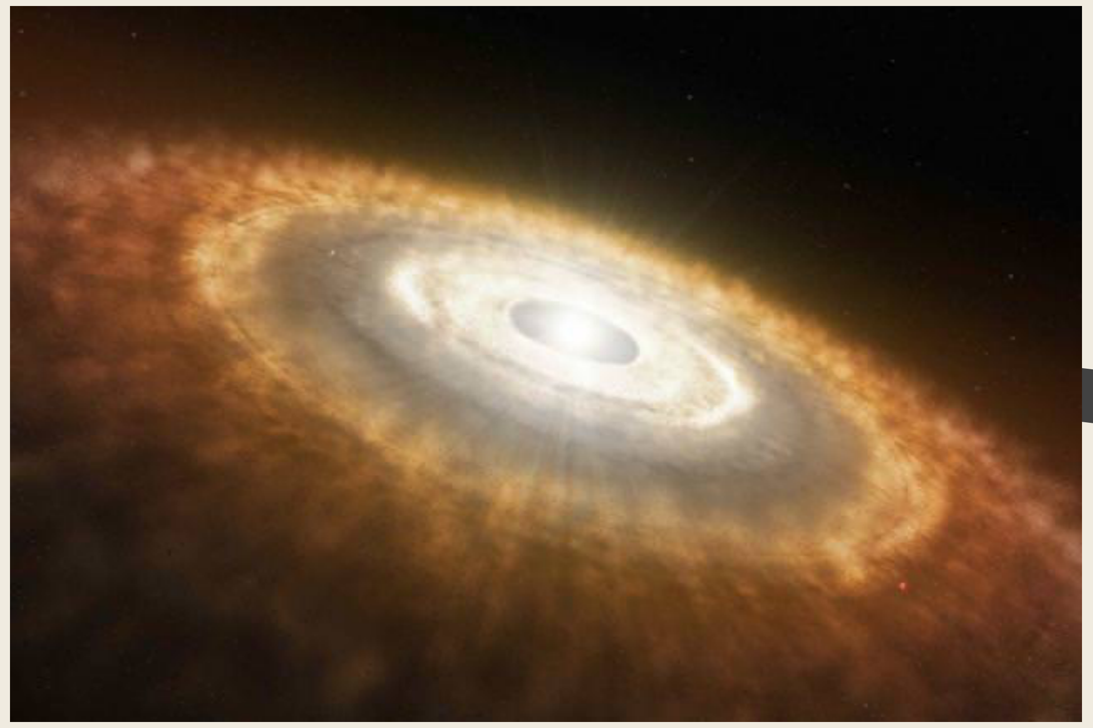
Formation of Mercury: A Review 2024

Ryuki Hyodo
JAXA

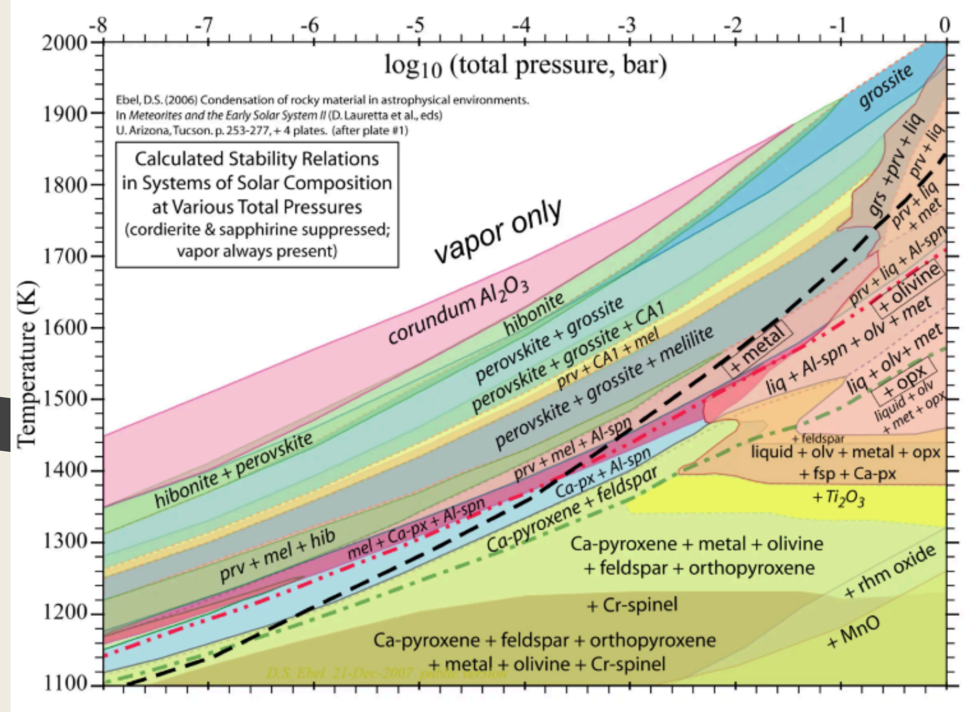
Today

1. Introduction
2. Mercury’s large core
    - 2.1 impact hypothesis
    - 2.2 condensation hypothesis
3. Planet formation models
4. Late Accretion
5. Super-Mercuries

1. Solar nebula formation (First ~0.1 Myrs)

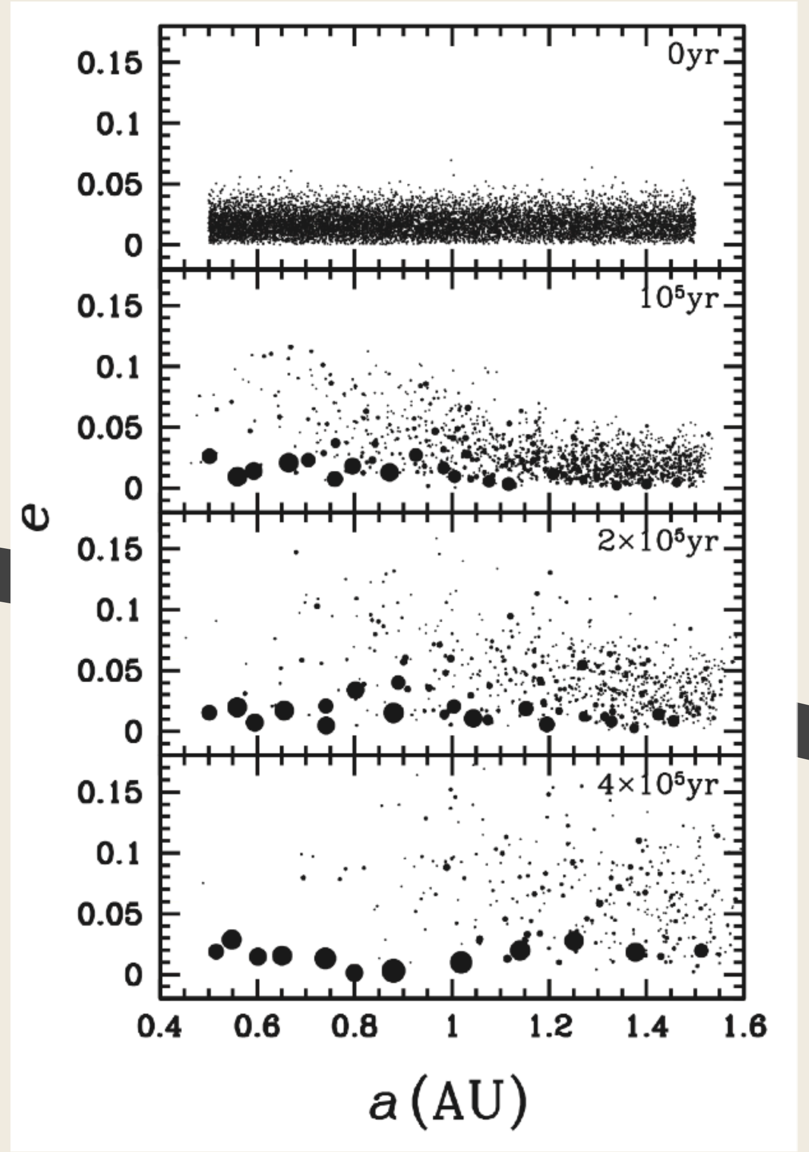


2. Condensation of solids (First ~1-10 Myrs)



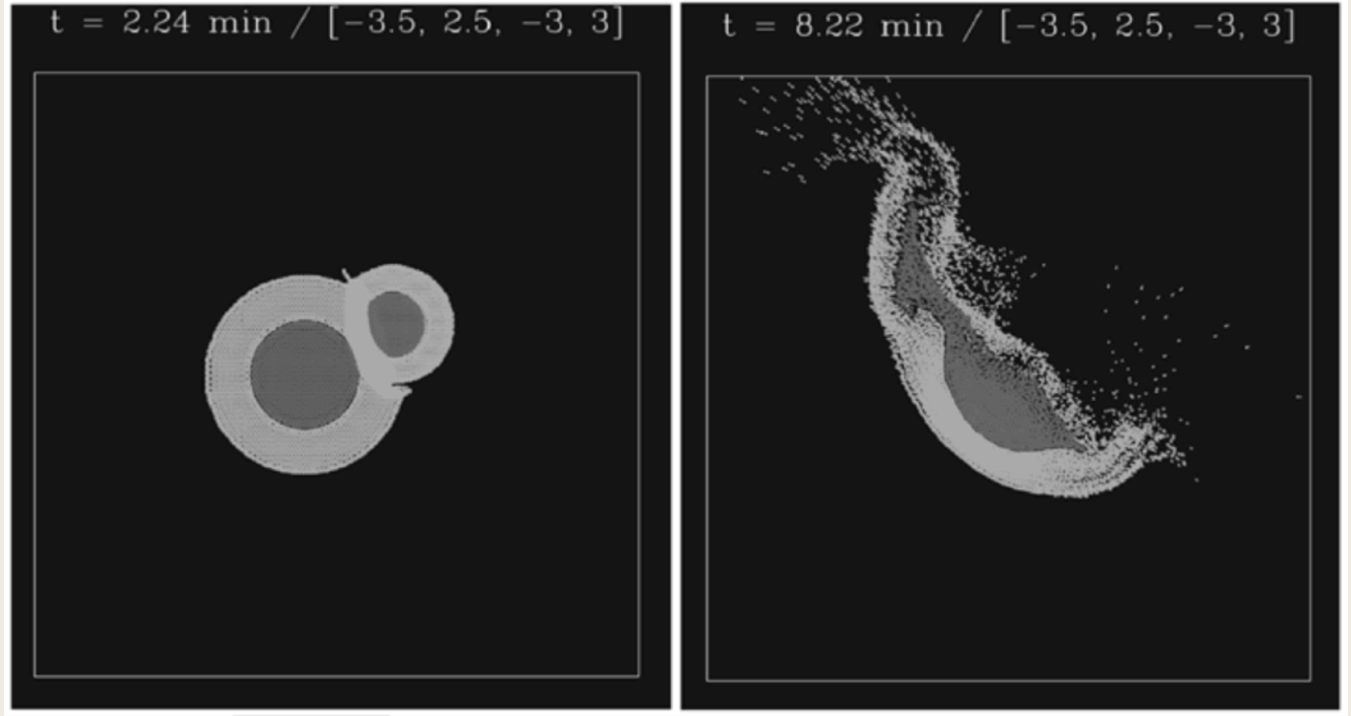
Ebel 2006

3. Growth of bodies (First ~1-100 Myrs)



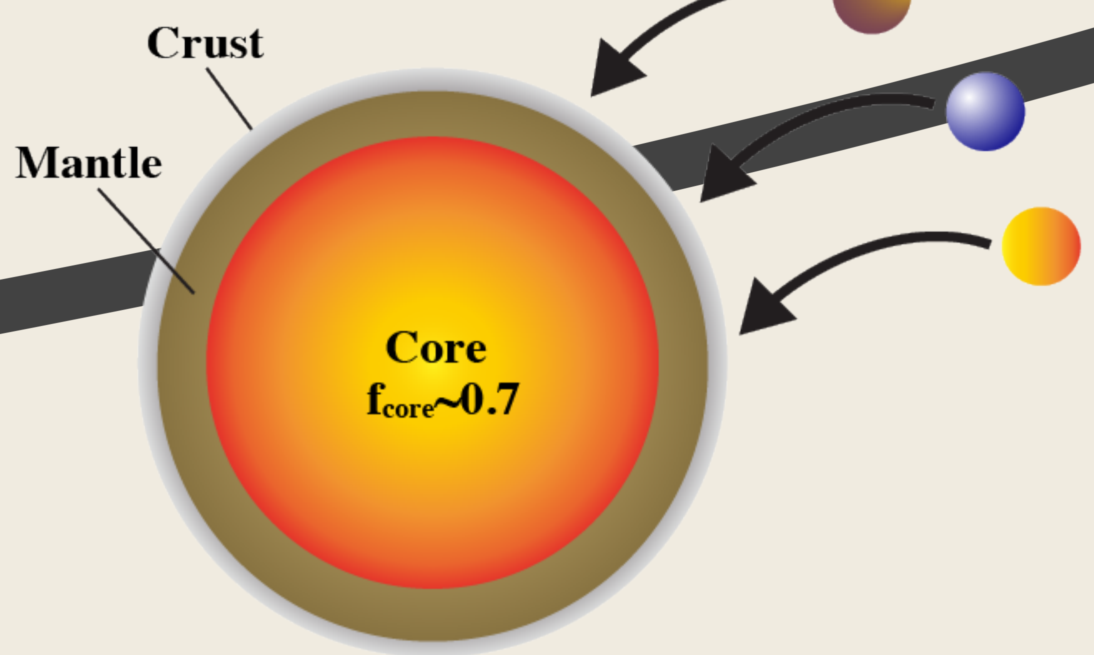
Kokubo & Ida 2012

4. Giant impact (First ~10-100 Myrs)



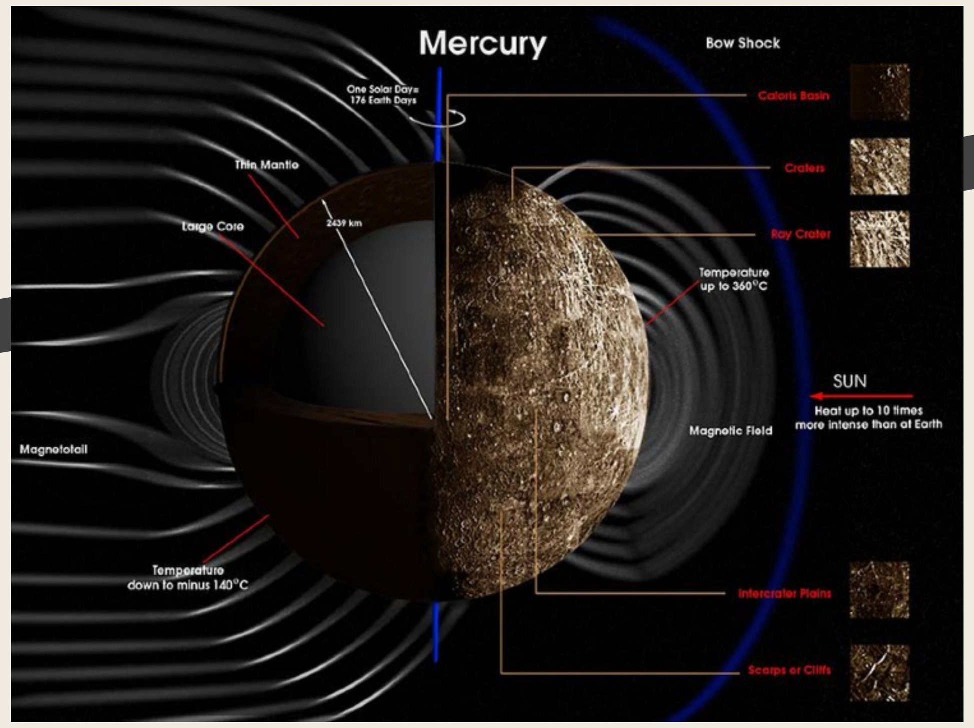
Benz 2007

5. Late accretion (Until ~4.0 Ga)



Hyodo et al. 2021

6.1. Long-term internal evolution
6.2. Generation of magnetic fields (After ~4.5 Ga)

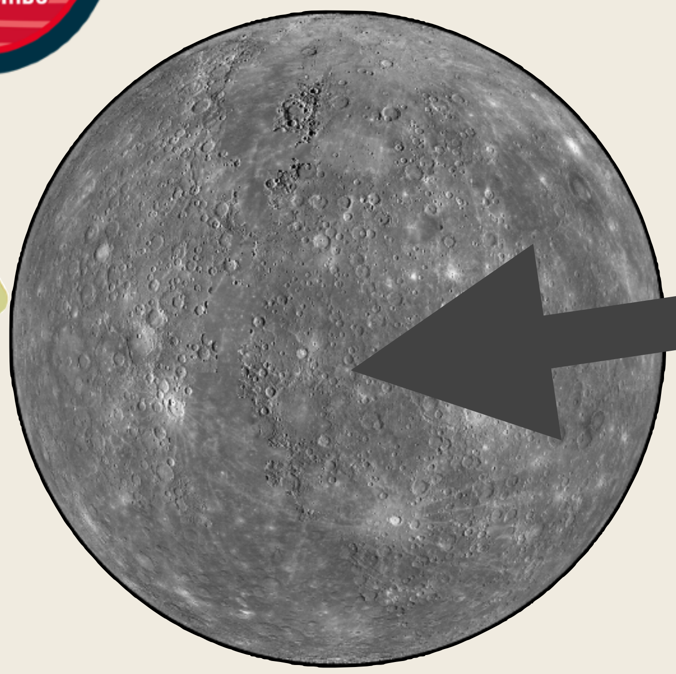


Slavin et al. 2007

7. Today

ESA | JAXA
bepicolombo

MESSENGER
MISSION TO MERCURY



Mercury’s key features in the context of terrestrial planets

- A large core (~70% by mass) (Hauck et al. 2013)
- Mantle is very reduced, i.e., FeO-free silicate (Warell & Blewett 2004; Ebel & Stewart 2018)
- High abundance of moderately volatile elements in the mantle (Peplowski et al. 2021)

$M=0.81M_\oplus$

Core fraction: ~0.23

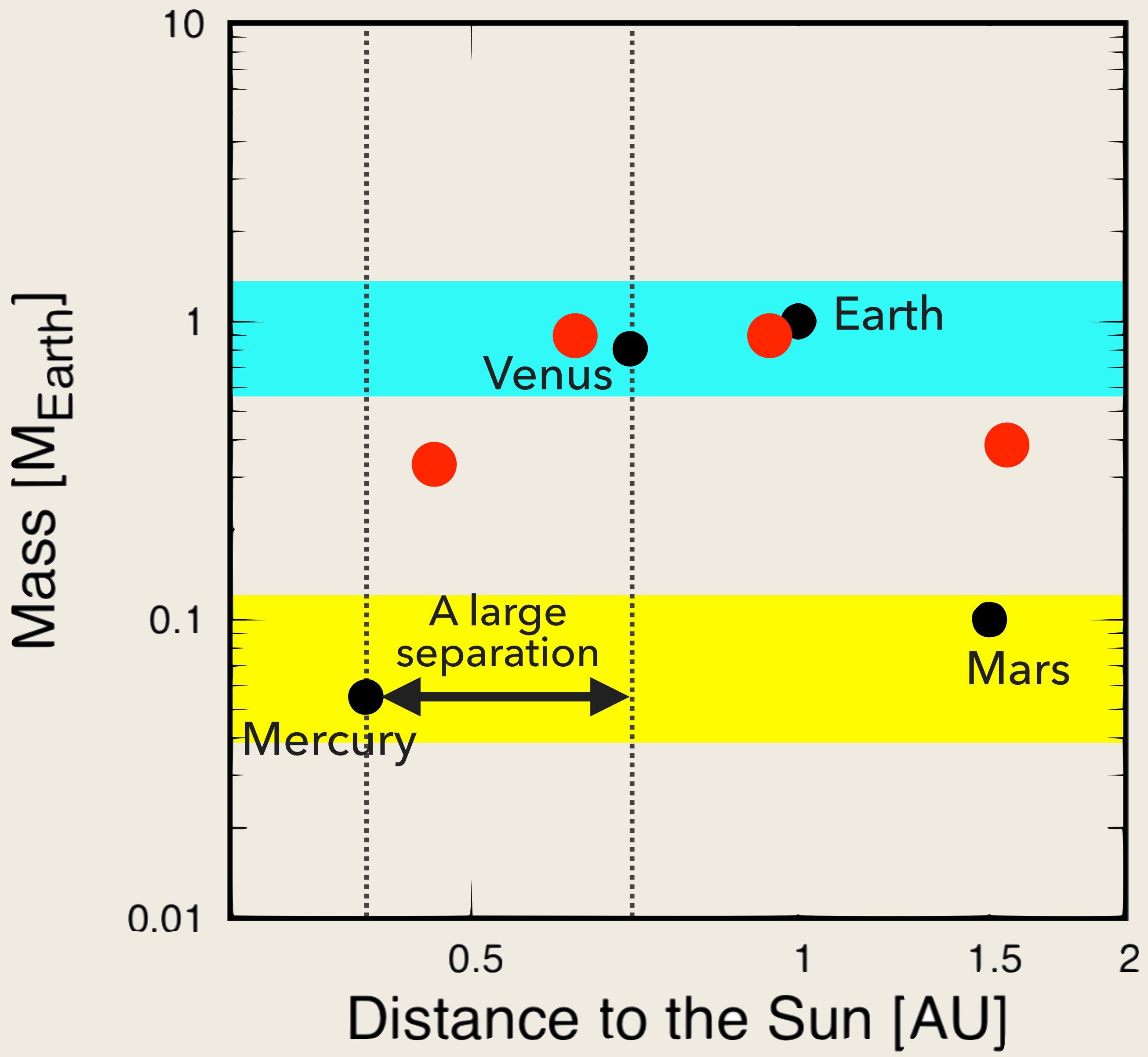
$M=0.055M_\oplus$

Core fraction: ~0.70

Mercury's key features in the context of terrestrial planets

☑ Radial Mass Concentration (RMC)

Mass is concentrated in Venus and Earth.



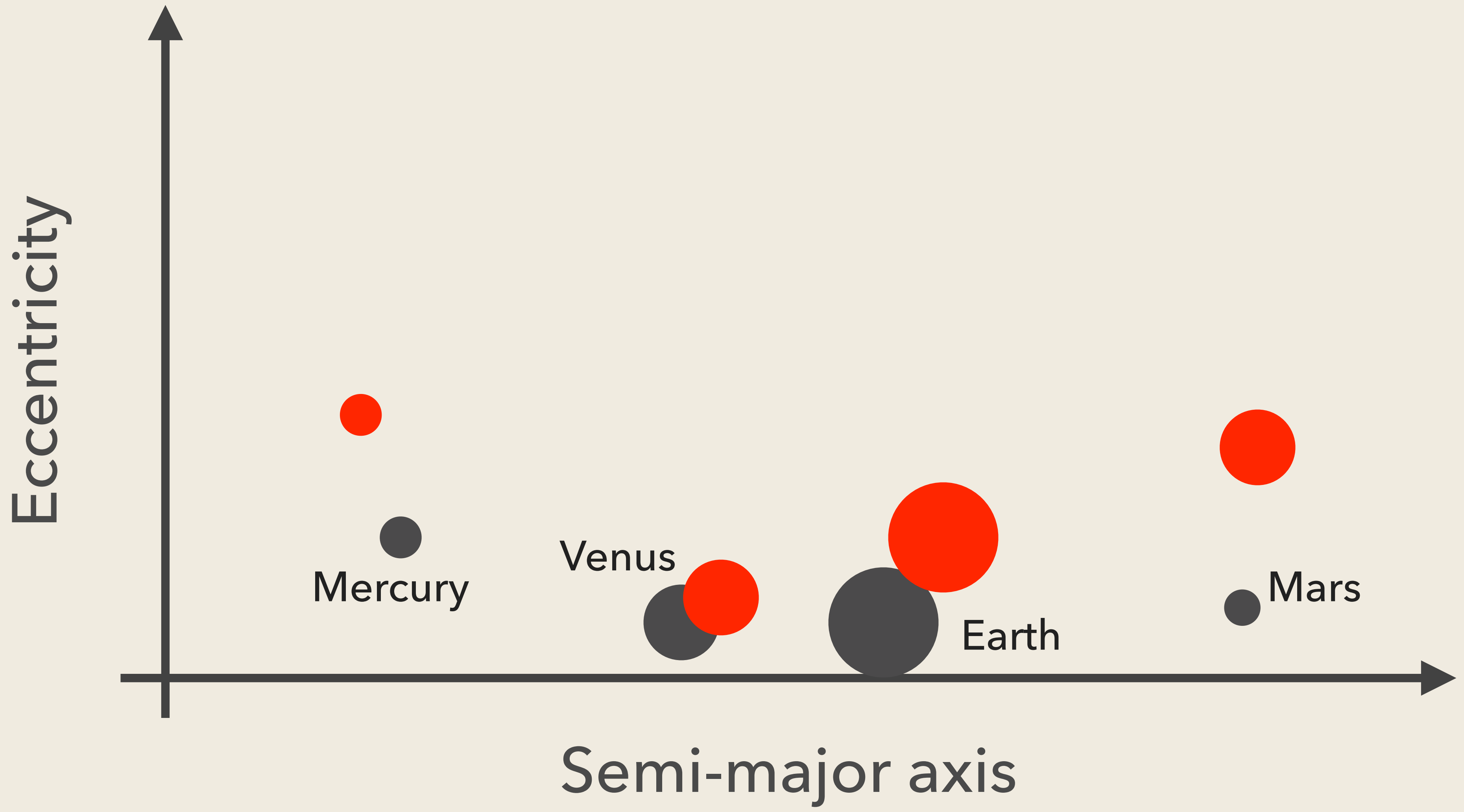
Real system: RMC=89.9

Numerical simulation: e.g., RMC= 45

$$\text{AMD} = \frac{\sum_i M_i\sqrt{a_i}\left[1-\sqrt{(1-e_i^2)}\cos i_i\right]}{\sum_i M_i\sqrt{a_i}}$$

☑ Angular Momentum Deficit (AMD)

The orbits of the terrestrial planets are not highly eccentric.



Real system: AMD=0.0018

Numerical simulation: e.g., AMD= 0.0045

$$\text{RMC} = \text{MAX}\left(\frac{\sum_i m_i}{\sum_i m_i\left[\log_{10}\left(a/a_i\right)\right]^2}\right)$$

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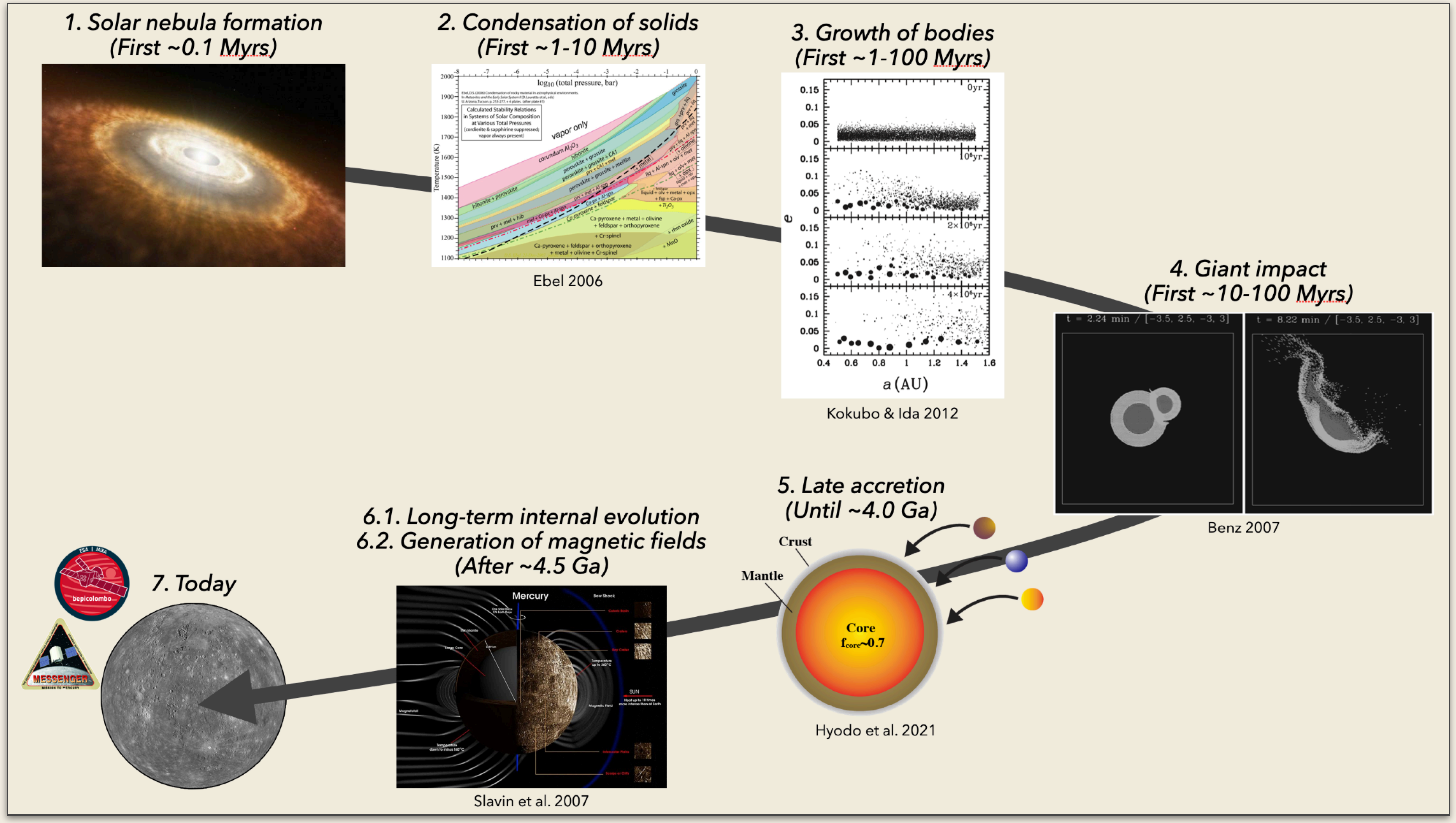
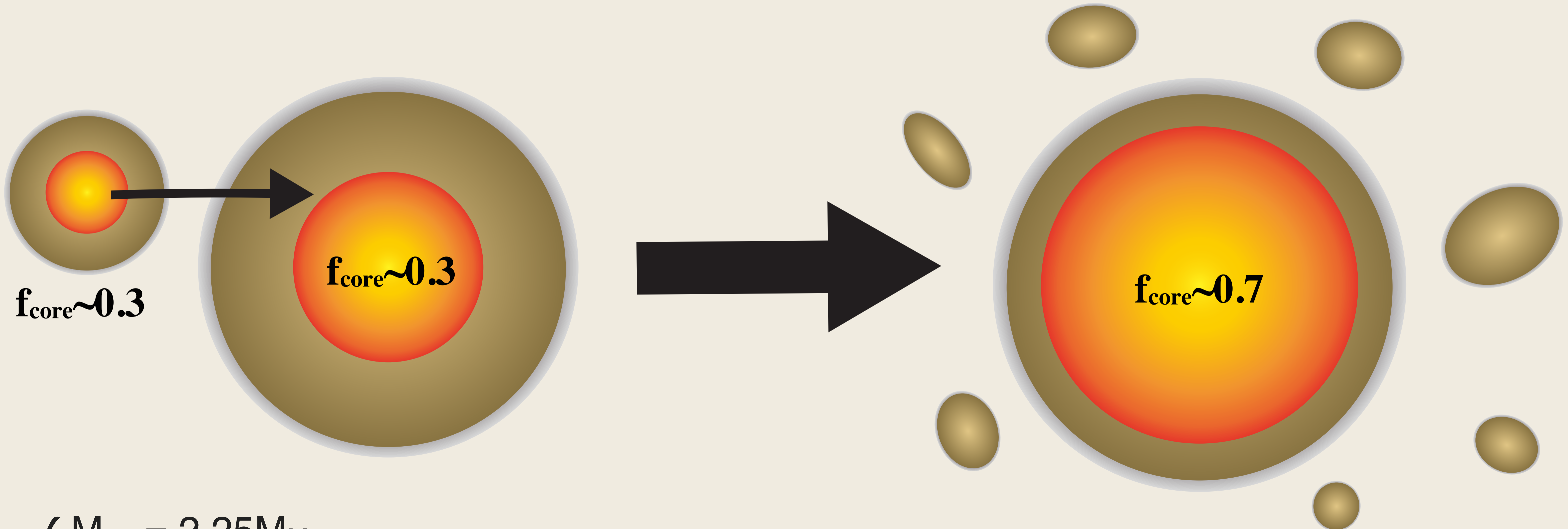


Catastrophic collision (e.g., Benz et al. 2007)

Target becomes Mercury

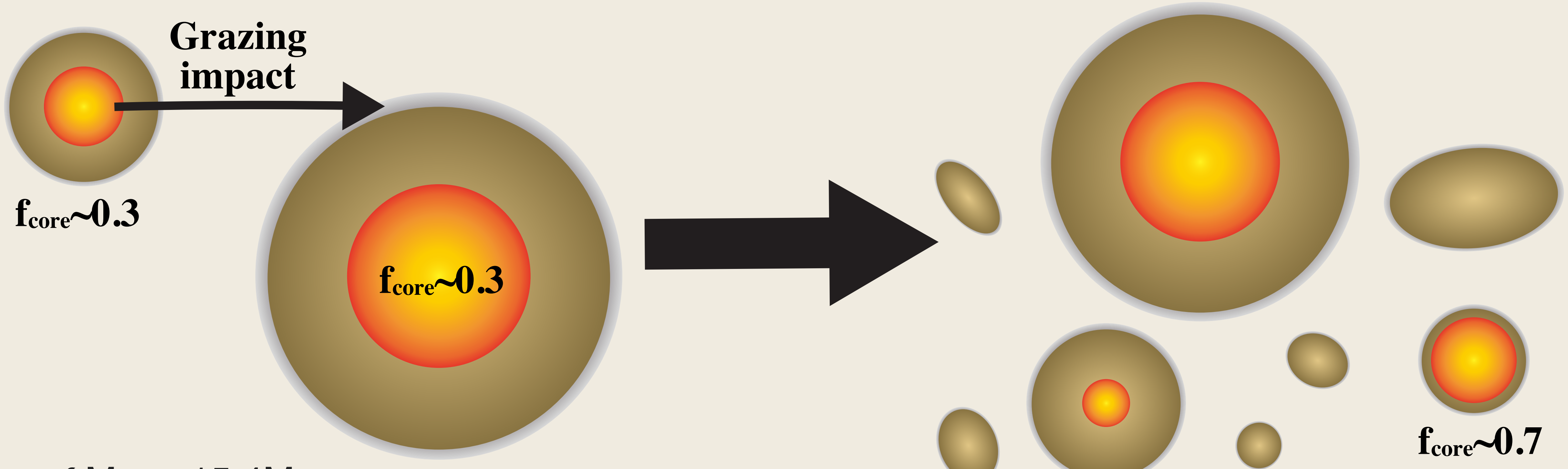


- ✓ M_{tar} = 2.25$M_{Mercury}$
- ✓ M_{imp} ~ 0.1M_{tar}
- ✓ v_{imp} ~ 20-30km/s (~7v_{esc})

Quick note:
– Low probability?
– Re-accretion of the debris (~40% of them?)

Hit-and-run (e.g., Asphaug & Reufer 2014)

Impactor becomes Mercury

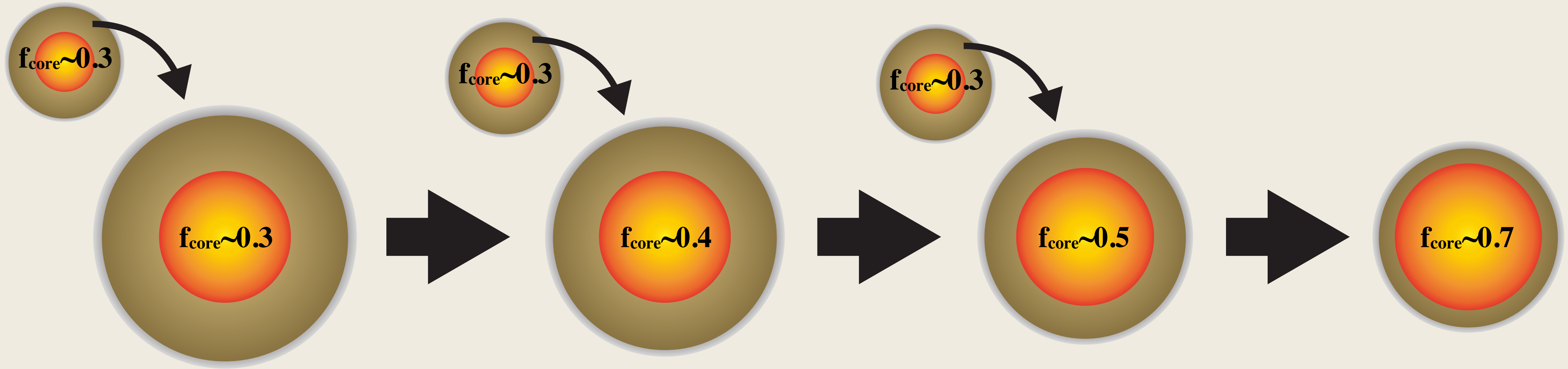


- ✓ M_{tar} = 15.4$M_{Mercury}$
- ✓ M_{imp} = 4.52$M_{mercury}$
- ✓ v_{imp} ~ 17km/s (~3v_{esc})

Quick note:
– The fate of largest remnant? Would it be Venus?

Erosion by multiple collisions (Chau et al. 2018)

Multiple embryo-embryo (e.g., ~1,000km-sized) collisions

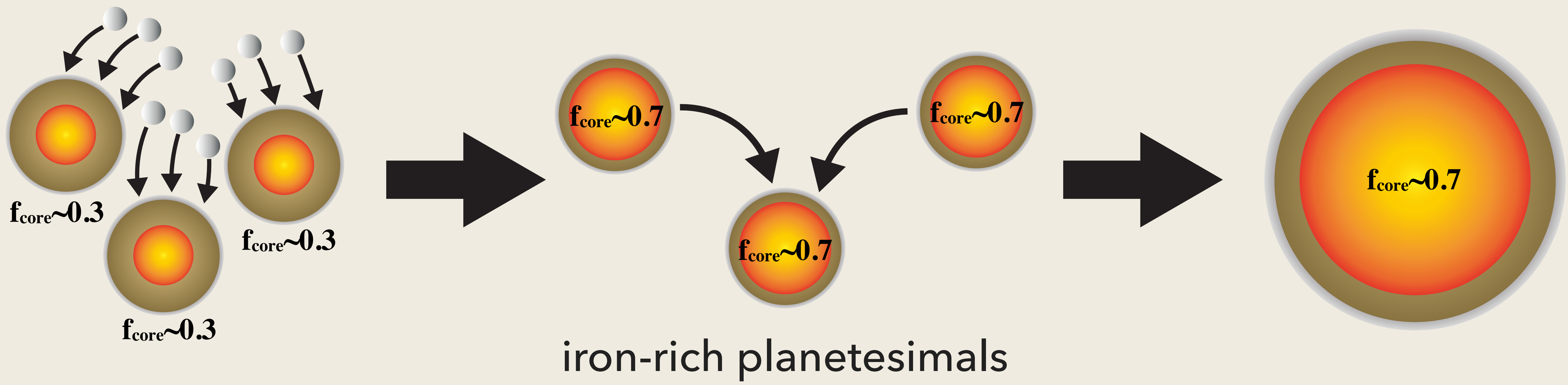


- ✓ M_{tar} ~ 2.25$M_{Mercury}$
- ✓ M_{imp} ~ 0.2M_{tar}
- ✓ v_{imp} ~ 10km/s (~3-4v_{esc})

Quick note:
– This process may be likely during planet accretion.
– Ejecta re-accretion? (ejecta's self-shielding to non-grav. forces?)
– Now, need to be tested in more N-body simulations

Cumulative erosive small impacts (Hyodo et al. 2021)

Planetesimals (~100km) are eroded by smaller impactors



Quick note:
– Re-accretion problem solved? (c.f., less ejecta at each impact and thus no self-shielding?)
– No one has ever modeled in the N-body simulations (i.e., the likelihood is unknown)

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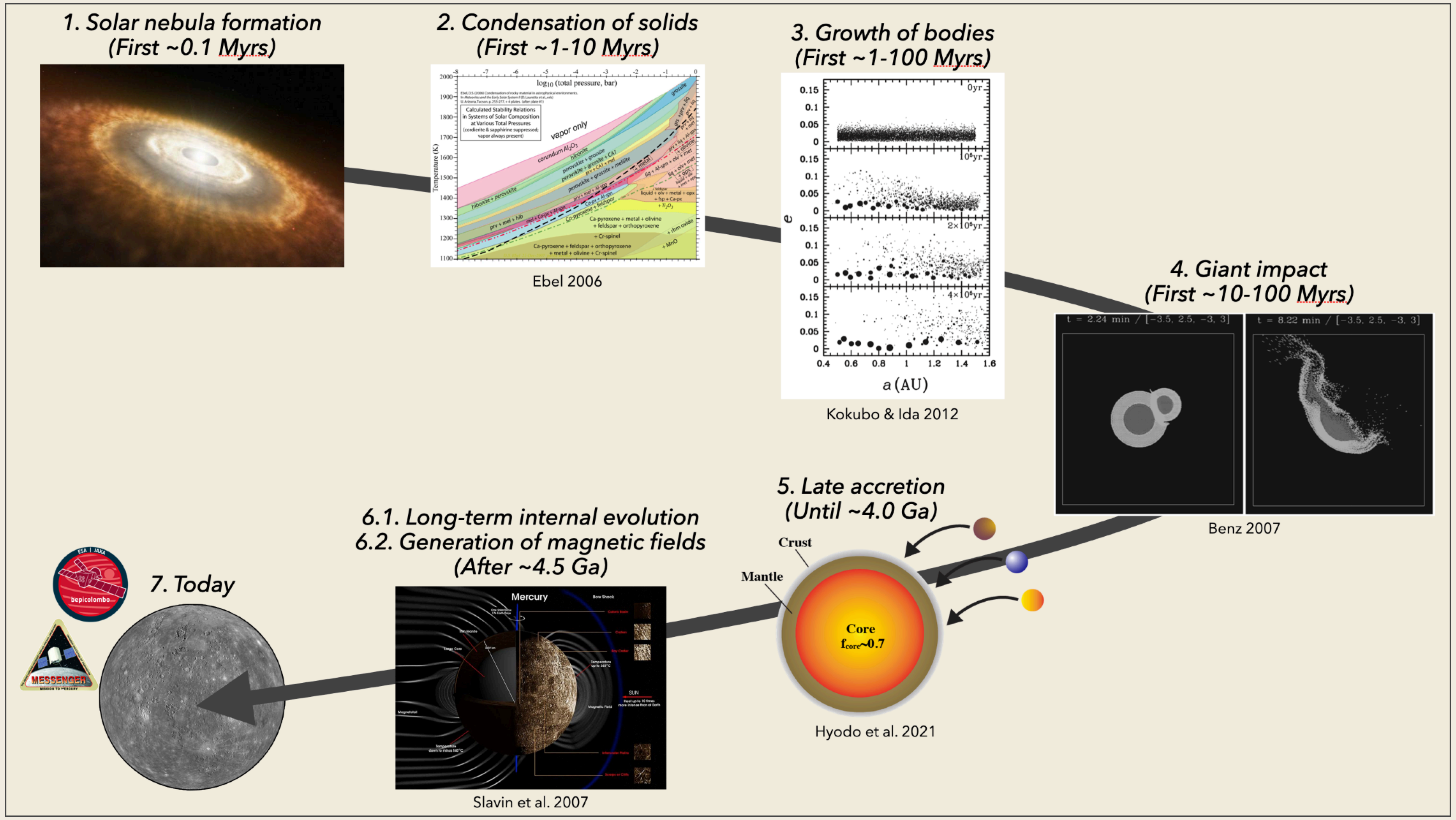
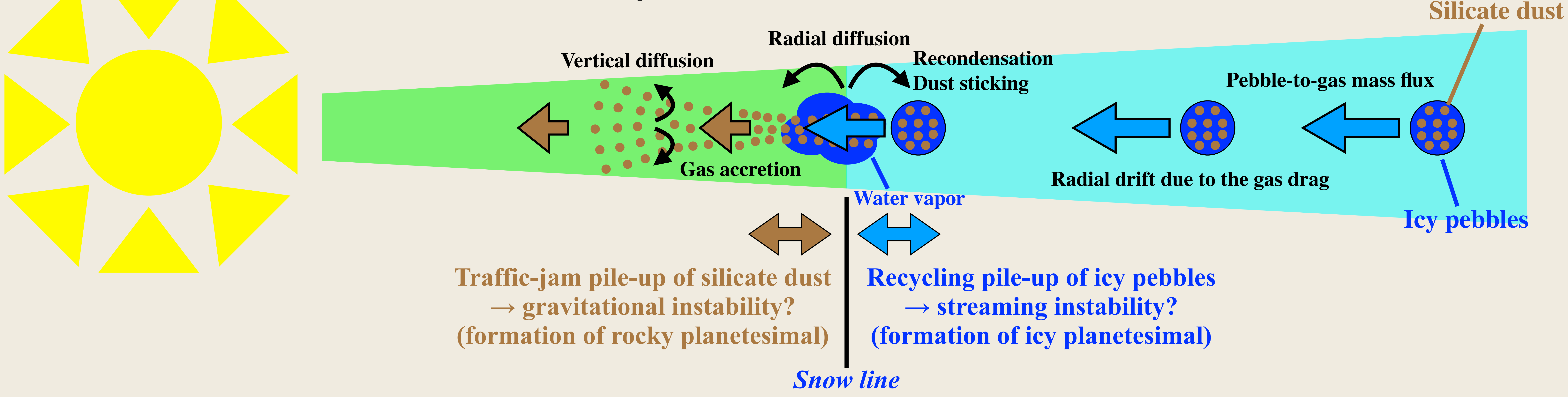


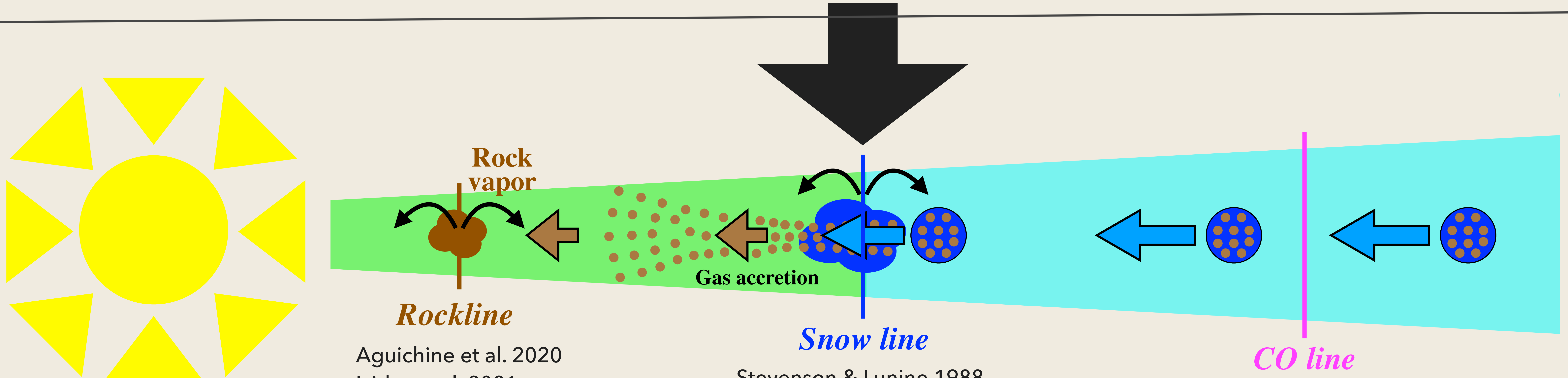
“Condensation line is the preferential location where materials pile up”

(Hyodo et al. 2019; 2021, A&A)



Traffic-jam pile-up of silicate dust
→ gravitational instability?
(formation of rocky planetesimal)

Recycling pile-up of icy pebbles
→ streaming instability?
(formation of icy planetesimal)



Aguichine et al. 2020
Izidro et al. 2021
Morbidelli+2021
Bogdan et al. 2023
Mah & Bitsch 2023

Stevenson & Lunine 1988
Ciesla & Cuzzi 2006
Ros & Johansen 2013
Schoonenberg & Ormel 2017
Drazkowska & Alibert 2017
Hyodo et al. 2019,2021

e.g. Oberg et al. 2011

Condensation of large iron-rich pebbles

"Large iron particles (i.e., large stokes number) preferentially experience the streaming instability, forming iron-rich planetesimals."

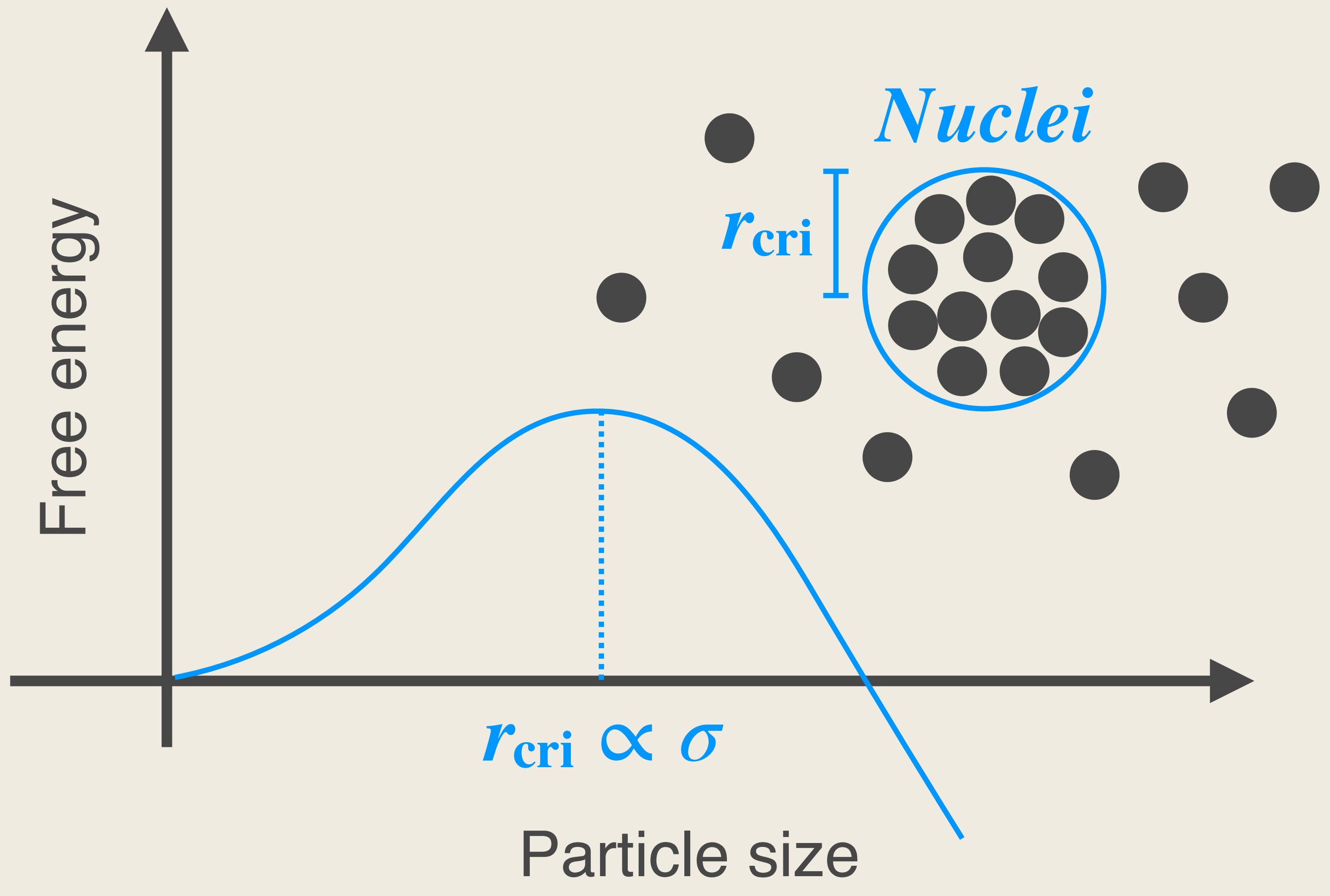
(Johansen & Dorn 2022)

Surface tension matters!

(as the nucleus formation rate is "exponentially" depends on σ)

$$\sigma_{\mathrm{Fe}} = 1.8\,\mathrm{J\,m^{-2}},\ \sigma_{\mathrm{Fe+S}} = 1.2\,\mathrm{J\,m^{-2}}$$

$$\sigma_{\mathrm{MgSiO_3}} = 0.4\,\mathrm{J\,m^{-2}},\ \sigma_{\mathrm{FeO}} = 0.6\,\mathrm{J\,m^{-2}}$$



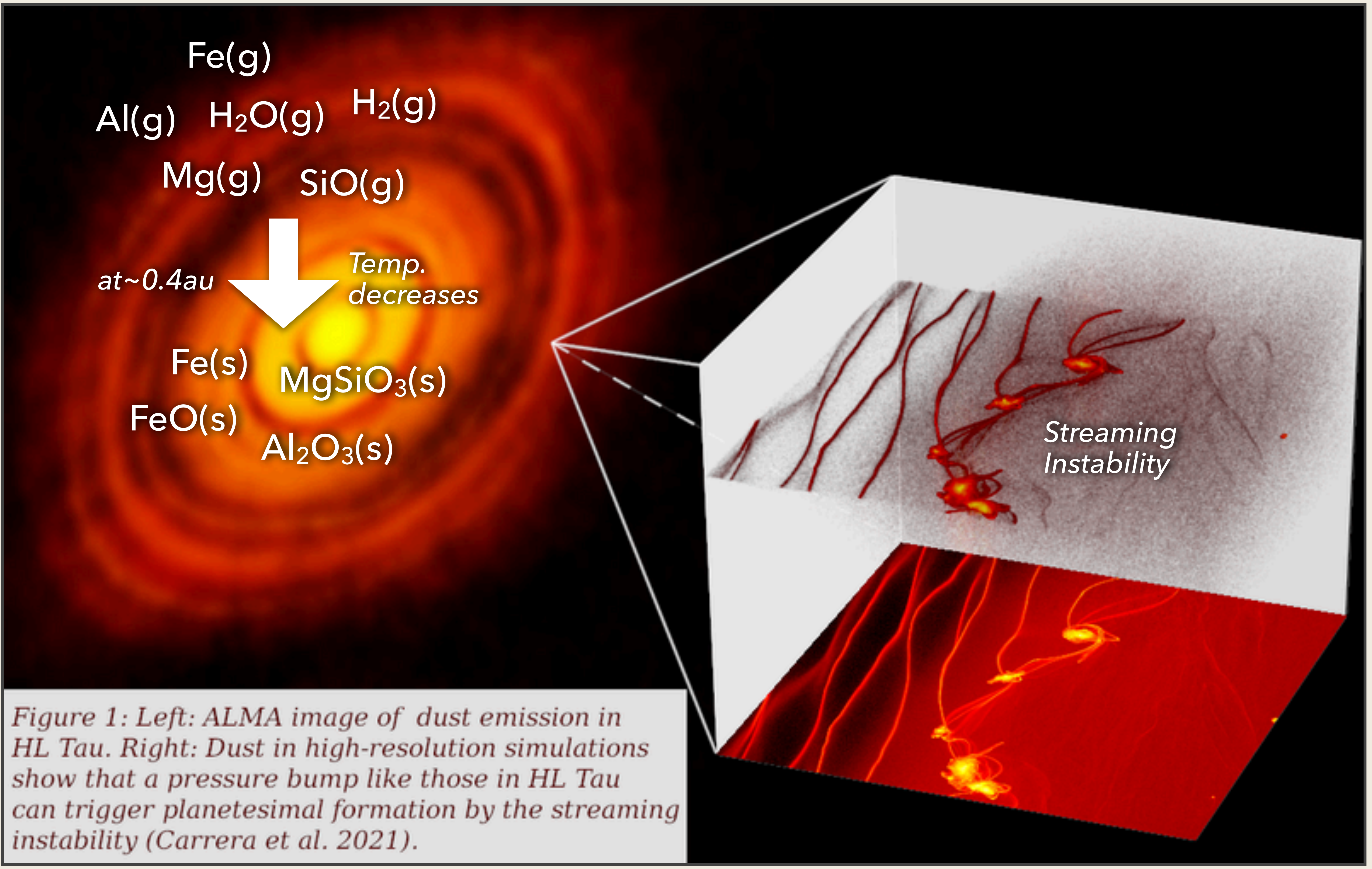
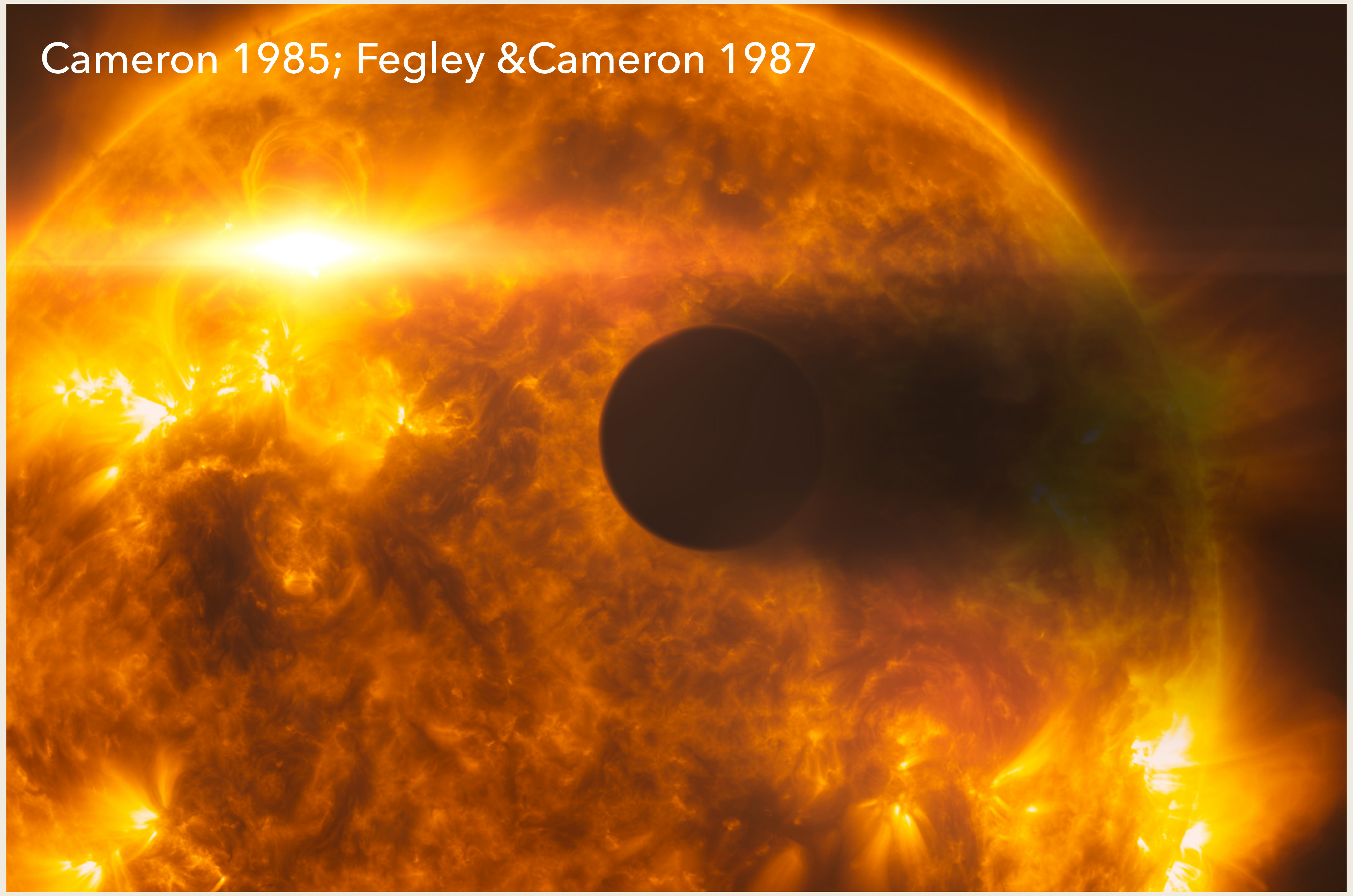


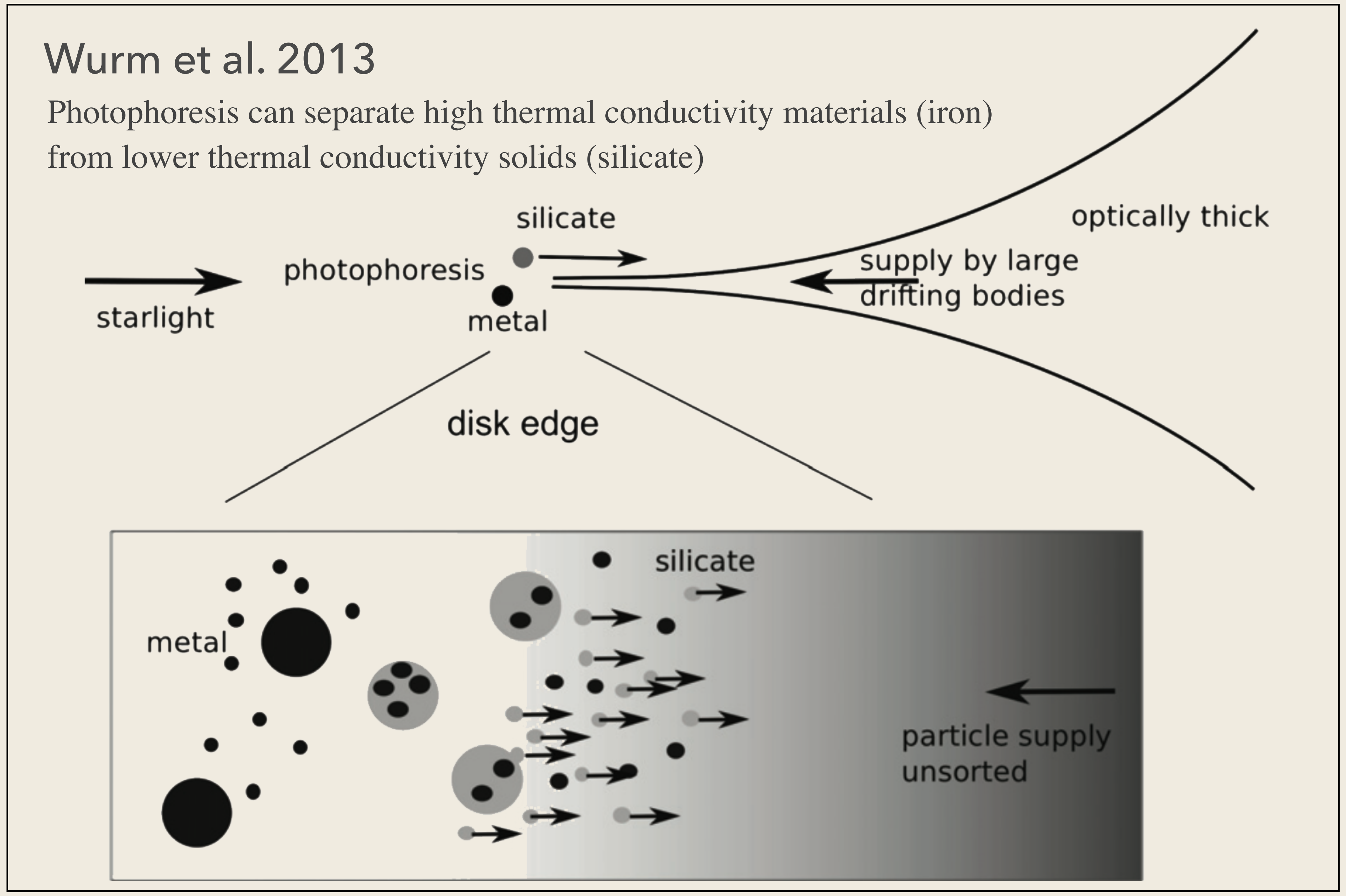
Figure 1: Left: ALMA image of dust emission in HL Tau. Right: Dust in high-resolution simulations show that a pressure bump like those in HL Tau can trigger planetesimal formation by the streaming instability (Carrera et al. 2021).

*Adding sulfur leads to condensation of Fe+S at a higher temperature than FeO.

And more from other ideas…

- Mantle evaporation (Cameron 1985; Fegley &Cameron 1987)
- Silicate/metal separation by photophoresis (Wurm et al. 2013)
- A compressed planetary core (Mocquet et al. 2014).




Wurm et al. 2013

Photophoresis can separate high thermal conductivity materials (iron) from lower thermal conductivity solids (silicate)

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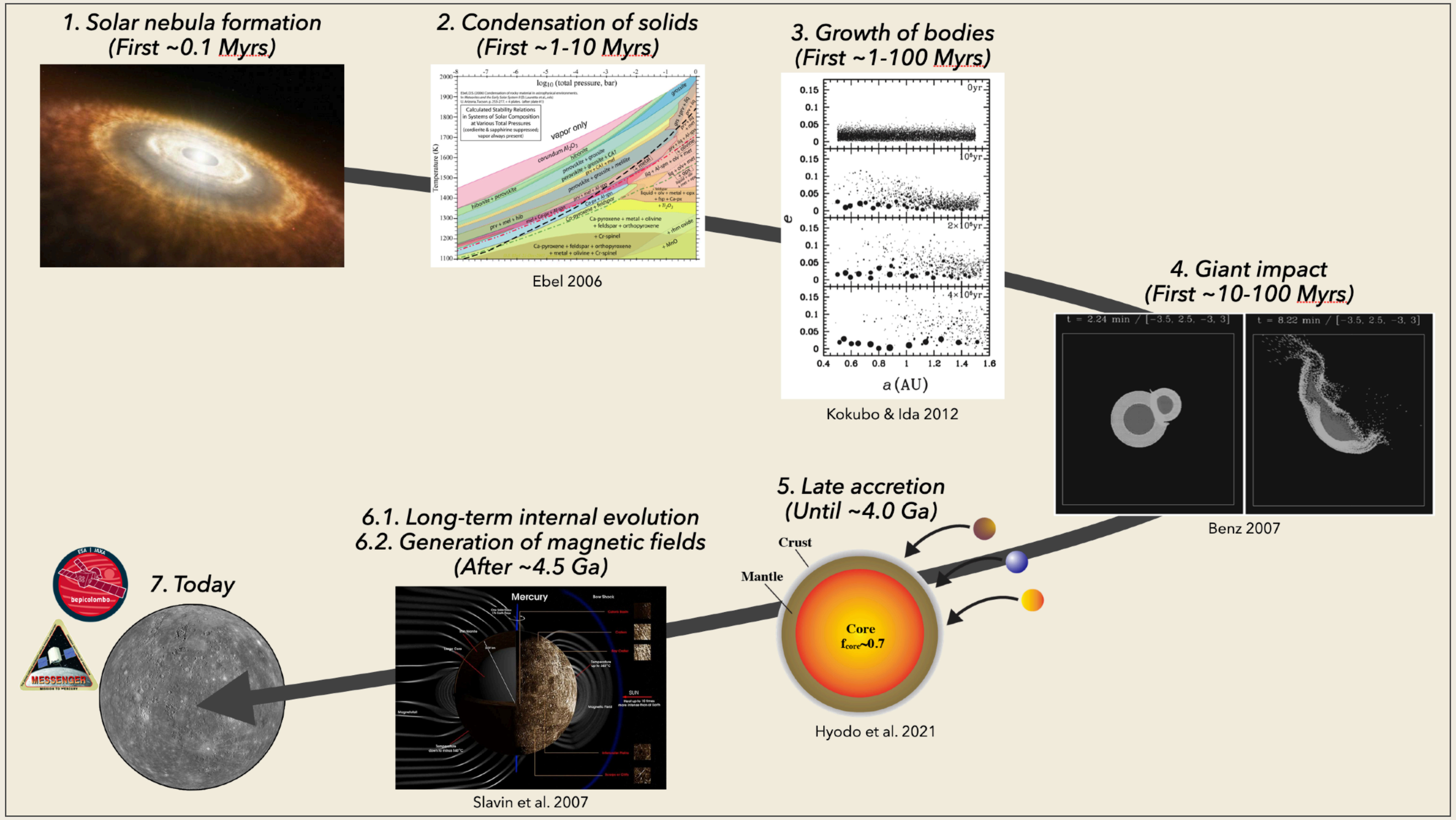

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(First ~0.1 Myrs)

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Ebel 2006

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(Until ~4.0 Ga)

Hyodo et al. 2021

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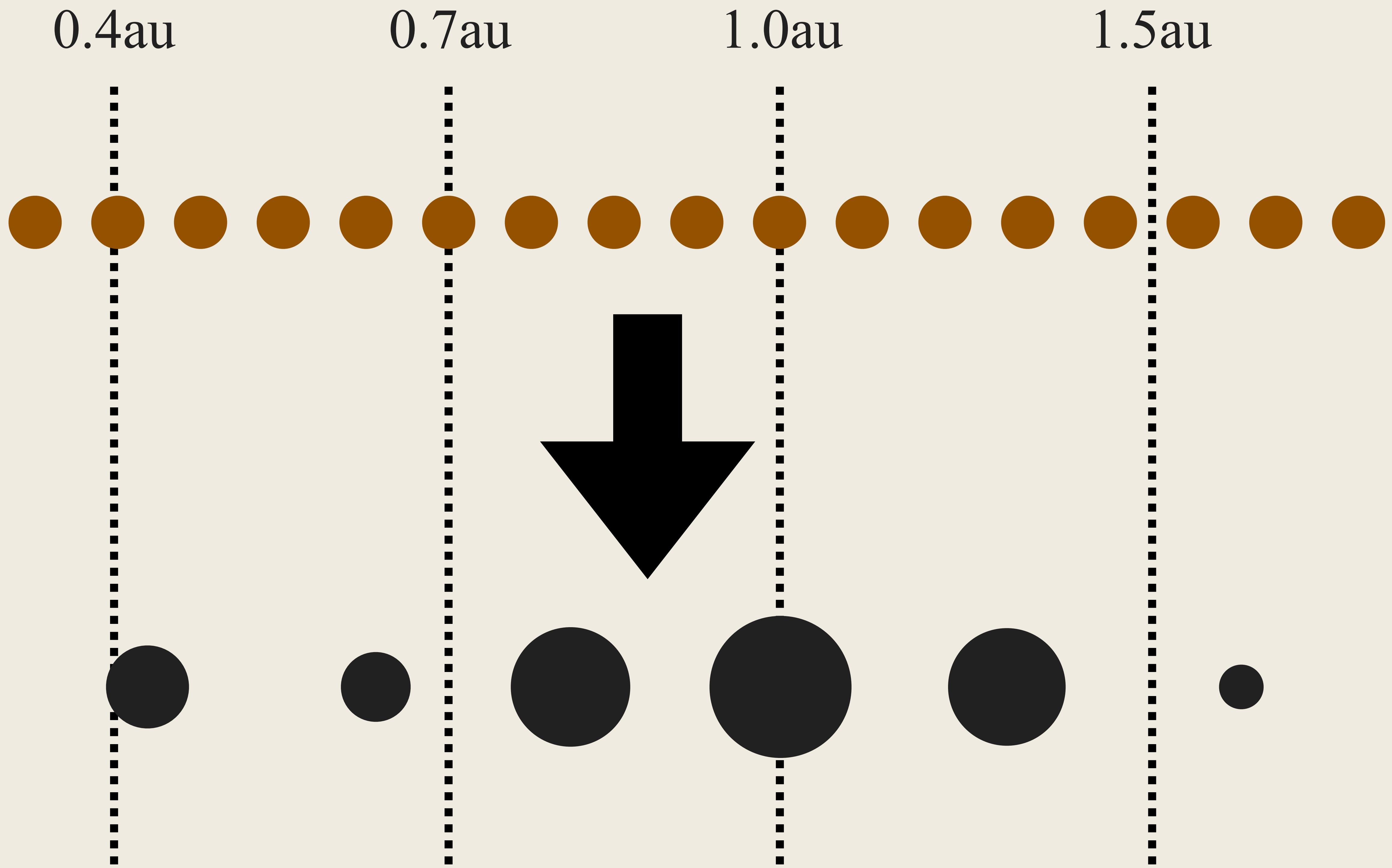
Slavin et al. 2007

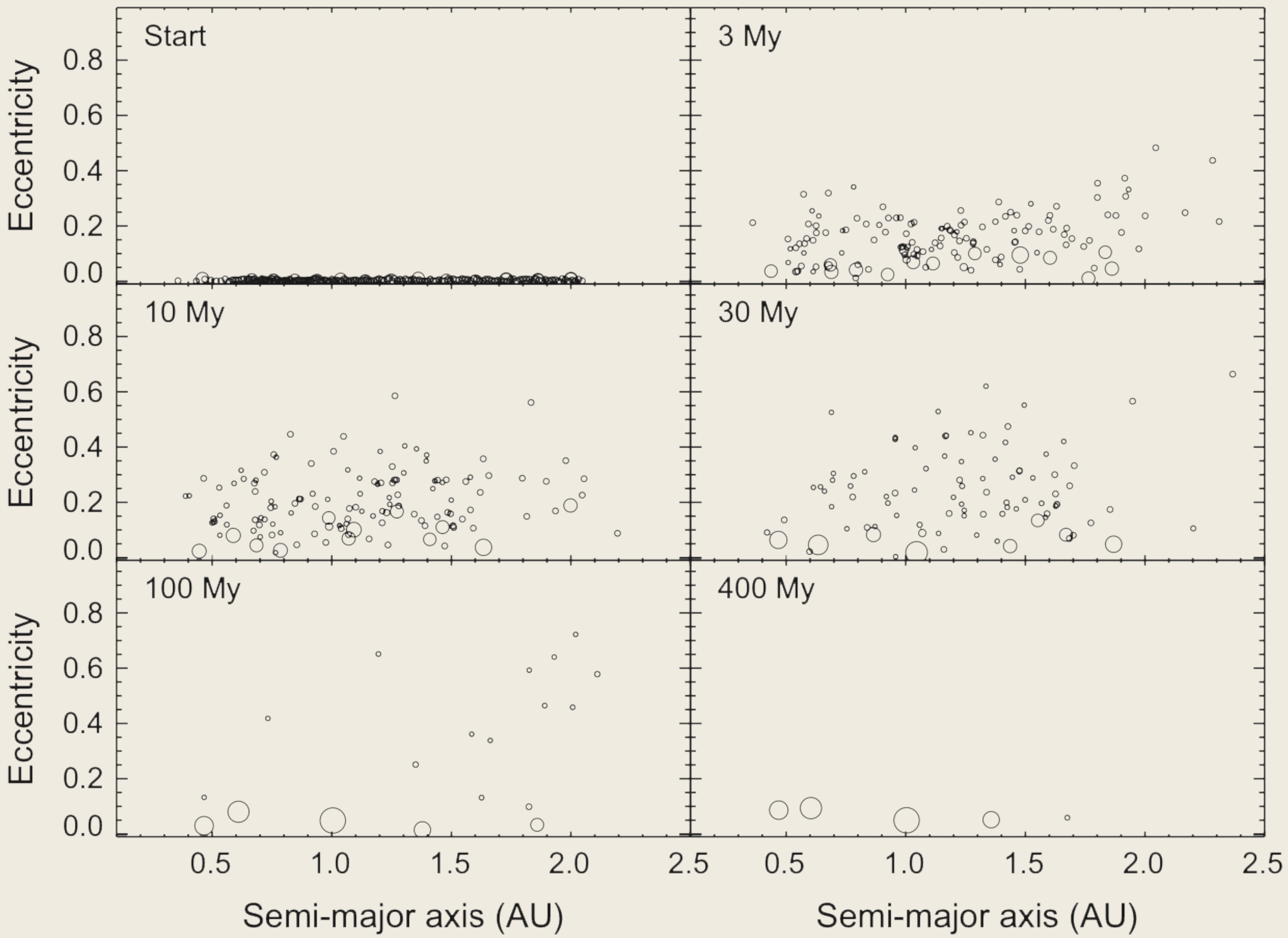
7. Today

Classical model

– a smooth continuous disk –

(Wetherill 1978; Hayashi 1981)



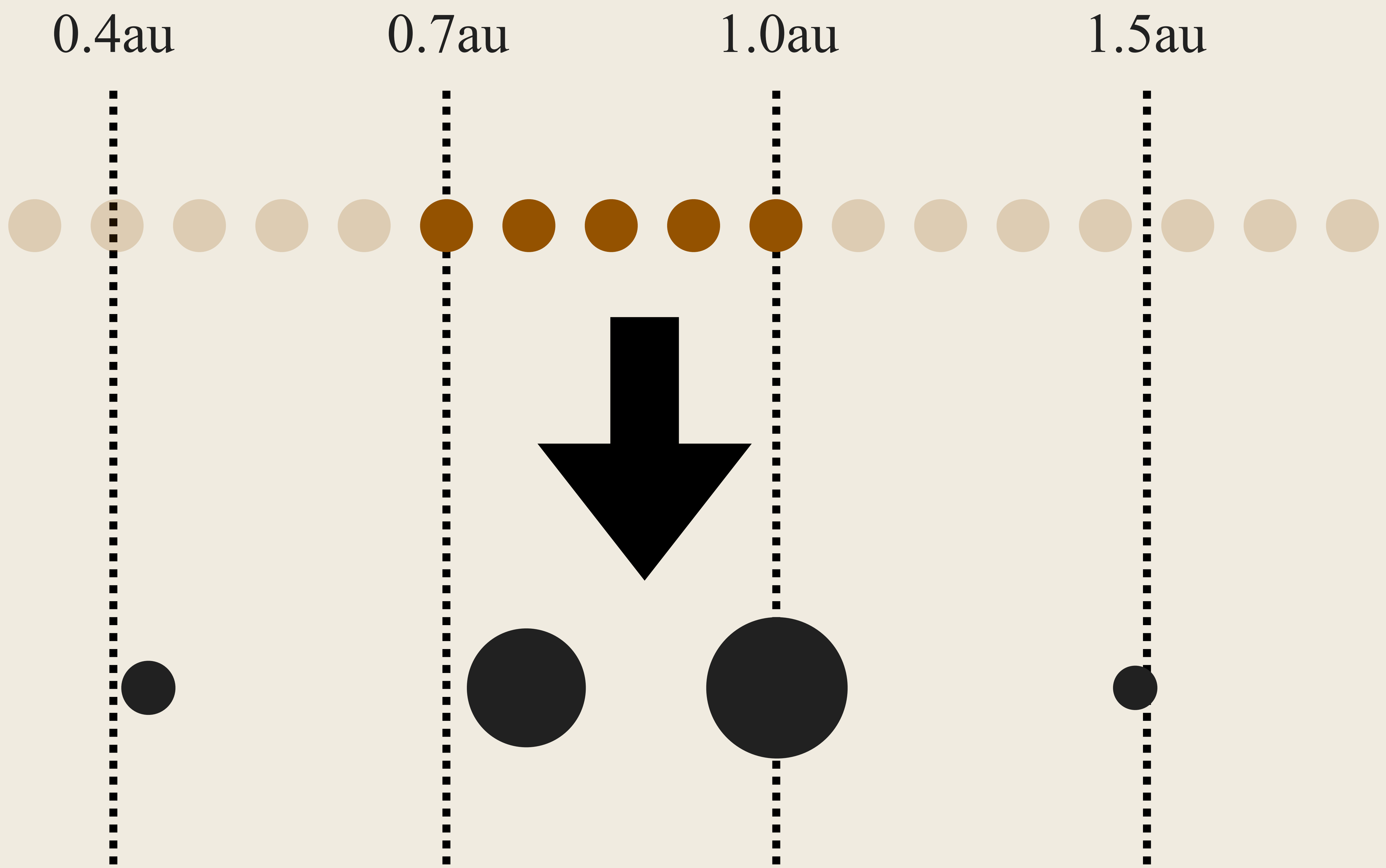


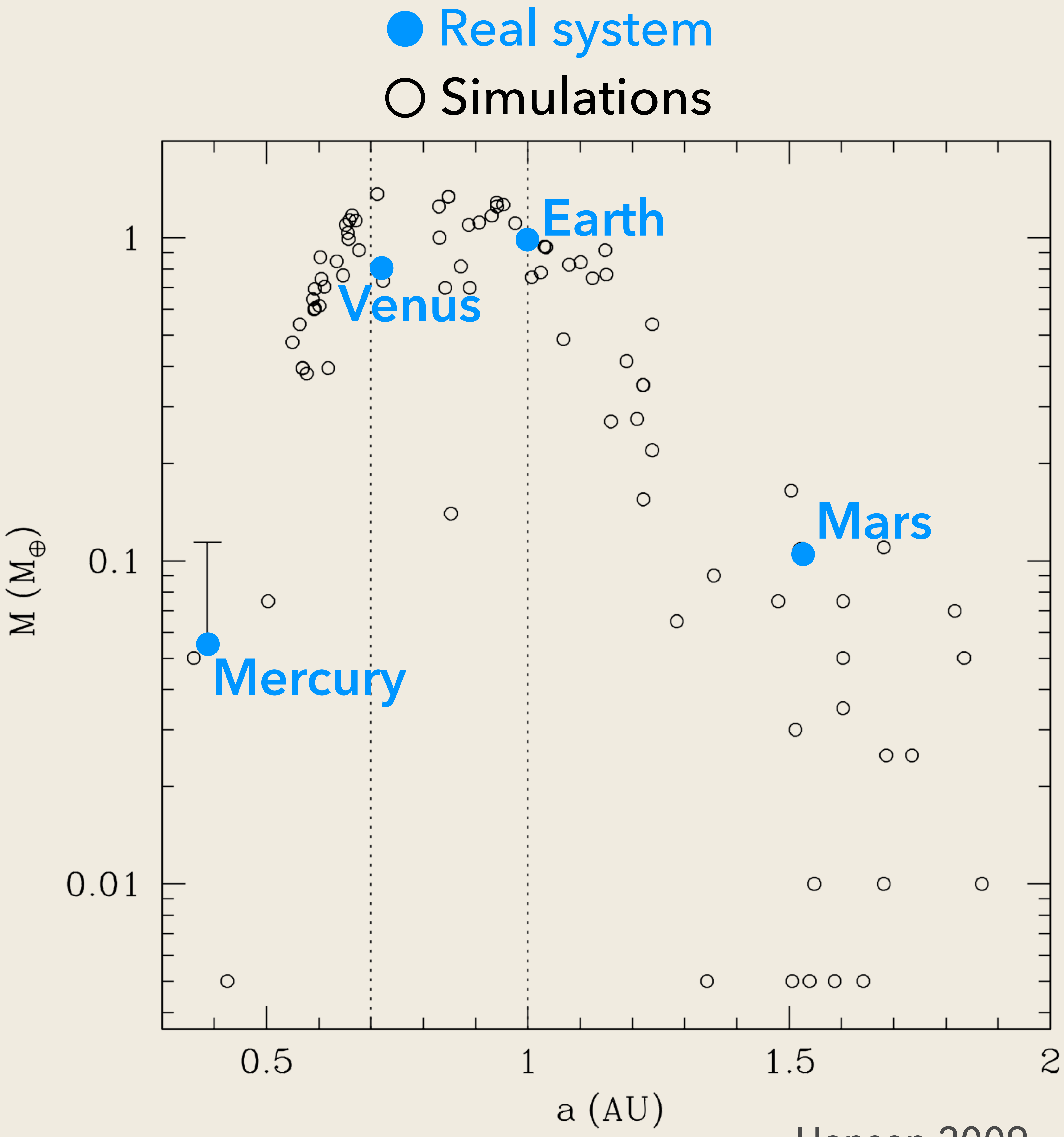
Chambers 2013; see also Chambers 2001

- Mass concentration (to Earth/Venus) is hardly explained.
- Fragmentation can explain real AMD, but not RMC.

Narrow ring model

(e.g., Hansen 2009; Walsh & Levison 2016, Woo 2024)



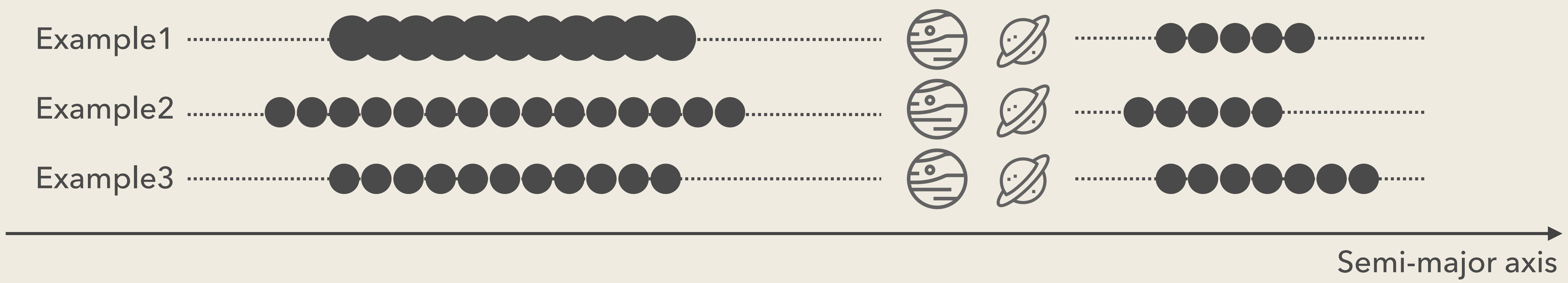


Hansen 2009

- Compact system
- Good AMD (the system is *not* too excited)
- Good RMC (Mass concentration at Venus and Earth)

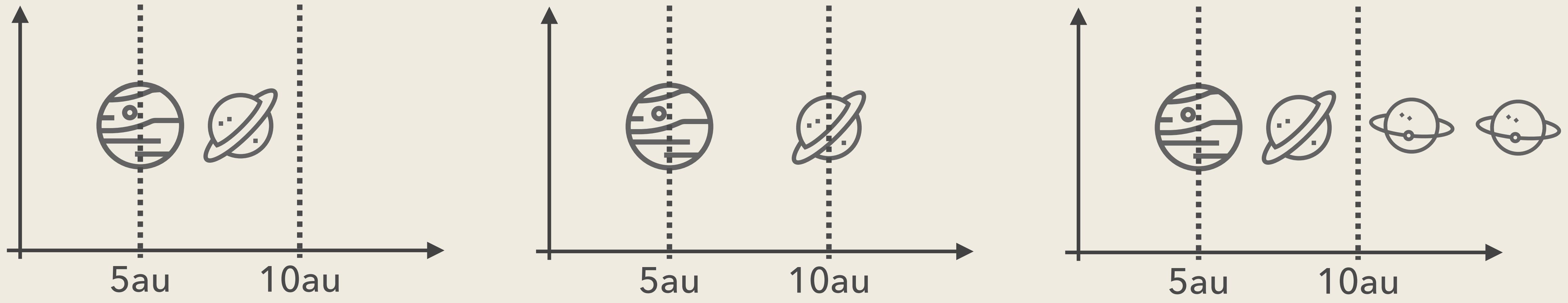
Now scientists are studying…

✓ Distribution w/w.o various gas disks



e.g.,
Chambers 20
Hansen 2009
Walsh & Levison 2016
Izidoro et al. 2021
Clement et al. 2001
Woo 2024

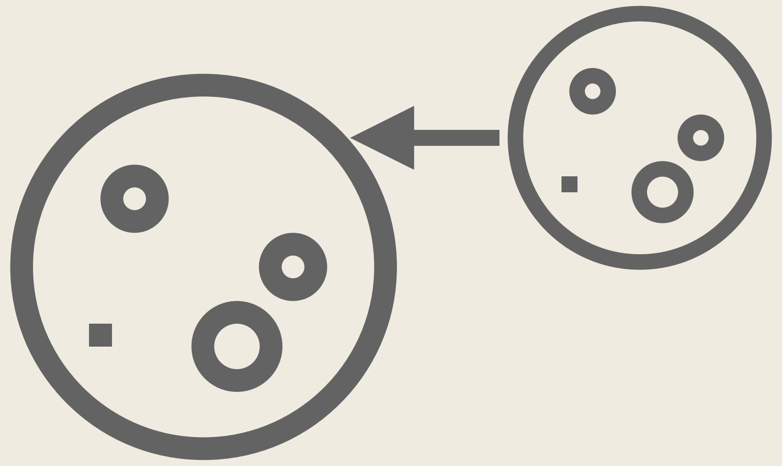
✓ Instability models



e.g.,
Chambers 2013
Raymond et al. 2016
Clement et al. 2019,2023
Franco et al. 2022
Woo et al. 2024

✓ Fragmentation models (*not* a single giant impact to form Mercury)

Destructive collisions among e.g. embryos



e.g.,
Marcus 2009
Stewart & Leignhardt 2009
Leinhardt & Stewart 2012
Carter et al. 2018
Gabriel et al. 2020

Cumulative erosion via numerous cratering impacts

e.g.,
Melosh 1989
Hyodo & Genda 2021,2022

See also
Reinhardt et al. 2022
Dou et al. 2024

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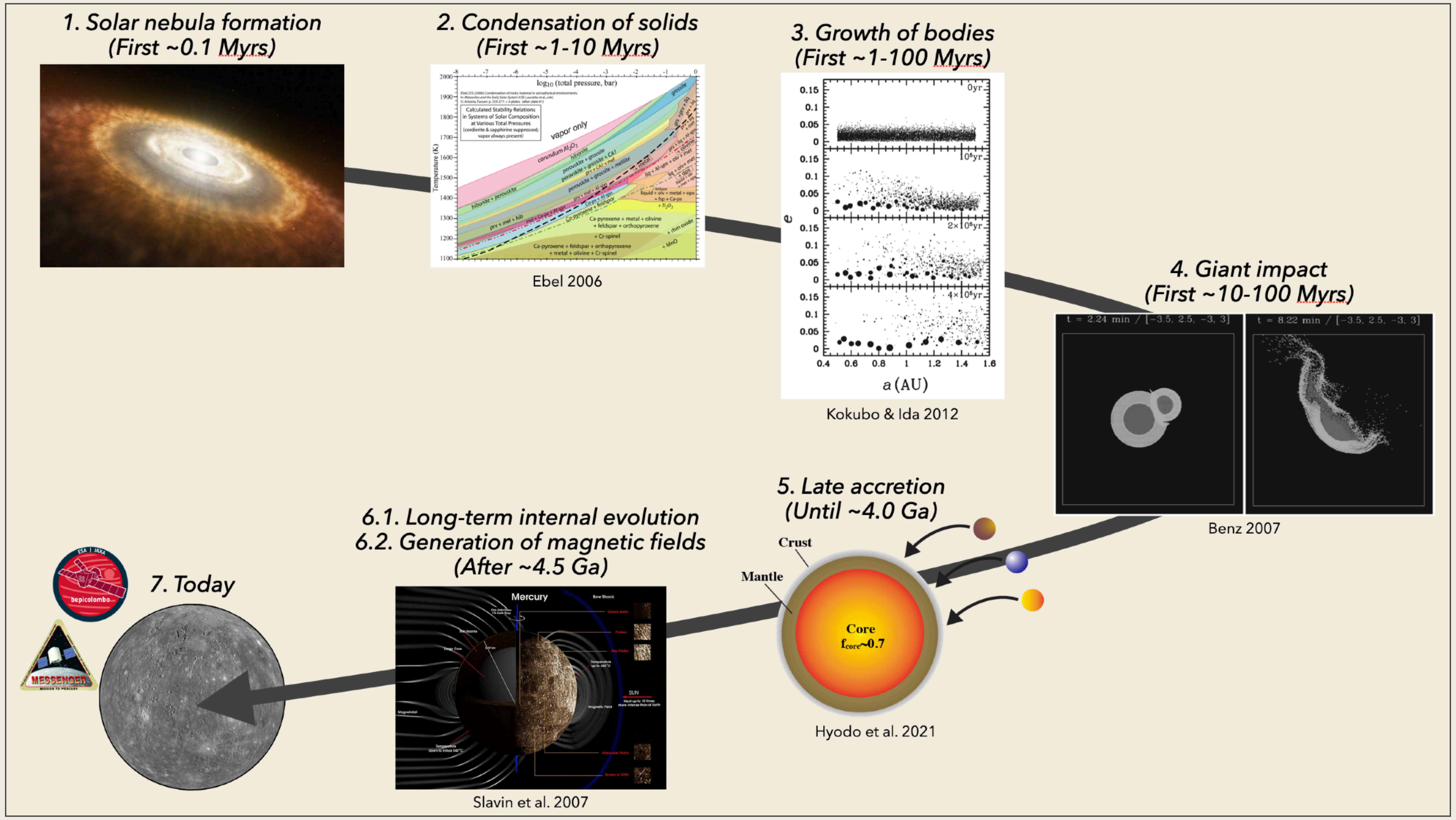

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Benz 2007

5. Late accretion (Until ~4.0 Ga)

Hyodo et al. 2021

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(After ~4.5 Ga)

Slavin et al. 2007

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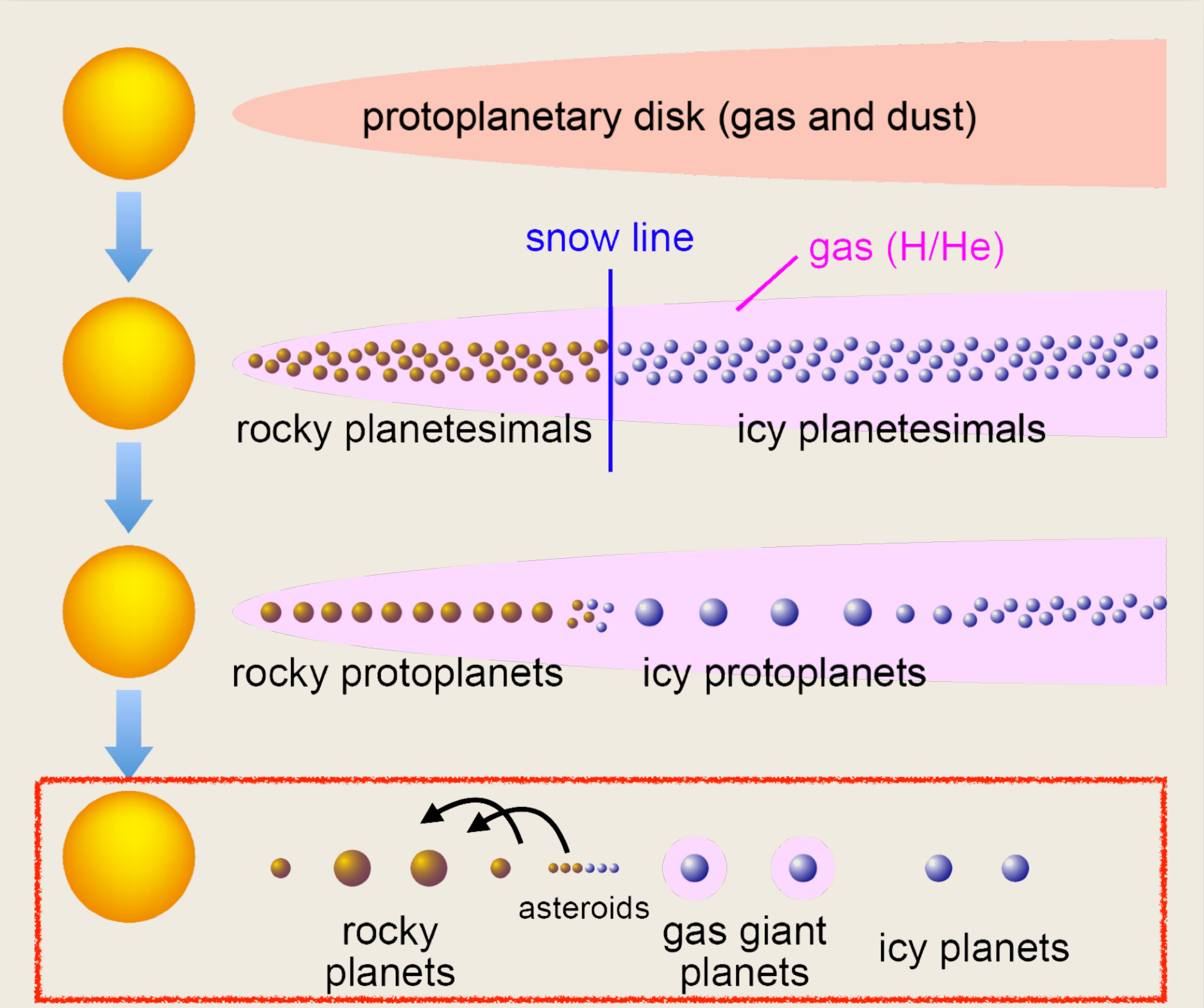
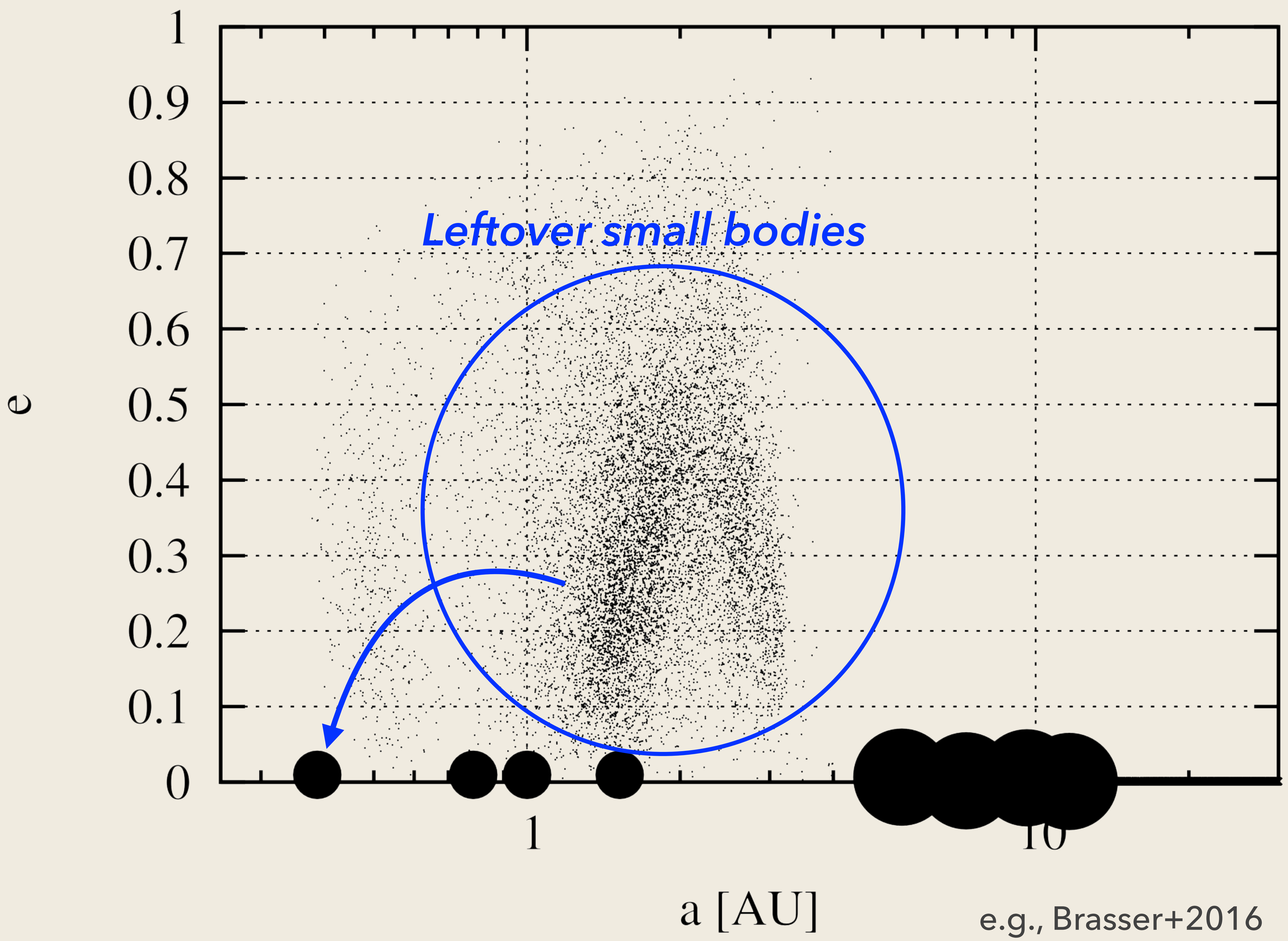
What is the late accretion?



Late accretion occurs at the last stage of planet formation

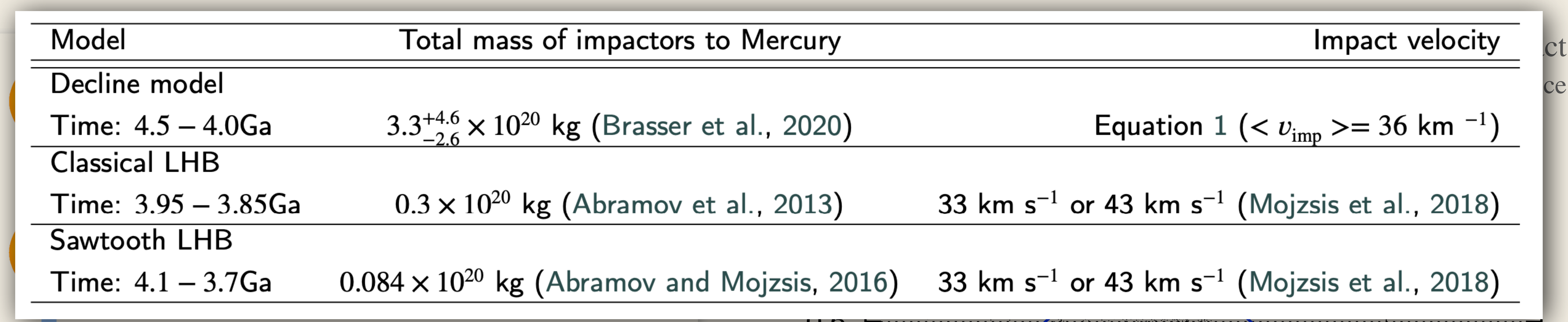
Late accretion is inevitable; i.e., a numerous crater-forming impacts.

*a giant impact is a *stochastic* process



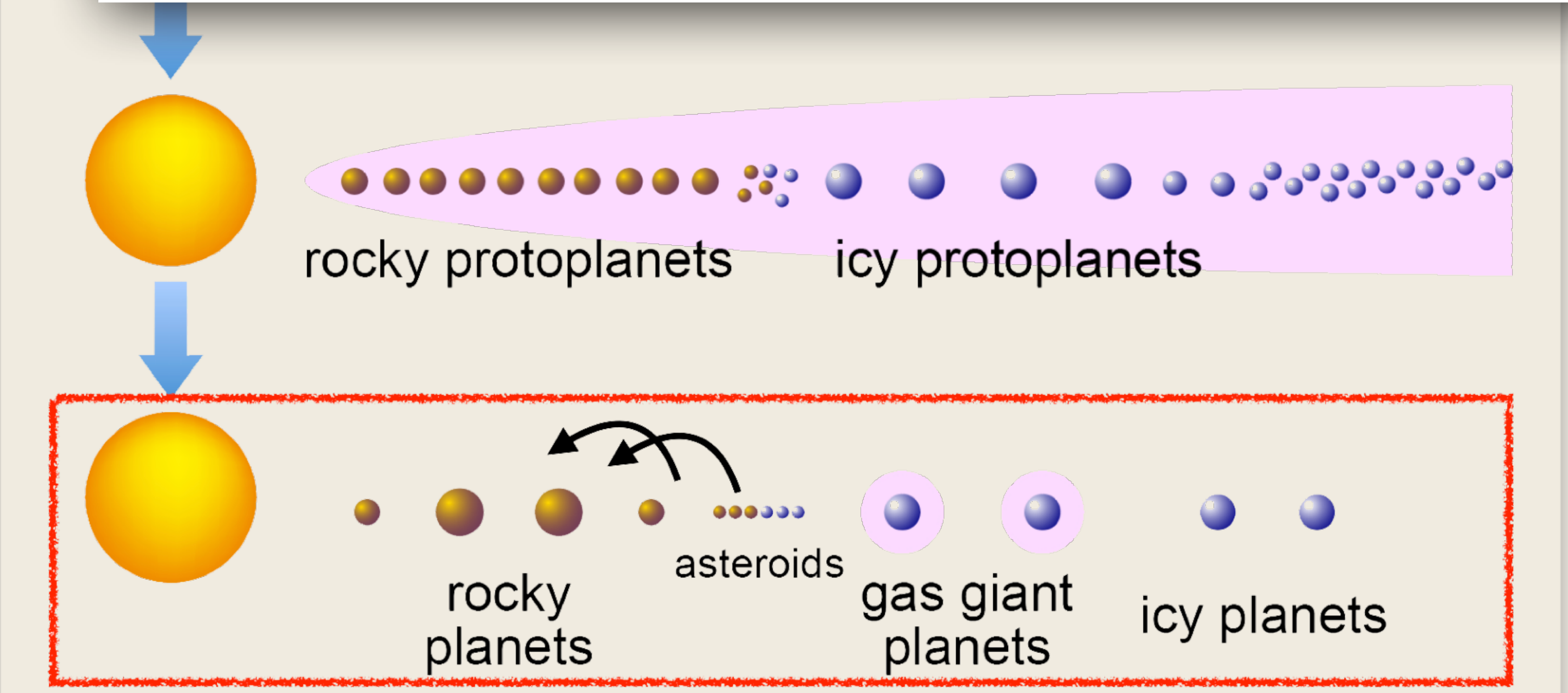
e.g., Brasser+2016

Late accretion depends on models



Model	Total mass of impactors to Mercury	Impact velocity
Decline model		
Time: $4.5-4.0$Ga	$3.3^{+4.6}_{-2.6}\times 10^{20}$ kg (Brasser et al., 2020)	Equation 1 ($< v_{\mathrm{imp}} >= 36$ km $^{-1}$)
Classical LHB		
Time: $3.95-3.85$Ga	0.3×10^{20} kg (Abramov et al., 2013)	33 km s^{-1} or 43 km s^{-1} (Mojzsis et al., 2018)
Sawtooth LHB		
Time: $4.1-3.7$Ga	0.084×10^{20} kg (Abramov and Mojzsis, 2016)	33 km s^{-1} or 43 km s^{-1} (Mojzsis et al., 2018)

cts.
cess



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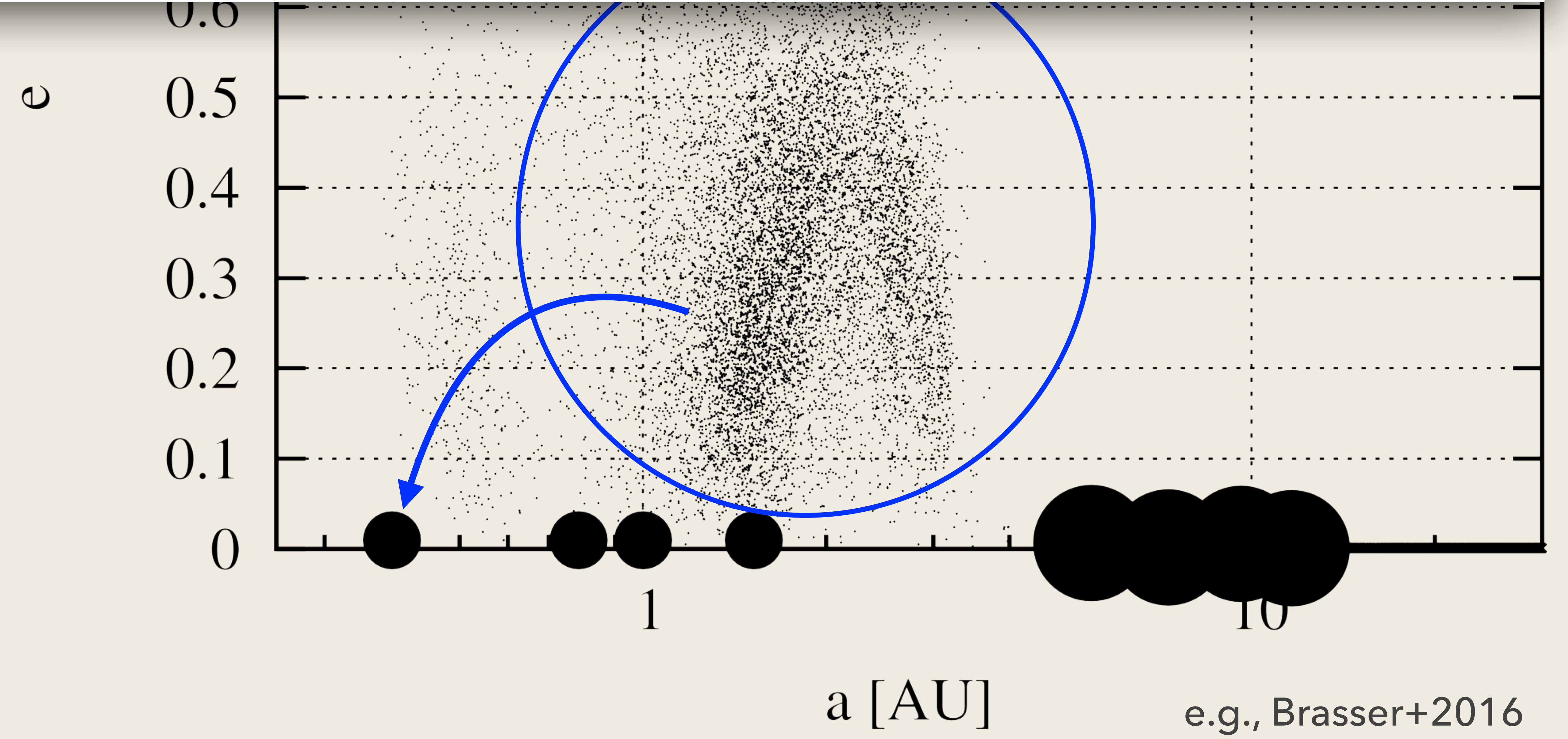


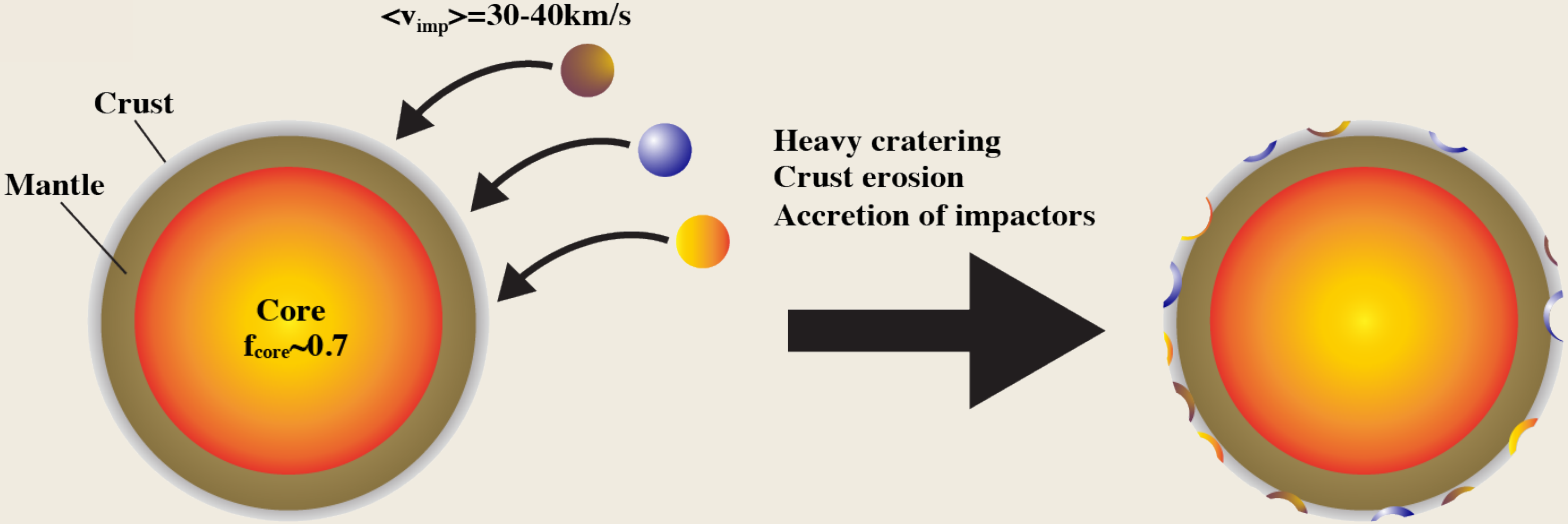
e.g., Brasser+2016

Late Accretion to Mercury

(Hyodo et al. 2021)

Late accretion is inevitable (~4 Ga):

- Surface composition would be *heterogeneously* modified.
  → i.e., volatiles can be provided even in a giant impact hypothesis.
- Global resurfacing with local crust melting would take place.



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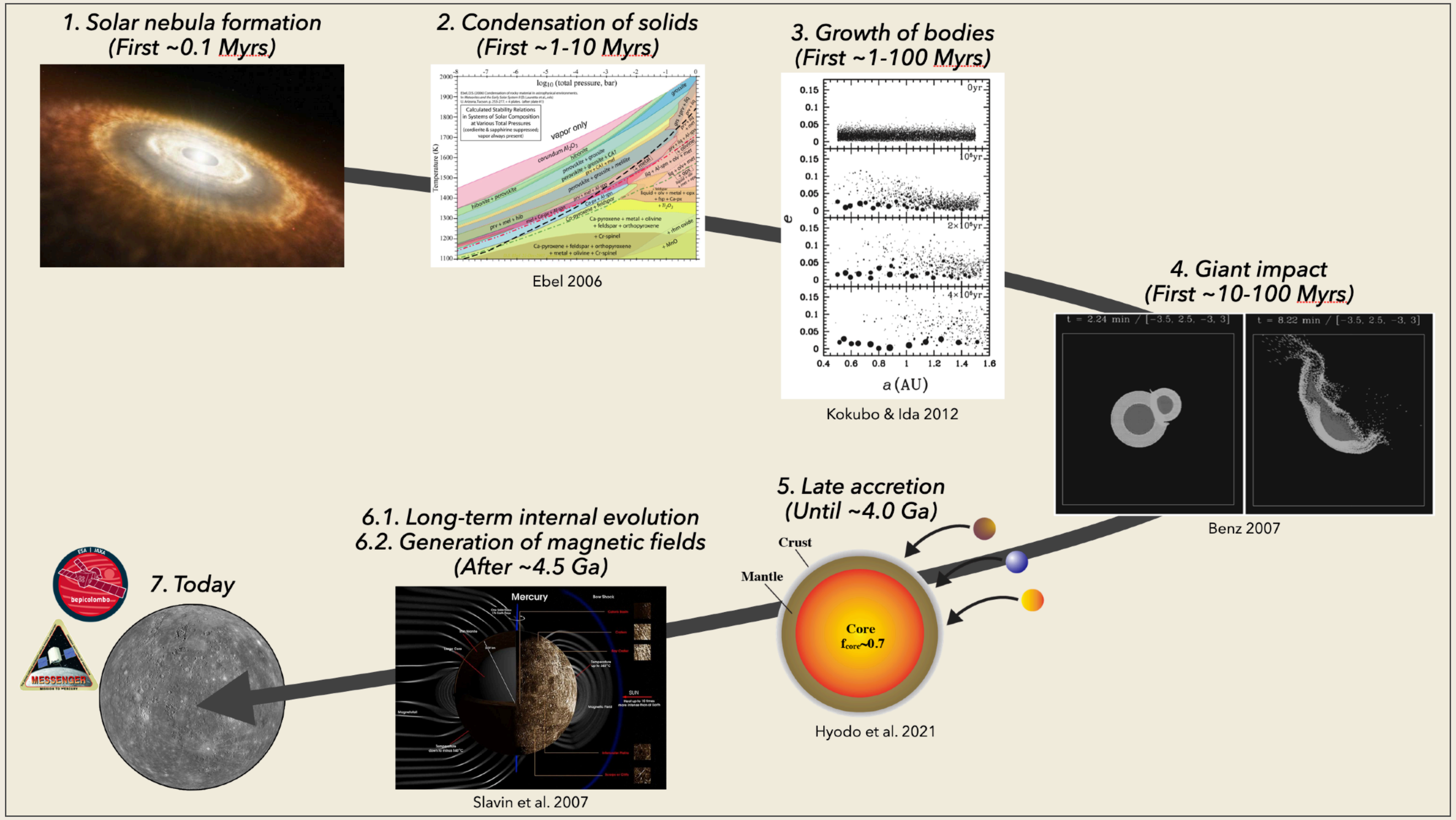

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Hyodo et al. 2021

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Slavin et al. 2007

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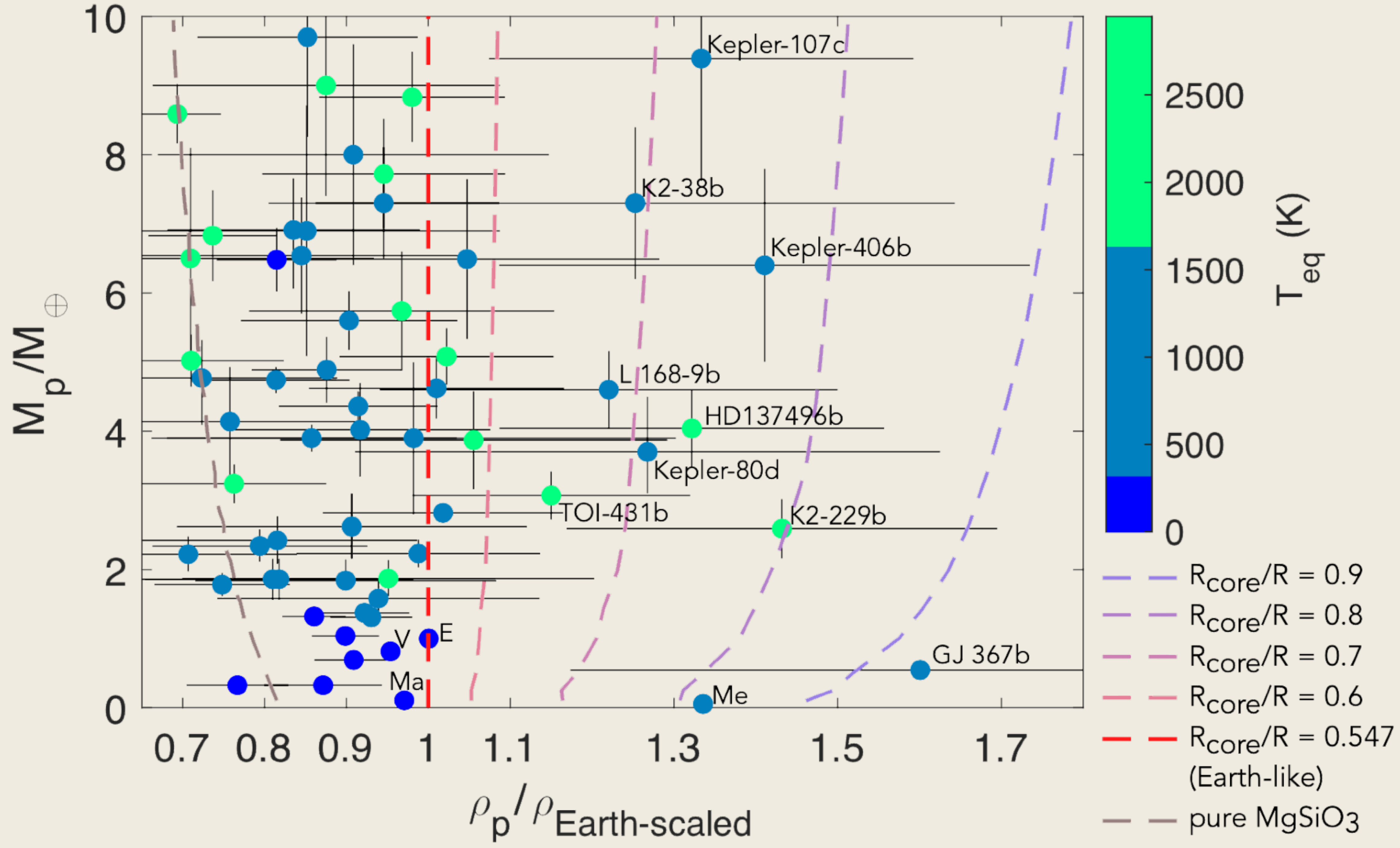
Super-Mercuries

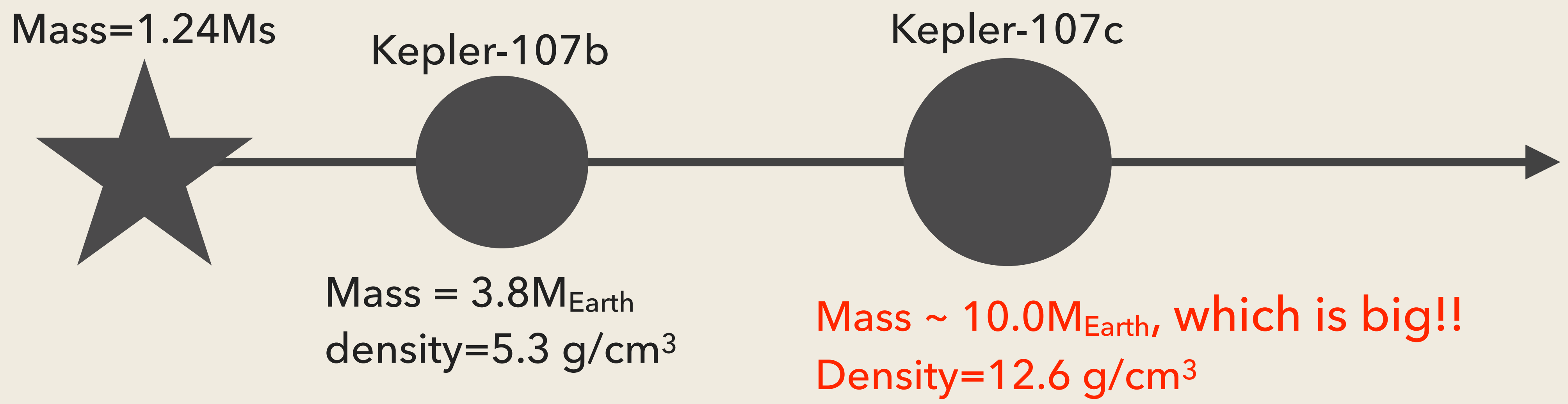
✓ Mercury is unique in the solar system.

✓ Super-Mercuries seem also unique in the exoplanet population.
→ An *unique* formation idea may be required for planet formation.



From Johansen & Dorn 2022

The inner most planet is not always the densest one.
(Bonomo et al. 2019)


Mass=1.24Ms

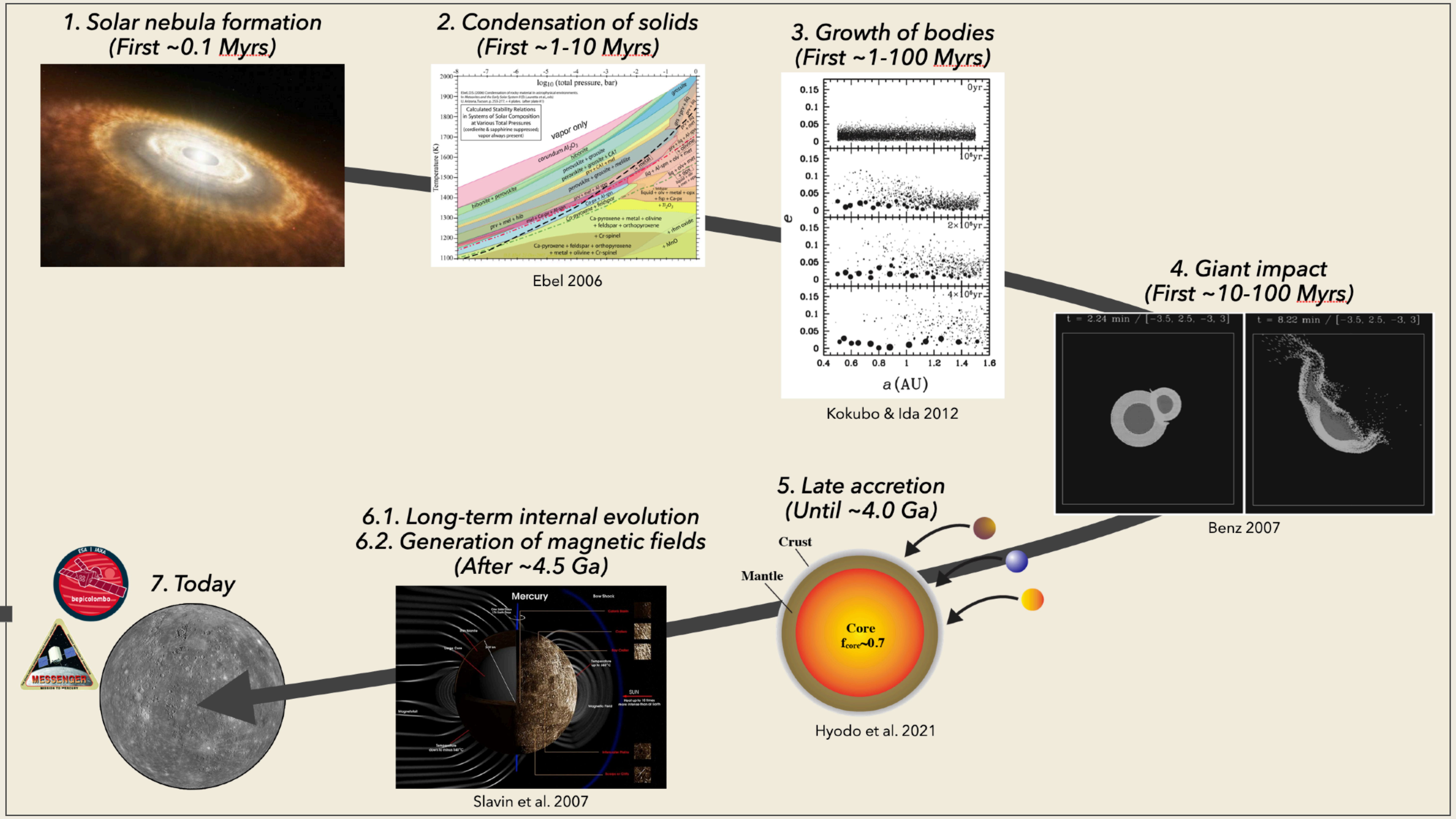
Kepler-107b
Mass = $3.8M_{Earth}$
density=5.3 g/cm^3

Kepler-107c
Mass ~ $10.0M_{Earth}$, which is big!!
Density=12.6 g/cm^3

- Not always the inner planet has a large core
  → Evaporation, separation, simple condensation models may not be preferred.
- A big planet can have a large core
  → A simple giant impact model may not be preferred.

Summary

- Condensation, accretion, fragmentation, and giant impact can all change the core fraction.
  → the dominant process is not yet understood.
- Late accretion can change the surface composition.
- Beyond Mercury's formation, the modeling needs to cover also super-Mercuries



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