Origin of Phobos and Deimos — Summary

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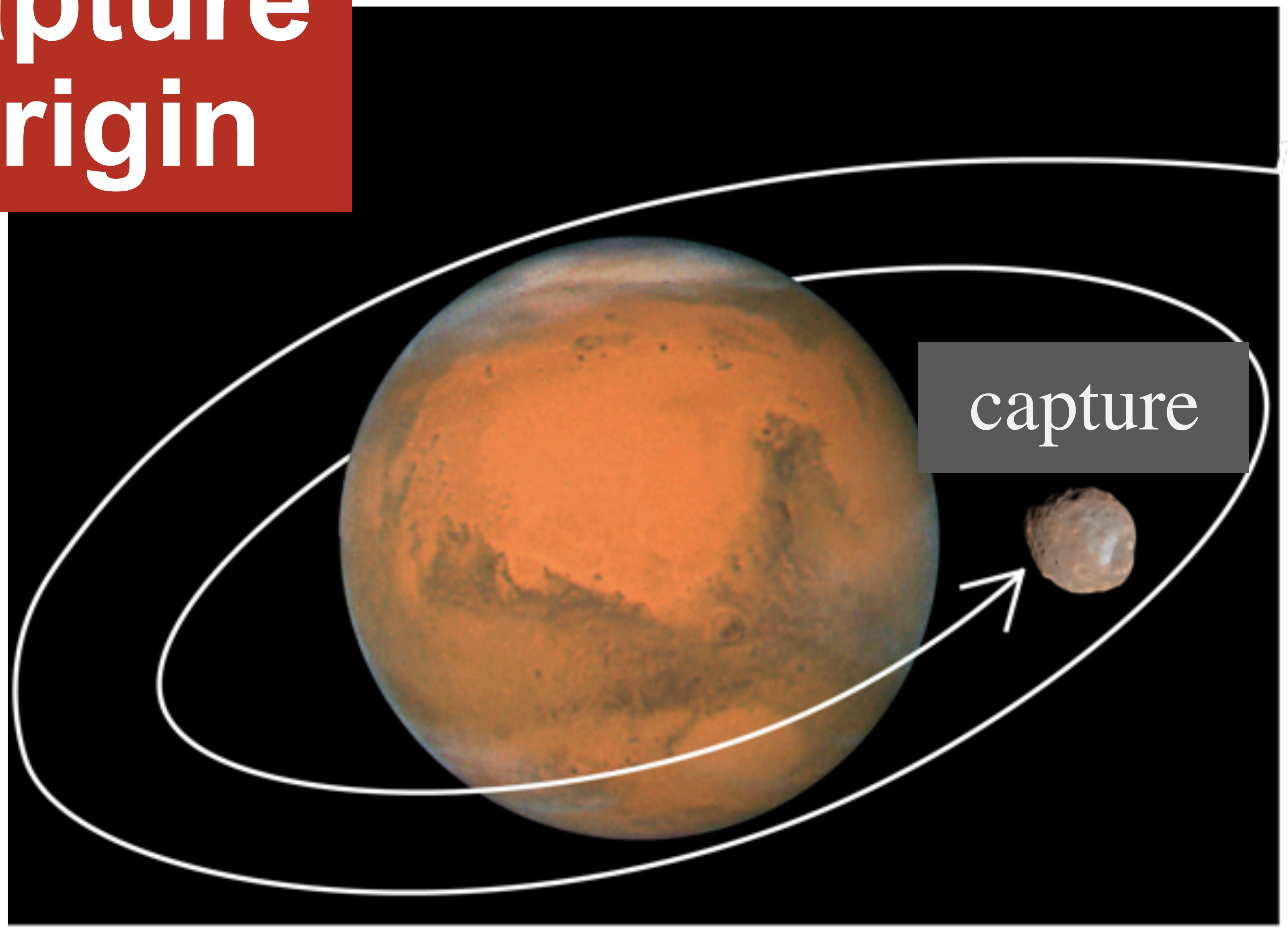
Today's Contents

- Two leading hypothesis — Capture and giant impact
  - Capture process
  - Giant impact process
    - Dynamical aspects
    - Physical aspects
    - Chemical aspects (composition, volatile, etc)
- Mass transfer from Mars to its moons — regardless of the origin
- Expected structures of Phobos and Deimos

Two Leading Hypothesis

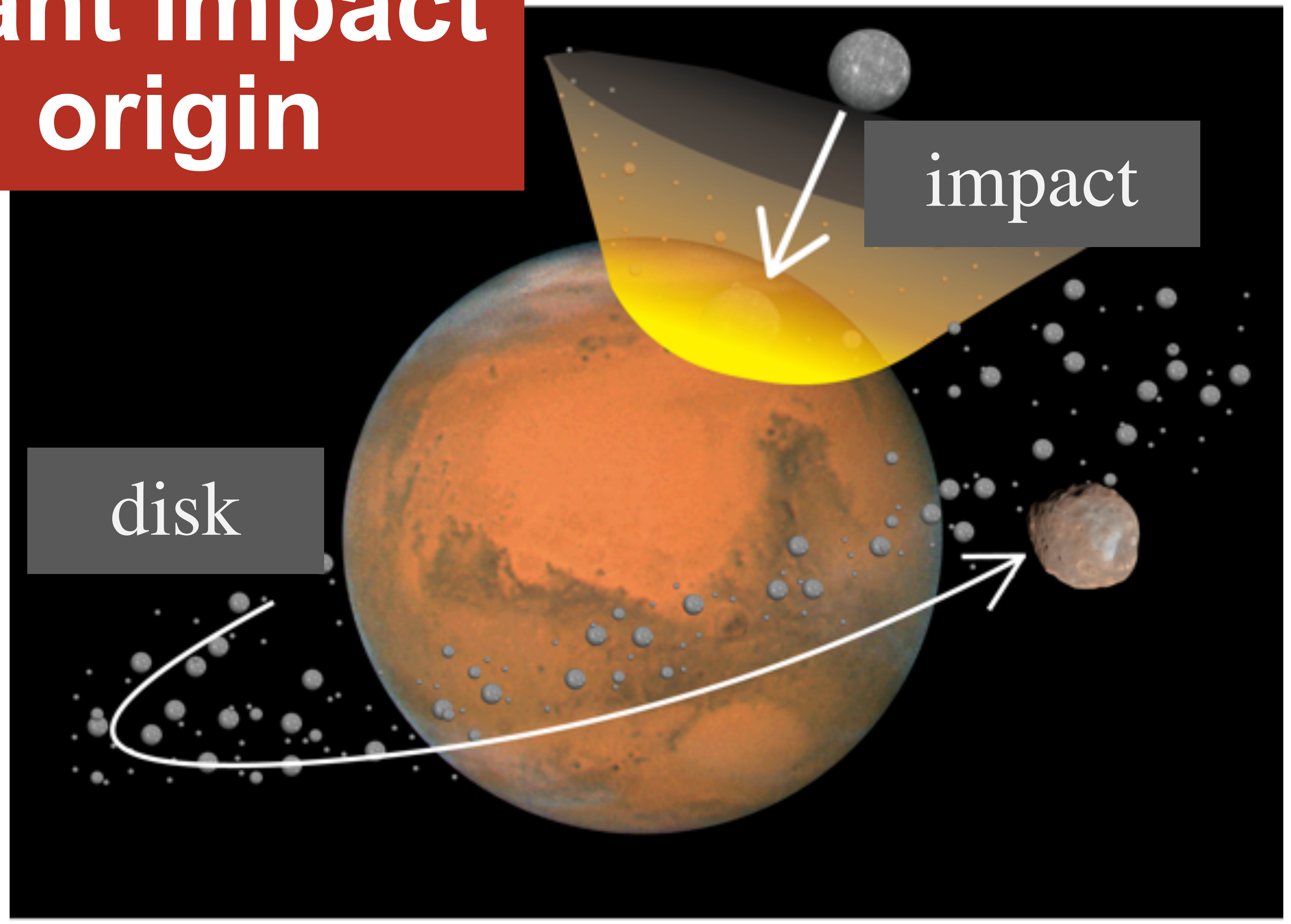
capture origin



supported by spectral features

Dark & Featureless — D-type?

giant impact origin



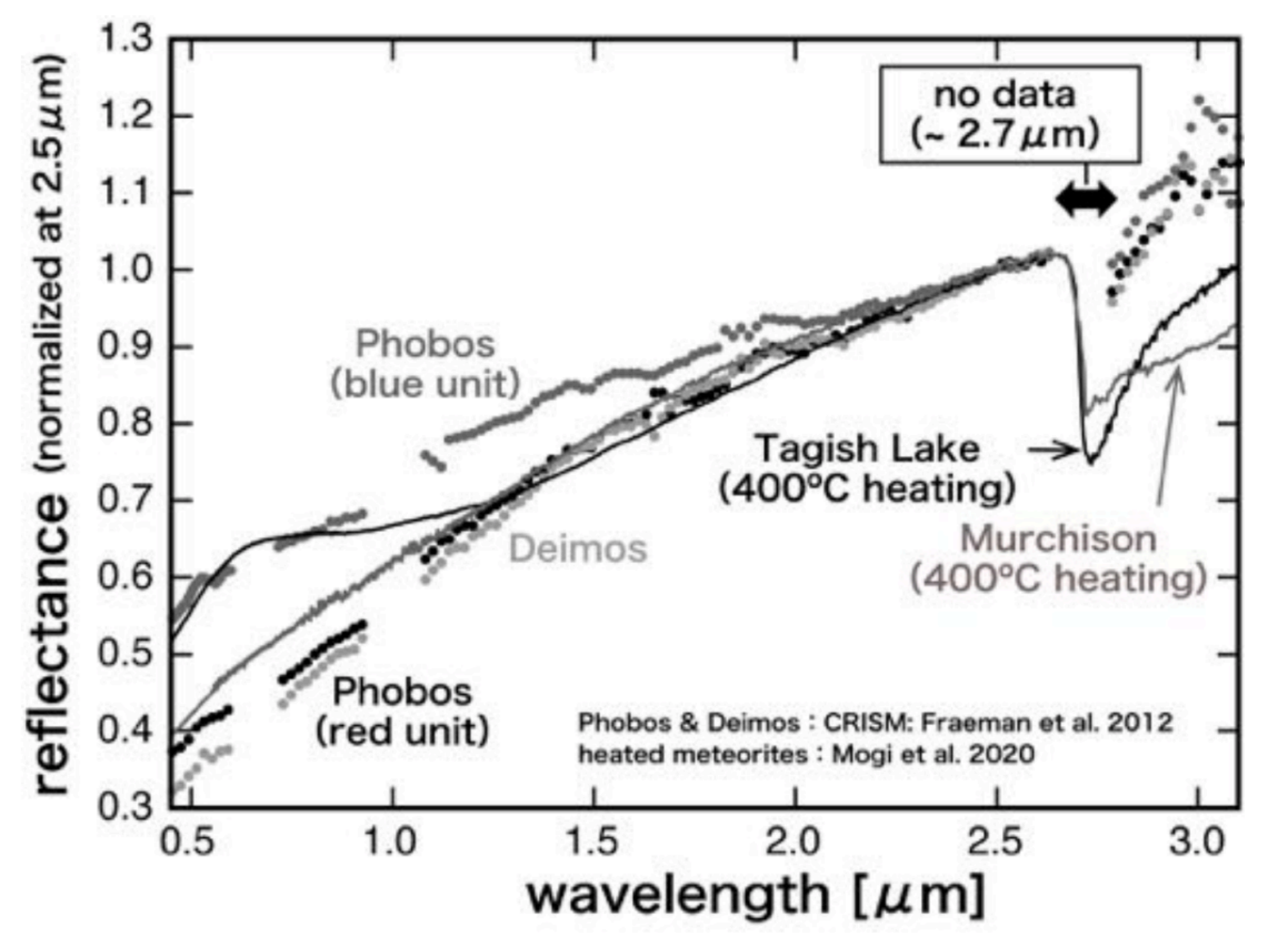
supported by orbital elements

Circular & Equatorial

Capture Origin

A random gravitational capture with successive orbital evolution.

Burns 1978; Murchie et al. 1991



Pro.

The spectral features — Dark & Featureless — might be naturally explained.

Challenges

How were initial eccentricity and inclination damped?

Why only “two” captured?

Giant Impact Origin

A giant impact forms a debris disk around Mars from which Phobos and Deimos accrete.

Pro.

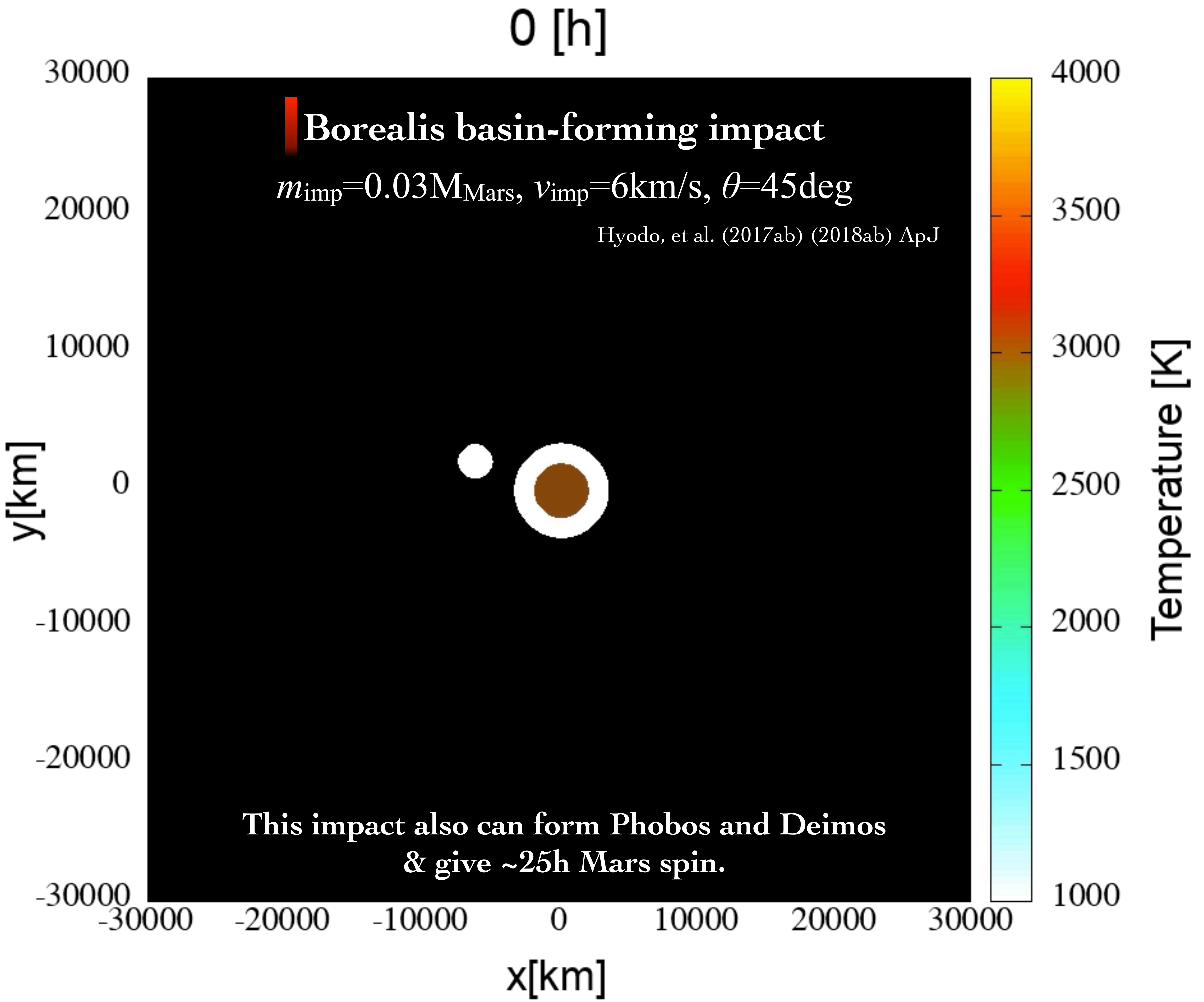
The orbital properties — nearly circular & equatorial — can be naturally explained.

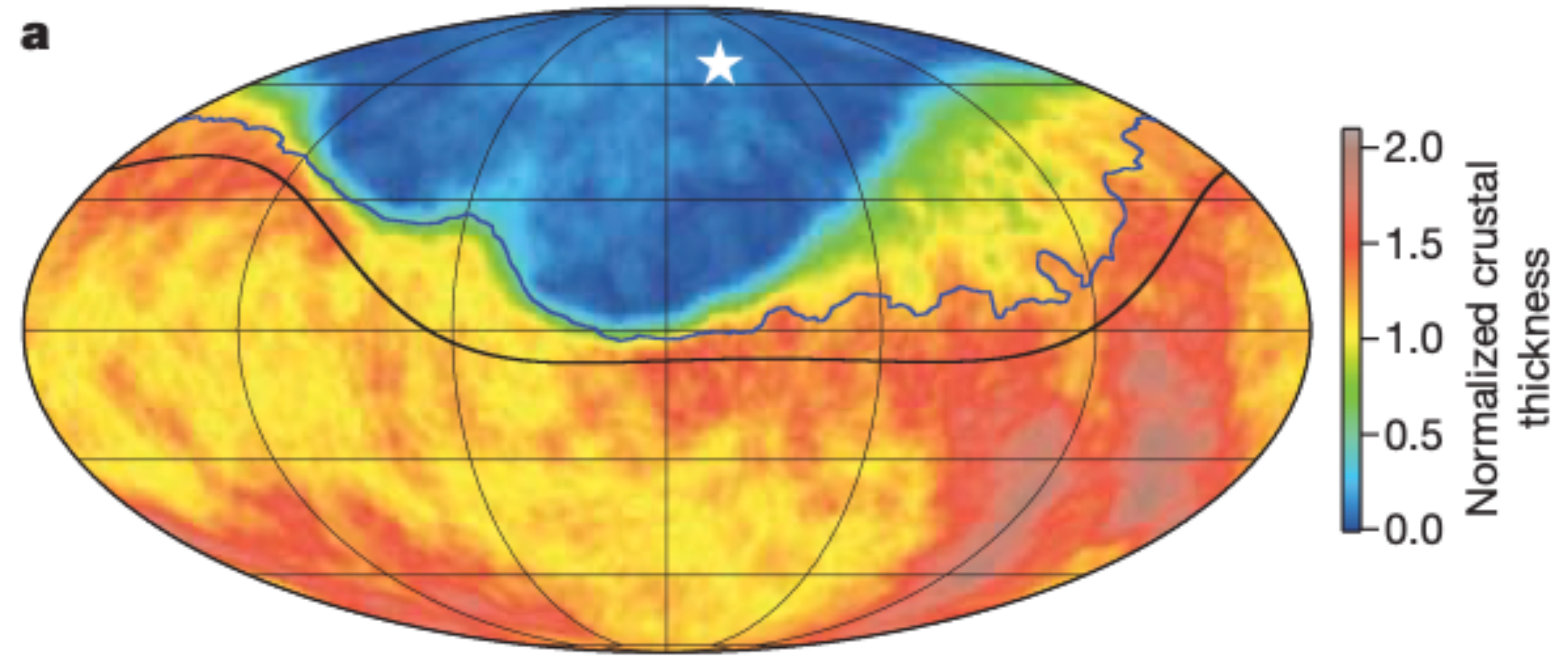
Challenges

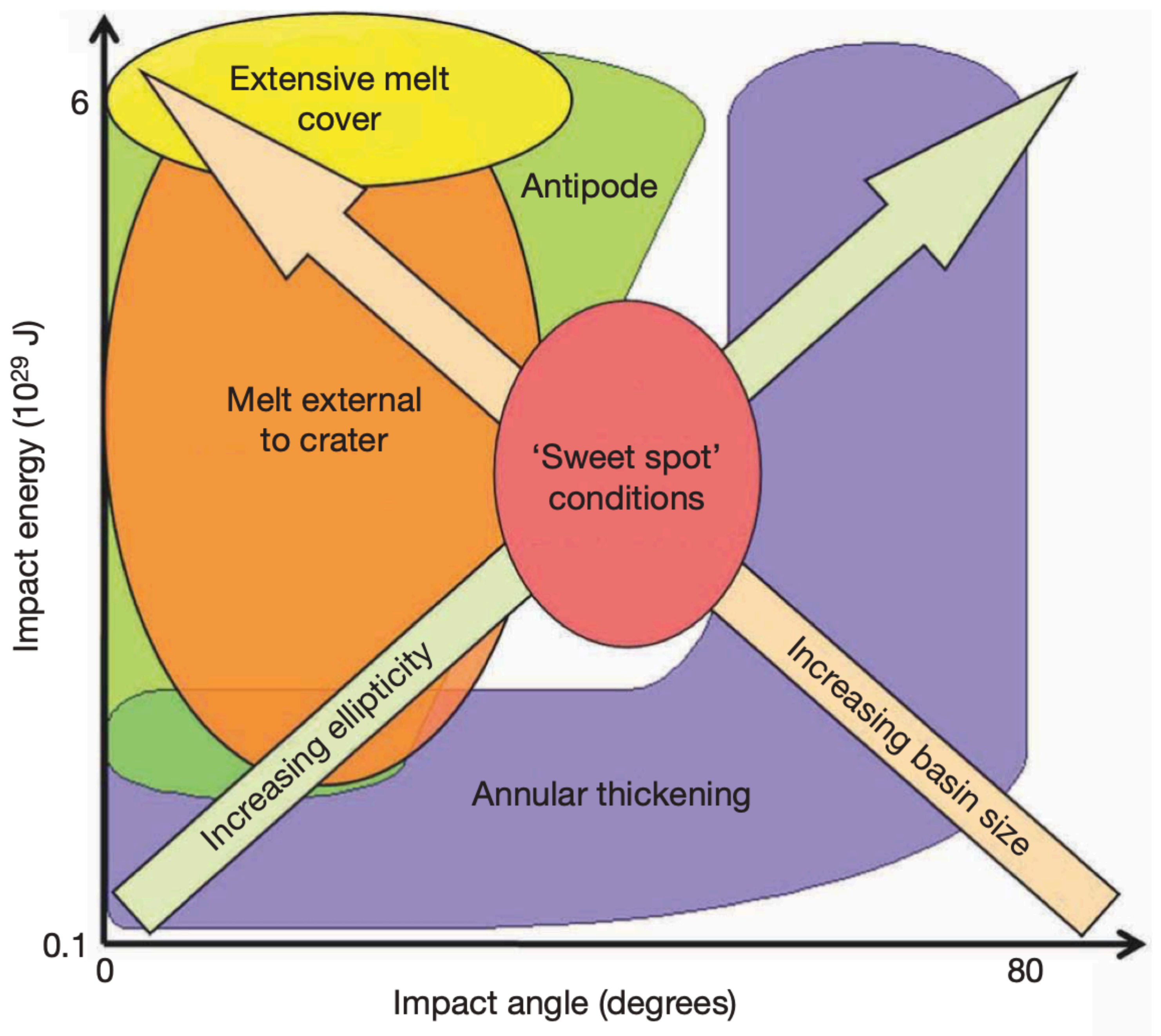
Why do the spectral features resemble those of D-type asteroids?

A Giant Impact

See also,
Craddock (1994, 2011),
Citron et al. (2015)

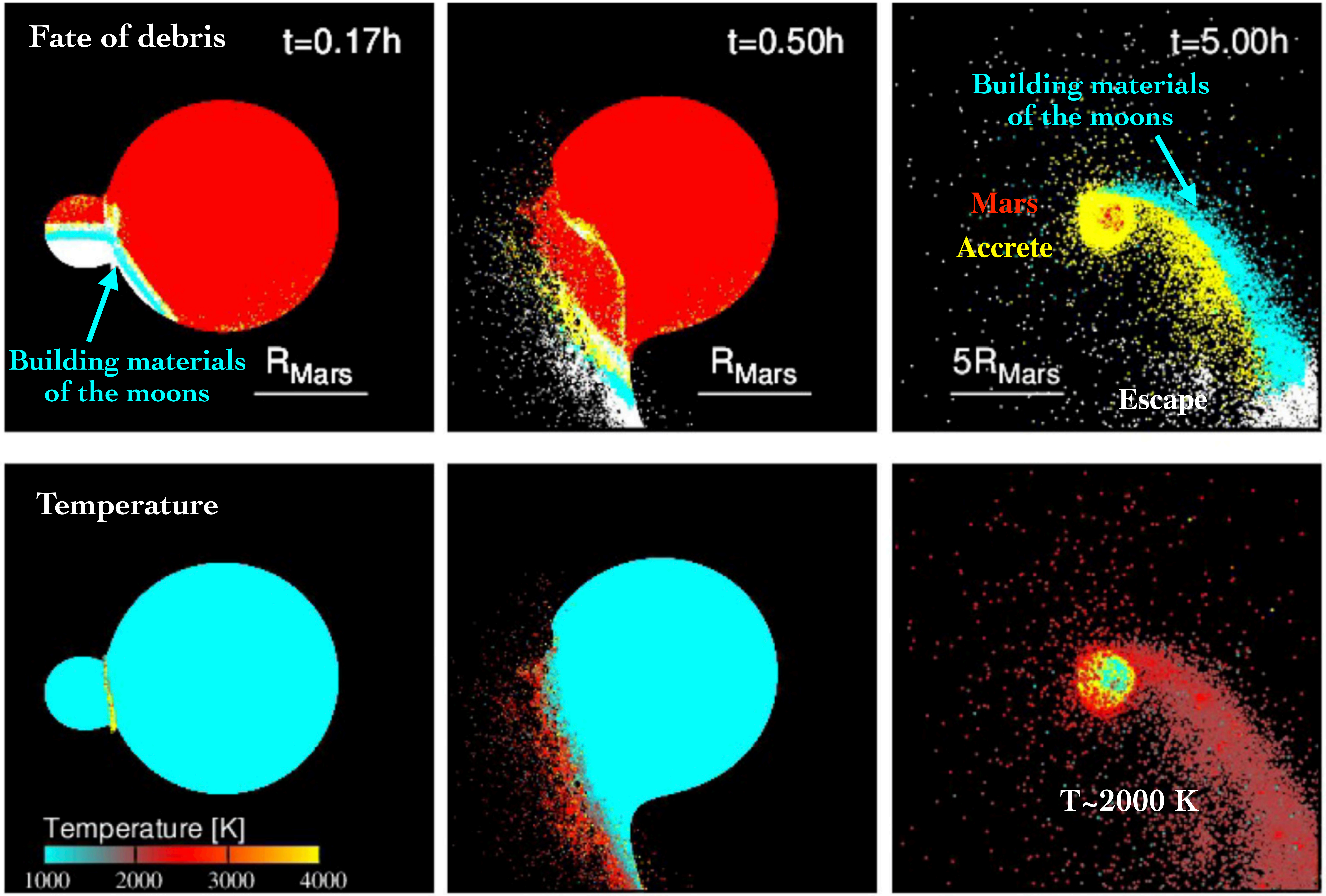






Marinova+ 2008

Building Blocks — Impact Debris

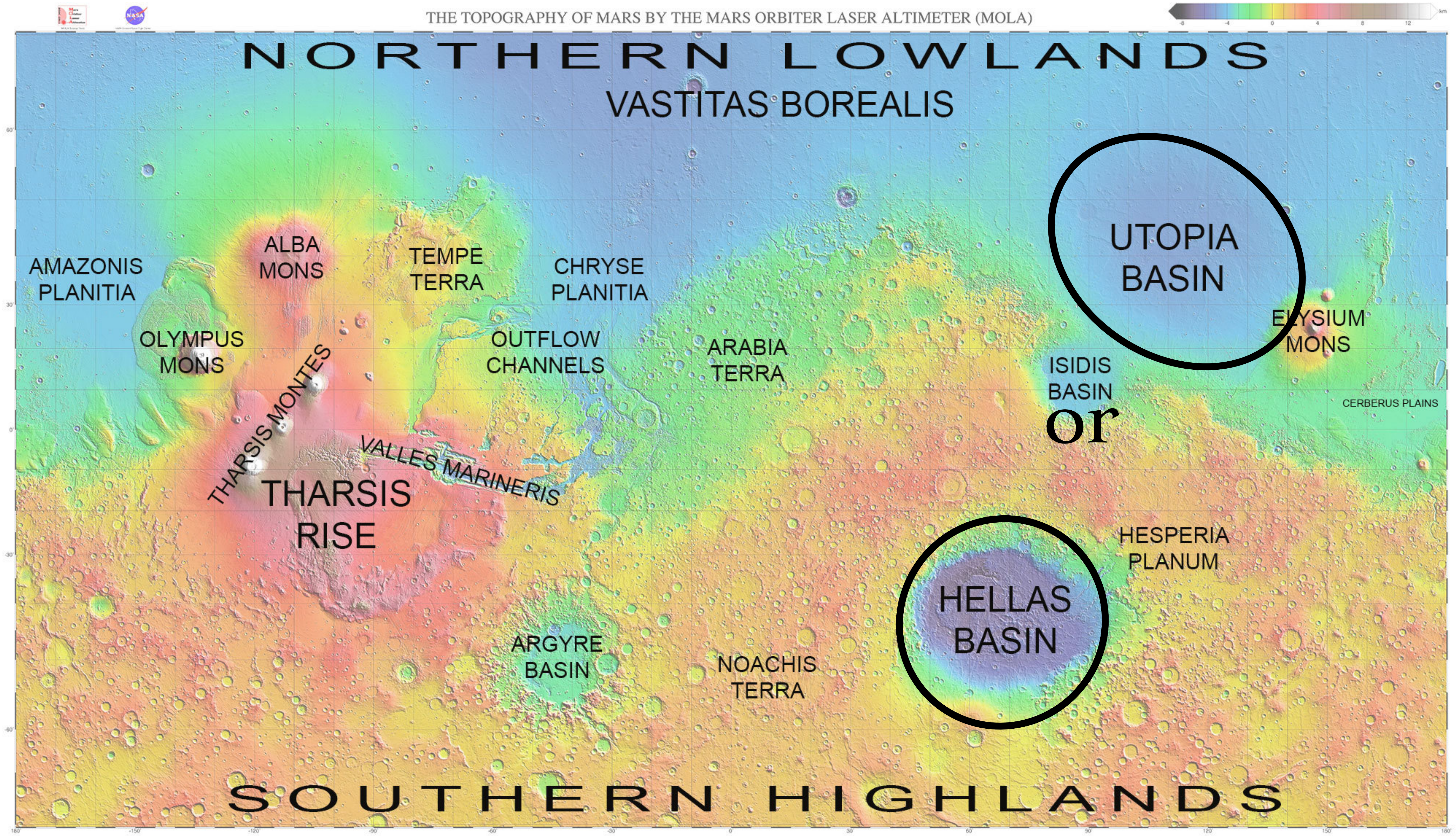


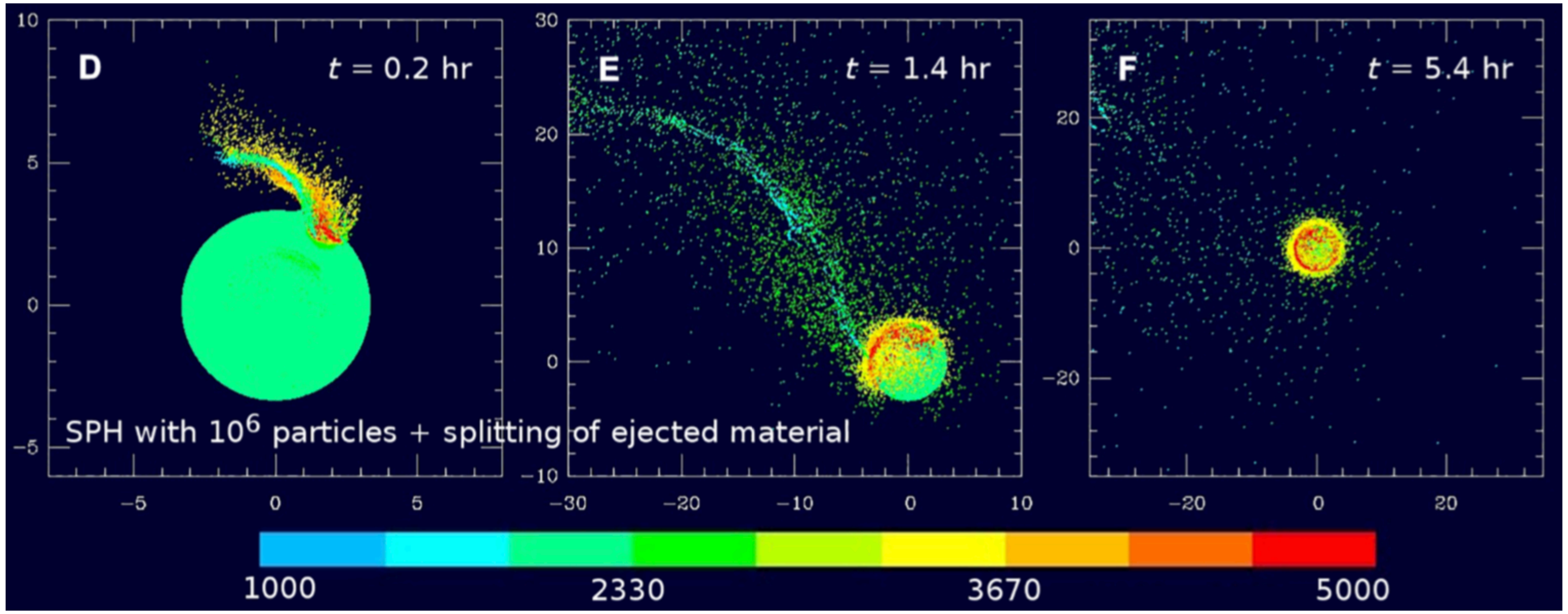
Hyodo, et al. (2017a)

Alternative Impacts

Utopia or Hellas, an alternative large basin, may be responsible for the Martian-moon forming giant impact.

Canup & Salmon (2018)





$\theta_{imp} = 45$ degs

$v_{imp} = 7$ km/s

$m_{imp} = 0.5\times10^{-3}\ M_{Mars}$

$M_{disk} = 5\times10^{18}$ kg

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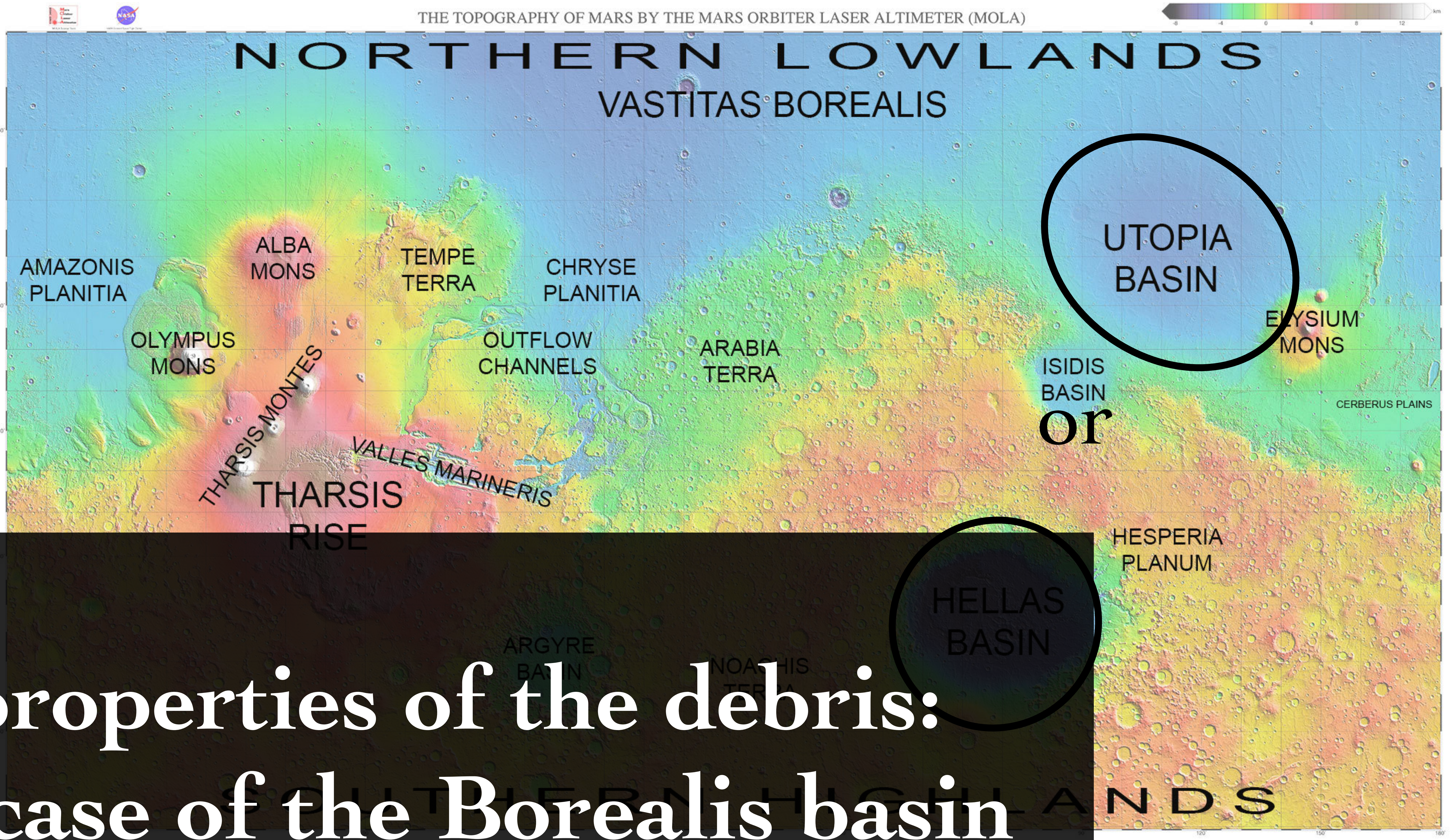
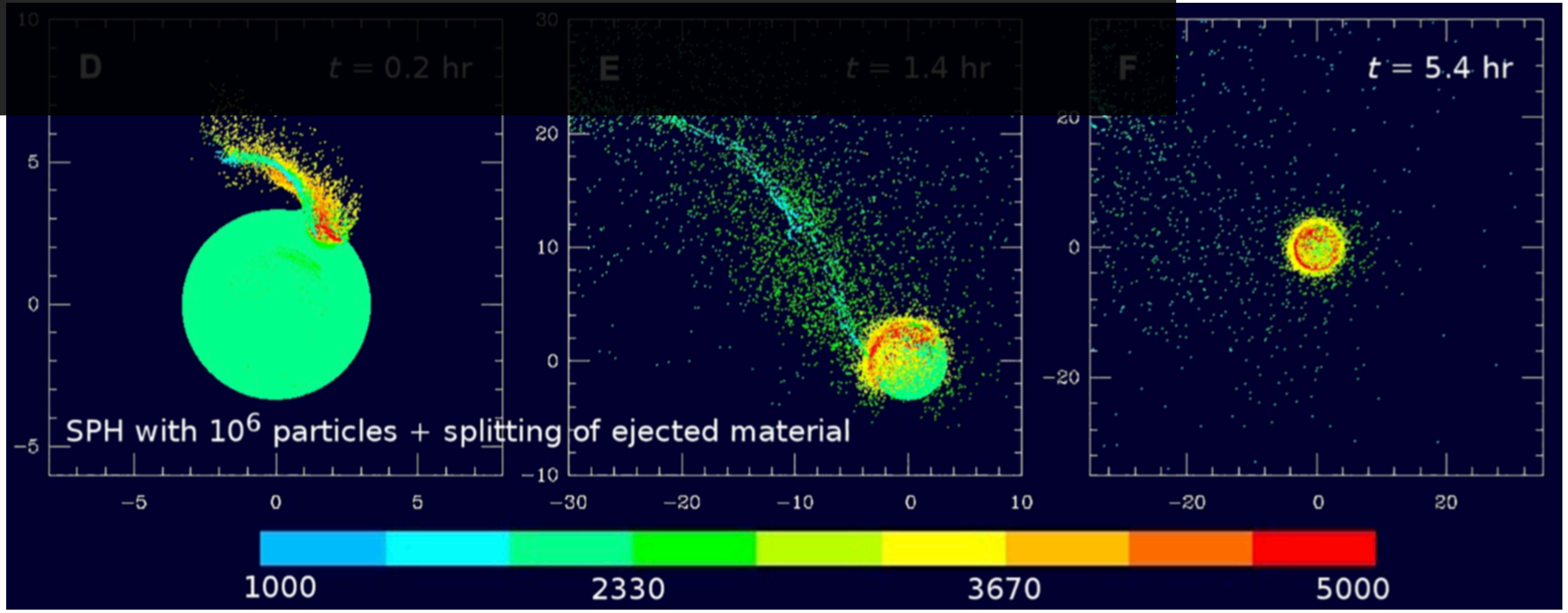
Phys/chem. properties of the debris: Similar to the case of the Borealis basin





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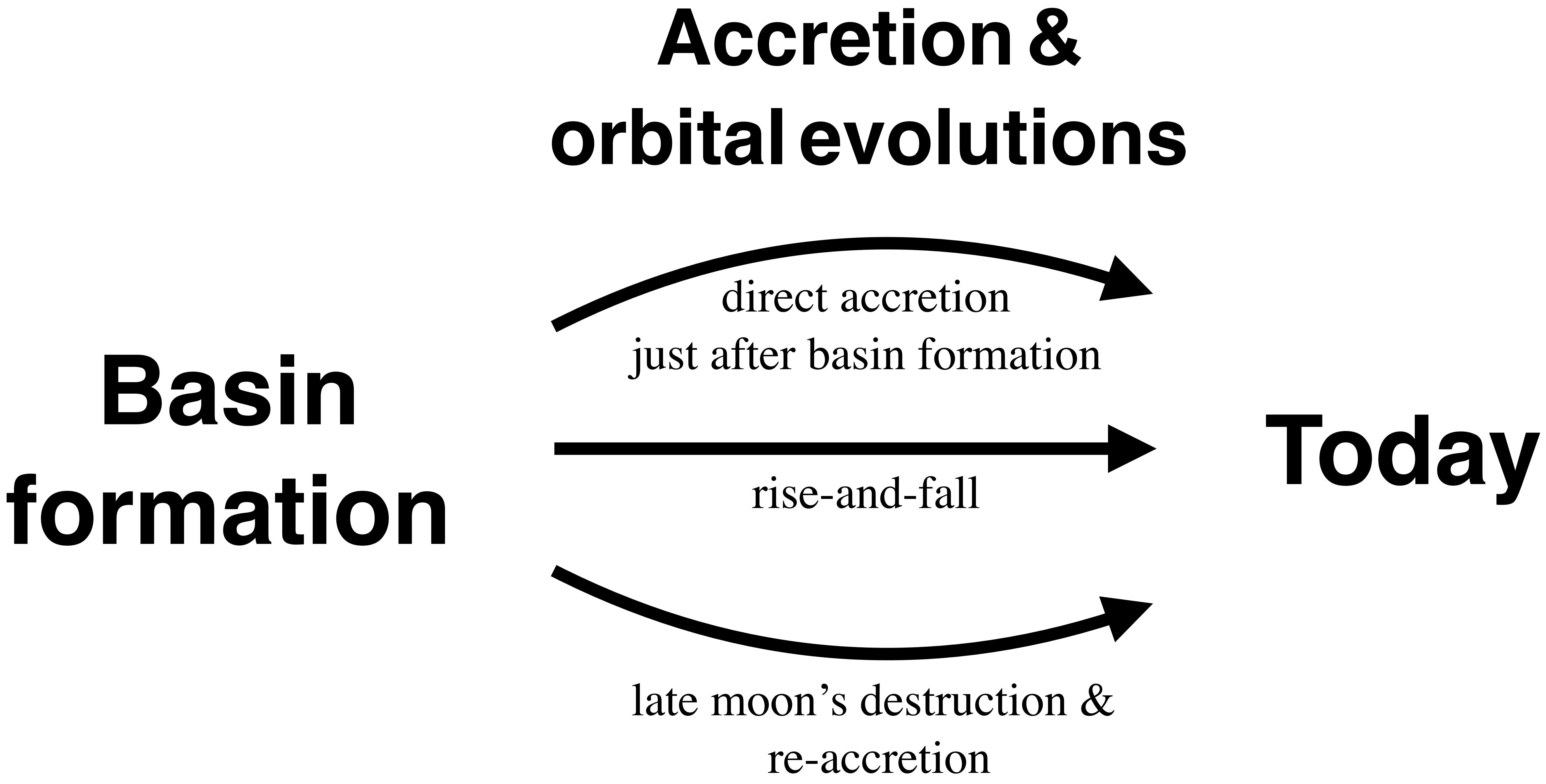
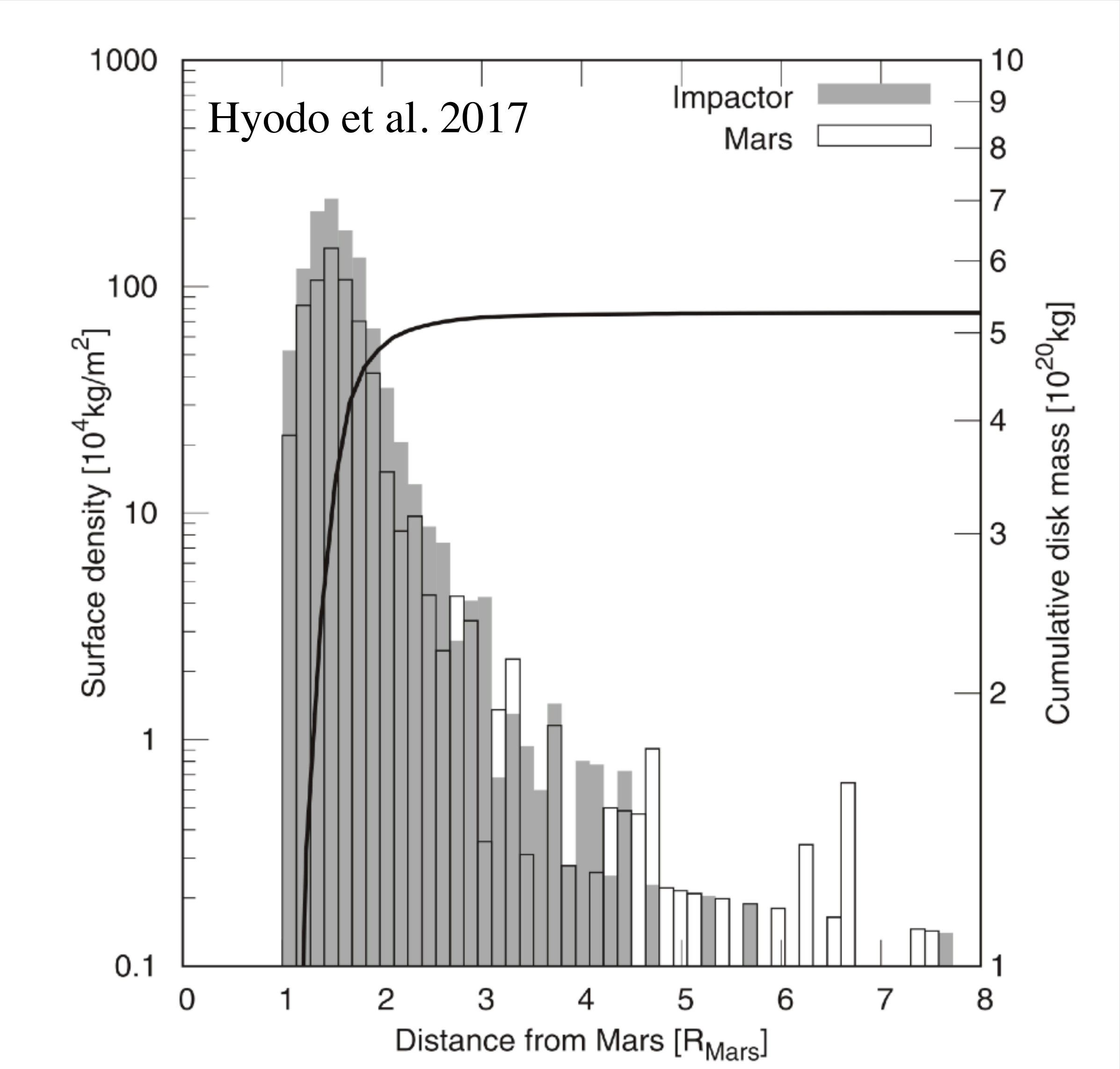
Different Paths of the Giant Impact Origin



The final accretion time of Phobos is very different at a different path.

Direct Accretion

Phobos and Deimos successively form after giant impact on Mars. In this case, moons are ~4 billion years old.



Rosenblatt+ (2016)
Canup&Salmon 2018

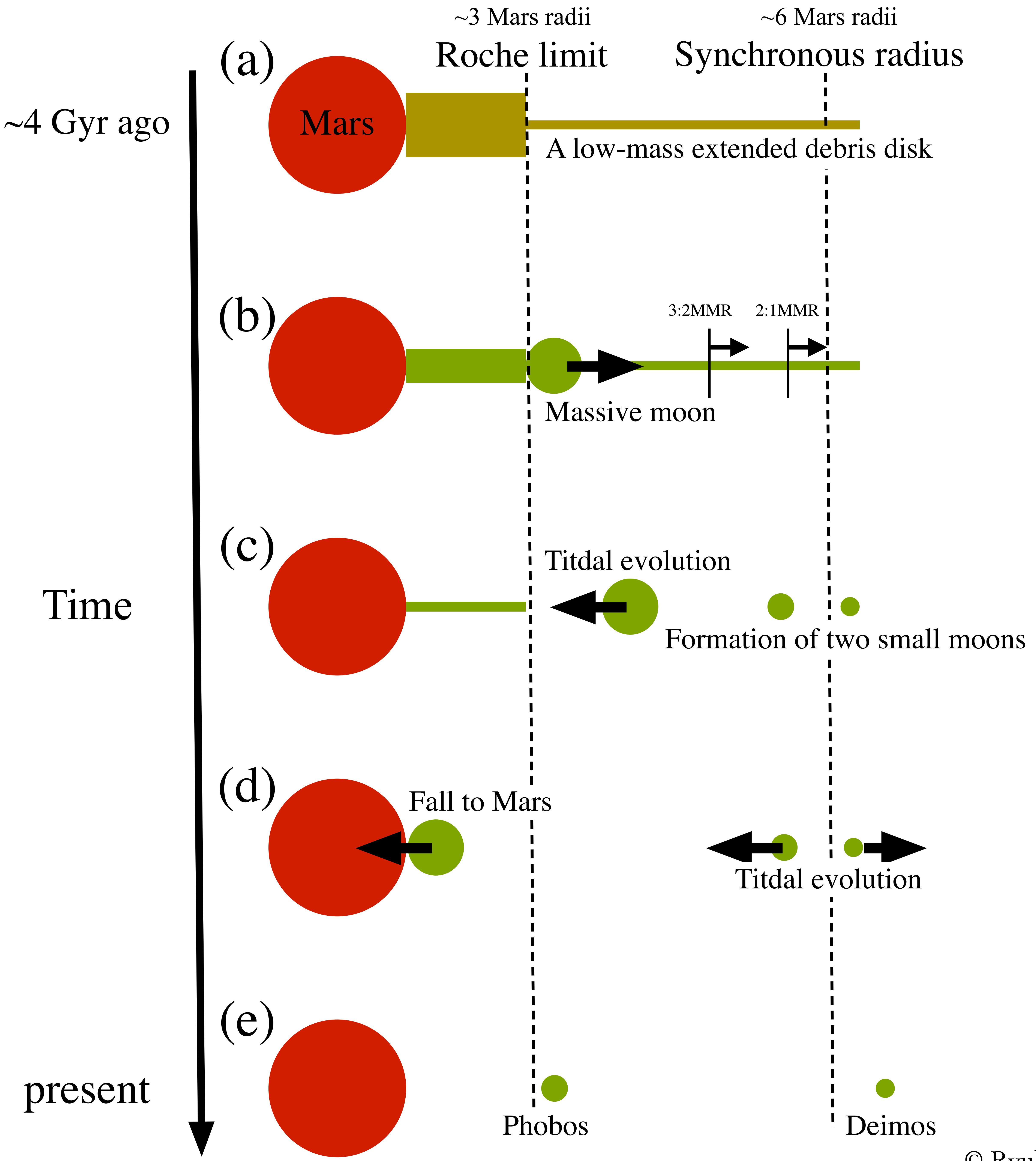


Table 1 | Masses and timescales for Mars ring/satellite cycles.

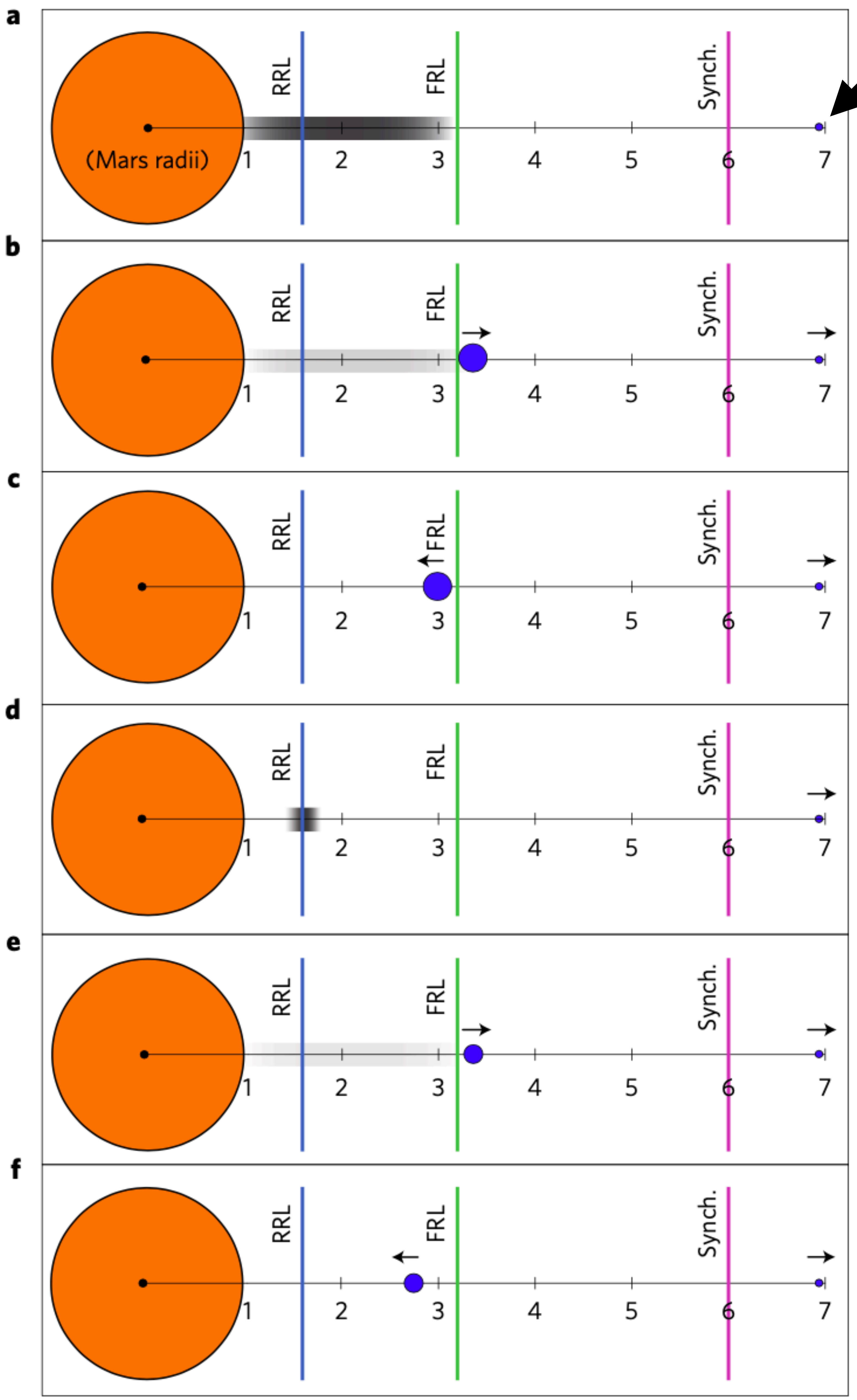
Cycle no.	Initial ring mass (g)	Final satellite mass (g)	Cycle time, 1 km particles (Myr)	Estimated cycle time, 0.18 m particles (Myr)
6	1.2×10^{23}	2.6×10^{22}	0.46	190
5	2.6×10^{22}	5.4×10^{21}	1.1	290
4	5.4×10^{21}	1.1×10^{21}	2.8	270
3	1.1×10^{21}	2.4×10^{20}	5.3	350
2	2.4×10^{20}	5.0×10^{19}	22	750
1	5.0×10^{19}	1.0×10^{19}	61	2,500

Here we show the initial mass for each cycle, the mass of the satellite produced at the end of the cycle, and how long the cycle takes to complete for our nominal 6-cycle case. Also included are estimated completion times for a ring composed of 0.18 m radius particles (see Supplementary Methods). The relatively long completion time for the first two cycles of a ring composed of 0.18 m particles is due to both the longer spreading time for rings with smaller particles, and the fact that the masses of the first cycles are sufficient for Lindblad torques to drive satellites far from the FRL, increasing the orbital evolution time. The time shown for Cycle 1 is when the satellite reaches the current orbit of Phobos, and not the RRL (as it is for the previous cycles).

Rise and Fall?

A 3-7 times of a rise-and-fall of Phobos, a cycle of accumulation, tidal evolution, and tidal disruption, over ~4 billion years. Today's Phobos is the one that completed its accretion in only the past ~few Myr[1,2]?

Hesselbrock & Minton (2017)



Deimos

assuming it is already formed by another process (e.g., Rosenblatt et al. 2016 without forming Phobos)

[1]Crater analysis, suggesting the surface age of ~4 Ga (Schmedemann et al., 2014)

[2]Future consideration — Can we remove the remnant rings within few Myr?

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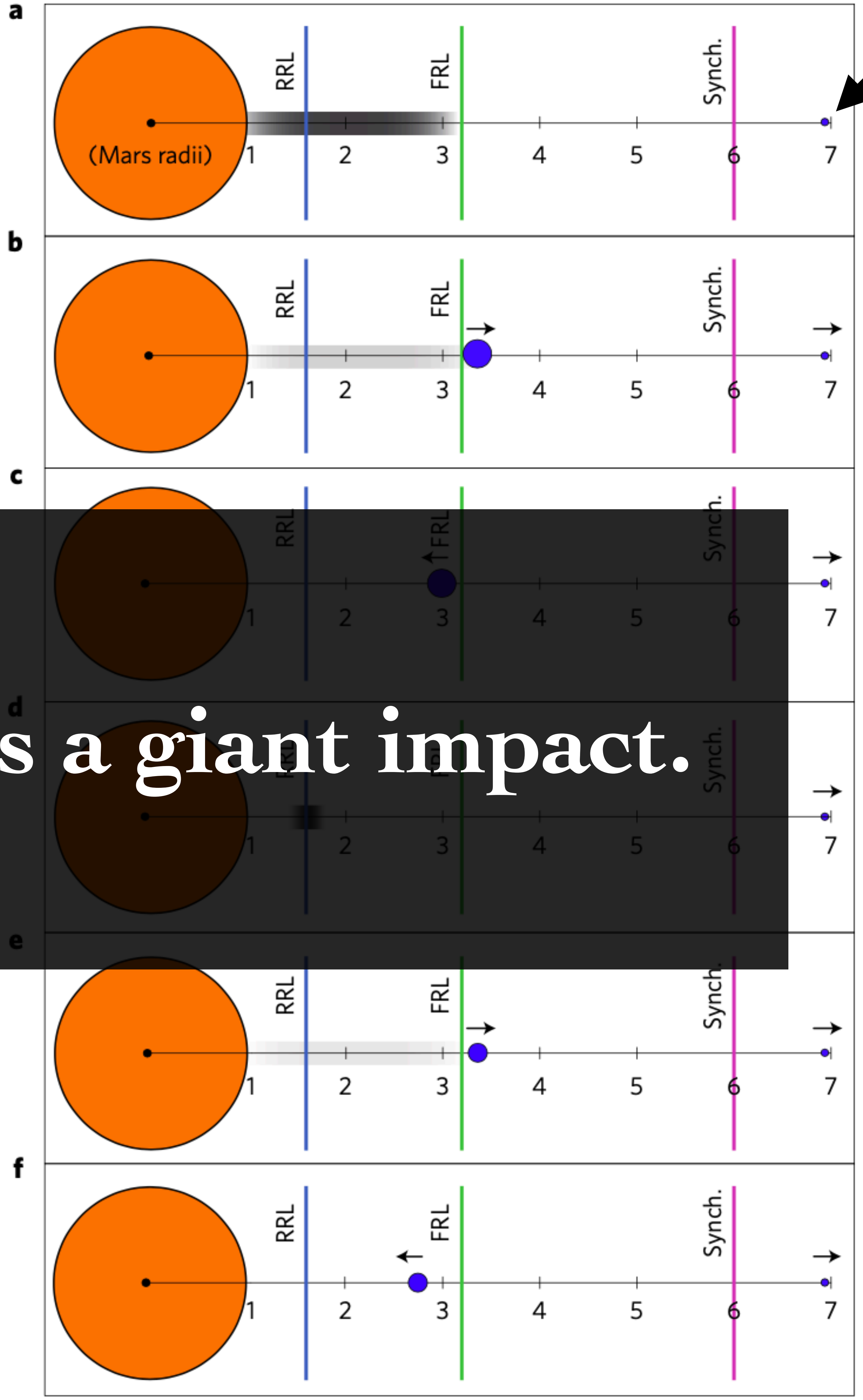
Anyway, this also needs a giant impact.



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[2]Future consideration — Can we remove the remnant rings within few Myr?

A single large moon

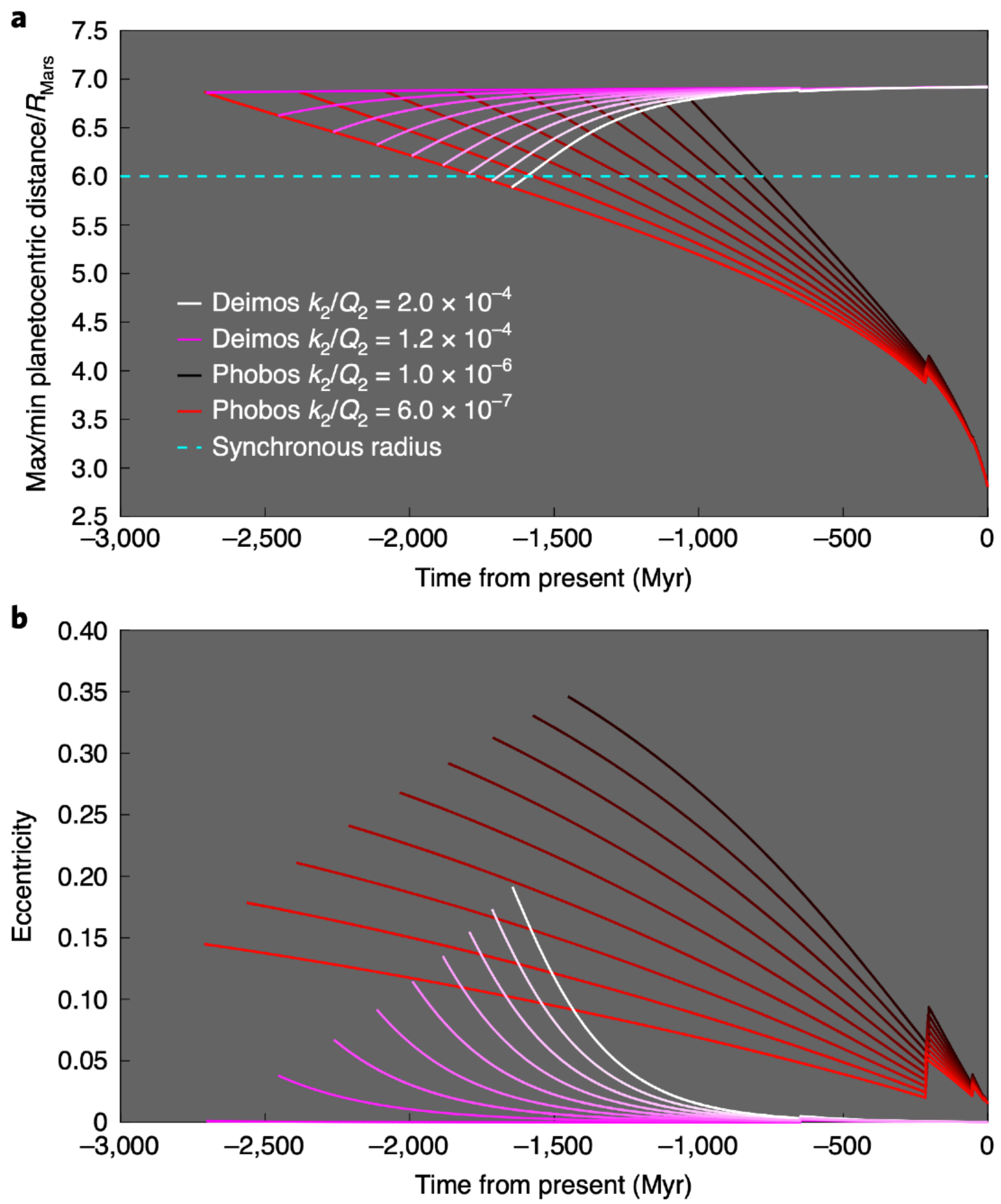
An origin of Phobos/Deimos by its disruption

The orbits of the moons might have intersected at recently as ~1-3 billion years ago, suggesting their progenitor was a larger moon that impact-shattered and was re-accreted to form Phobos and Deimos[1,2,3,4].

Bagheri et al. 2021
See also Brasser 2020

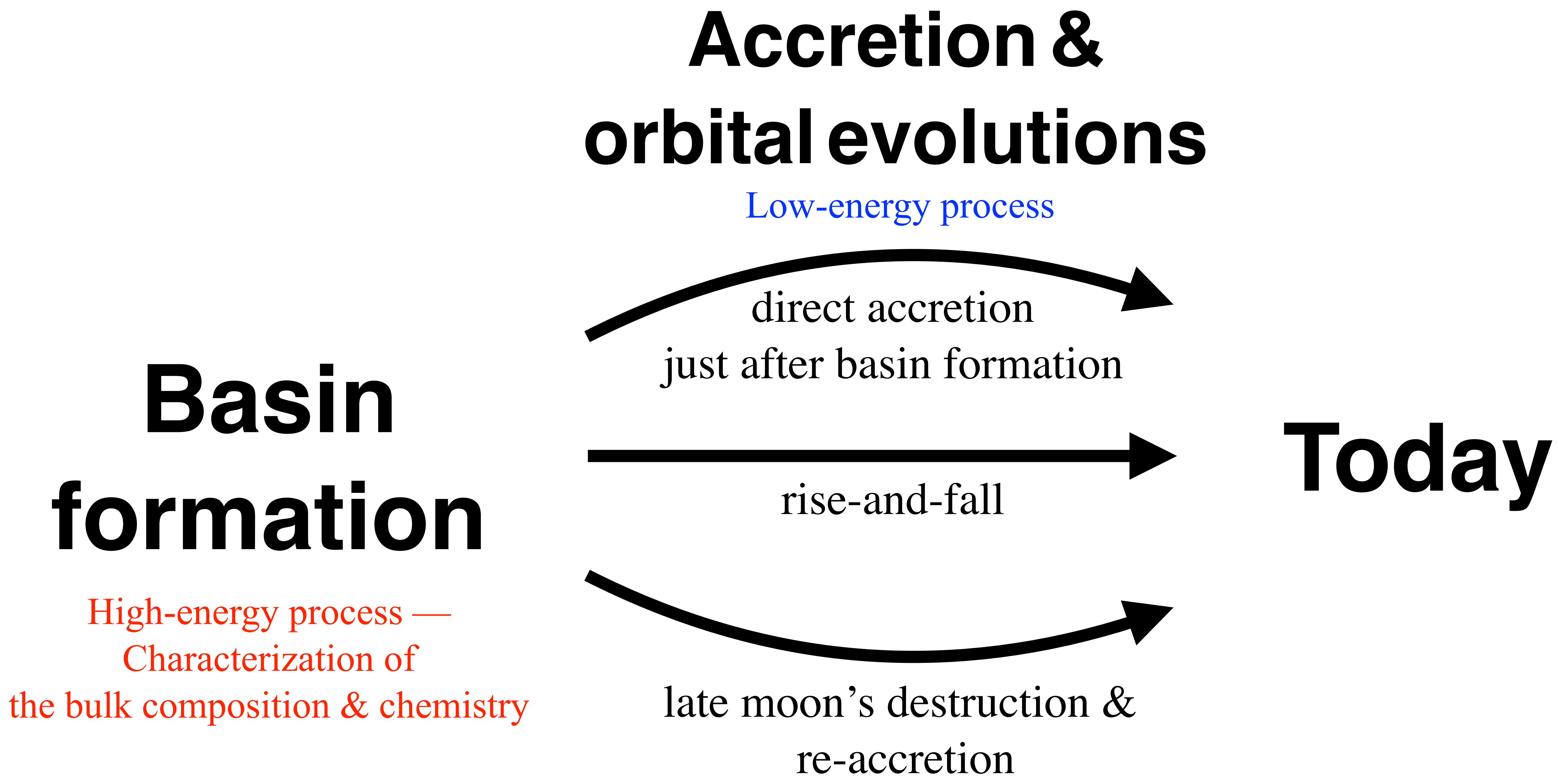
[1]Crater analysis, suggesting the surface age of ~4 Ga (Schmedemann et al., 2014)
[2]Future consideration — impact process and successive accumulation process are not studied yet. Why only two accumulated? Why not three, etc?
see also Hyodo & Charnoz 2017

[3]Impact flux at ~1-3 Ga also needs to be studied to validate this scenario.
[4]Internal structure, i.e., tidal parameter, of Phobos/Deimos is still not constrained.



Anyway, this also needs a giant impact on Mars to form a progenitor.

Different Paths of the Giant Impact Origin

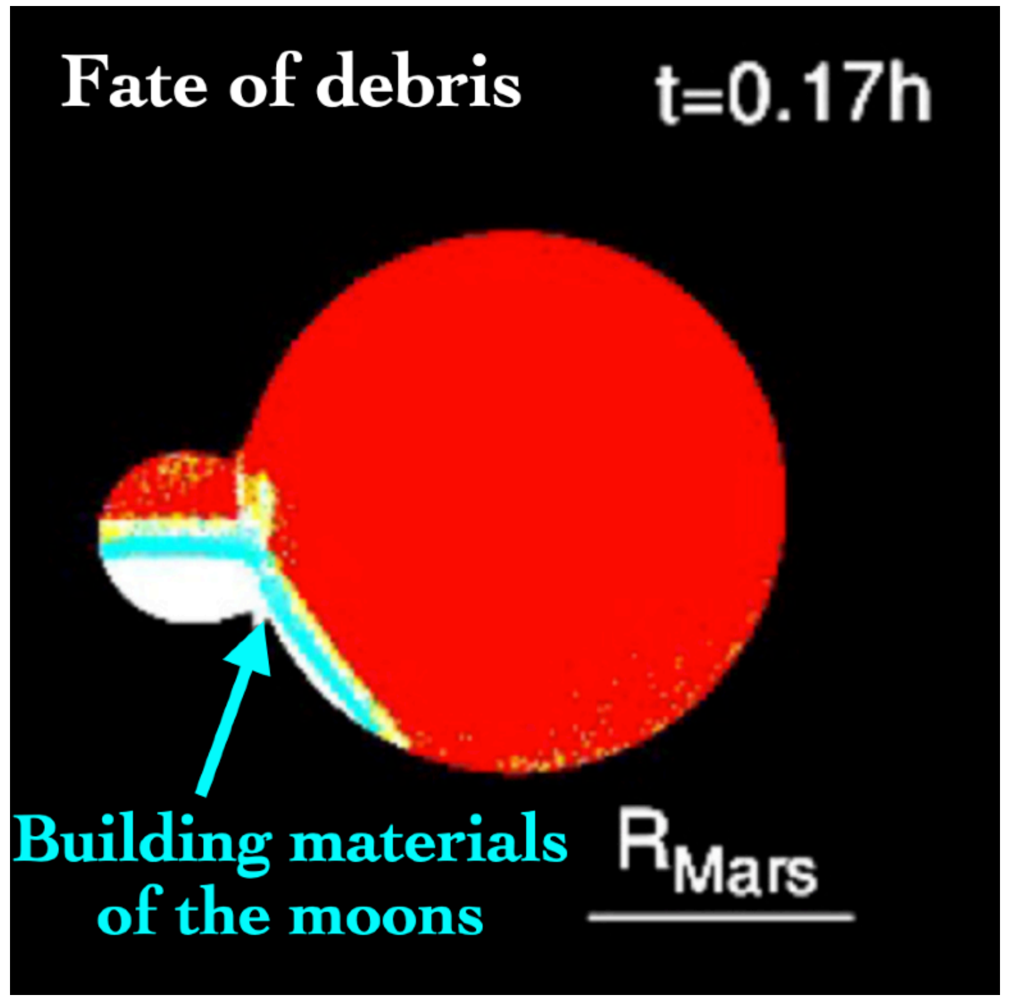


The final accretion time of Phobos is very different at a different path.

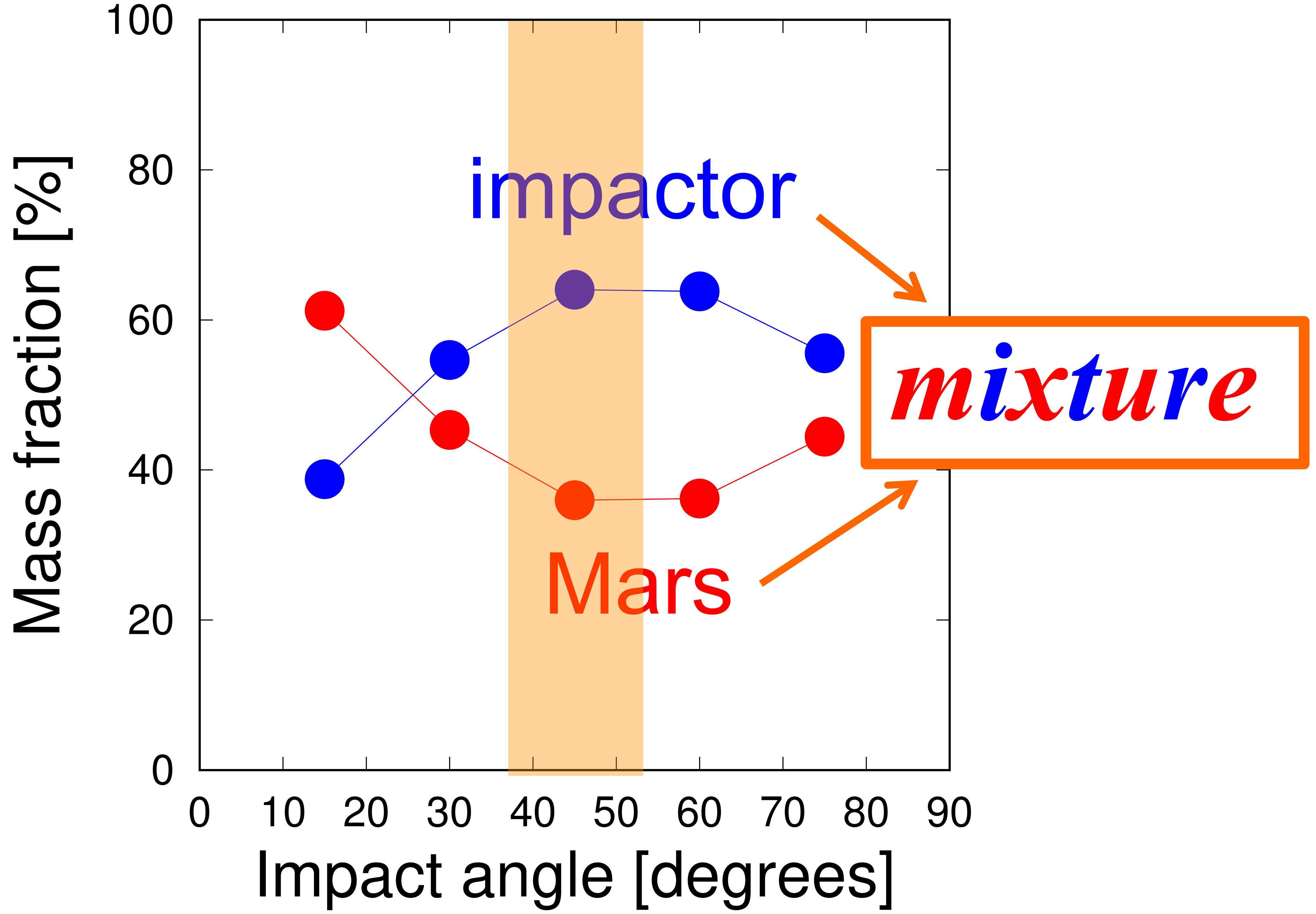
Building Blocks

Endogenous bulk composition of Martian moons

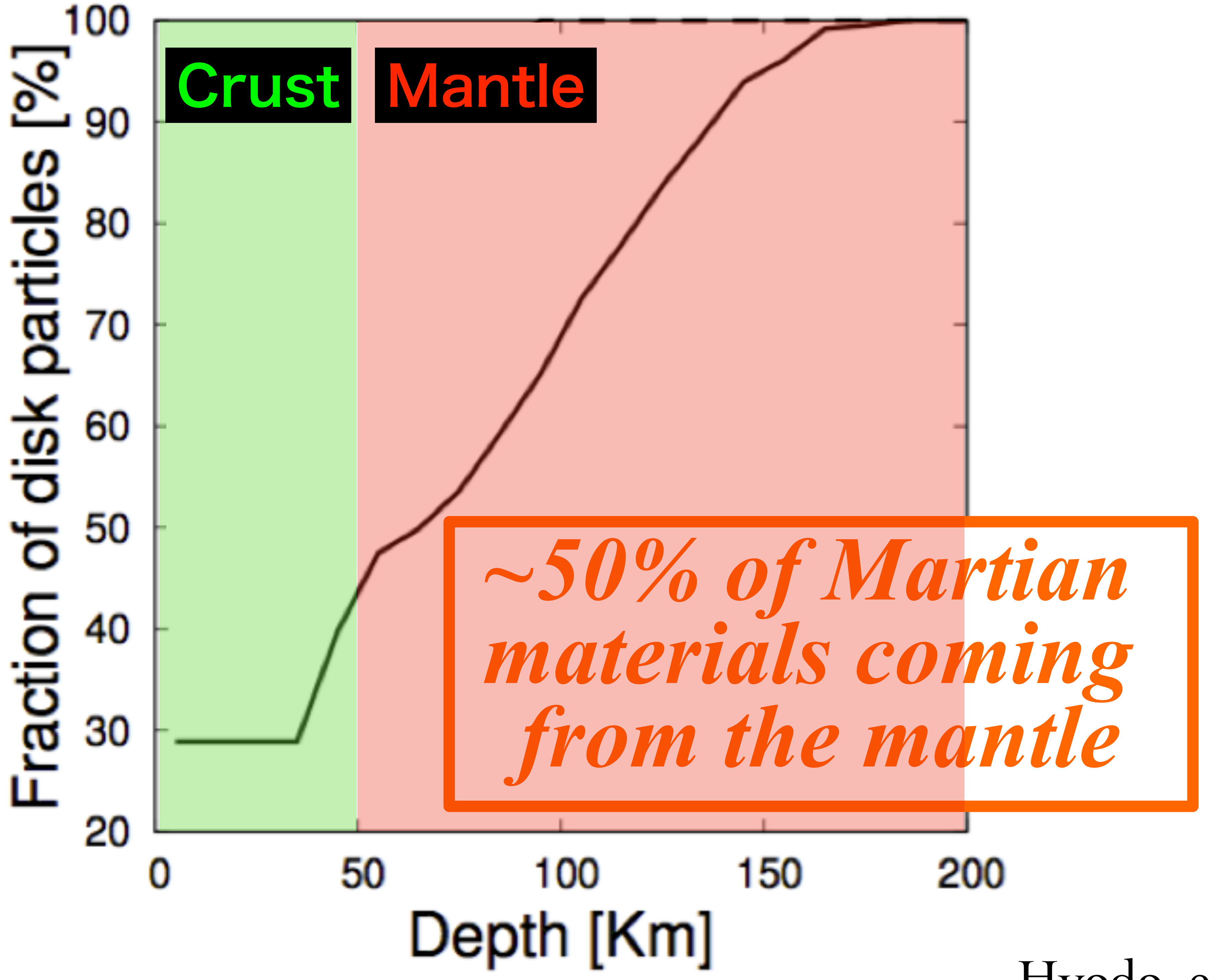
- Ancient Mars crust/mantle
- Impactor's materials



disk composition



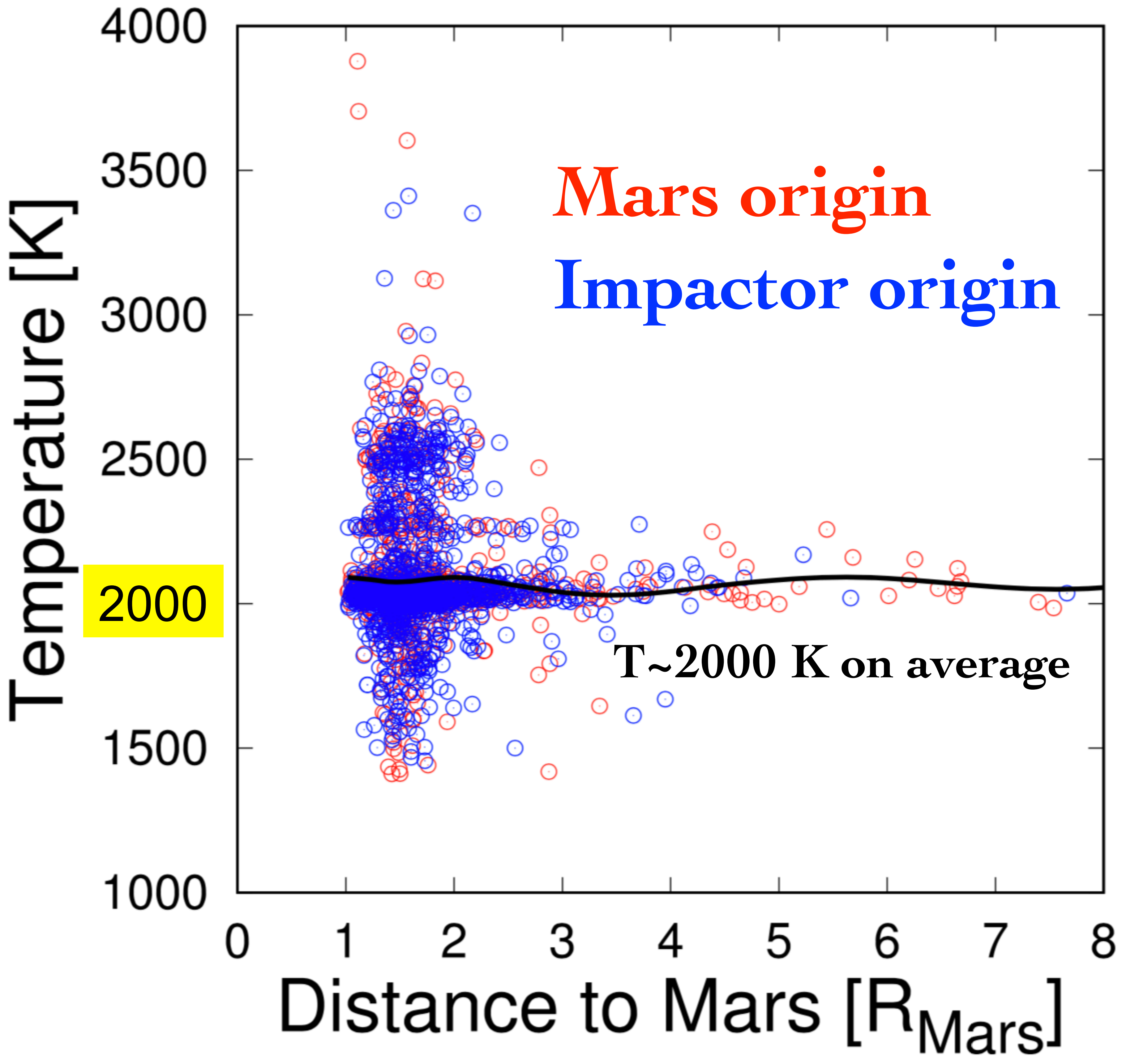
ejected depth



Hyodo, et al. (2017a) ApJ

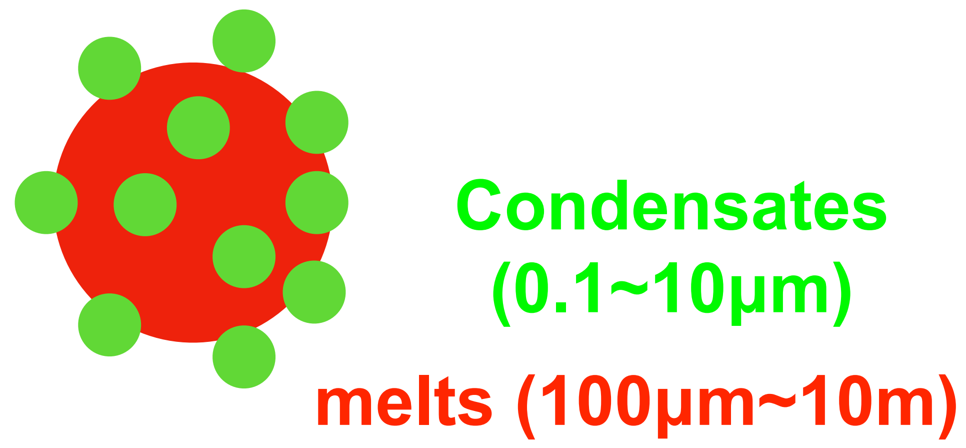
Thermal and Physical Aspects

Particle temperature



Thermal properties (~2000 K)

- almost fully molten
- low vapor fraction (~5%)



Particle sizes (after cooling)

- solidified melts: ~100 μm - 10 m
- condensates from vapor: ~0.1-10 μm

Hyodo, et al. (2017a) ApJ

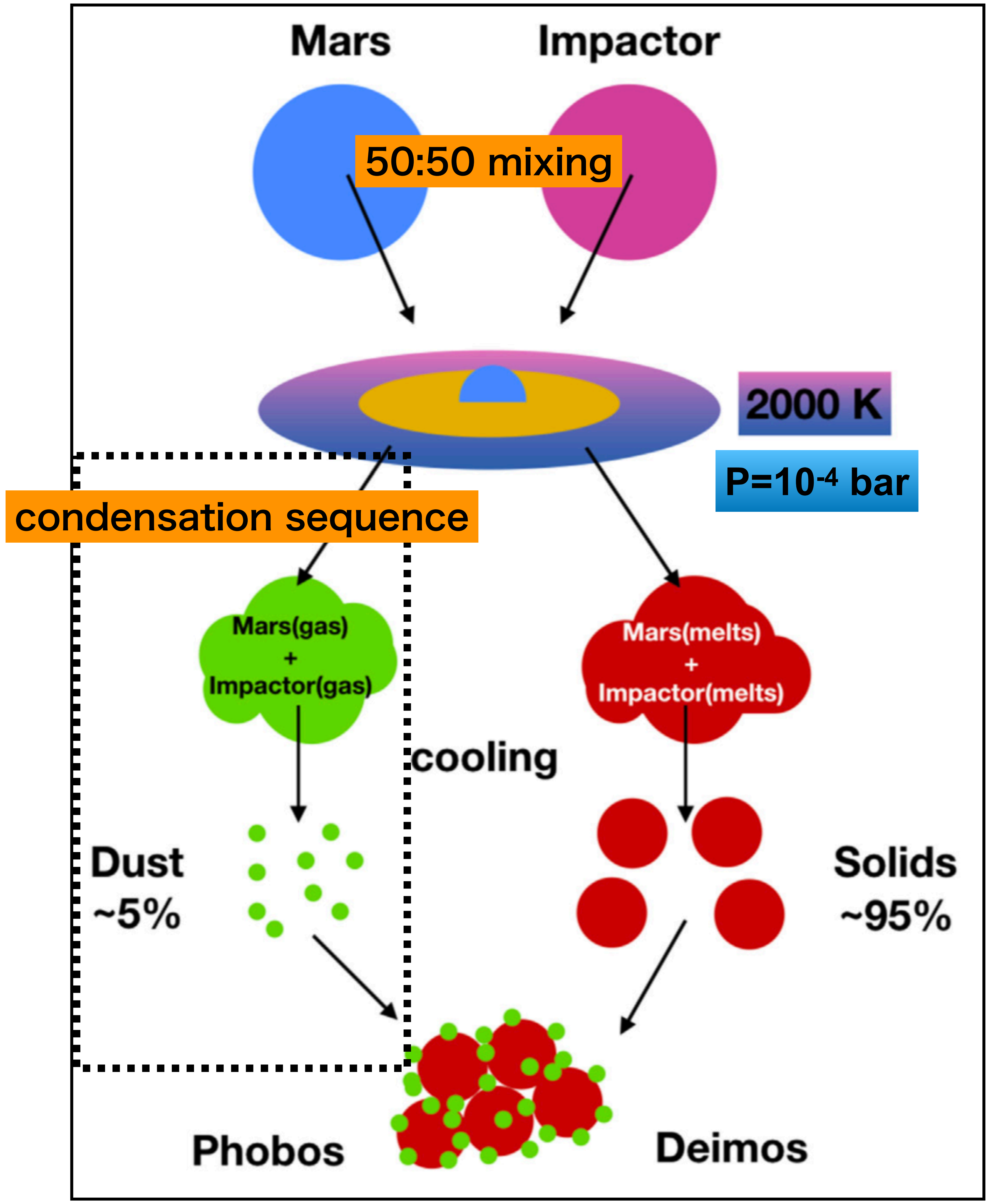
Very dark (FeS, C)
Pignatale et al (2018), ApJ

Featureless
Ronnet et al (2016), ApJ

Space-weathered anorthosite
Yamamoto et al (2018), GRL

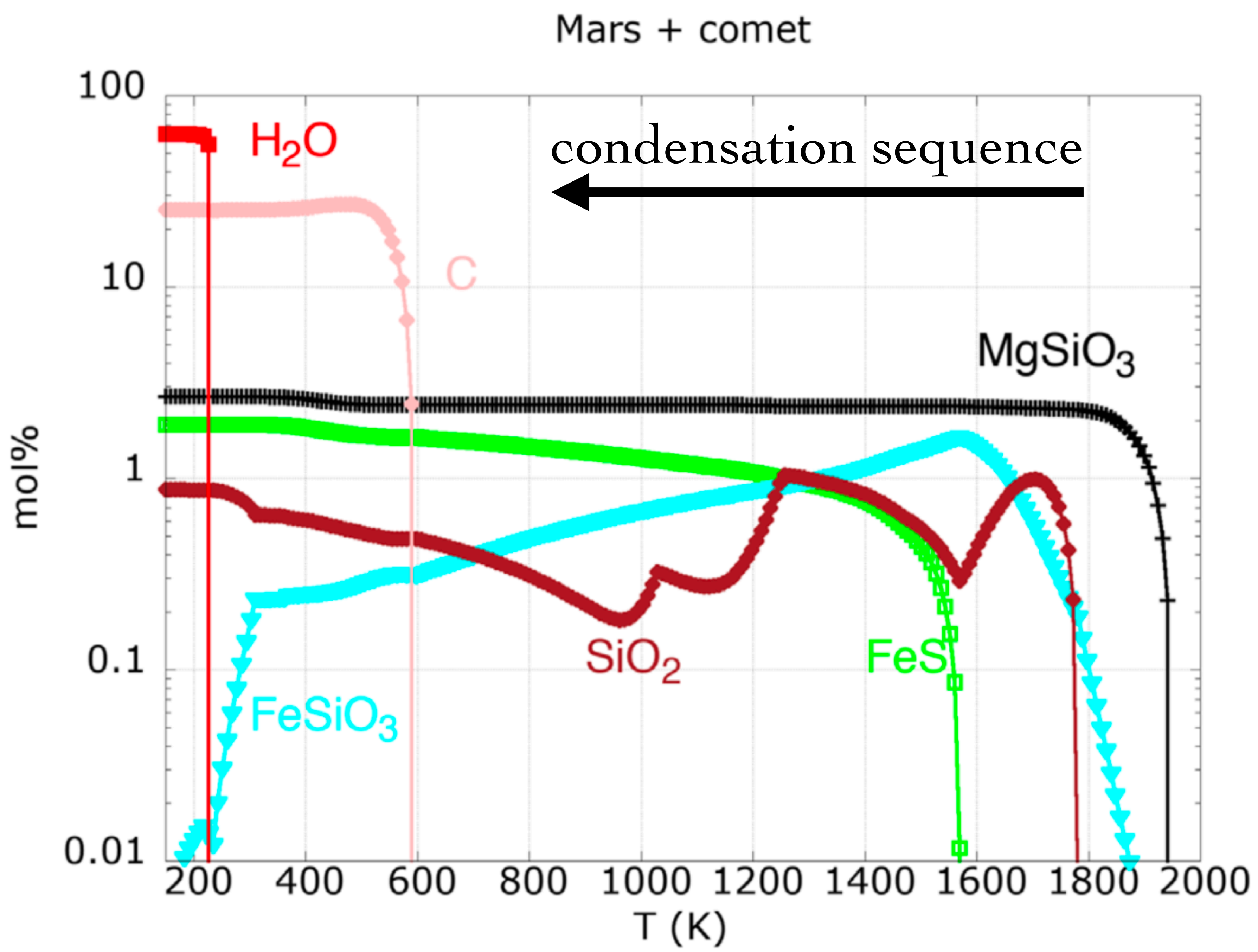
Also, see Tomoki's recent work.

Composition of Condensates



Thermodynamic equilibrium —

A glimpse of chemical composition of condensates

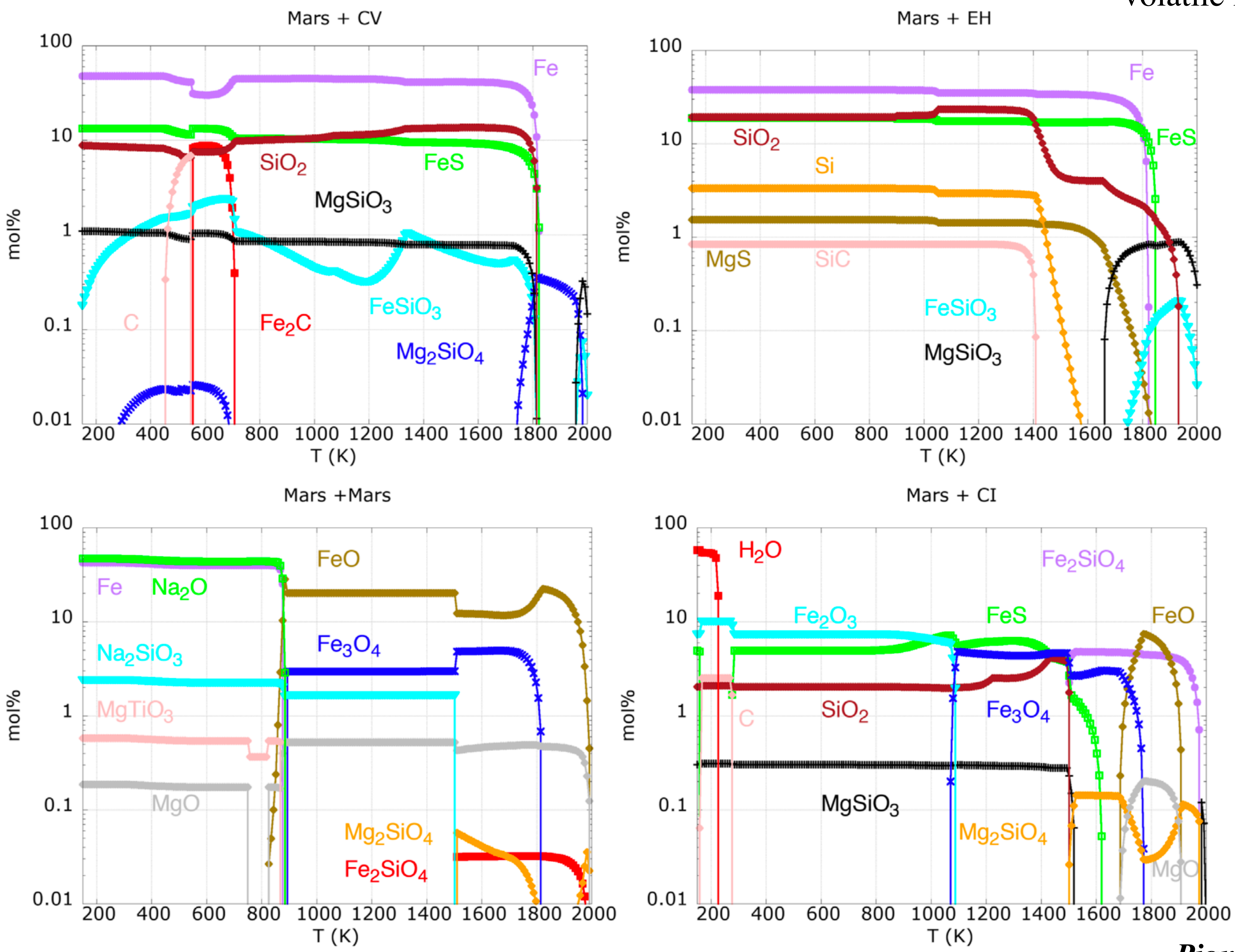


Pignatale et al. (2018)

Chemistry Depends on Impactor

*volatile loss process is *not* included here

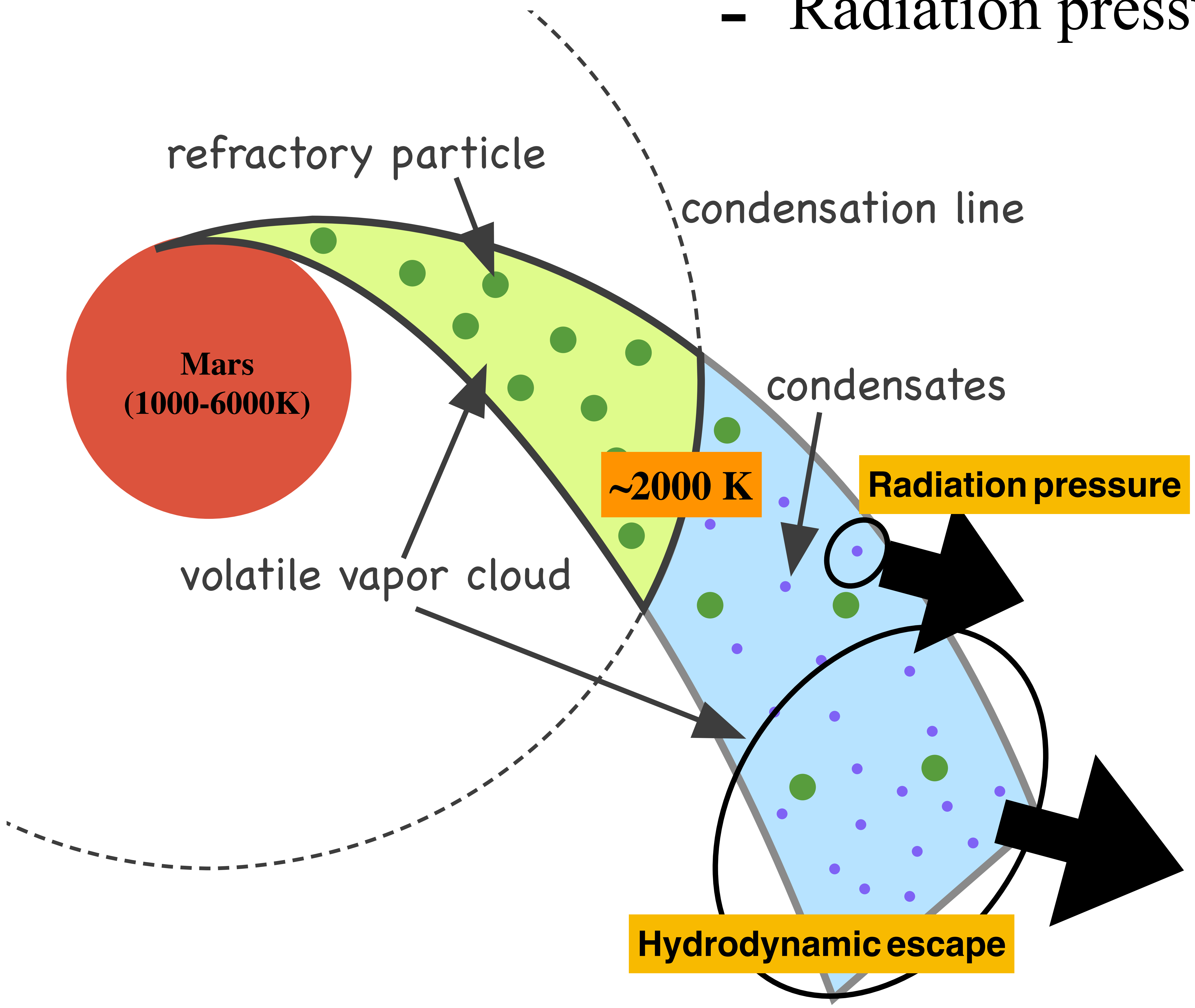
see Hyodo et al. 2018b



Pignatale et al. (2018)

Volatile Loss

- Hydrodynamic escape of the vapor
- Radiation pressure on condensed dust



Hydrodynamic Escape

~ 30% of vapor can escape
→ ~ 70% of volatile elements can survive

Radiation Pressure

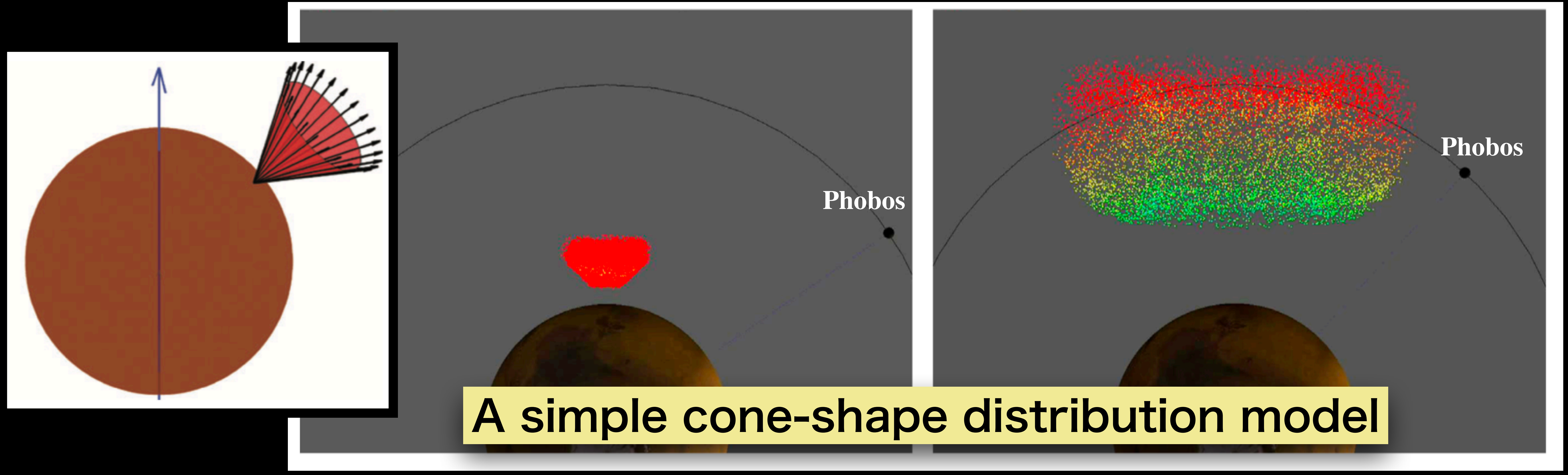
Moderately volatile elements (condensation $T > 1000$ K) are selectively removed.

Hyodo, et al. (2018b)

Next Topic…

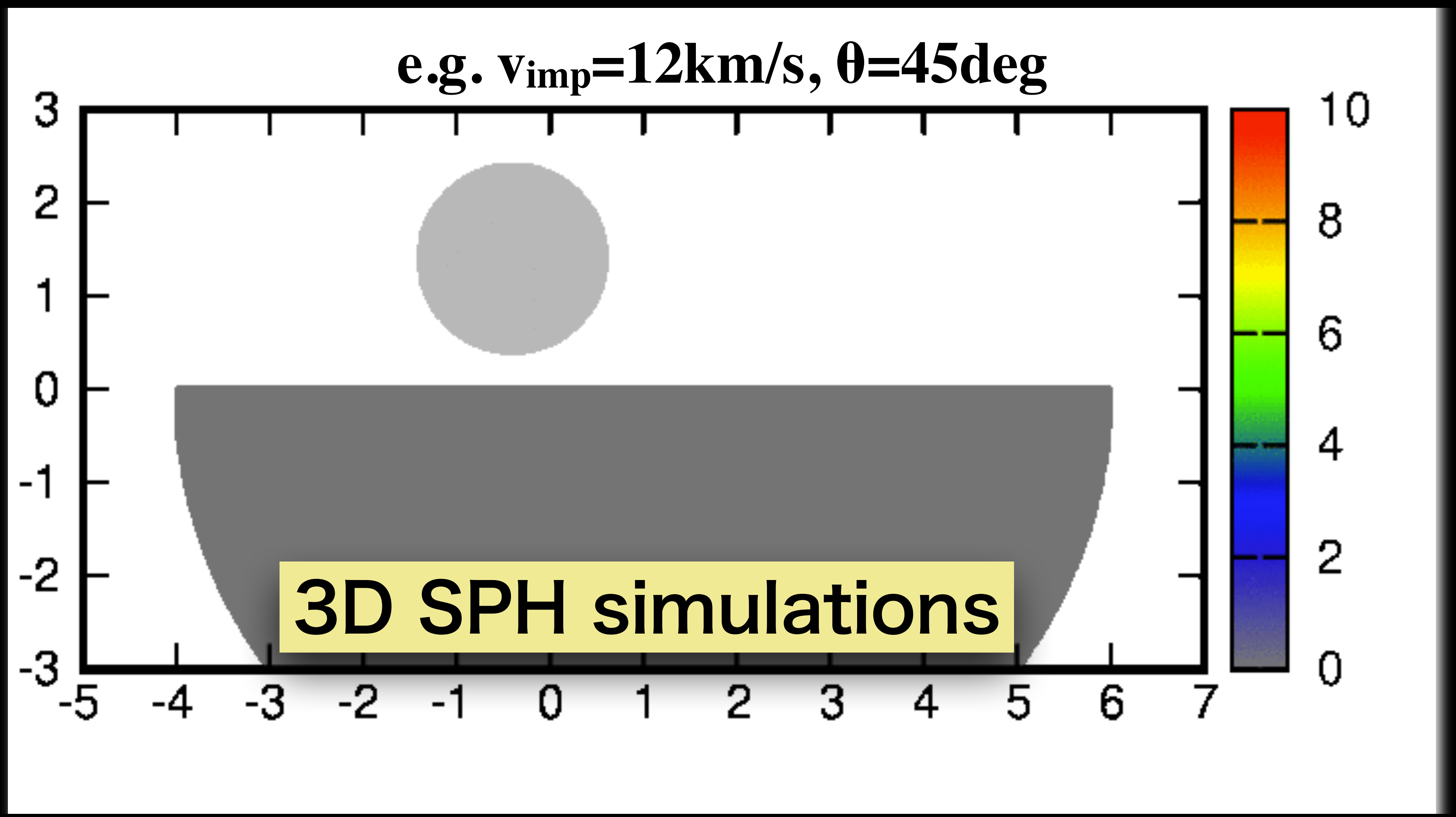
Something regardless of the origin

Ejecta from Mars to its moons



Chappaz et al. (2013)
Ramsley&Head (2013)

Re-evaluated —
Hyodo et al. (2019) SciRep



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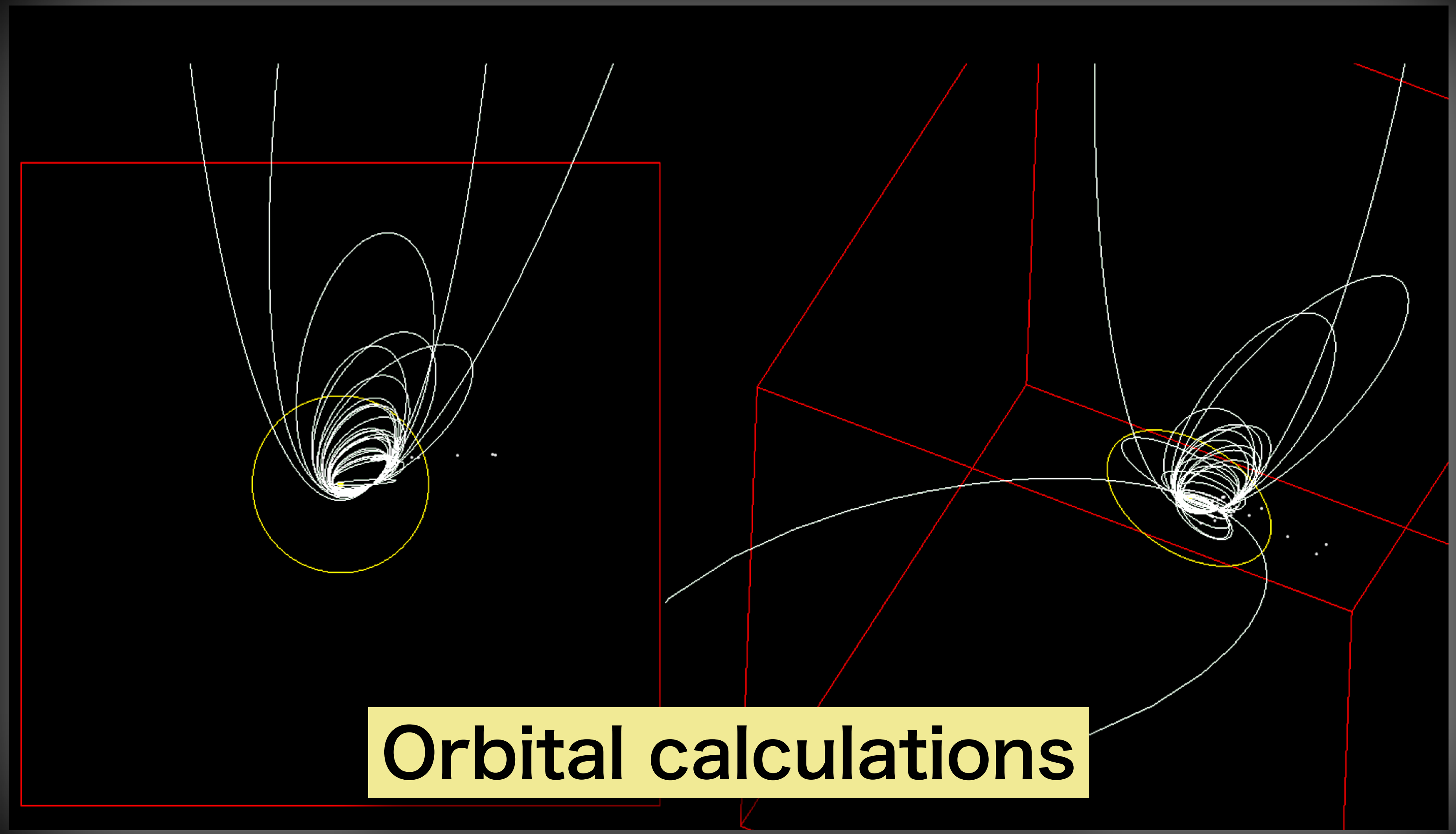
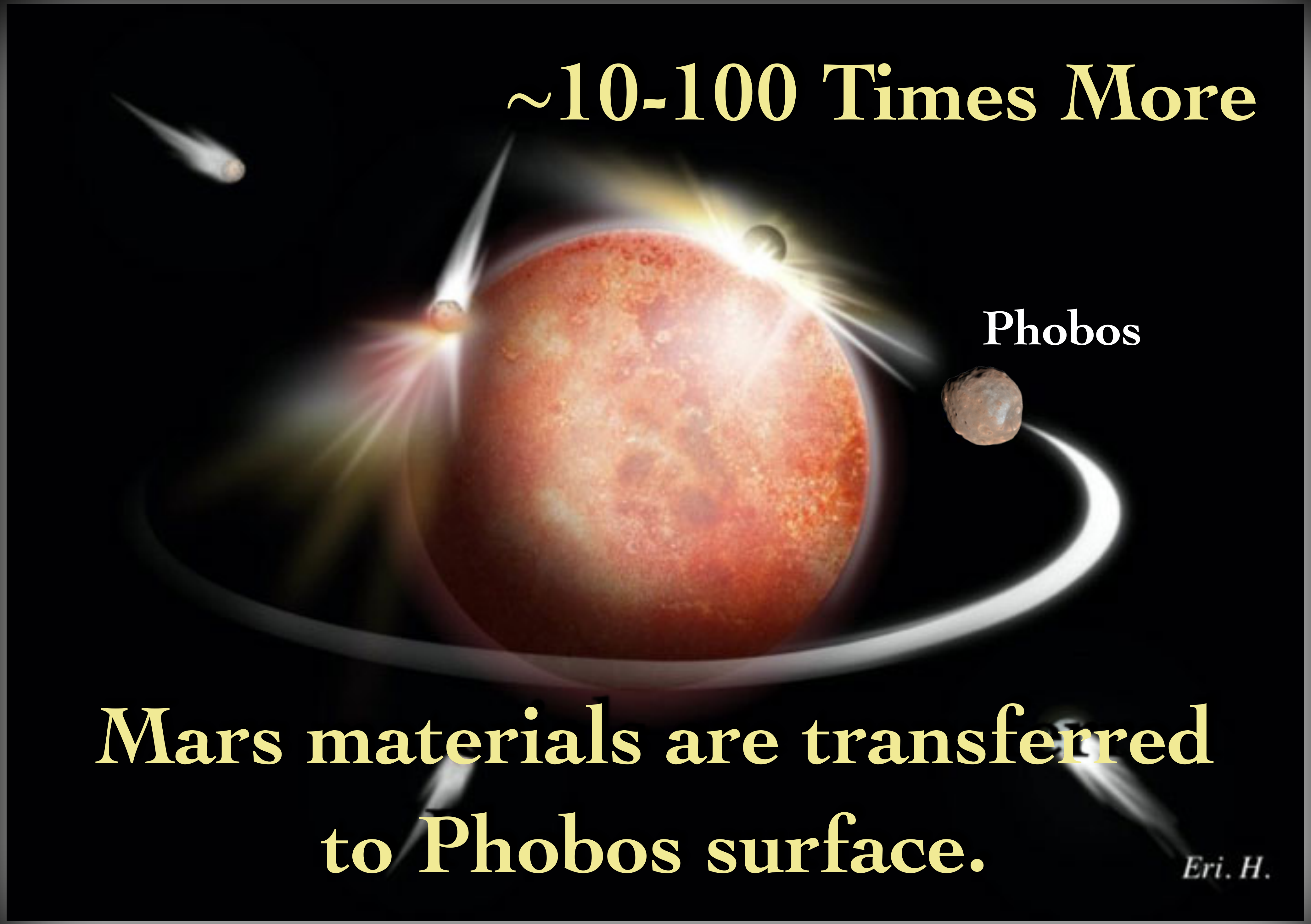
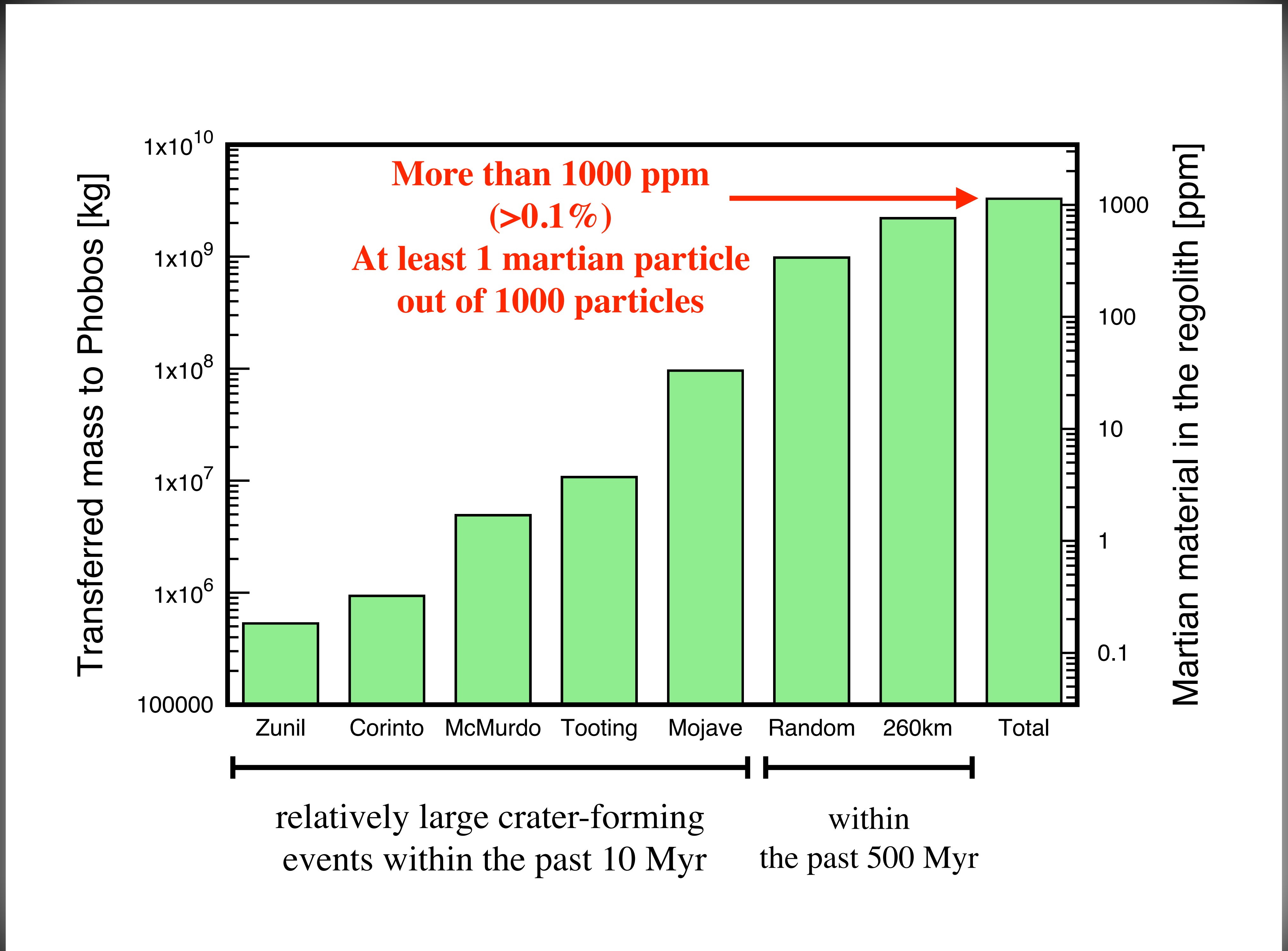


Significant Update From Previous Estimates

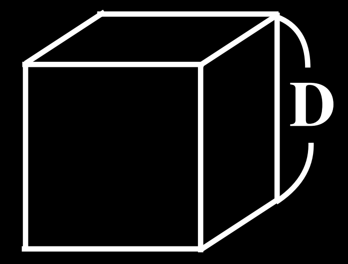




Hyodo et al. 2019, SciRep

MMX mission: ≳10 g samples

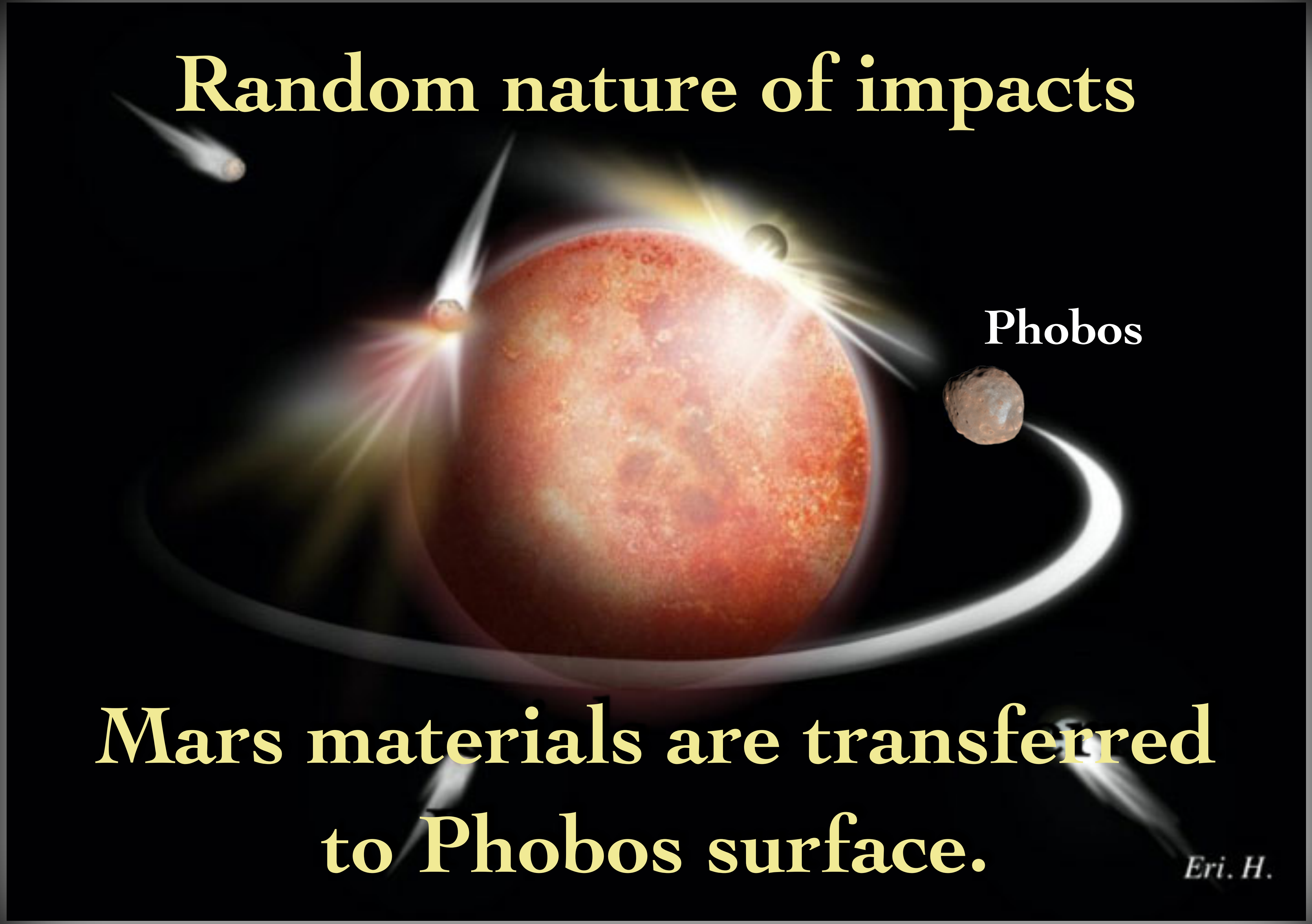
Cubic particle



$3\ g/cm^3$

D=300μm → ≳100,000 Total Particles → ≳100 Martian Particles

D=100μm → ≳3,000,000 Total Particles → ≳3,000 Martian Particles



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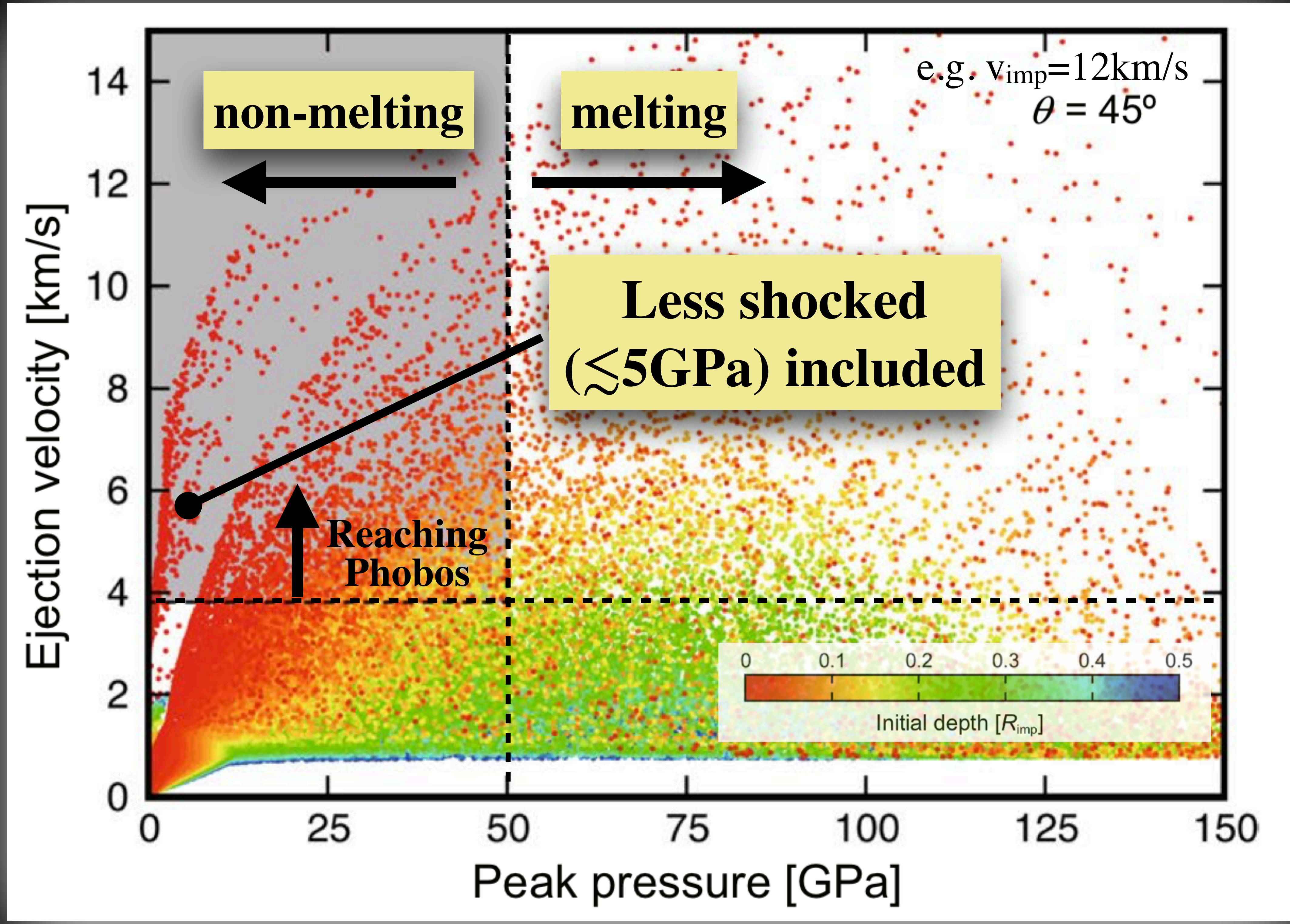


Hyodo et al. 2019, SciRep

cf. Martian meteorites:

- all igneous rocks
- mostly young (<1.3Ga)
- relatively shocked (≫5GPa)

Phobos Sample

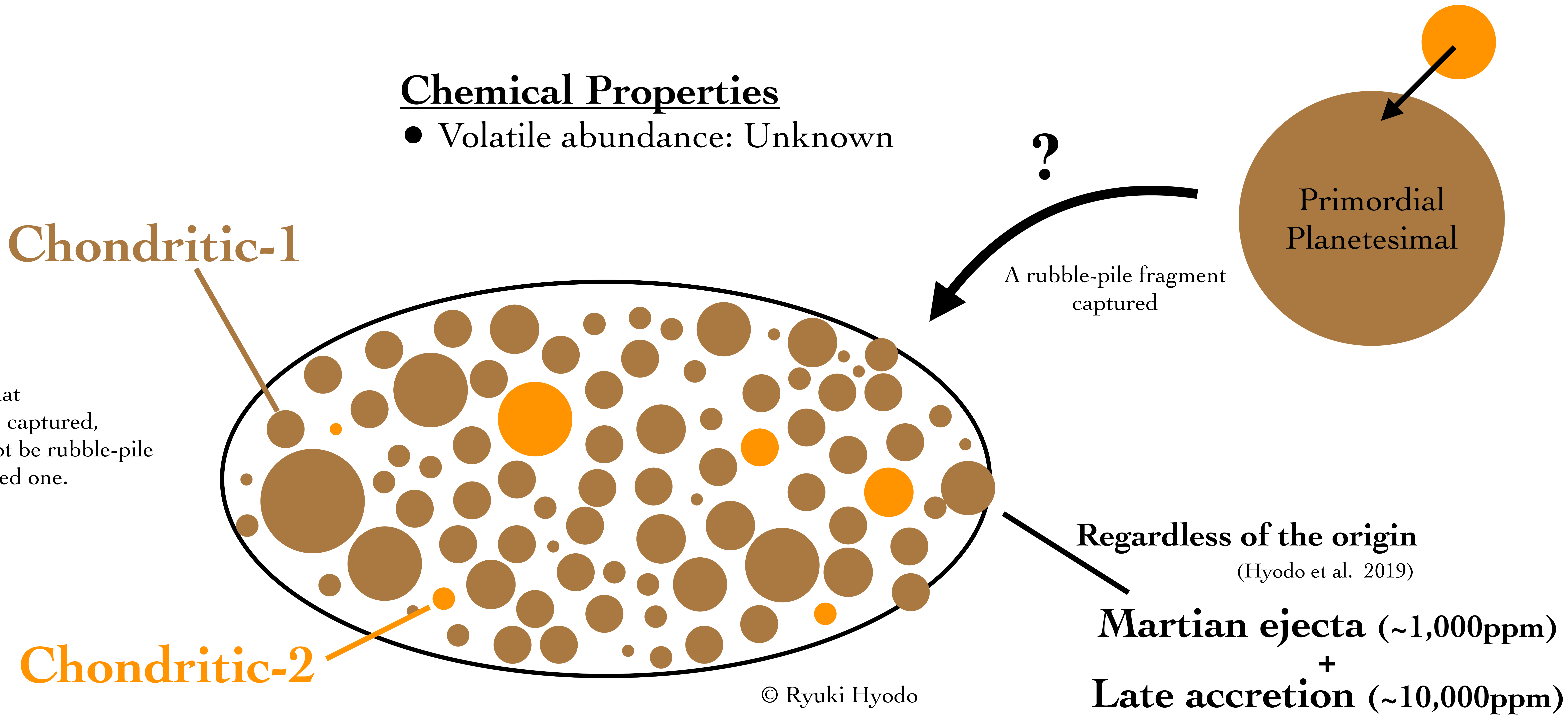
Potentially, covers *all* Martian geological eras &
consists of *all* types of rocks, from sedimentary to igneous

Expected Structures — Capture Origin

Bulk Composition
- A kind of chondritic material
- Possibly contain “two" different origins

Physical Properties
- Particle size: Unknown

Chemical Properties
- Volatile abundance: Unknown



*Please note that
if a primordial object is captured,
the internal structure may not be rubble-pile
but could be a layered one.

Expected Structures — Giant Impact

Bulk Composition (Hyodo et al. 2017ab)

- ~50wt.% Martian material
  - ↪ Ancient martian crust and mantle
- ~50wt.% impactor's material (as a result of giant impact on Mars)

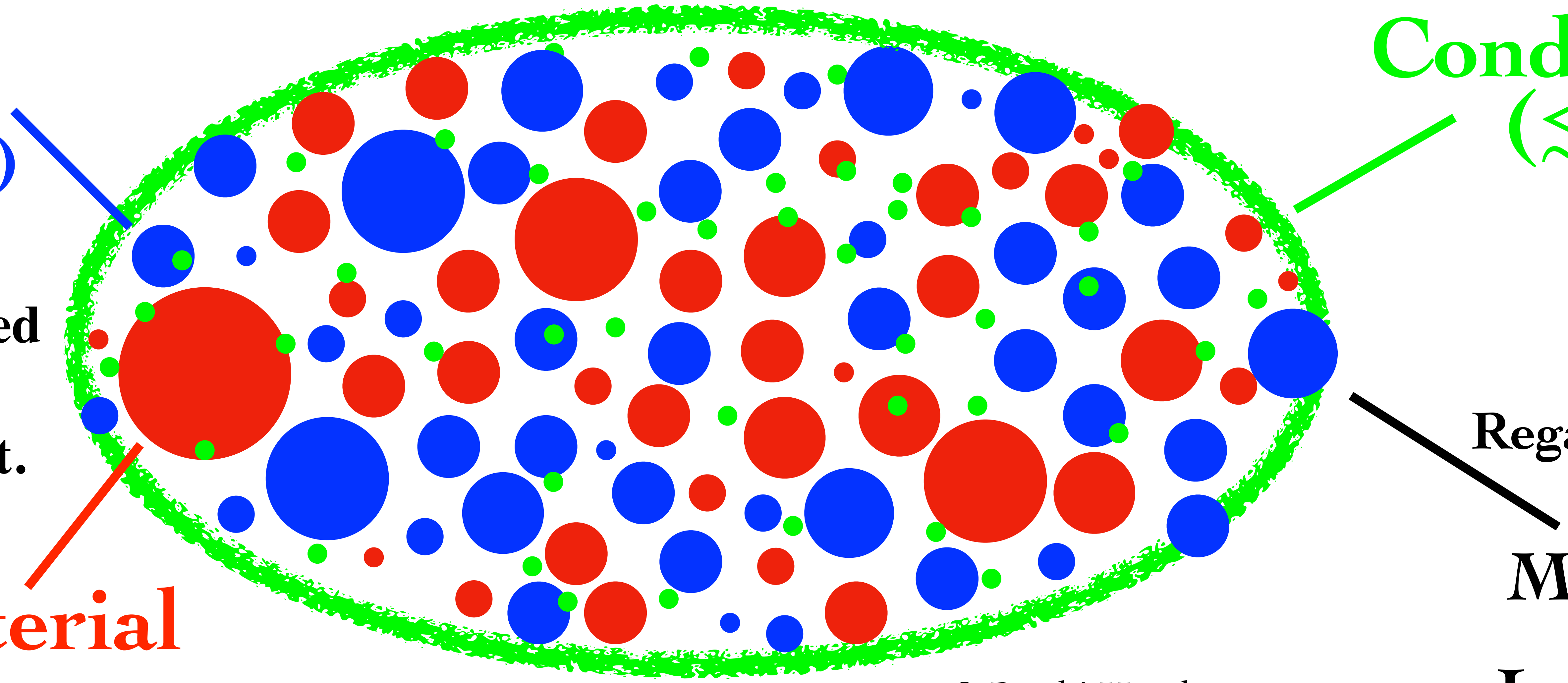
*In the case where a *late* destruction and re-accretion occurs — materials from *a late impactor* may be potentially mixed (as the *third* bulk material).

Physical Properties (Hyodo et al. 2017ab)

- Solidified melts: 100μm-10m
- Condensed dust: 0.1-1μm
  - ↪ featureless (Ronnet et al. 2016)

Chemistry of the Condensed Dust

- Chemistry strongly depends on the impactor (Pignatale et al. 2018)
  - ↪ A clue to understand the impactor
- Volatile element would be depleted (Hyodo et al. 2018b)



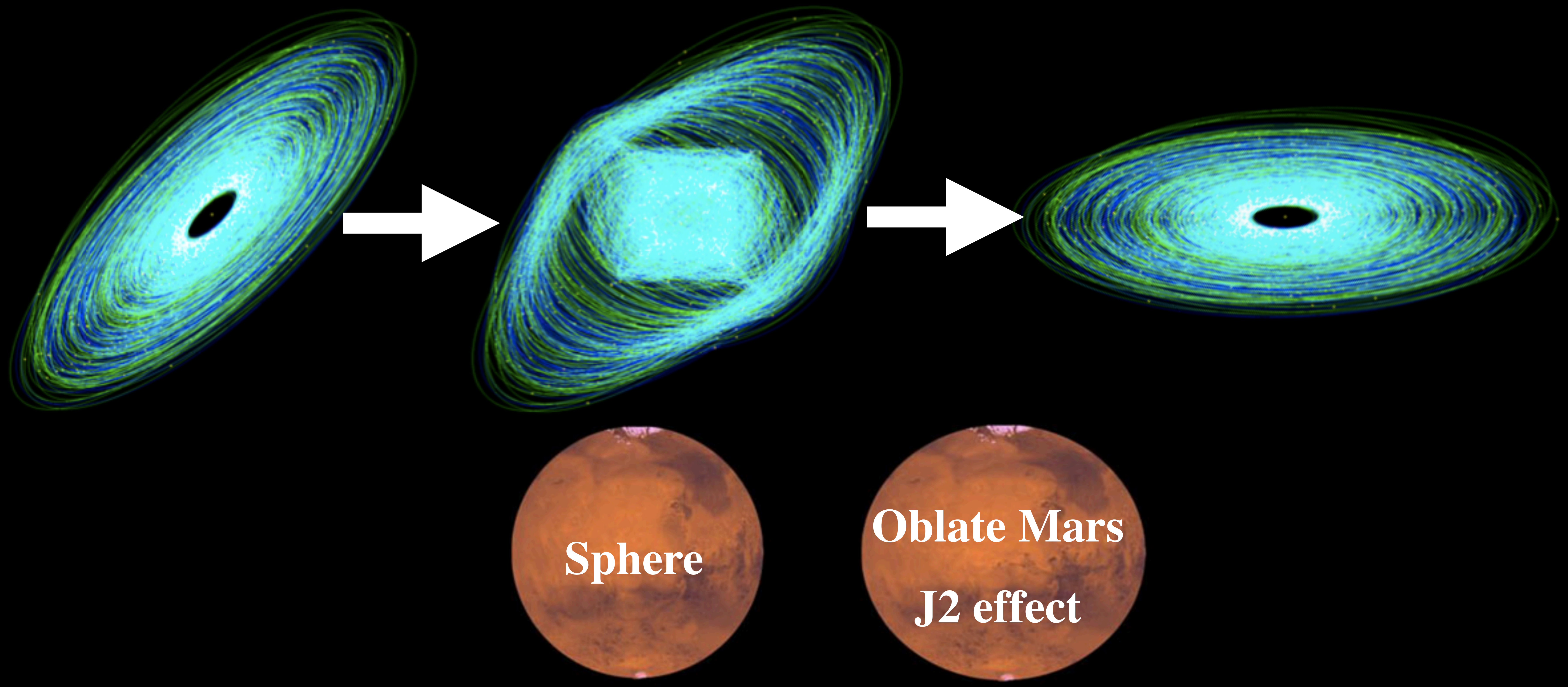
***Some of blue/red would be fully mixed before cooling/solidification. But, its fraction is not constrained yet.**

Regardless of the origin (Hyodo et al. 2019)

Martian ejecta (~1,000ppm)
+
Late accretion (~10,000ppm)

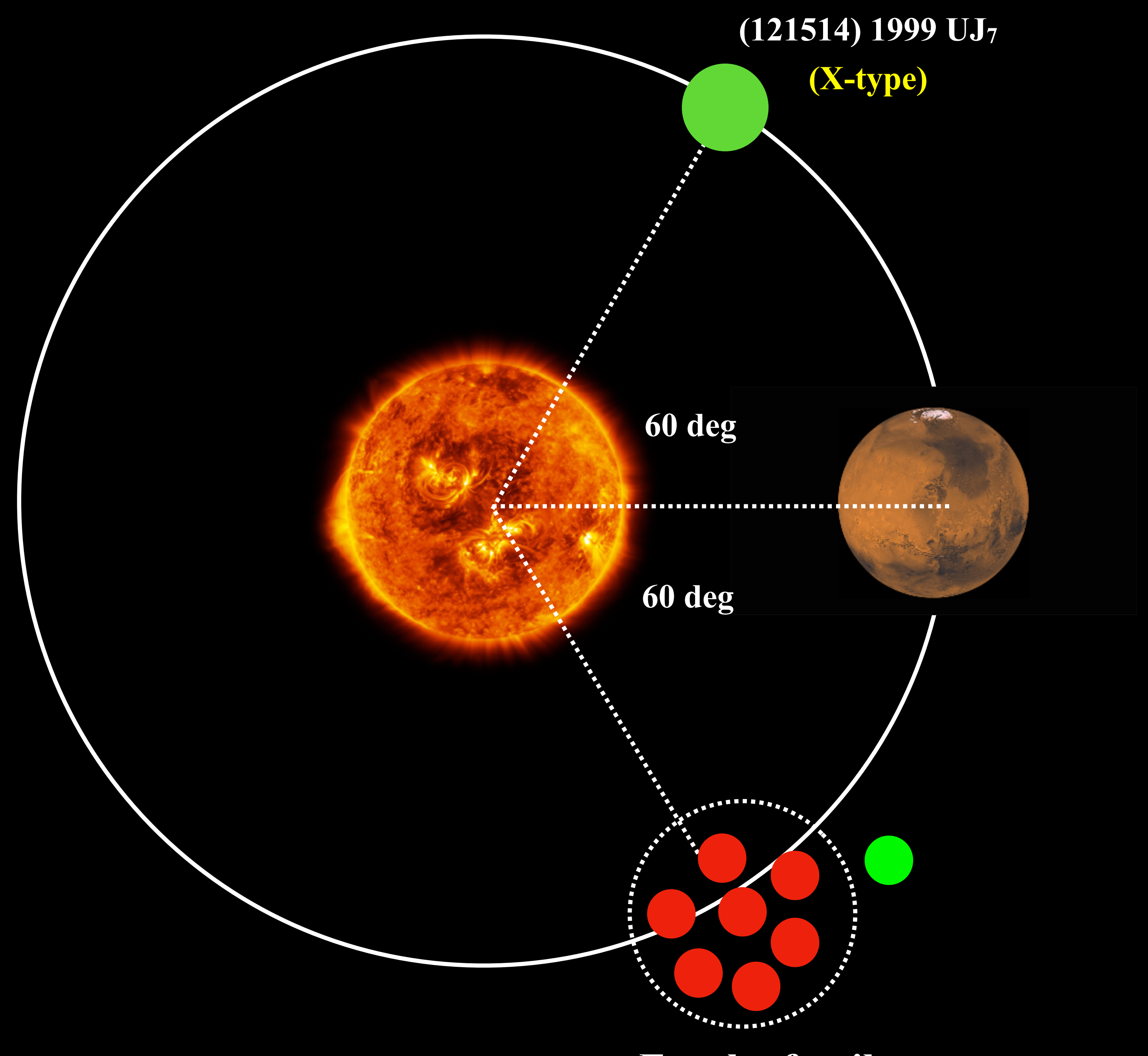
Even if the initial disk is *not* in the Martian equatorial plane

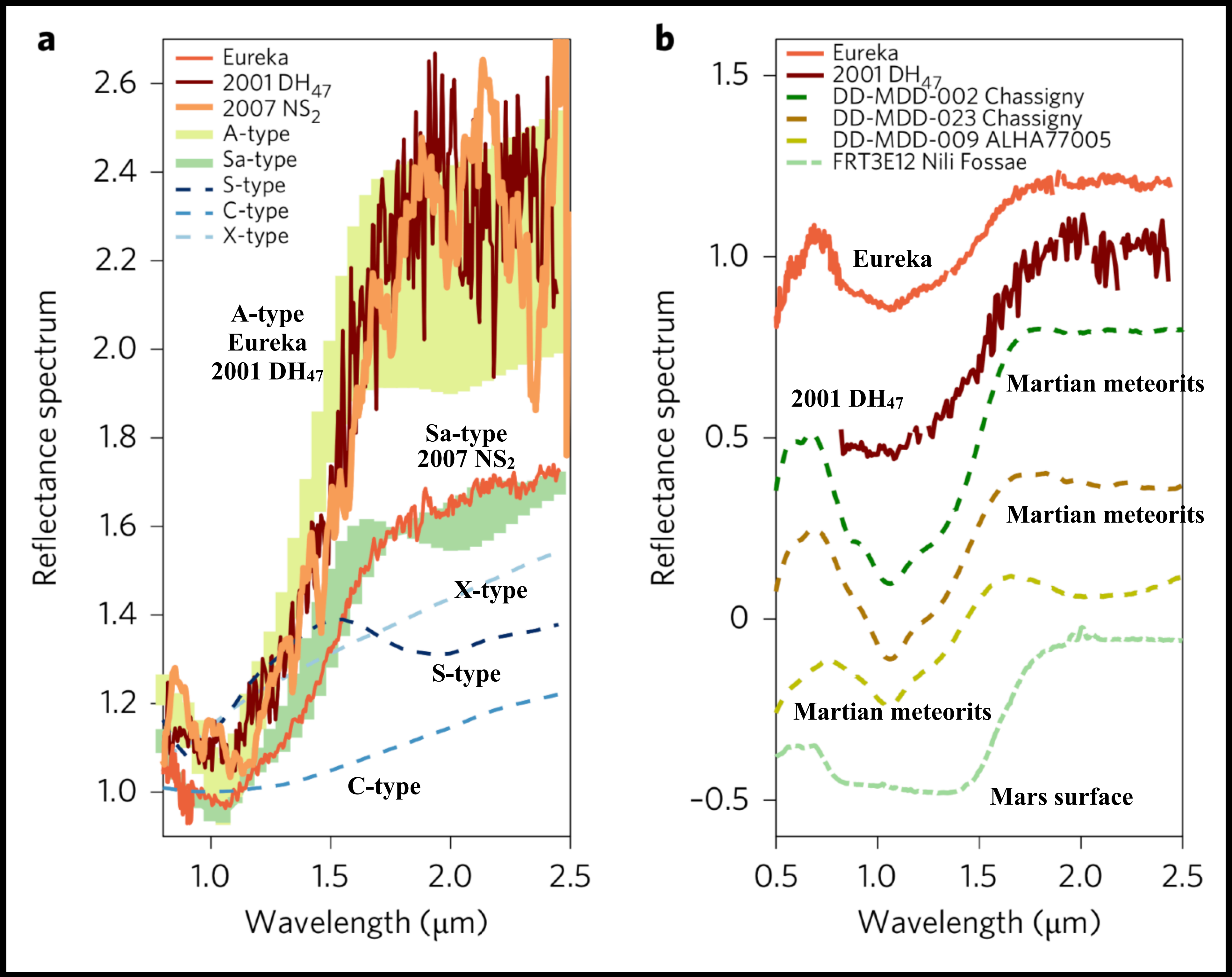
Hyodo et al. 2017b



Martian "Eureka" Trojan asteroids

- Seven out of known nine Mars Trojan Trojans — *Oivine-rich features*
- They form a family, called "Eureka family"





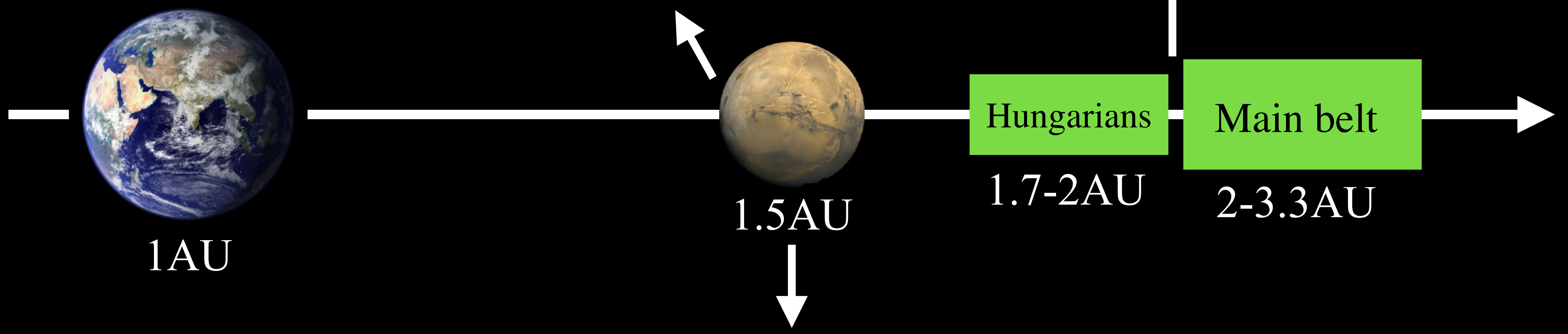
Polishook 2017 Nature Ast.

Any connection with a giant impact on Mars?

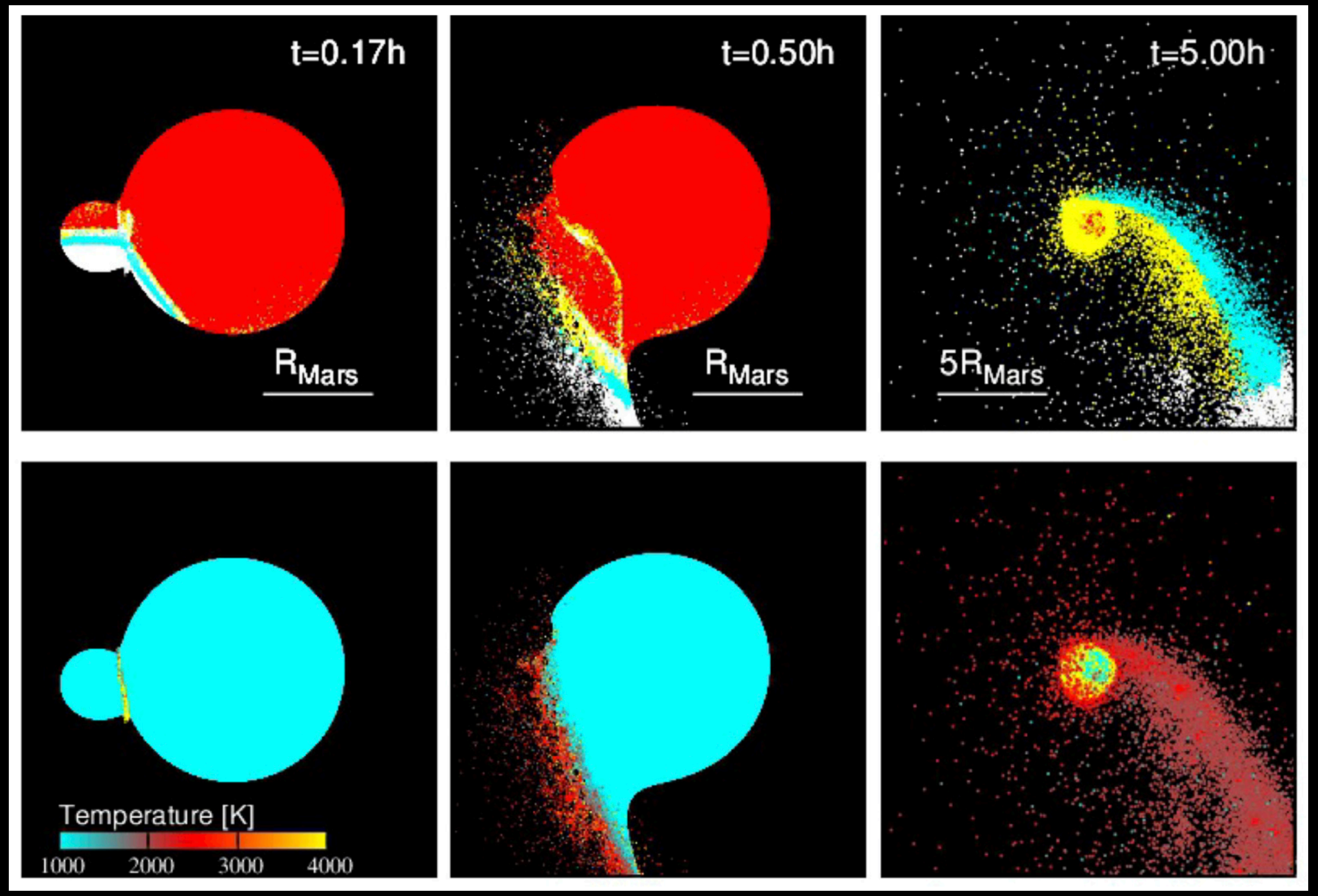
Martian meteorites
- Olivin-rich features are found in some Martian meteorites (e.g. Chassigny and Allan Hills: McSween 1985)

A-type asteroids
- Rare A-type asteroids are found in Hungaria and Main belt regions (e.g. DeMeo&Carry 2014)

Mars Trojan
- 7 of 9 Mars Trojan are olivine-rich (e.g. Polishook 2017)

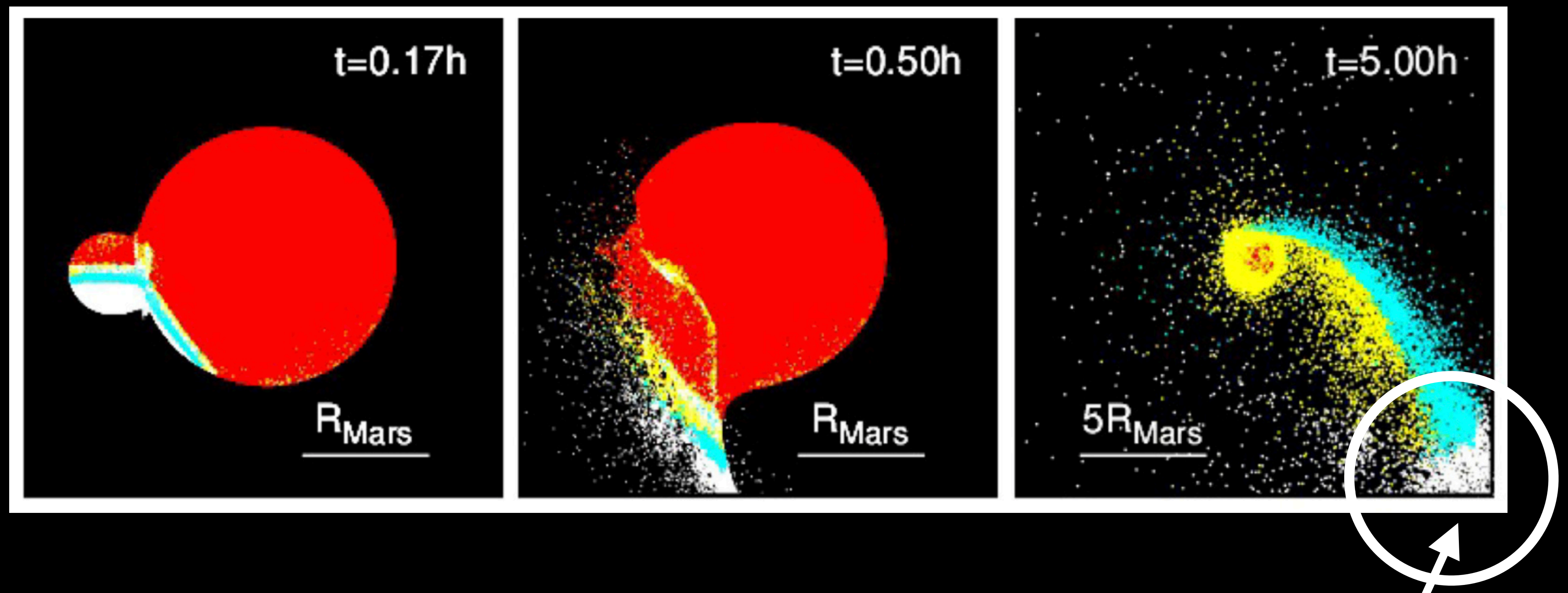


Martian material
- Olivine is a major mineral of the Martian upper mantle with ~60 wt% (Bertka & Fei 1997; Zuber 2001)
- At the surface of Martian grabens, such as Nili Fossae, an olivine-rich signature is detected (Hoefen et al. 2003; Mustard et al. 2009)

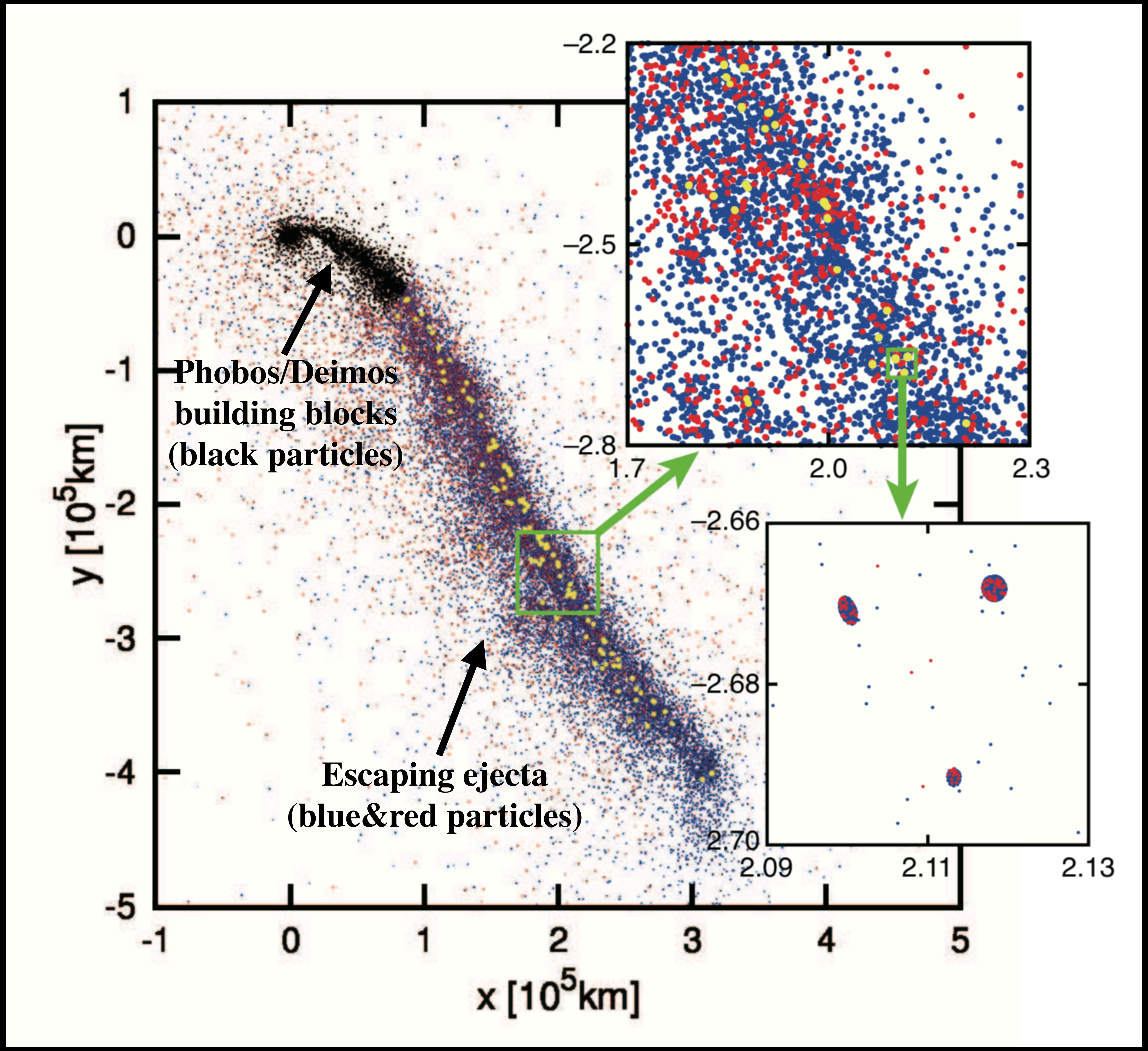


Hyodo et al. 2017b

A fraction of giant impact ejecta is distributed outside Mars gravitational field

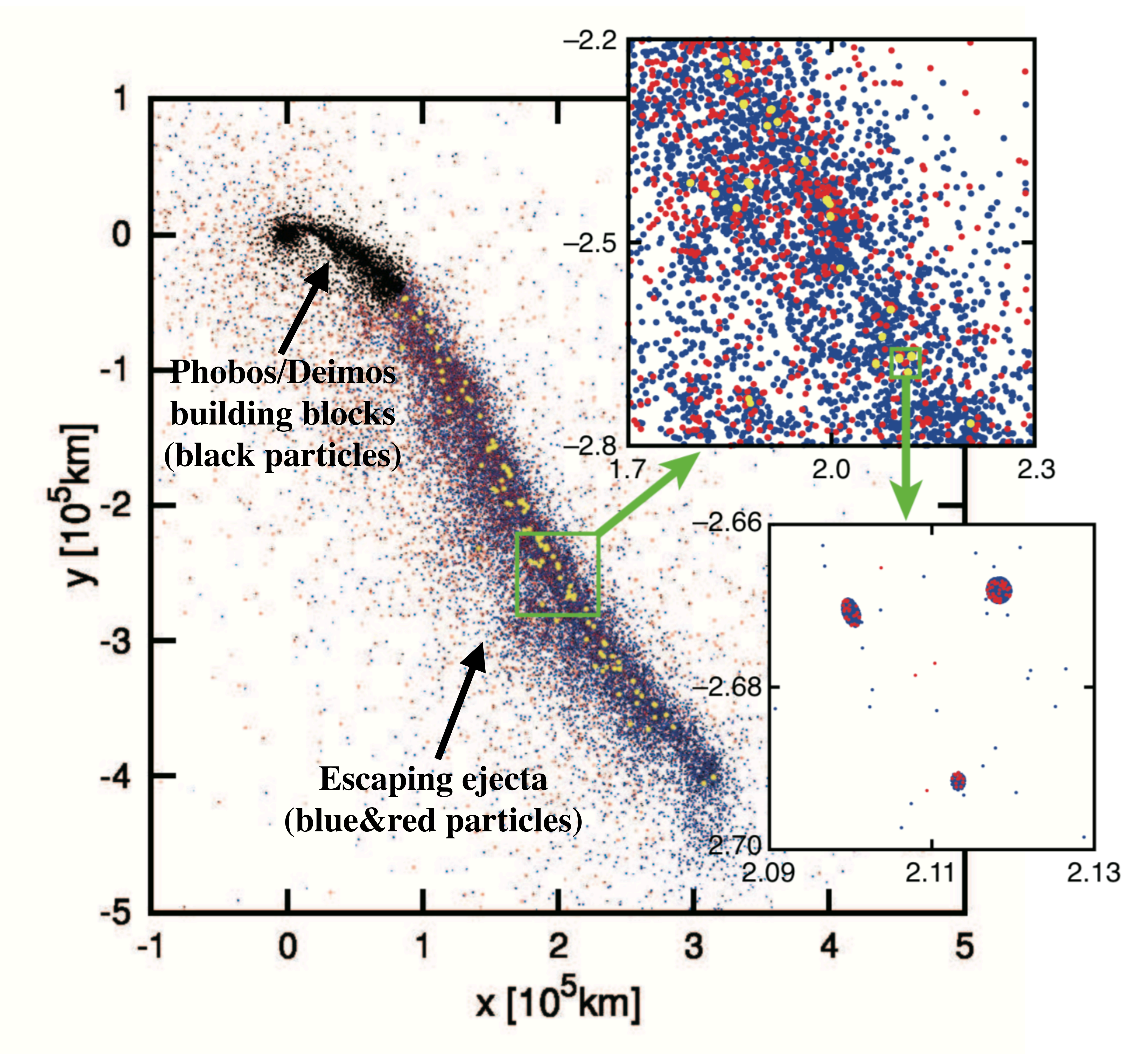


White particles:
escaping ejecta from the gravity of Mars

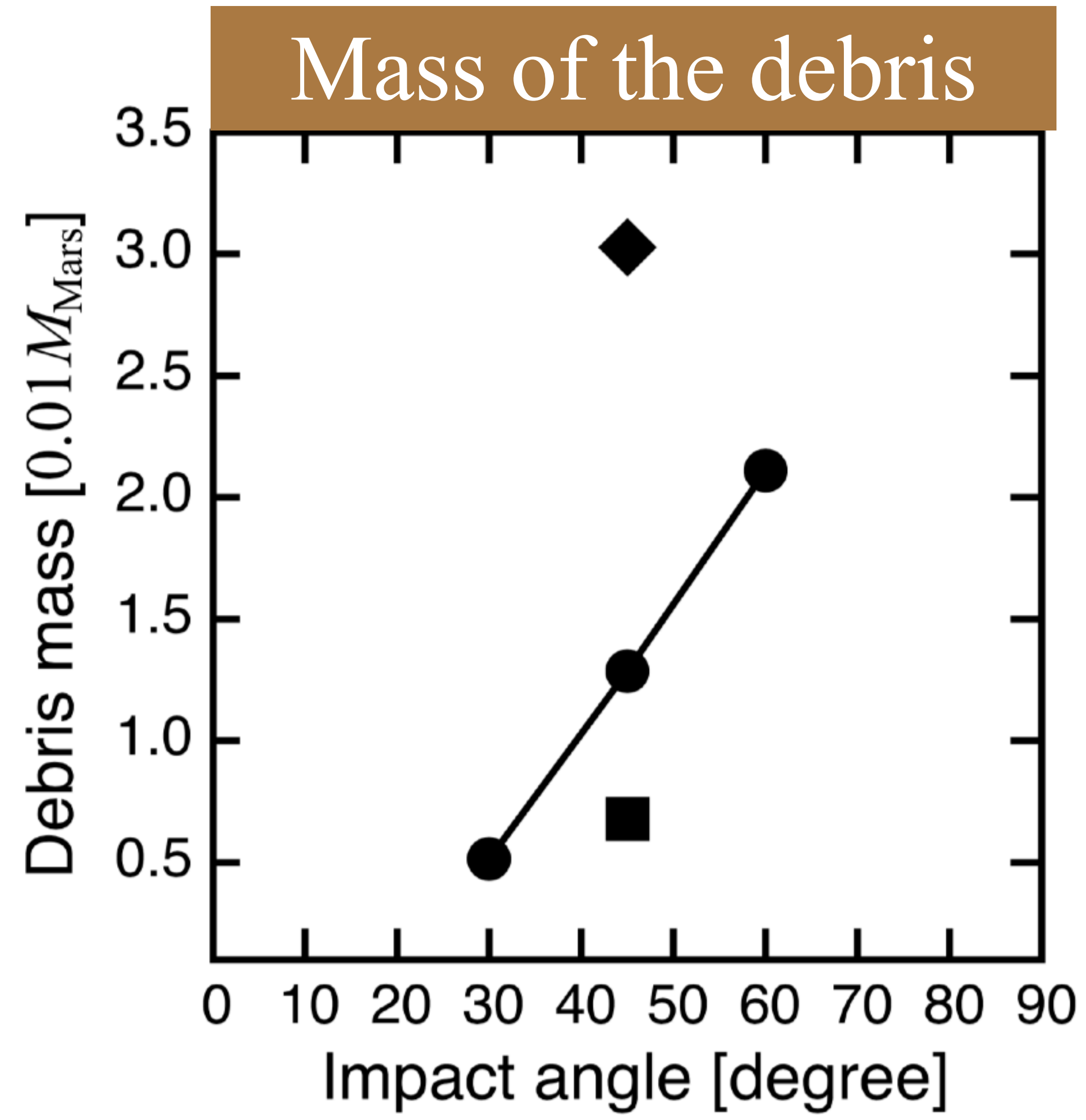


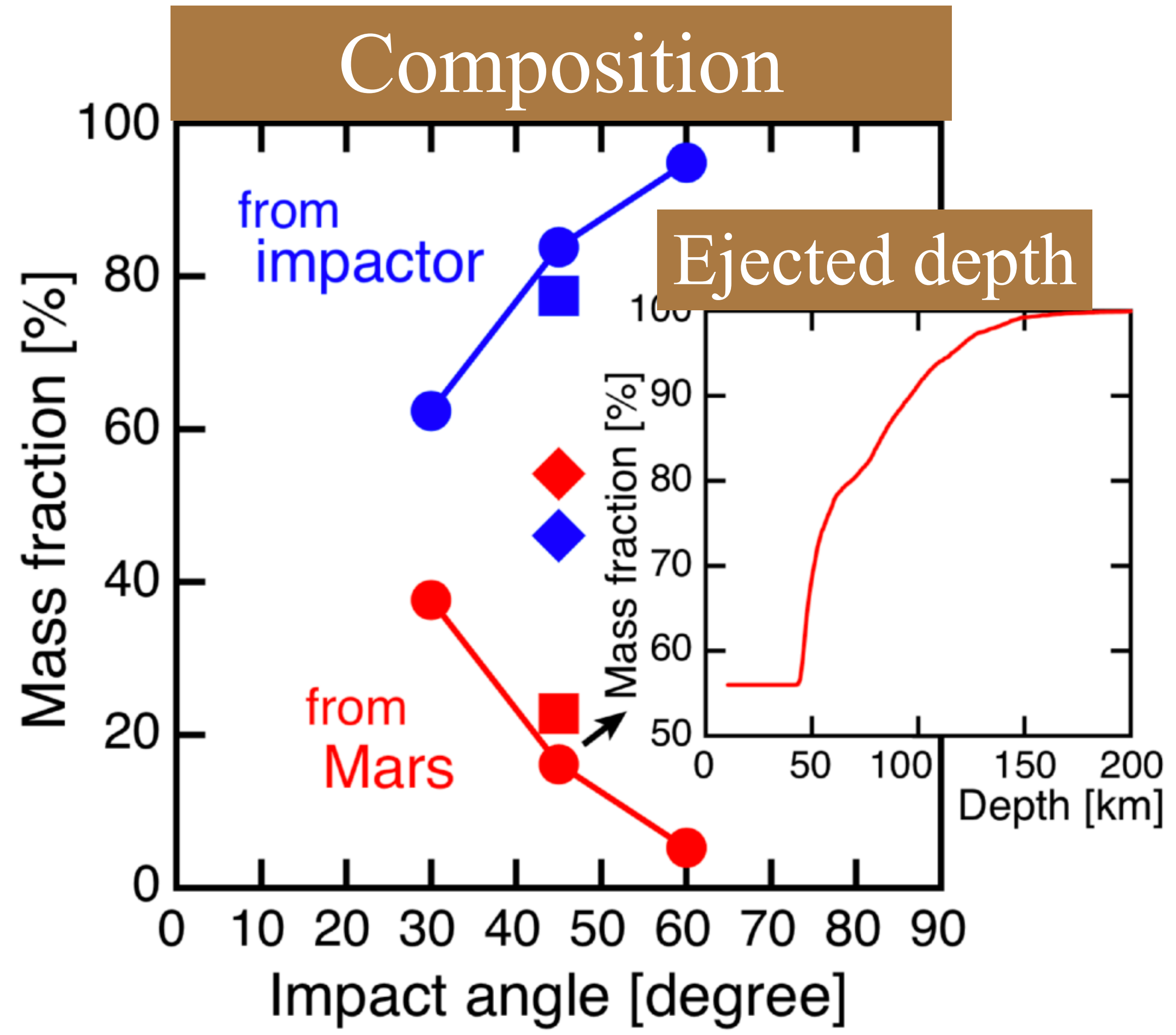
Hyodo, & Genda 2018, ApJL

Escaping ejecta can be the source of
(1) Mars Trojans
(2) A fraction of rare A-type asteroids



Composition of the escaping ejecta





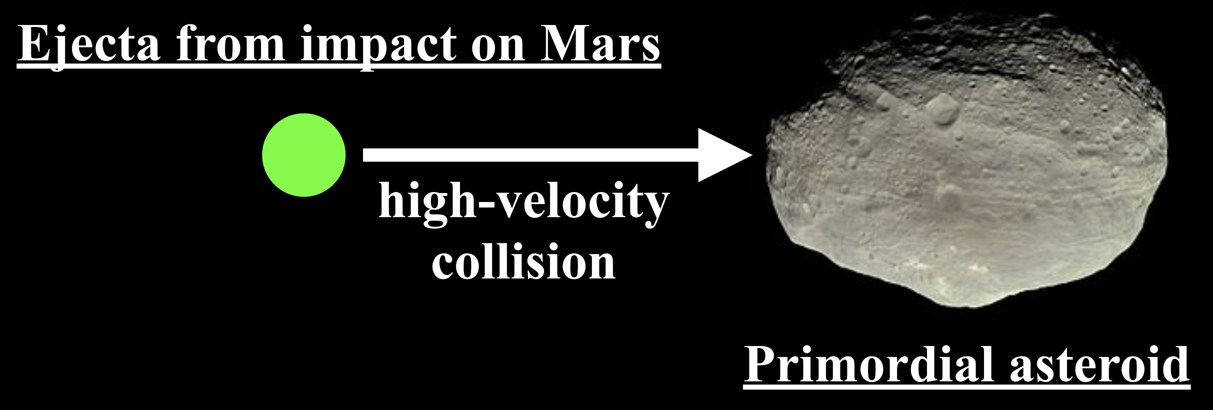
Results of the typical impact:

- **Total debris mass M_{debris} ~ 2% of M_{Mars}**
- **~20wt% of M_{debris} originates from Mars**
- **~50wt% of Mars-debris comes from Martian mantle (< 50km depth)**

Hyodo, & Genda 2018, ApJL

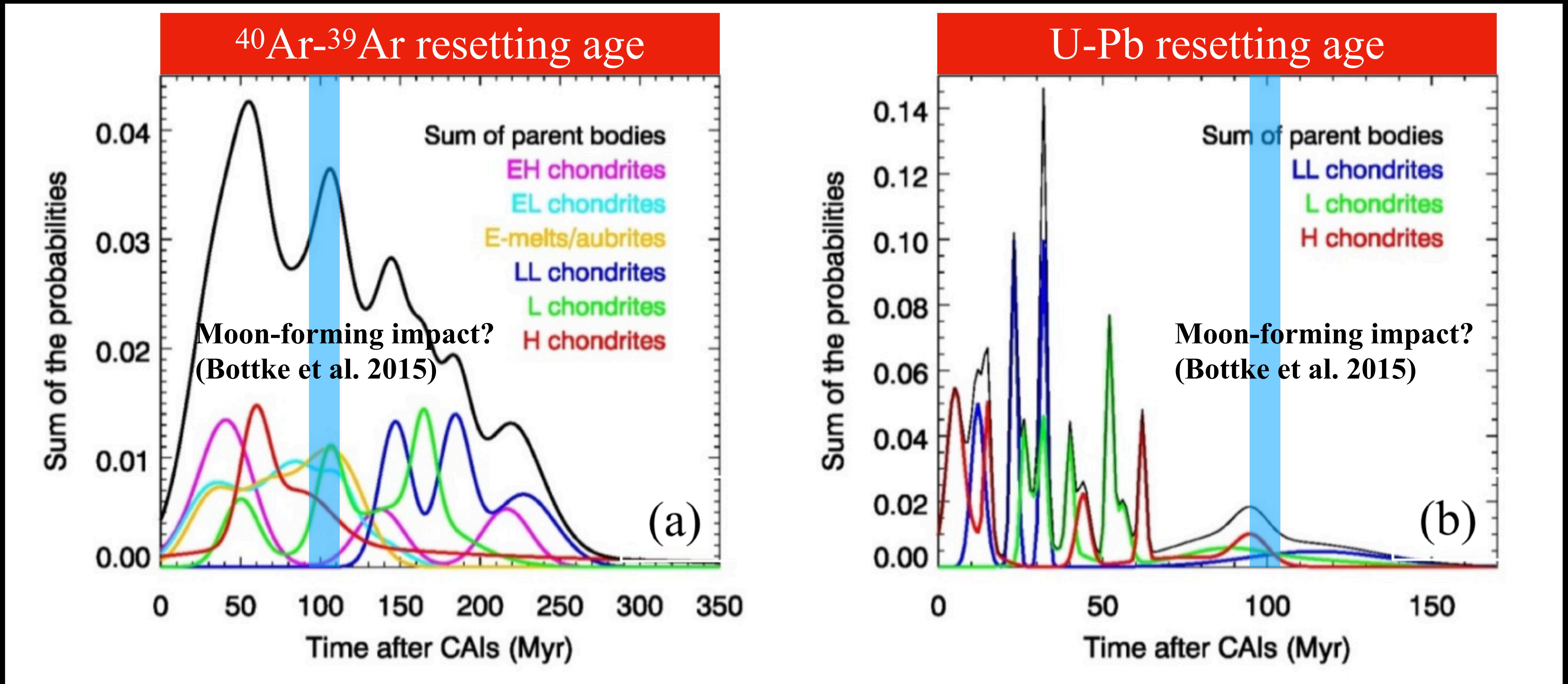
Mars' giant impact is recorded in meteorites?

Hyodo & Genda 2018, ApJL



High-velocity collisions btw asteroids and the ejecta

- Produce ^{40}Ar-^{39}Ar age resetting ?
- Produce U-Pb age resetting ?
- Produce impact melts ?
- etc ?



see also Bottke et al. 2015, Science
for the case of the Moon-forming giant impact

A single event can explain many?

The same single giant impact on Mars can potentially explain:

- produce the Borealis basin
- produce Phobos and Deimos
- produce Mars Trojans and a fraction of the rare A-type asteroids
- record the signatures of high-velocity impacts in meteorites
- deliver ancient Martian material to the Earth and Moon