A Crisis on the Standard Scenario of Planet Formation:
Catastrophic Atmospheric Erosion of super-Earths in Giant Impact Events

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Take-home messages

What we did?

We calculate the giant impact simulation by the SPH simulation and analyze the internal structure and the impact-induced atmosphere loss.

What's new finding?

About 30% of the sum of the impact energy and the released energy from the merged core determines the atmosphere loss fraction, while the rest of the 70% of the energy is absorbed by atmospheric expansion and core heating.

Results & *Implications*

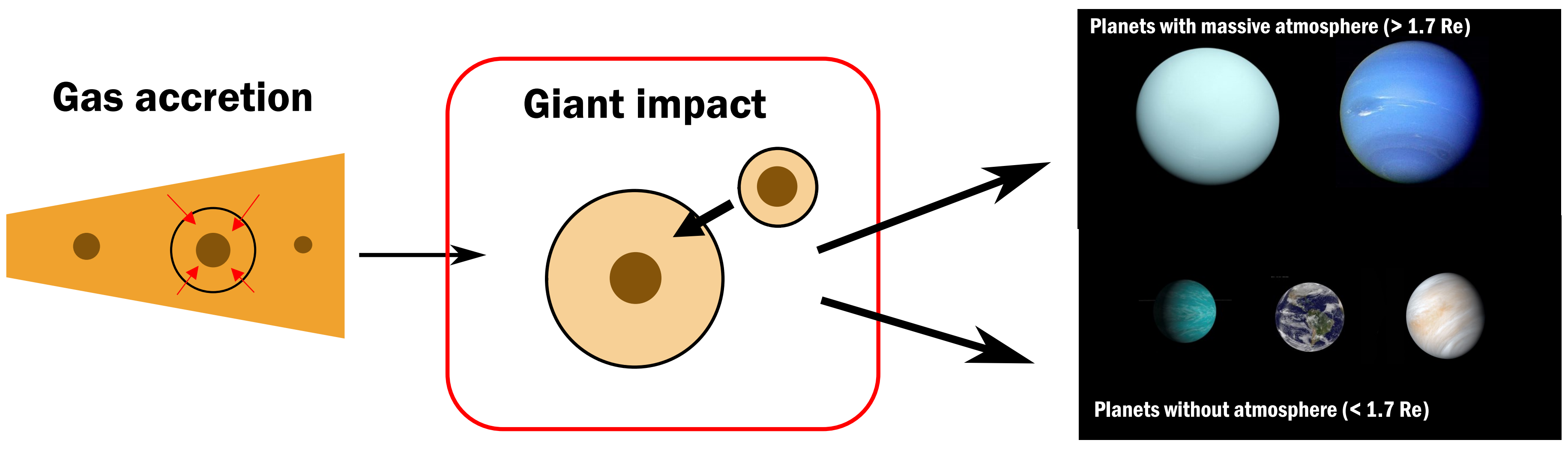
When the planet has experienced an impact with a comparable mass, most of the atmosphere is lost.

➡ **A planet with a massive atmosphere may have avoided the giant impact.**

When the atmosphere loss due to the head-on impact is significant, the core material is mixed with the atmosphere.

➡ **The atmospheric composition may reflect the history of the giant impact.**

Introduction



- The solid core obtains the atmosphere from the PPDs
- Planets have a primordial atmosphere composed of H_2 and He.
- Planets should have experienced giant impacts in the late stage.

➡ Planetary atmosphere changes during the formation

Aim of this study

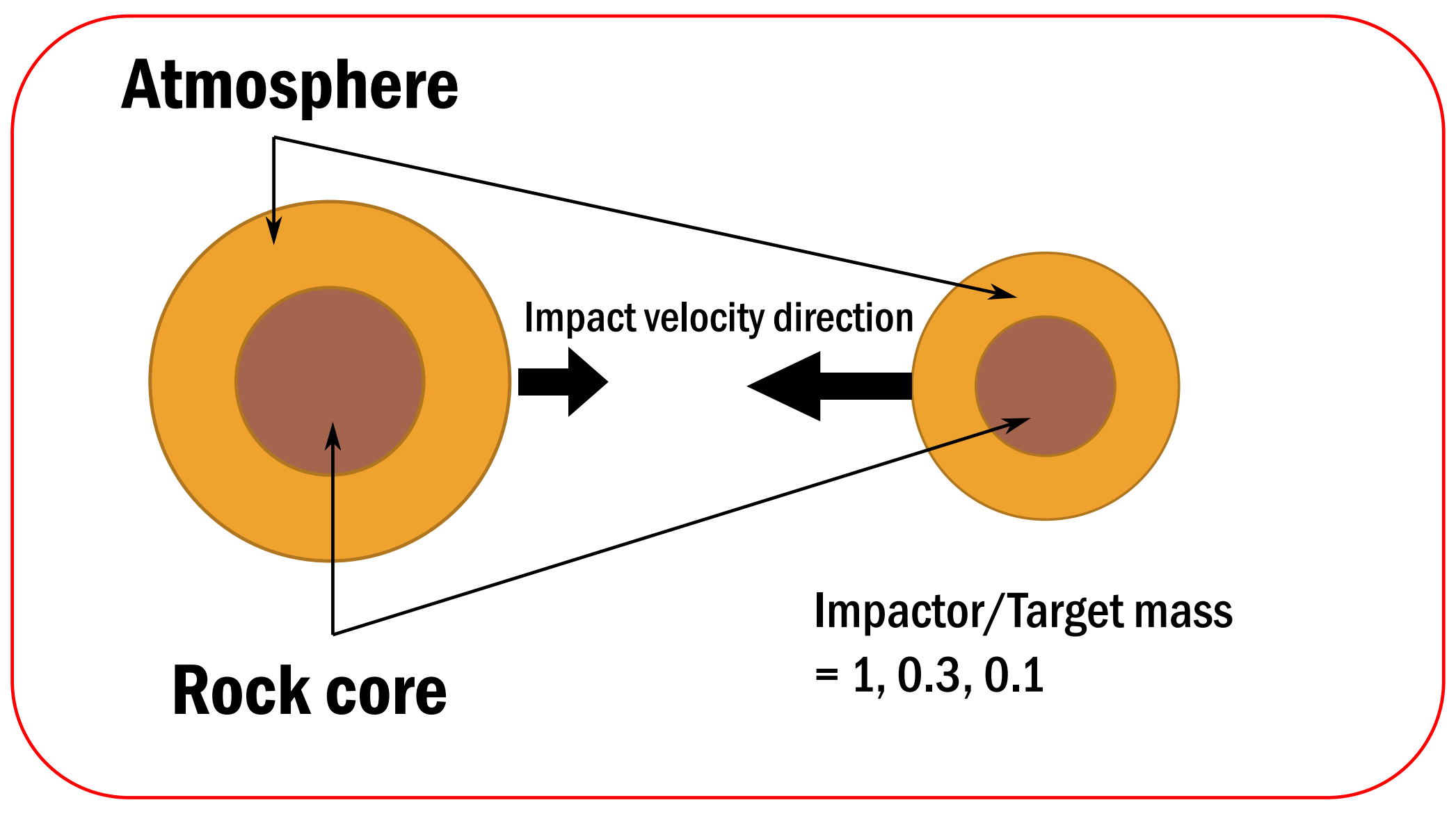
We investigate the giant impact for a super-Earth with an 10-30% atmosphere to consider the energy scaling law for the impact-induced atmosphere loss.

Method

Numerical scheme:
Smoothed Particle Hydrodynamics method

Parallelization:
FDPS with Fortran interface

EOS: non-ideal, tabulated EOS
Atmosphere: H_2 & He (Saumon et al. 1995)
Rock core: ANEOS Basalt (Pierazzo+2005)



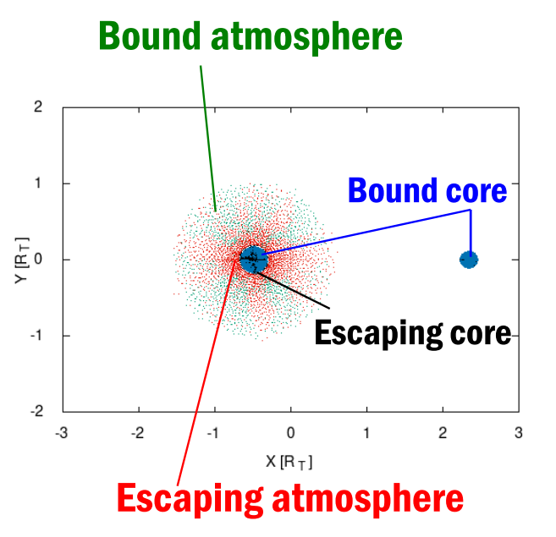
Properties of the target and impactor

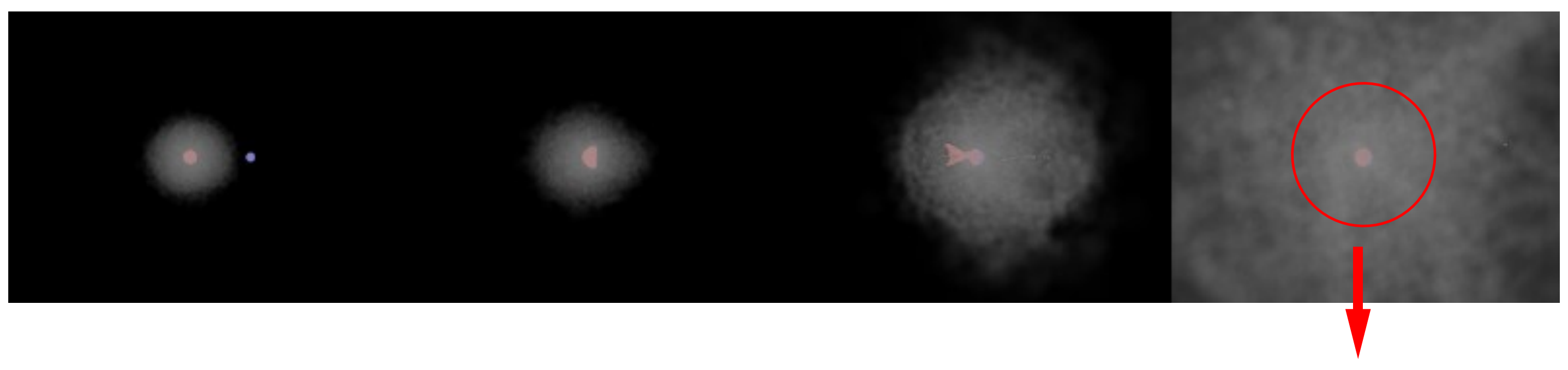
Name	$M\ [M_\oplus]$	Y	$T_{\rm surf}$ [K]	$R\ [R_\oplus]$
A1	0.10	0.1	660	2.1
A2	0.30	0.1	810	3.0
A3	1.0	0.1	1080	4.3
A4	3.0	0.1	1410	5.3
A5	10.0	0.1	2500	7.0
B1	0.10	0.2	590	2.6
B2	1.0	0.2	960	5.3
B3	3.0	0.2	1300	6.7
B4	10.0	0.2	1800	7.1
C1	1.0	0.3	900	6.1
C2	3.0	0.3	1200	7.8
C3	10.0	0.3	1650	8.1
D1	0.21	0.0	1500	0.73
D2	0.70	0.0	1500	1.0
D3	2.1	0.0	1500	1.4
D4	7.0	0.0	1500	1.9

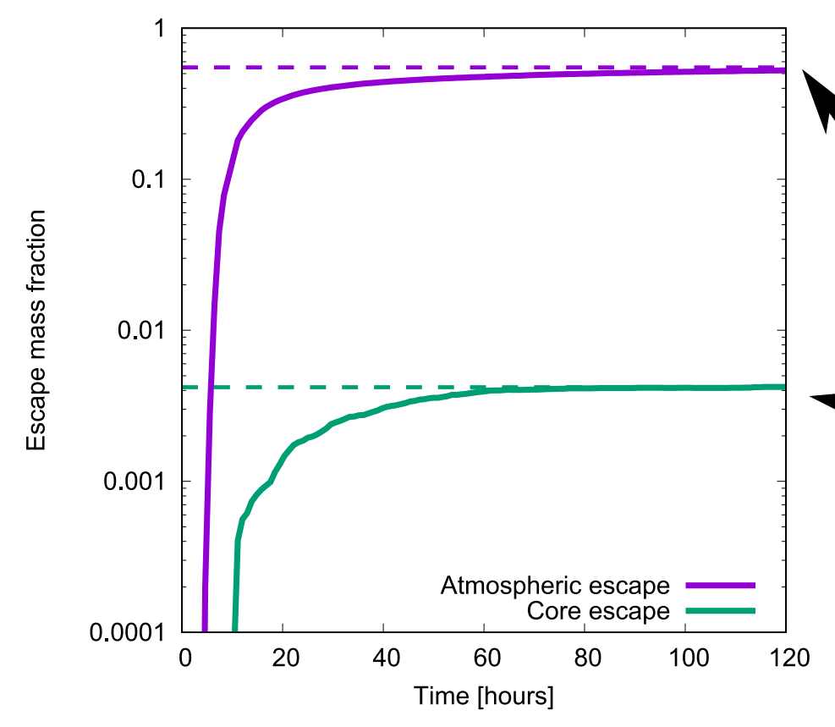
Impact velocity:
1.0-2.6 escape velocity
Impact angle:
0 deg, 10 deg

Results

Head-on impact: 1 M_E (20%) & 0.3 M_E colliding with 1.0 v_{esc}





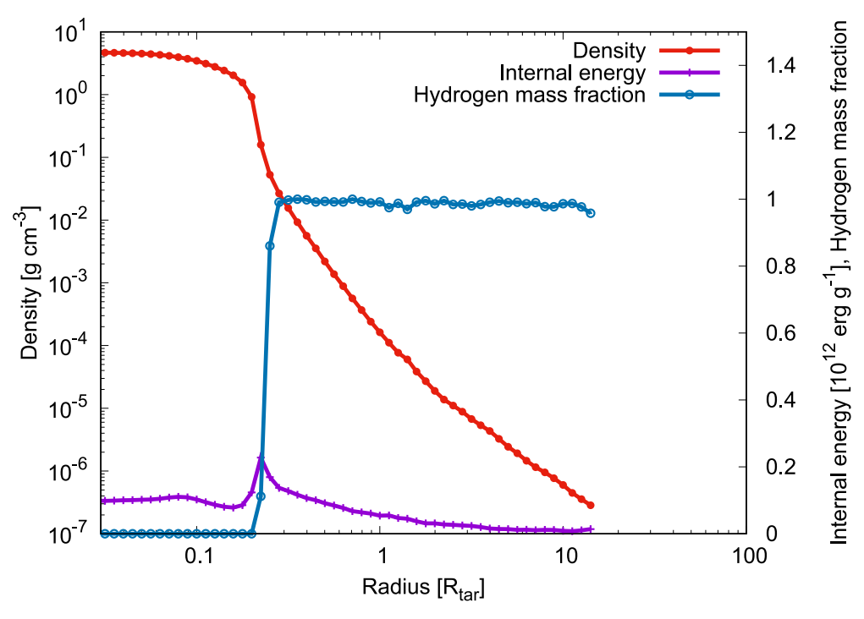


We define escaping atmosphere or core particles whose kinetic energy exceeds their gravitational energy.

$$\frac{m_i v_i^2}{2} - \sum_{j=1}^{N} \frac{G m_j m_i}{|\mathrm{r}_i - \mathrm{r}_j|} \geq 0$$

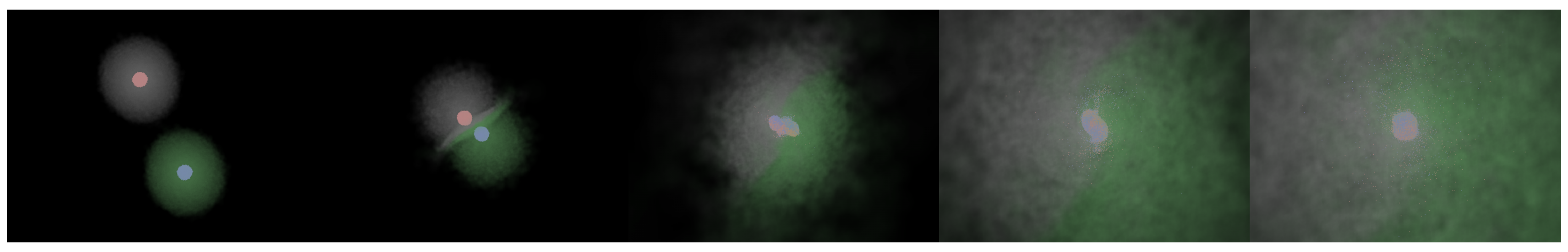
40% of the atmosphere escaped.
0.4% of the core escaped.

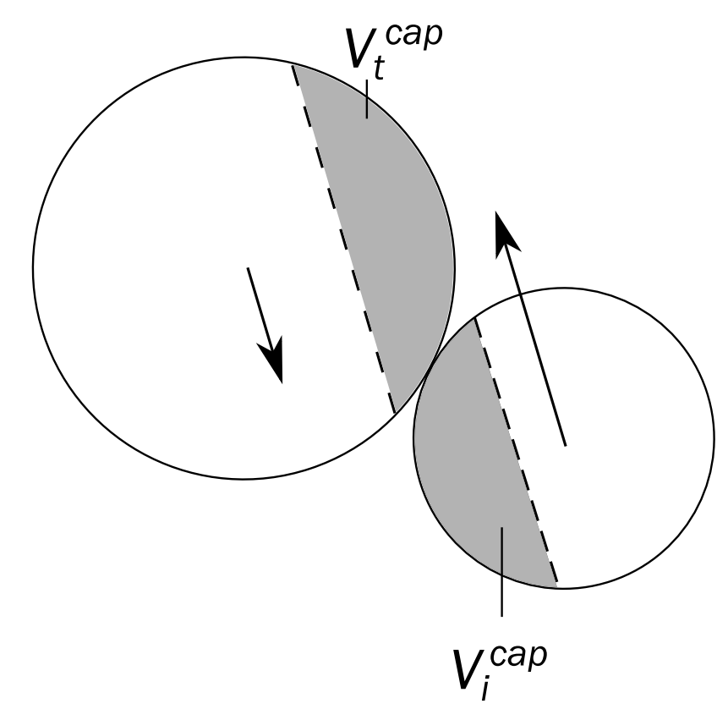
Most of the escaping mass is the atmosphere, while the core is merged almost completely.



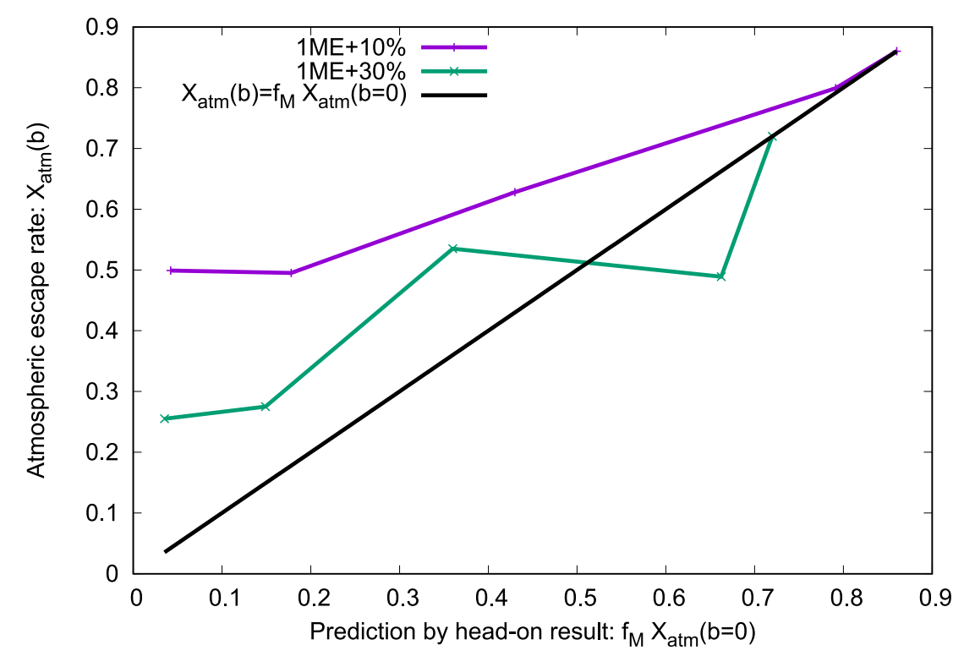
The post-impact planet keeps a layered structure.

Oblique impact: 1 M_E (20%) & 1 M_E (20%) colliding with 1.0 v_{esc}, 10 deg.

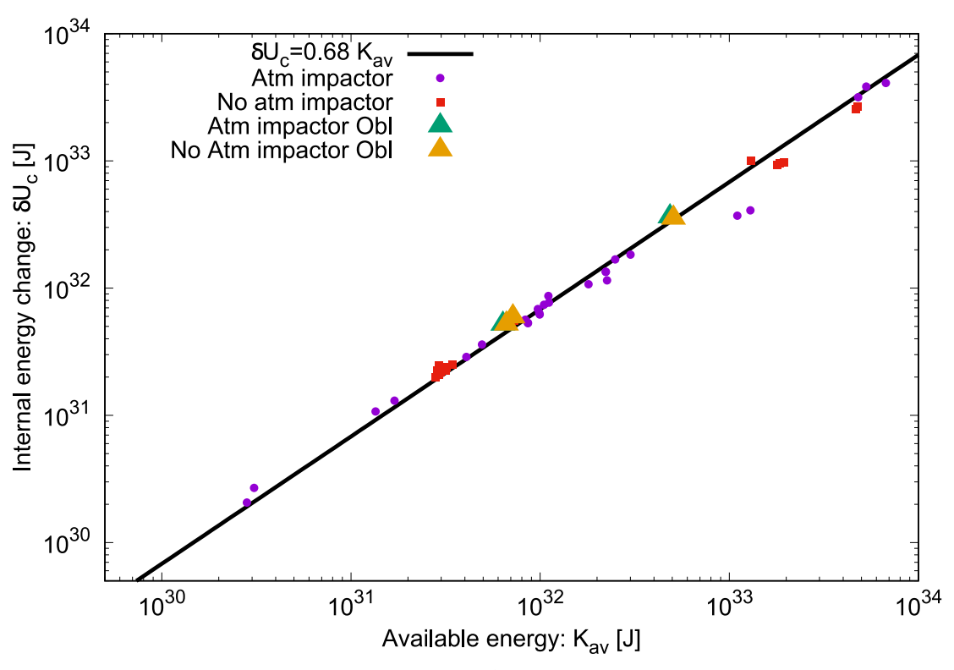




A simple mass exchange factor can reproduce the atmosphere loss for a small impact angle.



Mass exchange factor: $f_M = \frac{\rho_{\rm t} V_{\rm t}^{\rm cap} + \rho_{\rm i} V_{\rm i}^{\rm cap}}{\rho_{\rm t} V_{\rm t} + \rho_{\rm i} V_{\rm i}}$



When the core merges after the impact, the atmosphere loss, and the core heating resemble the head-on impact mechanism.

Analysis: Energy budget of the atmosphere loss

Here describes the energy distribution between the kinetic energy of escaping the atmosphere, the bound energy of the atmosphere, and the internal energy of the core before and after the impact. There are three parameters to describe the distribution, the atmospheric bound energy ratio, the correlation between the kinetic energy of escaping atmosphere and the post-impact planet's escape velocity, and the ratio of the kinetic energy of the escaping atmosphere to the heating of the rock core.

$$K_{\rm imp} + \underline{U_{\rm T} + \Phi_{\rm T} + U_{\rm I} + \Phi_{\rm I}} = K_{\rm esc} + \underline{U_{\rm B} + \Phi_{\rm B}}$$

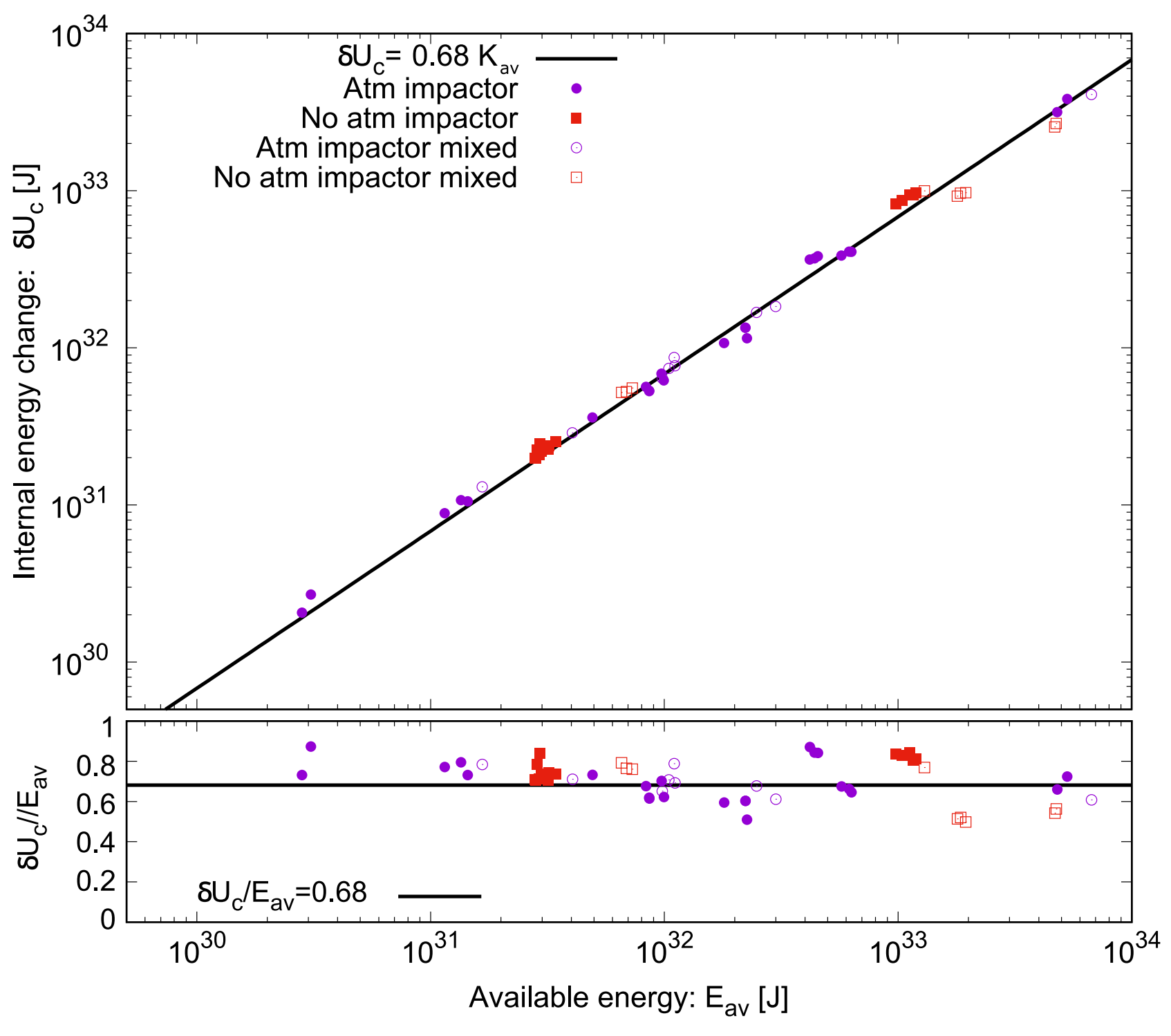
Dividing the energy to the atmosphere and core parts

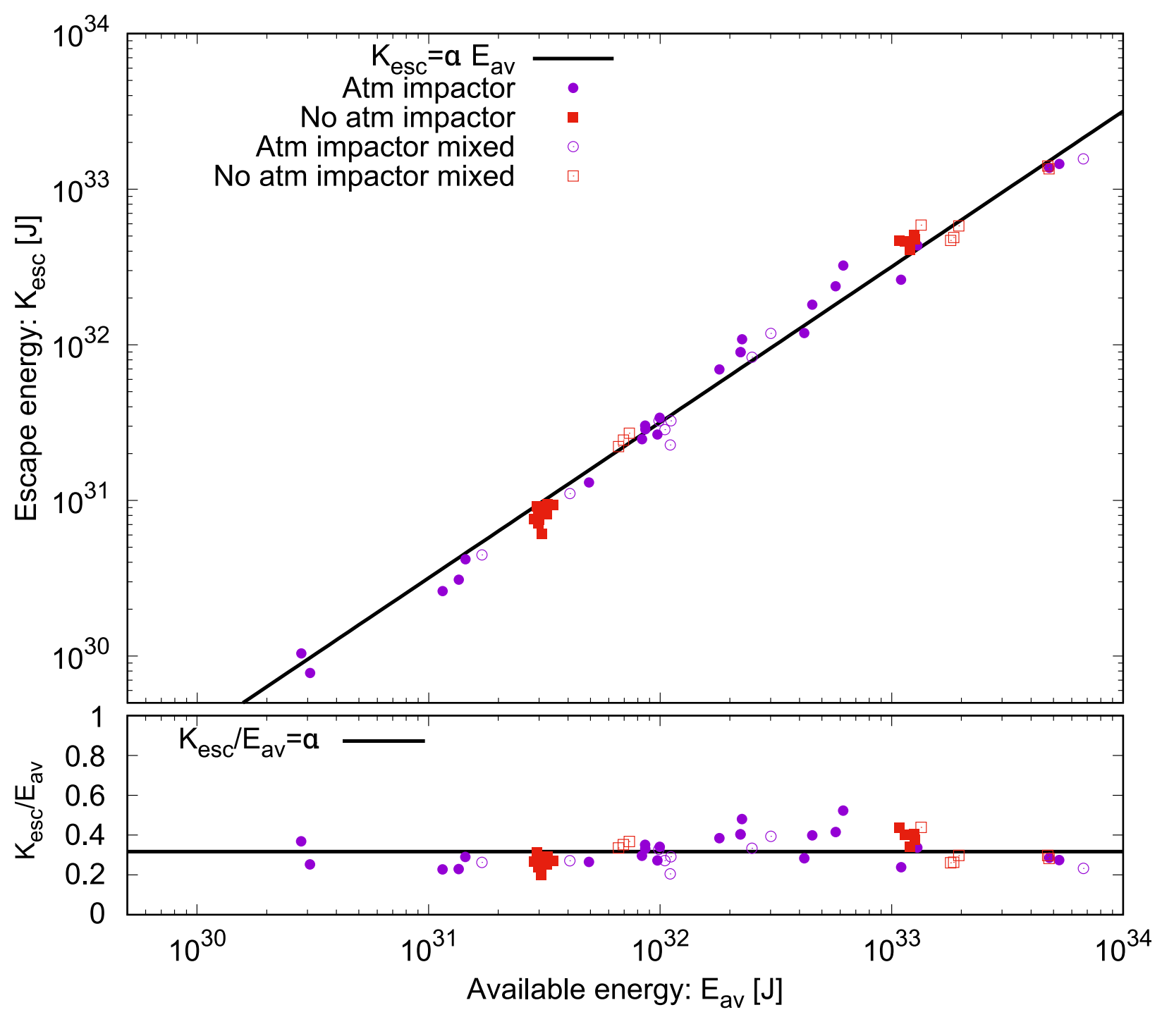
$$K_{\rm esc} = \underbrace{K_{\rm imp}}_{\text{Kinetic energy}} - \underbrace{(E_{\rm B,atm} - E_{\rm T,atm} - E_{\rm I,atm})}_{\text{Atmospheric expansion}} - \underbrace{(U_{\rm B,c} - U_{\rm T,c} - U_{\rm I,c})}_{\text{Core heating}} - \underbrace{(\Phi_{\rm B,c} - \Phi_{\rm T,c} - \Phi_{\rm I,c})}_{\text{Core gravitational energy}}$$

$$K_{\rm esc} = E_{\rm av}\left(1 - \underbrace{\boxed{\frac{\delta U_c}{E_{\rm av}}}}_{\text{Heating fraction}}\right)$$

Available energy: Heating energy subtracted by the atmospheric expansion

$$E_{\rm av} = K_{\rm imp} - \delta\Phi_c + (1-\epsilon)(E_{\rm T,atm} + E_{\rm I,atm}) + \epsilon X_{\rm atm}(E_{\rm T,atm} + E_{\rm I,atm})$$

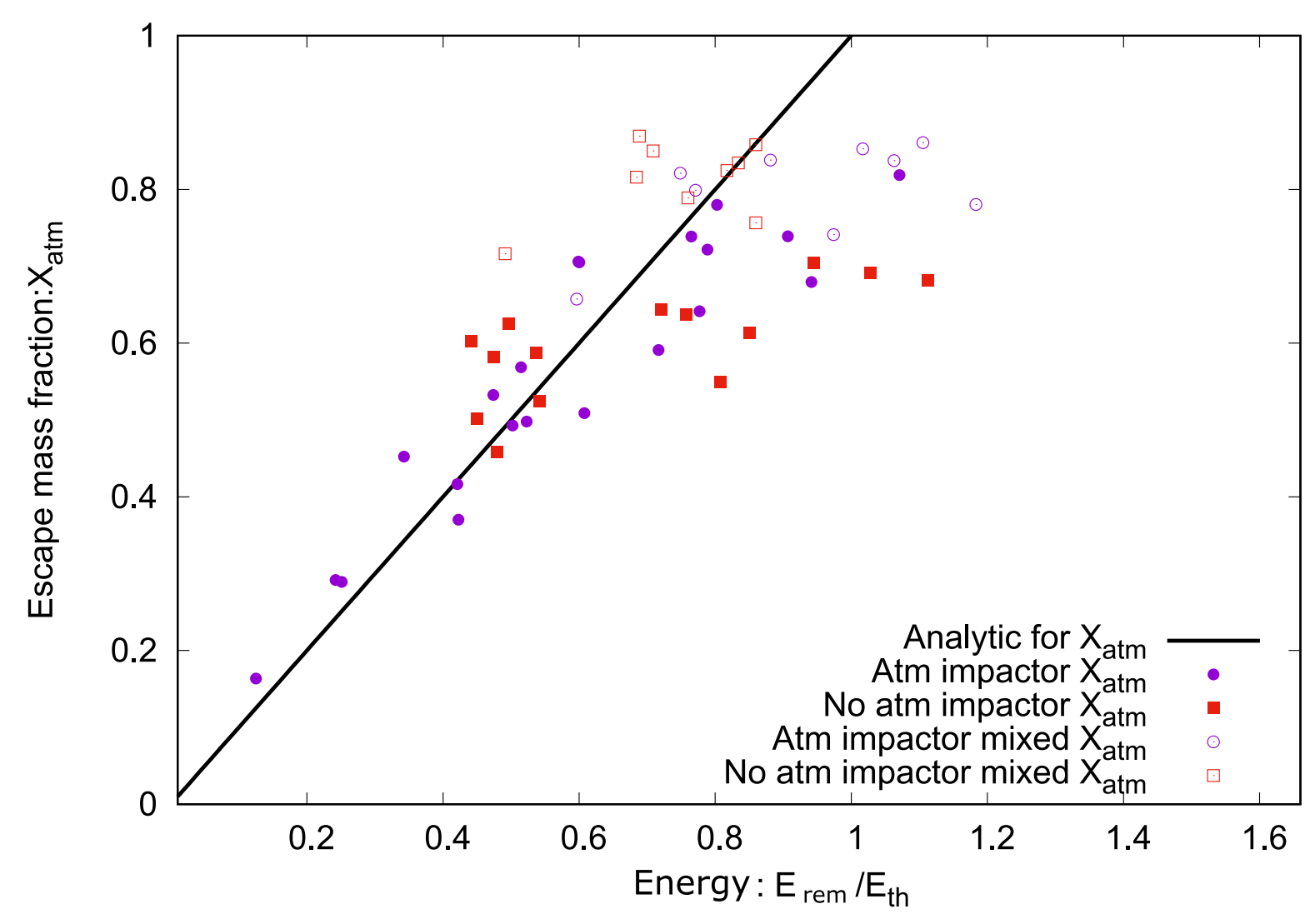




Since the core undergoes a non-spherically symmetric oscillation, the remainder of the impact energy subtracted by the atmospheric expansion is expected to contribute to the heating of the core. Our simulation indicates that 68% of the available energy transports to the core, and the rest 32% of the available energy is distributed in the kinetic energy of the escaping atmosphere.

Implications

Impact-induced atmosphere loss



Scaling law for the atmosphere loss

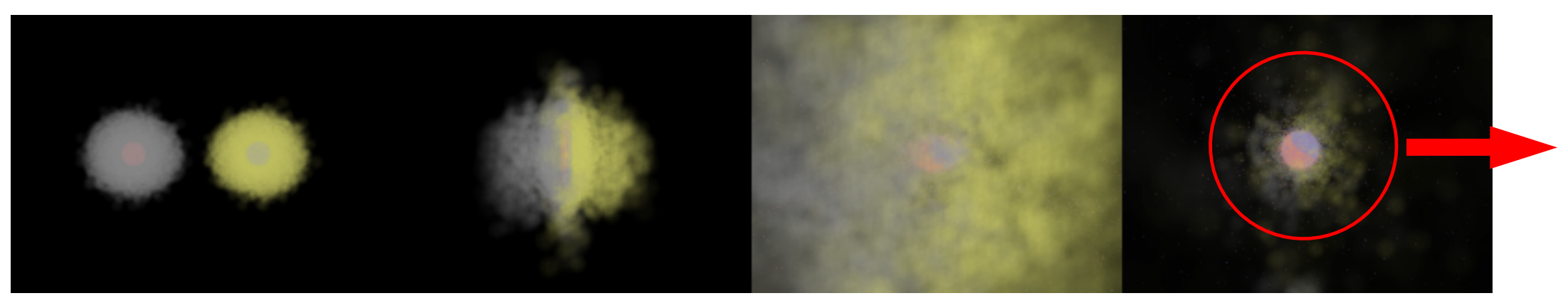
$$X_{\rm atm} = \frac{K_{\rm imp} - \delta\Phi_c + (1-\epsilon)(E_{\rm T,atm} + E_{\rm I,atm})}{E_{\rm th}},$$
$$E_{\rm th} = \frac{\beta}{\alpha}\frac{G M_B M_{\rm atm}}{R_B} - \epsilon(E_{\rm T,atm} + E_{\rm I,atm}),$$

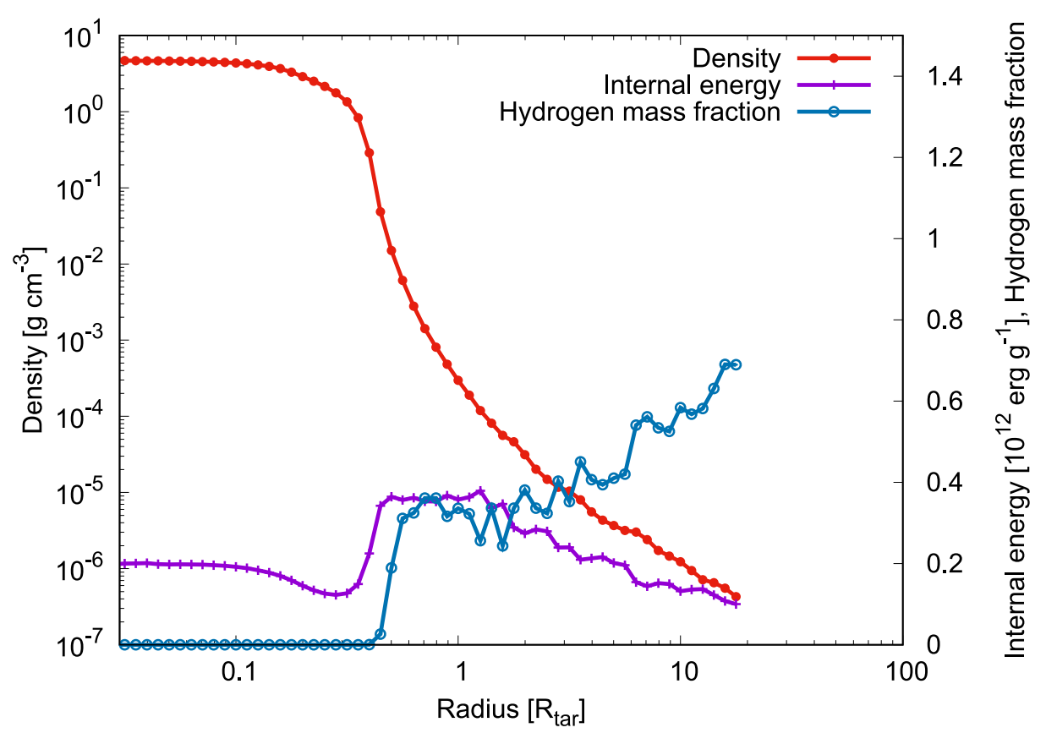
Most of the atmosphere is lost by the comparable impactor mass

Since the standard theory of planet formation implies planets are formed by coagulation by similar masses, planets with a massive atmosphere may be formed in the PPD without giant impacts!

Post-impact planetary structure

1 M_E (10%) & 1 M_E (10%) colliding with 1.0 v_{esc}





The rock component evaporates and mixes with the atmosphere component.

The planetary atmosphere may become a metal-rich atmosphere because the impact-induced rock vapor may react with the primordial atmosphere if the planet has experienced a nearly head-on impact with a comparable impactor mass.