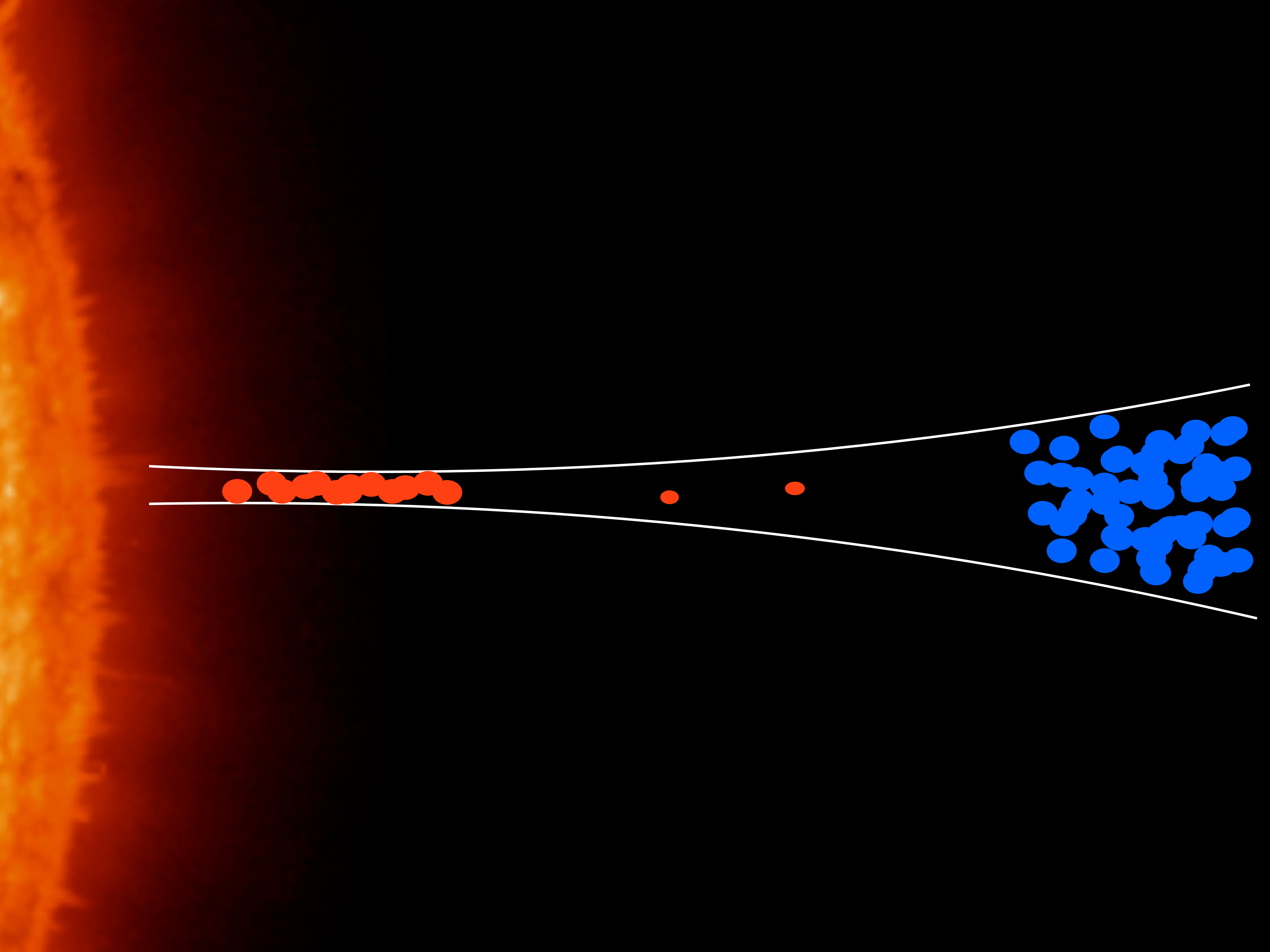
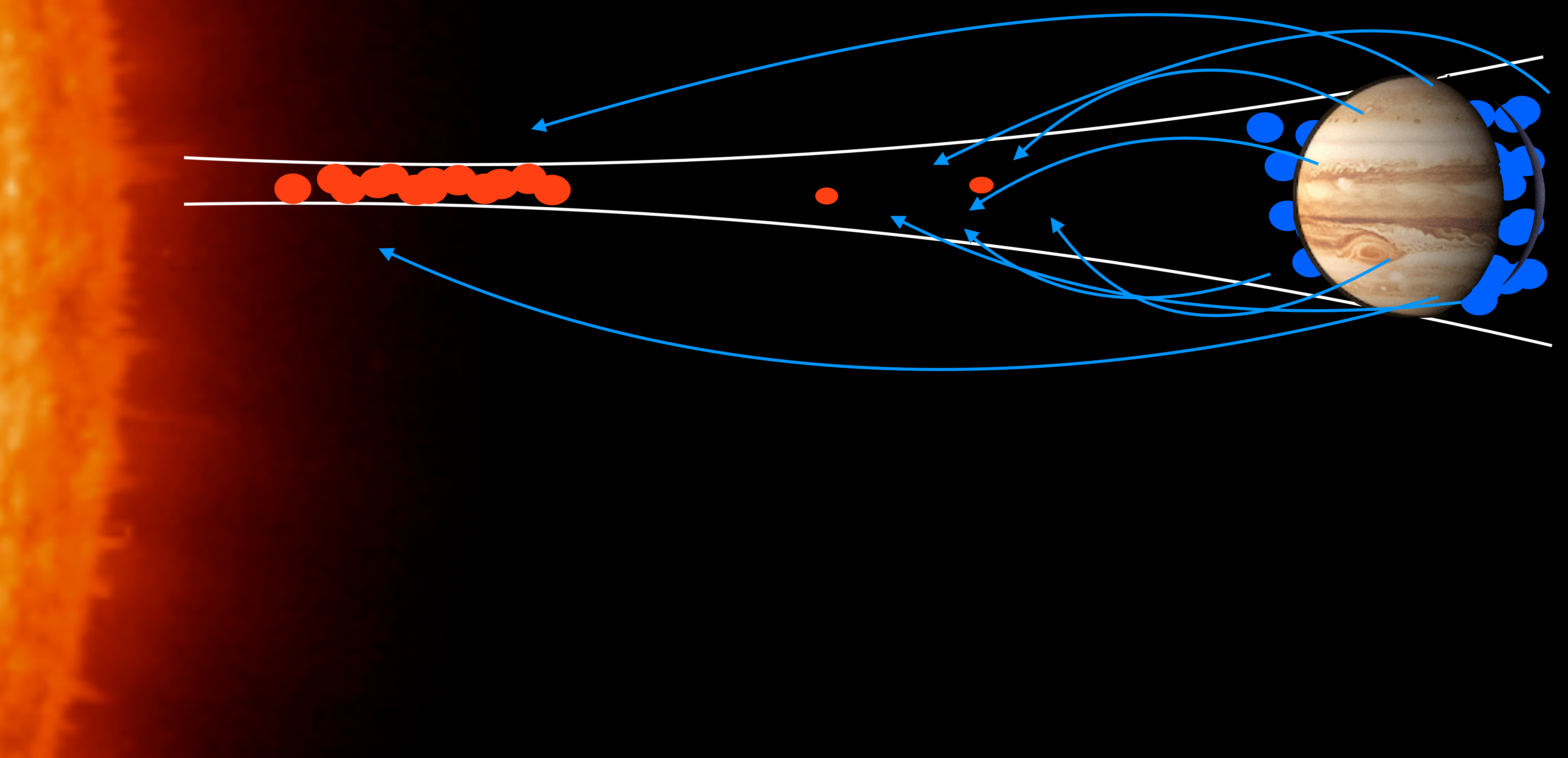


C-types and Earth's water from giant planet region



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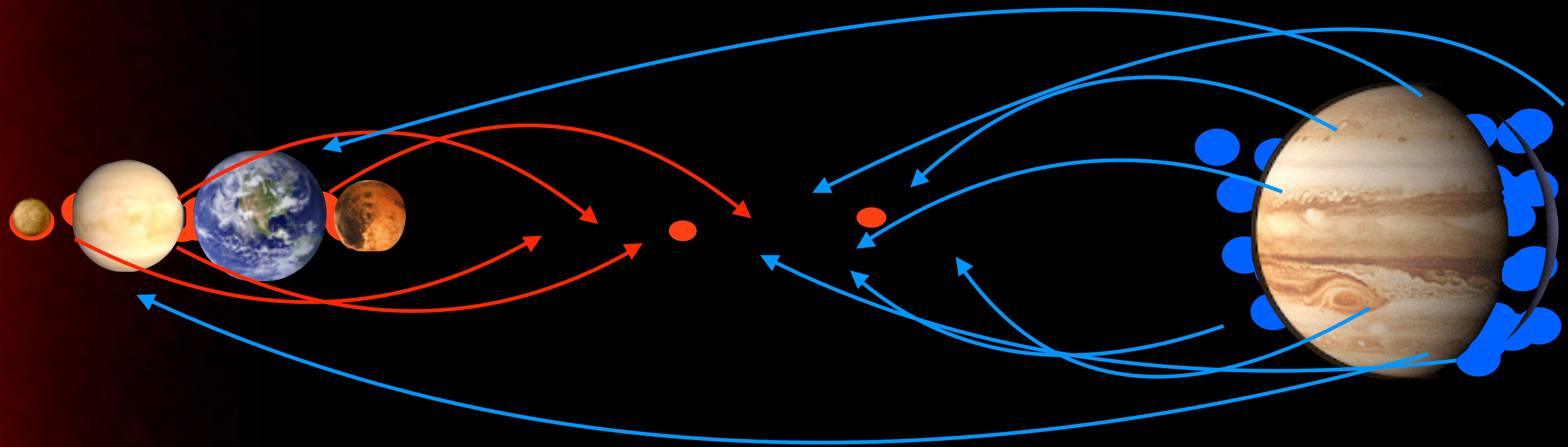
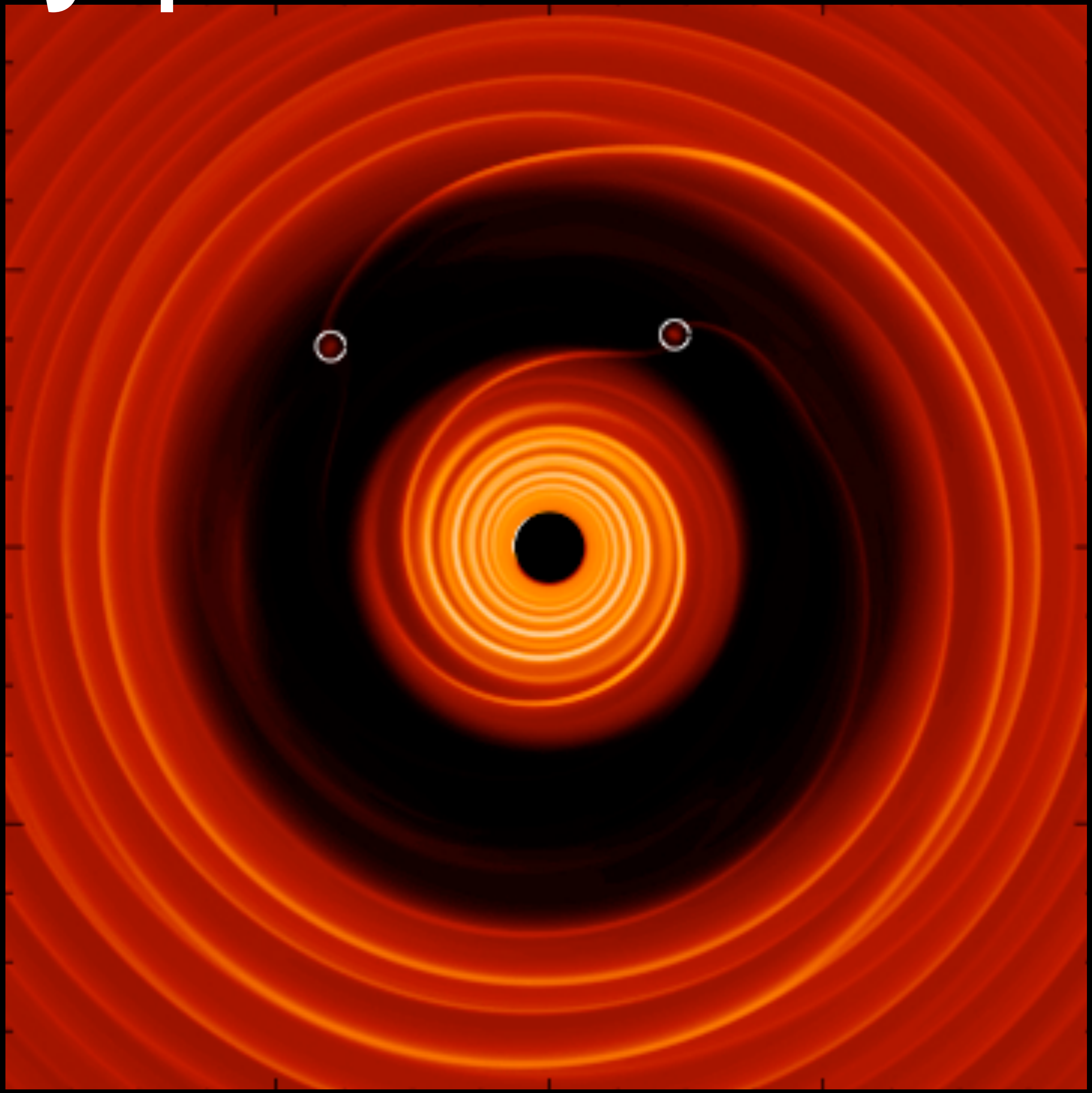


Some asteroids (Vesta? Irons? S-types?) scattered out from terrestrial planet region

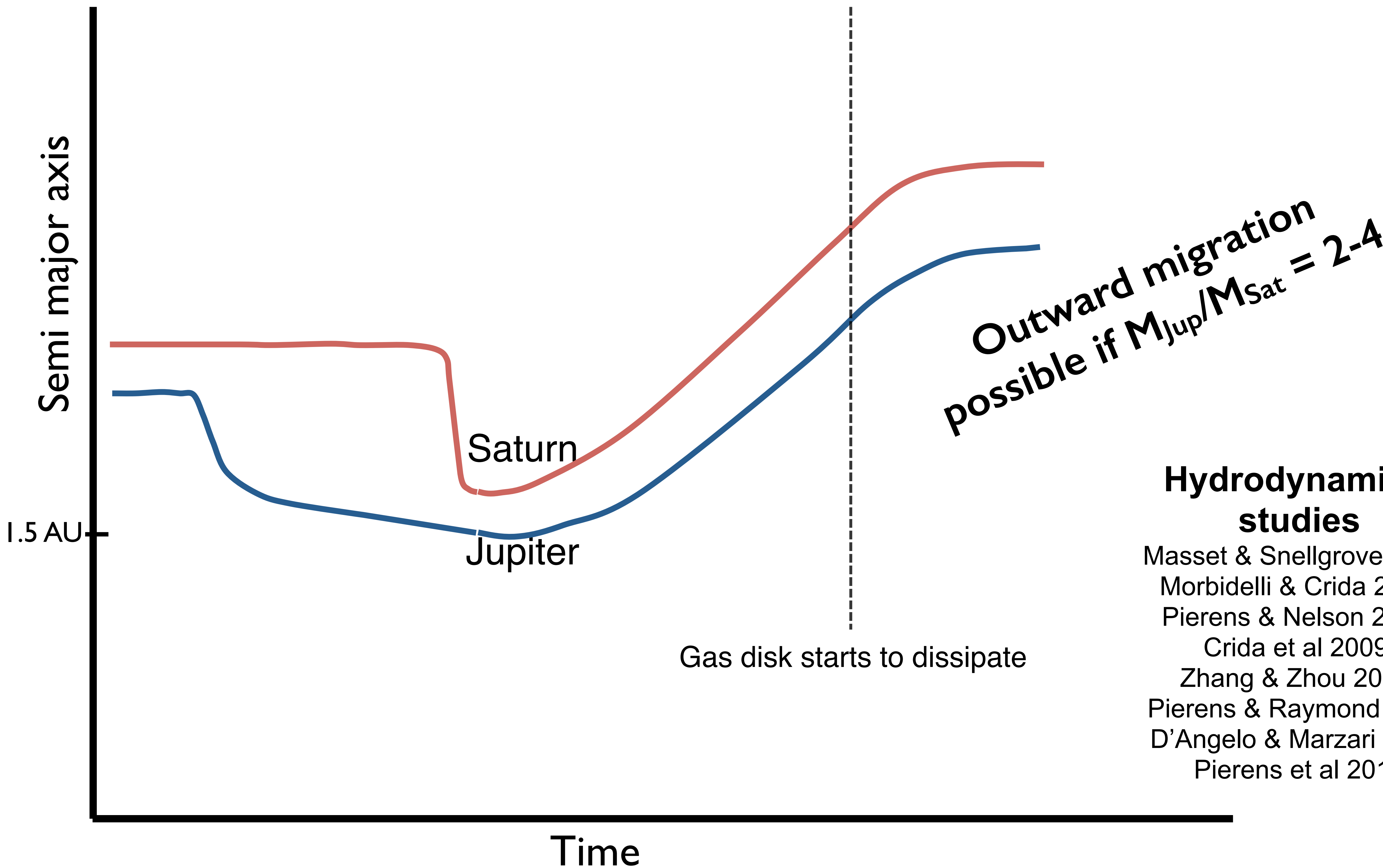
Raymond & Izidoro (2017a,b); also Bottke et al (2006); Ronnet et al (2018), Mastrobuono-Battisti & Perets (2017); Pirani et al (2019); Raymond & Nesvorny (2020)

Solution 2: migration of Jupiter and Saturn



Pierens & Raymond (2011)

The Grand Tack model
(Walsh et al 2011)



Hydrodynamical studies
Masset & Snellgrove 2001;
Morbidelli & Crida 2007;
Pierens & Nelson 2008;
Crida et al 2009;
Zhang & Zhou 2010;
Pierens & Raymond 2011;
D'Angelo & Marzari 2012;
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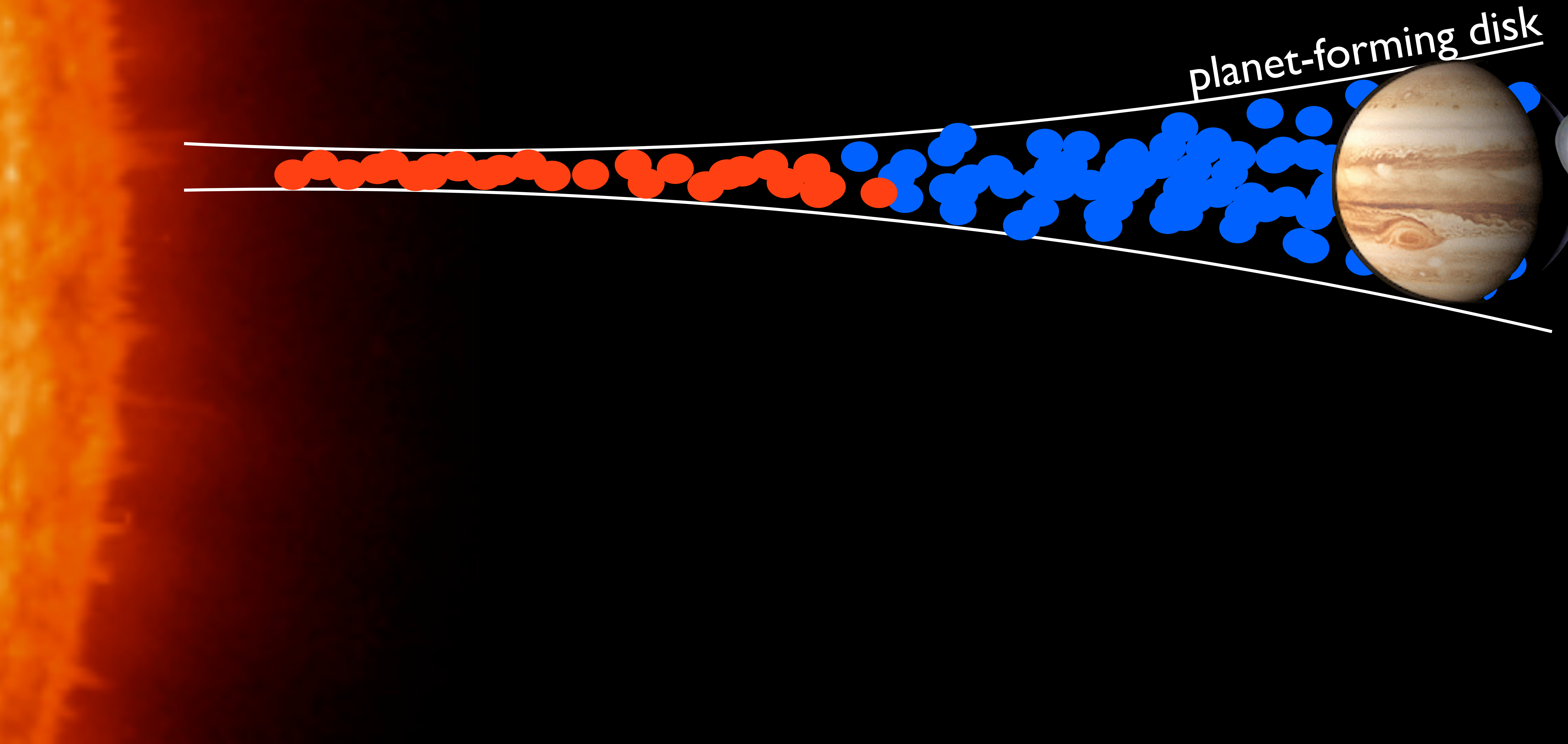

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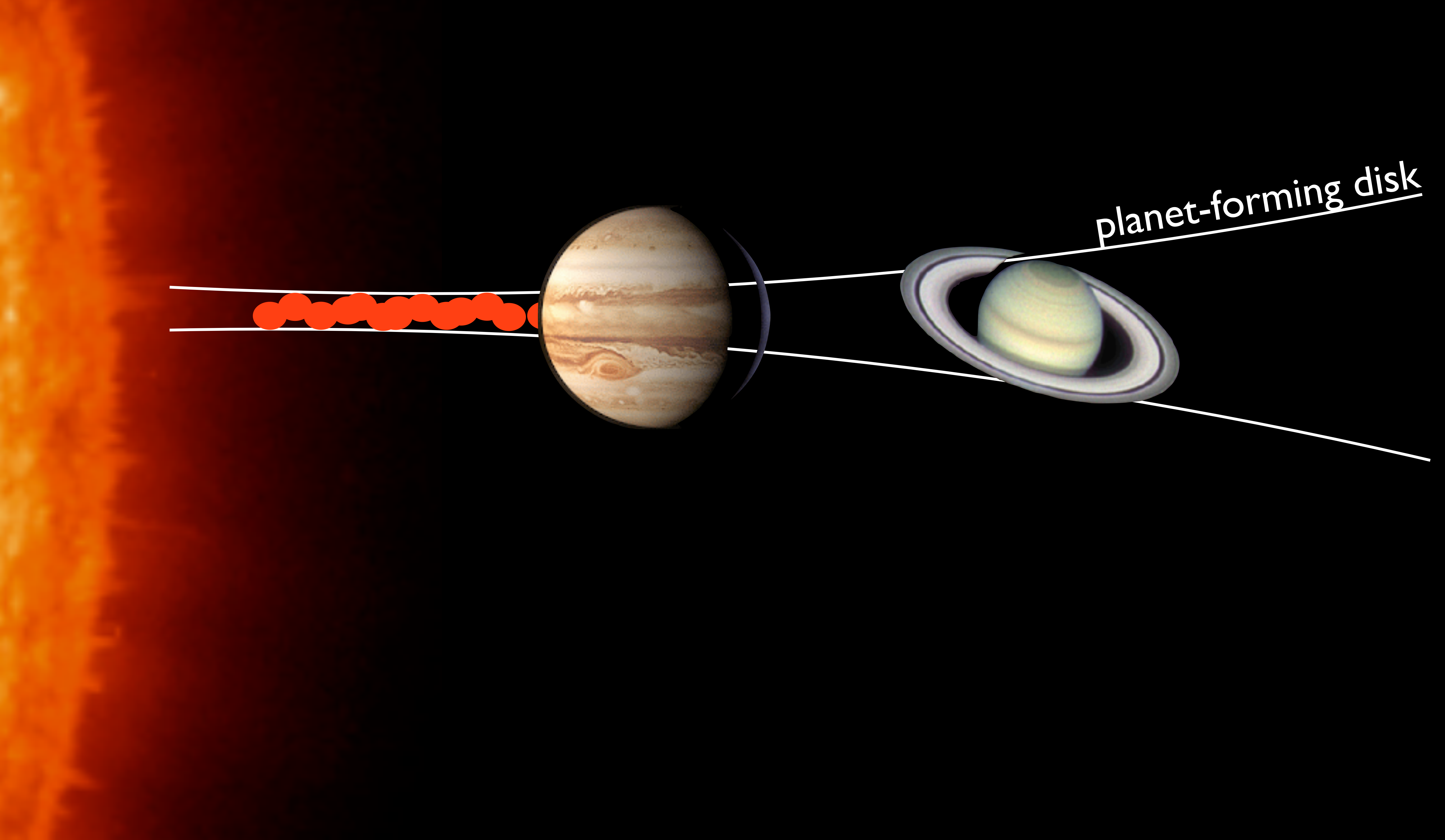

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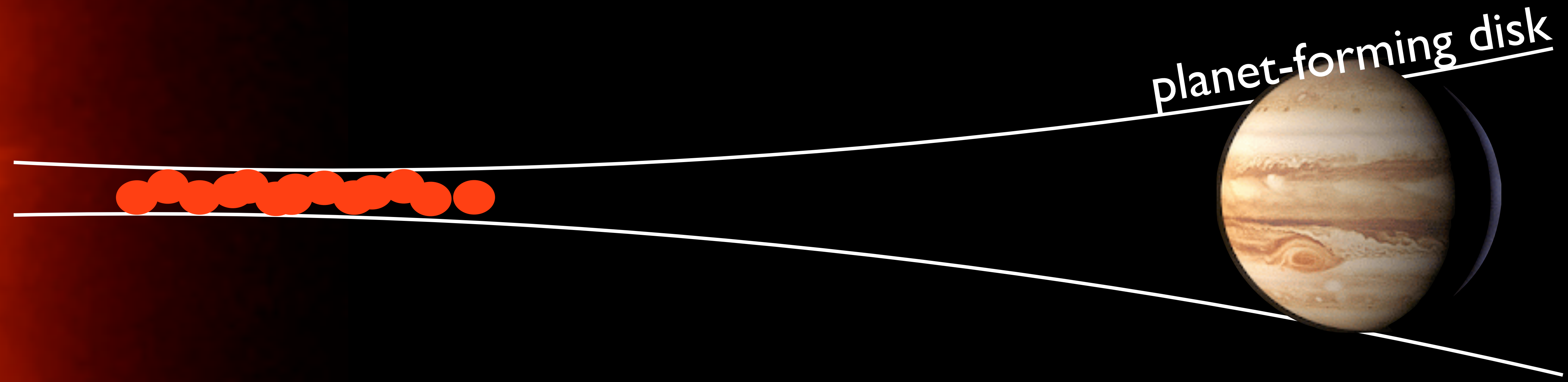
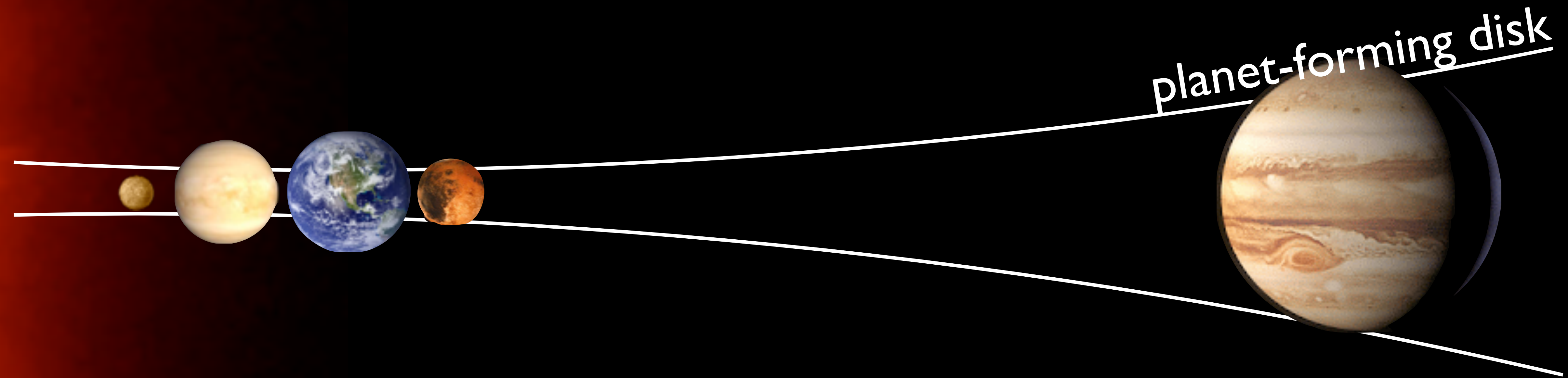


The “Grand Tack” model

(Walsh et al 2011)

Solution 2: migration of Jupiter and Saturn

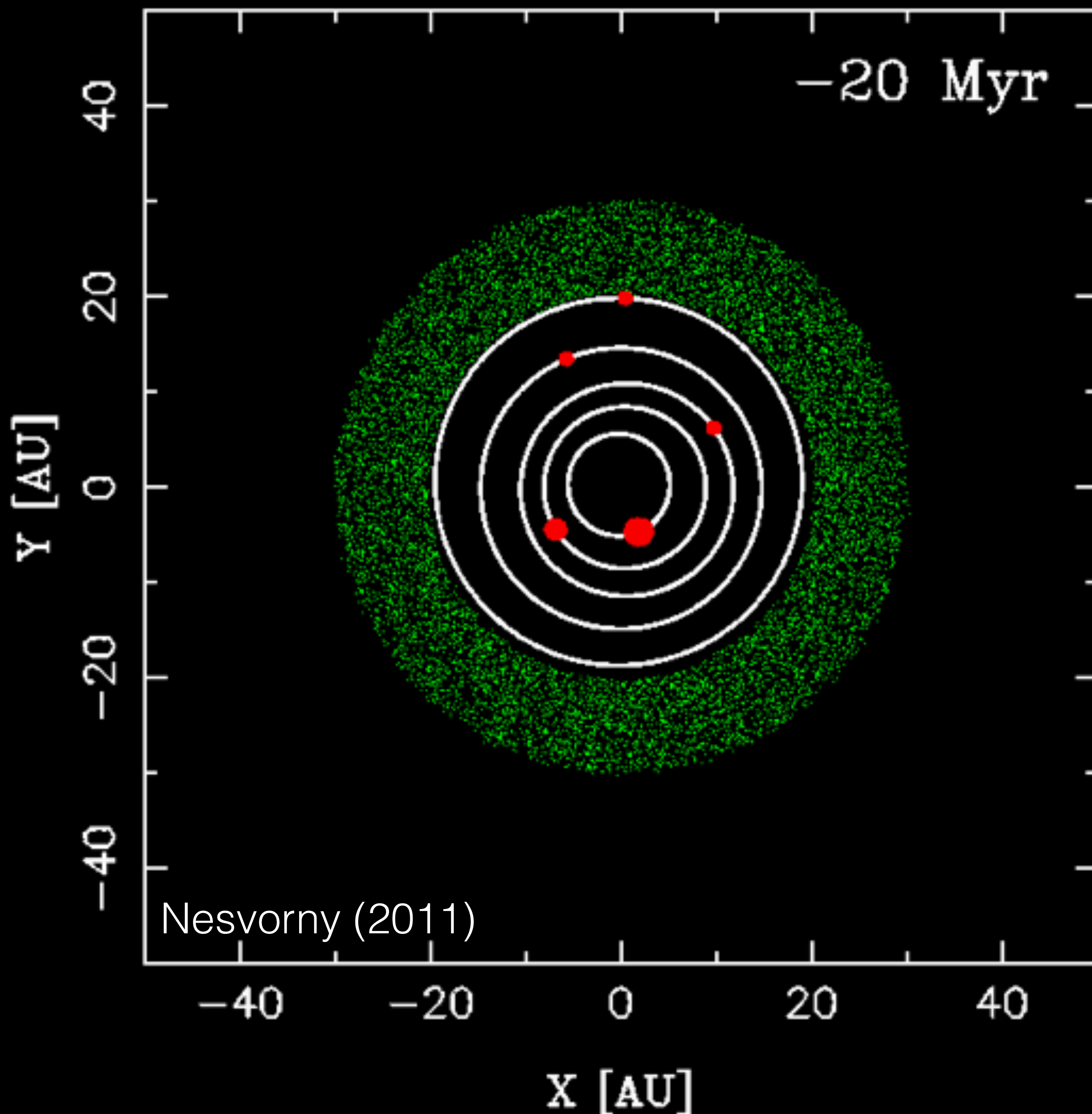


The "Grand Tack" model

(Walsh et al 2011)

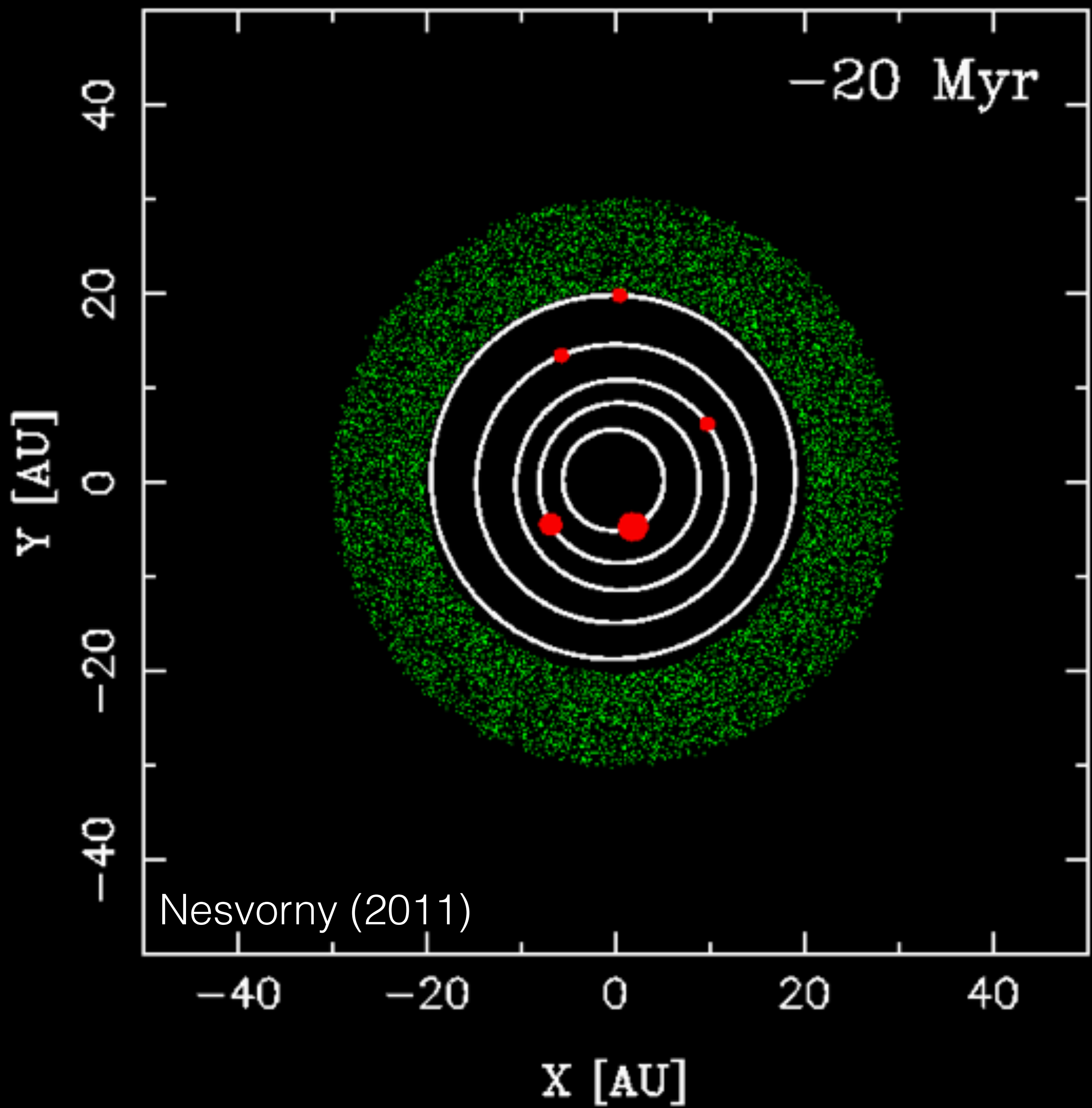
The Solar System's instability

(Thommes et al 1999, 2005; Tsiganis et al 2005; Morbidelli et al 2005, 2007, 2009; Levison et al 2011; Batygin & Brown 2011; Nesvorny & Morbidelli 2012; Deienno et al 2016, 2018, **Nesvorny 2018**…)



The Solar System's instability

(Thommes et al 1999, 2005; Tsiganis et al 2005; Morbidelli et al 2005, 2007, 2009; Levison et al 2011; Batygin & Brown 2011; Nesvorny & Morbidelli 2012; Deienno et al 2016, 2018, **Nesvorny 2018**…)



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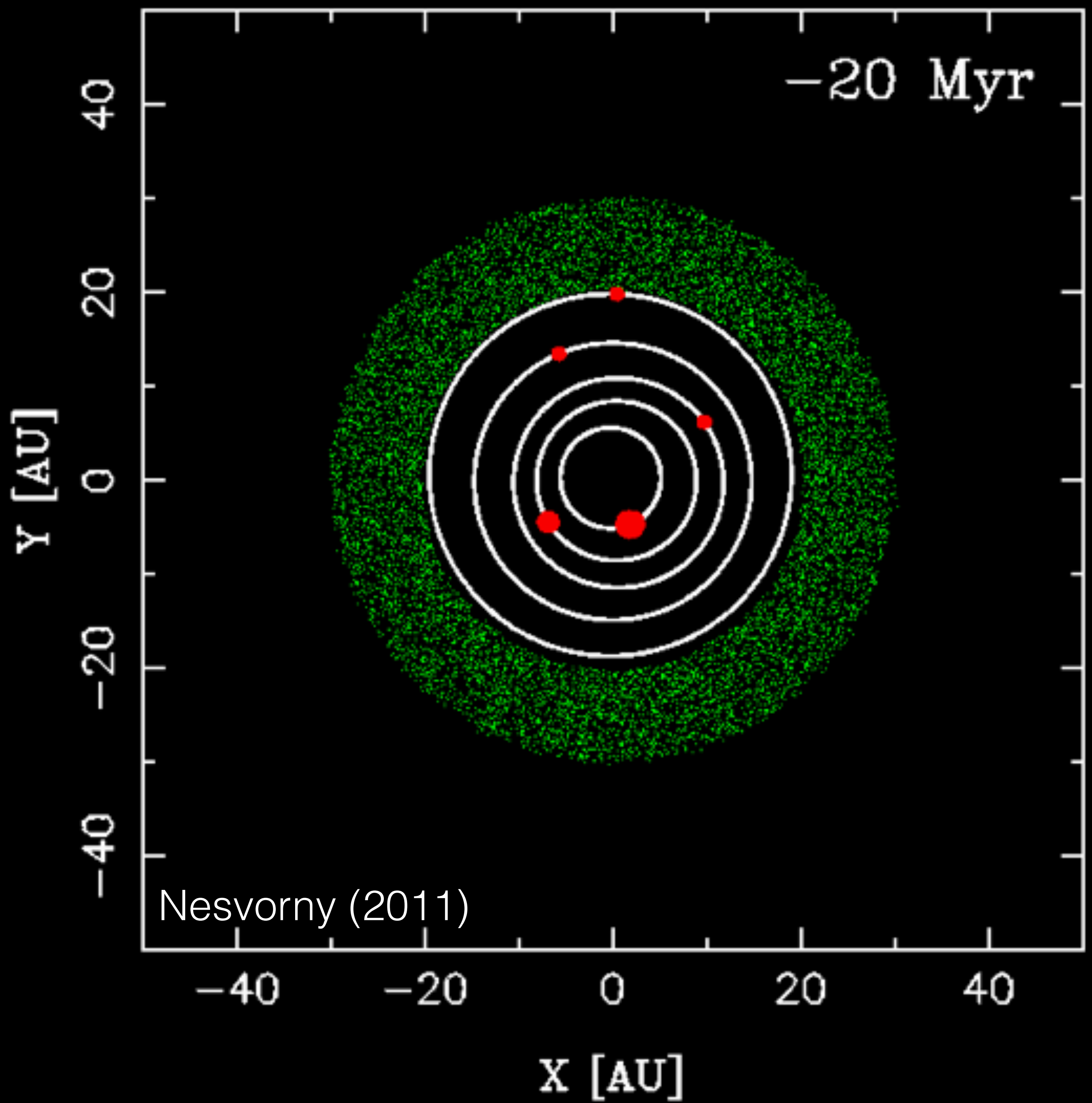
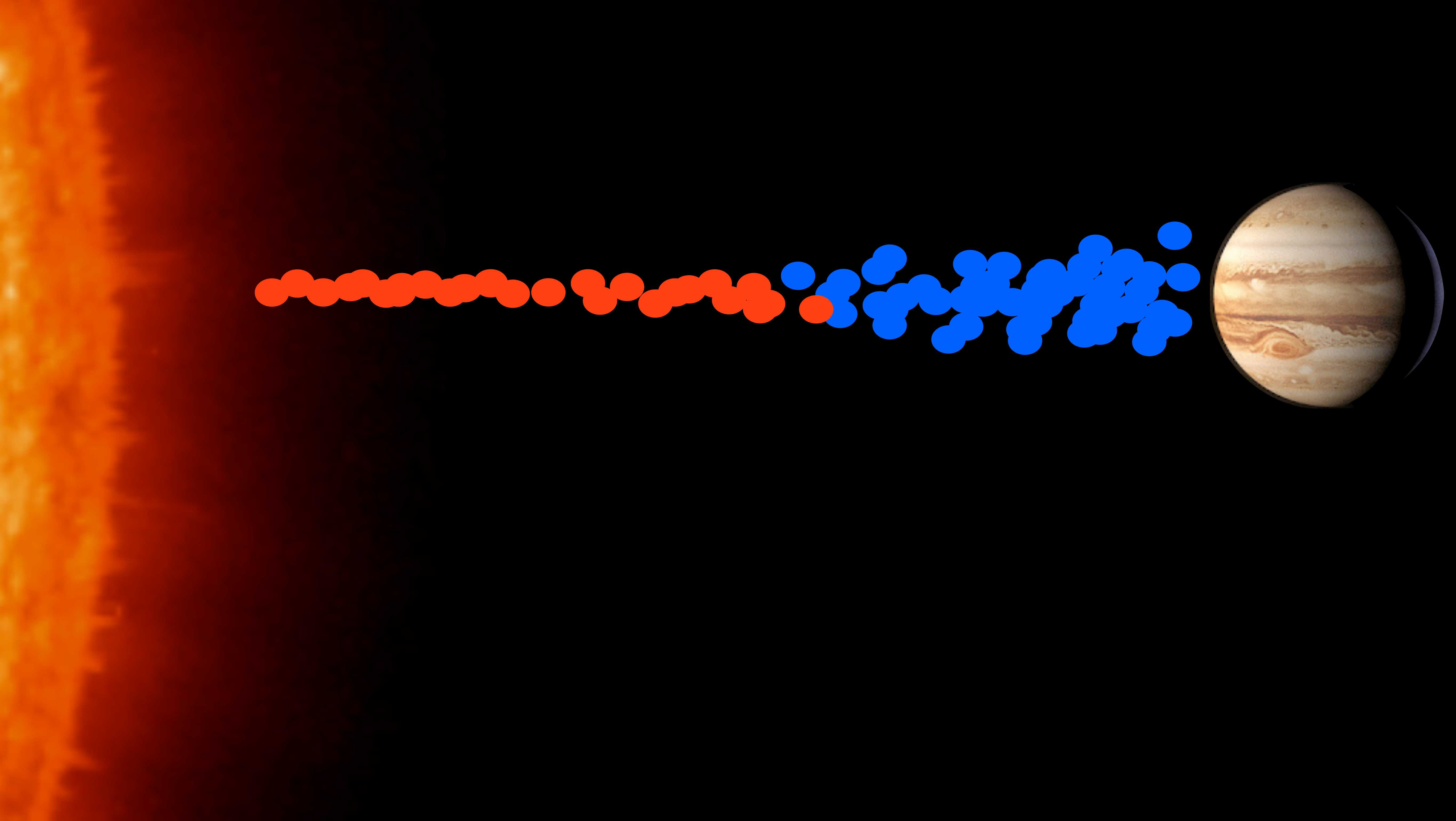


NEW: instability was early, likely in first ~10-100 Myr

(Zellner 2017; Morbidelli et al 2018; Nesvorny et al 2018; Mojzsis et al 2019)

Solution 3: dynamical instability among giant planets



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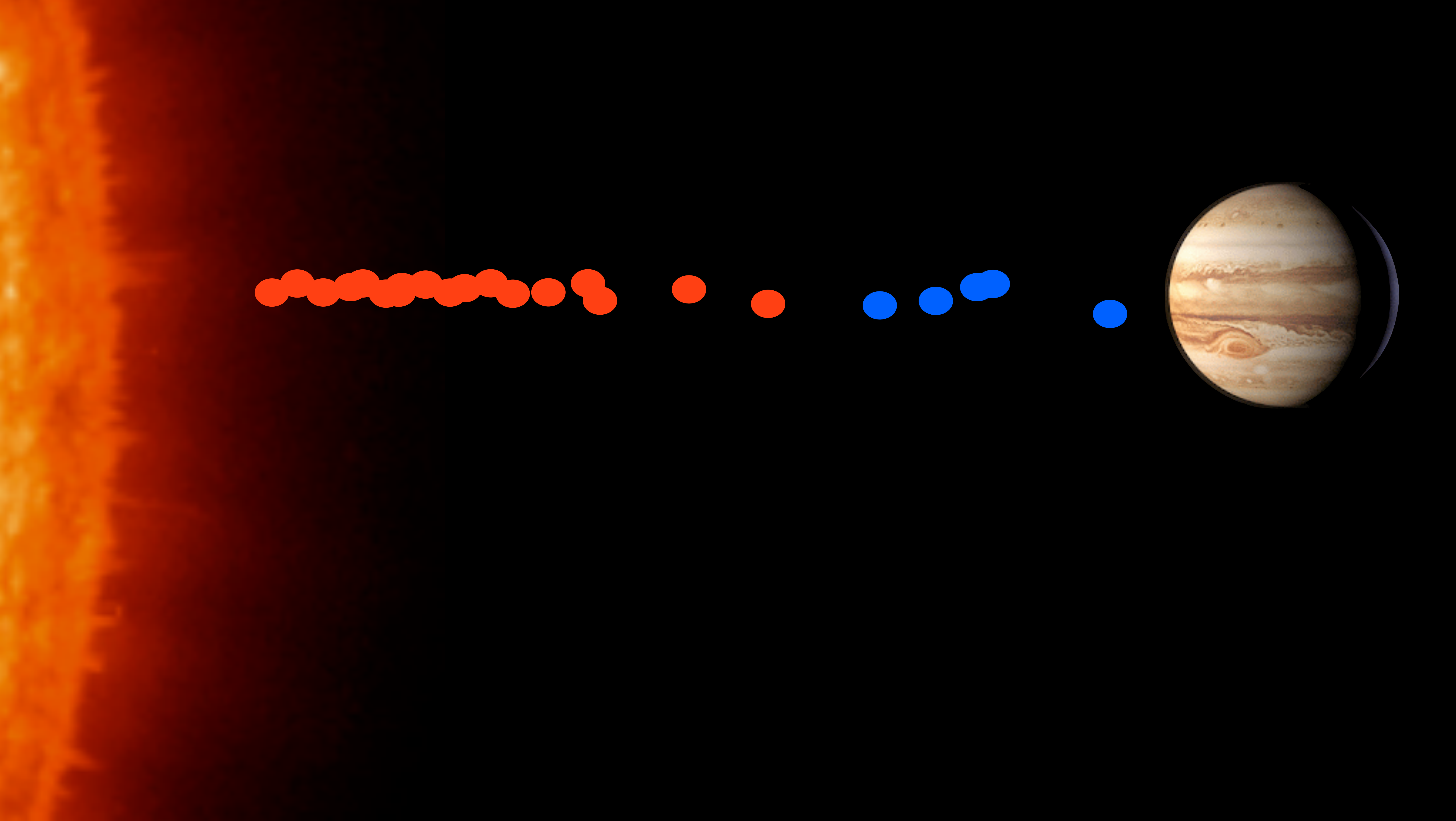

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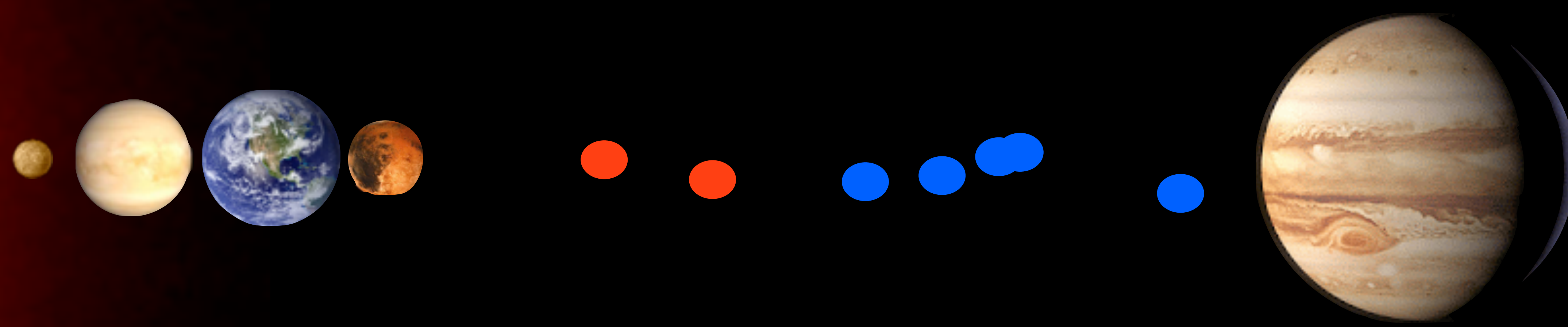
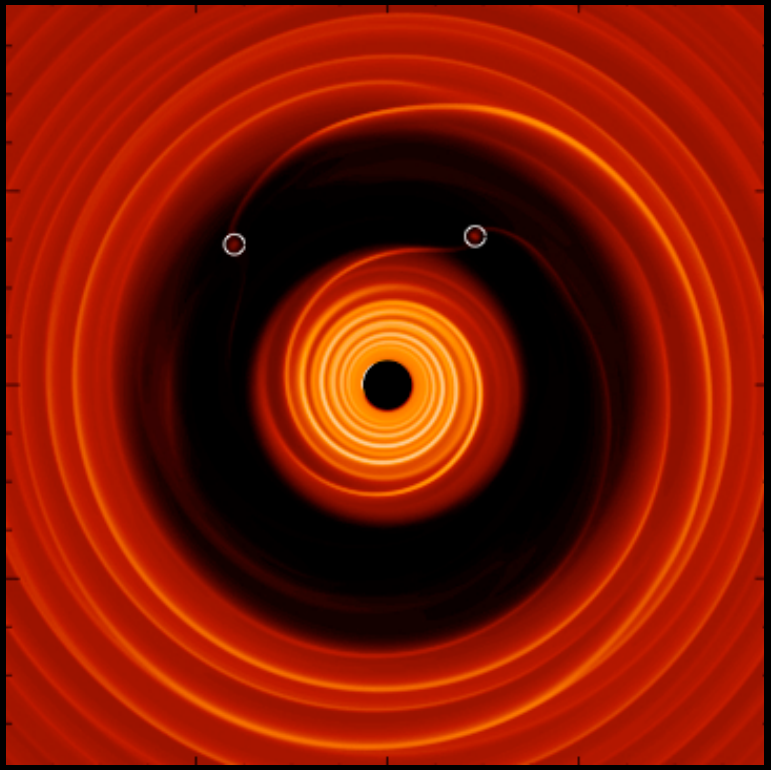


The “Early Instability” model

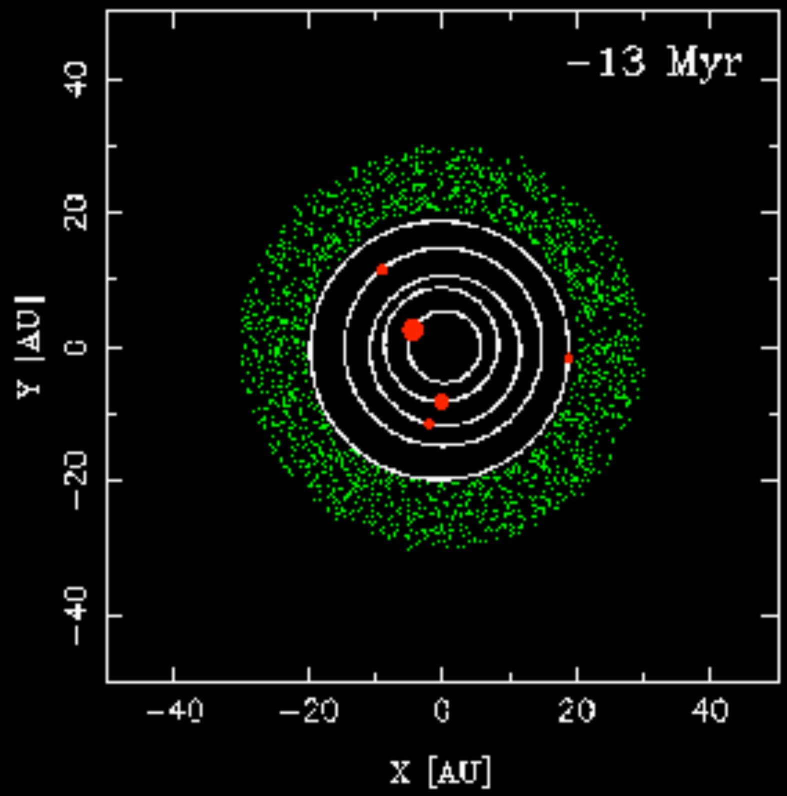
(Clement et al 2018, 2019ab)

3 possible solutions

"Low-mass asteroid belt"

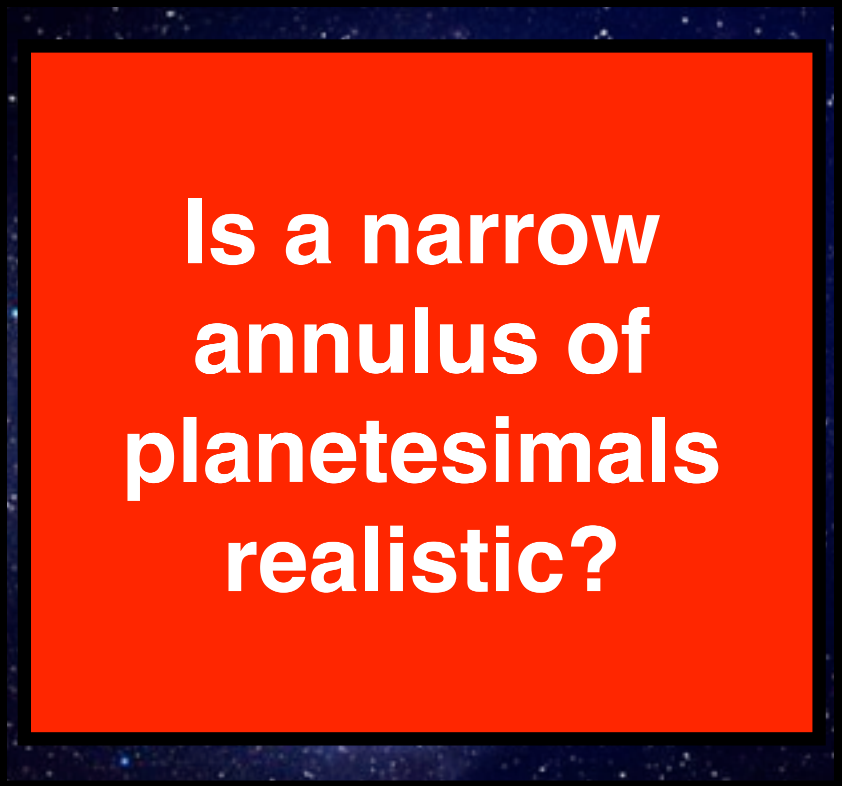


The "Grand Tack"



Early instability

3 possible solutions



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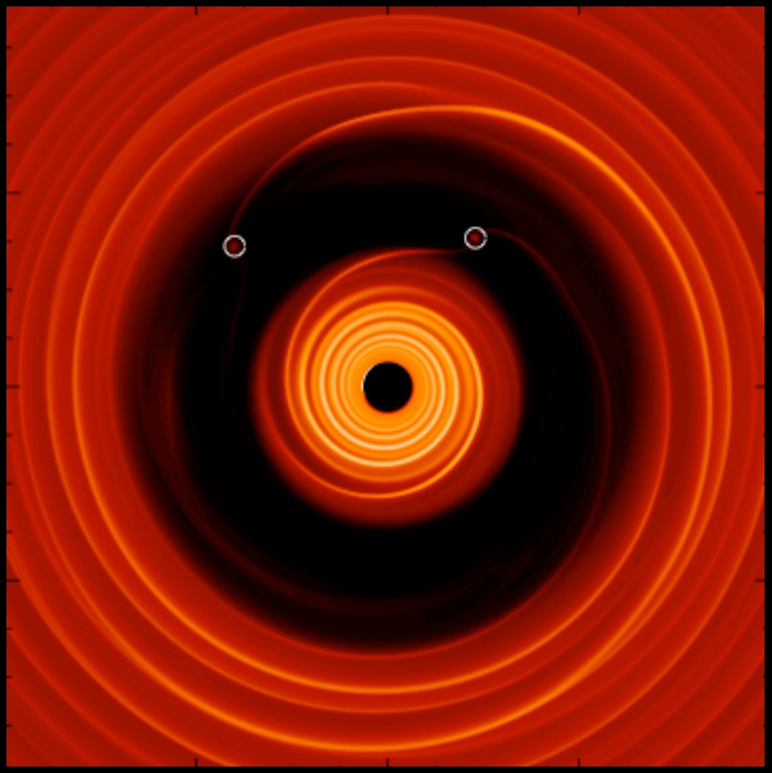

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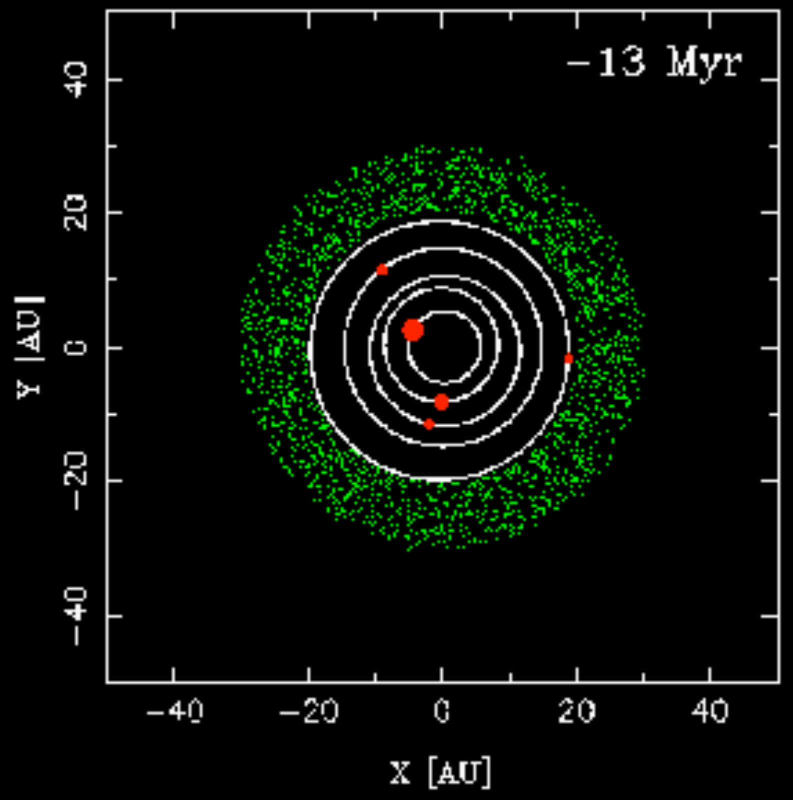


Early instability

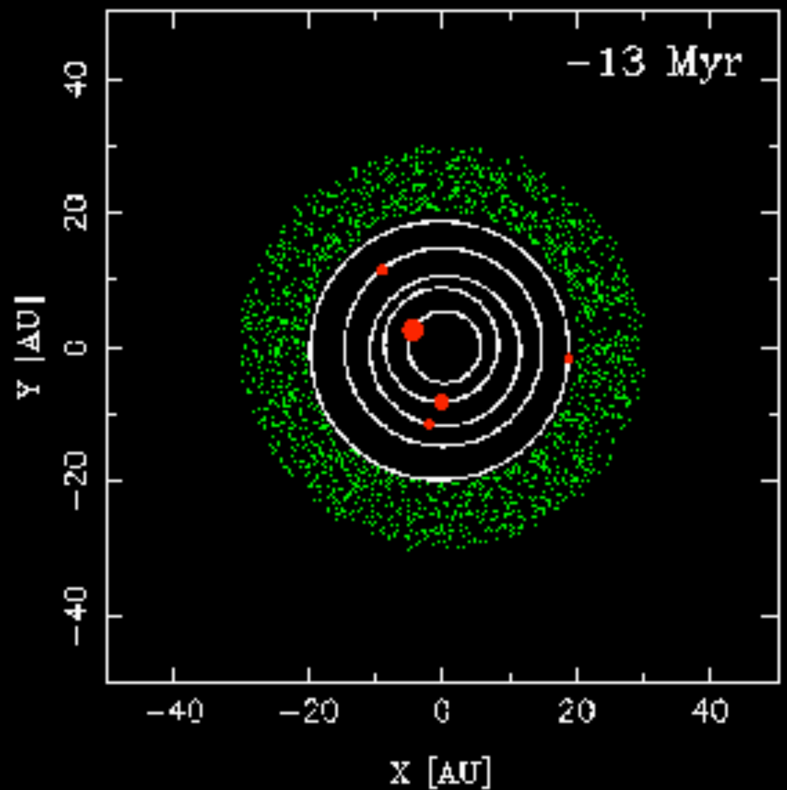
3 possible solutions

Is a narrow annulus of planetesimals realistic?

"Low-mass asteroid belt"

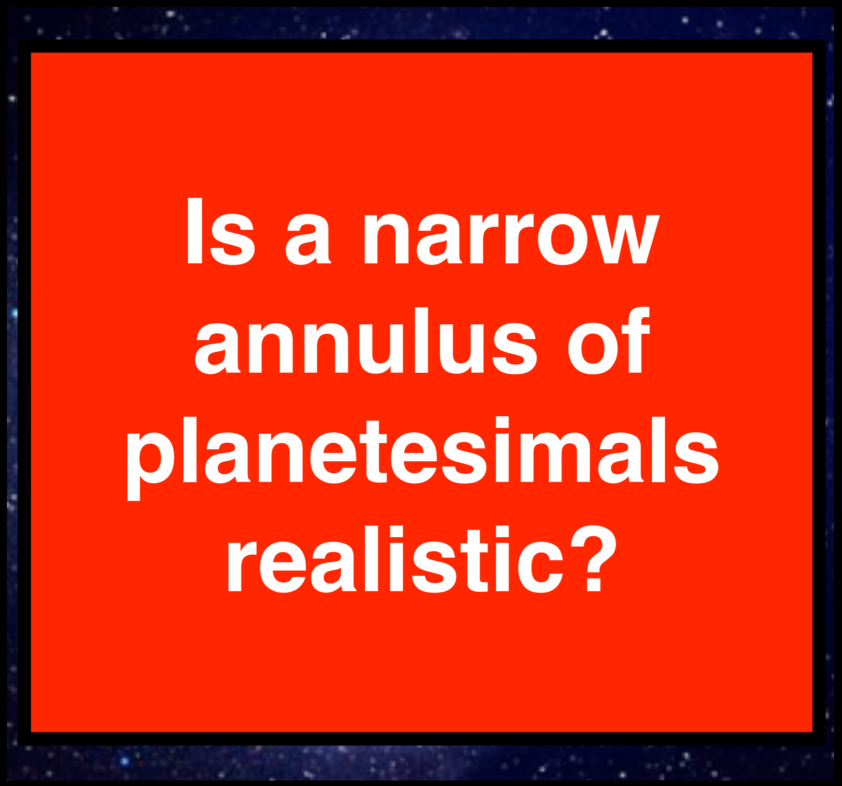
Does outward migration work with gas accetion?

The "Grand Tack"



Early instability

3 possible solutions



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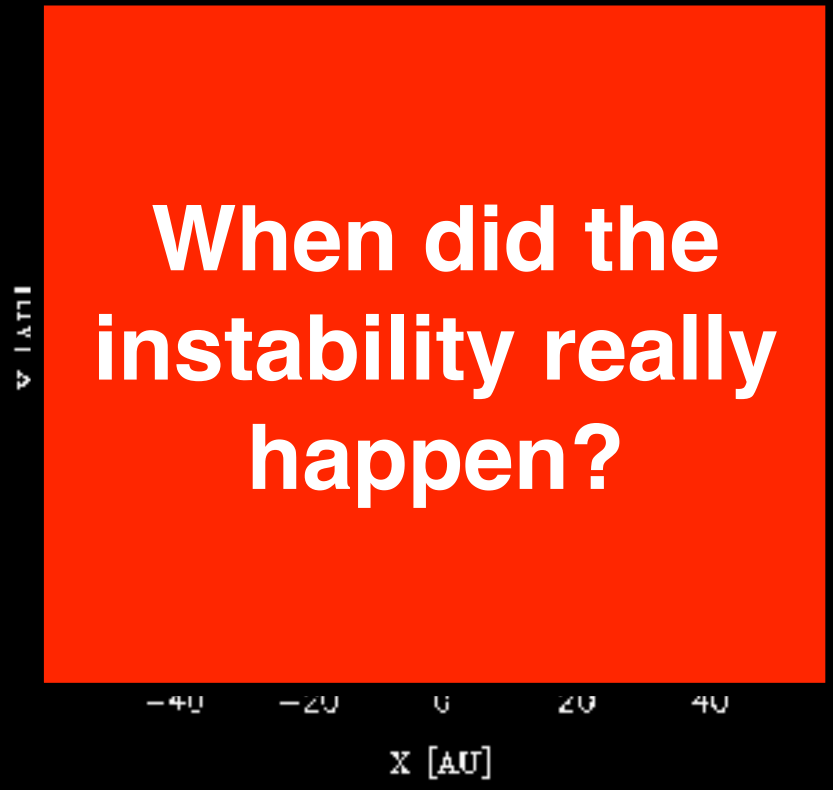
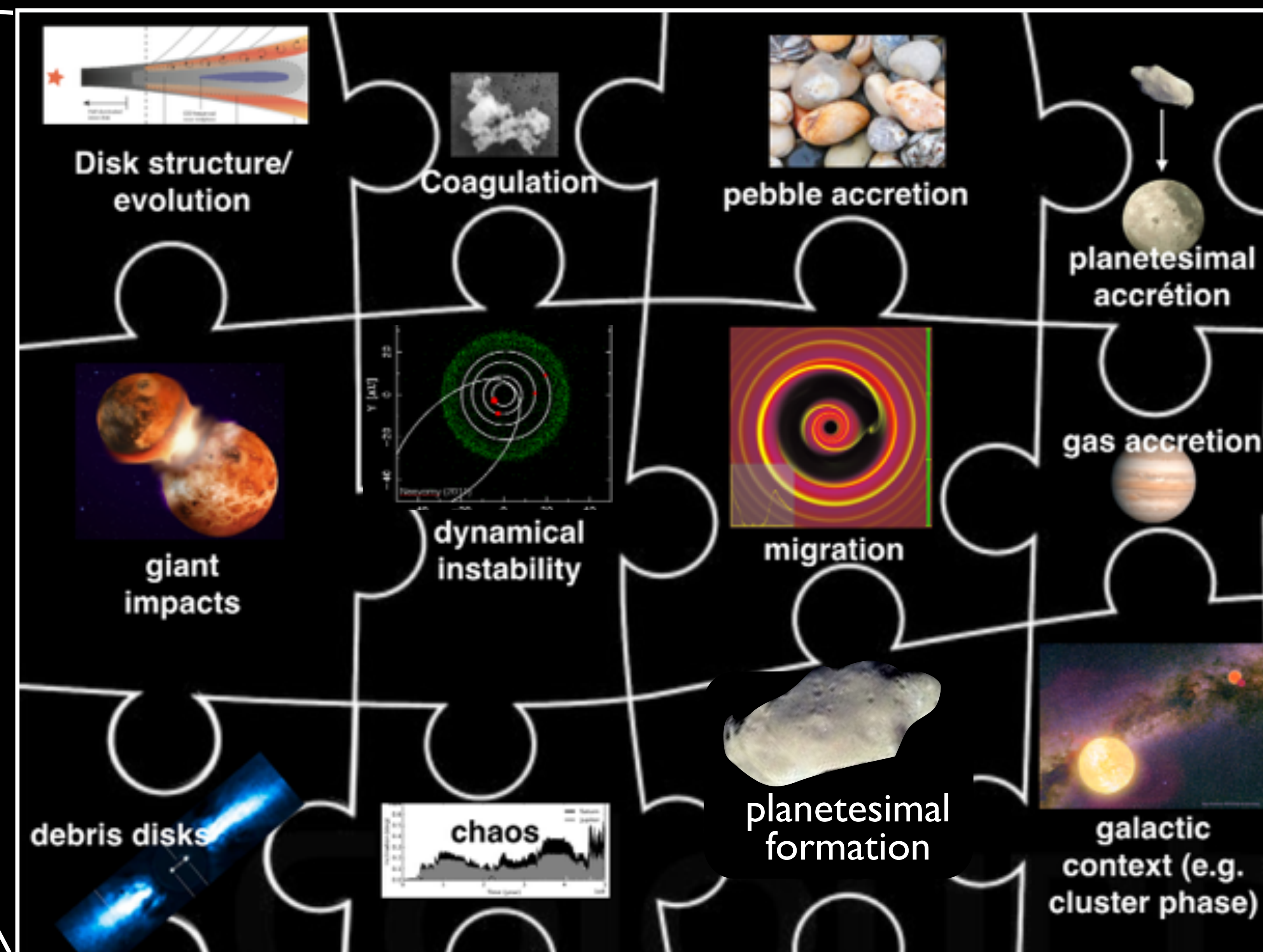


When did the instability really happen?

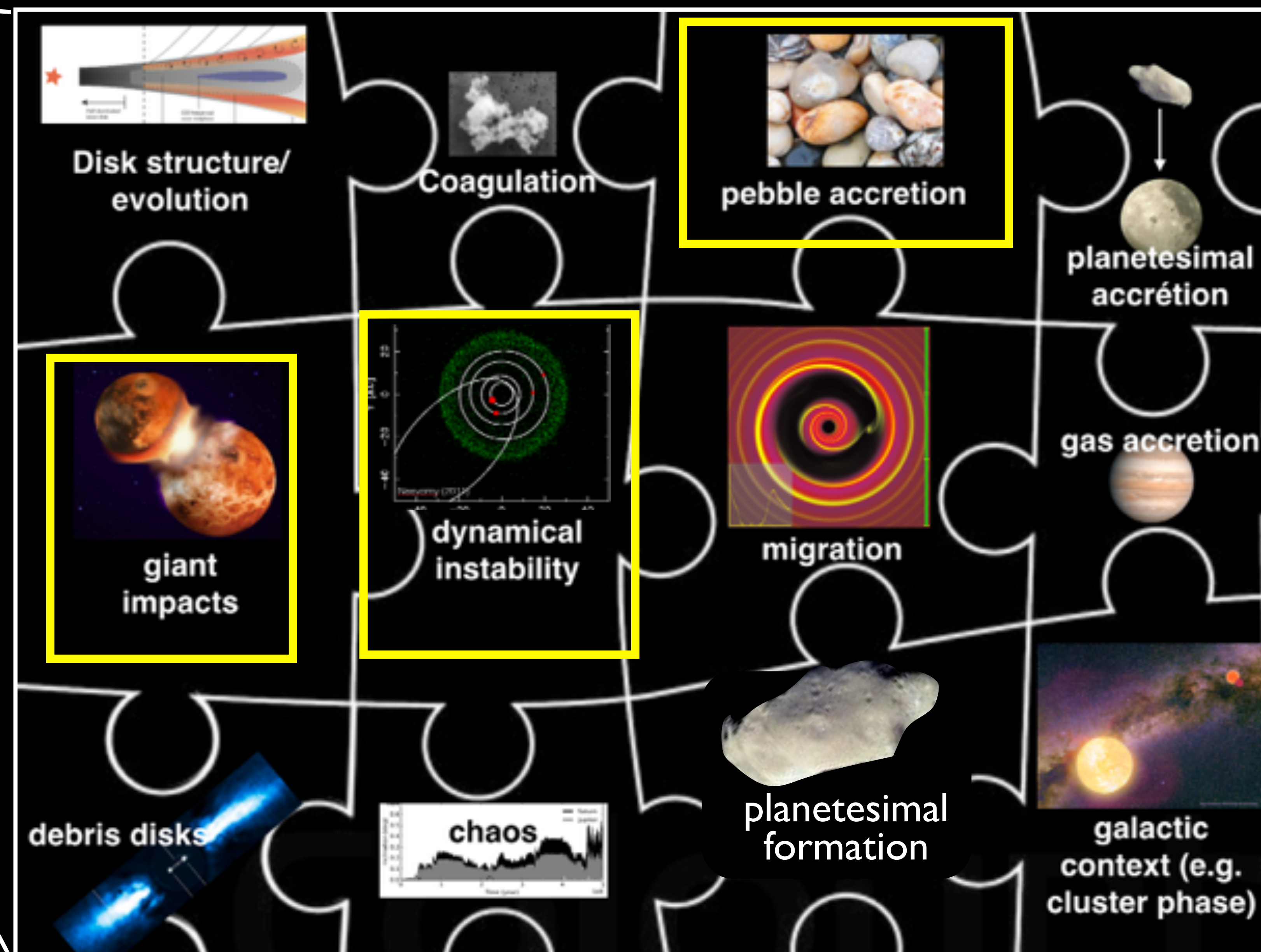
Early instability

Mudpuppy puzzles, ages 5-9



Key pieces

Mudpuppy puzzles, ages 5-9



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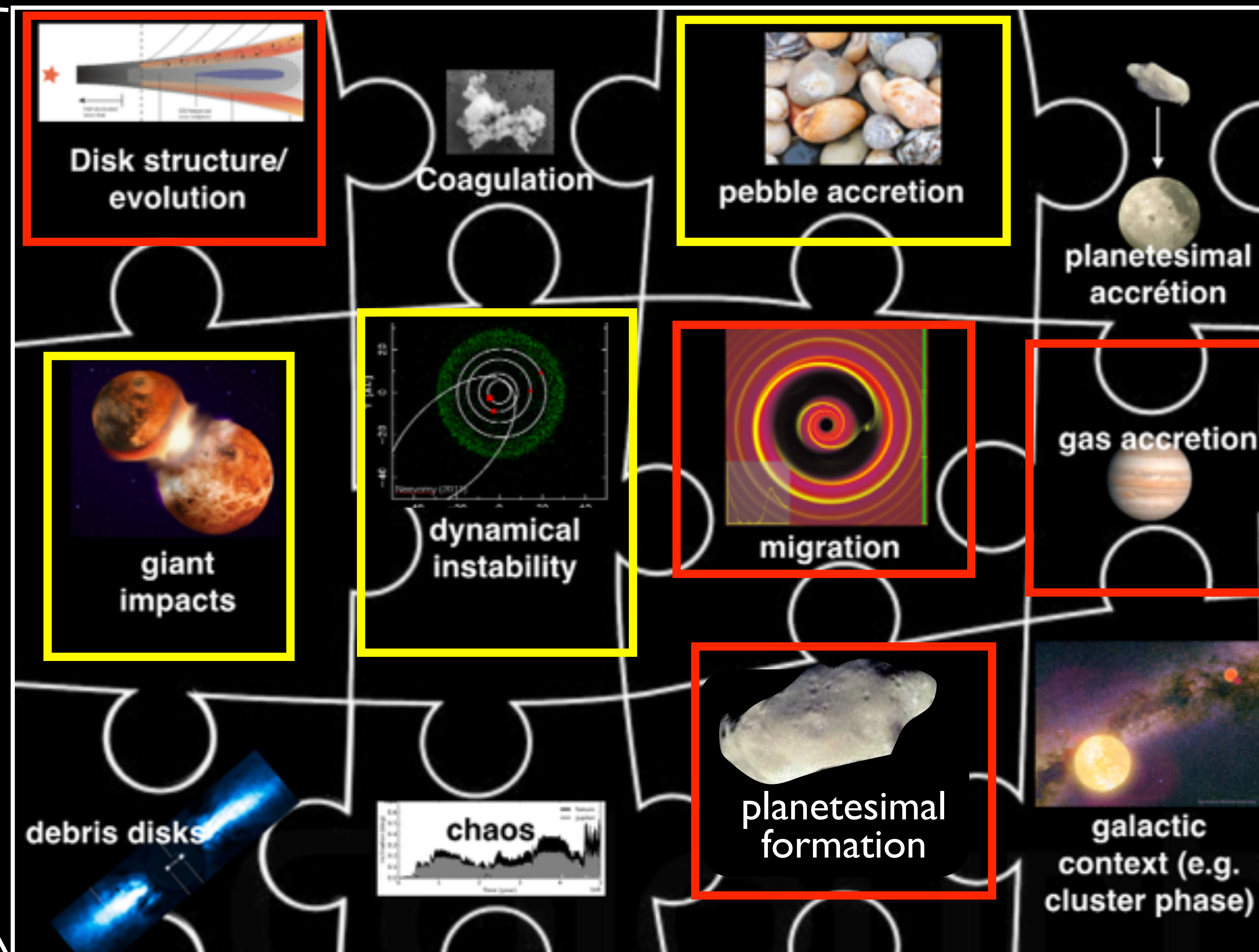


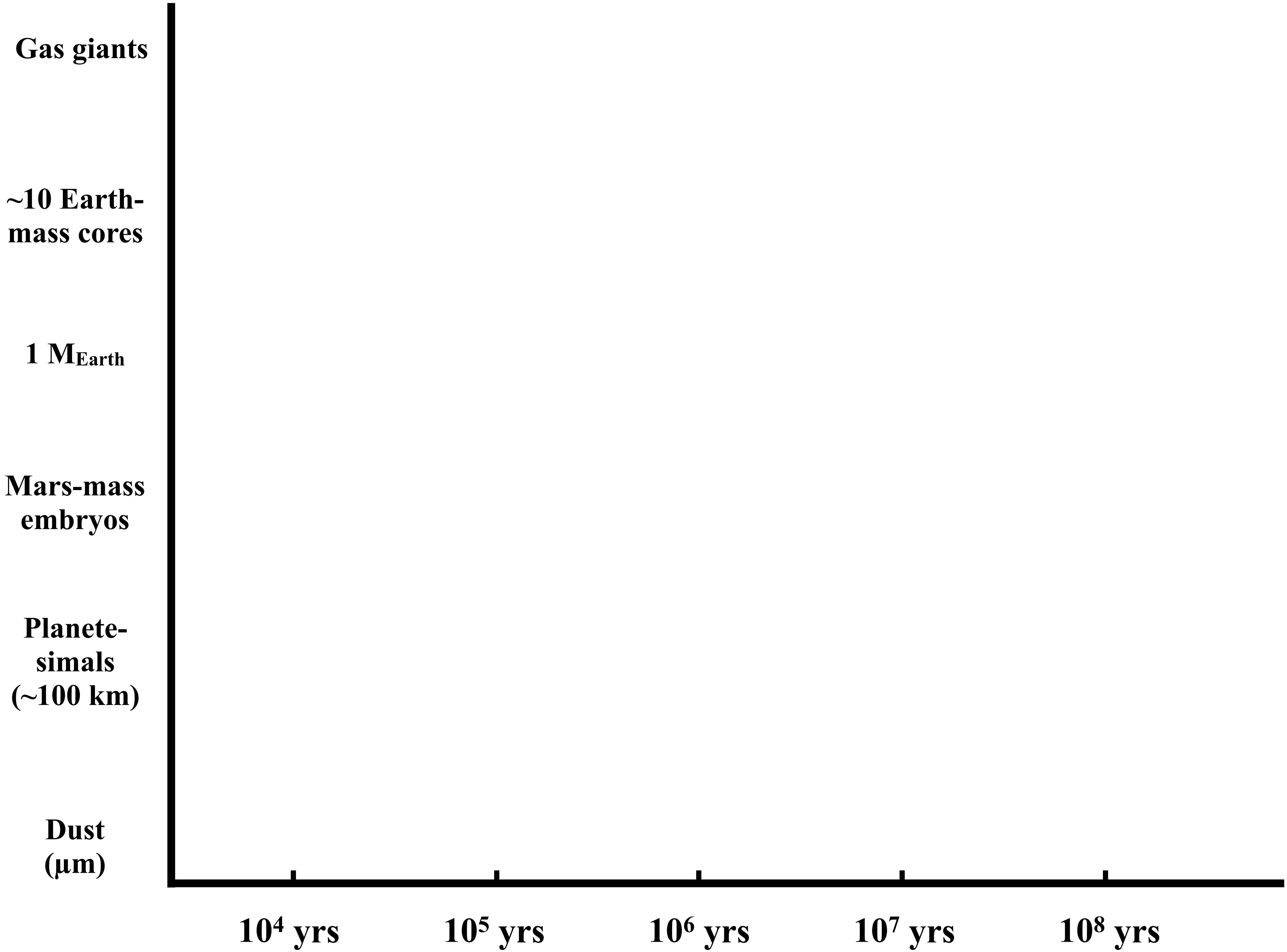
Uncertain but super important

More information

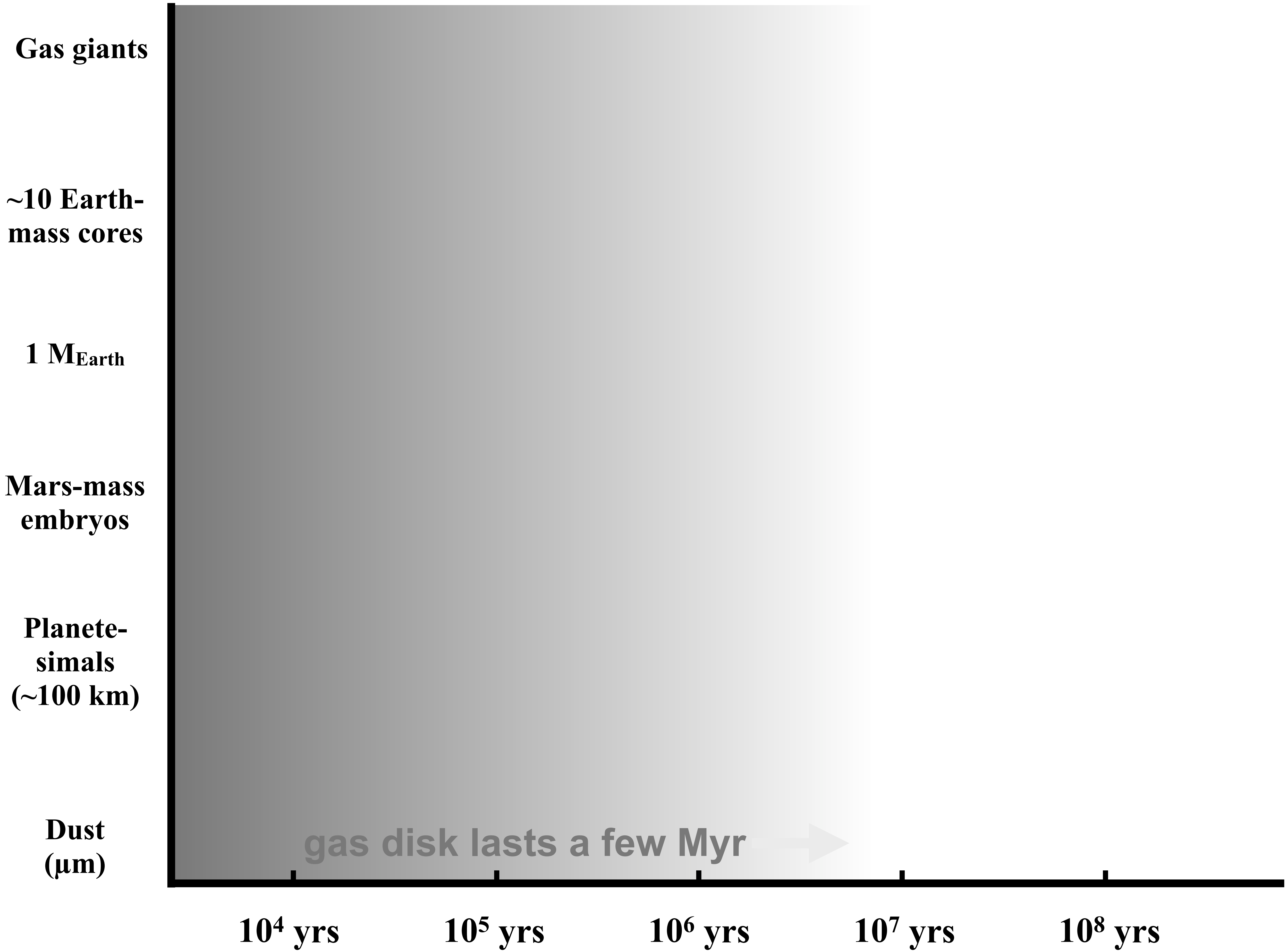
- *Solar System formation in the context of extra-solar planets*
  Raymond, Izidoro, & Morbidelli 2018 (*arxiv:1812.01033*)
- MOJO videos (YouTube)

- <u>planetplanet.net</u>

Extra Slides



Gas giants
~10 Earth-mass cores
1 M Earth
Mars-mass embryos
Planete-simals (~100 km)
Dust (µm)
10^4 yrs
10^5 yrs
10^6 yrs
10^7 yrs
10^8 yrs


Gas giants
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Planete-simals (~100 km)
Dust (µm)
gas disk lasts a few Myr
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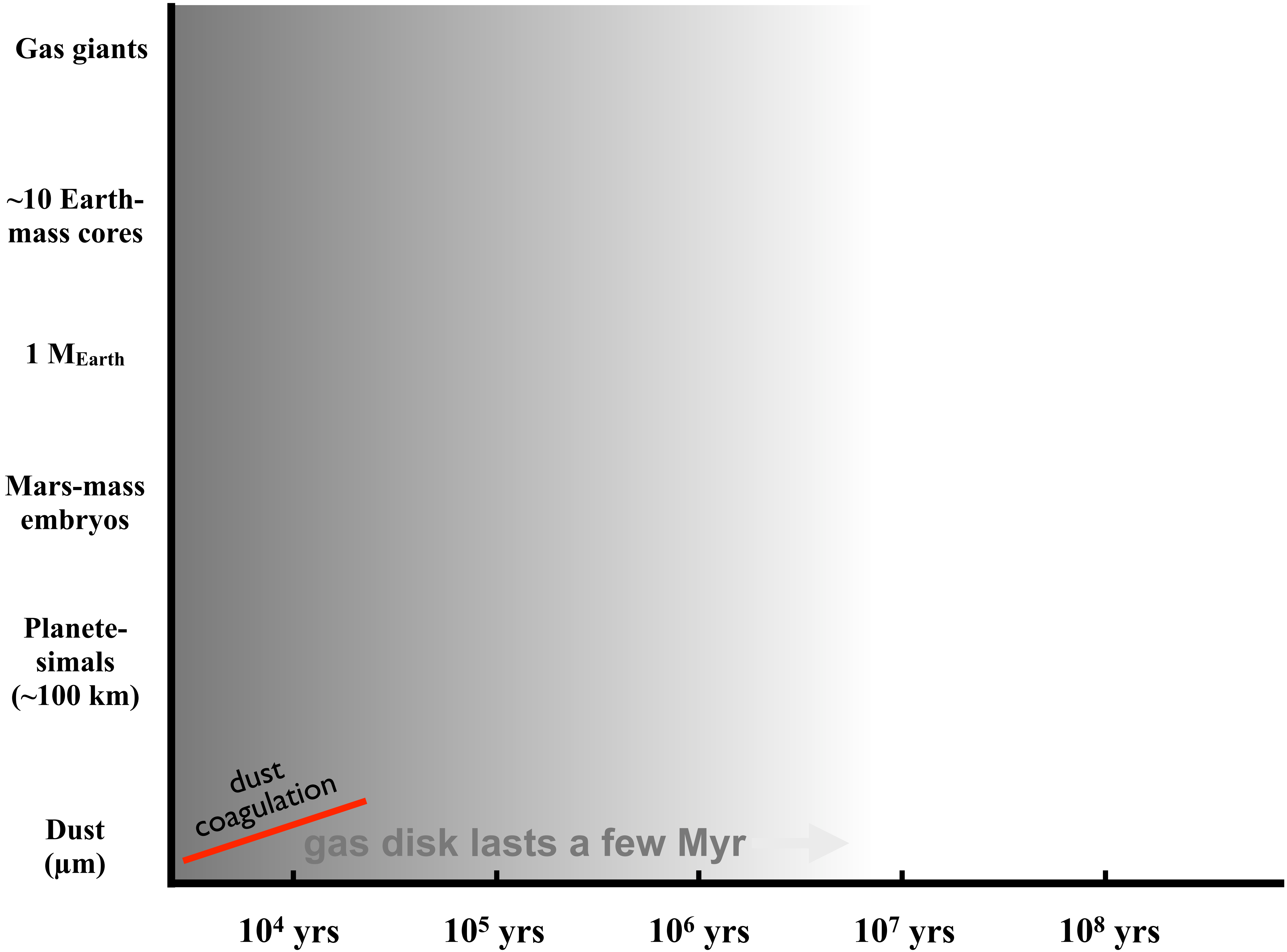
10^7 yrs
10^8 yrs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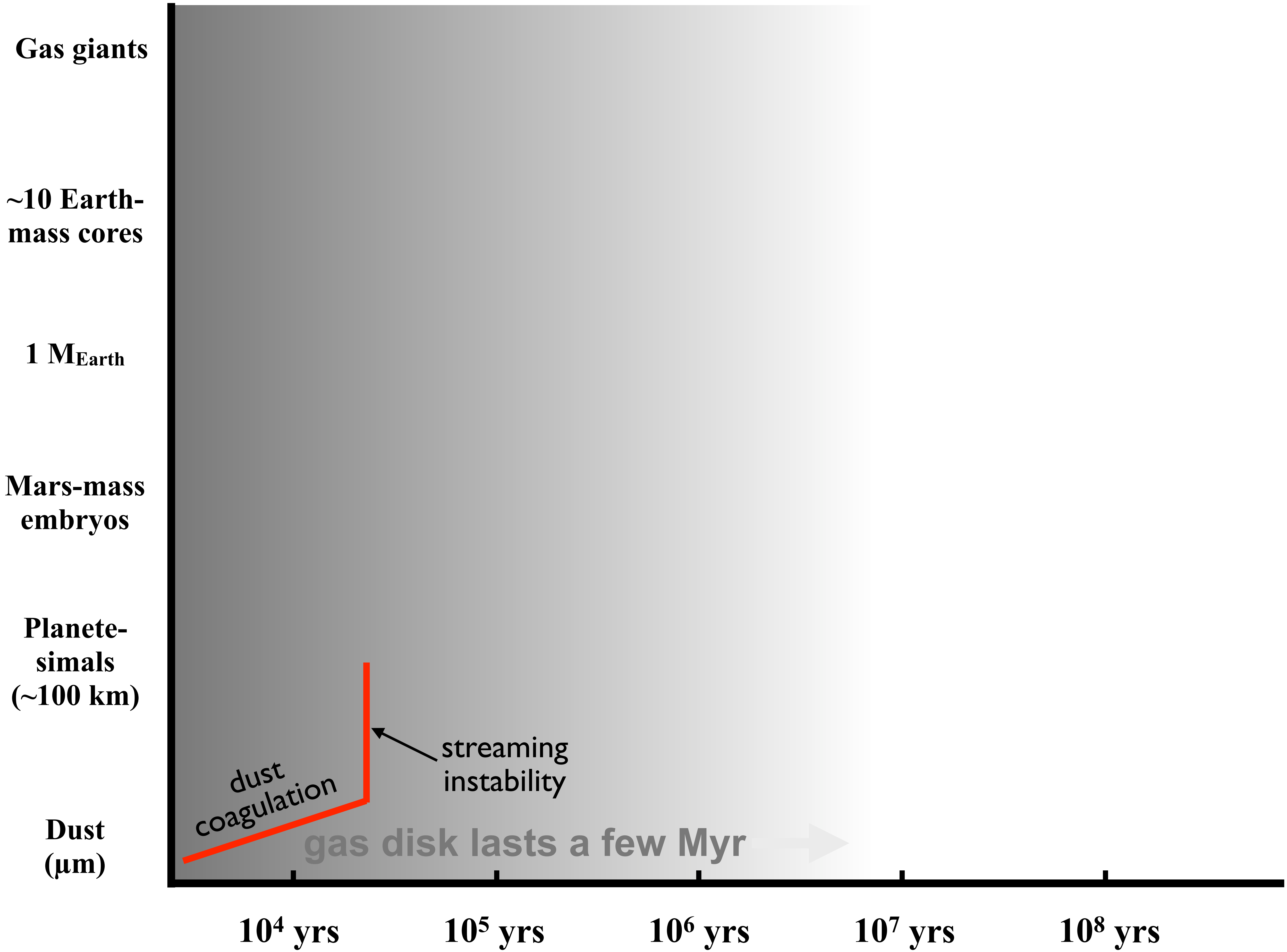

Gas giants
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Mars-mass embryos
Planete-simals (~100 km)
Dust (µm)
dust coagulation
streaming instability
gas disk lasts a few Myr
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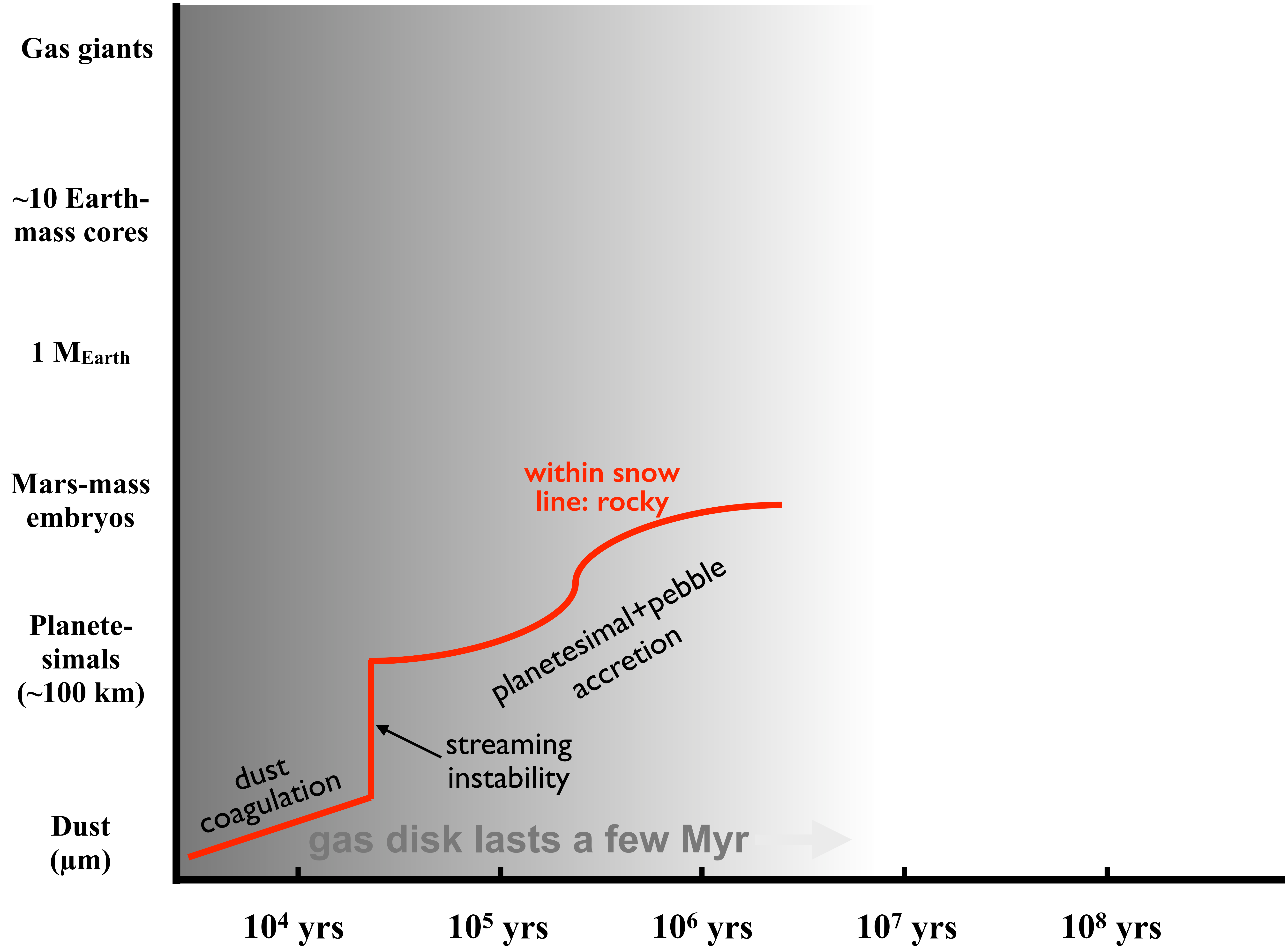
10^8 yrs



Gas giants
~10 Earth-mass cores
1 MEarth
Mars-mass embryos
Planete-simals (~100 km)
Dust (µm)
within snow line: rocky
planetesimal+pebble accretion
streaming instability
dust coagulation
gas disk lasts a few Myr
10^4 yrs
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10^6 yrs
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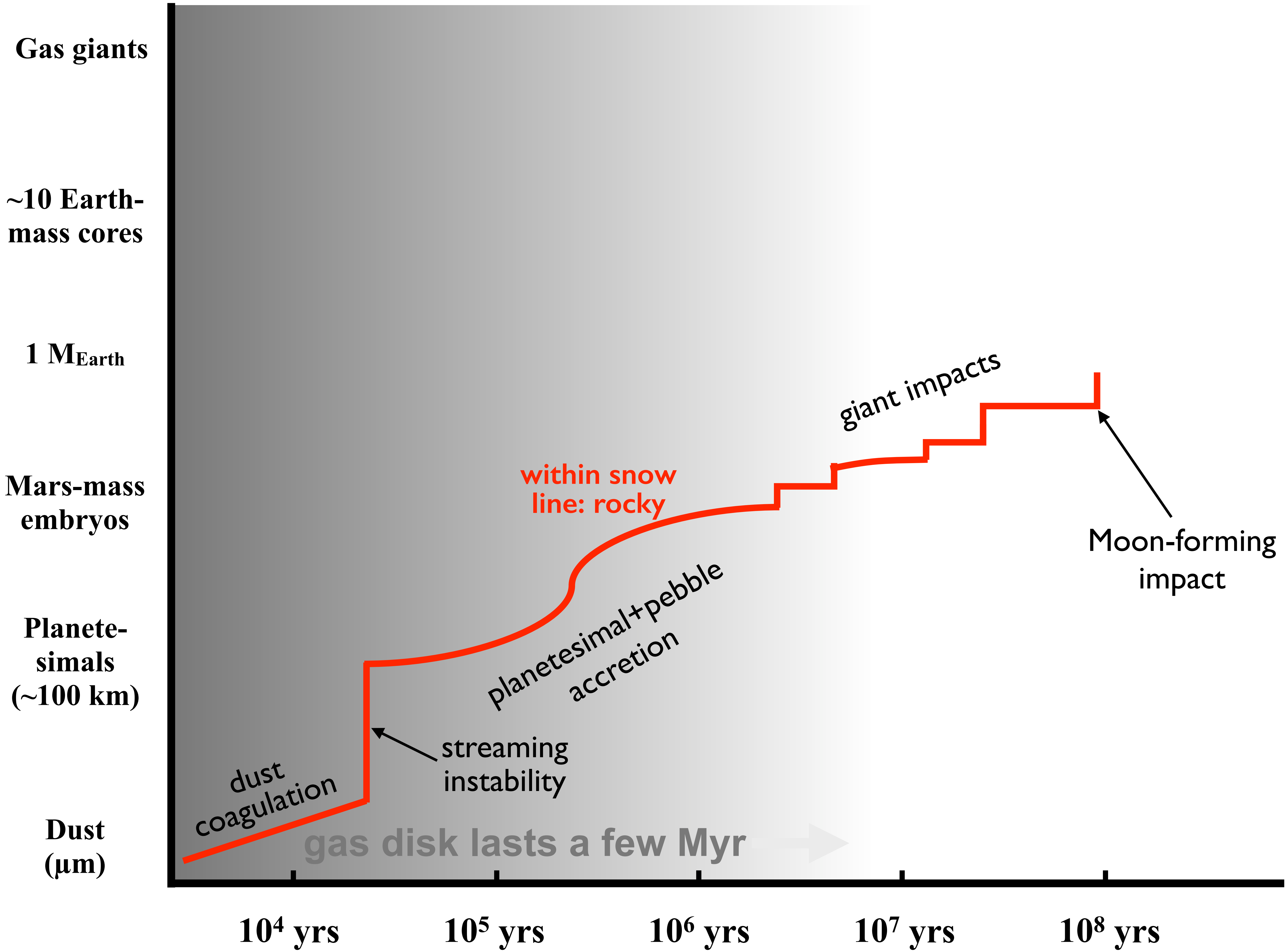
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Moon-forming impact
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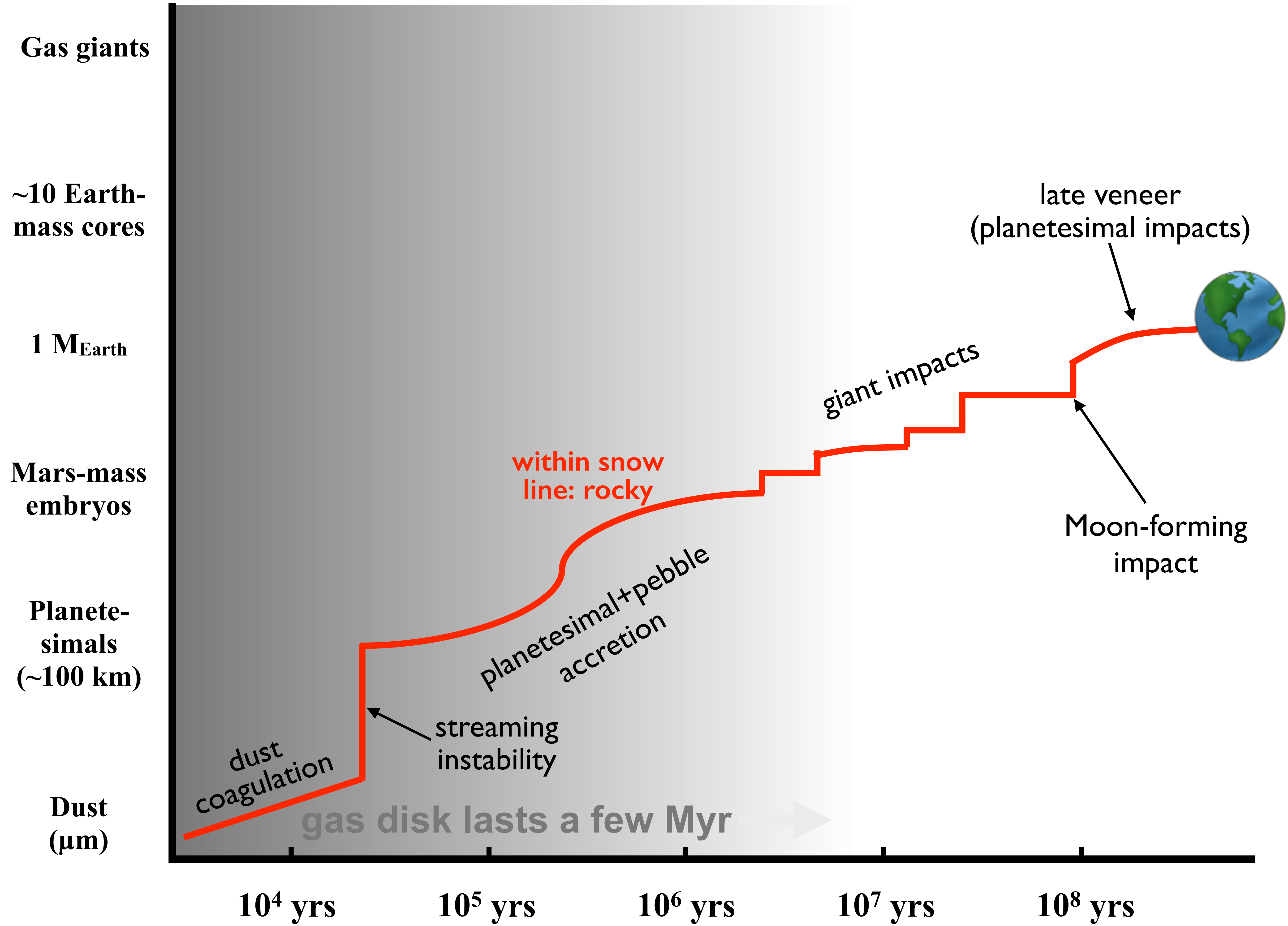
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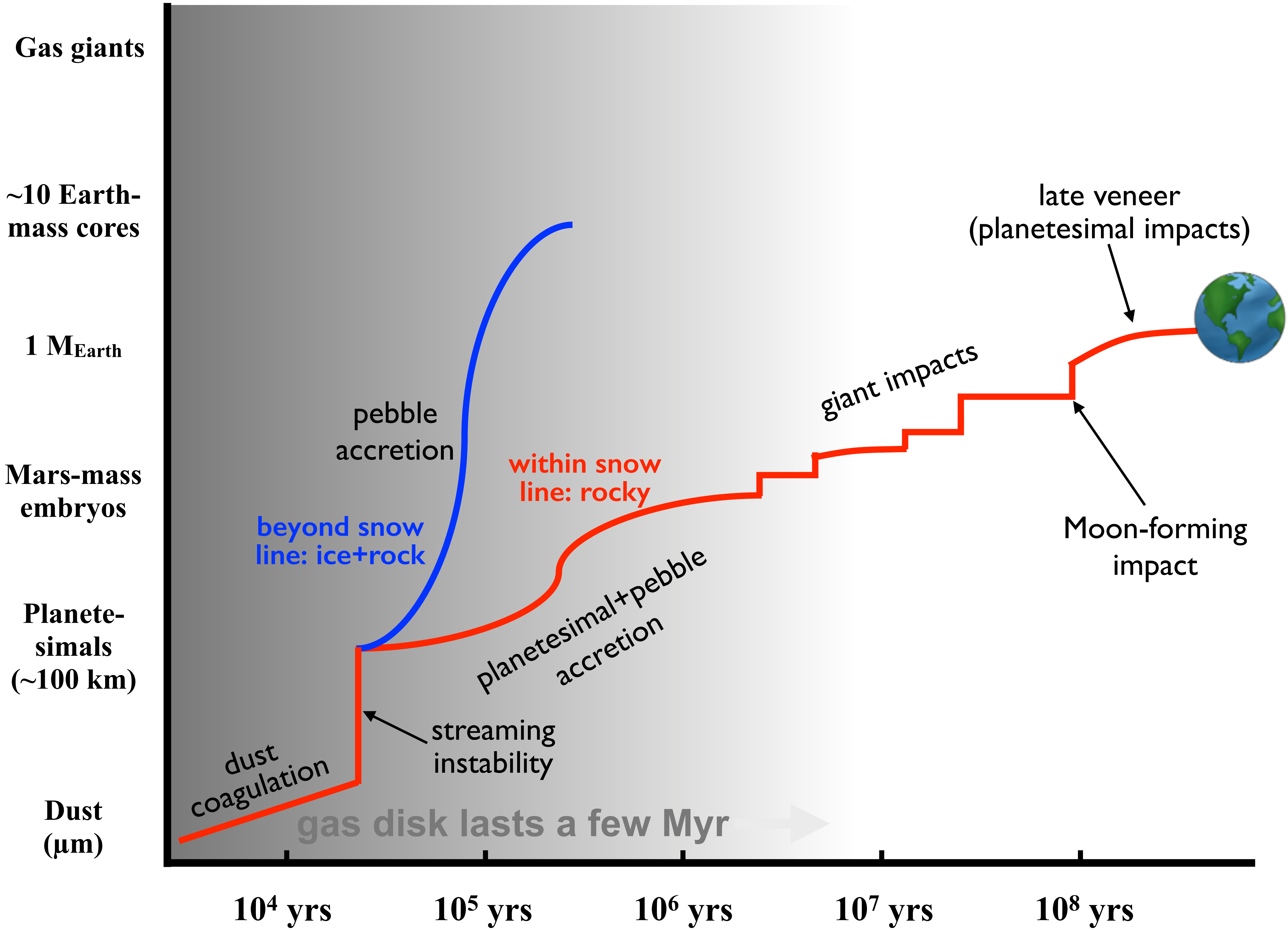
late veneer (planetesimal impacts)
Moon-forming impact
gas disk lasts a few Myr
10⁴ yrs
10⁵ yrs
10⁶ yrs
10⁷ yrs
10⁸ yrs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within snow line: rocky
beyond snow line: ice+rock
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streaming instability
dust coagulation
gas disk lasts a few Myr
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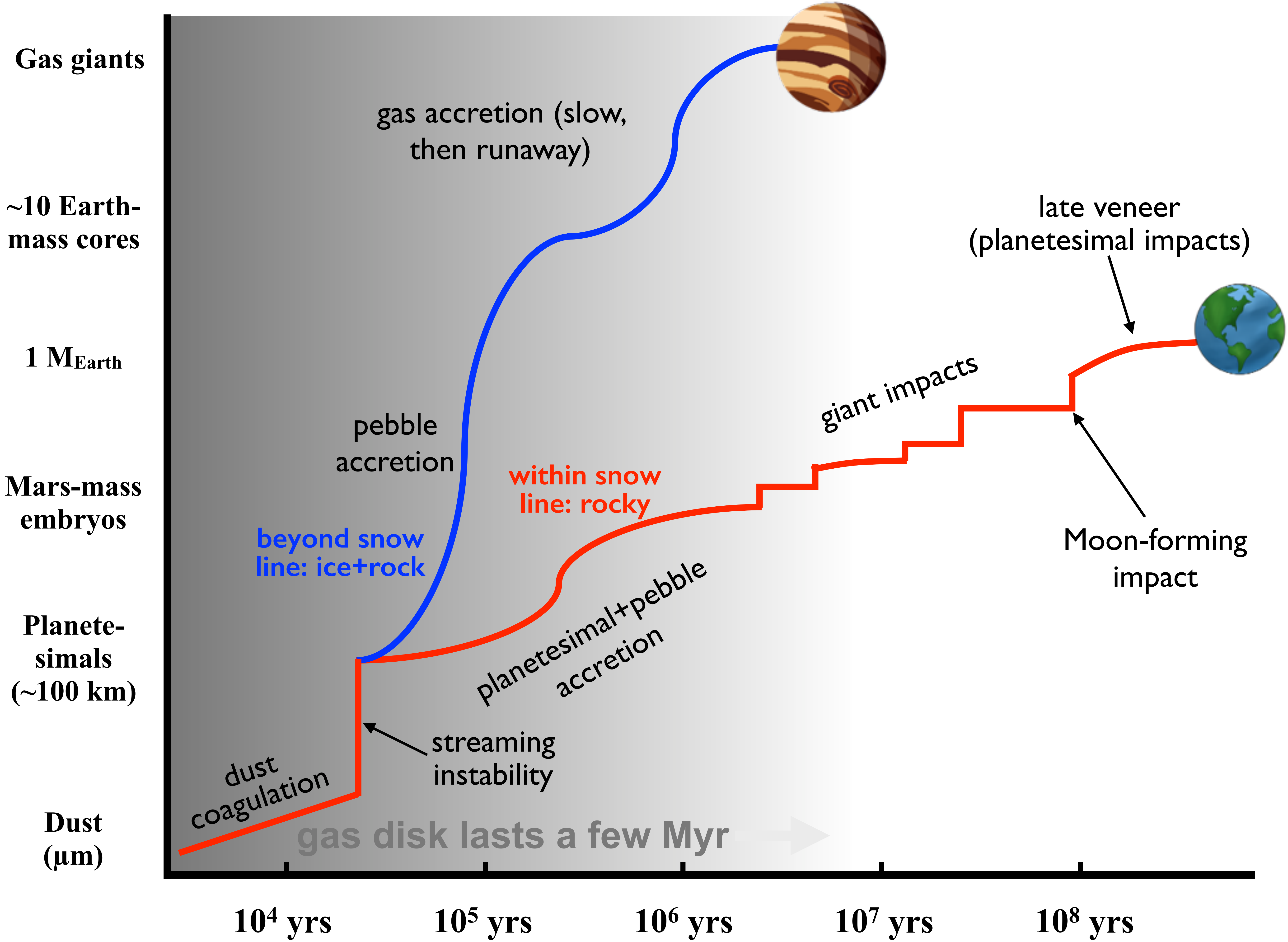
Gas giants
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Mars-mass embryos
Planetesimals (~100 km)
Dust (µm)
gas accretion (slow, then runaway)
pebble accretion
beyond snow line: ice+rock
within snow line: rocky
planetesimal+pebble accretion
giant impacts
late veneer (planetesimal impacts)
Moon-forming impact
streaming instability
dust coagulation
gas disk lasts a few Myr
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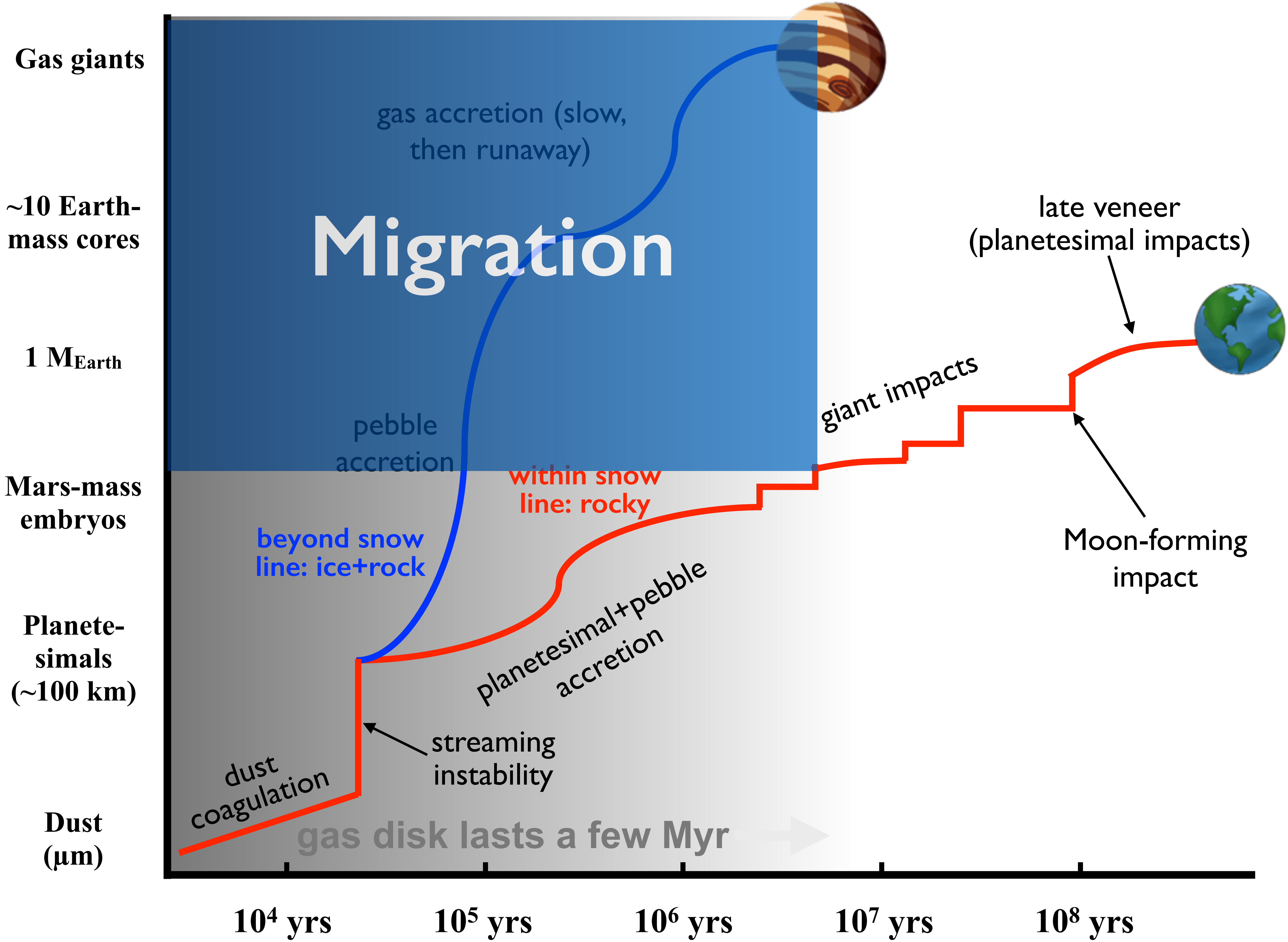
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within snow line: rocky
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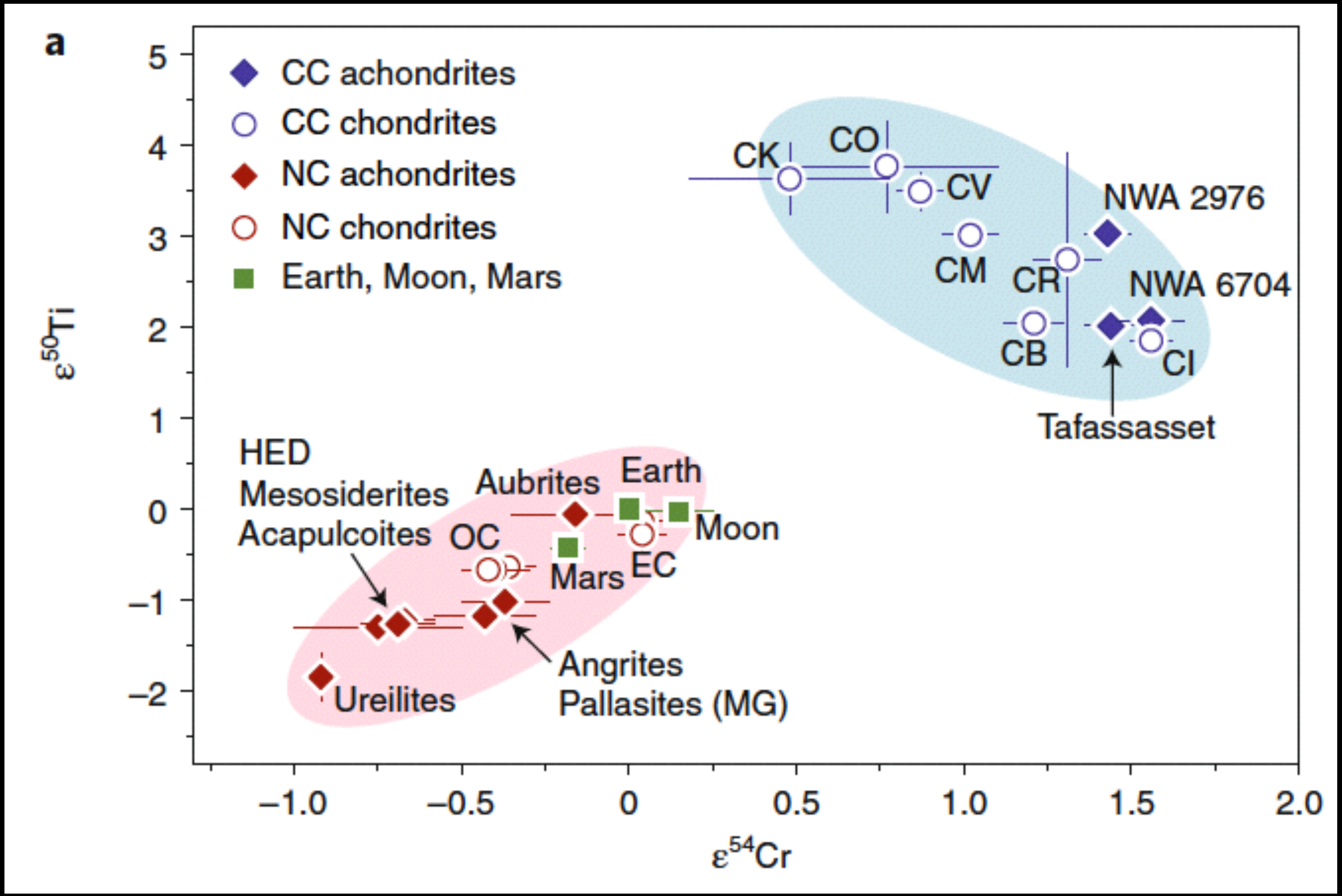
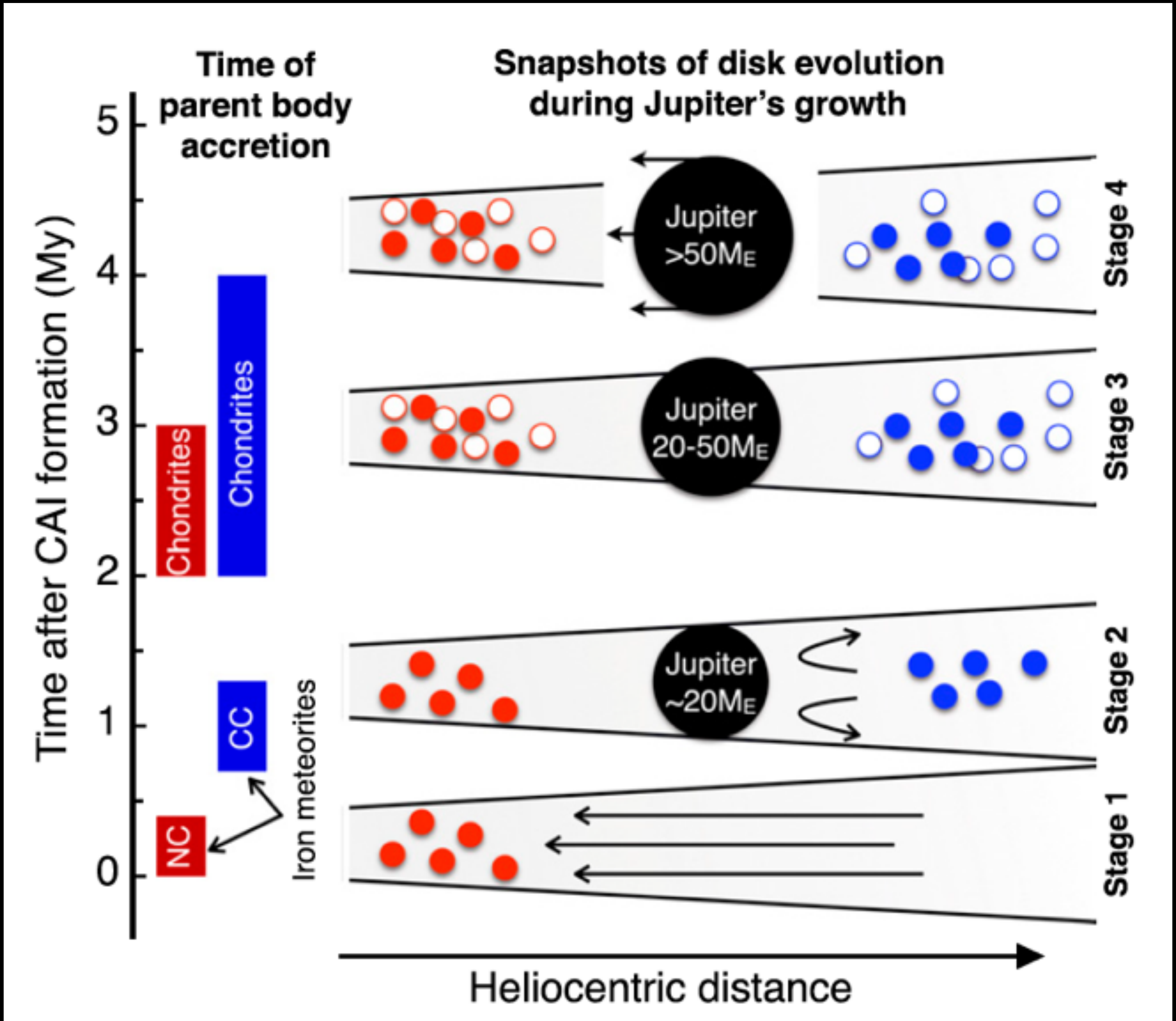
Meteorites can be broken in two classes: carbonaceous and non-carbonaceous



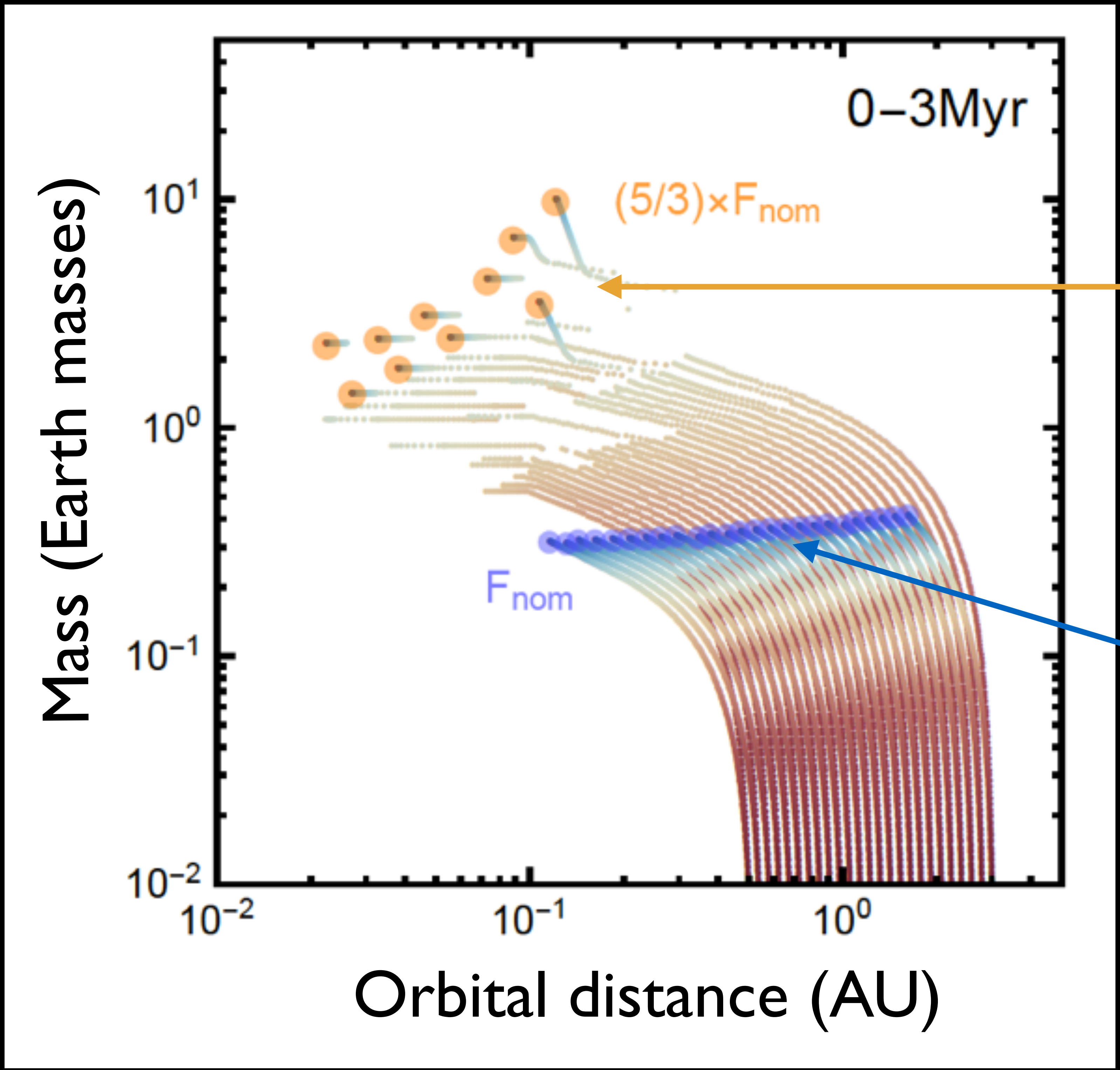
Kruijer et al (2017, 2020); after Warren (2011) and others.

Meteoritic evidence for early growth of Jupiter's core



Kruijer et al (2017)

What if the pebble flux into inner Solar System was not blocked?

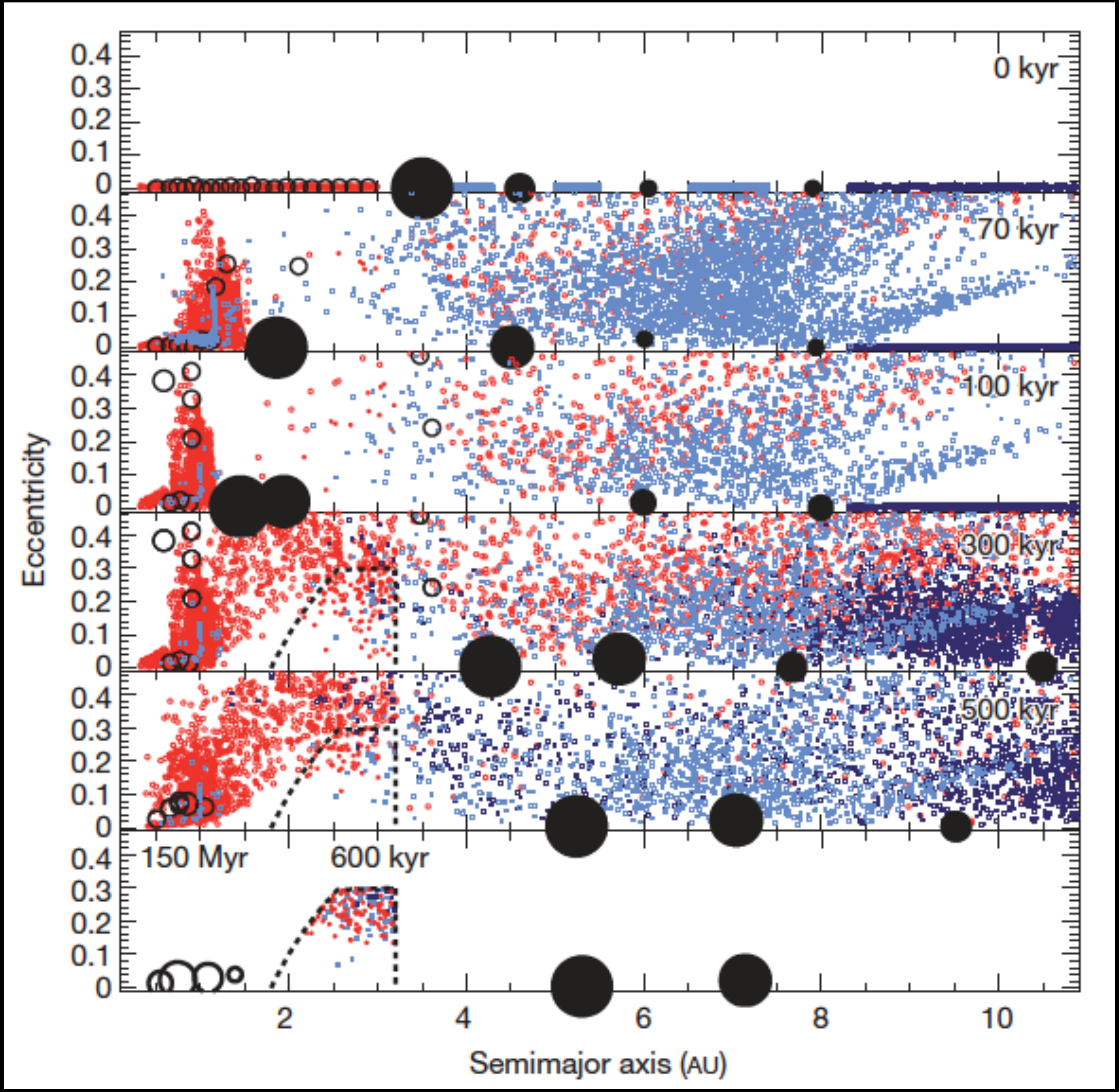


Continuous pebble flux: **super-Earths**

Pebble flux blocked: **terrestrials**

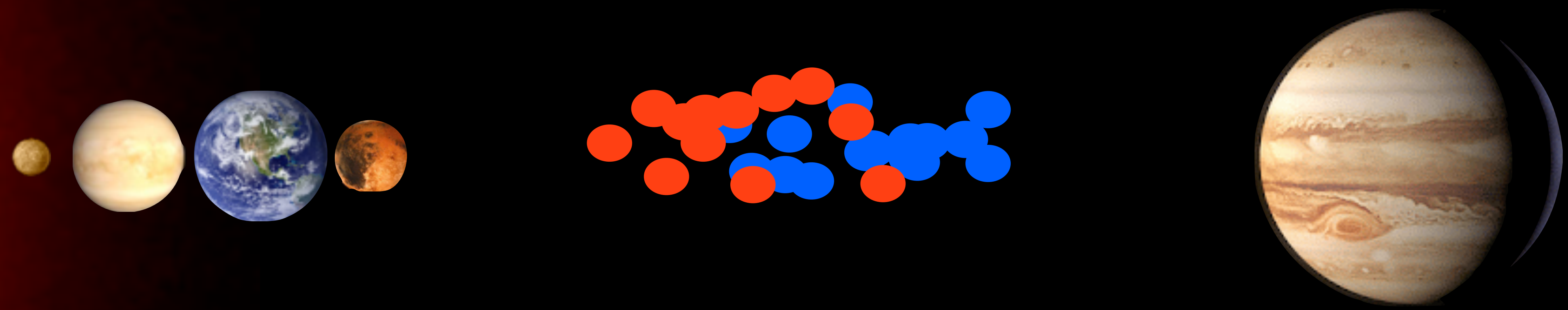
Lambrechts et al (2019)

The Grand Tack



Walsh et al 2011

Chaotic excitation of the asteroid belt



Izidoro et al (2016)

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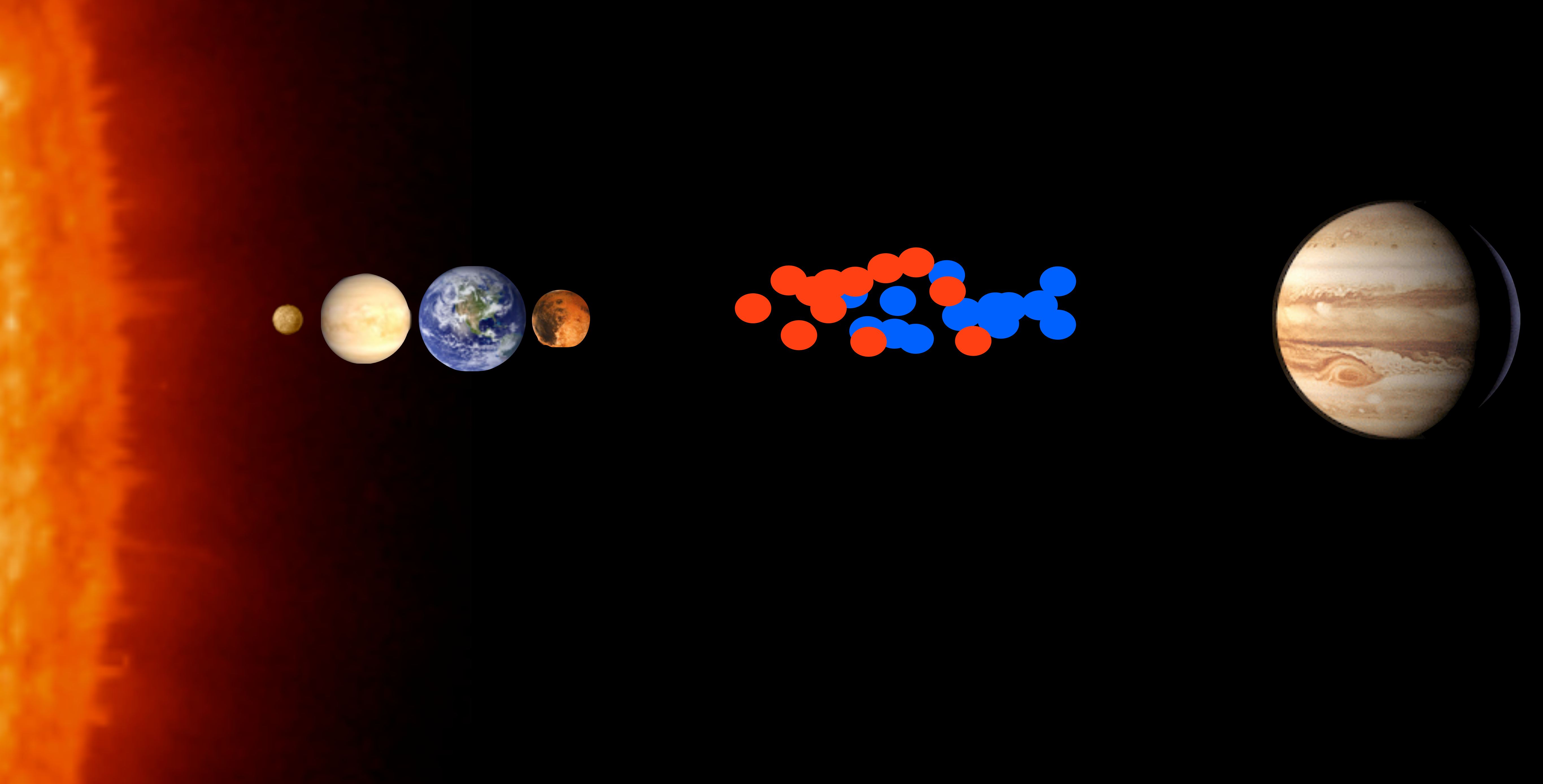
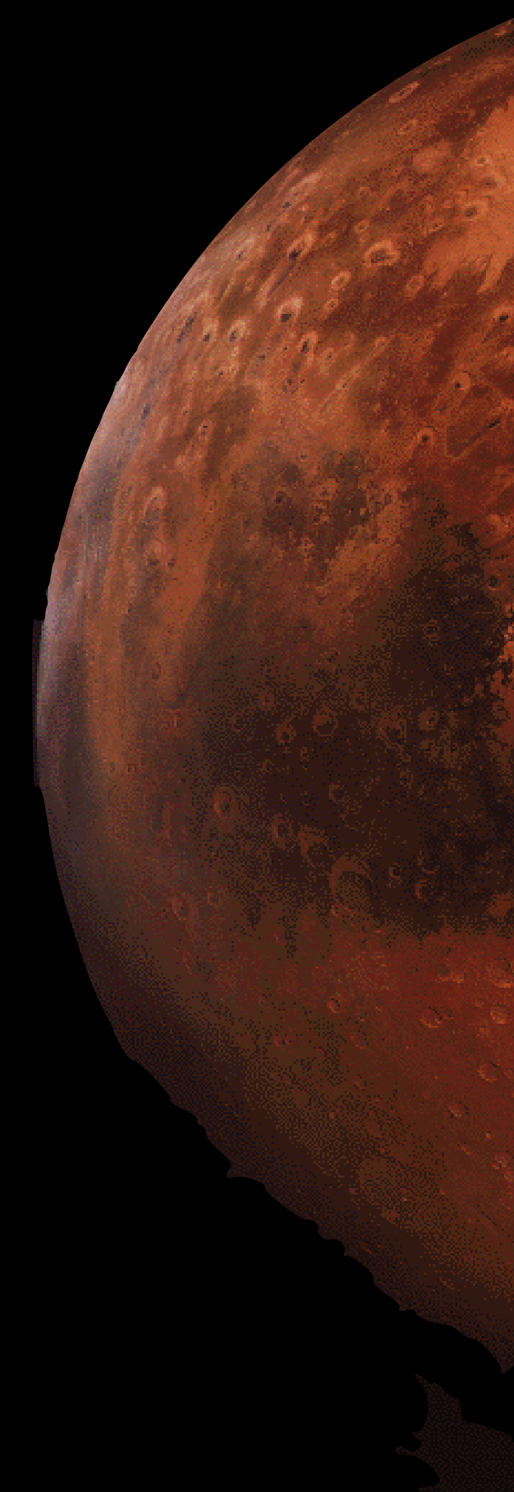
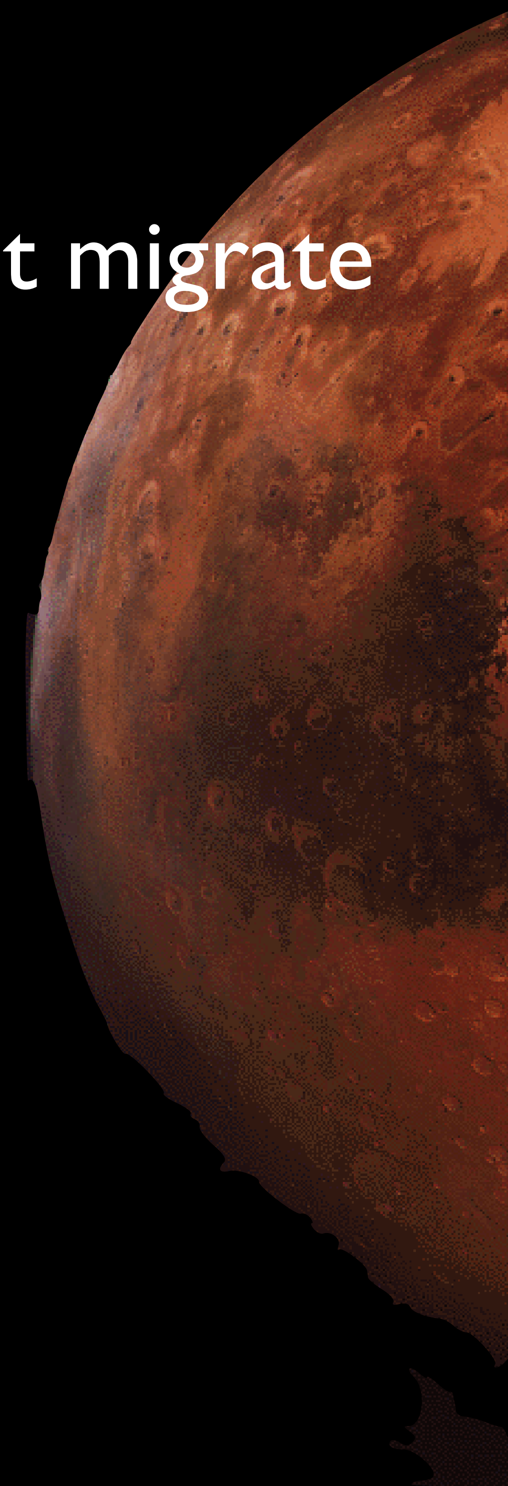


Izidoro et al (2016)

Unsolved mysteries



Unsolved mysteries



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- When did instability happen, and what was the trigger?
- What's up with Mercury anyway?