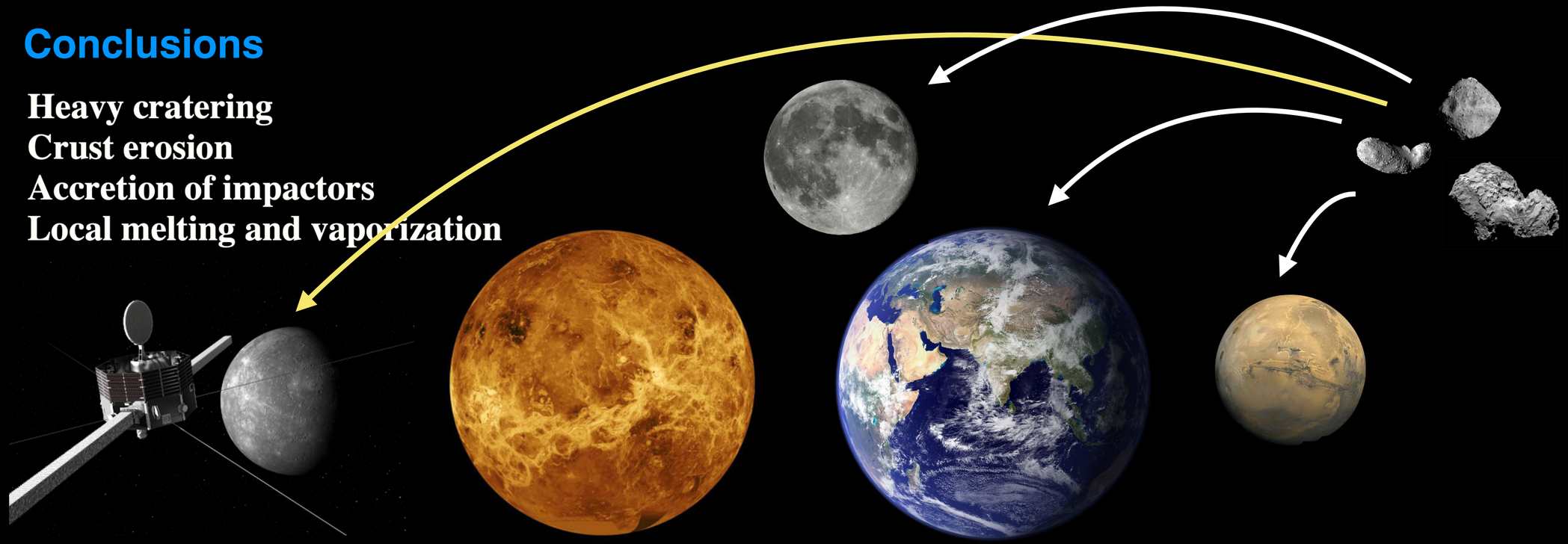
Modification of the composition and density of Mercury from late accretion

Conclusions

Heavy cratering
Crust erosion
Accretion of impactors
Local melting and vaporization



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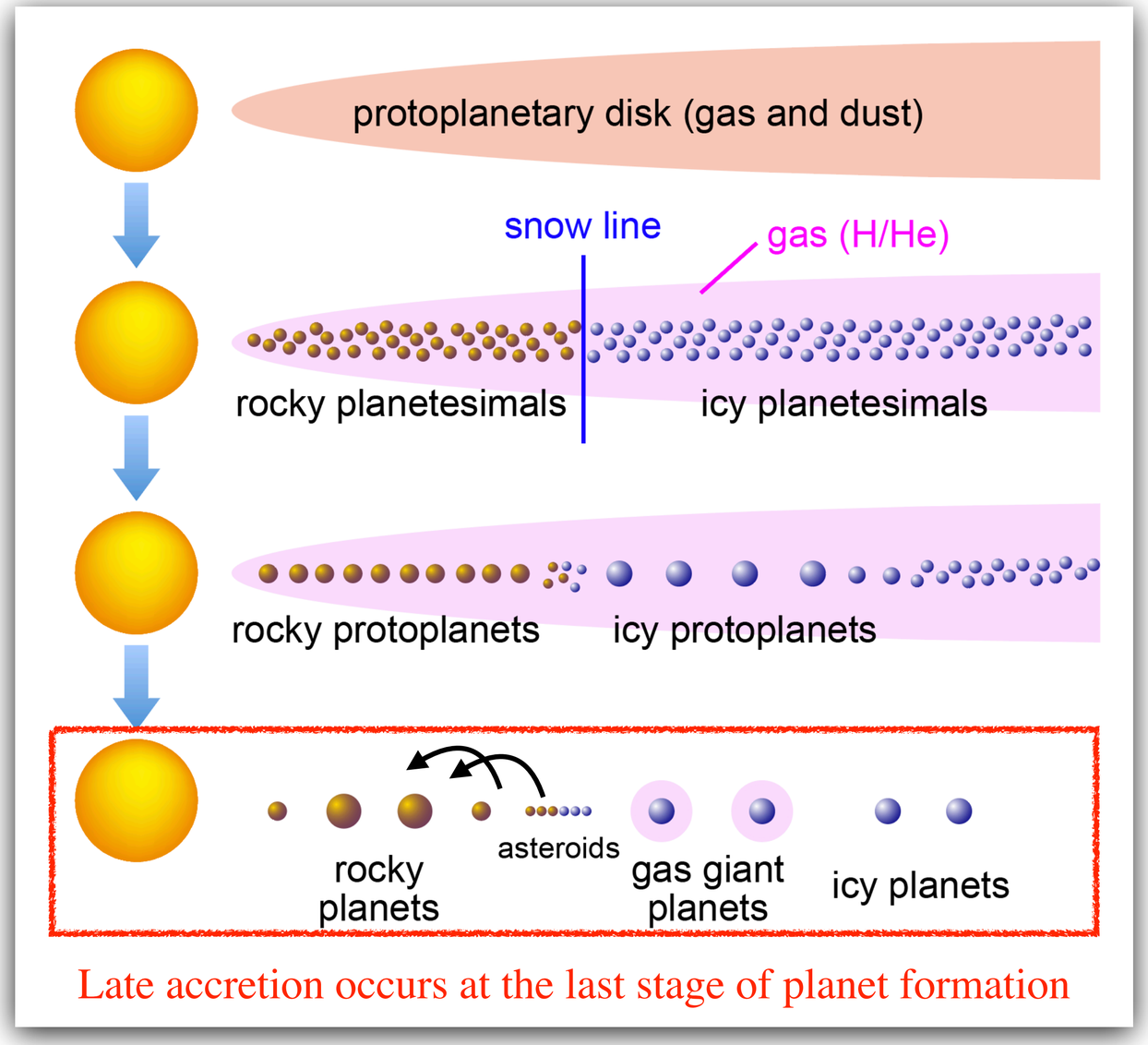
JAXA

Hyodo, Genda & Brasser (2021) *Icarus*

Today's Contents

- Introduction
  - What is "late accretion"?
  - Late accretion depends on planet formation model
- Methods → Consequences of late accretion
  - How significantly could Mercury's surface be eroded?
  - How much of impactors' materials could be implanted on Mercury's surface?
  - What are the fate of impactors? — Melted? Vaporized?
- Summary
- Discussion
  - What should we do in the future?

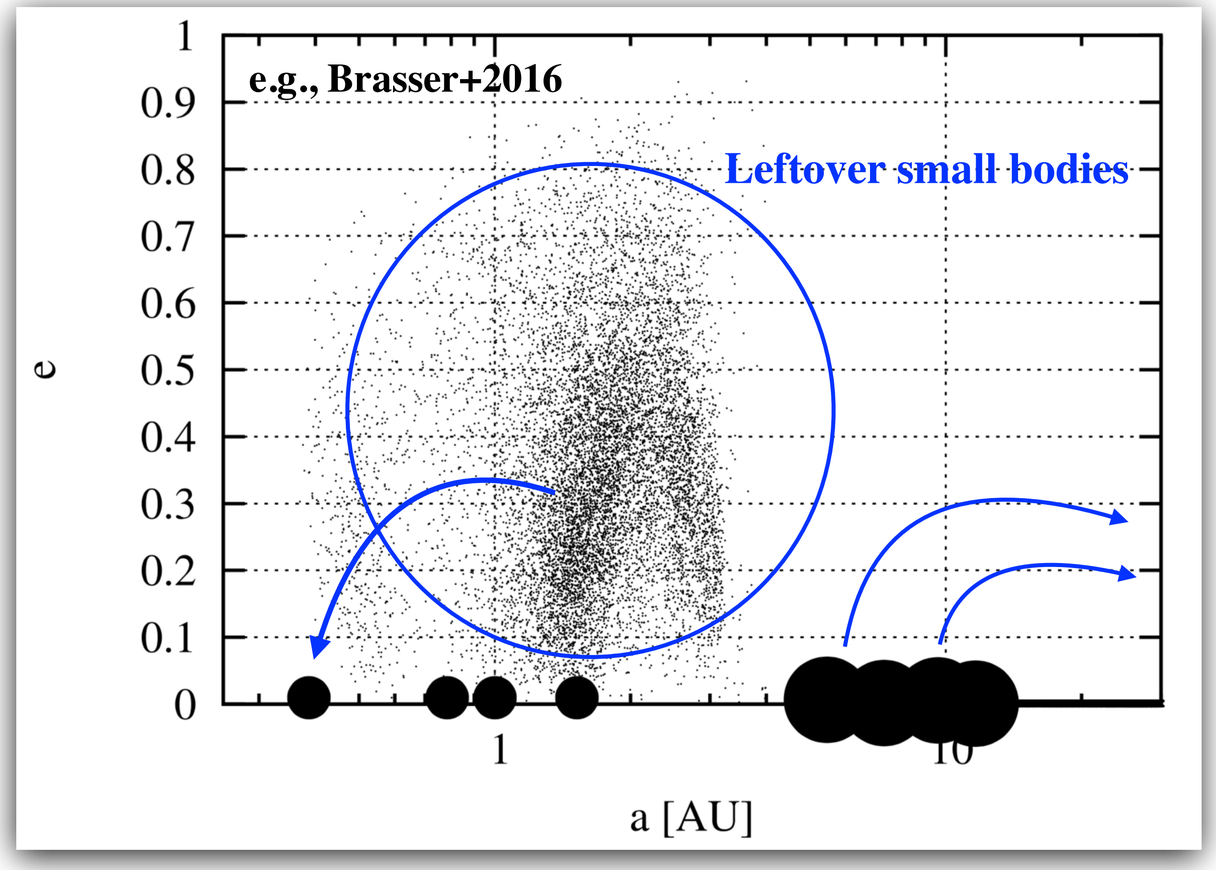
What is “late accretion”?



Late accretion occurs at the last stage of planet formation

Late accretion leads to numerous crater-forming impacts: that is, a *statistical* approach can be applied.

*A giant impact is a *stochastic* process

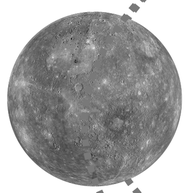


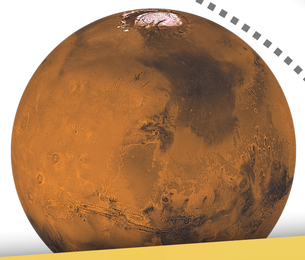
Late accretion depends on planet formation model

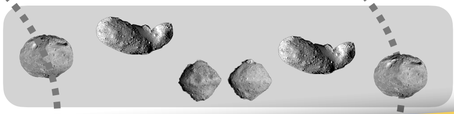
Model	Total mass of impactors to Mercury	Impact velocity
Decline model		
Time: $4.5 - 4.0$Ga	$3.3^{+4.6}_{-2.6} \times 10^{20}$ kg (Brasser et al., 2020)	Equation 1 ($< v_{\rm imp} >= 36$ km $^{-1}$)
Classical LHB		
Time: $3.95 - 3.85$Ga	0.3×10^{20} kg (Abramov et al., 2013)	33 km s^{-1} or 43 km s^{-1}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

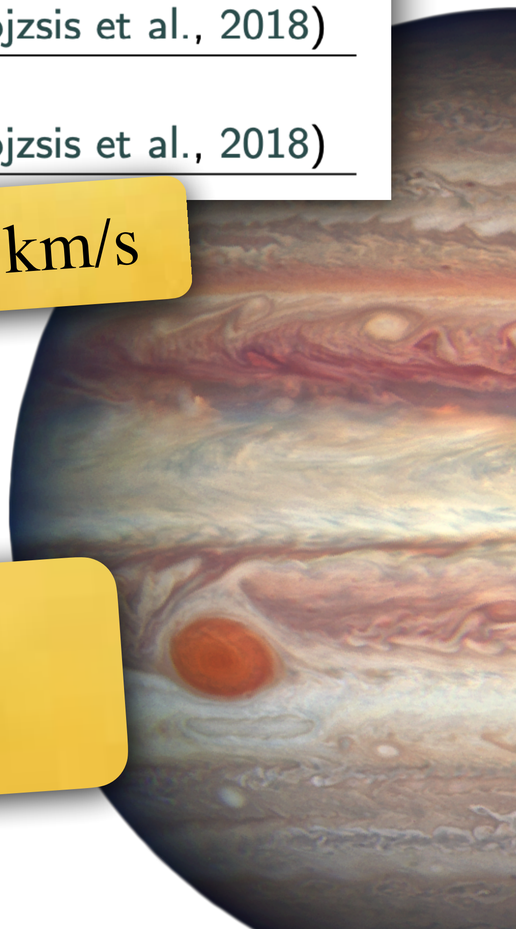
$M_{\rm imp,tot}$=8×10^{18}~8×10^{20} kg

<$v_{\rm imp}$>=30~40 km/s









Total mass of impactors & typical impact velocity depend on planet formation models.

A strategic consideration

Every few years(!), models are updated..
Total mass of impactors ($M_{\mathrm{tot,imp}}$) & typical impact velocity (v_{imp}) could be changed.

Therefore, instead of studying a *specific* case,
I try to derive scaling laws for the *consequences* of late accretion
as a function of $M_{\mathrm{tot,imp}}$ and v_{imp}.

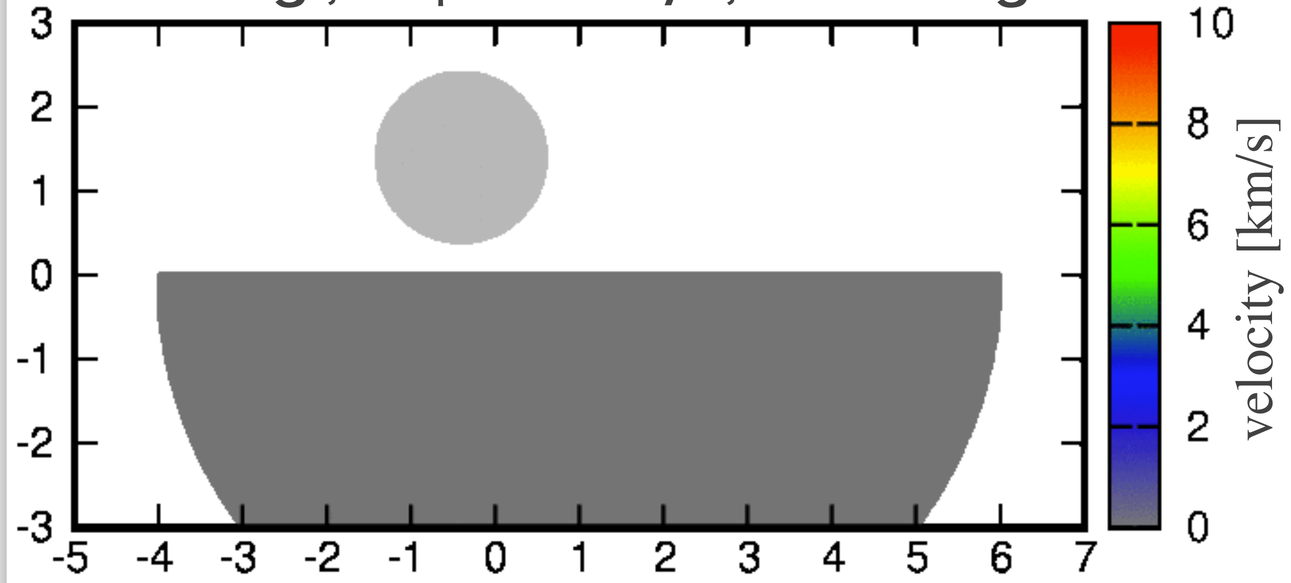
Here, the studied *consequences* are
(1) How significantly could Mercury's surface be eroded?
(2) How much of impactors' materials could be implanted on Mercury's surface?
(3) What are the fate of impactors? — Melted? Vaporized?

Preparation

Hyodo & Genda (2020, 2021), ApJ

SPH simulations

e.g., v_{imp}=12km/s, θ=45deg



Scaling laws

Erosion mass from target

$$\frac{M_{\mathrm{HG20,esc,imp}}(>v_{\mathrm{esc}})}{m_{\mathrm{imp}}} = C_{\mathrm{HG20,imp}}(\theta)\left(\frac{v_{\mathrm{esc}}}{v_{\mathrm{imp}}\sin(\theta)}\right)^{-3\mu_{\mathrm{HG20,imp}}(\theta)}$$

Accretion mass from impactor

$$\frac{M_{\mathrm{HG20,acc,imp}}(<v_{\mathrm{esc}})}{m_{\mathrm{imp}}} = 1 - C_{\mathrm{HG20,imp}}(\theta)\left(\frac{v_{\mathrm{esc}}}{v_{\mathrm{imp}}\sin\theta}\right)^{-3\mu_{\mathrm{HG20,imp}}(\theta)}$$

*C, μ: coefficients

v_{imp}: impact velocity, m_{imp}: impactor mass, v_{esc}: escape velocity

Scaling laws are derived
for erosion and accretion by cratering impacts

Monte-Carlo Statistical Model of Late Accretion

Erosion mass from target

$$\frac{M_{\mathrm{HG20,esc,imp}}(>v_{\mathrm{esc}})}{m_{\mathrm{imp}}} = C_{\mathrm{HG20,imp}}(\theta)\left(\frac{v_{\mathrm{esc}}}{v_{\mathrm{imp}}\sin(\theta)}\right)^{-3\mu_{\mathrm{HG20,imp}}(\theta)}$$

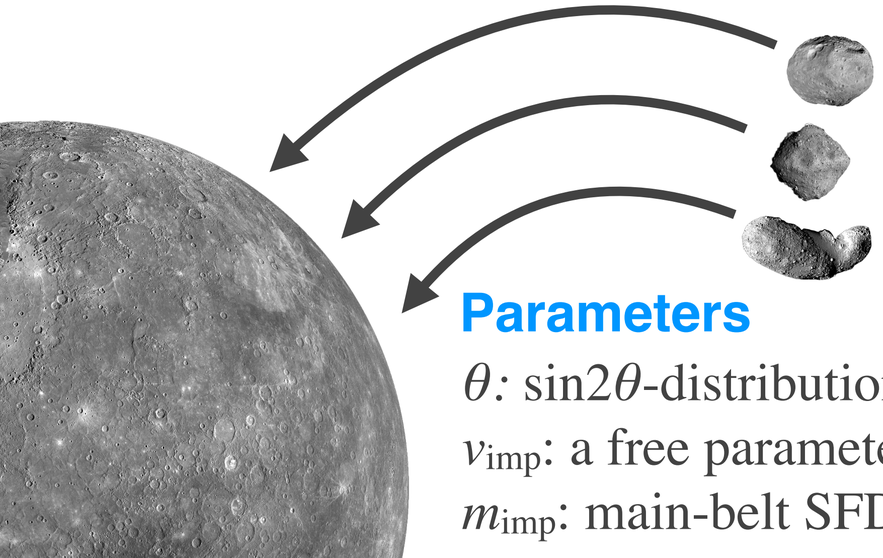
Accretion mass from impactor

$$\frac{M_{\mathrm{HG20,acc,imp}}(<v_{\mathrm{esc}})}{m_{\mathrm{imp}}} = 1 - C_{\mathrm{HG20,imp}}(\theta)\left(\frac{v_{\mathrm{esc}}}{v_{\mathrm{imp}}\sin\theta}\right)^{-3\mu_{\mathrm{HG20,imp}}(\theta)}$$

*C, μ: coefficients

Late accretion — inevitable

(e.g., $M_{\mathrm{imp,tot}}$=8×10^{18}~8×10^{20} kg, v_{imp}=30~40 km/s)



Parameters

θ: sin2θ-distribution

v_{imp}: a free parameter

m_{imp}: main-belt SFD

What is the consequences of late accretion?

(1) How significantly could Mercury's surface be eroded?
(2) How much of impactors' materials were implanted on Mercury's surface?
(3) What are the fate of impactors? — Melted? Vaporized?

We will derive scaling laws as a function of $M_{\mathrm{imp,tot}}$ & v_{imp}

(so that any planet formation models can be applied)

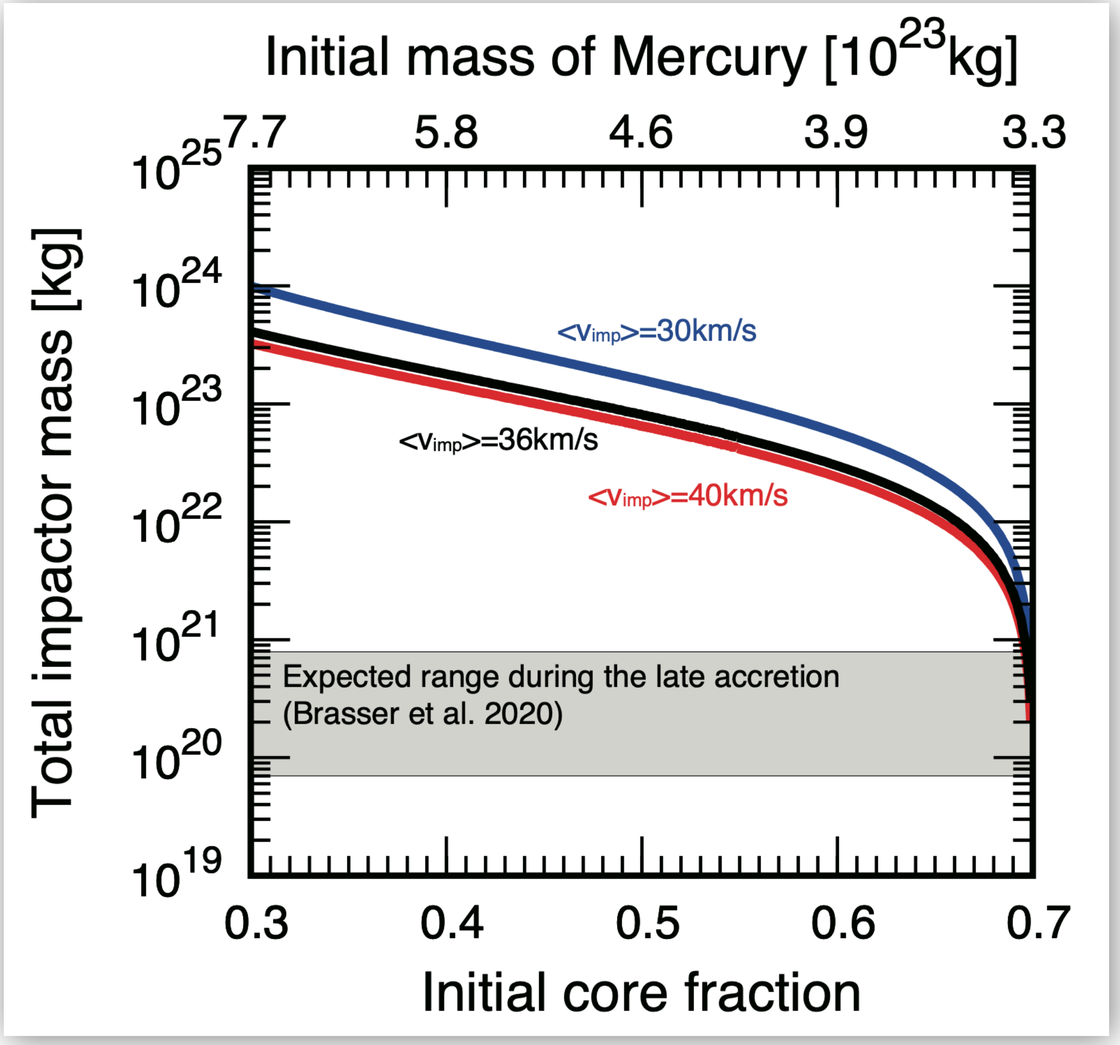
Consequence I:

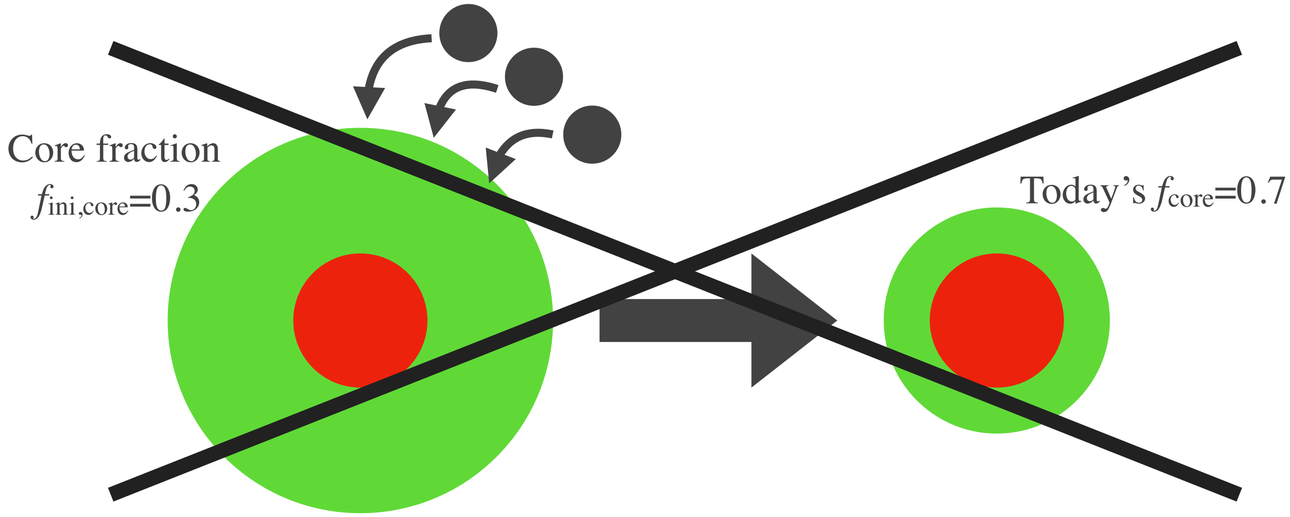
How significantly could Mercury’s surface be eroded?

- Can late accretion significantly change the core fraction?
- What is the total crater are?

Can late accretion significantly change core fraction?

Figure: Total impactors mass necessary to change the core fraction from $f_{ini,core}$ to f_{core}=0.7

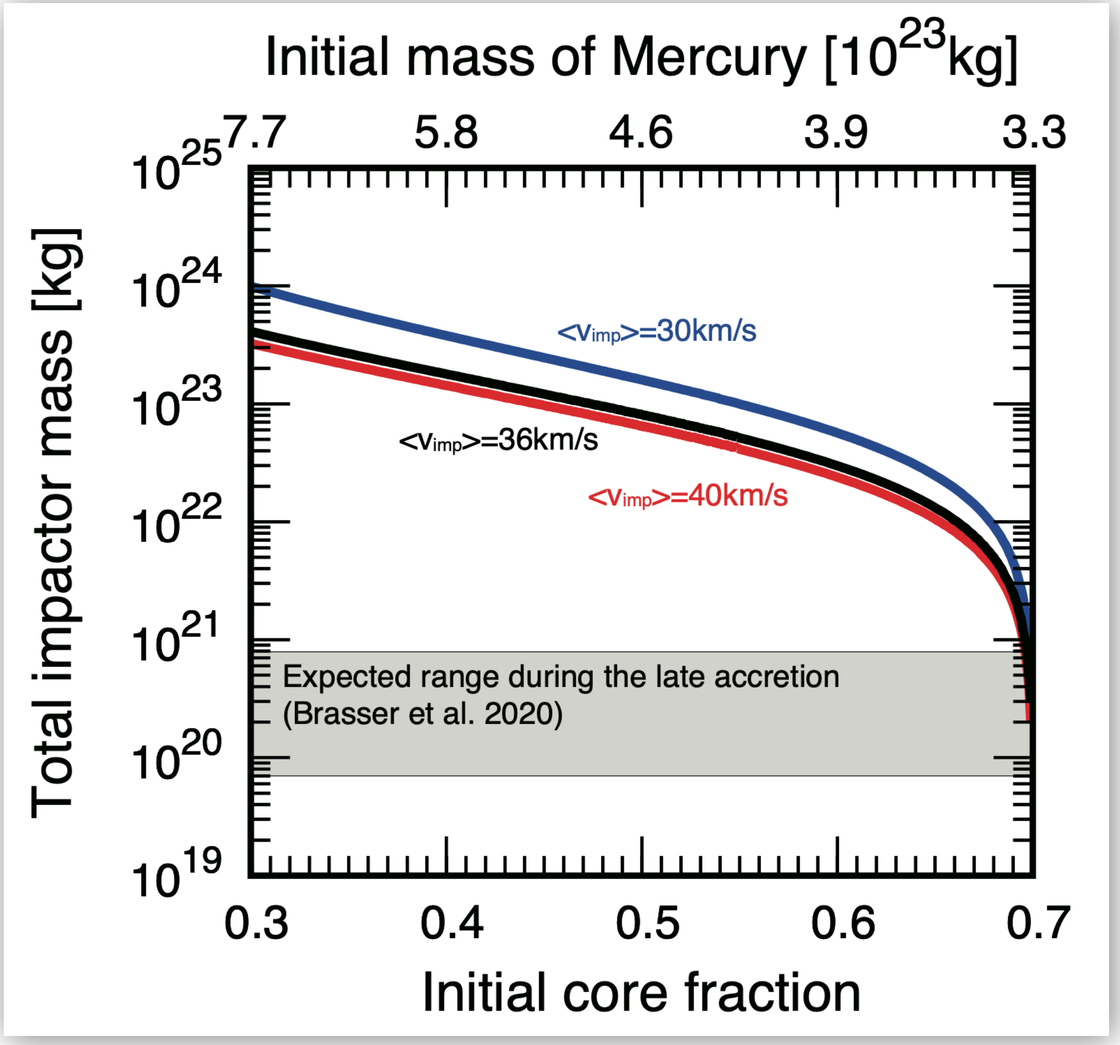


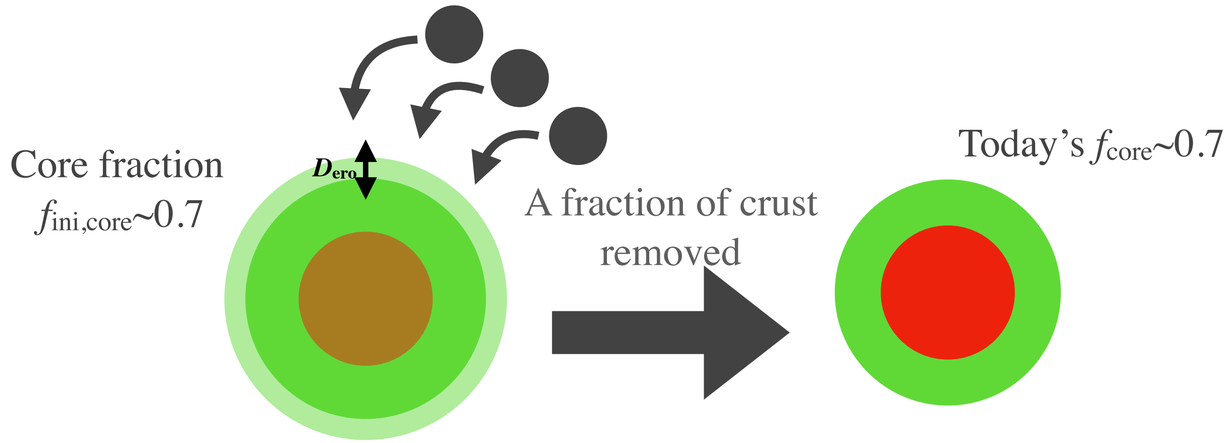


Late accretion itself *cannot* significantly change the core fraction.

Can late accretion significantly change core fraction?

Figure: Total impactors mass necessary to change the core fraction from $f_{\mathrm{ini,core}}$ to f_{core}=0.7





However, the *surface/crust* could be significantly eroded.

Derived scaling law

Depth of crustal erosion by late accretion (D_{ero}):

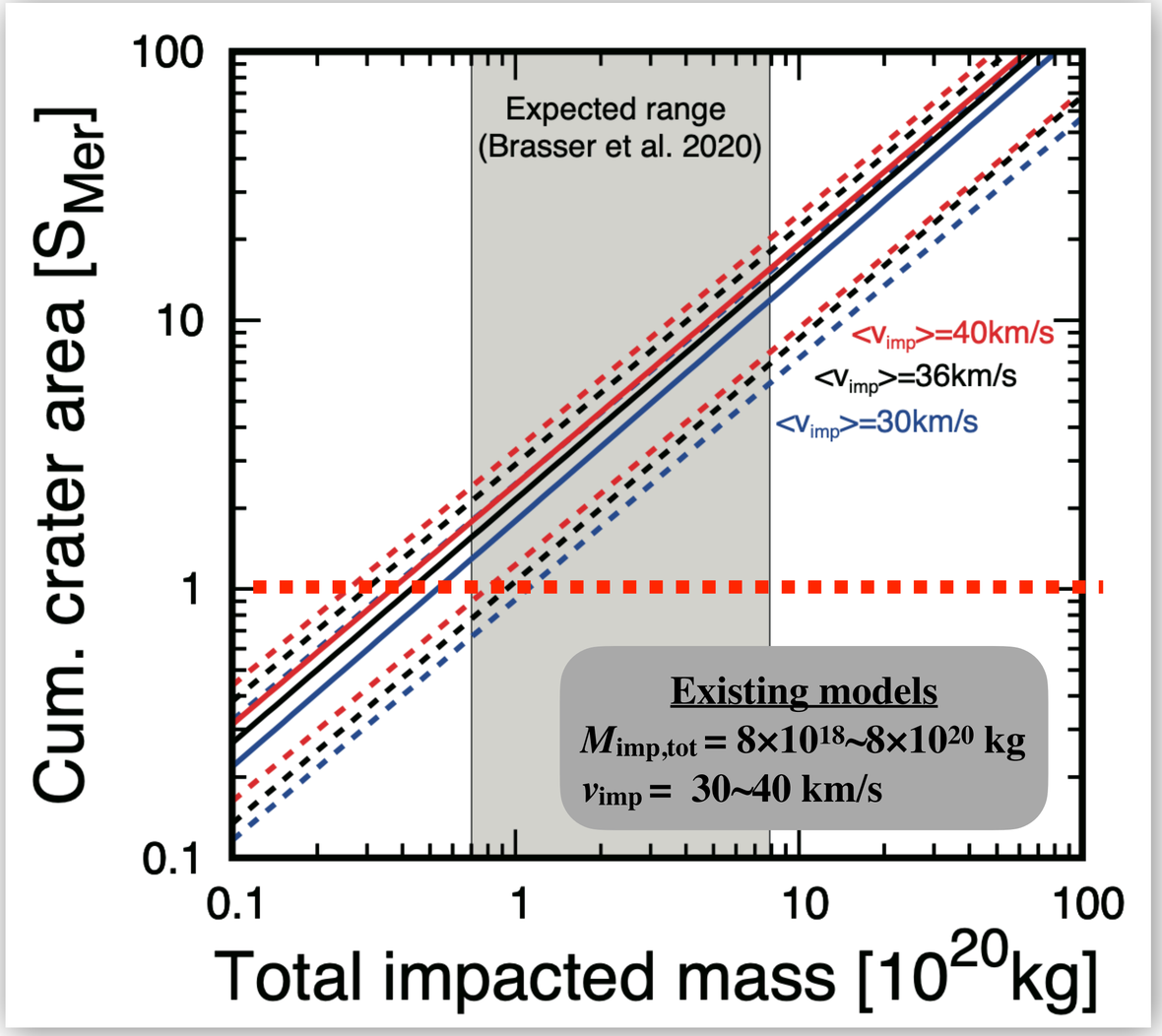
$$D_{\mathrm{ero}} \simeq \frac{M_{\mathrm{esc,tot}}}{4\pi\rho R_{\mathrm{Mer}}^2} \simeq 1\mathrm{km} \times \left(\frac{v_{\mathrm{imp}}}{36\mathrm{km/s}}\right)^{2.2} \left(\frac{M_{\mathrm{imp,tot}}}{10^{20}\mathrm{kg}}\right)$$

From the existing models ***assuming today's Mercury size***

$M_{\mathrm{imp,tot}}$=8×10^{18}~8×10^{20} kg & v_{imp}=30~40 km/s

→ 50m~50 km surface was eroded

What is the total crater are?

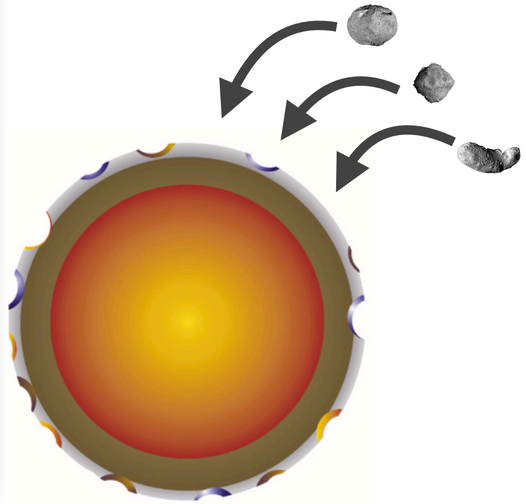


Derived scaling law

Total crater area to Mercury's surface area
(i.e., the degree of resurfacing)

$$\frac{S_{tot,cra}}{S_{Mer}} = a \times \left(\frac{M_{imp,tot}}{10^{20}\mathrm{kg}} \right)^{b}$$

a & b: coefficients from pi-scaling law and Monte-Carlo simulations (see Hyodo+2021)



From the existing models

If $M_{imp,tot} > 4\times10^{19} \sim 5\times10^{19}$ kg
→ global resurfacing
(i.e., $S_{tot,cra}/S_{Mer} > 1$)

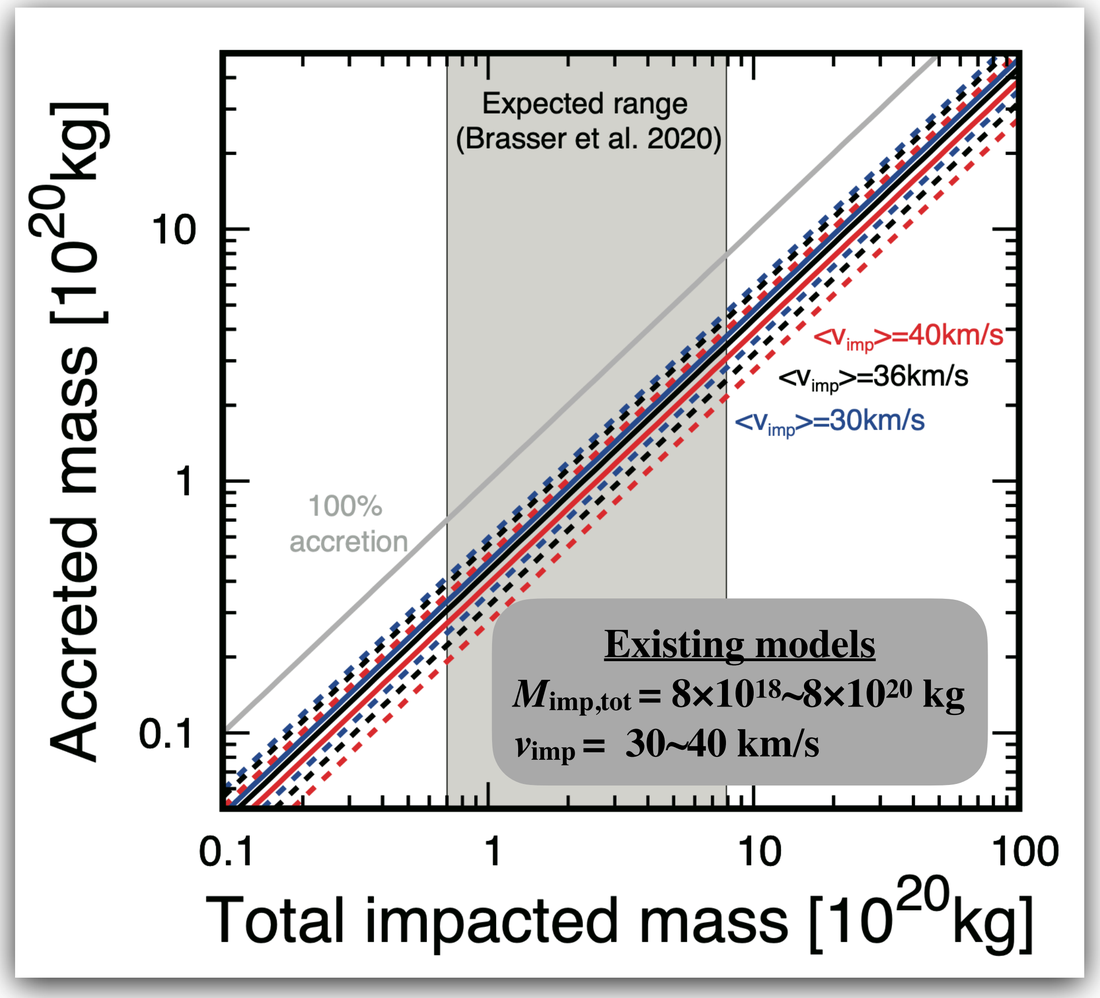
The oldest surface age for Mercury:
~4.0 – 4.1 Ga
(Marchi et al., 2013; Werner, 2014)

Consequence II:

How much of impactors' materials were implanted on Mercury's surface?

*This is the process to deliver exogenic impactor's materials, including the volatile-bearing materials, onto Mercury's surface.

How much of impactors' materials were implanted on Mercury's surface?

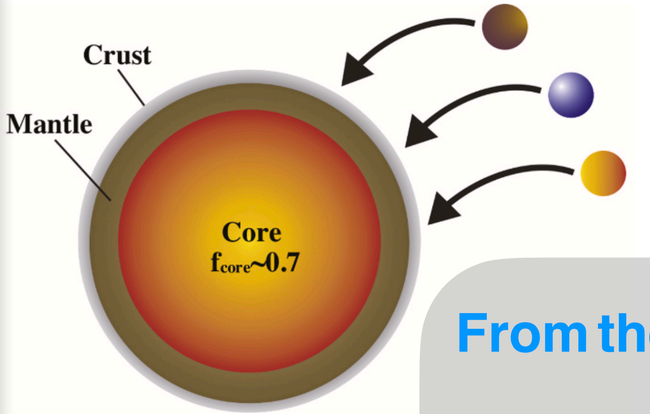


Derived scaling law

If $M_{\mathrm{imp,tot}}$ is impacted, $M_{\mathrm{acc,imp,tot}}$ is implanted onto Mercury:

$$M_{\mathrm{acc,imp,tot}} = \gamma M_{\mathrm{imp,tot}}$$

γ=0.39-0.48
for v_{imp}=30-40 km/s



From the existing models

Global resurfacing with $M_{\mathrm{imp,tot}} > 5\times10^{19}$ kg

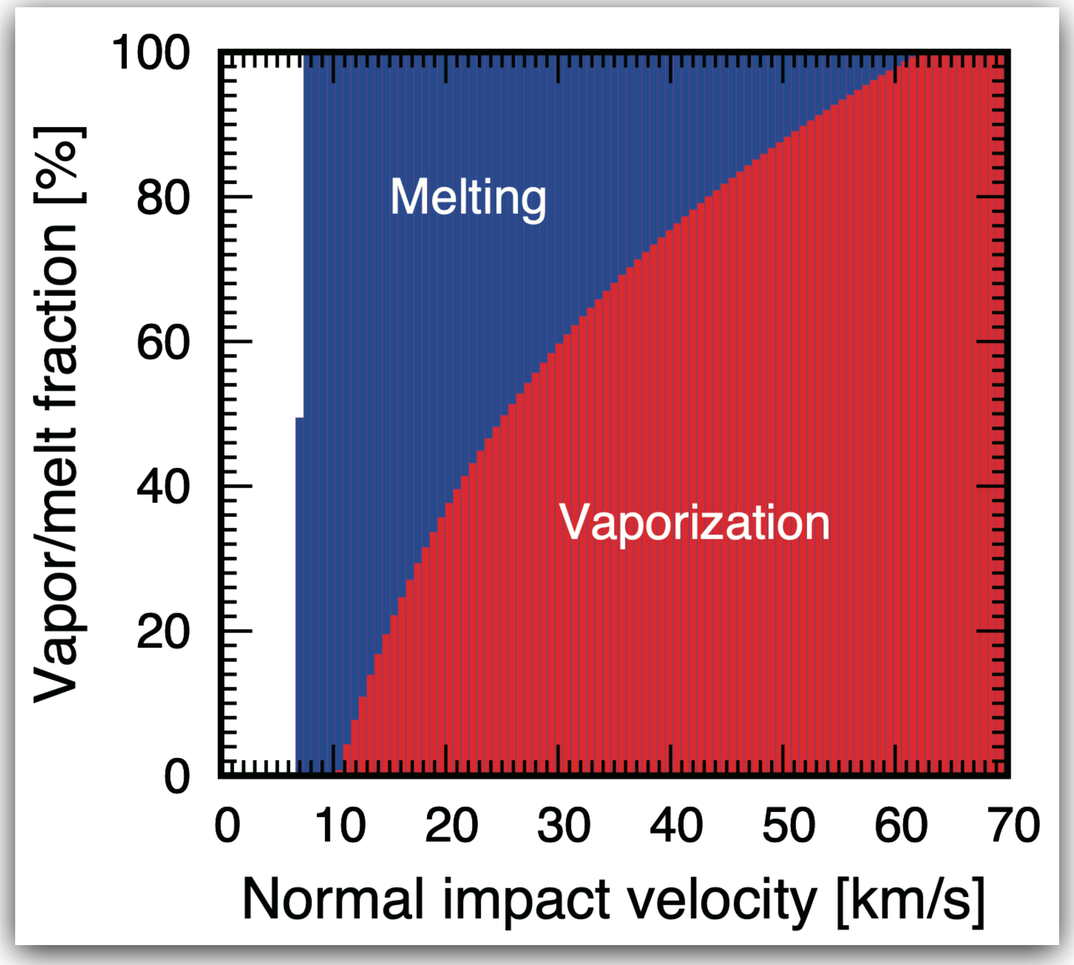
i.e., at least
more than $M_{\mathrm{acc,imp,tot}} = 3\times10^{18}$ kg is implanted.

Consequence III:

What are the fate of impactors? Melted? Vaporized?

*This is the very first step to understand potential geochemical features produced by late accretion impacts.

What are the fate of impactors? — Melted? Vaporized?



Using the lever rule, the melt/vapor fraction estimated

- **Entropy calculation along Hugoniot**
- **Basalt assumed with the initial temperature 293K**

Used impact conditions

- **30~40 km/s with 45-degree impact**
- **Vertical component is used (Pierazzo and Melosh, 2000)**

~50% of the impactor materials are vaporized; rest melted

***This is a cratering impact; thus a local phenomenon**

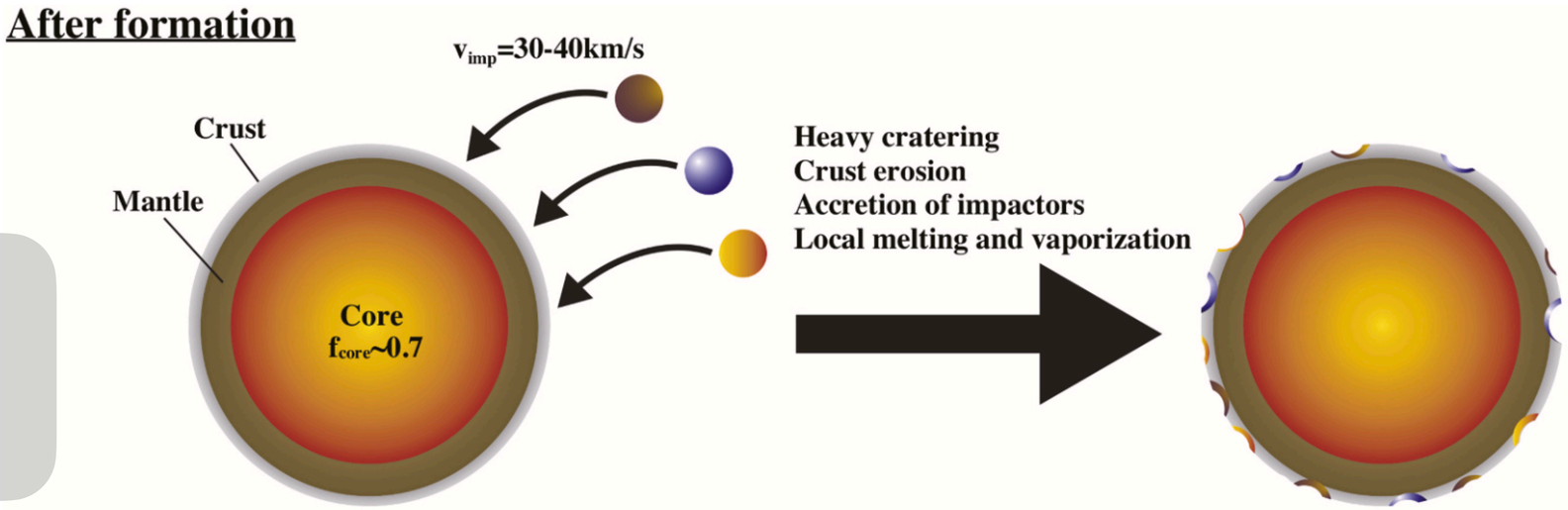
Summary

Hyodo, Genda & Brasser (2021) *Icarus*

Existing models

$M_{\mathrm{imp,tot}} = 8\times10^{18}\sim8\times10^{20}$ kg

$v_{\mathrm{imp}} = 30\sim40$ km/s



How significantly could Mercury's surface be eroded?

$$D_{\mathrm{ero}} \simeq \frac{M_{\mathrm{esc,tot}}}{4\pi\rho R_{\mathrm{Mer}}^2} \simeq 1\mathrm{km}\times\left(\frac{v_{\mathrm{imp}}}{36\mathrm{km/s}}\right)^{2.2}\left(\frac{M_{\mathrm{imp,tot}}}{10^{20}\mathrm{kg}}\right)$$

→ 50m~10 km of crust removed

How much impactors materials were implanted?

$$M_{\mathrm{acc,imp,tot}} = \gamma M_{\mathrm{imp,tot}}$$

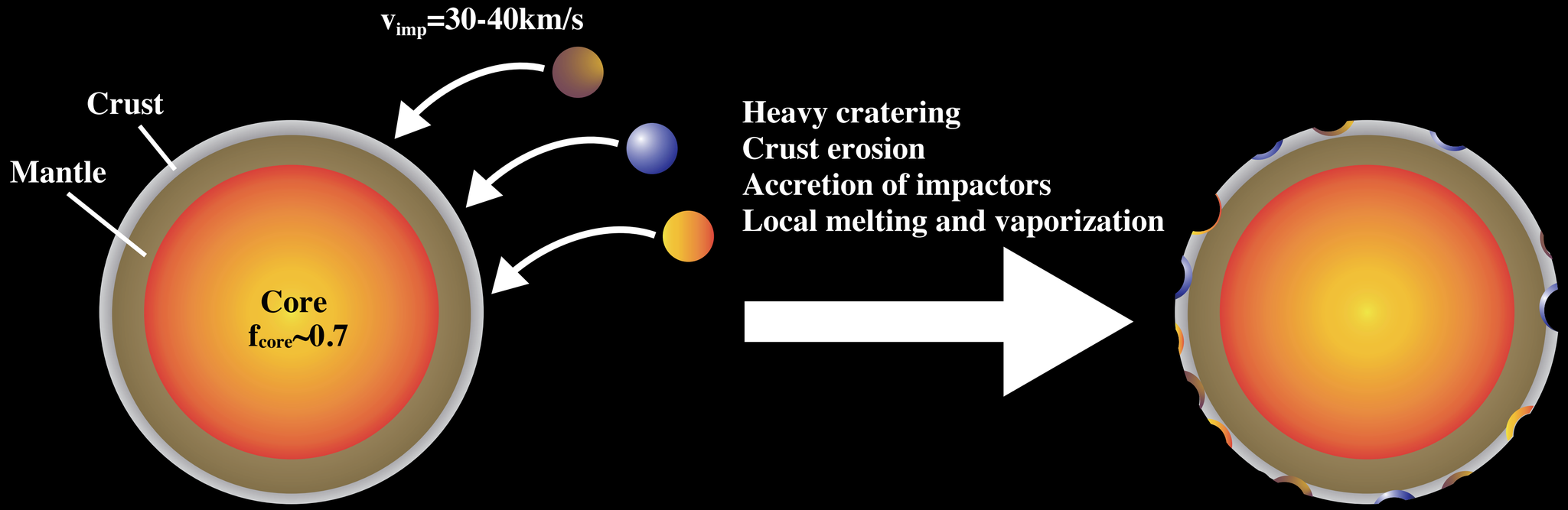
→ $>3\times10^{18}$ kg exogenic materials implanted

What is the total crater area to Mercury's surface area?

$$\frac{S_{\mathrm{tot,cra}}}{S_{\mathrm{Mer}}} = a\times\left(\frac{M_{\mathrm{imp,tot}}}{10^{20}\mathrm{kg}}\right)^{b}$$

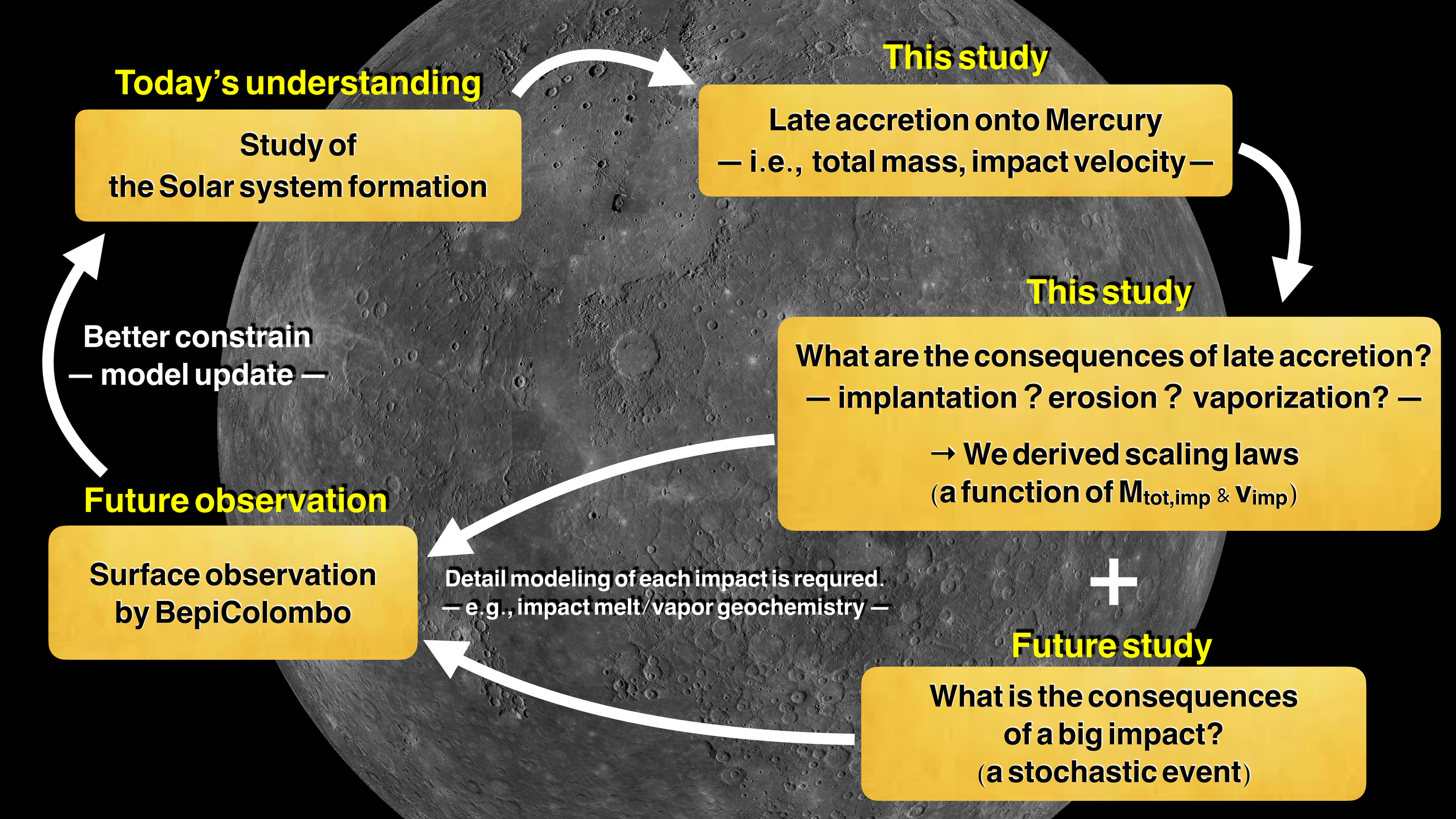
→ $M_{\mathrm{imp,tot}} > 5\times10^{19}$ kg leads to global resurfacing

What should we do in the future?



Can we find an evidence of late accretion?

- Need to study a local geochemical/geophysical evolution of impact melt/vapor after the impact togethr with observational evidences to constrain the impactor's composition (e.g., icy or rocky impactor).
- Understanding late accretion leads to a better understanding of the solar system formation.


Today's understanding
Study of
the Solar system formation
This study
Late accretion onto Mercury
— i.e., total mass, impact velocity —
This study
What are the consequences of late accretion?
— implantation ? erosion ? vaporization? —
→ We derived scaling laws
(a function of $M_{tot,imp}$ & v_{imp})
+
Future study
What is the consequences
of a big impact?
(a stochastic event)
Detail modeling of each impact is requred.
— e.g., impact melt/vapor geochemistry —
Future observation
Surface observation
by BepiColombo
Better constrain
— model update —

Mercury is *Special* among Terrestrial Planets

Hyodo & Genda (2021) *ApJ*

Name (rocky/icy)	$v_{\rm imp}$ [km s^{-1}] ($v_{\rm imp}$ [$v_{\rm esc}$])	Description (Reference)
Mercury (rocky)	$\sim$36 km s^{-1} ($\sim 8.5 v_{\rm esc}$; $v_{\rm esc} \simeq 4.25$ km s^{-1})	Instability phase (e.g., Hyodo et al. 2021)
Venus (rocky)	$\sim$26 km s^{-1} ($\sim 2.5 v_{\rm esc}$; $v_{\rm esc} \simeq 10.4$ km s^{-1})	Instability phase (e.g., Mojzsis et al. 2019)
Earth (rocky)	$\sim$22 km s^{-1} ($\sim 2.0 v_{\rm esc}$; $v_{\rm esc} \simeq 11.2$ km s^{-1})	Instability phase (e.g., Mojzsis et al. 2019)
Moon (rocky)	$\sim$19 km s^{-1} ($\sim 8.0 v_{\rm esc}$; $v_{\rm esc} \simeq 2.4$ km s^{-1})	Instability phase (e.g., Brasser et al. 2020)
Mars (rocky)	$\sim$13 km s^{-1} ($\sim 2.6 v_{\rm esc}$; $v_{\rm esc} \simeq 5.0$ km s^{-1})	Instability phase (e.g., Mojzsis et al. 2019)
Ceres (rocky)	$\sim$5 km s^{-1} ($\sim 9.8 v_{\rm esc}$; $v_{\rm esc} \simeq 0.5$ km s^{-1})	Today's population (e.g., Bottke et al. 1994)
Vesta (rocky)	$\sim$5 km s^{-1} ($\sim 13.9 v_{\rm esc}$; $v_{\rm esc} \simeq 0.35$ km s^{-1})	Today's population (e.g., Bottke et al. 1994)
Rhea (icy)	$\sim$15 km s^{-1} ($\sim 23.6 v_{\rm esc}$; $v_{\rm esc} \simeq 0.64$ km s^{-1})	Instability phase (e.g., Wong et al. 2020)
Europa (icy)	$\sim$24 km s^{-1} ($\sim 12.0 v_{\rm esc}$; $v_{\rm esc} \simeq 2.0$ km s^{-1})	Instability phase (e.g., Wong et al. 2020)
Pluto (icy)	$\sim$2 km s^{-1} ($\sim 1.7 v_{\rm esc}$; $v_{\rm esc} \simeq 1.2$ km s^{-1})	Today's population (e.g., Dell'Oro et al. 2013)

During late accretion,
only Mercury experiences a net erosive outcome.