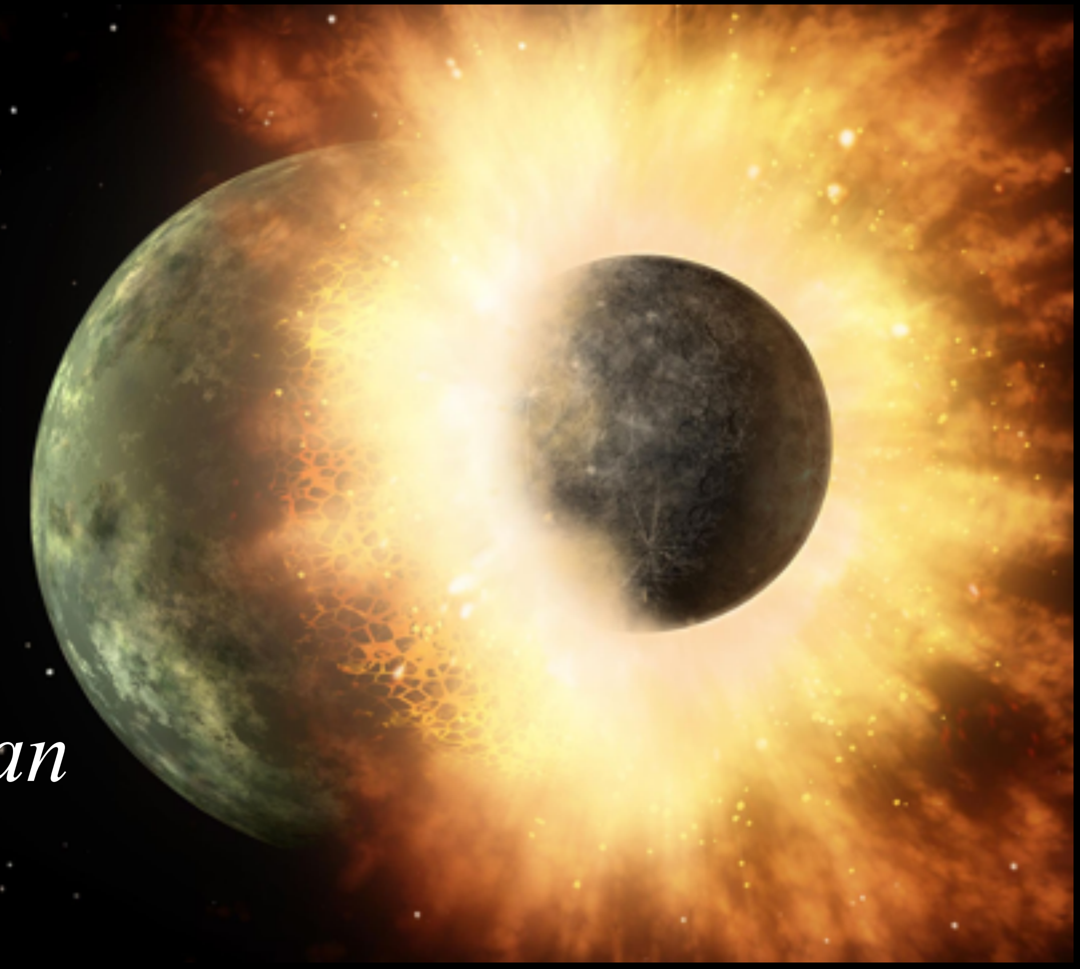
A Collisional Origin for the Coexistence of Volatile-poor Super-Earths and Mini-Neptunes in the Proximity of Stars



Yasunori Hori

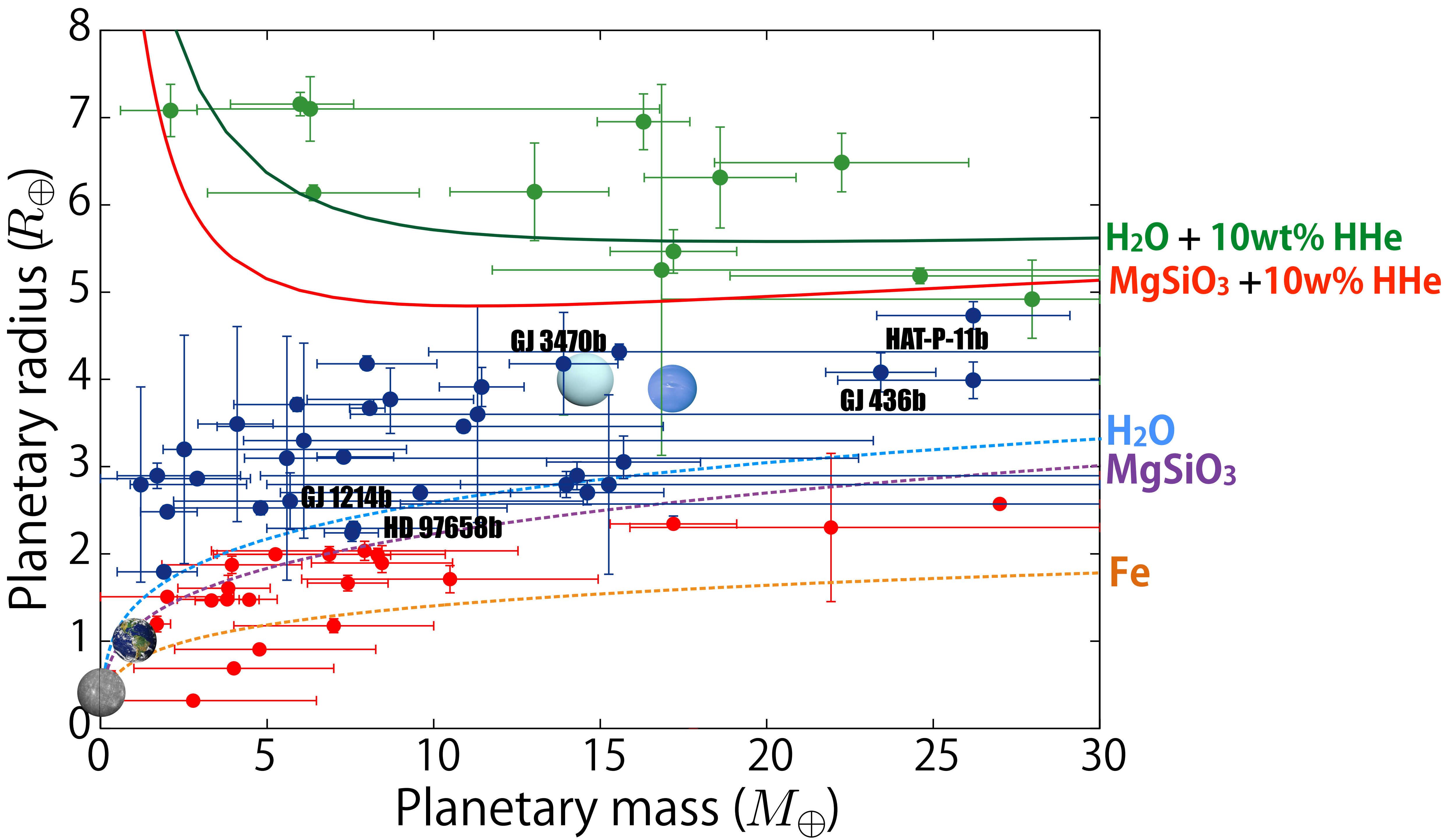
National Astronomical Observatory of Japan
Astrobiology center,
National Institutes of Natural Sciences

***Collaborators*: Shang-fei Liu (UCSC)**
Douglas N.C. Lin (UCSC)
Erik Asphaug (Arizona State Univ.)

Exoplanetary Atmospheres and Habitability (Nice, 12-15, Oct.)

Prevalence of Low-Mass Planets with Atmospheres

Mass-radius relationship of transiting planets with mass of $< 30\ M_\oplus$



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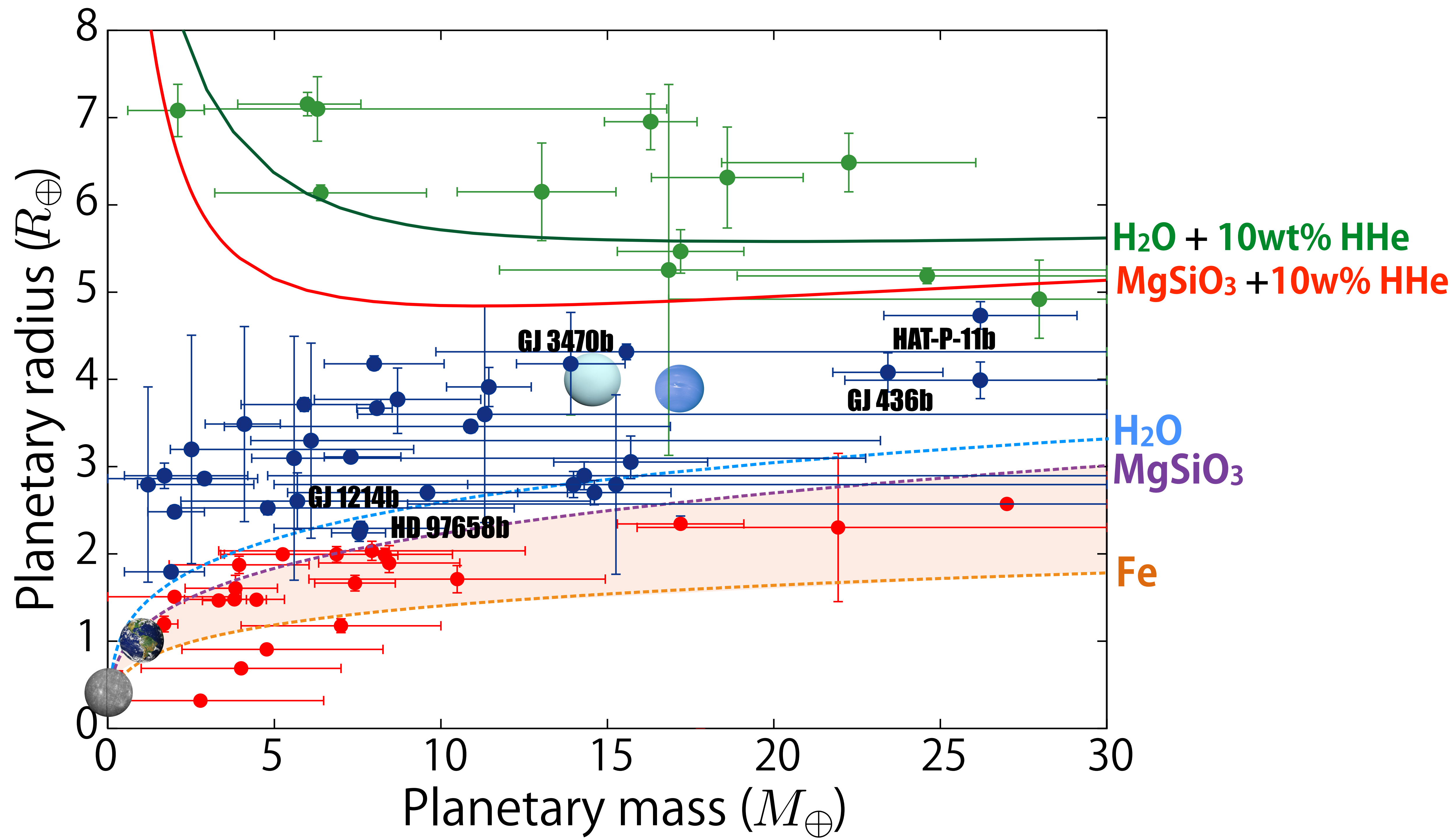

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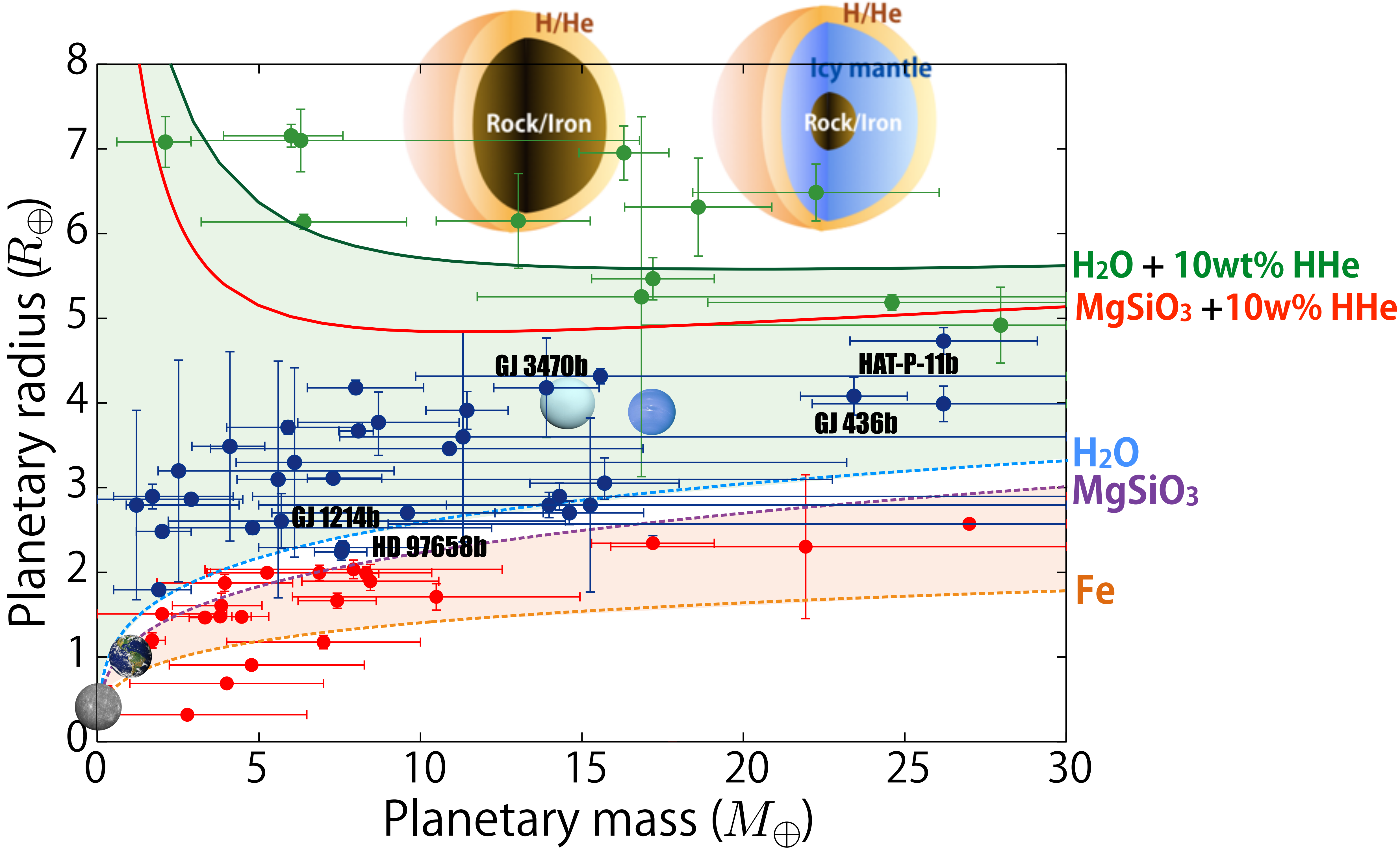

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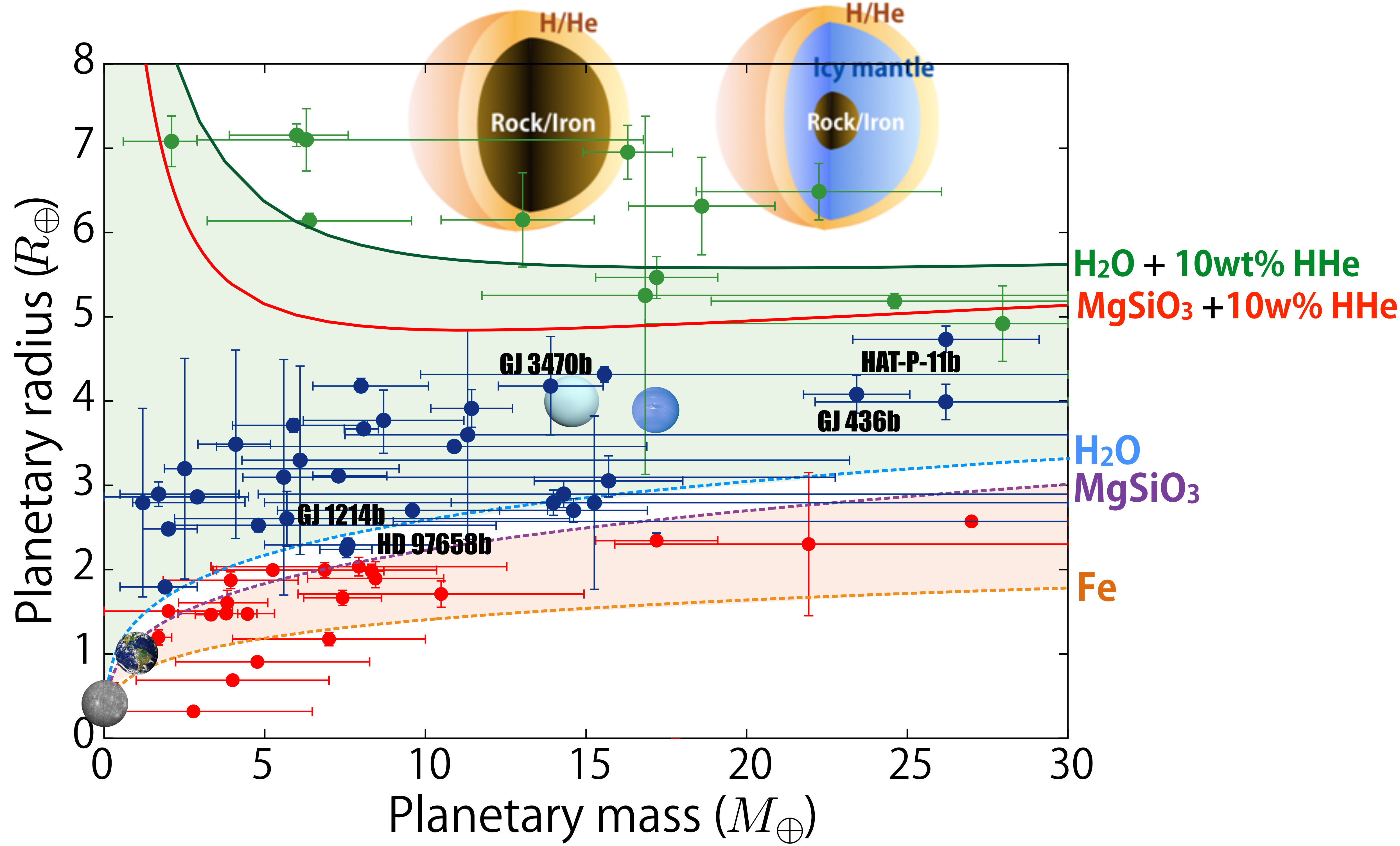
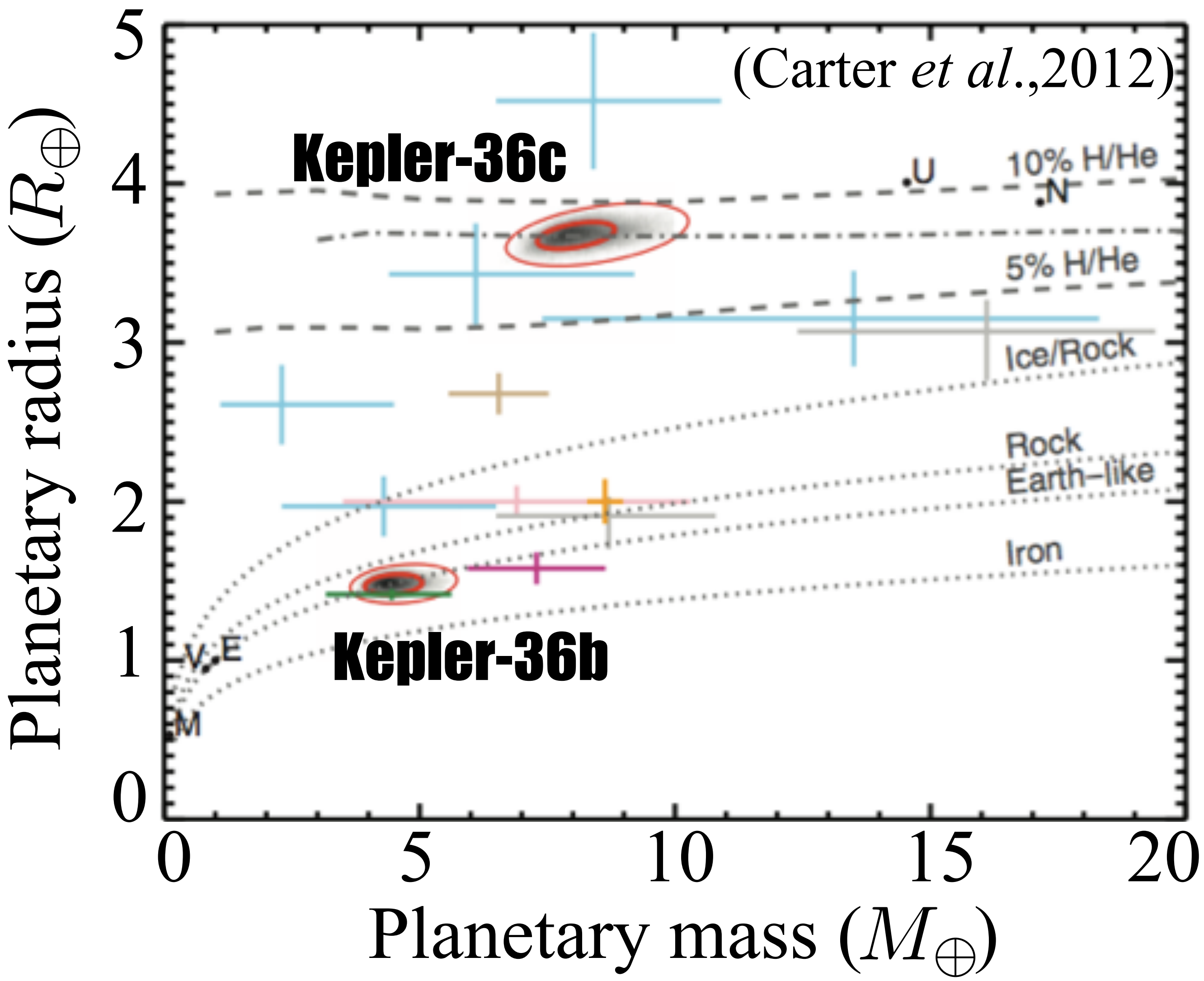


Most of short-period planets should have atmospheres (typically < 10wt%)

A Weird Kepler-36 and Kepler-11 System



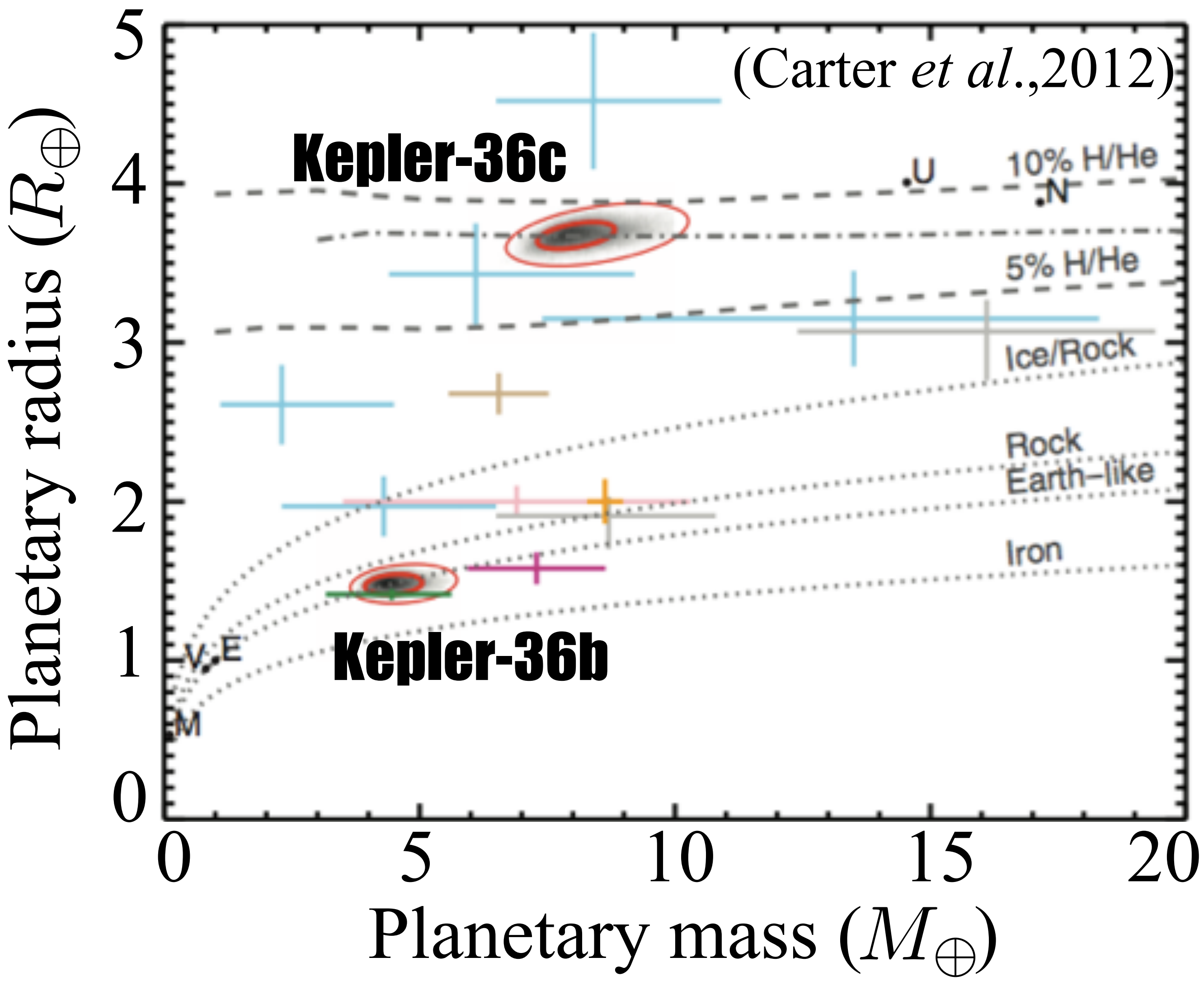
Kepler-36b @13.8 days

Earth-like composition

Kepler-36c @16.2 days

H/He atmosphere atop the core (~ 8.6wt%) (Lopez & Fortney, 2013)

A Weird Kepler-36 and Kepler-11 System



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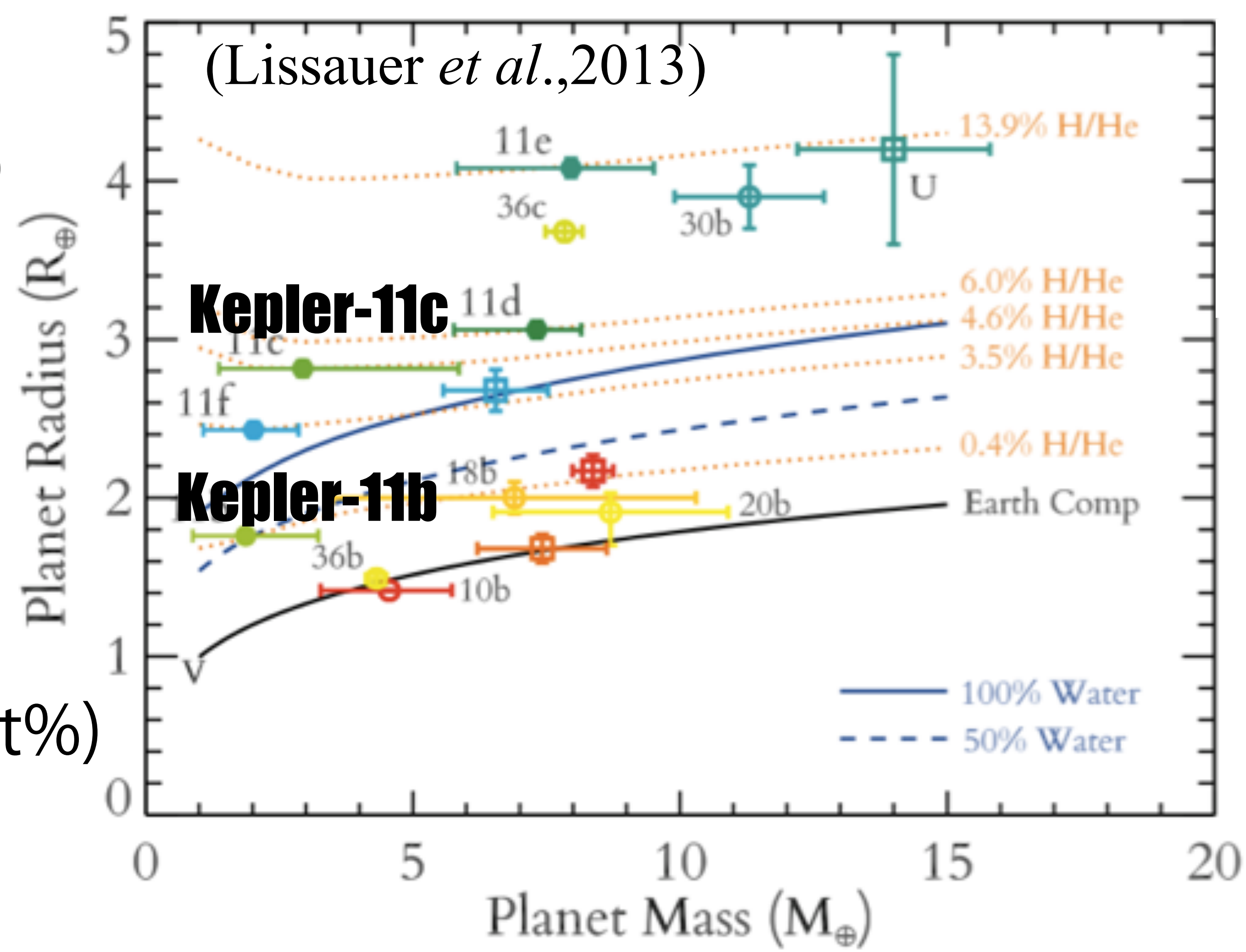

Kepler-11b @10.3 days
a tenuous atmosphere (0.5wt%)

Kepler-11c @13.0 days
a relatively-thick atmosphere (5.0wt%)

Compositional Dissimilarity of Low-Mass Planets On Adjacent Orbits Near Host Stars

The origin of a high density contrast b/w neighboring planets?

(1) **Degassing** from accreting material (e.g.Elkins-Tanton & Seager, 2008)

(2) **Photo-evaporation** via stellar XUV irradiation or a Parker wind (e.g. Owen & Wu, 2013)

(3) **Regulation of disk accretion** onto a core

- in-situ accumulation in a dissipating disk (e.g. Ikoma & YH,2012; Lee *et al*.,2014)
- rapid in/outflow of the disk gas (Ormel *et al*., 2014)
- magnetic suppression of gas accretion (?)

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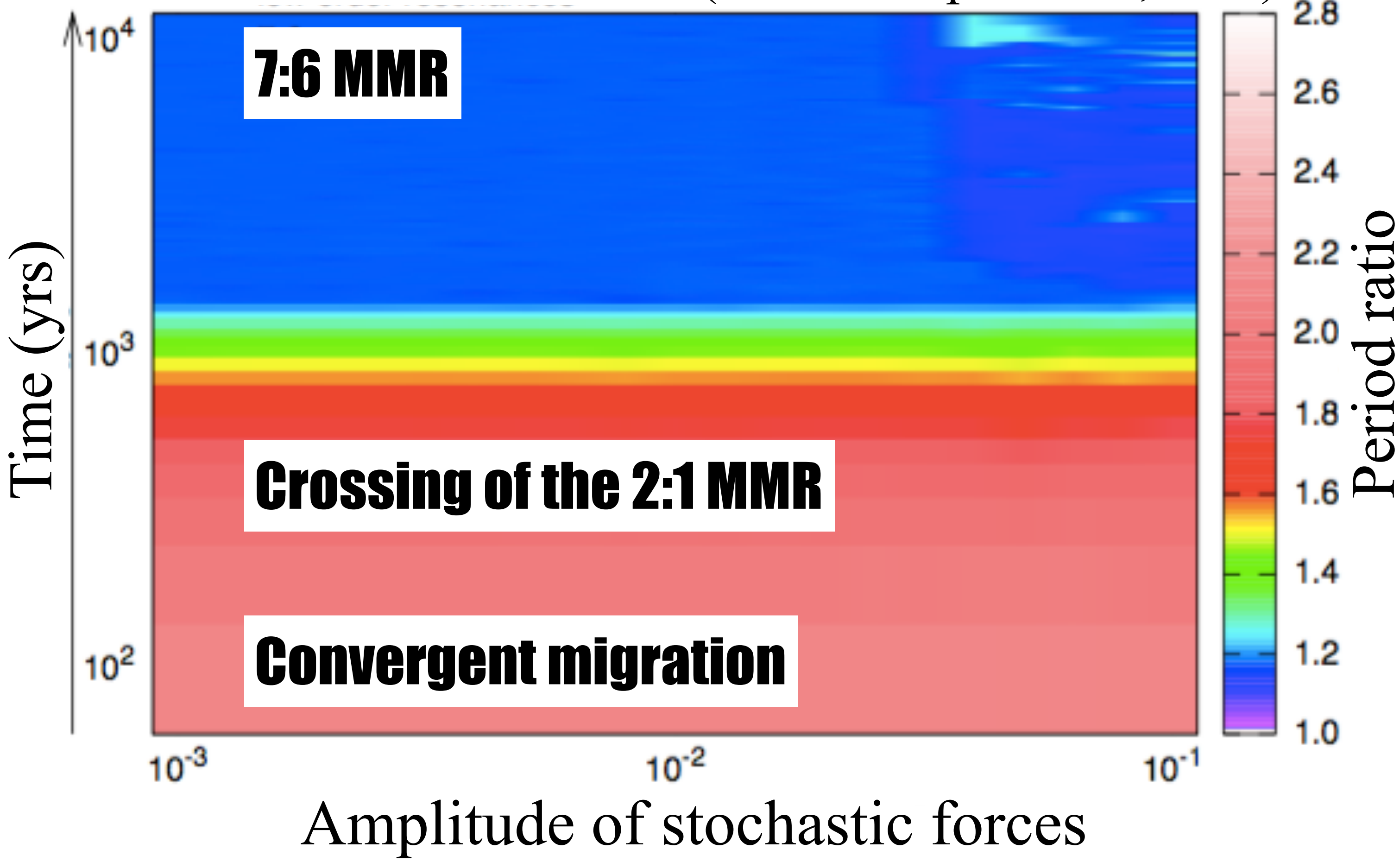
Compositional diversity of close-in super-Earths likely reflects their **formation histories**

(e.g.) planetary migration, core growth, and giant impacts

Possible Origin of A Closely-Packed MMR System

(Paardekooper *et al.*,2013)



Smooth Type I migration

+

Stochastic forcing due to turbulent density fluctuations

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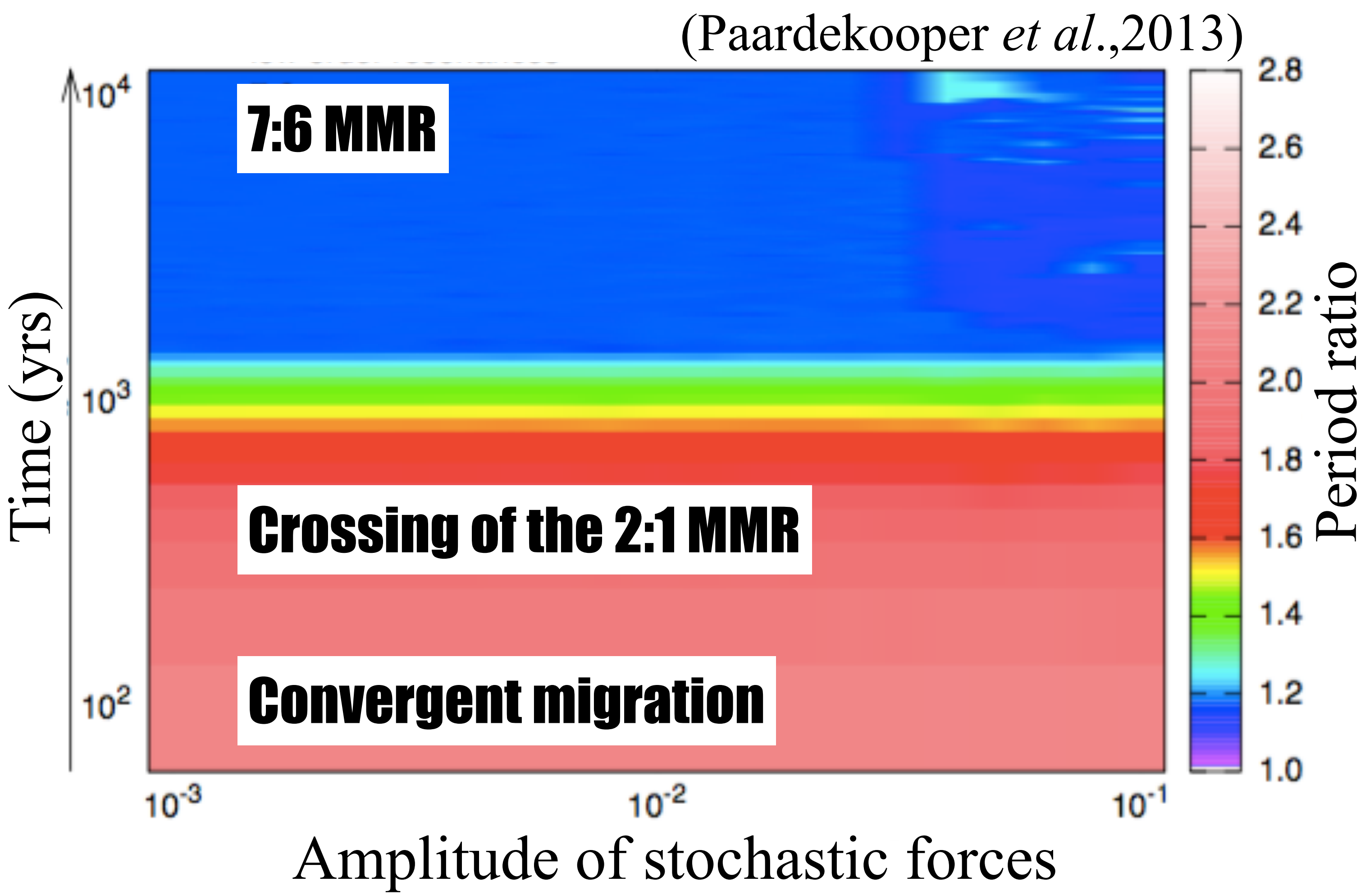

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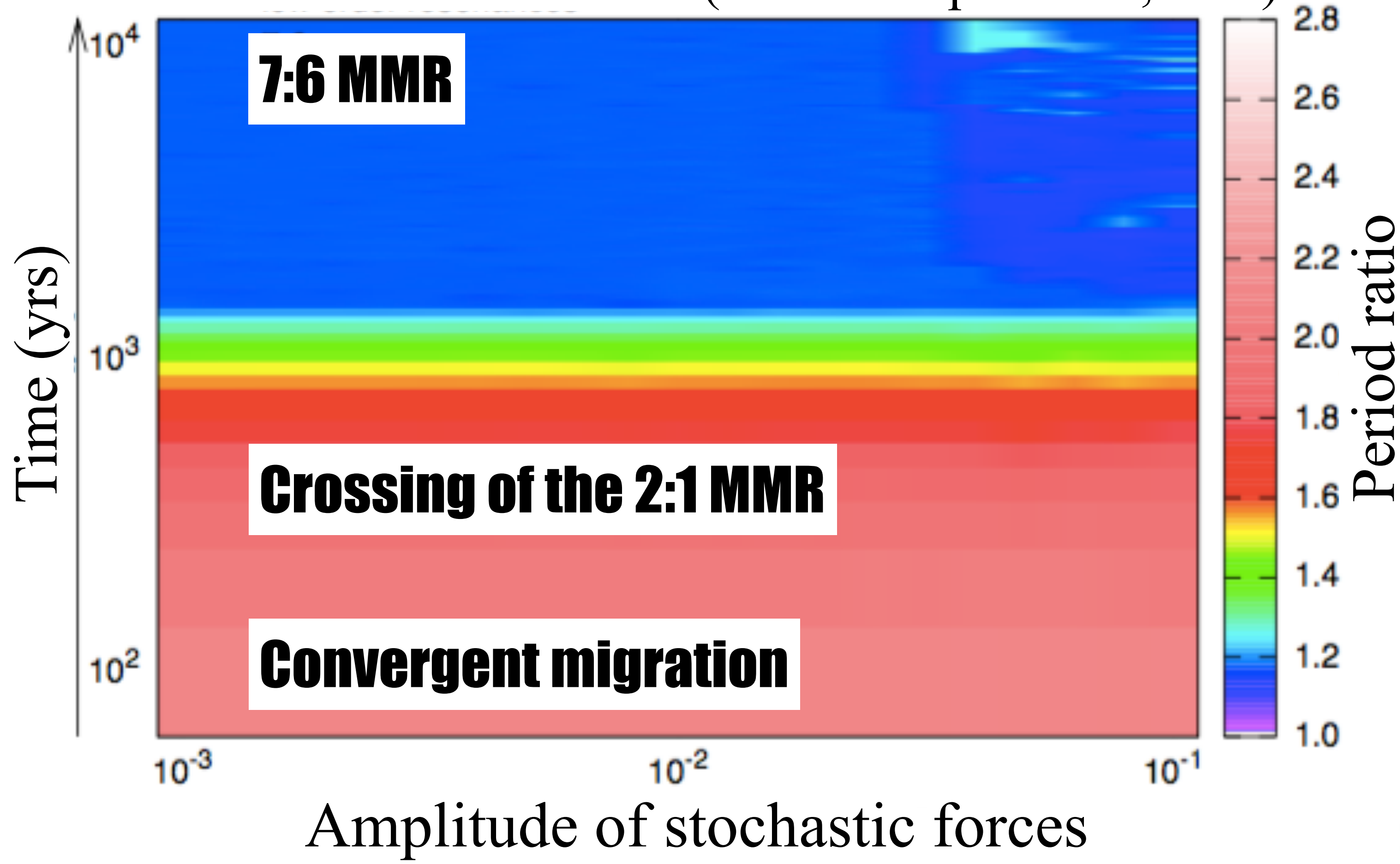

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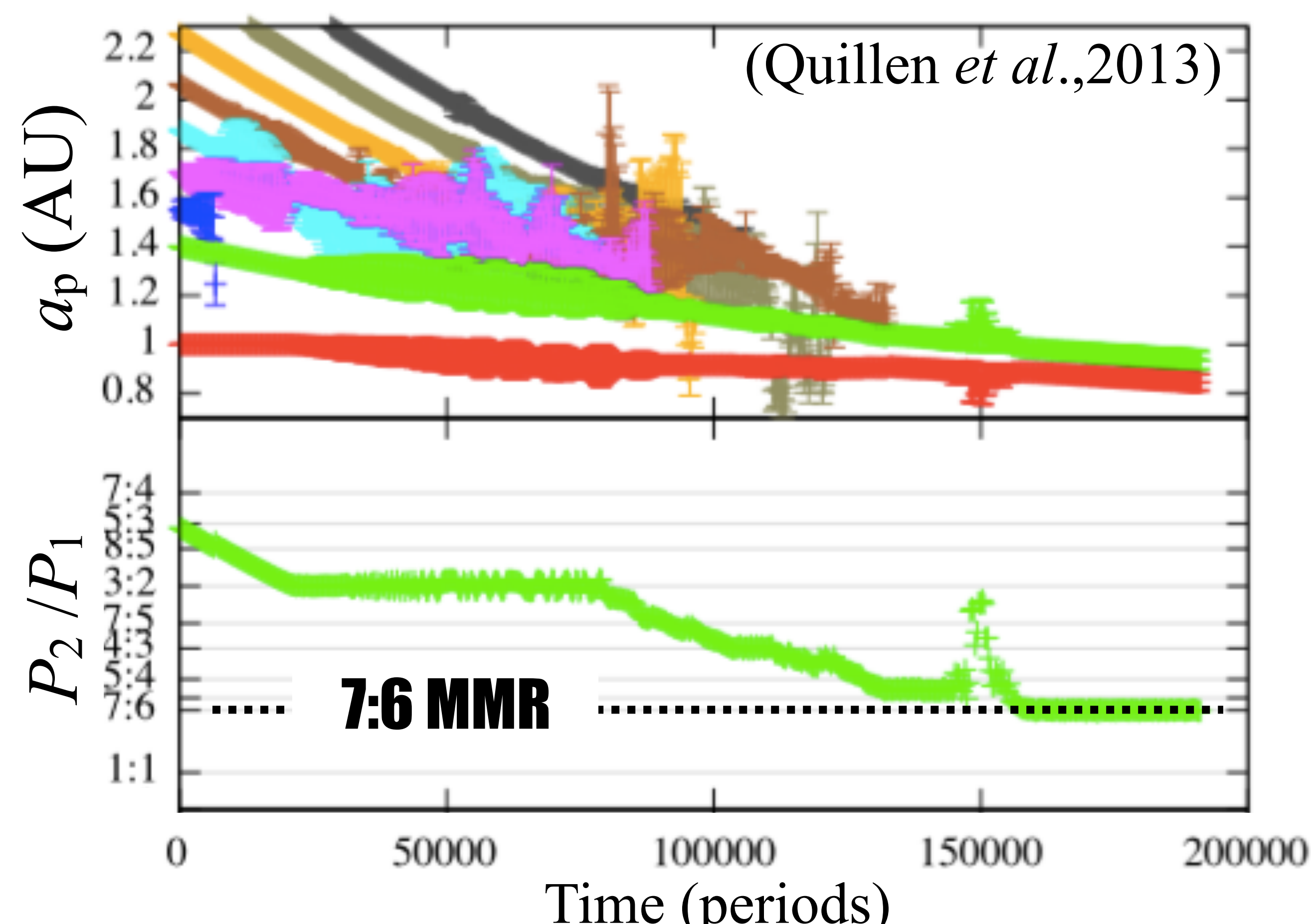

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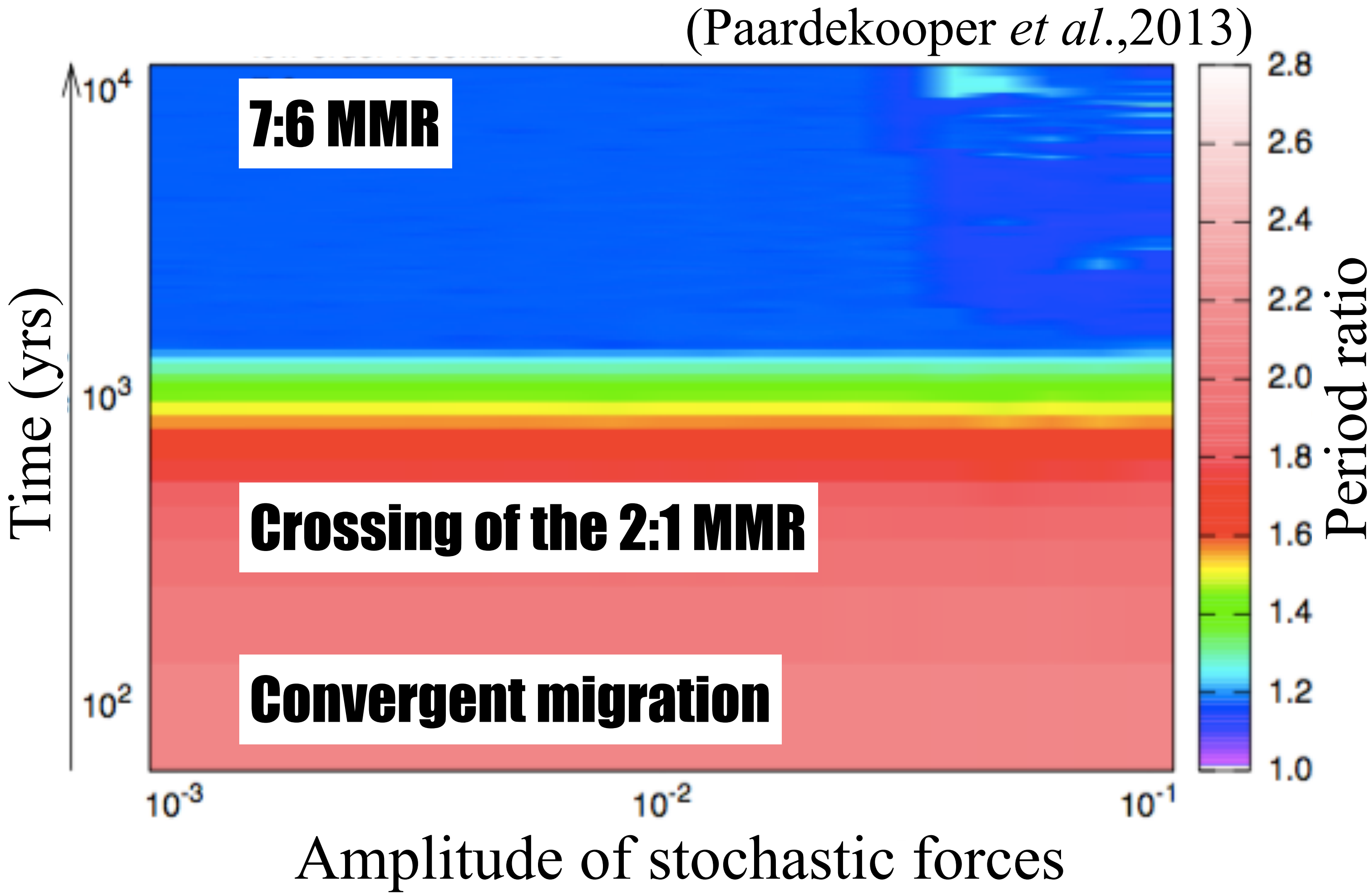

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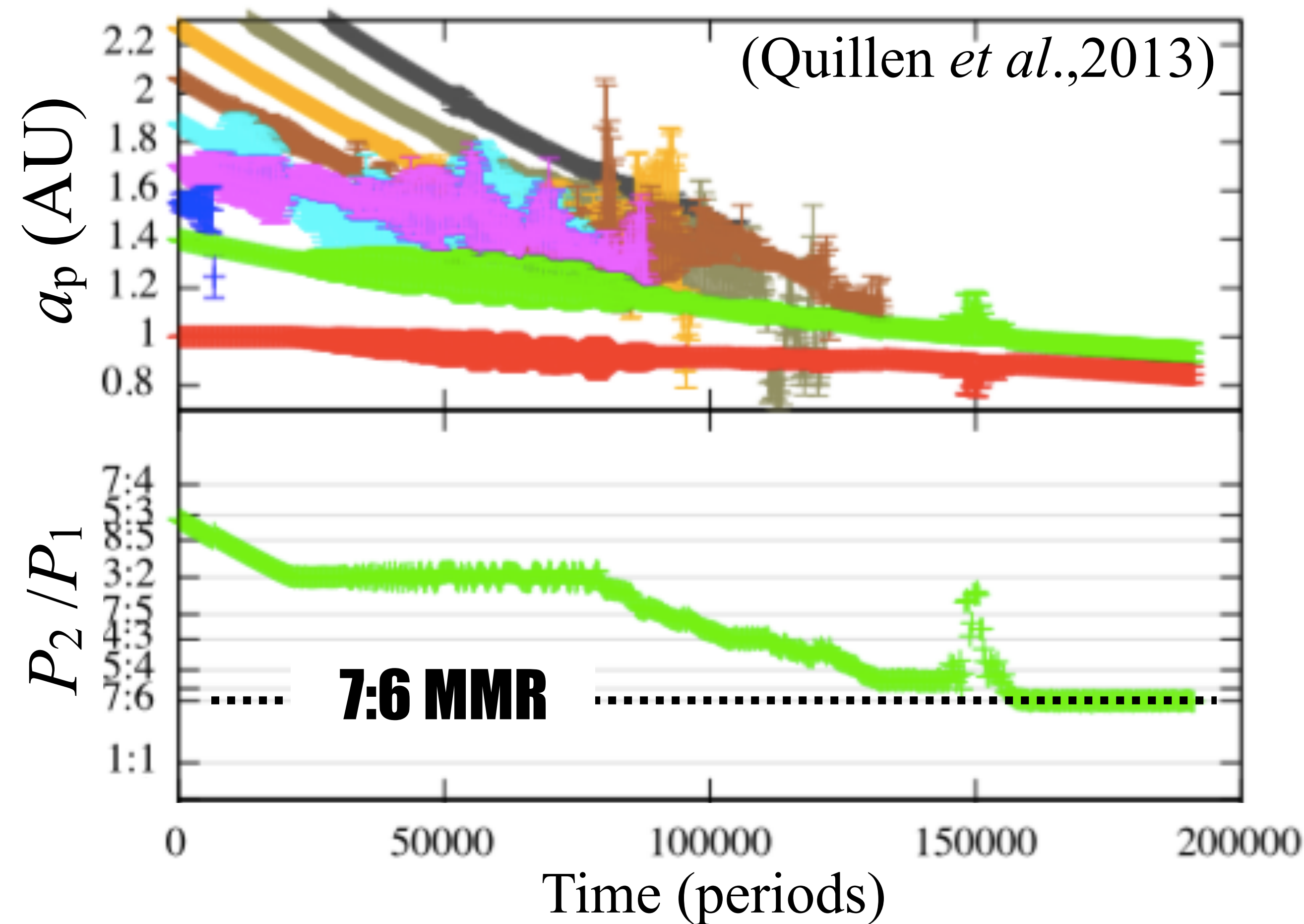
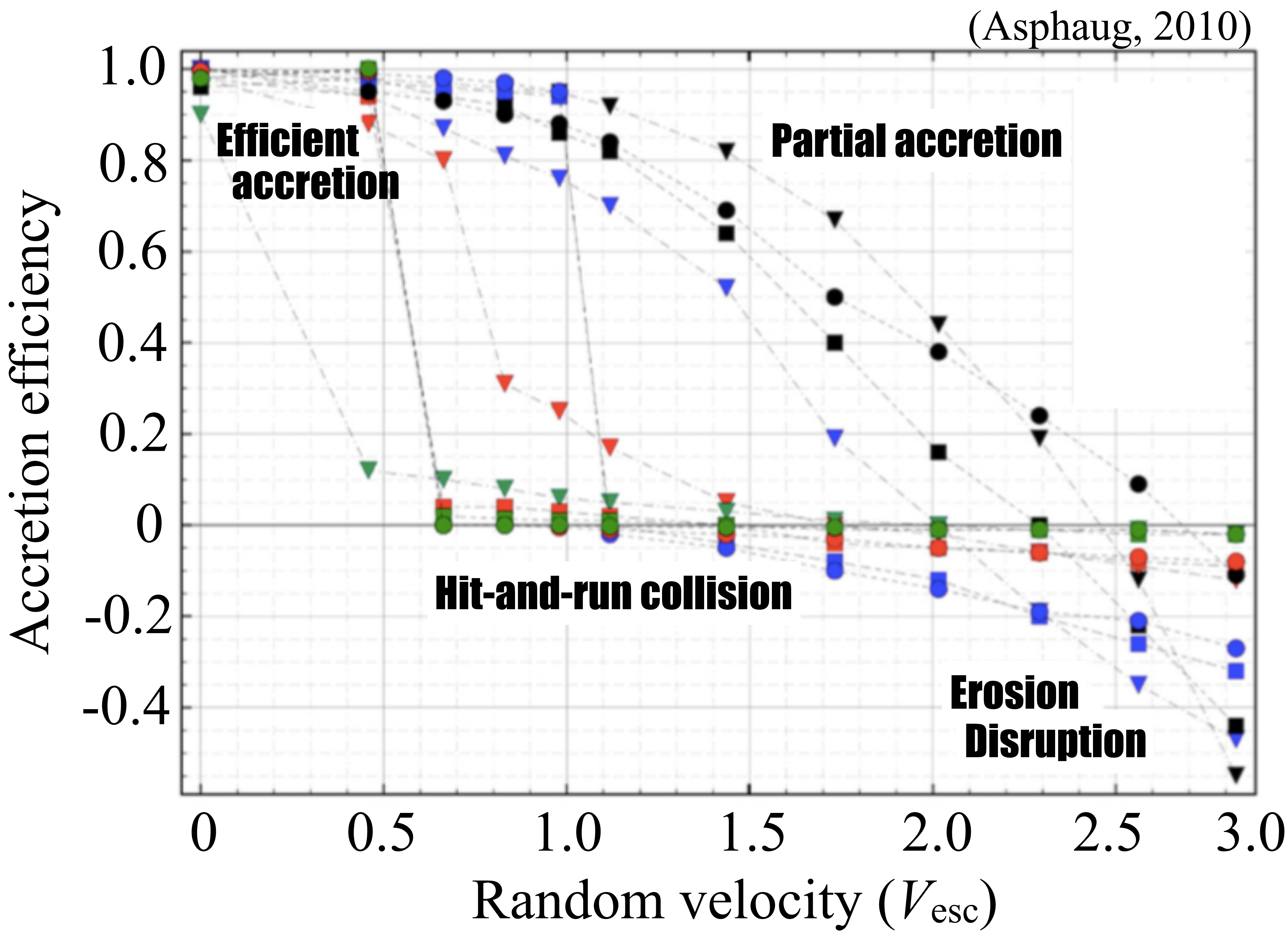
A compact system in high-p MMR like the Kepler-36 system

Two migrating planets likely experience **collisions with embryos** in a turbulent disk during their excursion



Giant Impacts: Accretionary and Destructive

Accretion efficiency as a function of mass ratio (0.1▼, 0.5■, 1.0●), impact angle (0, 30, 45, 60°), and impact velocity



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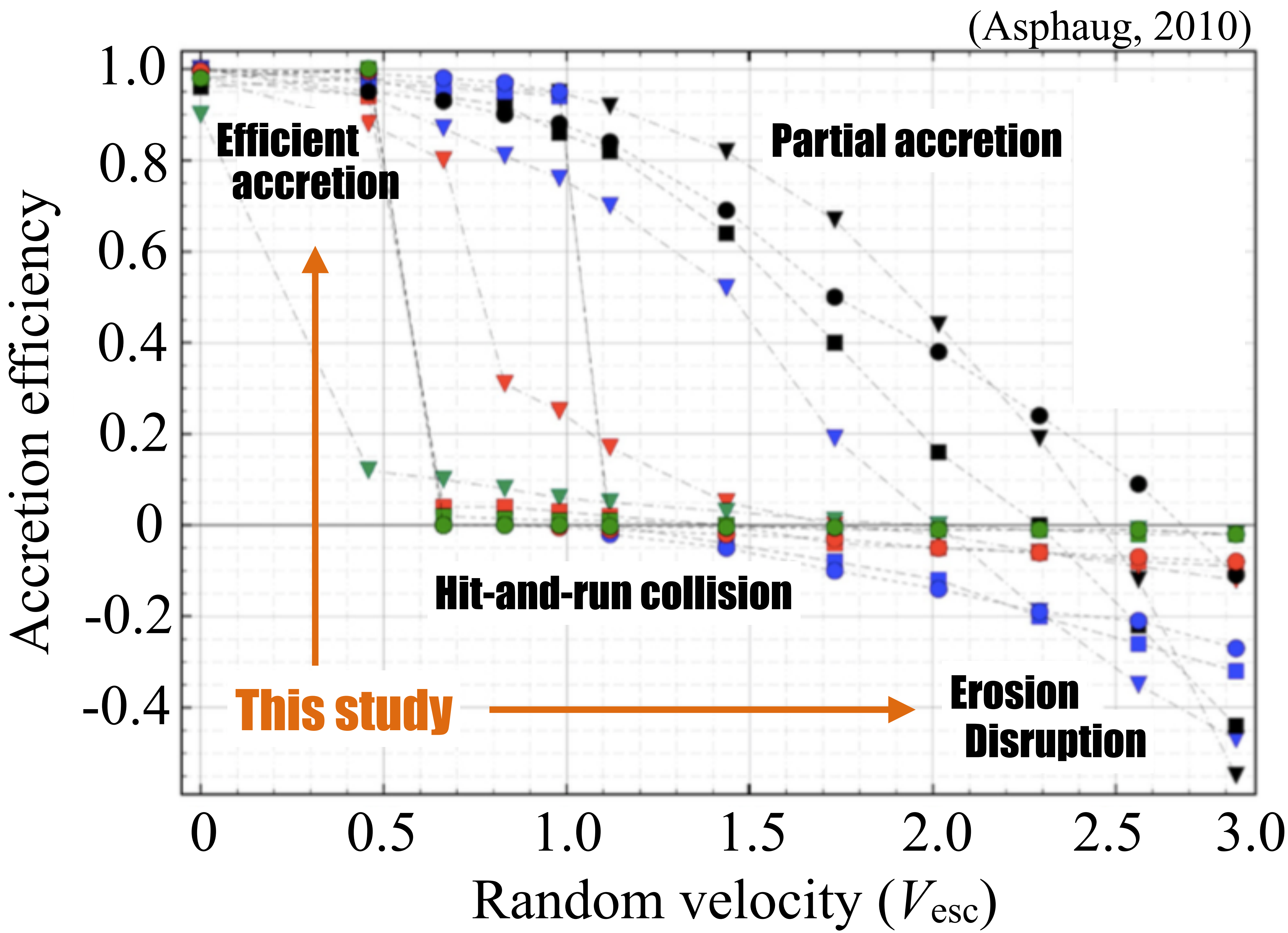

Modeling of a Giant Impact

Three-dimensional hydrodynamic simulations : **FLASH** with **the AMR**

(Fryxell *et al*., 2000)

- A pair of planets' center of mass frame
- The width of a computational domain ~ 1 AU
- include the tidal force from a central star
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Three-Layered interior structures of a target and an impactor

Tillotson EoS for rocky and iron material (Melosh, 1989)

rock (silicate) : **iron** = **2:1**

Only a target has an atmosphere (7.5wt%)

Polytropic EoS for H/He gas (H_2 : He = 7 : 3)

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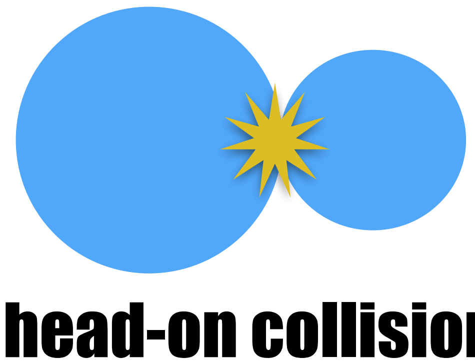
Giant impacts (@ **0.1 AU**)



(1) Low-speed model (accretion regime) : $V_{\rm imp} = V_{\rm esc}$

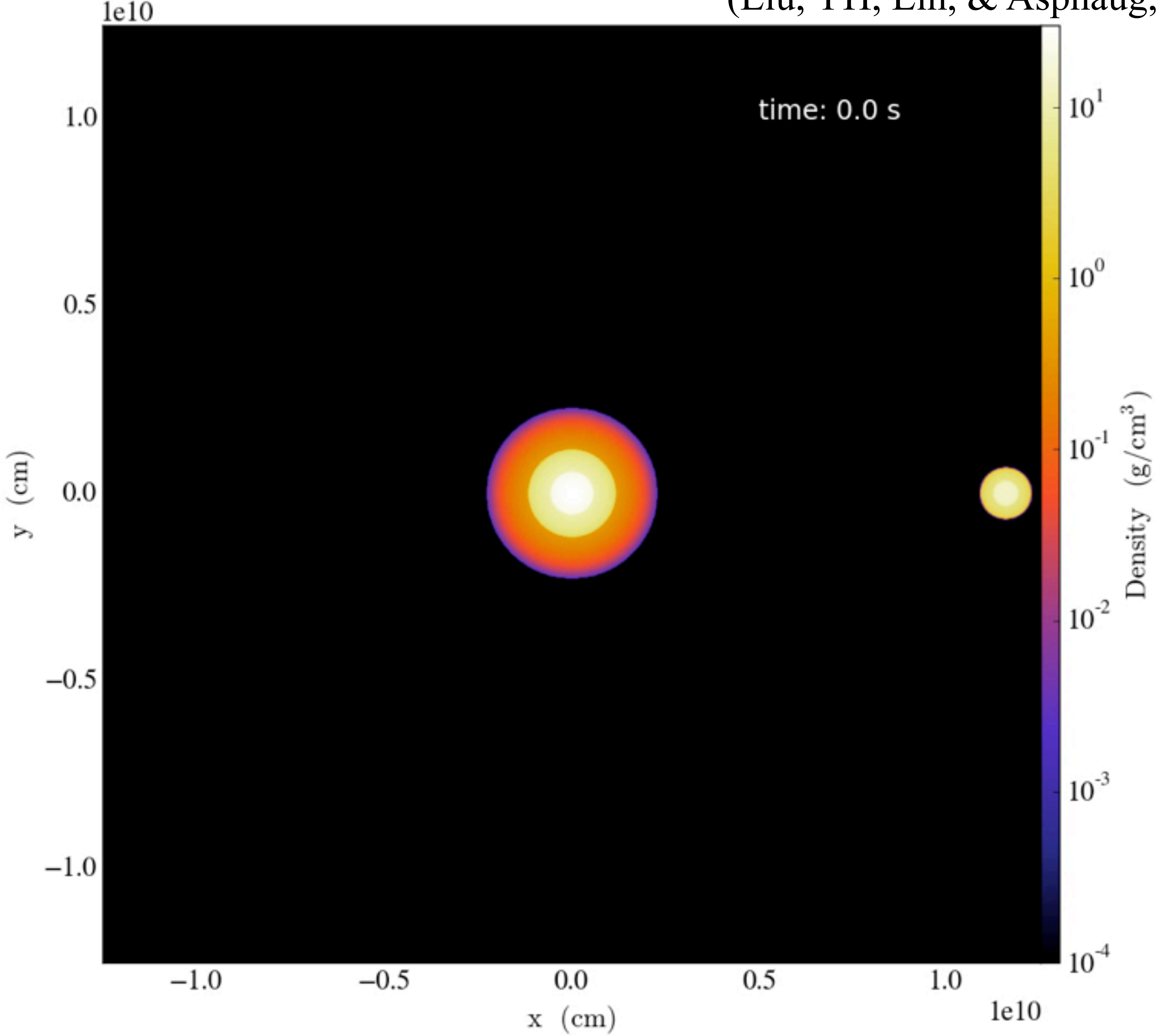
$$4.3\,M_\oplus \;\&\; 1.0\,M_\oplus$$

(2) high-speed model (destructive regime) : $V_{\rm imp} = 3V_{\rm esc}$

$$10\,M_\oplus \;\&\; 1.0\,M_\oplus$$

Simulation Movie : A High-Speed Head-On Collision

(Liu, YH, Lin, & Asphaug, 2015)



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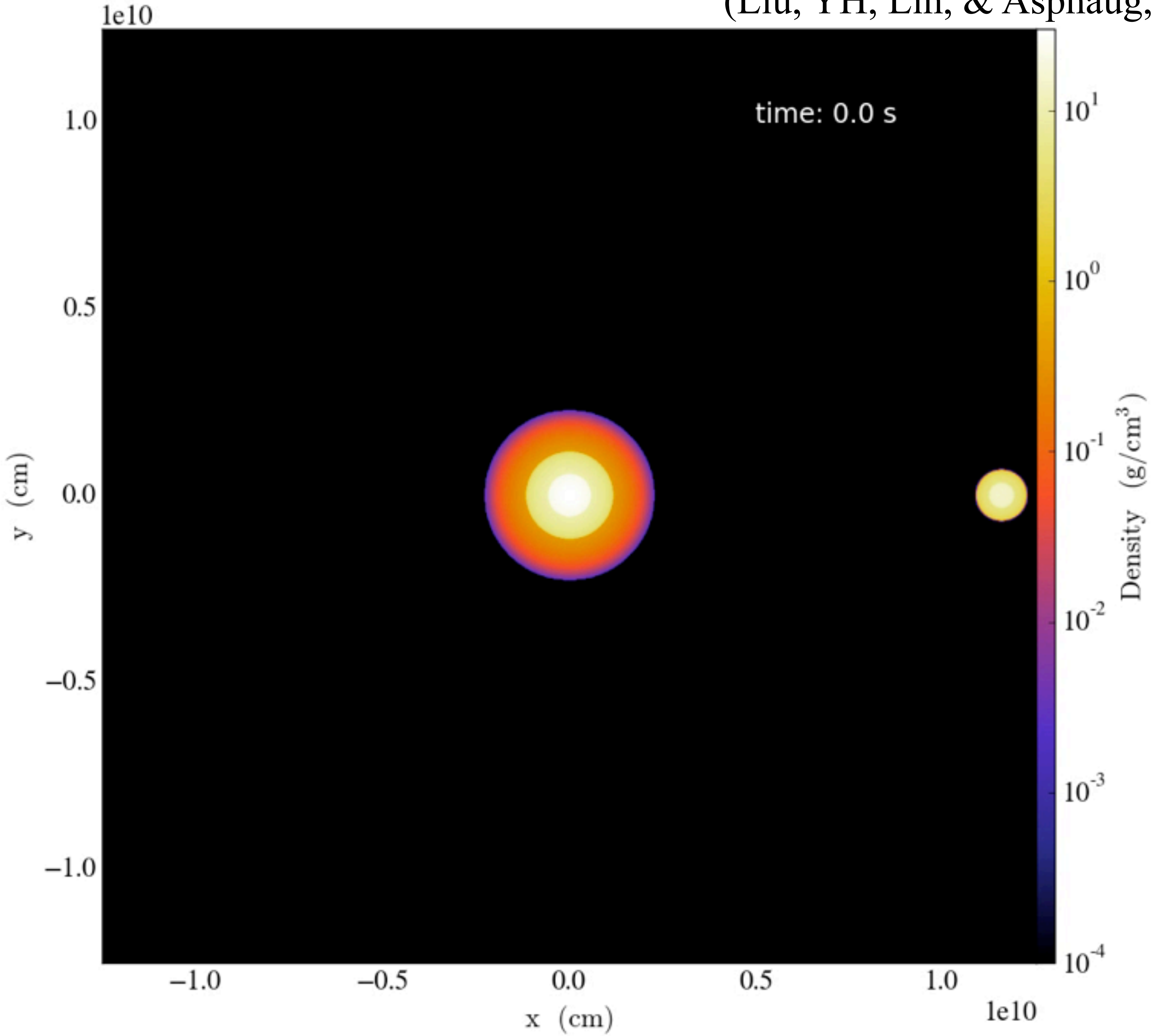

Snapshots of Two Head-On Collisions : Density Contours

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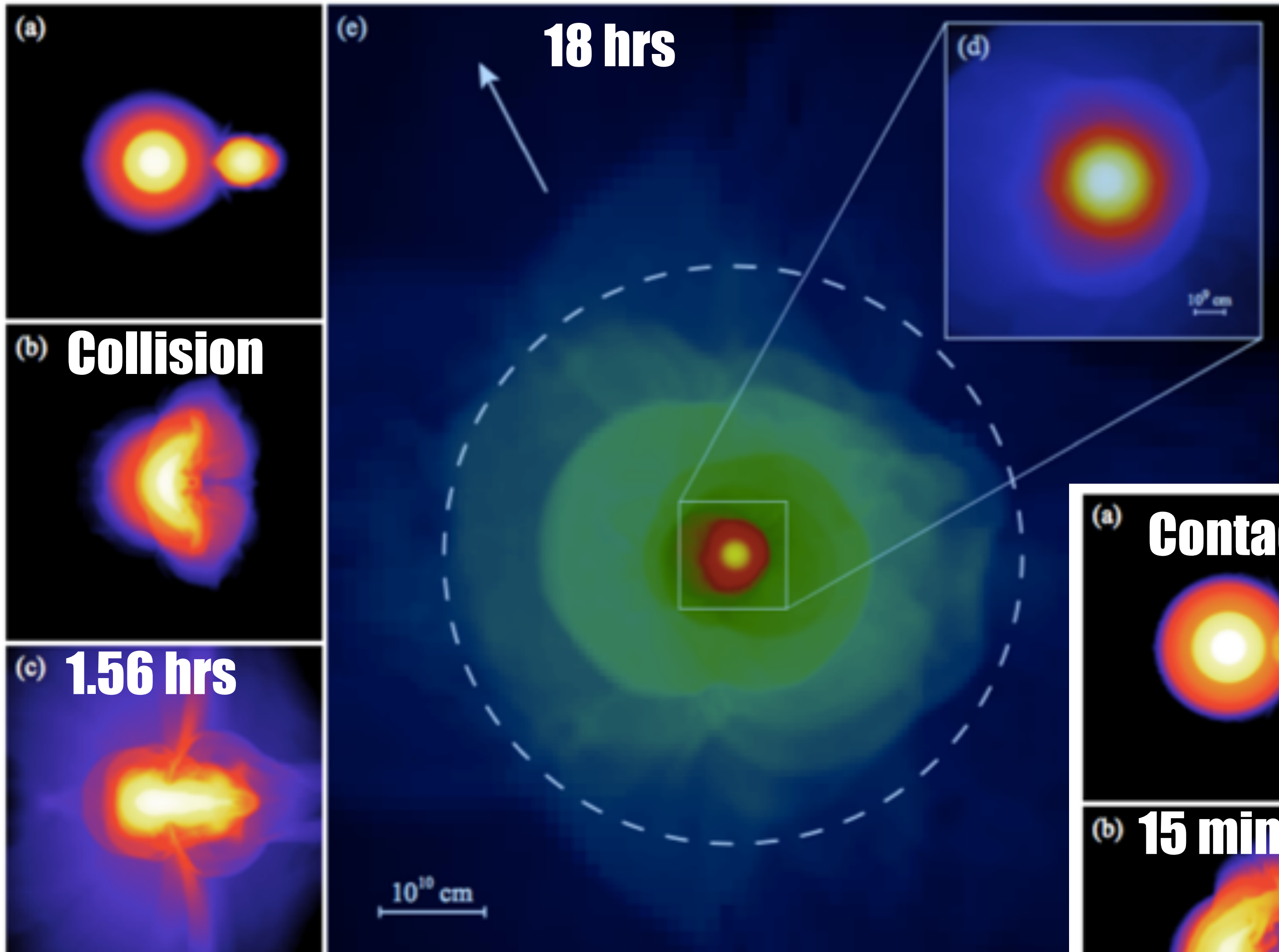
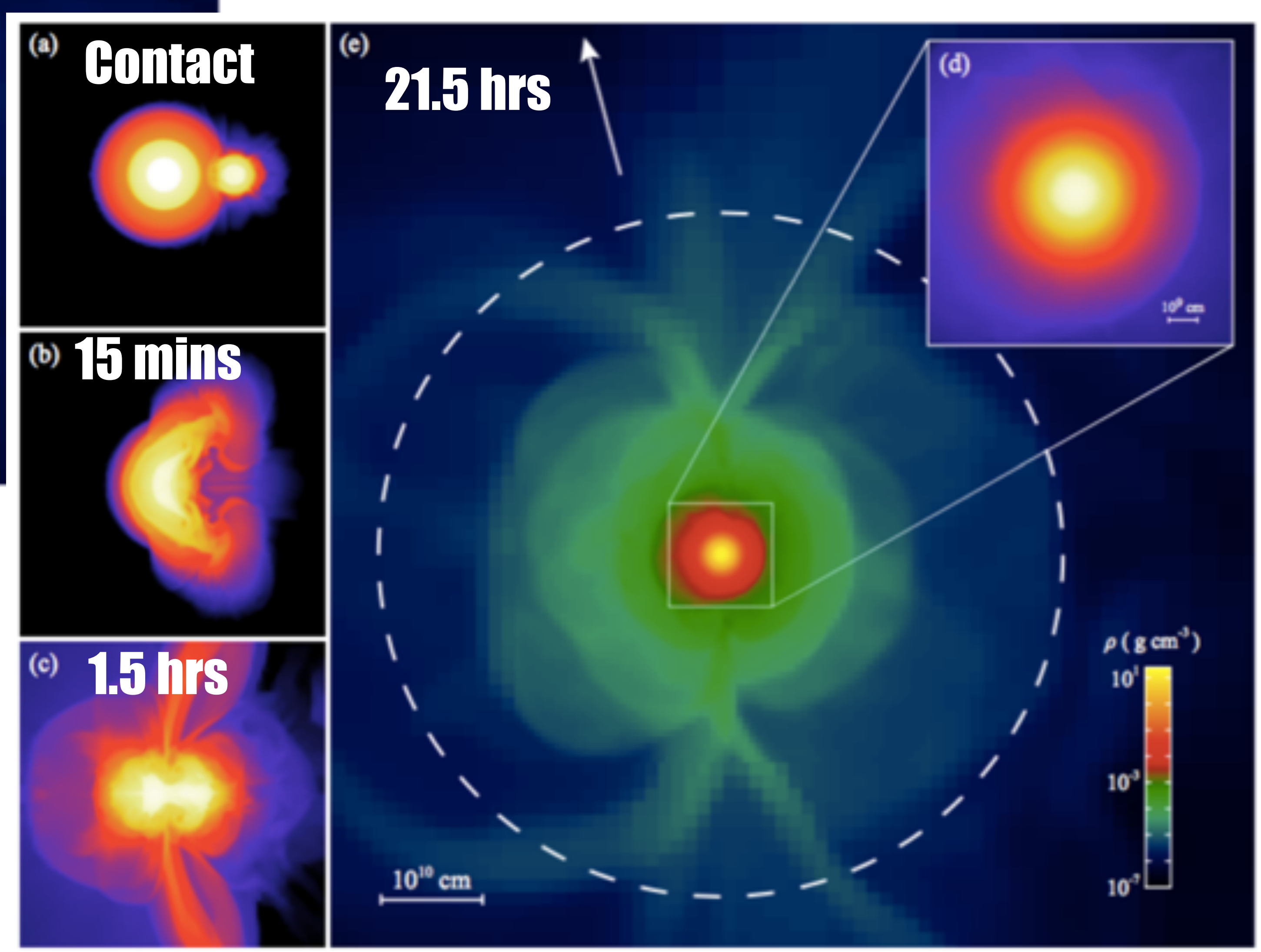


Low-speed impact

High-speed impact



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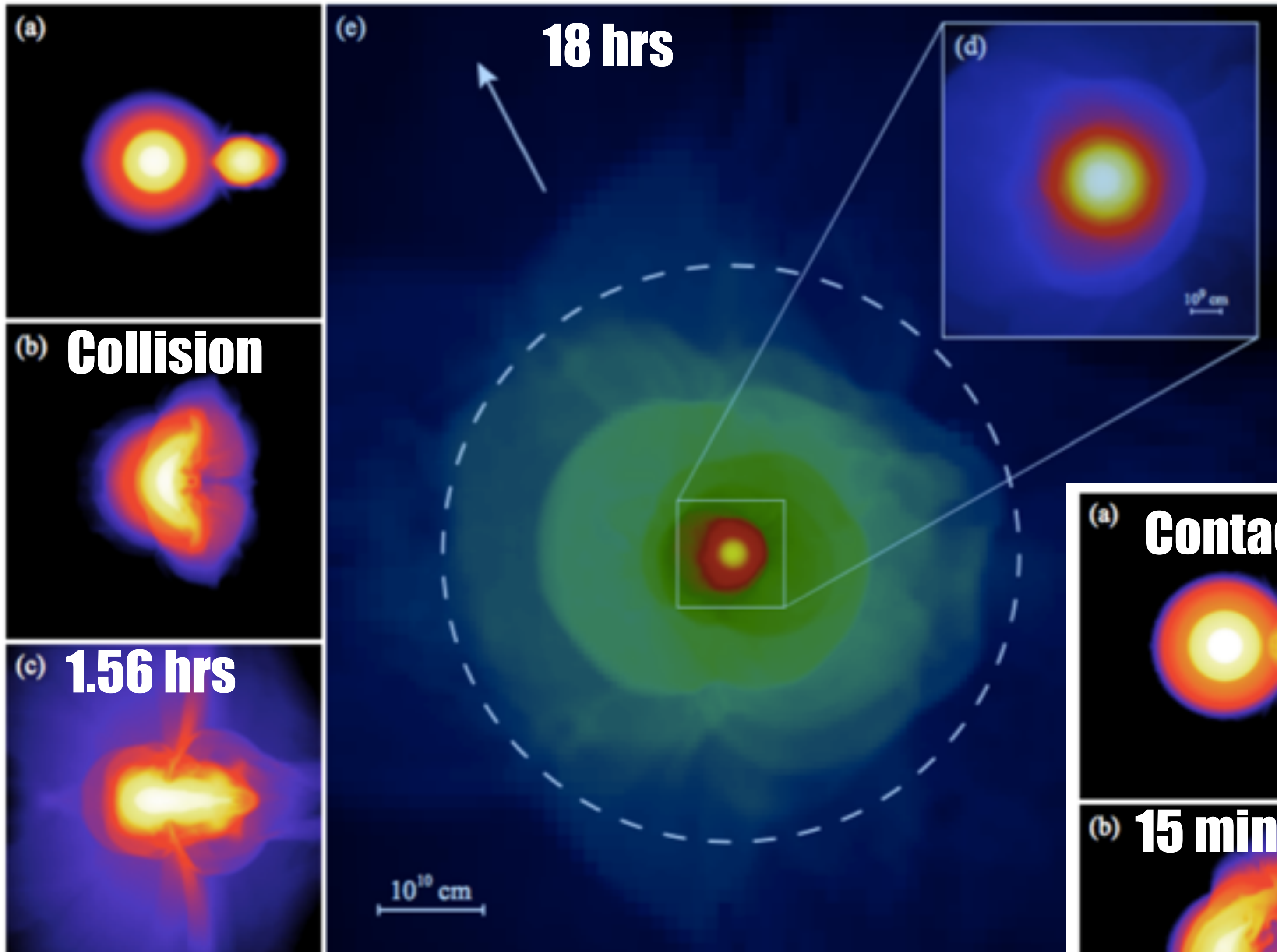
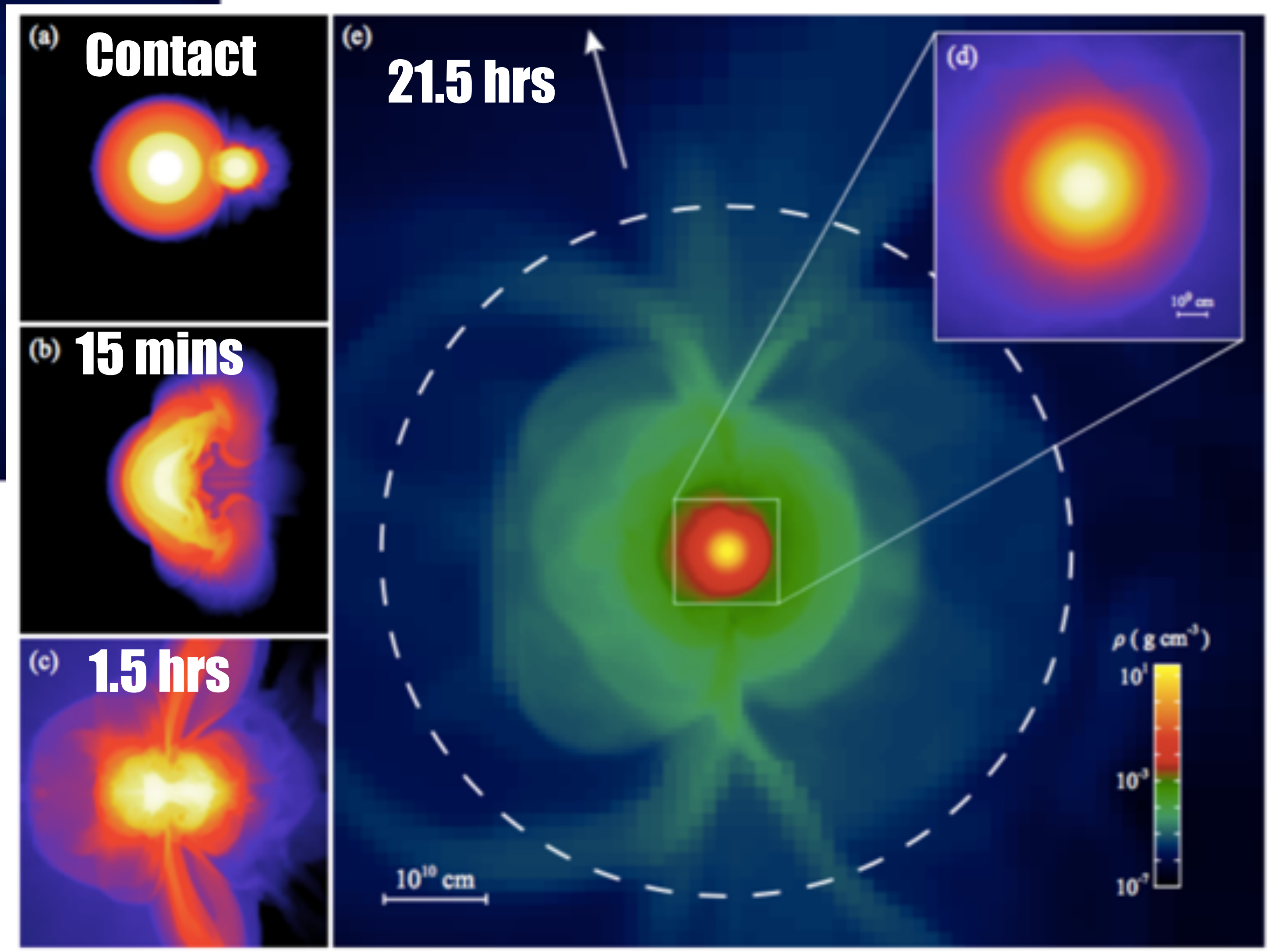


Low-speed impact

The atmosphere is lost by ~30%

High-speed impact



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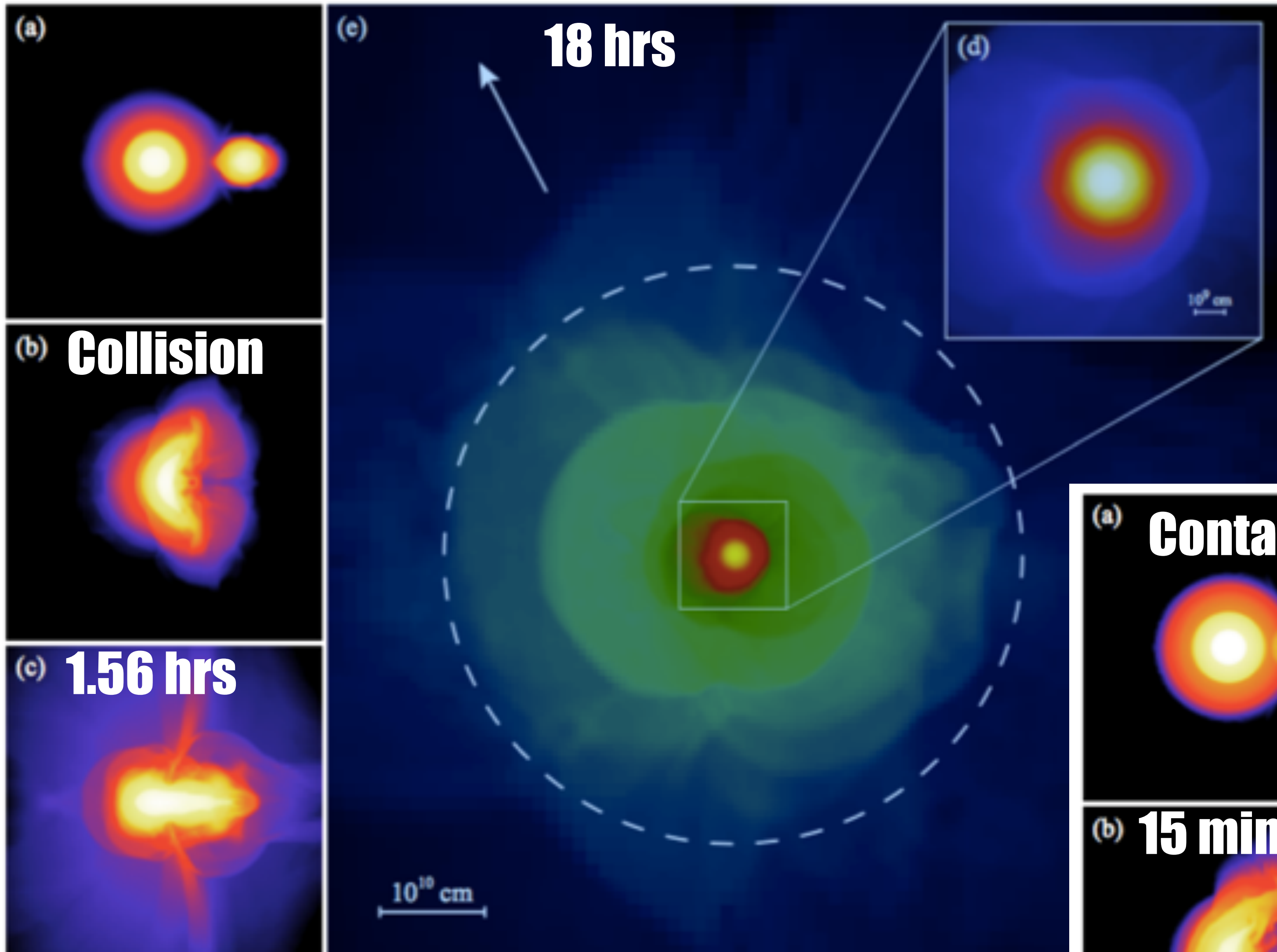
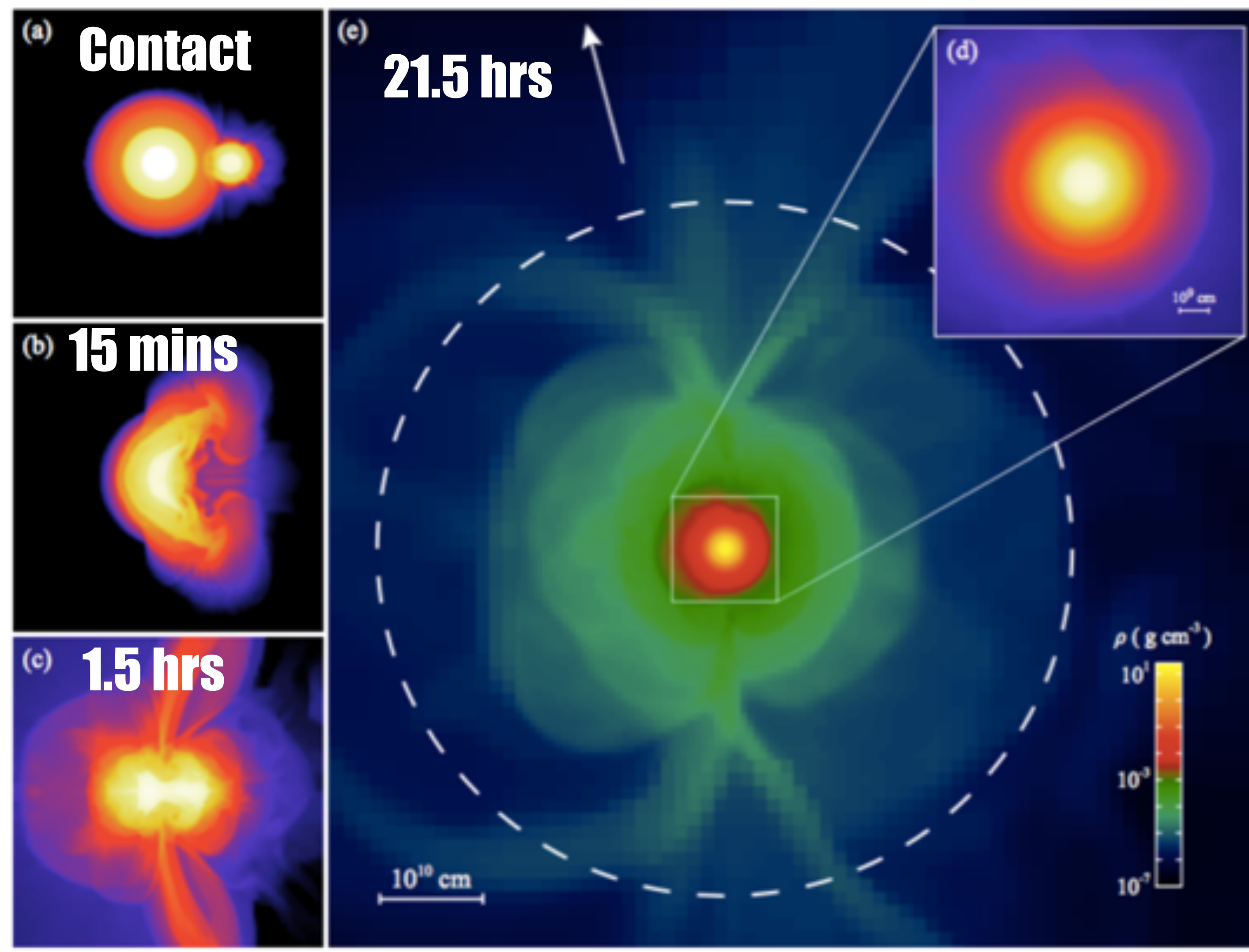


Low-speed impact

The atmosphere is lost by ~30%

The atmosphere is lost by ~80%

High-speed impact



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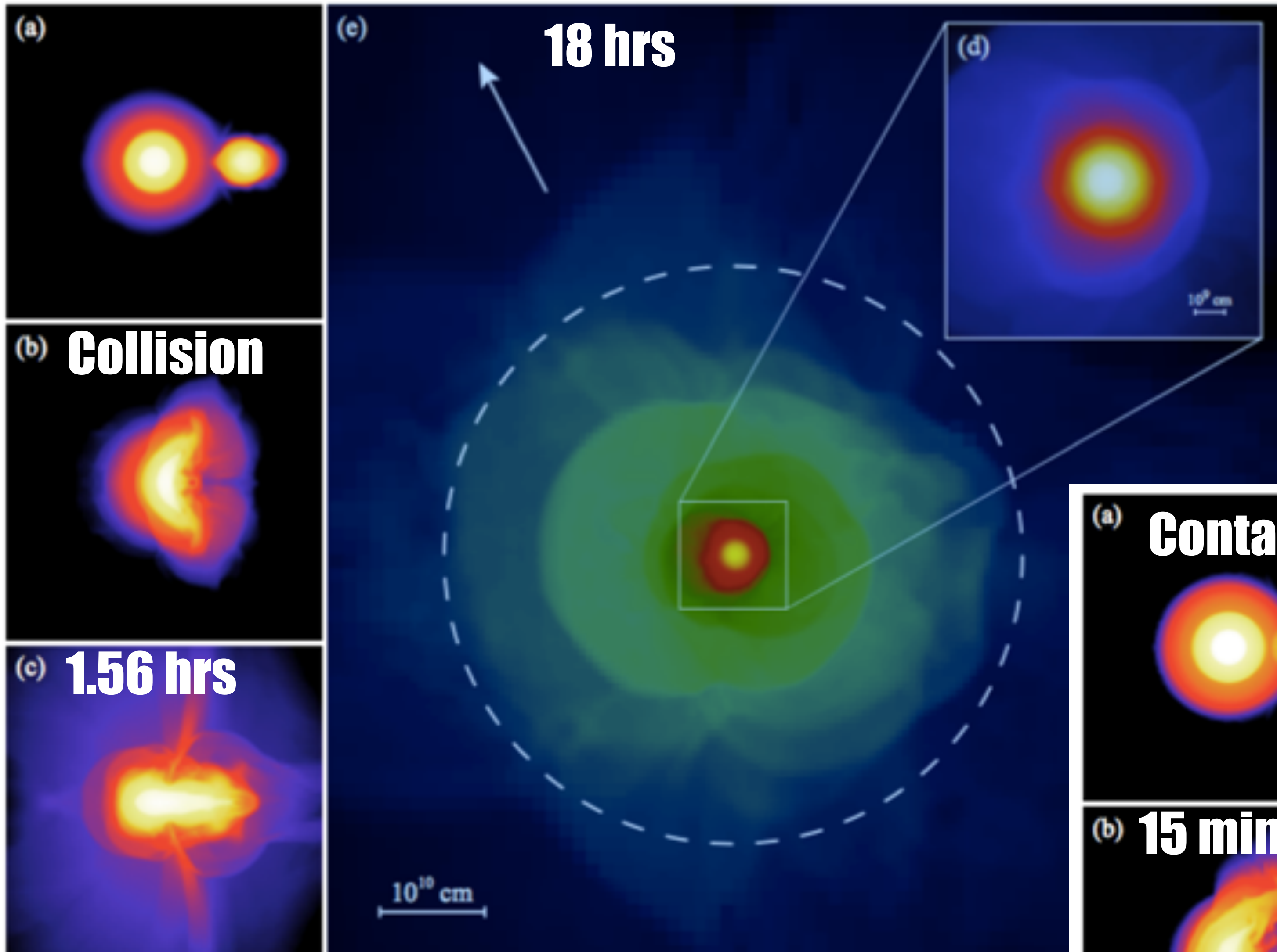

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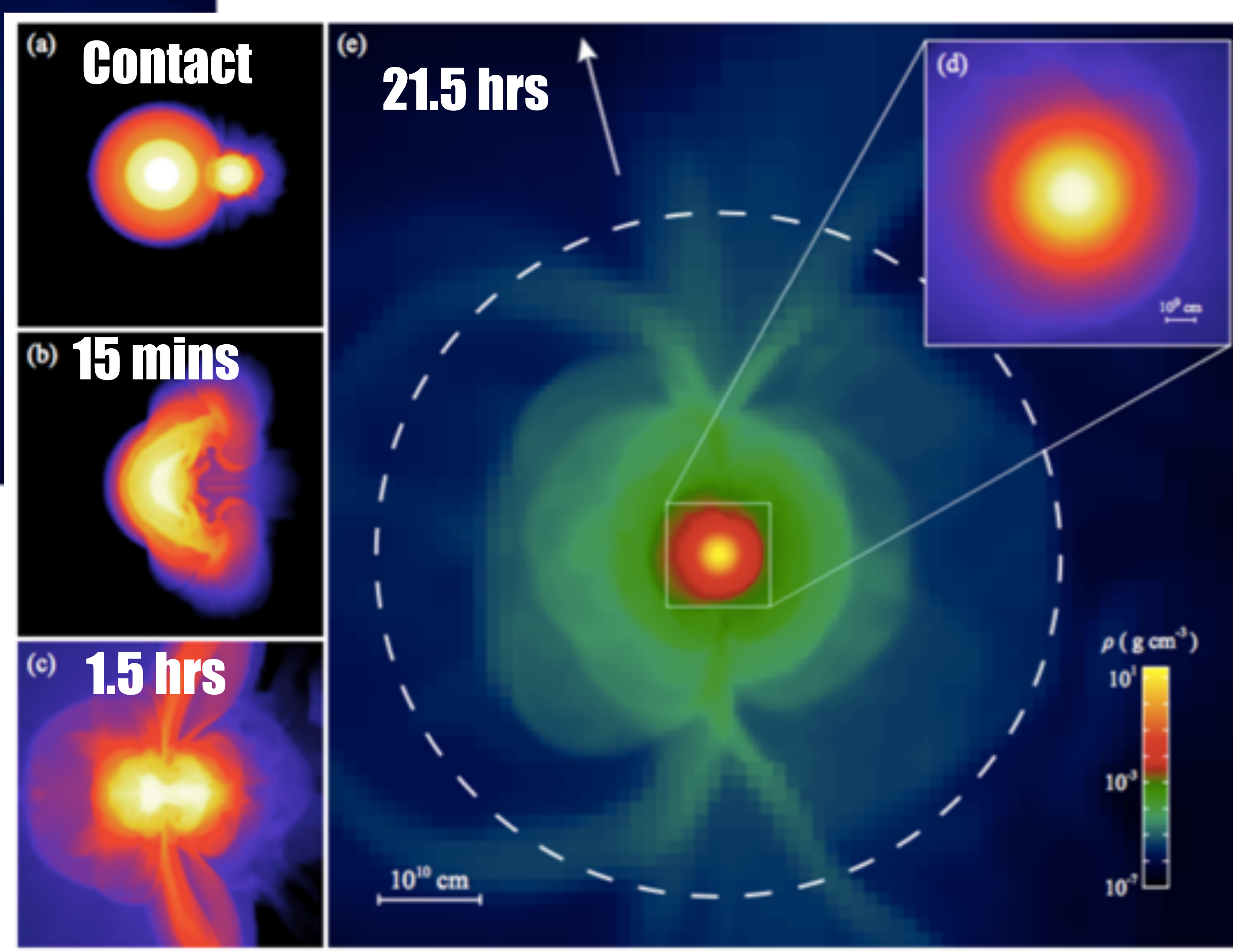


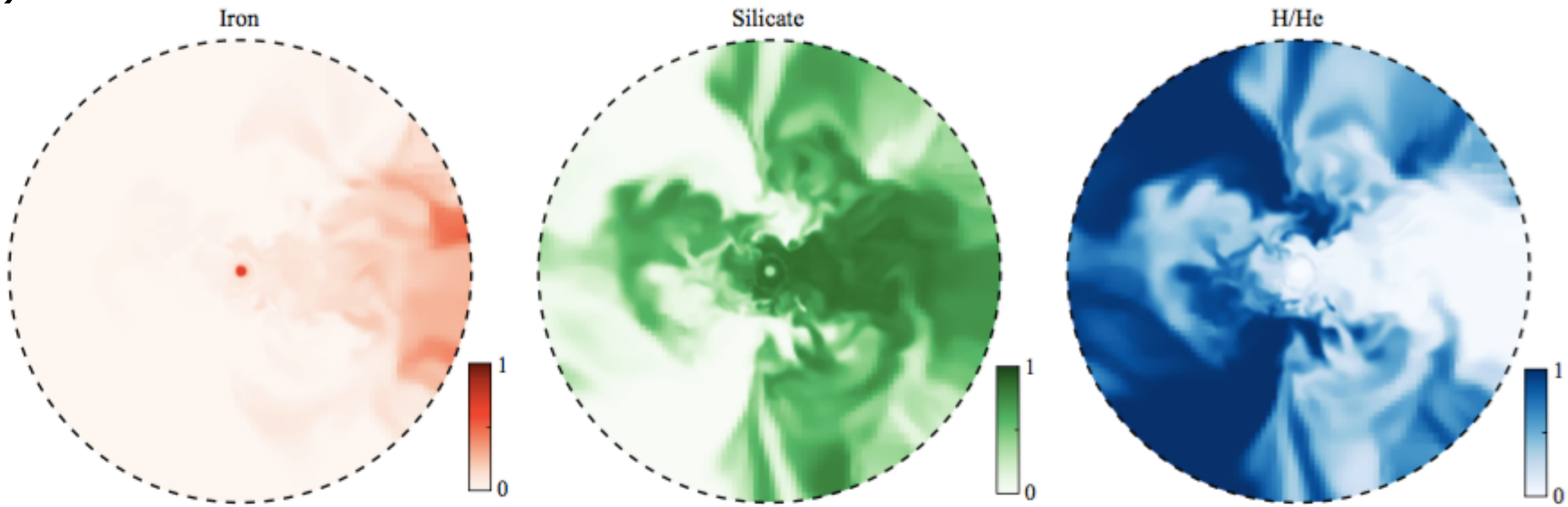
Low-speed impact

The atmosphere is lost by ~30%

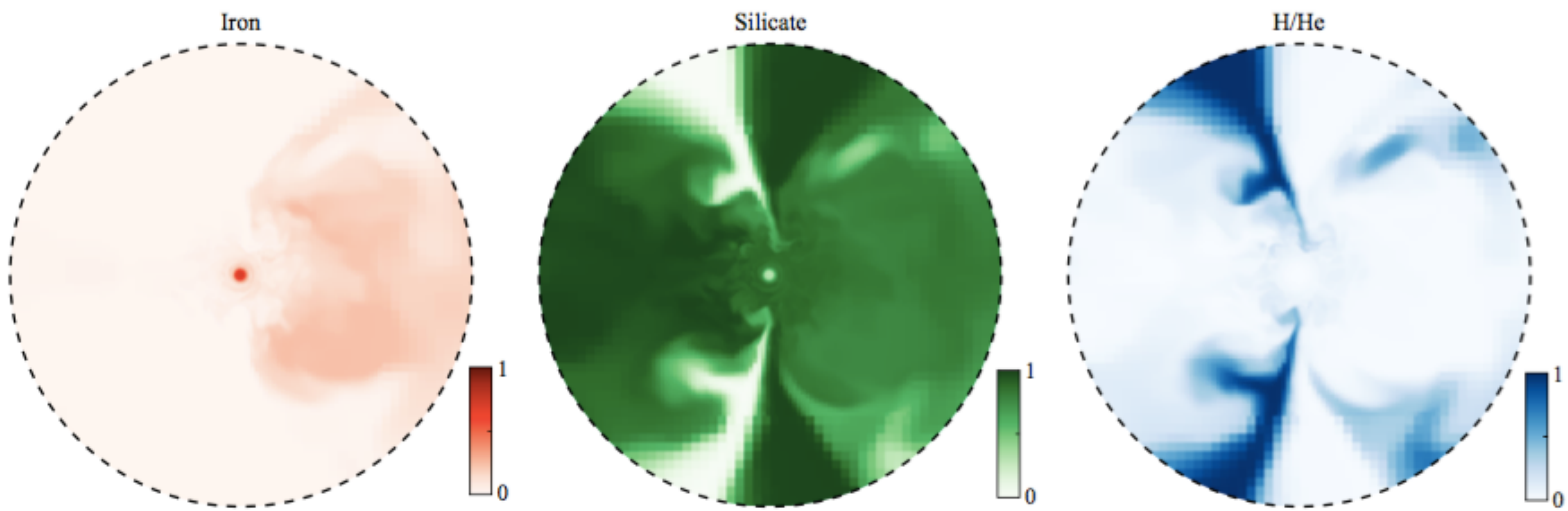
A hot atmosphere extends beyond the Hill radius and continues to lose via **the Roche-lobe overflow**

Snapshots of Material Mixing After Giant Impacts

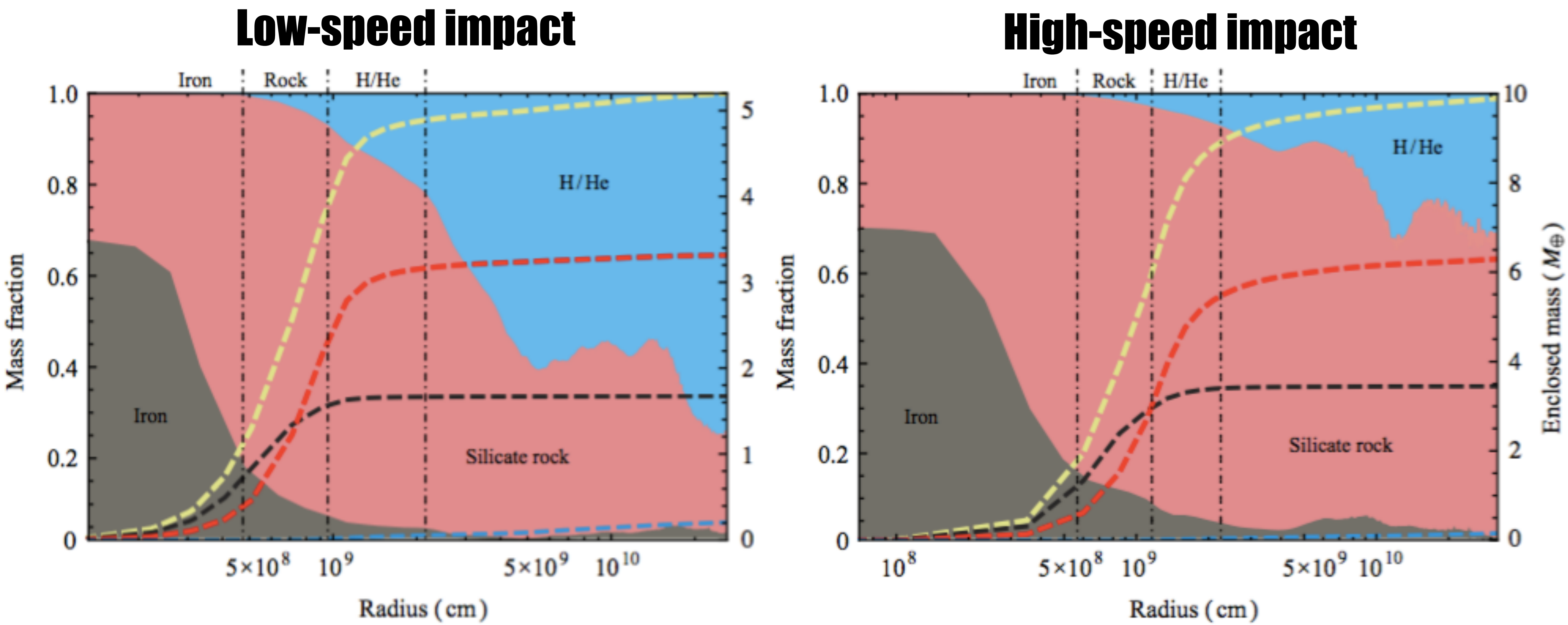
(a) 18 hrs after a low-speed impact



(b) 21.5 hrs after a high-speed impact



Radial Distribution of Each Species After a Collision



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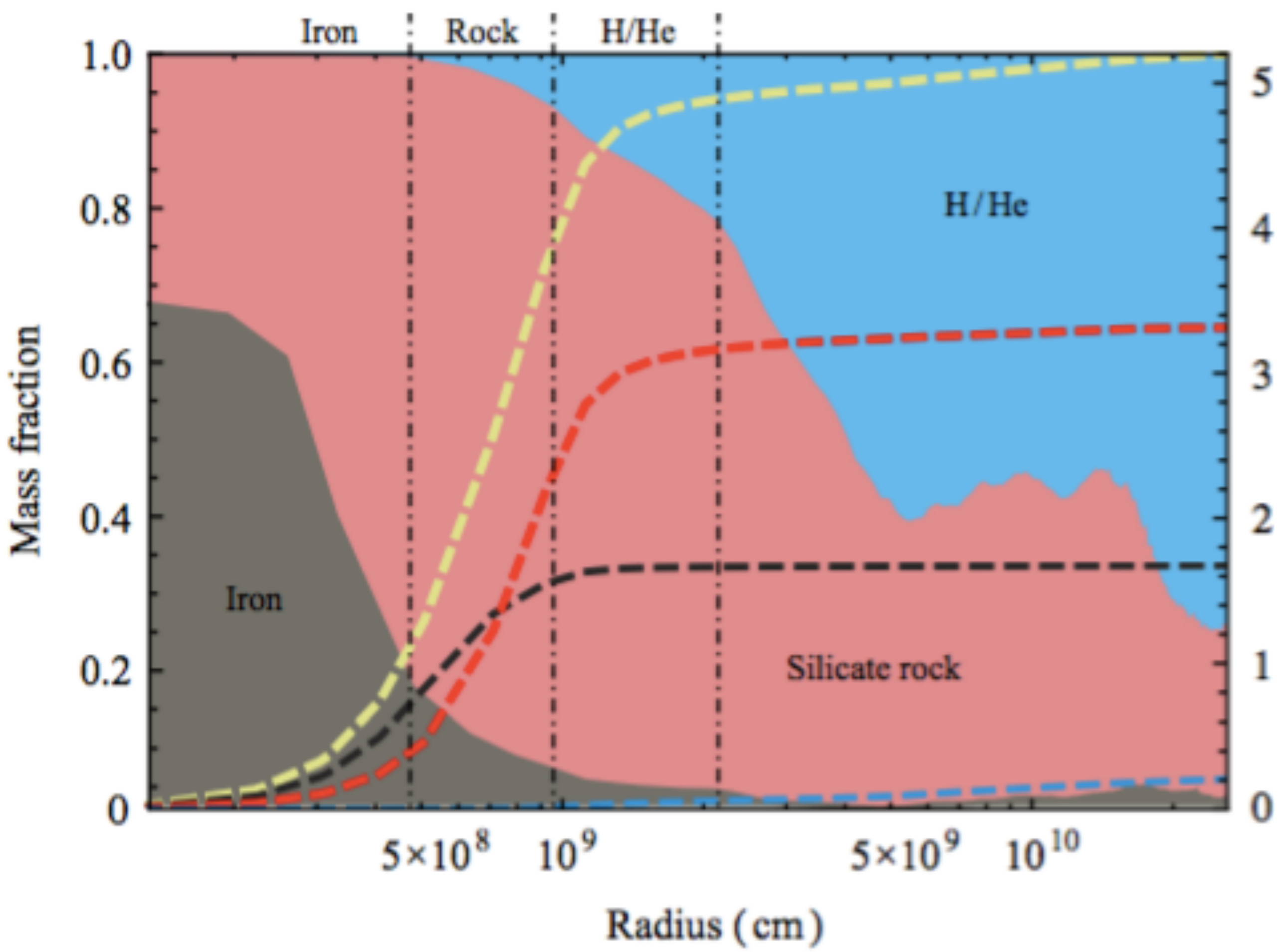
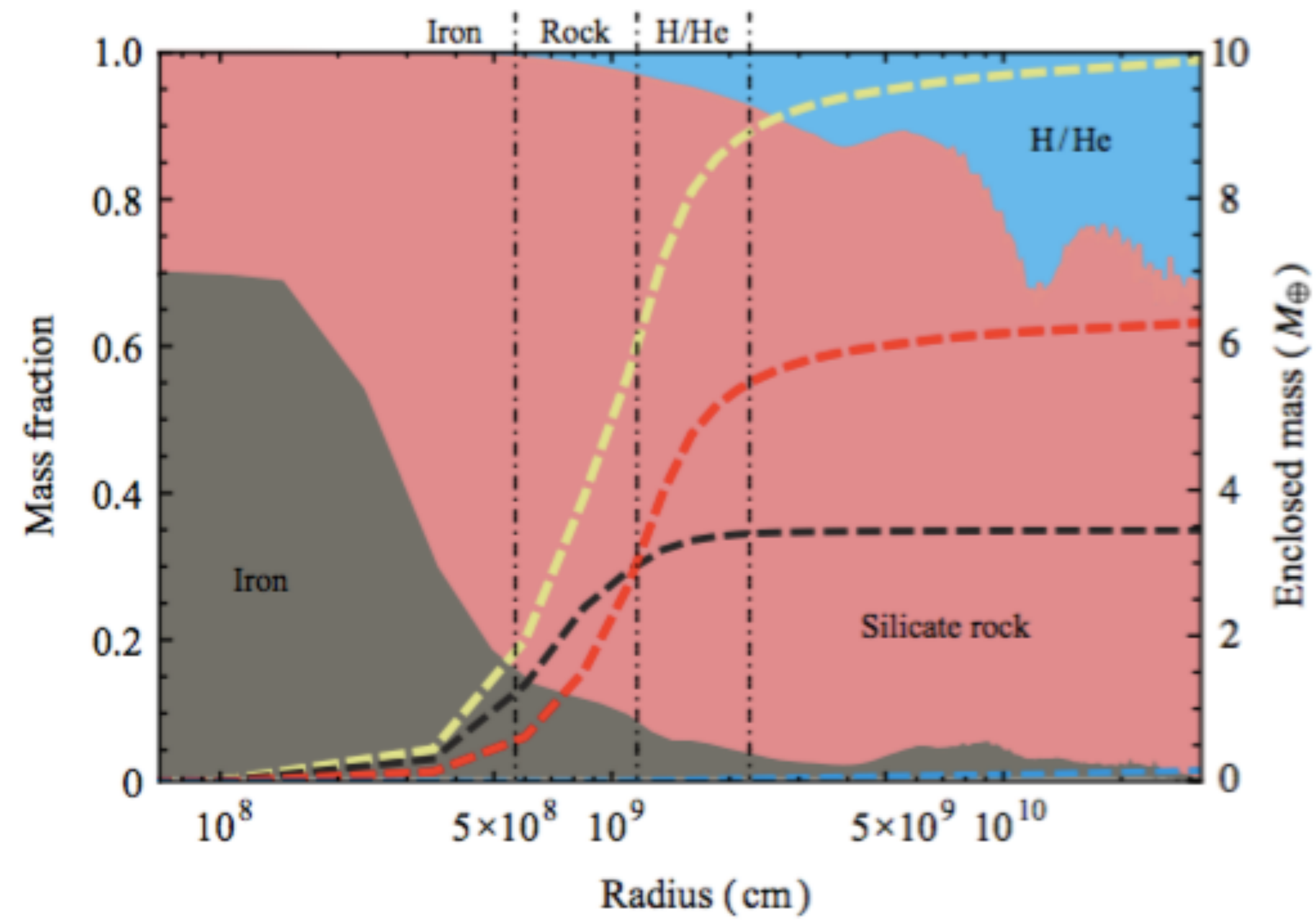
Low-speed impact

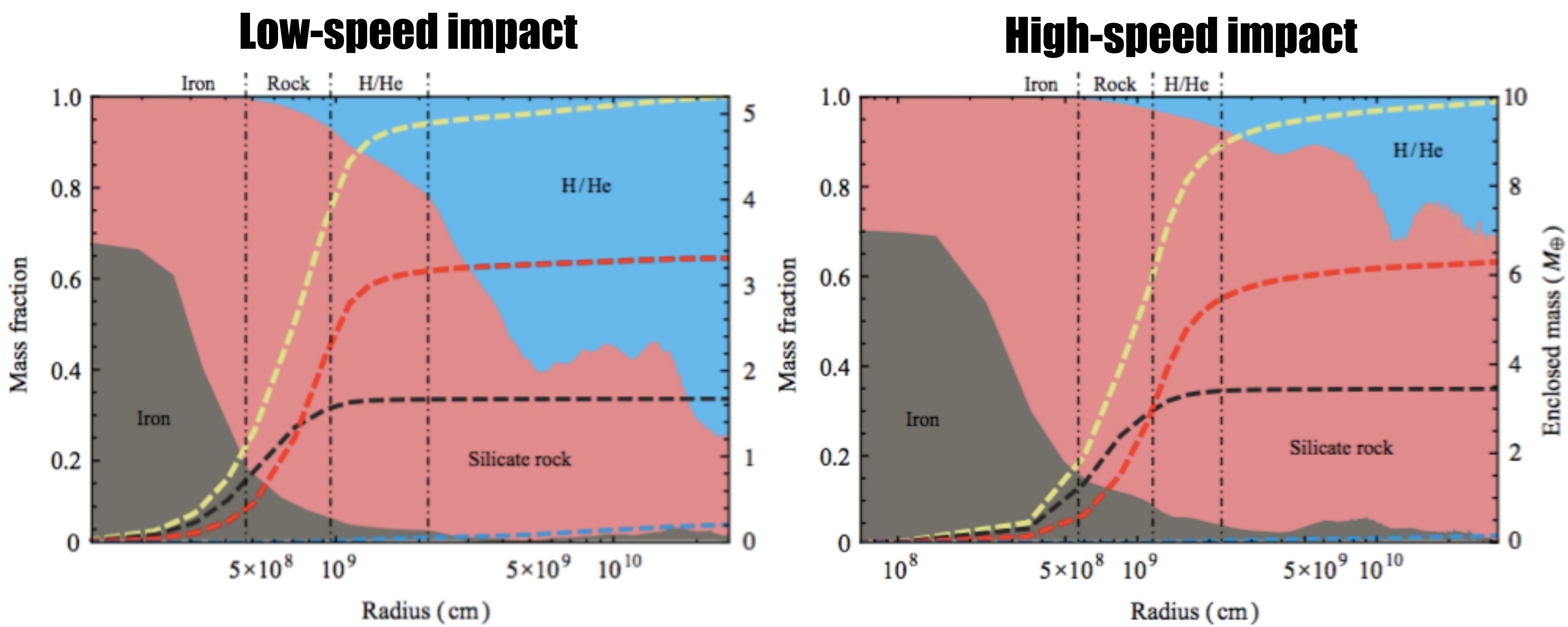


High-speed impact



- An initial layered structure is partly maintained after the collision

Radial Distribution of Each Species After a Collision



- An initial layered structure is partly maintained after the collision
- An iron core of the target survives from the impact in both cases and grows in a coalescence manner

Radial Distribution of Each Species After a Collision

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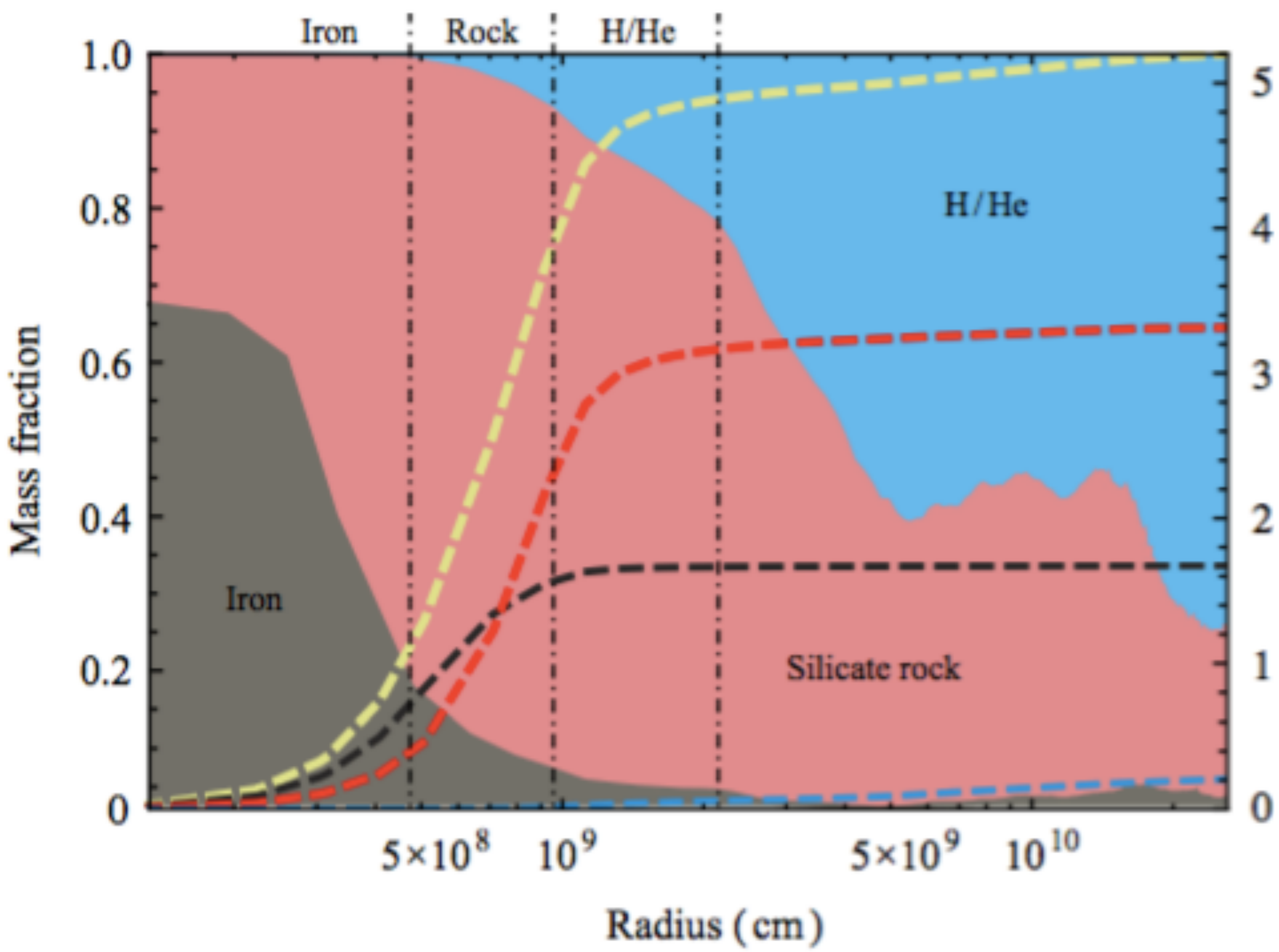

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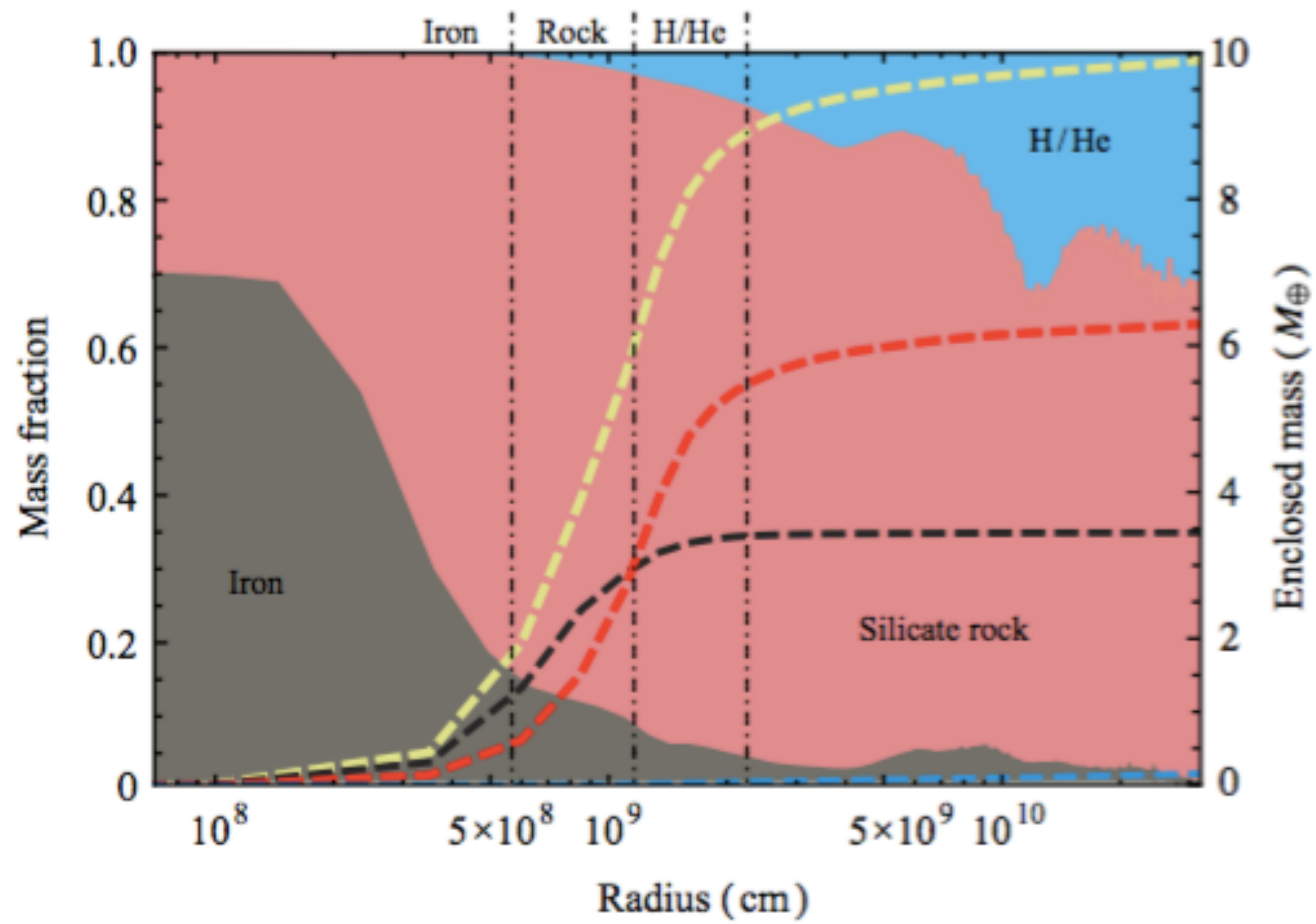
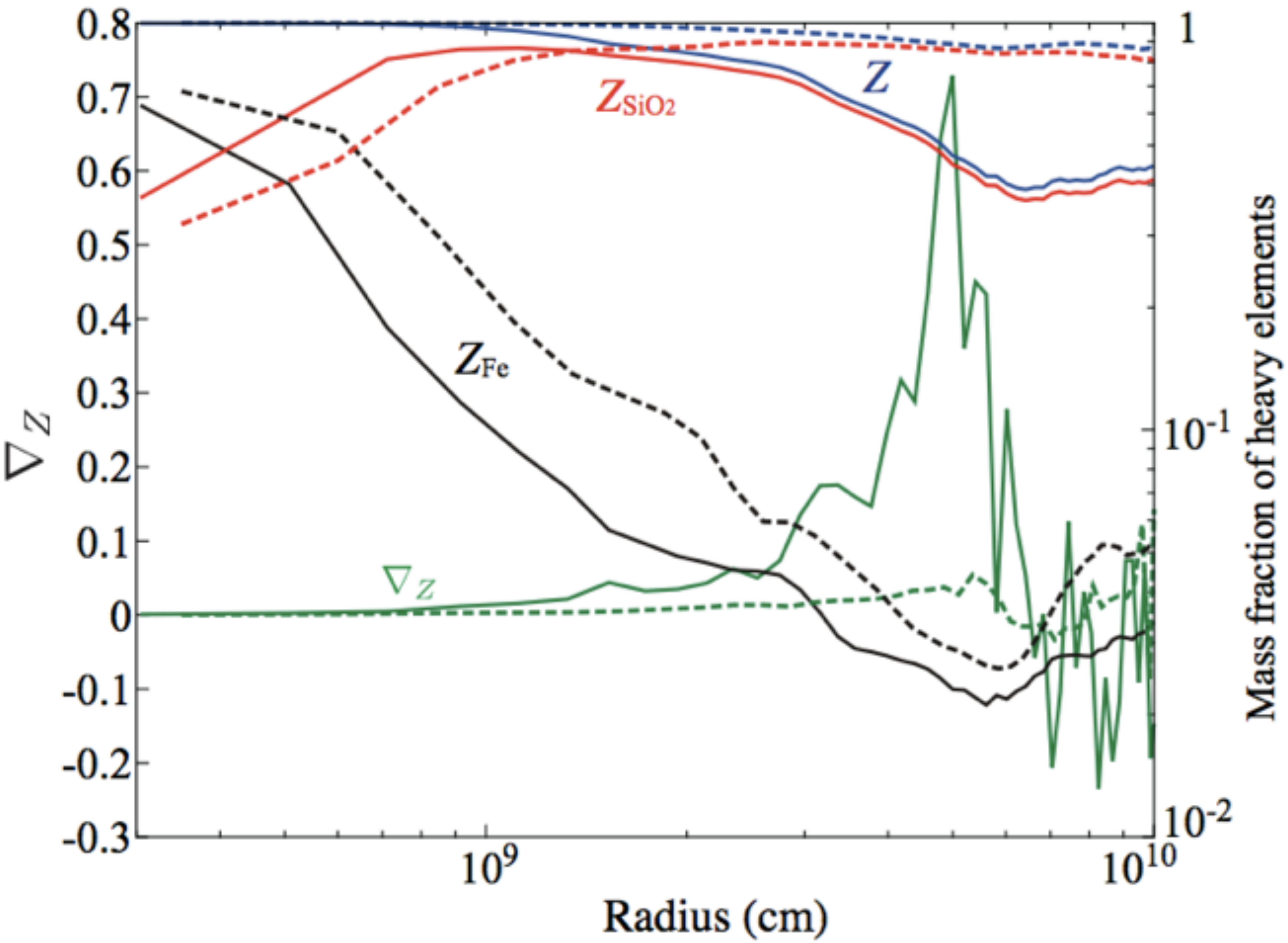


- An initial layered structure is partly maintained after the collision
- An iron core of the target survives from the impact in both cases and grows in a coalescence manner
- A fraction of rocky material is dredged up in a H/He atmosphere
  → the remaining atmosphere is polluted with heavy elements

Compositional Gradient Inside a Target After an Impact

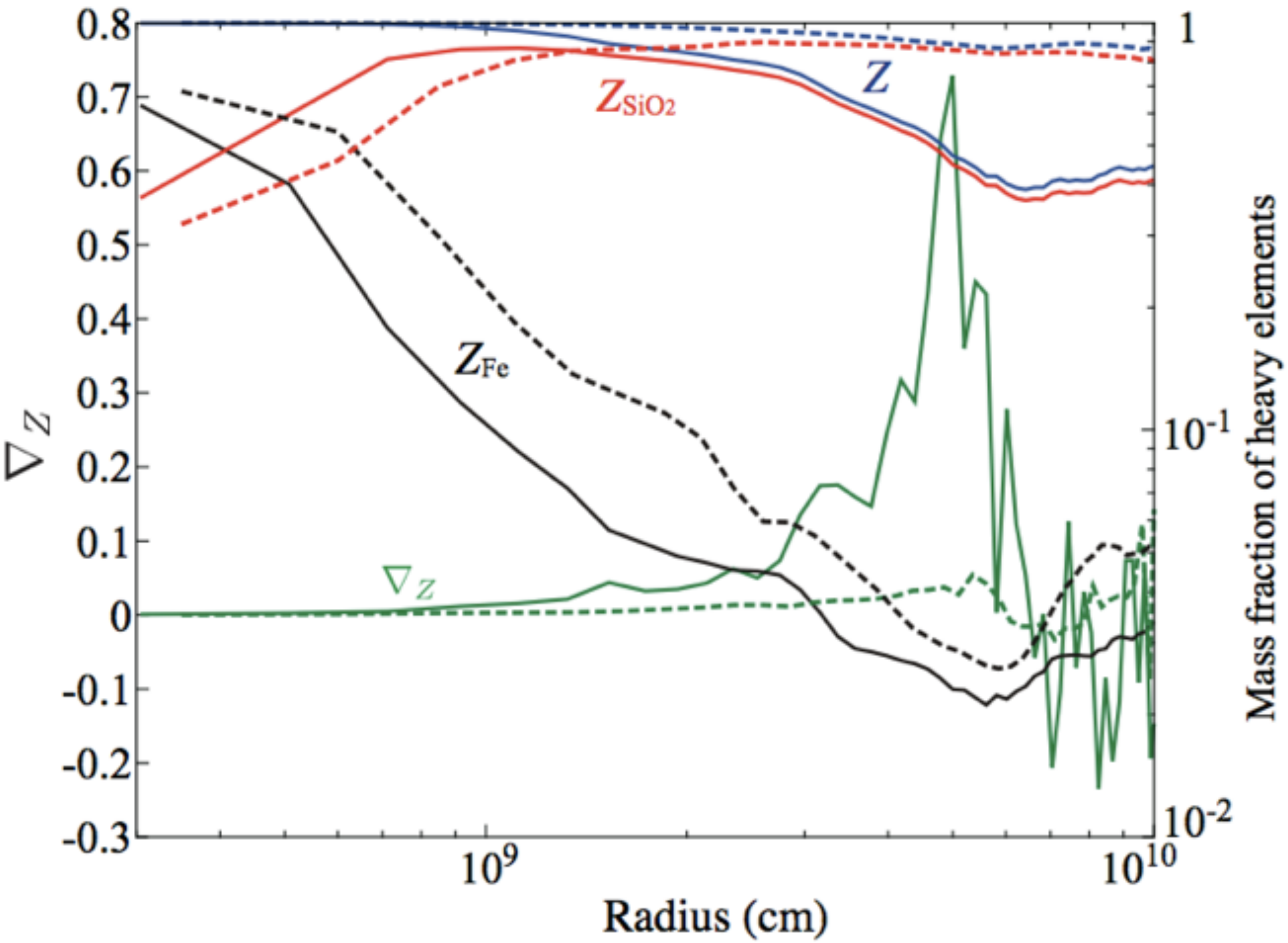


low-speed model

high-speed model

Mass fraction of **iron**, **silicate**, & **total**

Compositional Gradient Inside a Target After an Impact



low-speed model

high-speed model

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A low-speed head-on collision develops a hot and inhomogeneous interior
→ **a steep, positive compositional gradient** suppresses efficient heat transfer(?)

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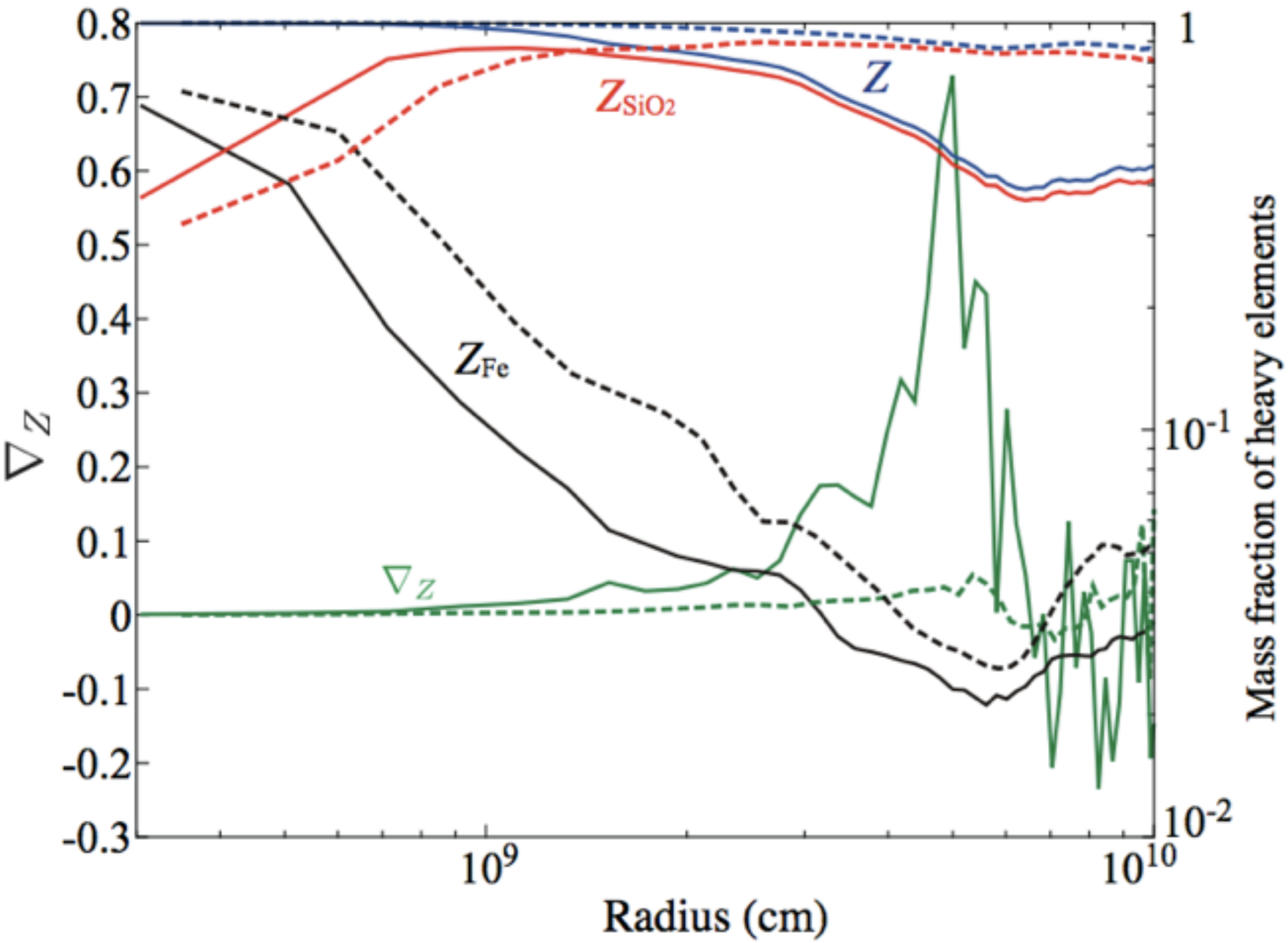

low-speed model
high-speed model

Mass fraction of
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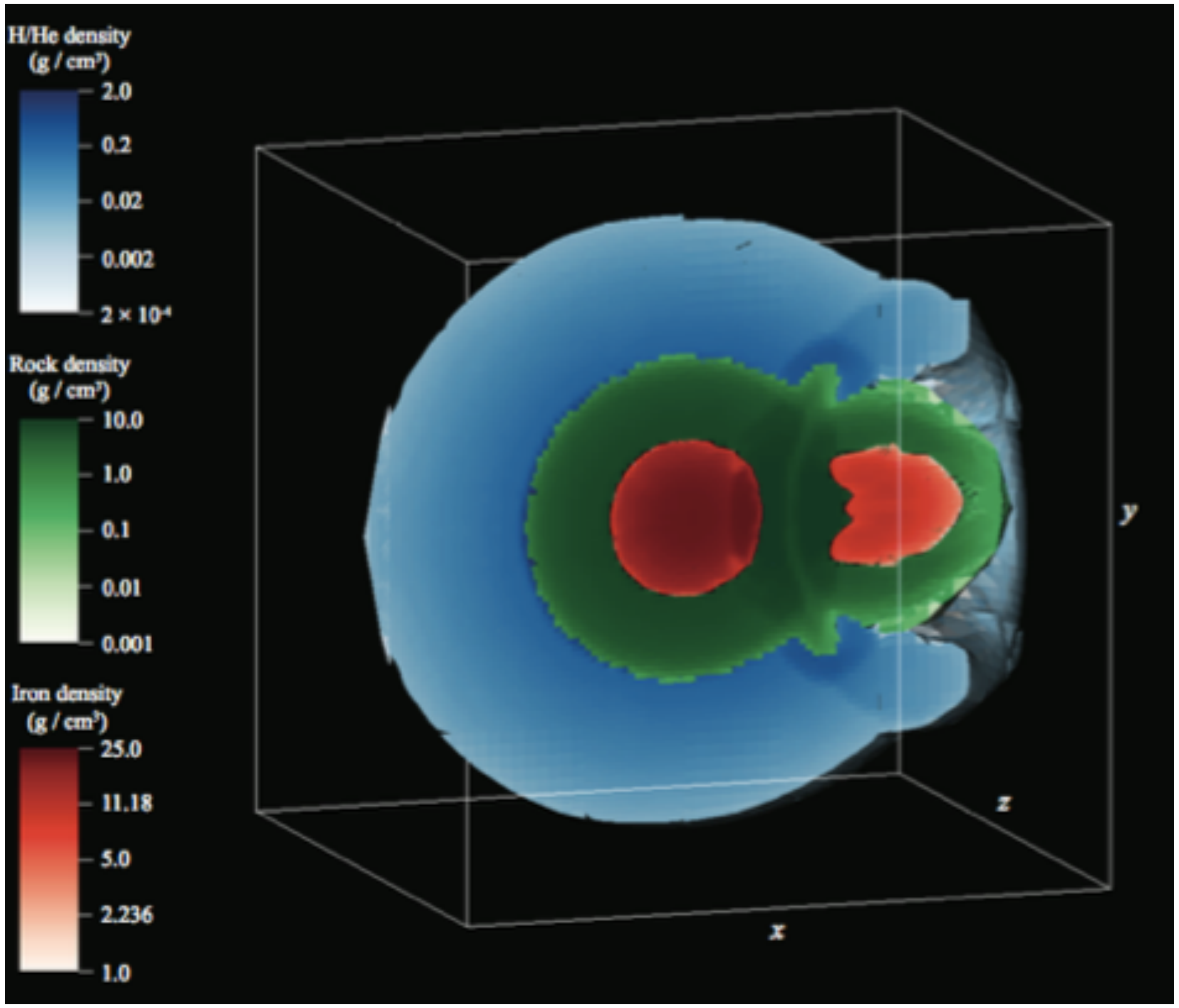
A low-speed head-on collision develops a hot and inhomogeneous interior
→ **a steep, positive compositional gradient** suppresses efficient heat transfer(?)

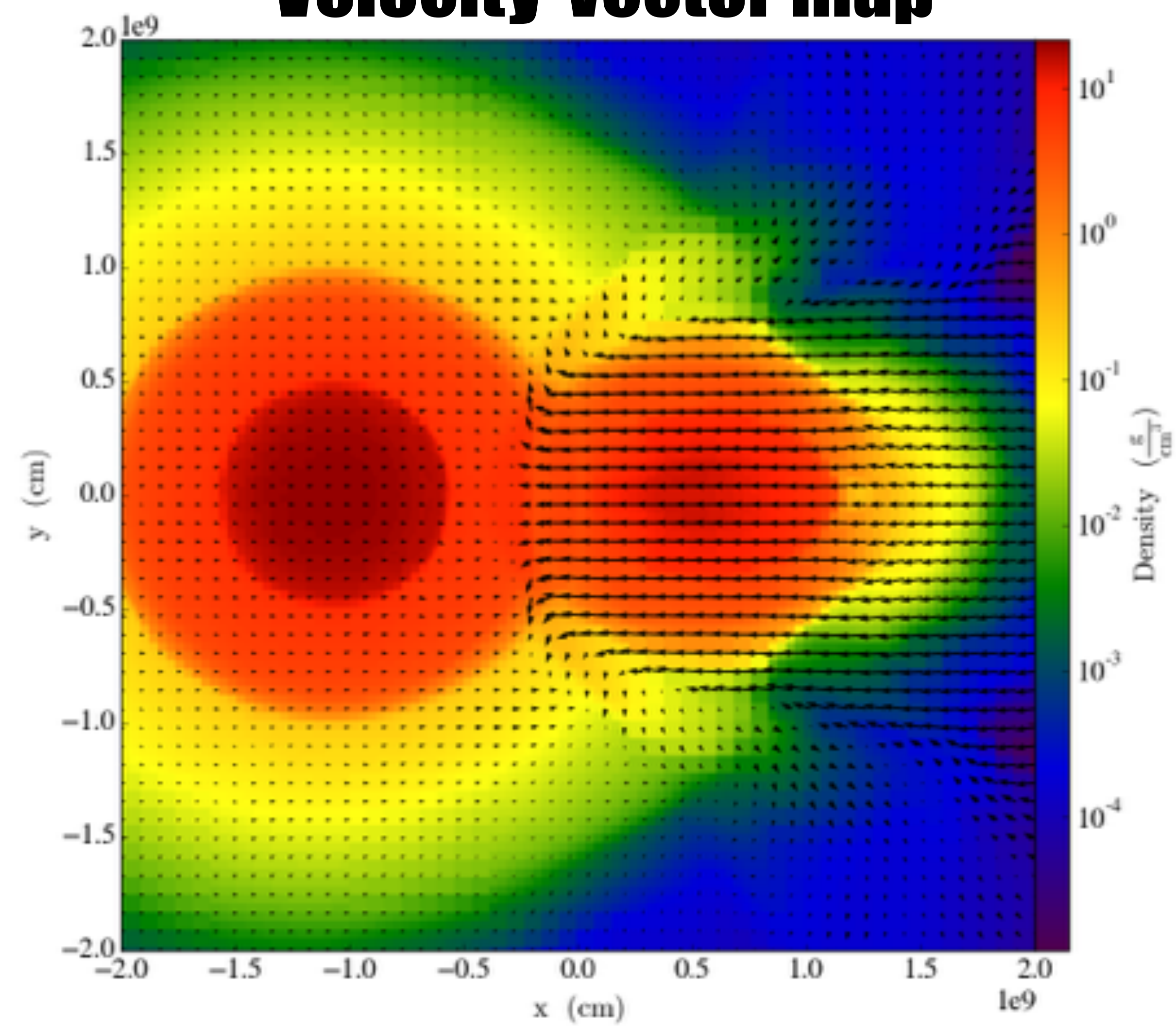
For a high-speed head-on collision,
refractory material is homogenized in the target's interior

Turbulence or Hydrodynamic Instability?

Species contour



Velocity-vector map



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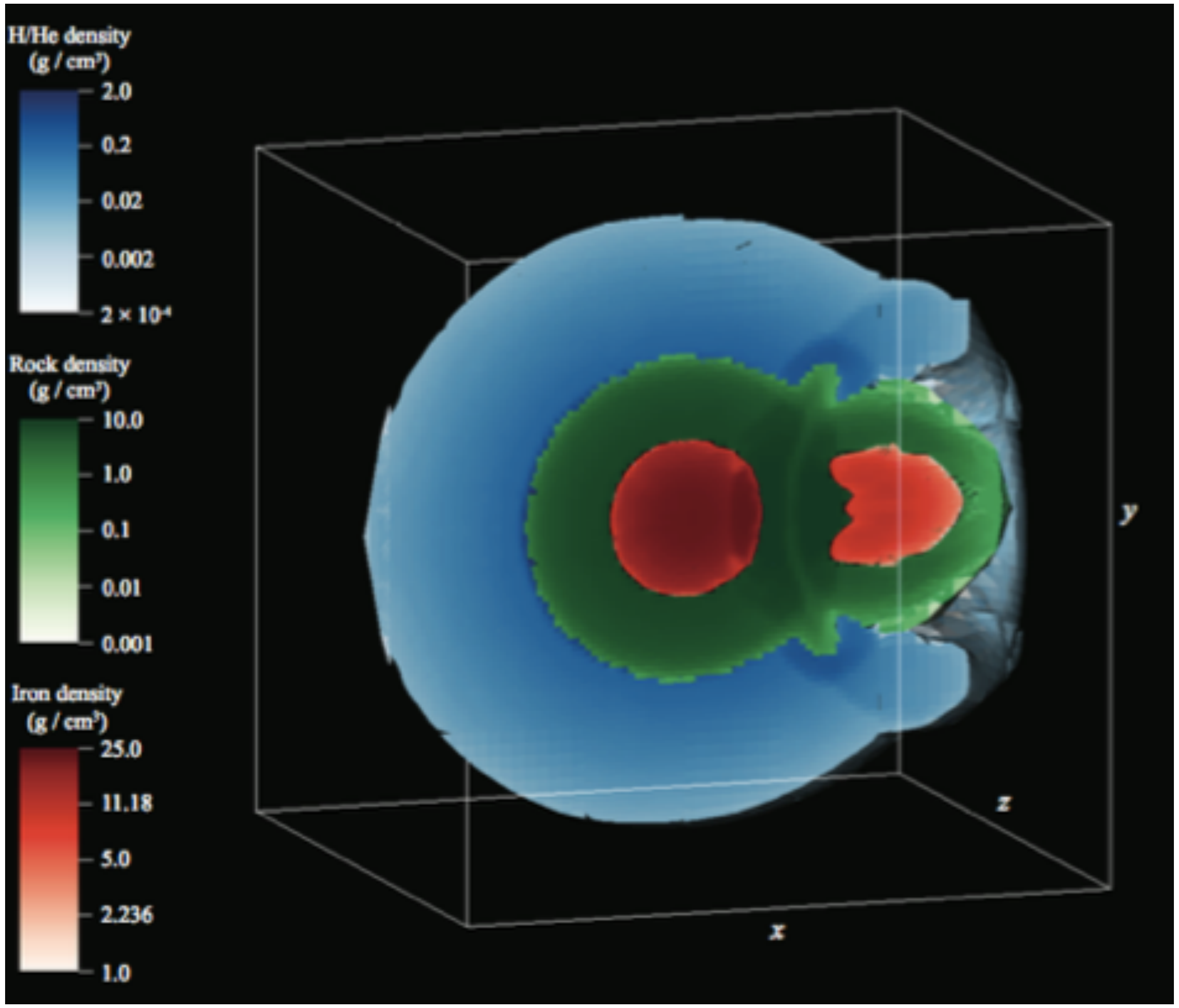

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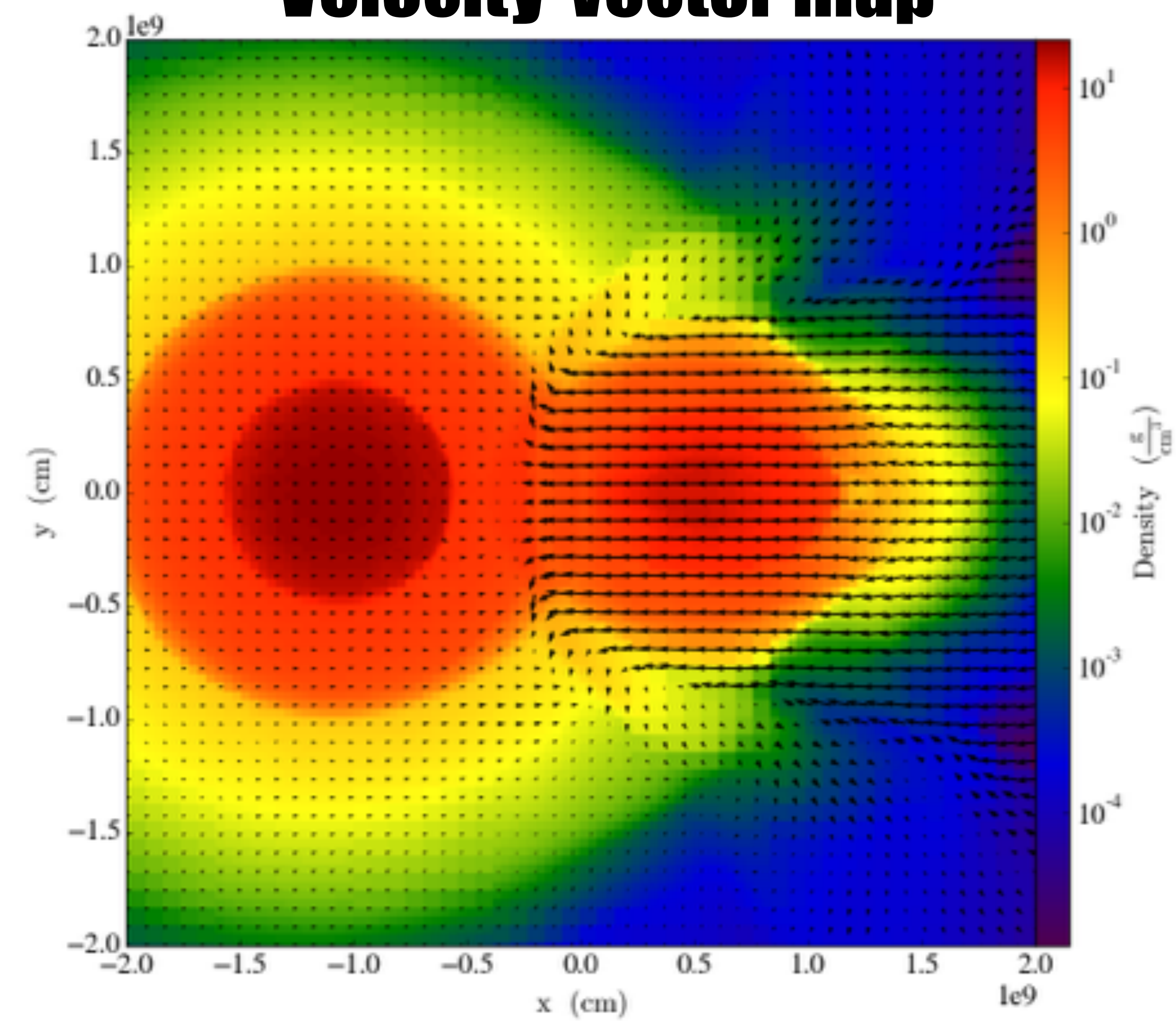
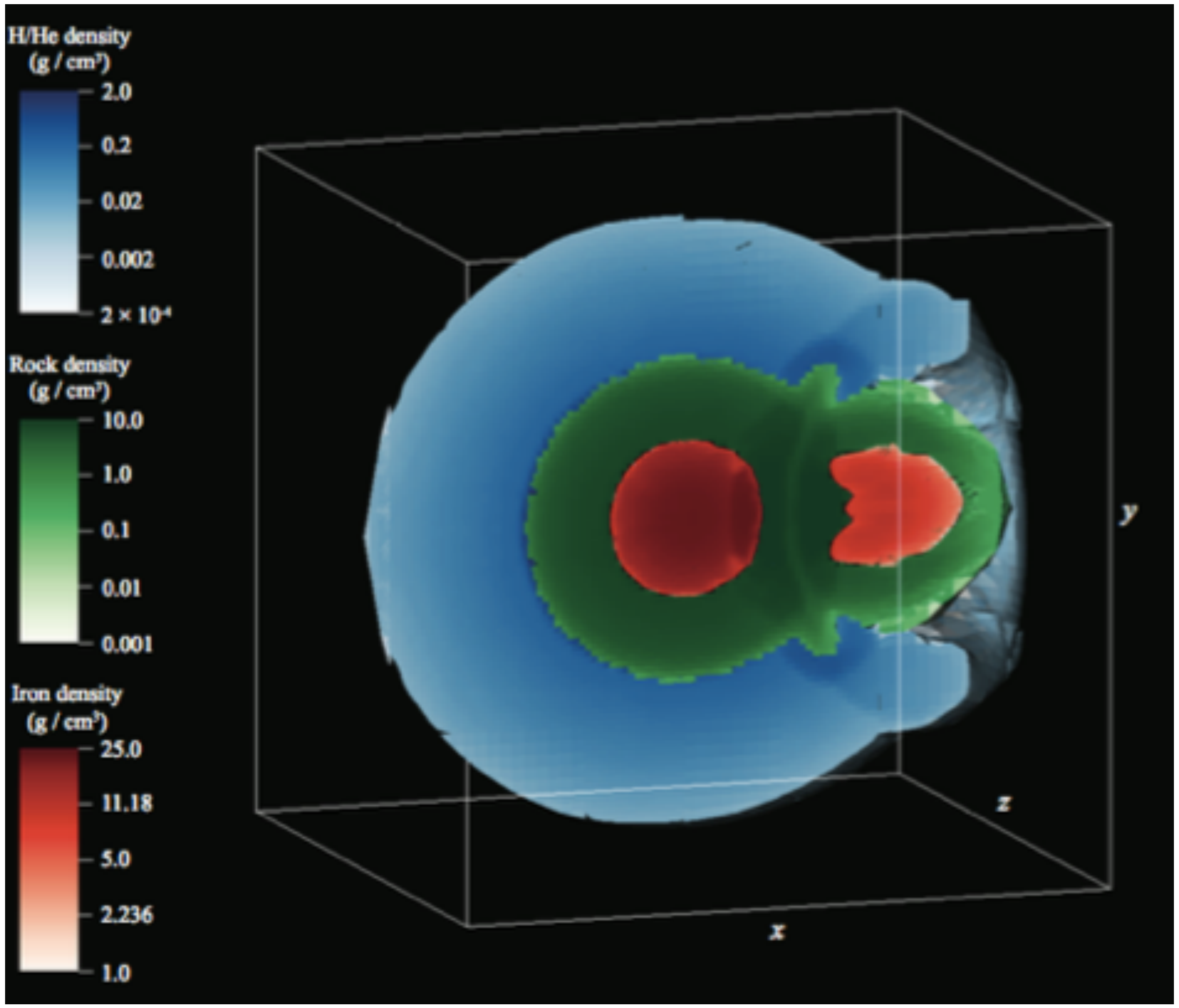


- **A velocity shear** at the interface between two species after an impact

Turbulence or Hydrodynamic Instability?

Species contour



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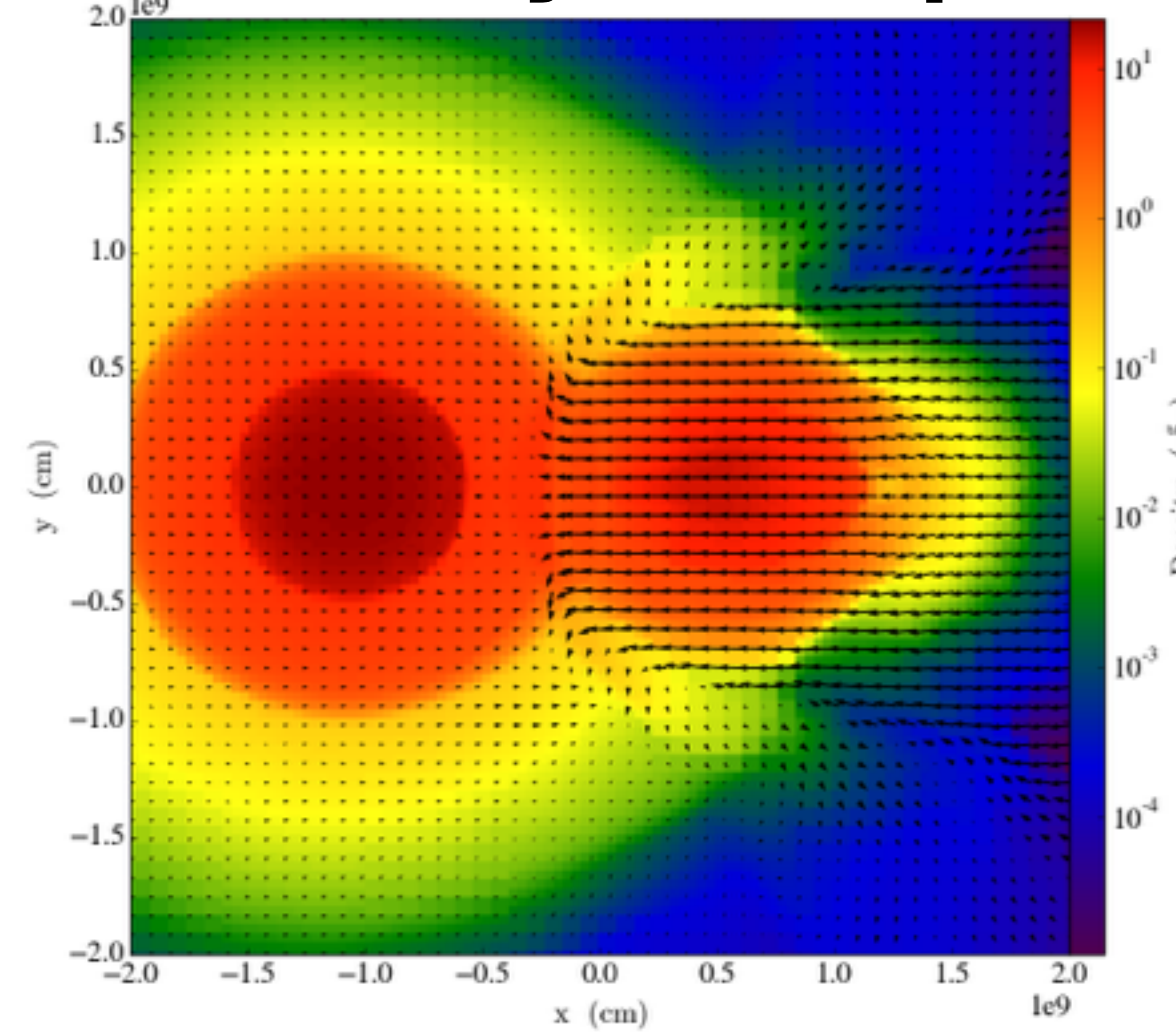
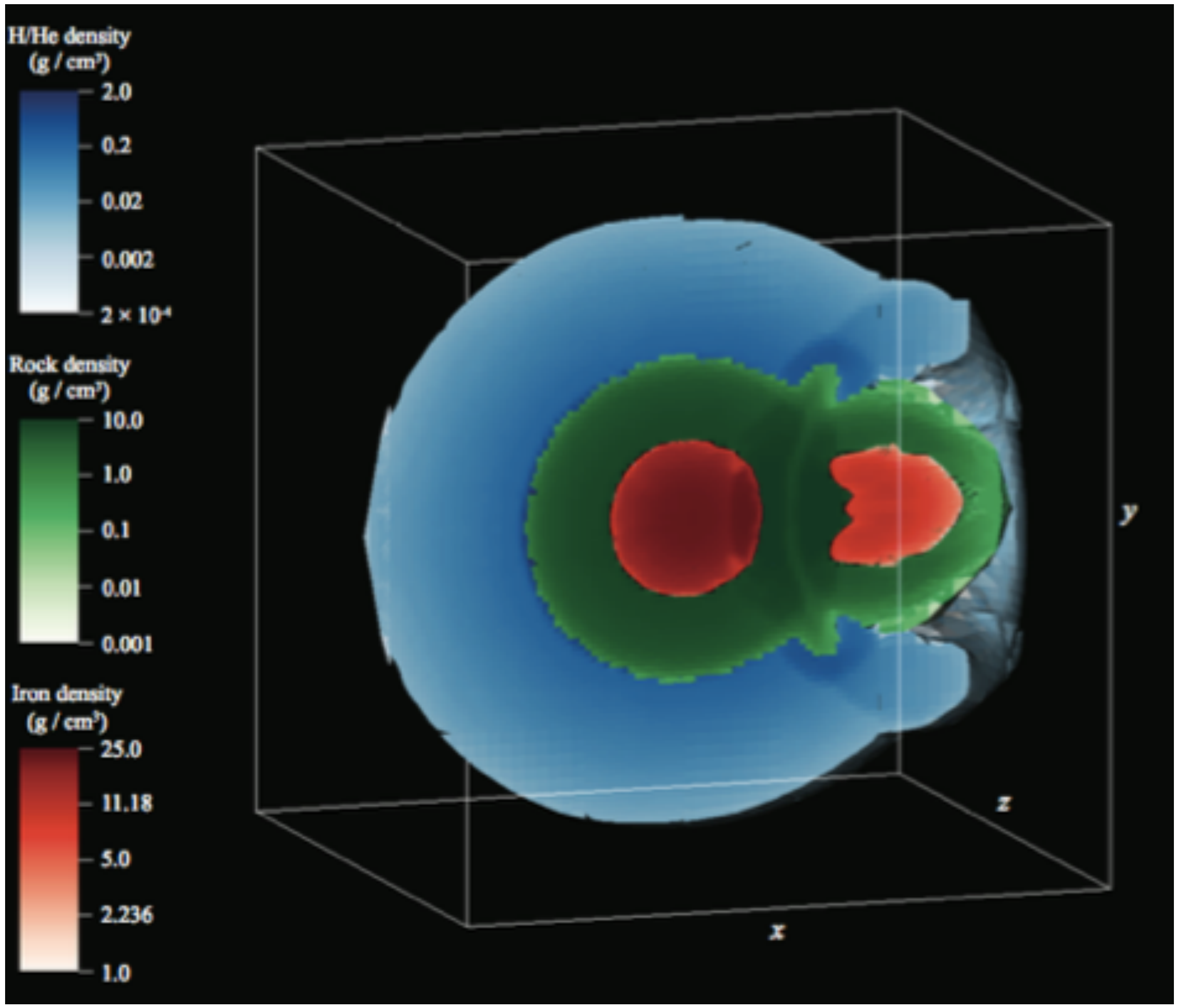


- **A velocity shear** at the interface between two species after an impact → **K-H instability** (at least for short wavelengths)

Turbulence or Hydrodynamic Instability?

Species contour



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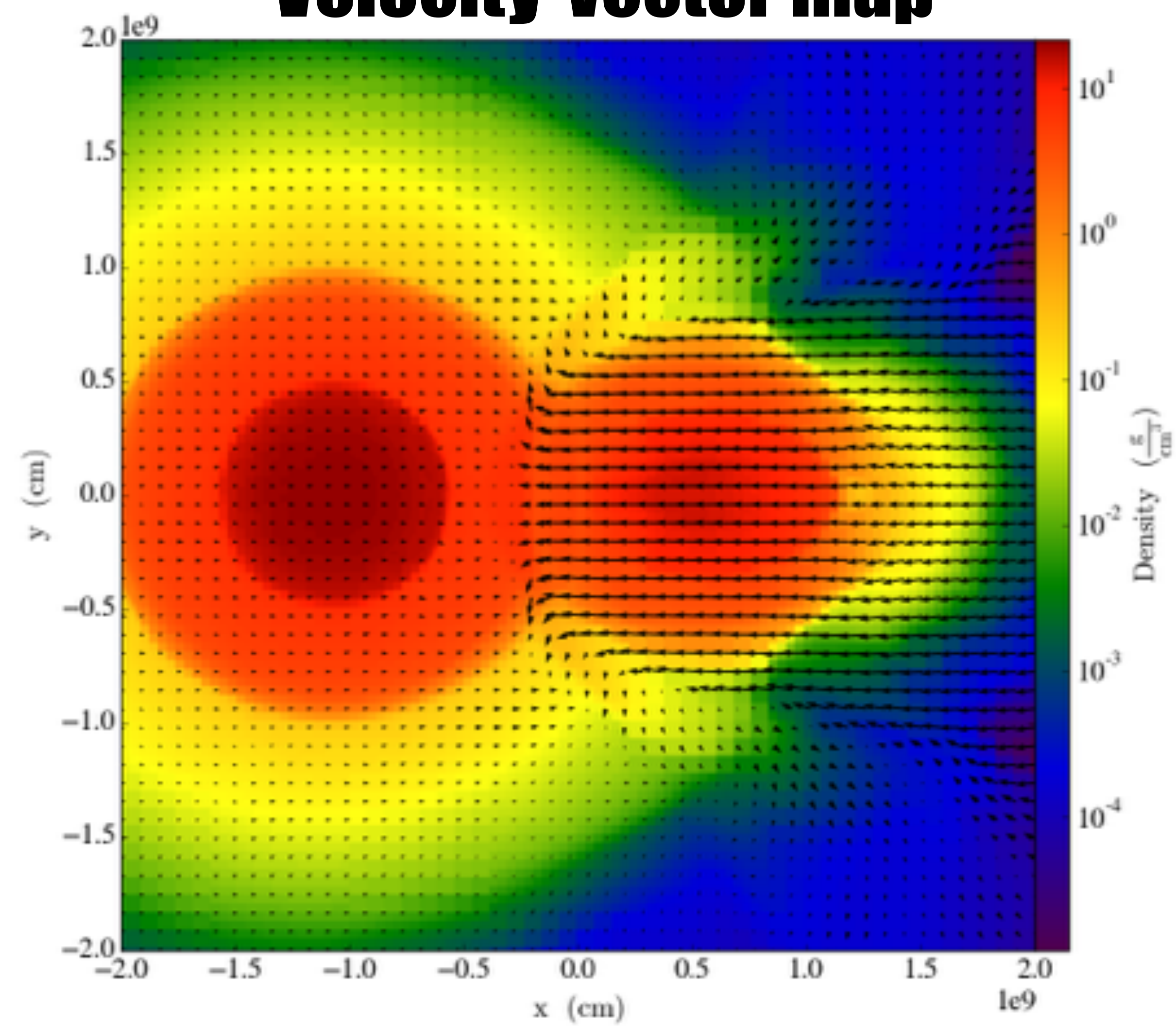
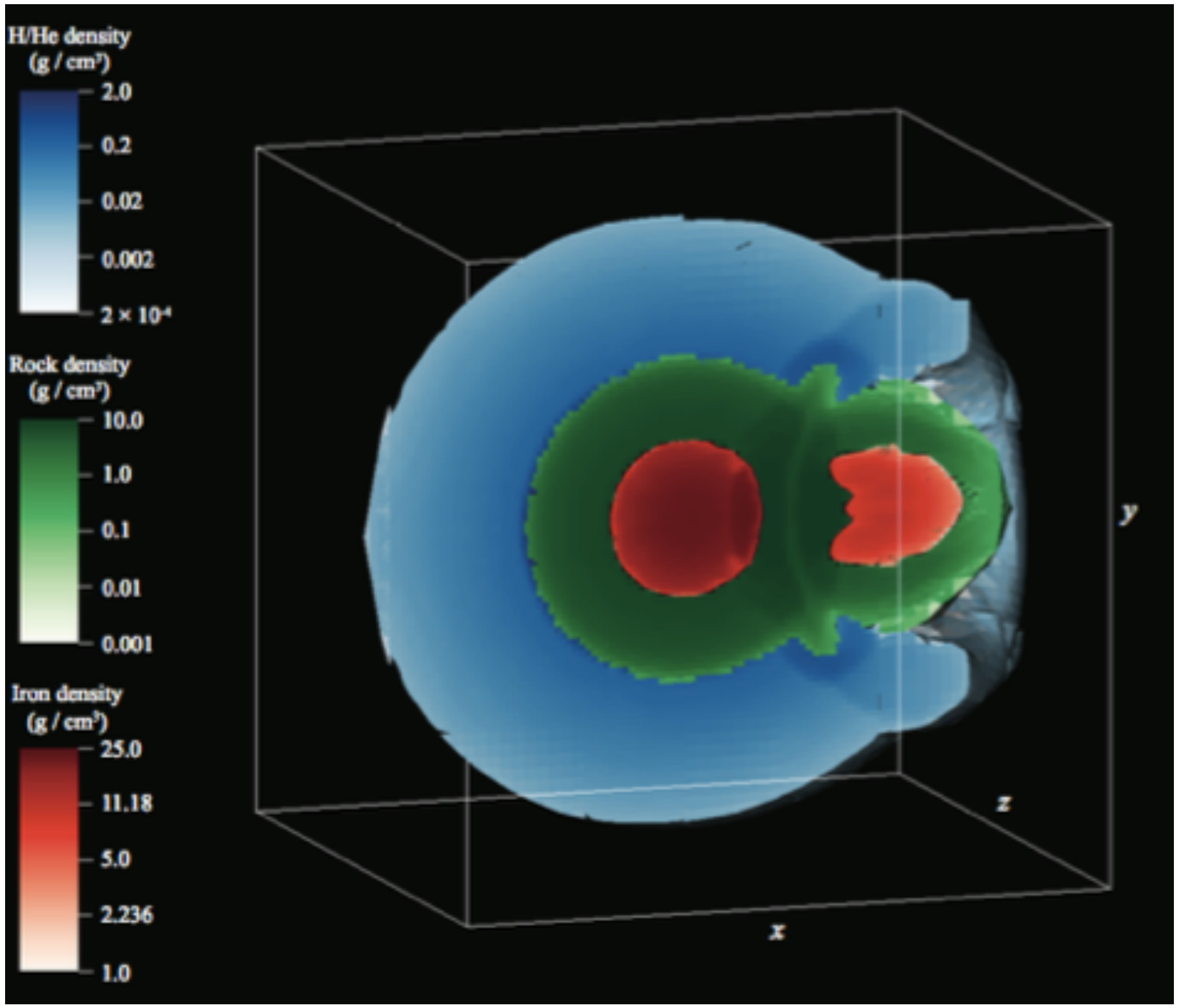


- **A velocity shear** at the interface between two species after an impact
  → **K-H instability** (at least for short wavelengths)
- **An impact-induced shock wave propagation** → **R-T instability**

Turbulence or Hydrodynamic Instability?

Species contour



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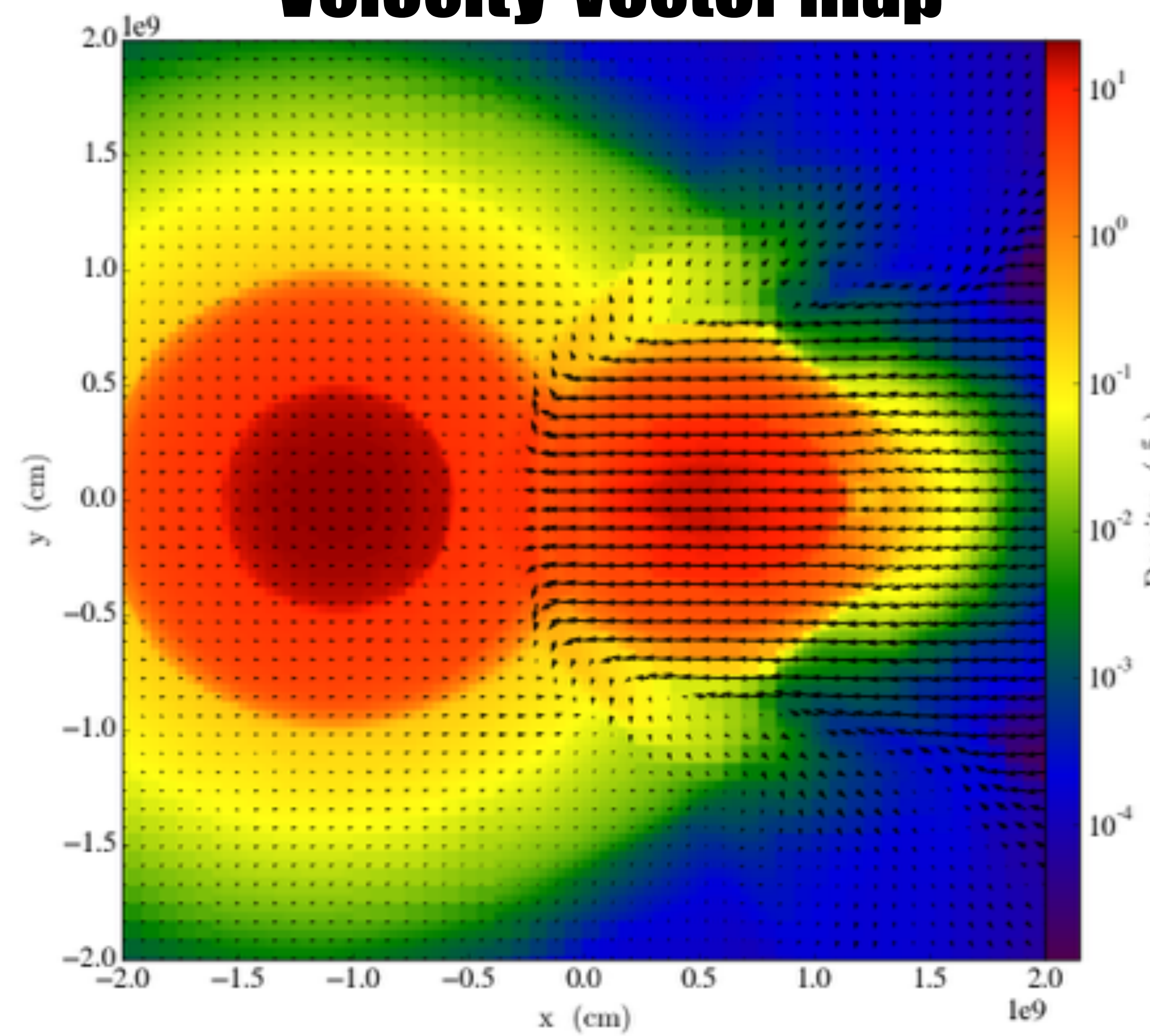

- **A velocity shear** at the interface between two species after an impact → **K-H instability** (at least for short wavelengths)
- **An impact-induced shock wave propagation** → **R-T instability**

However,

An impact-driven turbulence is responsible for **the global mixing**

Discussions : The Fate of a Super-Earth After a Giant Impact

A protracted state of a hot and inflated atmosphere

(a) Mass loss via a Parker wind (Owen & Wu, 2015)

(b) Mass loss from the Roche lobe via a stellar XUV irradiation

Discussions : The Fate of a Super-Earth After a Giant Impact

A protracted state of a hot and inflated atmosphere

(a) Mass loss via a Parker wind (Owen & Wu, 2015)

About 80% of the remaining atmosphere is lost

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Discussions : The Fate of a Super-Earth After a Giant Impact

A protracted state of a hot and inflated atmosphere

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About 80% of the remaining atmosphere is lost

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$\epsilon = 0.1$ (Yelle, 2004)

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A typical decay timescale of a XUV flux for a Sun-like star **~ 0.1Gyr**

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The target in the high-speed model is unlikely to lose the entire envelope

Take-Home Messages

Different histories of giant impacts result in

(1) **compositional diversity** of super-Earths (Inadmar & Schlichting,2015)

(2) **homogeneous or inhomogeneous** interior

→ suppresses efficient heat transfer

(e.g.) double diffusive convection

(3) **a hot and inflated atmosphere** (extended beyond the Hill radius) which **enhances mass loss** via photo-evaporation or a Parker wind

(4) **the survival of a planetary iron core** through a merger

(5) **dredge-up of rocky material into a H/He atmosphere** caused by turbulence driven by an impact-induced shock wave

(6) **a partial disruption of a three-layered structure**

(cf) A violent head-on collision can account for thermal evolution of Neptune, i.e., a initially-hot and homogeneous interior (but a grazing impact would retain a stably-stratified interior)

(Liu, YH, Lin, & Asphaug, *in preparation*)