要旨

「“惑星形成論の現状”と“太陽系内の物質輸送”」

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惑星系の形成過程を考える場合、次の３つの進化段階に大別できる – (i) 原始惑星系円盤内でのダストから微惑星への初期の成長過程、(ii) 微惑星から惑星までの後期の集積進化過程（主に重力で支配される）、(iii) 数十億年をかけた secular な進化段階。

太陽系においては、これまで観測的アプローチによって積み重ねてきた膨大な研究成果が存在し、太陽系小天体の質量-軌道-化学情報の分布（例えば、小惑星帯からカイパーベルト天体）が明らかになってきている。

一方、上述の後期の集積進化段階（ステージ ii）において、様々な太陽系小天体が持つローカルな“小規模構造分布”（例えば、軌道長半径-離心率-軌道傾斜角のローカル分布）を可能な限り同時に（一つのモデルで）説明するためには、ある特定の微惑星（小天体の母天体とする）の初期分布（軌道、サイズ、および総質量など）が必要であるということが数値計算的アプローチにより示唆されている。

しかし一方で、“微惑星がどのように形成されるのか？”、“形成される初期微惑星分布は後期の集積進化段階が要求するものになりうるのか？”という重要な問いに対する答えは明らかになっていない状況である。つまり、原始惑星系円盤内でのダストから微惑星への進化素過程（ステージ i）に対する我々の理解が乏しい現状がある。

原始惑星系円盤におけるダストから微惑星への進化は様々な物理化学プロセスの複雑な絡み合いによって支配されている。これらの理解を包括的に深めるためには、円盤内での局所的な化学的および力学的進化の素過程の理解と同時に、円盤全体の進化を理解し考慮する取り組みが今後はますます重要になると考えられる。

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と
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JAXA

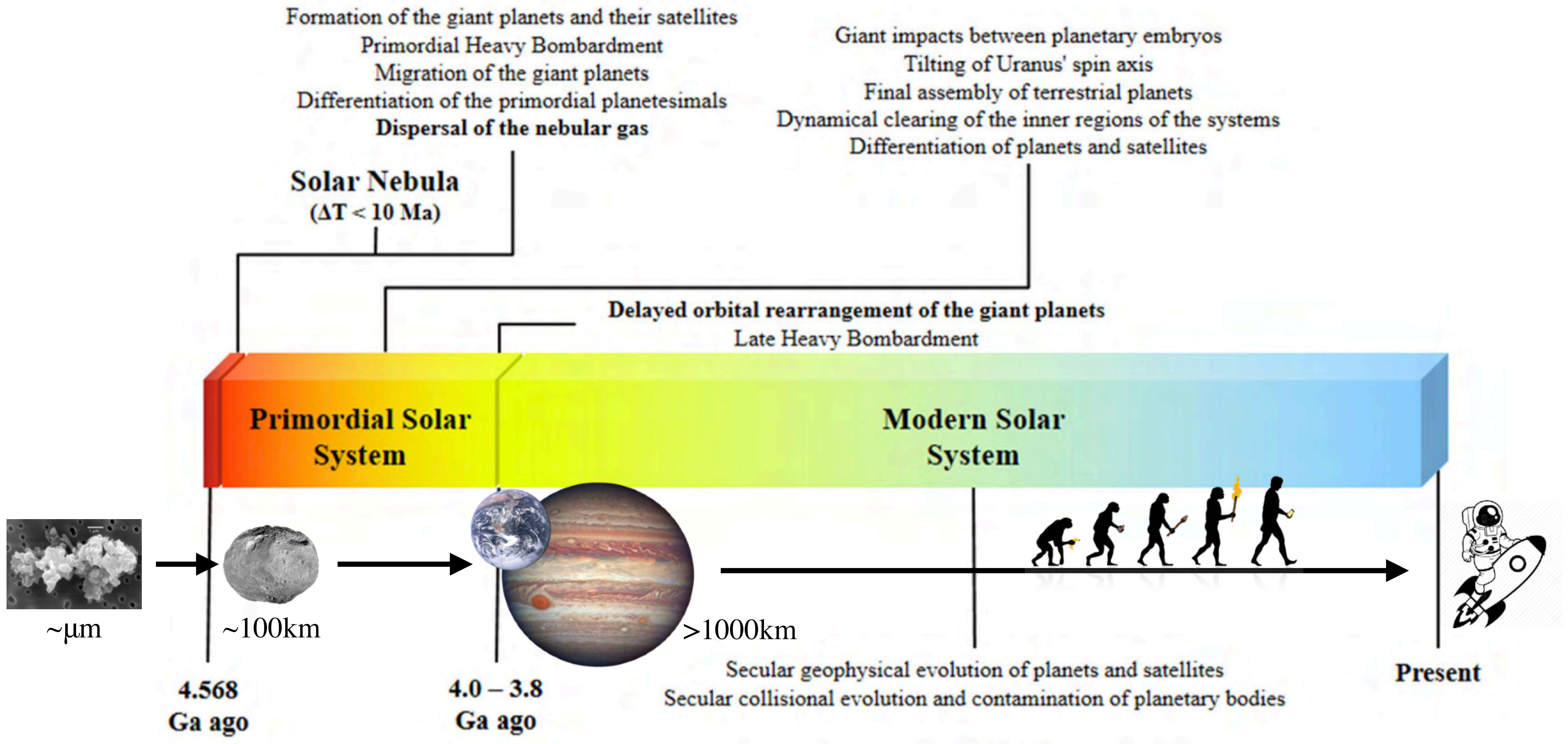
Solar System History

The formation and evolution of the Solar System, chronologically divided into three ages:

1) The Solar Nebula (first <10 Myr)
   dust → planetesimals

2) The Primordial Solar System (before ~4 Ga)
   planetesimals → planets

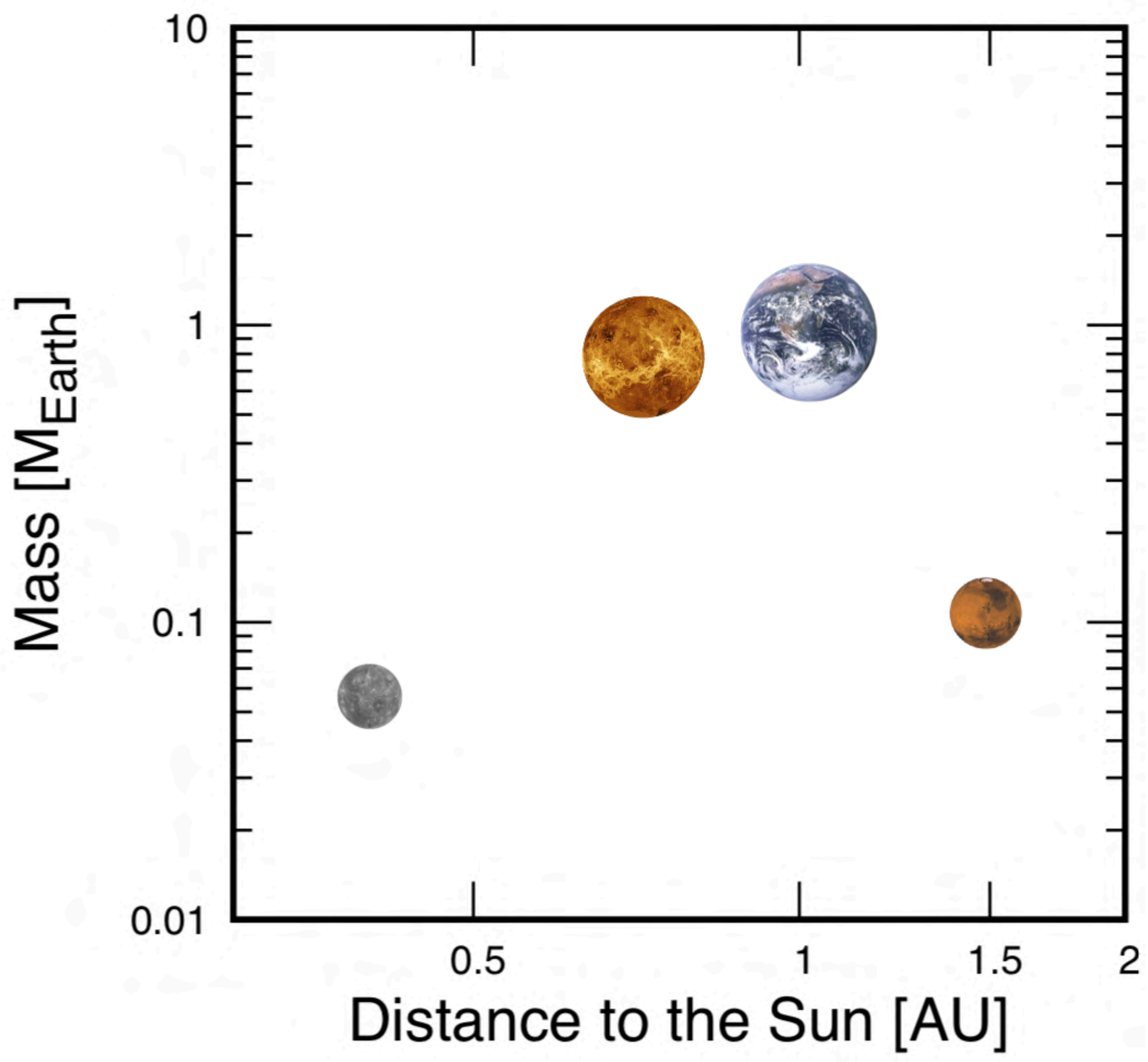
3) The Modern Solar System (after ~4 Ga)
   billion years of secular evolutions



modified from Turrini et al. (2014)

Terrestrial Planets

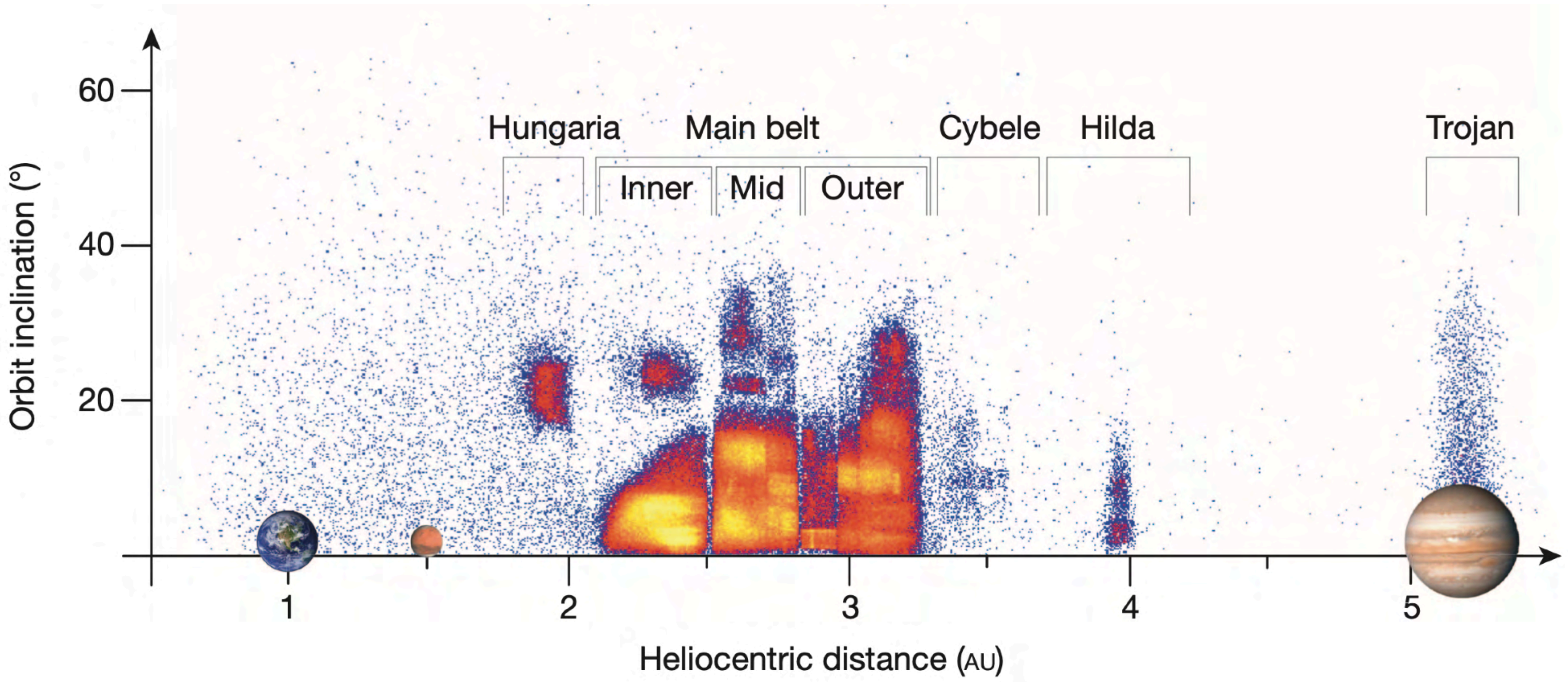
A bimodal mass and narrow localized distributions of the terrestrial planets.



The Asteroid Belt

A dynamically excited structure with a mass of less than one one-thousandth of an Earth mass.

DeMeo & Carry 2014

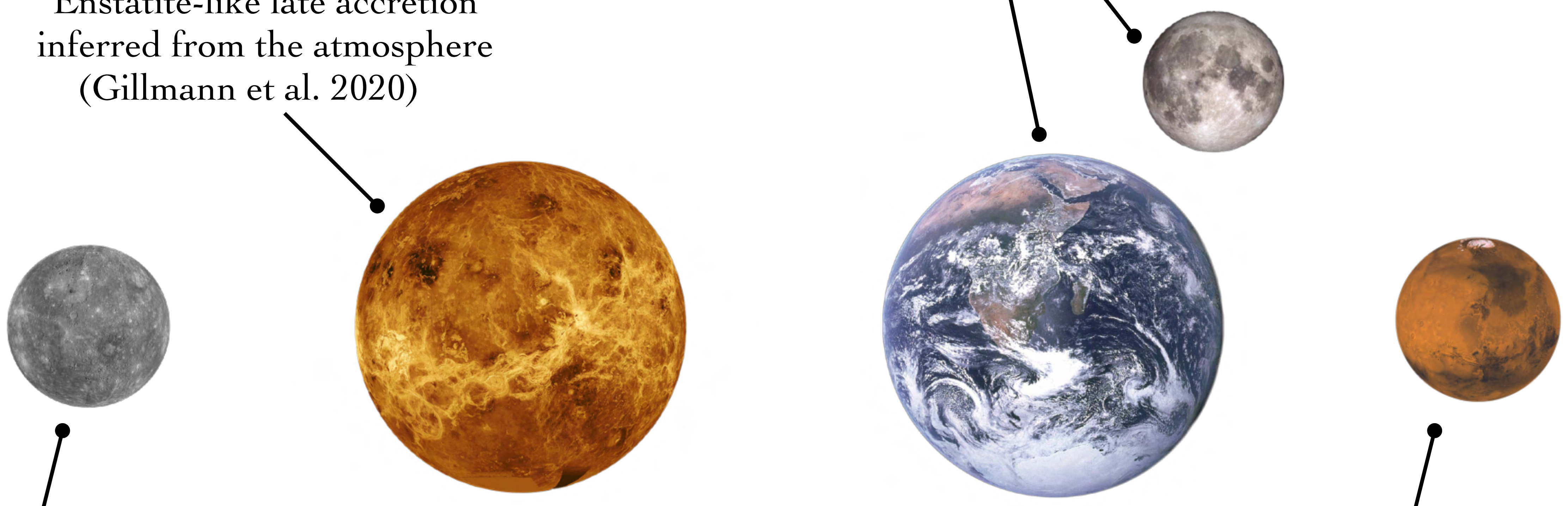


Terrestrial Planets

A bimodal mass and narrow localized distributions of the terrestrial planets.

Isotopically most similar to enstatite chondrites
(Dauphas, 2017; Fischer-Gödde & Kleine, 2017)

Enstatite-like late accretion
inferred from the atmosphere
(Gillmann et al. 2020)



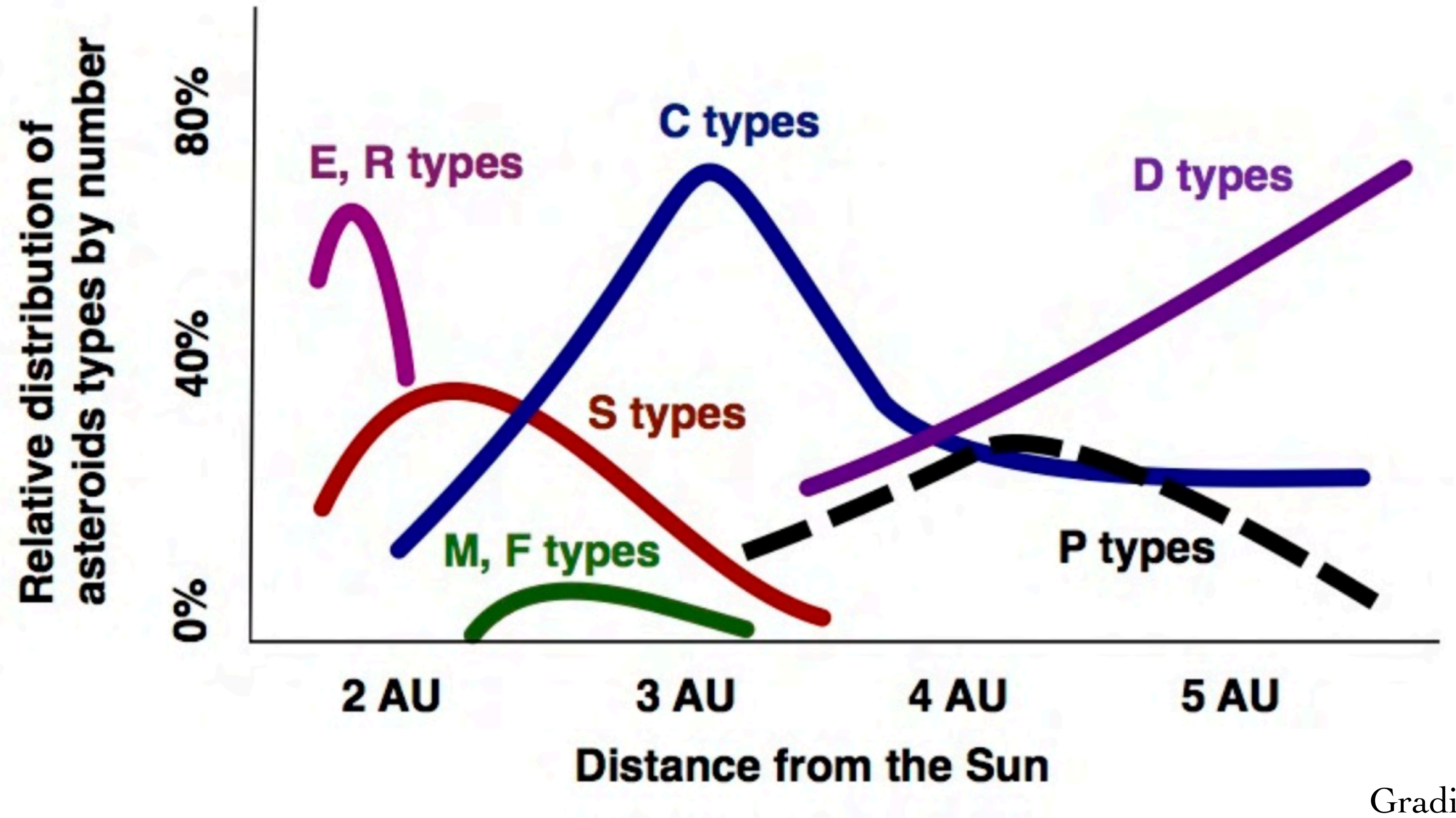
Enstatite-like surface inferred from
Messenger X-Ray Spectrometry
(Weider et al. 2012)

Isotopically most similar to ordinary chondrites
(e.g., Yoshizaki & McDonough 2020)

The Asteroid Belt

A dynamically excited structure with a mass of less than one one-thousandth of an Earth mass.

DeMeo & Carry 2014



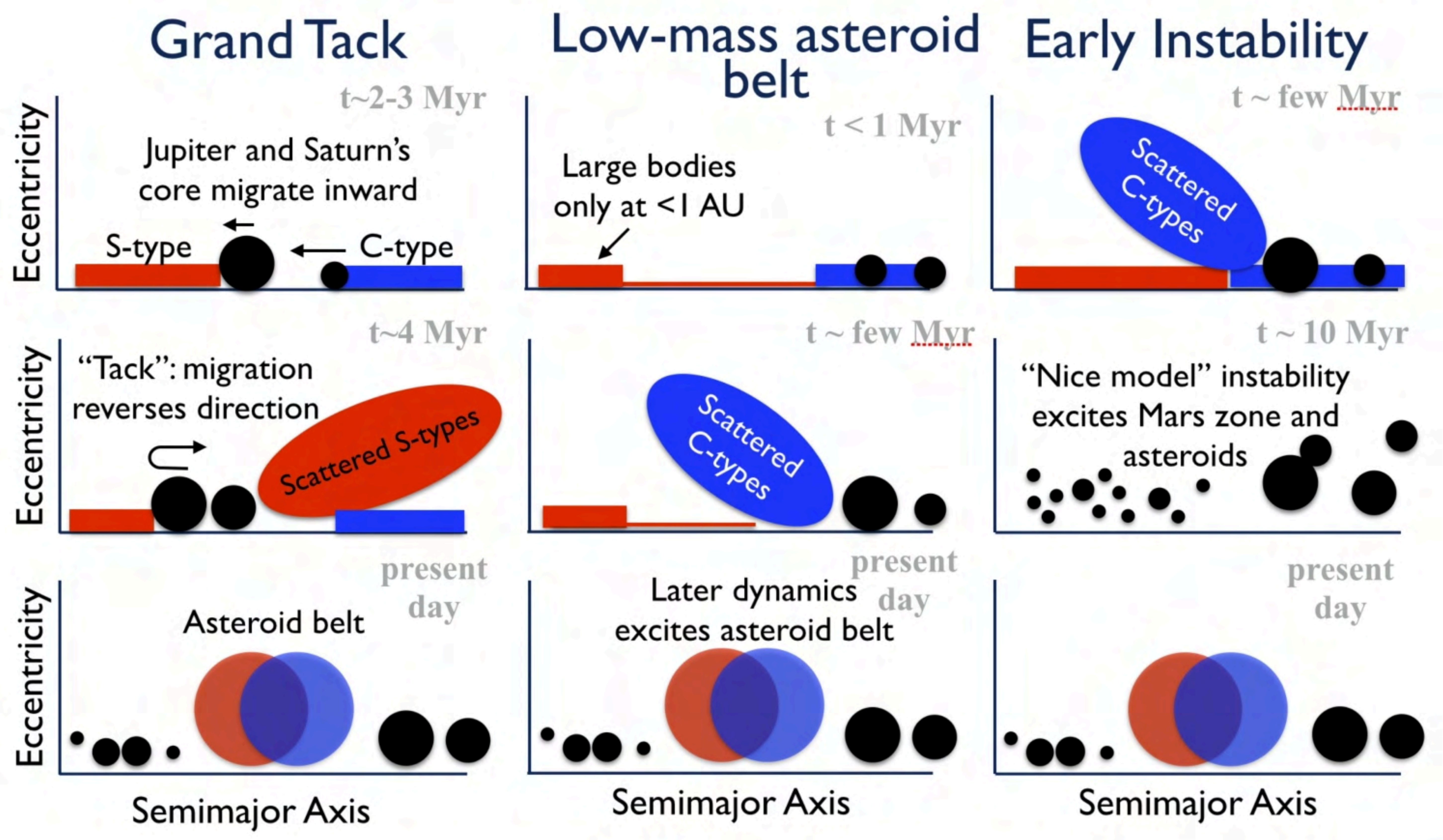
Gradie & Tedesco 1982

A specific initial planetesimal distribution required

Planet formation

planetesimals → planets

Today, three viable solutions to the small Mars issue are proposed.



w. Gas
+ successive late instability

w. Gas

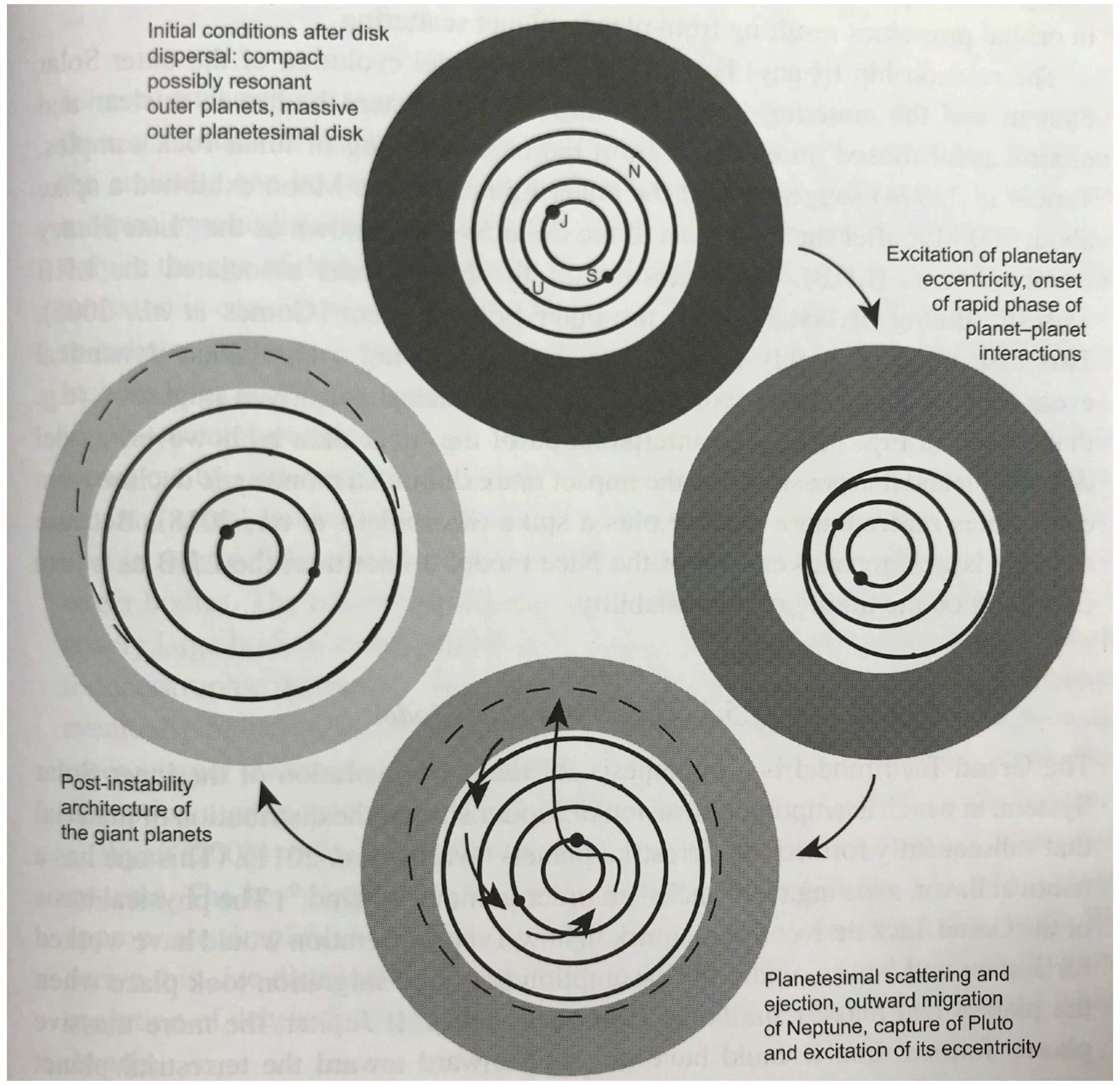
w/o. Gas

Instability Model

Originally,"Nice model" (Malhotra 1993; Gomes et al. 2005)

or "Planetesimal-driven migration" (Fernandez & Ip 1984)

or later "Jumping-Jupiter model"
(Brasser et al. 2009; Nesvorný 2011; Batygin et al., 2012)



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Pro.

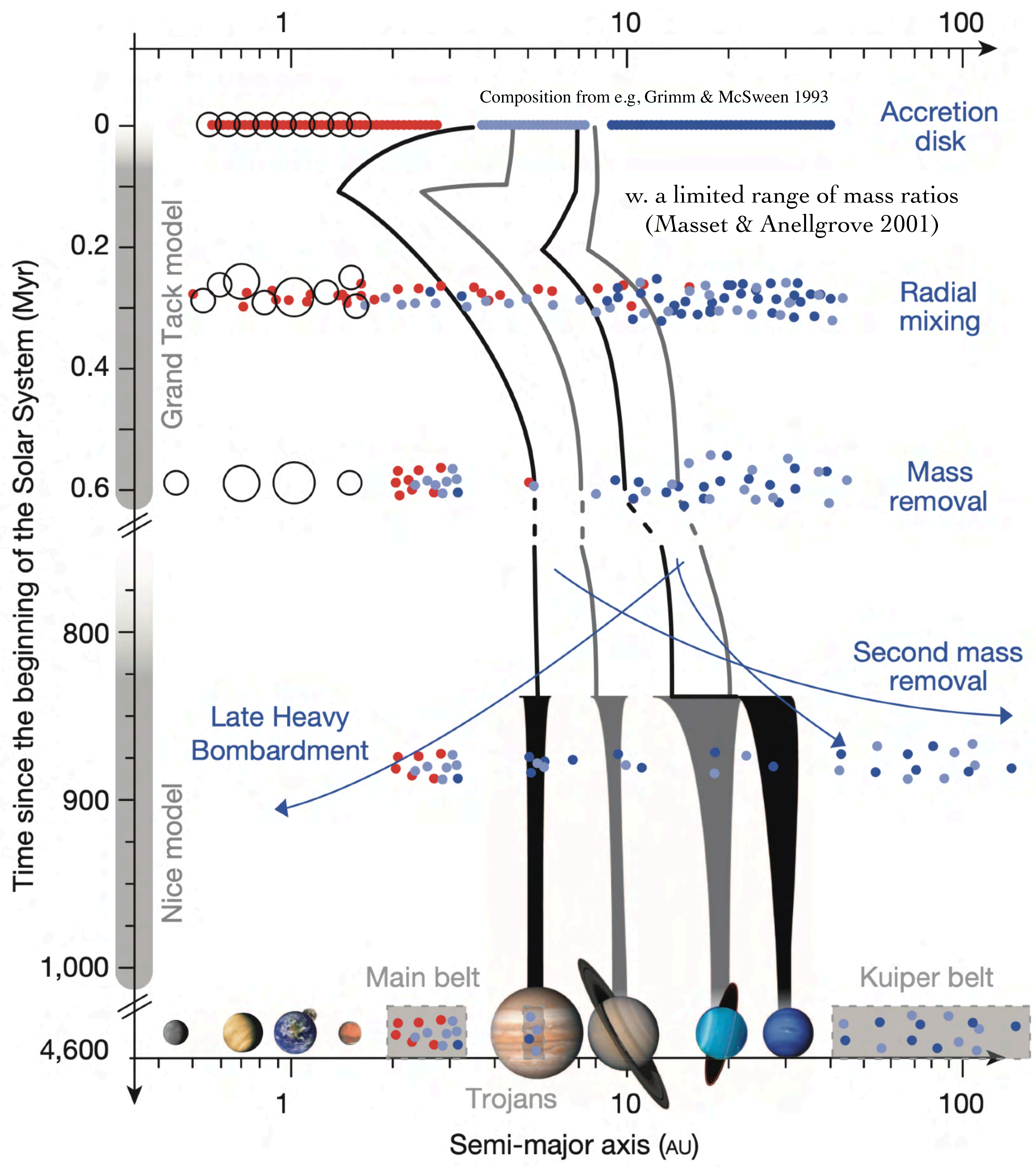
- The resonant structure of the Kuiper belt (Malhotra 1993; Hahn & Malhotra 2005)
- Jupiter Trojan (Morbidelli et al. 2015)
- Neptune Trojan (Nesvorny & Vokrouhlicky 2009)
- Irregular satellites (Nesvorny+2017)
- The final orbital sculpting of the asteroid belt (Morbidelli et al., 2010; Roig and Nesvorny, 2015; Deienno et al. 2016)
- The different components (cold, hot) of the Kuiper belt (Nesvorny, 2015)
- The origin of the Oort cloud and scattered disk (Brasser and Morbidelli, 2013; Nesvorny et al., 2017)
- Ring formation around giant planets (Hyodo et al. 2017)

Challenges

- Excessive excitation of the terrestrial planet orbits
- Excessive mixing of the terrestrial planet building blocks
- Uncertainty with the connection to the early nebula stage

A famous but not certain

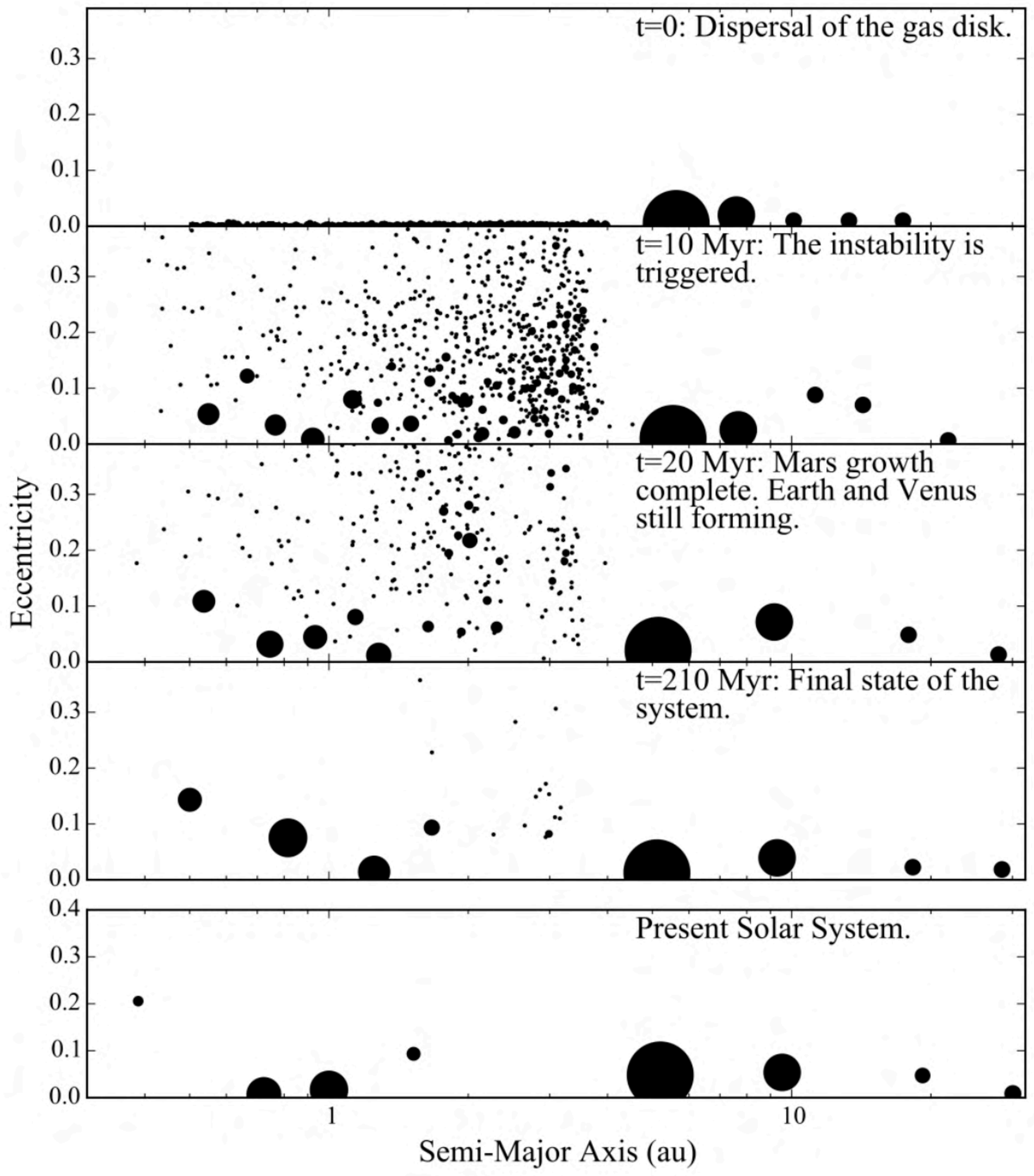
- The terrestrial planets were already in place before instability.
  (Gomes et al. 2005; Morbidelli et al. 2005; Tsiganis et al. 2005)
- However, the excitation of the terrestrial planet orbits may be significant.
  (Agnor & Lin 2012, Kaib & Chambers 2016; Brasser et al. 2013; Roig et al. 2016)
- Originally, a spike model. Now, a smooth decay.
  (Boehnke and Harrison 2016; Zellner 2017; Morbidelli et al. 2018; Hartmann 2019)



Walsh et al. 2011
DeMeo & Carry 2014

Early Instability

~1–10Myr after gas disk dispersal limits the mass and formation time of Mars.



Clement et al. (2018)

Pro.

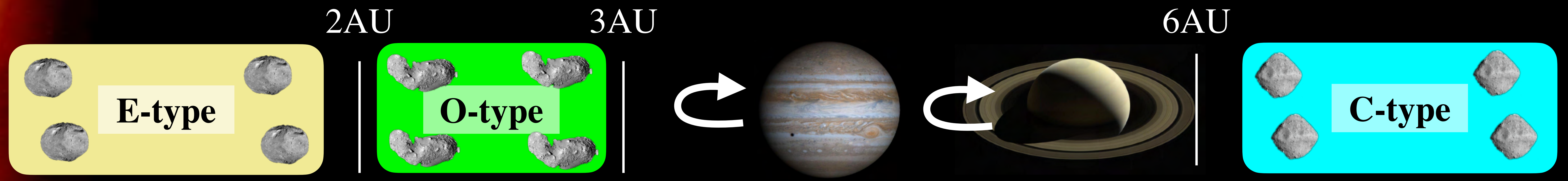
- Instability may occur during the terrestrial planet formation. (Boehnke & Harrison 2016; Zellner 2017; Morbidelli et al. 2018; Nesvorný et al. 2018)
- A simple explanation w/o. "grand-tack".

Challenges

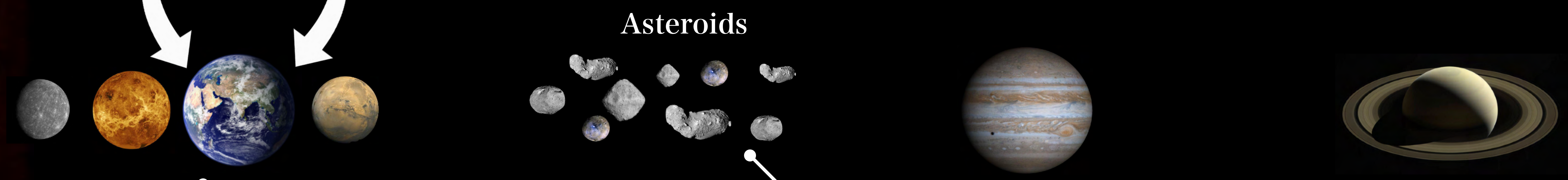
Note sure whether this instability can account for the irregular satellites (inc. Trojan) of giant planets.

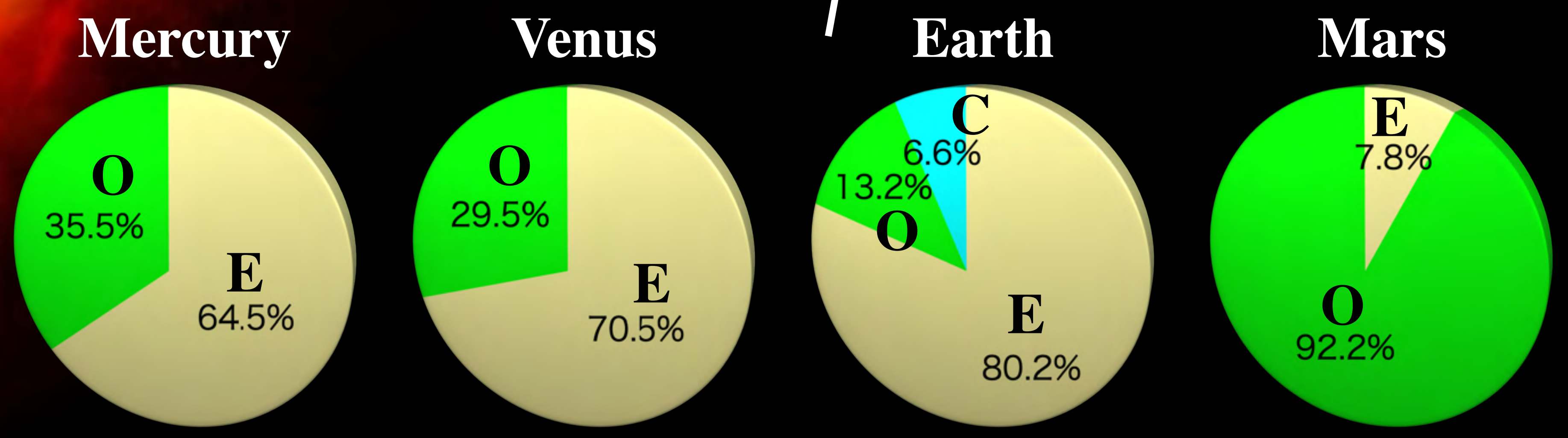
惑星形成論は、
ある物質分布に帰結する

ある集積モデルは、ある特定の初期分布を要求し、
そして最終的にある特定の物質分布に達する。

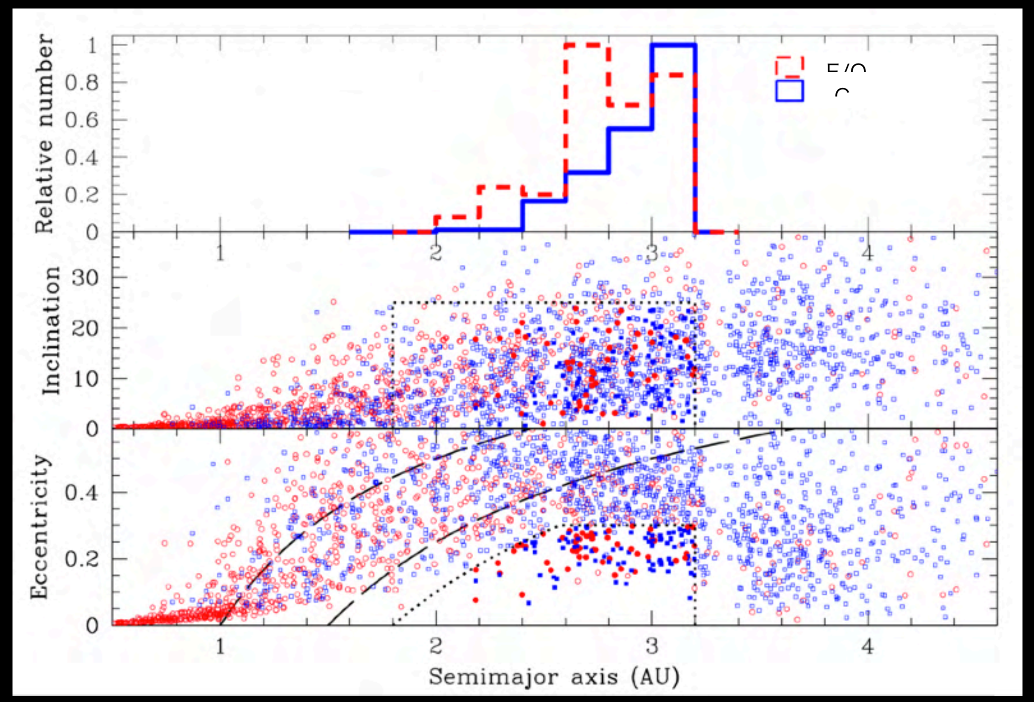


例) Grand Tack model (Walsh+ 2011)





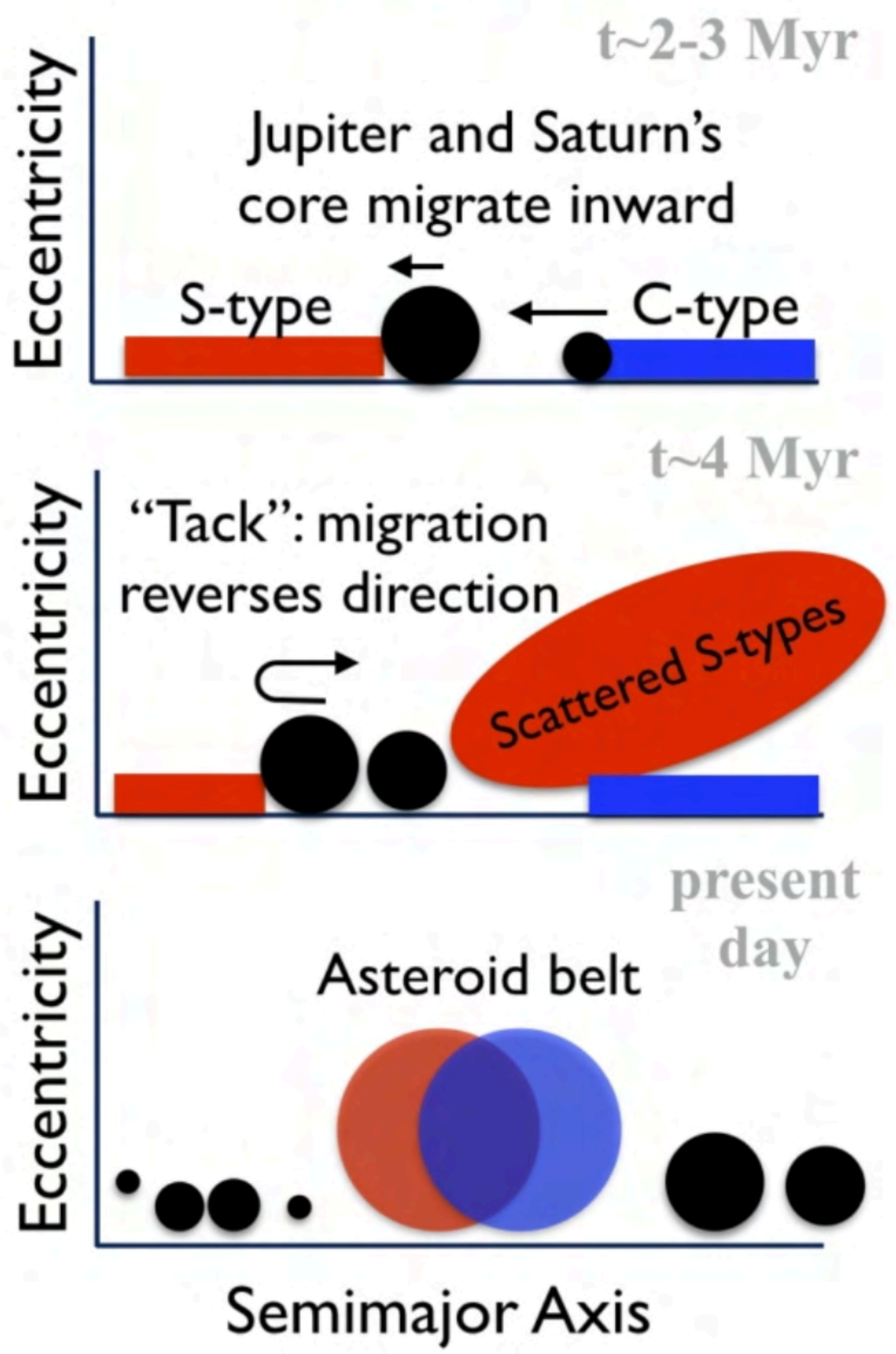
＊一例 (値は正しくはない)



Walsh+ 2011

See more statistical arguments in Lykawka & Ito 2019; Nesvorny´+2021

Grand Tack



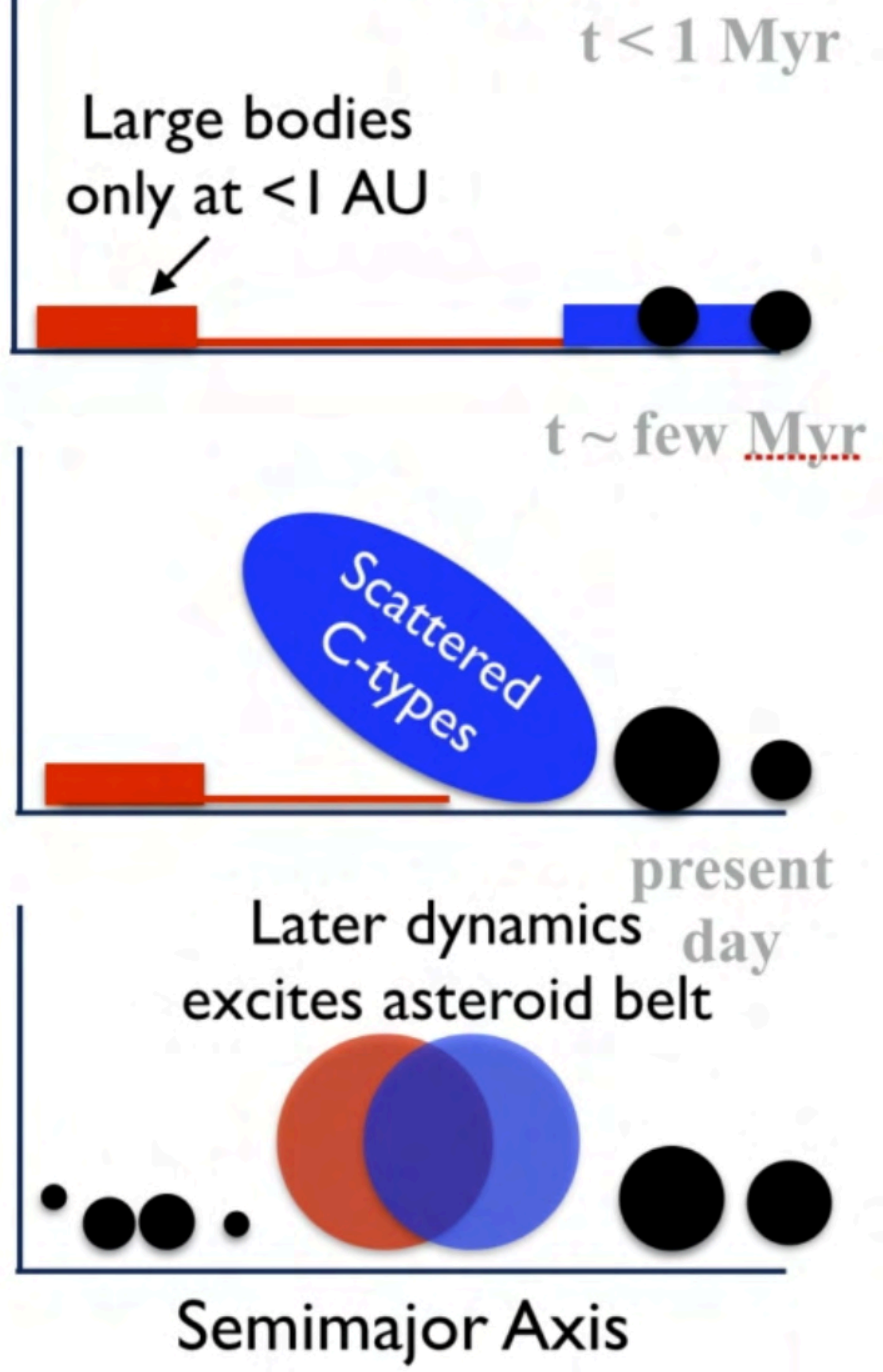
Mars-Earth isotope difference

✗ well mixed (Woo et al. 2018)

Radial mixing of C- and S-types

○ sufficient mixing (Walsh et al. 2011)

Low-mass asteroid belt



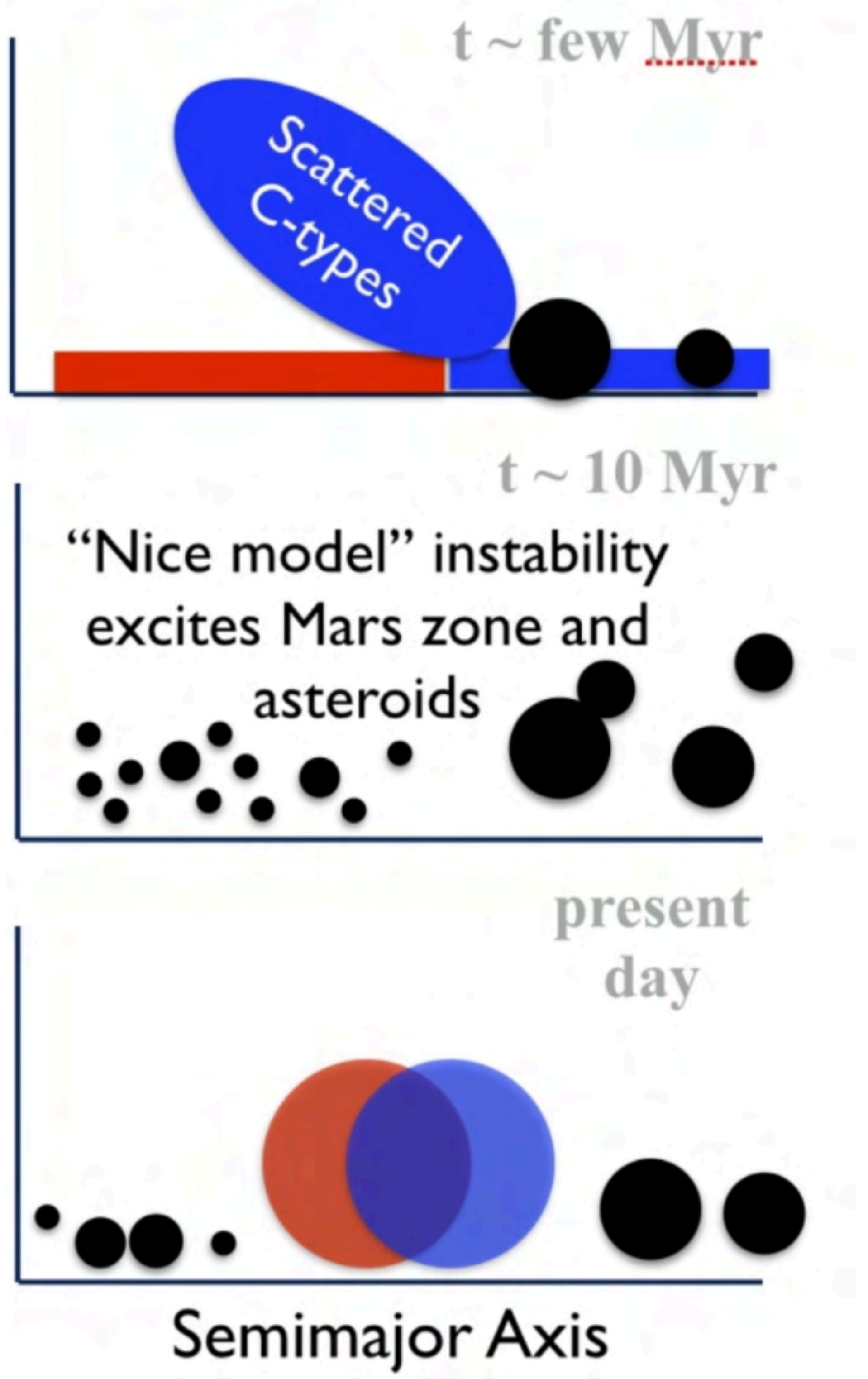
Mars-Earth isotope difference

○ local accretion (Mah et al. 2021)

Radial mixing of C- and S-types

△ giant planet required (Raymond&Izidoro 2017)

Early Instability



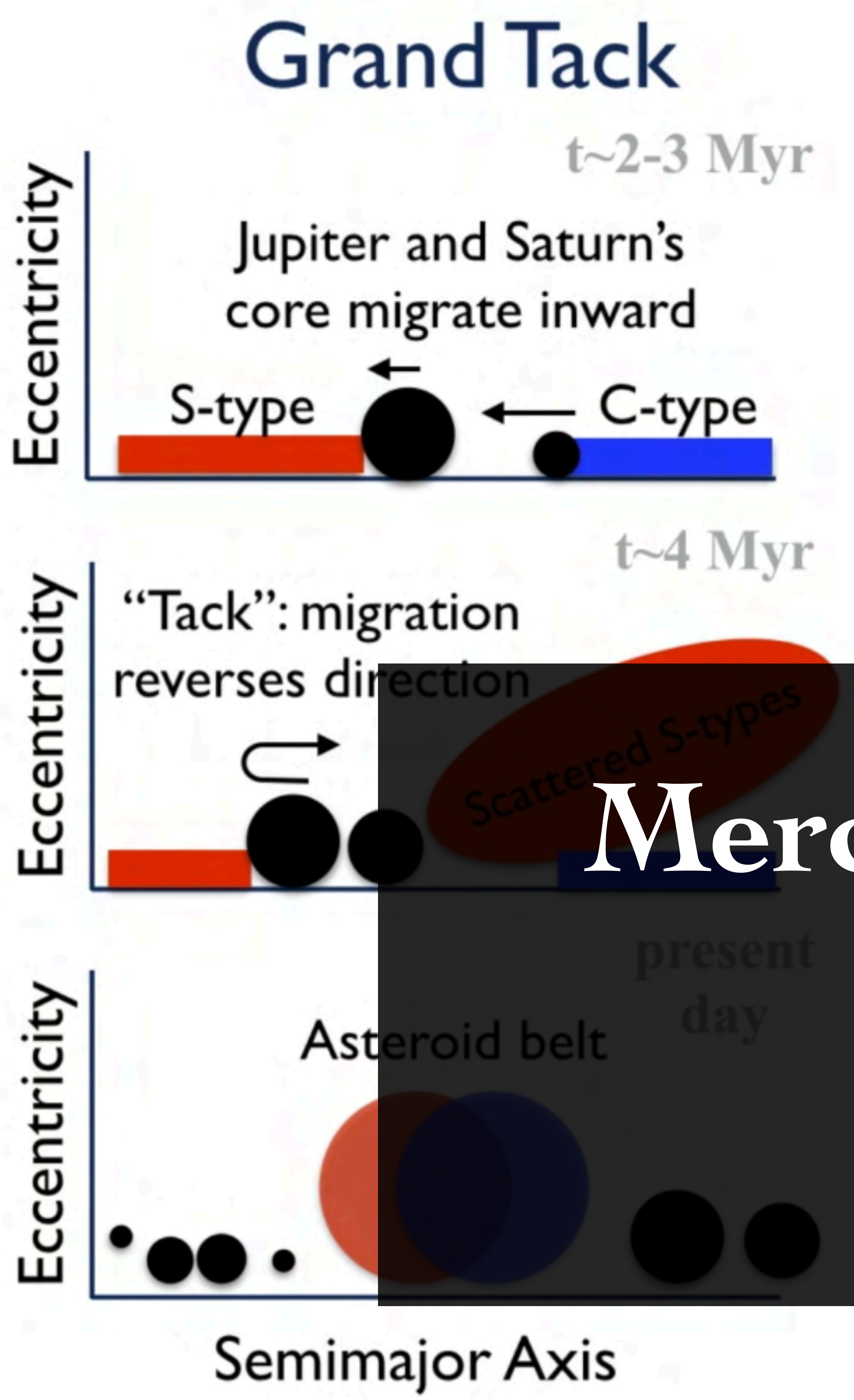
Mars-Earth isotope difference

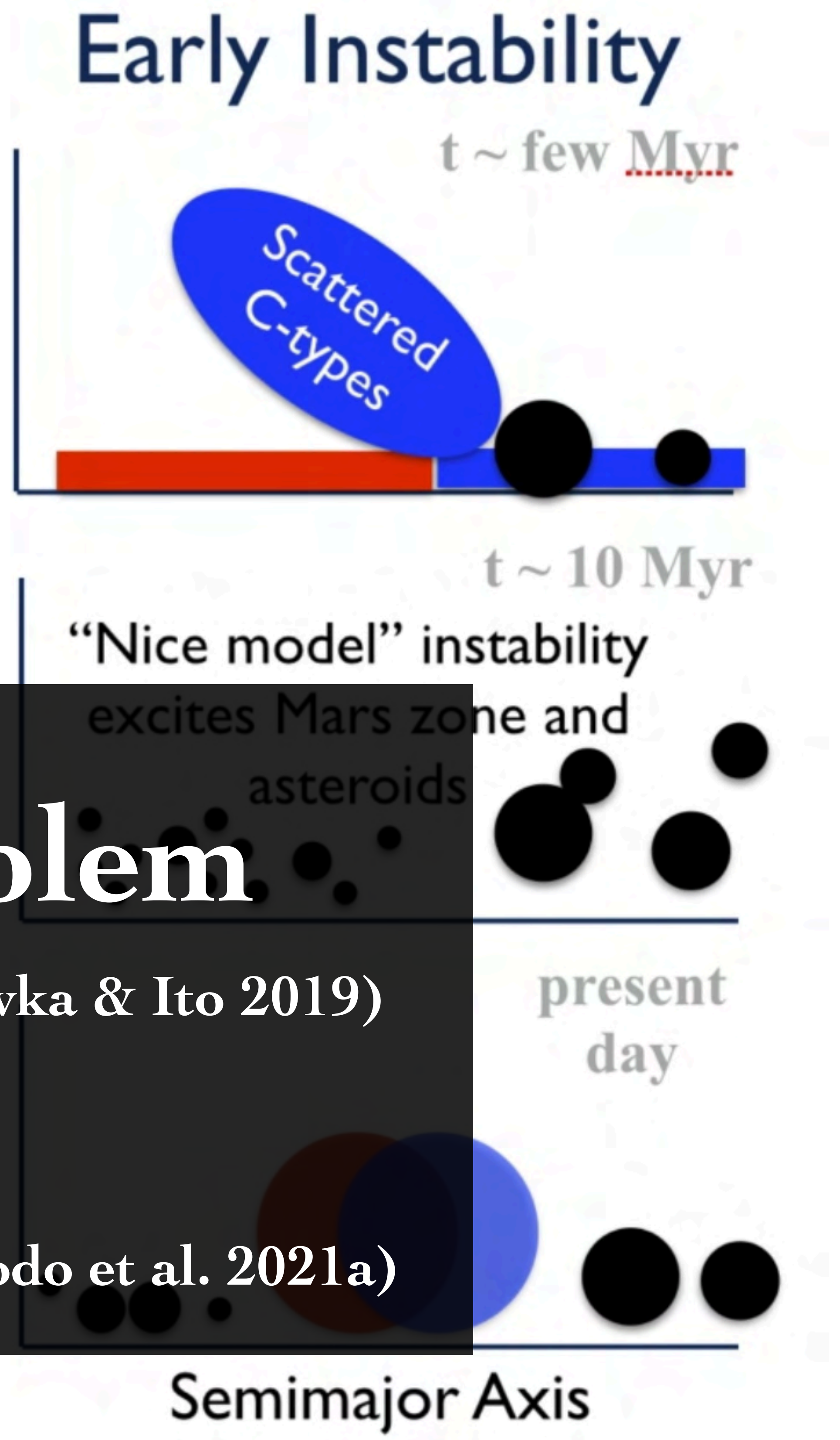
? not studied

Radial mixing of C- and S-types

△ if inherited from a mixing via growing giant planet (Clement et al. 2019)

See more statistical arguments in Lykawka & Ito 2019; Nesvorny´+2021





Mercury origin remains a glaring problem

(e.g., Chau+2018; Clement+2019; Lykawka & Ito 2019)

Numerous cratering impacts may do a job (Hyodo et al. 2021a)

Grand Tack

Mars-Earth isotope difference

✗ well mixed (Woo et al. 2018)

Radial mixing of C- and S-types

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Low-mass asteroid belt

Mars-Earth isotope difference

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Early Instability

Mars-Earth isotope difference

? not studied

Radial mixing of C- and S-types

△ if inherited from a mixing via growing giant planet (Clement et al. 2019)

Looking at an earlier phase —
What is the initial planetesimal distribution?

Smooth or Annulus?

dust → planetesimals

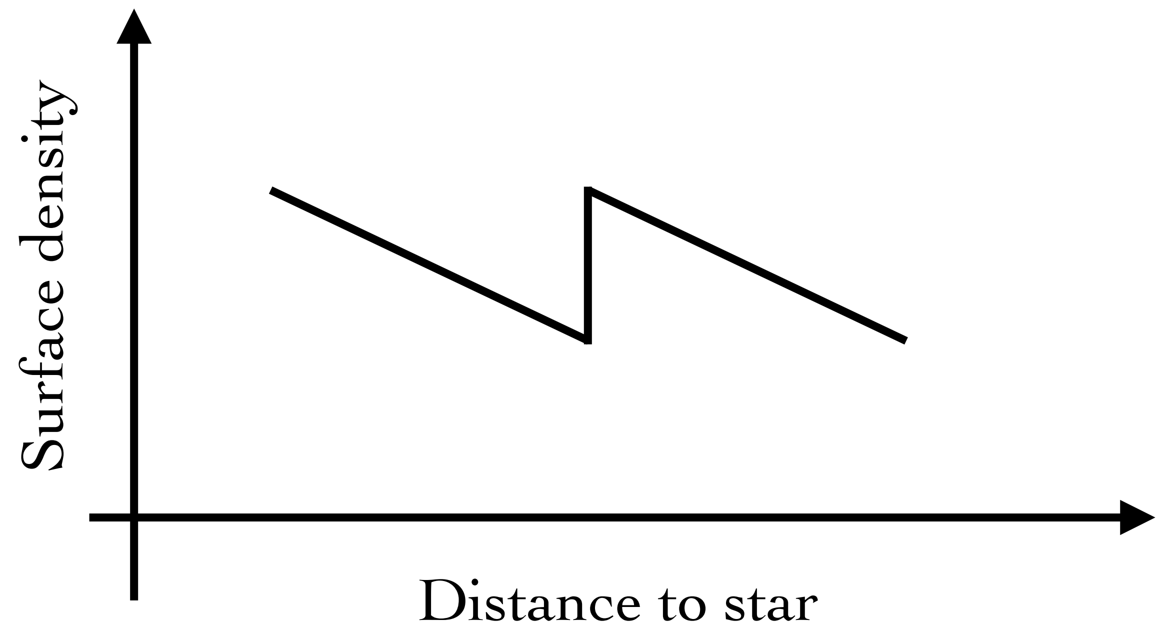
The initial planetesimal distribution borns smooth, or borns in an annulus?

A smooth distribution

The classical view

Asteroid belt depleted (~1/1000)

Present

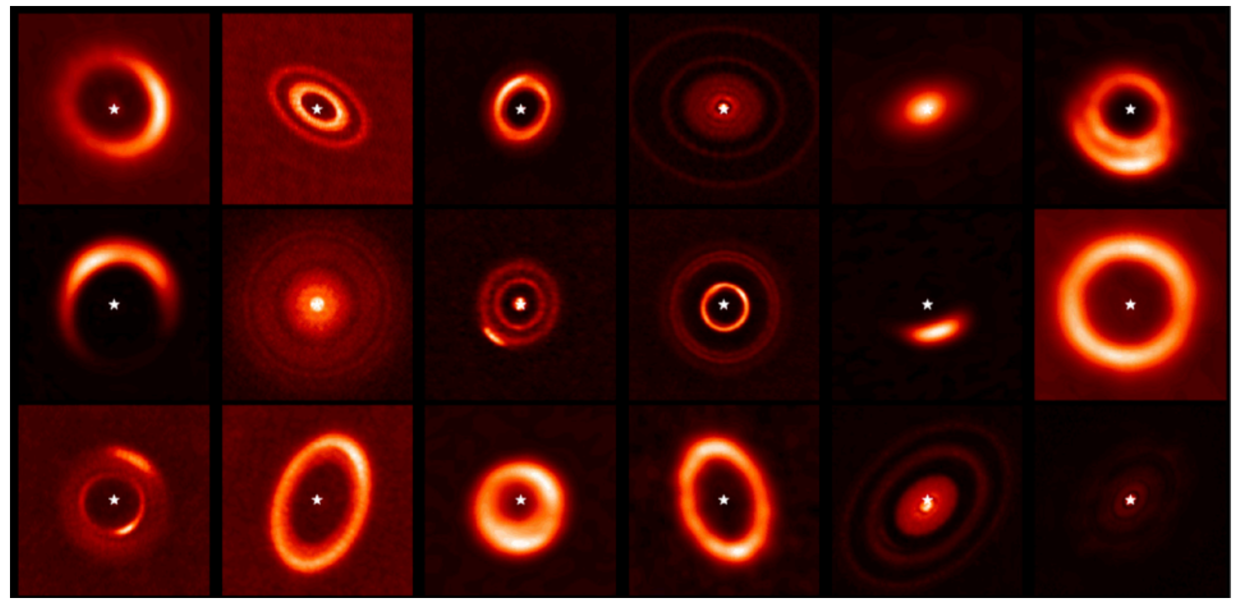


An annulus distribution

ALMA observations & planetesimal formation

Asteroid belt implanted

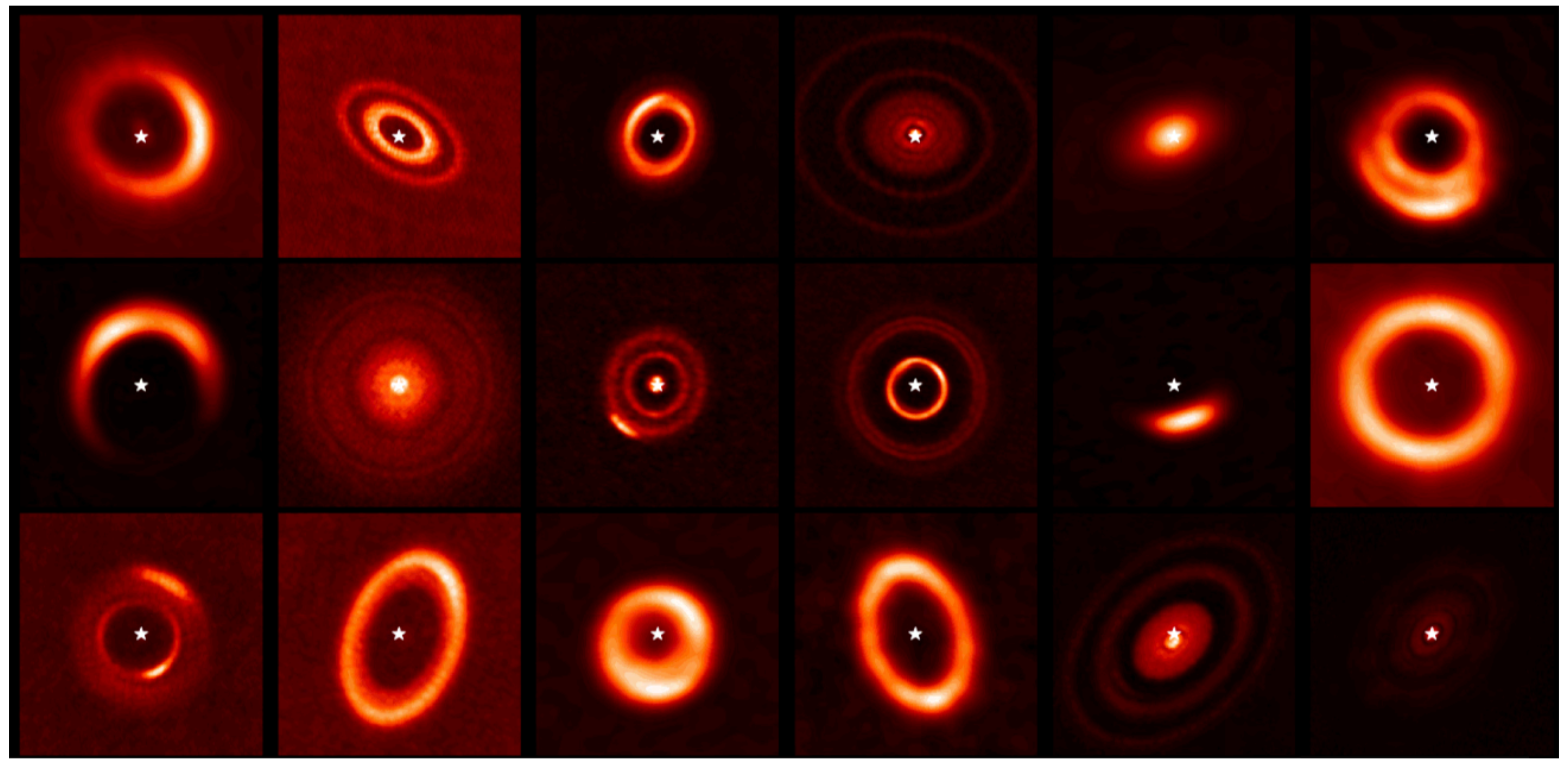
Present



Marel et al. 2019

Planetesimal Formation

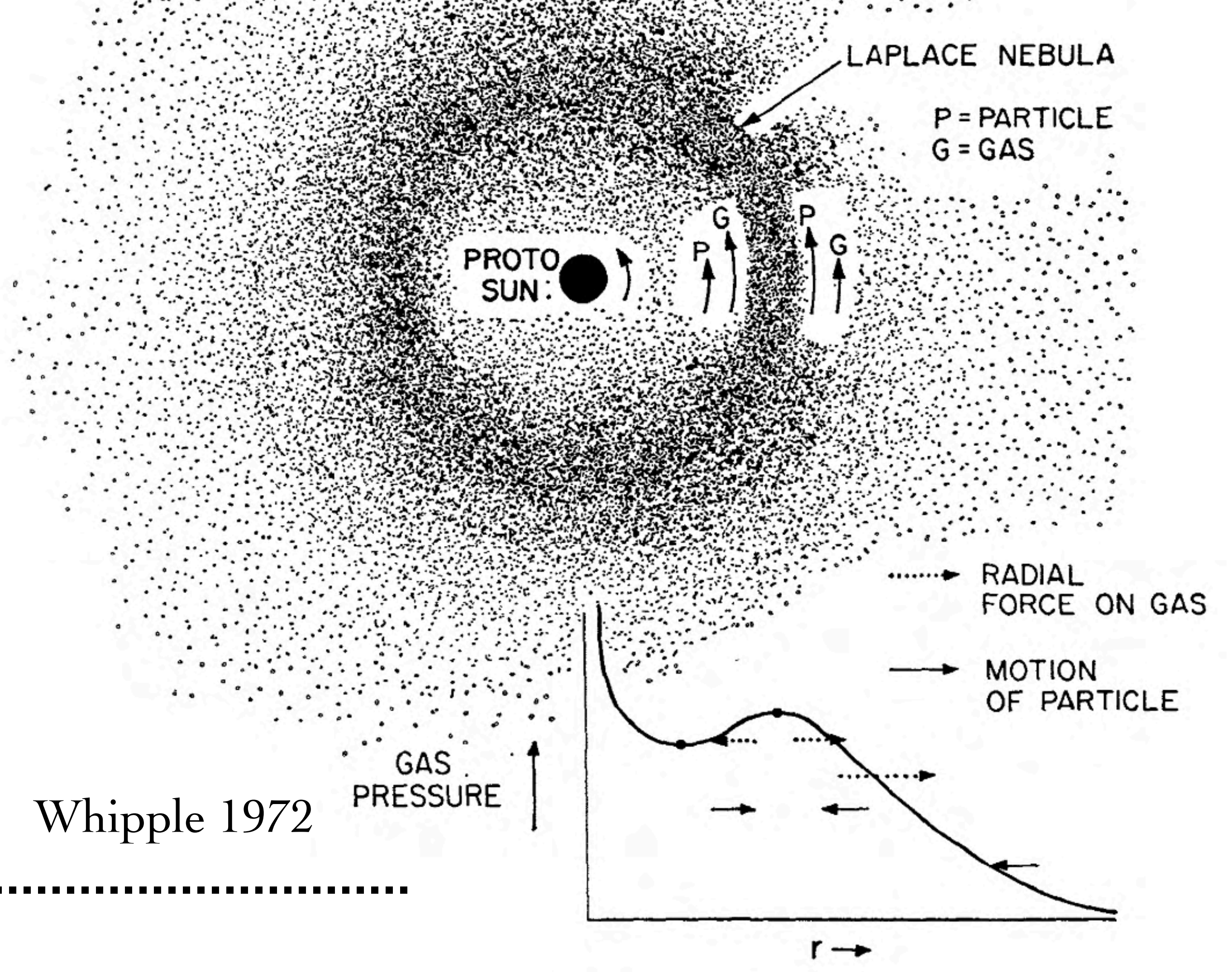
A local elevated concentration of solids may be a favorable condition for planetesimal formation, followed by streaming instability and/or gravitational instability.



Marel et al. 2019

Pressure Bump

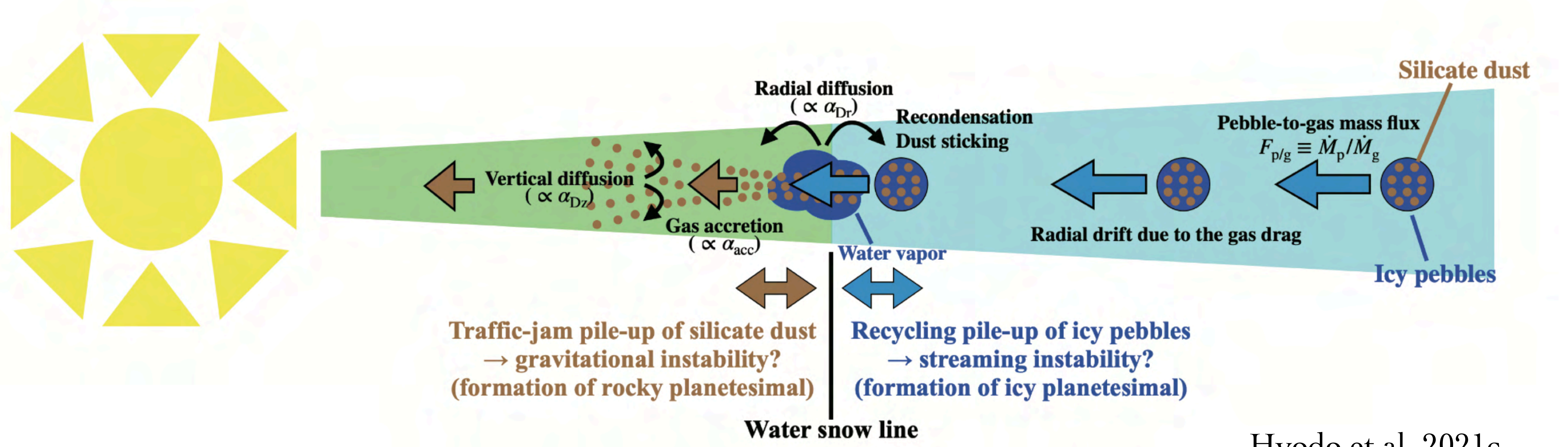
- edges of dead zones
  (e.g., Charnoz+2019; Ueda+2019)
- curved by planet gravity
  (e.g., Pinilla+2012; Kanagawa+ 2015)
- etc.



Whipple 1972

Snow Line

Saito & Sirono 2011
Ida & Guillot 2016
Okuzumi et al. 2016
Drazkowska & Alibert 2017
Lichtenberg et al. 2021



Hyodo et al. 2021c

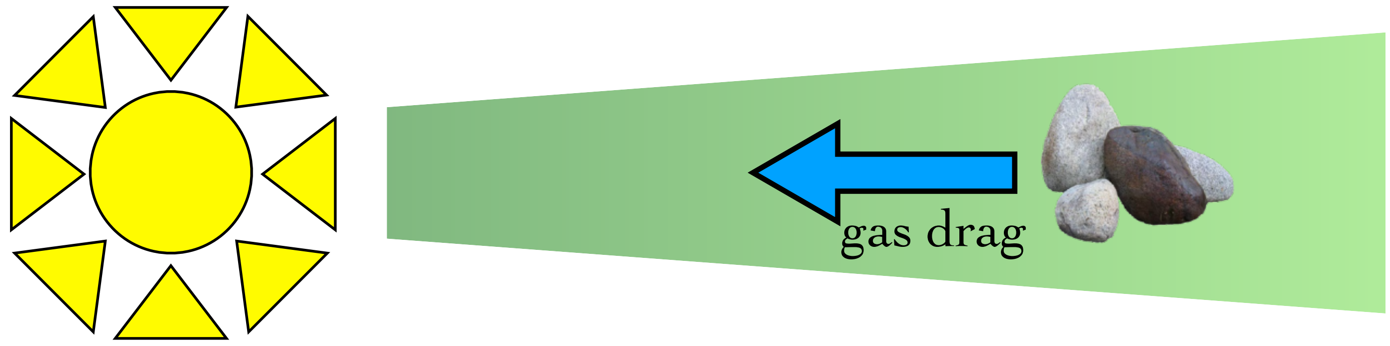
Others

- Dust evolution (e.g., Wada et al, 2009; Okuzumi et al. 2012; Zhang et al. 2015)
- Secular GI (e.g., Takahashi & Inutsuka 2014; Tominaga et al. 2020)
- Anti-cyclonic vortex (e.g., Barge & Sommeria 1995; Inaba & Barge 2006)
- “No-Drift” mechanism (e.g., Hyodo et al. 2021b)
- etc.

Pebbles

Drifting Pebbles

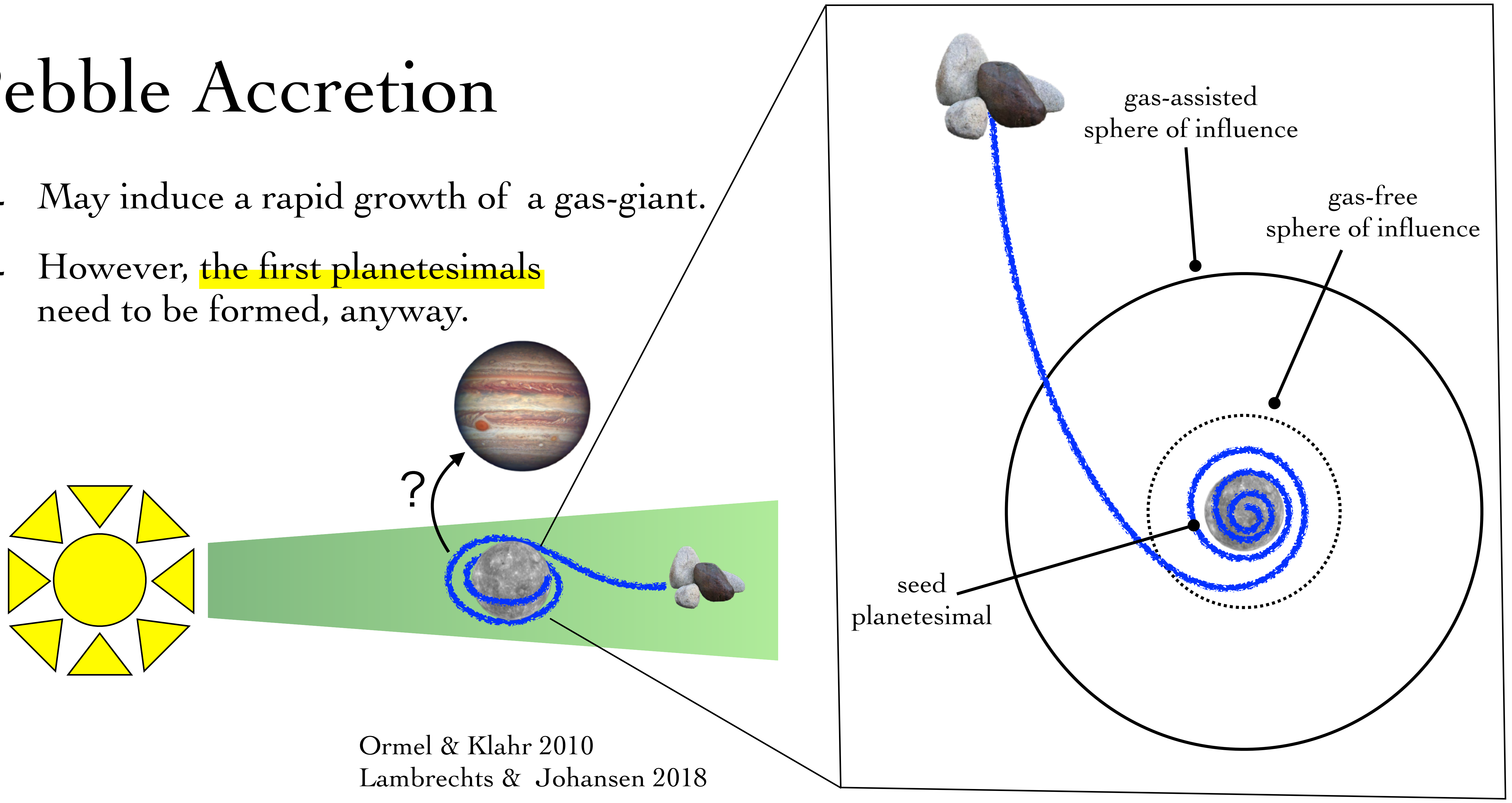
- A barrier to forming planetesimals
- But, may pile up at a specific radial location
- A process that delivers materials from one place to another.



e.g., Garaud 2007
Lambrechts et al. 2012
Morbidelli et al. 2015
Ida et al. 2016
Hyodo et al. 2021bc
Johansen et al. 2021

Pebble Accretion

- May induce a rapid growth of a gas-giant.
- However, the first planetesimals need to be formed, anyway.



Ormel & Klahr 2010
Lambrechts & Johansen 2018

惑星形成論は、ある物質分布に帰結する

ある集積モデルは、ある特定の初期分布を要求し、
そして最終的にある特定の物質分布に達する。

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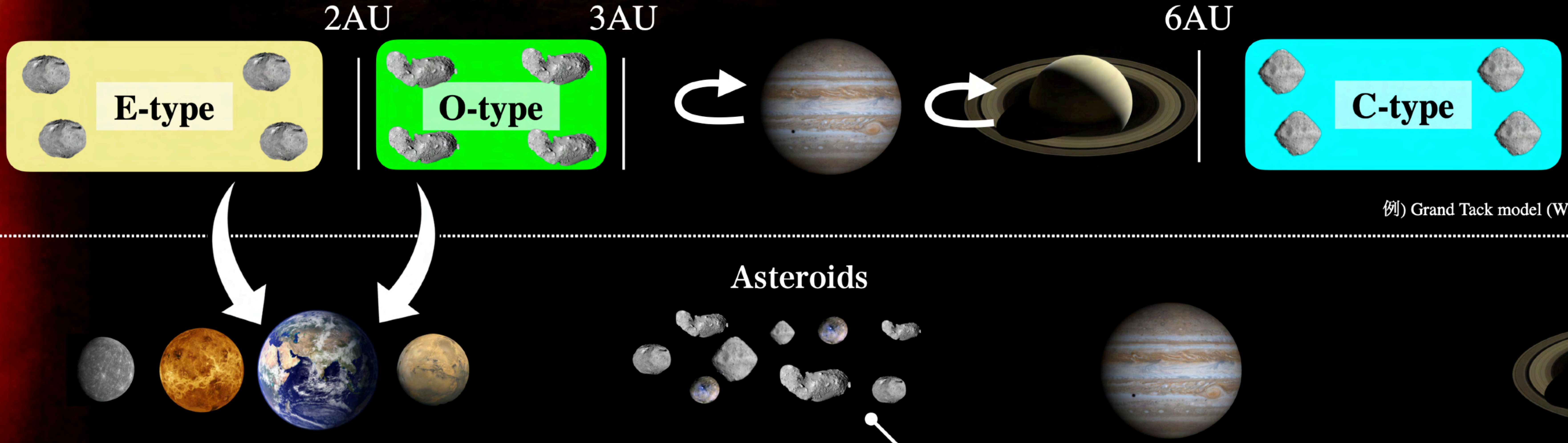
適切な初期条件の理解が必要不可欠

原始惑星系円盤での微惑星形成は未解決問題 &
提唱される太陽系後期の集積モデルが要求する
微惑星分布になりうるのか？

Smooth? ? Annulus?



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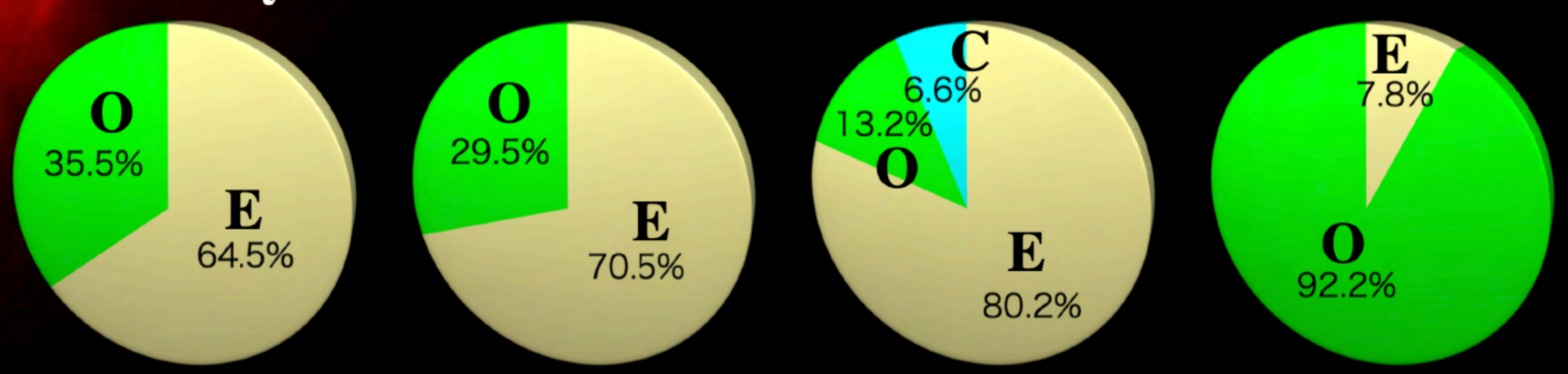

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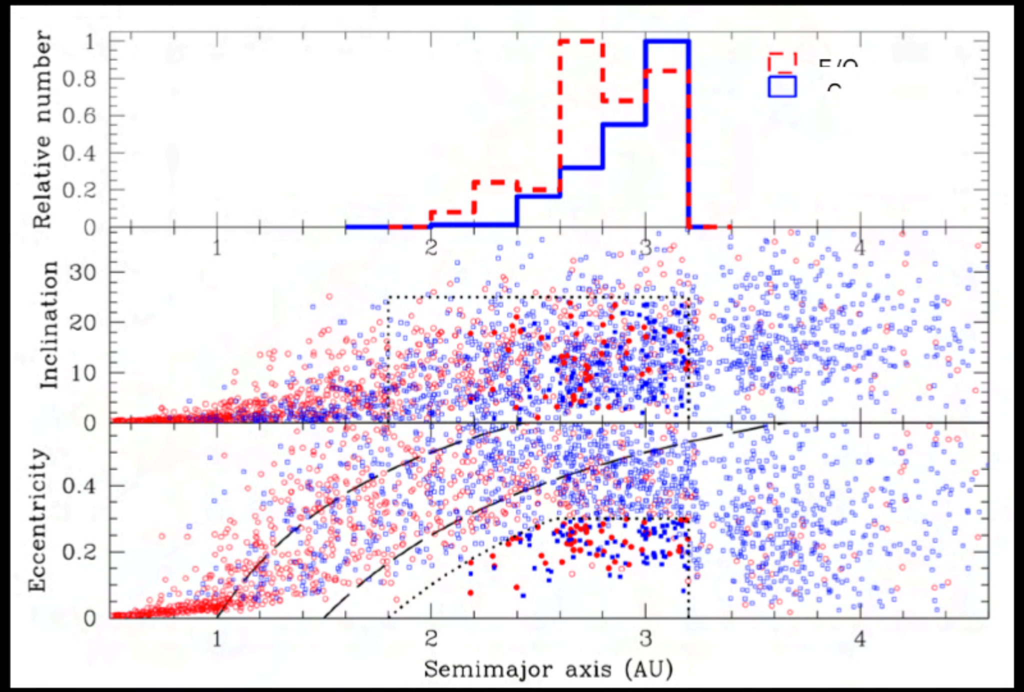

Walsh+ 2011