火星衛星フォボスとデイモスの起源と進化の現状理解

Ryuki Hyodo (ELSI, Tokyo Tech),

Thanks to S. Charnoz (IPGP), H. Genda (ELSI, Tokyo-Tech),
K. Kurosawa (Chiba Institut.), T. Nakamura (Tohoku Uni.)
and
MMX science team

Related papers:

Rosenblatt, Charnoz, … Hyodo, … (2016), *Nature Geo.*
Hyodo et al. (2017a), *ApJ*
Hyodo et al. (2017b), *ApJ*
Pignatale, Charnoz, … Hyodo, … (2018), *ApJ*
Hyodo & Genda (2018), *ApJL*
Hyodo et al. (2018), *ApJ*
Hyodo et al. (2018) in prep, *Astrobiology*

本日の内容

1. Dynamical origin and evolution of Martian moons

2. Physical & chemical properties of Martian moons

3. Recent delivery of Martian material to Martian moons

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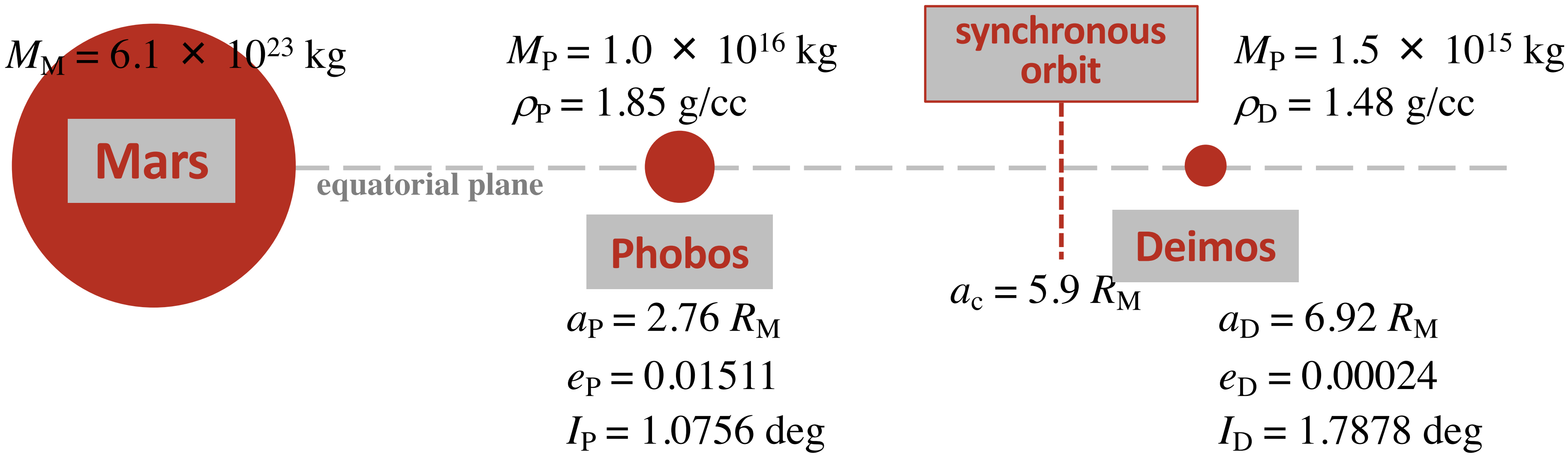
Dynamical origin and evolution of Martian moons

Phobos and Deimos



- **Orbits:** very circular ($e \sim 0$) and parallel to the Mars' equatorial plane ($I \sim 0$).

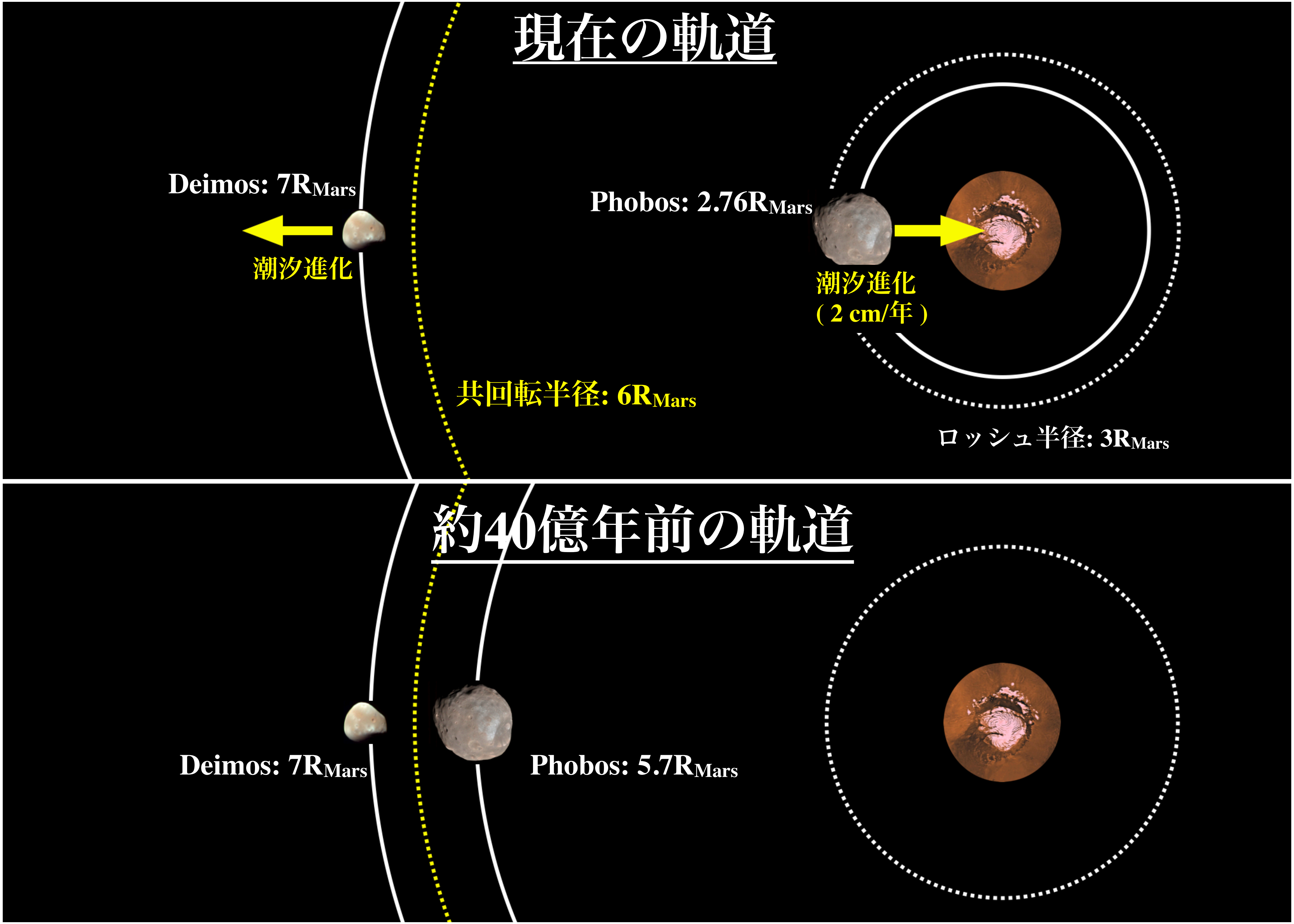
  e.g., Rosenblatt (2011) A&A Rev.

- **Tide:** Deimos is migrating outward because of tidal interaction with Mars
  Phobos is migrating inward, and will break apart or hit on Mars in 30 Mrys.

  Black & Mittal (2015) Nature Geo.

- **Spectra:** featureless & very dark (similar to D-type asteroids)

  e.g., Murchie (1999) JGR

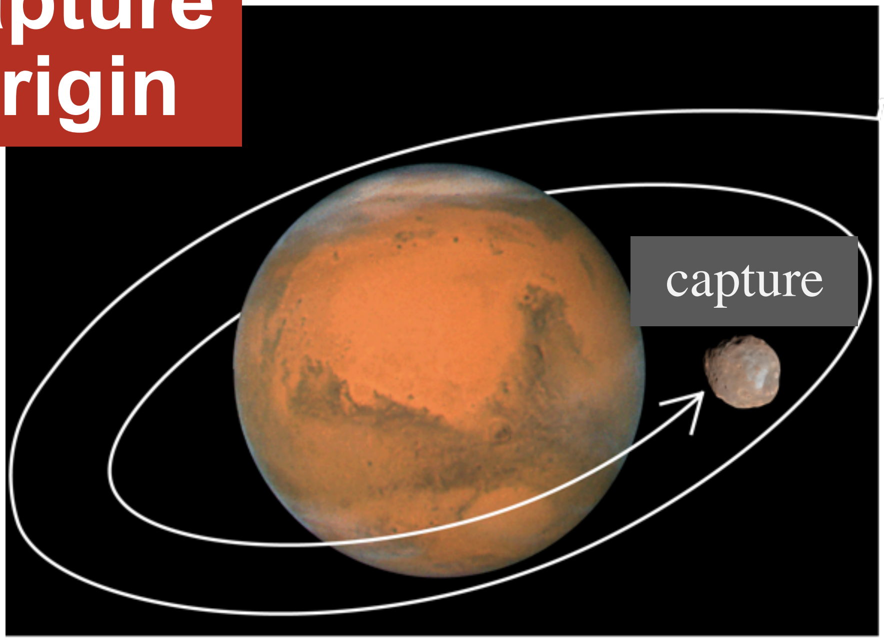


現在の軌道
Deimos: 7RMars
潮汐進化
Phobos: 2.76RMars
潮汐進化
(2 cm/年)
共回転半径: 6RMars
ロッシュ半径: 3RMars
約40億年前の軌道
Deimos: 7RMars
Phobos: 5.7RMars

Two Leading Hypothesis

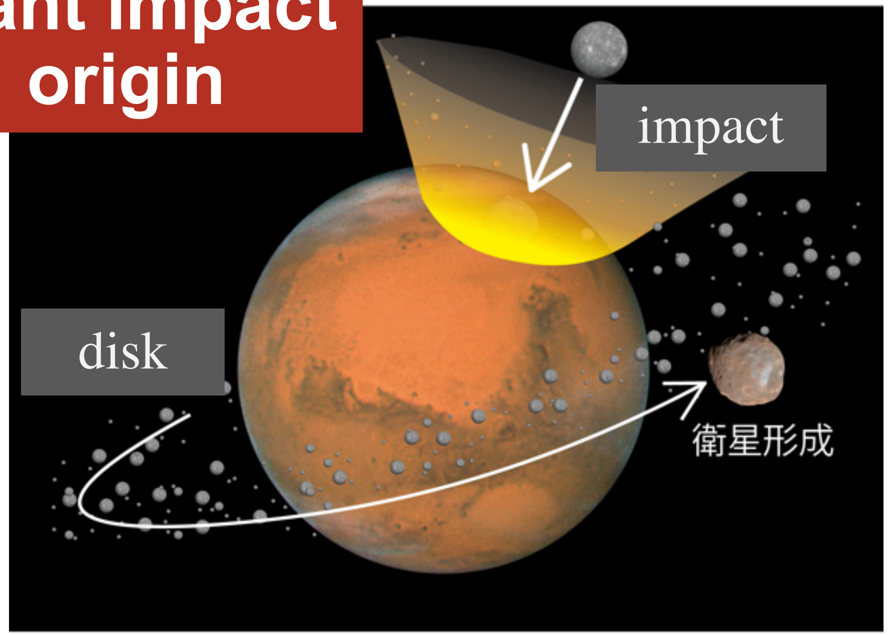
MMX is a JAXA's sample return mission to Martian moons
Primary goal of *MMX* mission is to solve moons' origin

capture origin



supported by spectral features

giant impact origin



supported by orbital elements

Dark & Featureless: D-tyep?

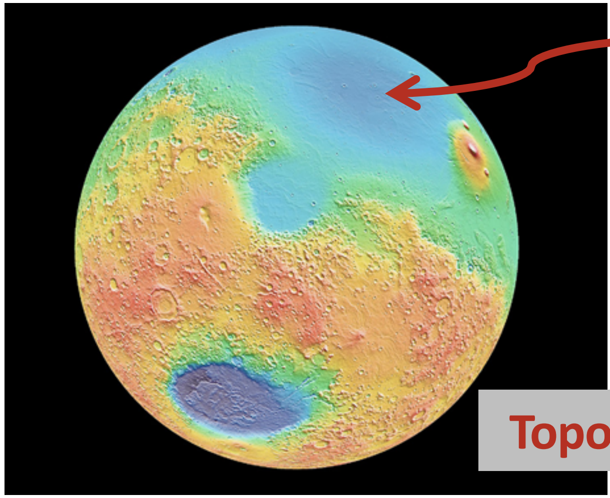
Circular & Equatorial

->This talk

Impact Origin?

Giant impact hypothesis for Moon

- If this happens on Mars, satellites with $e \sim 0$ and $I \sim 0$ may be naturally formed.
- Phobos and Deimos are small.
  → small impactor is sufficient

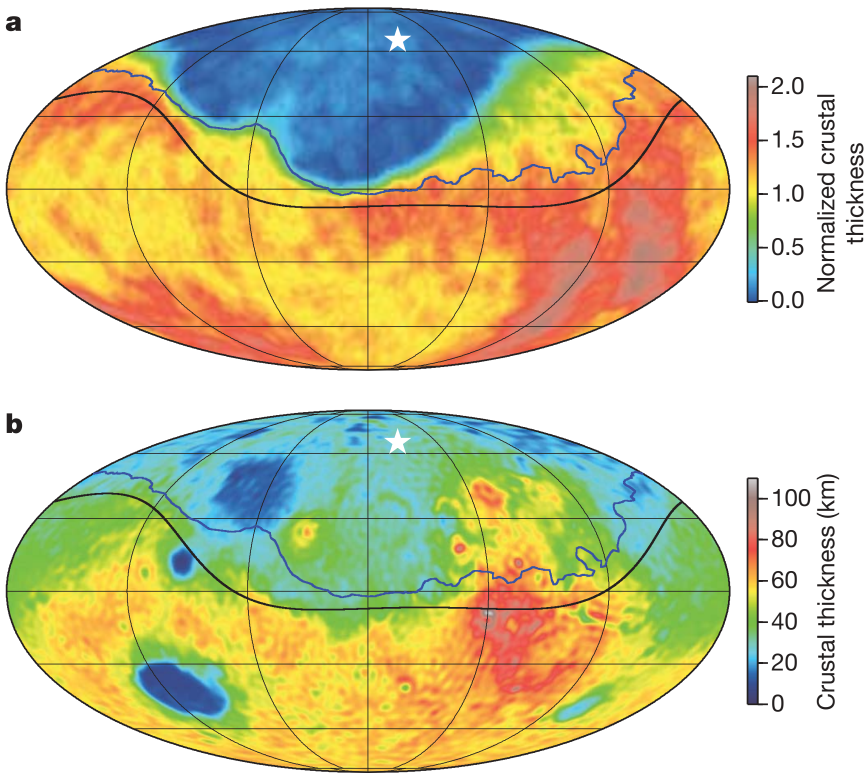


Topography of Mars

Craddock (2011) proposed the impact which made northern lowlands on Mars (Borealis basin) may create Martian moons.

Marinova et al. (2008) showed
the impact condition to form the Borealis basin
-> we use the same impact conditions to form Martian moons

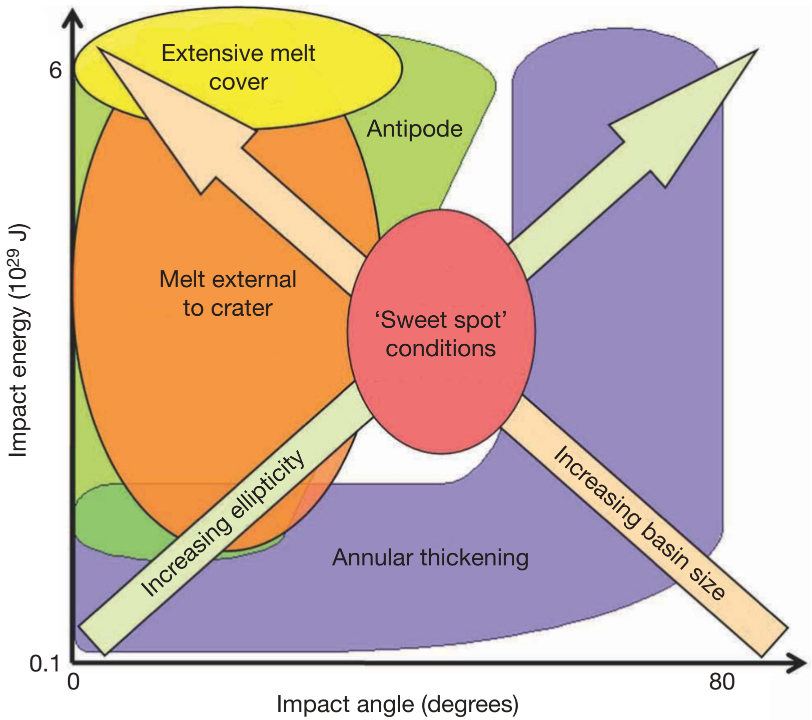
Borealis Basin-forming Impact



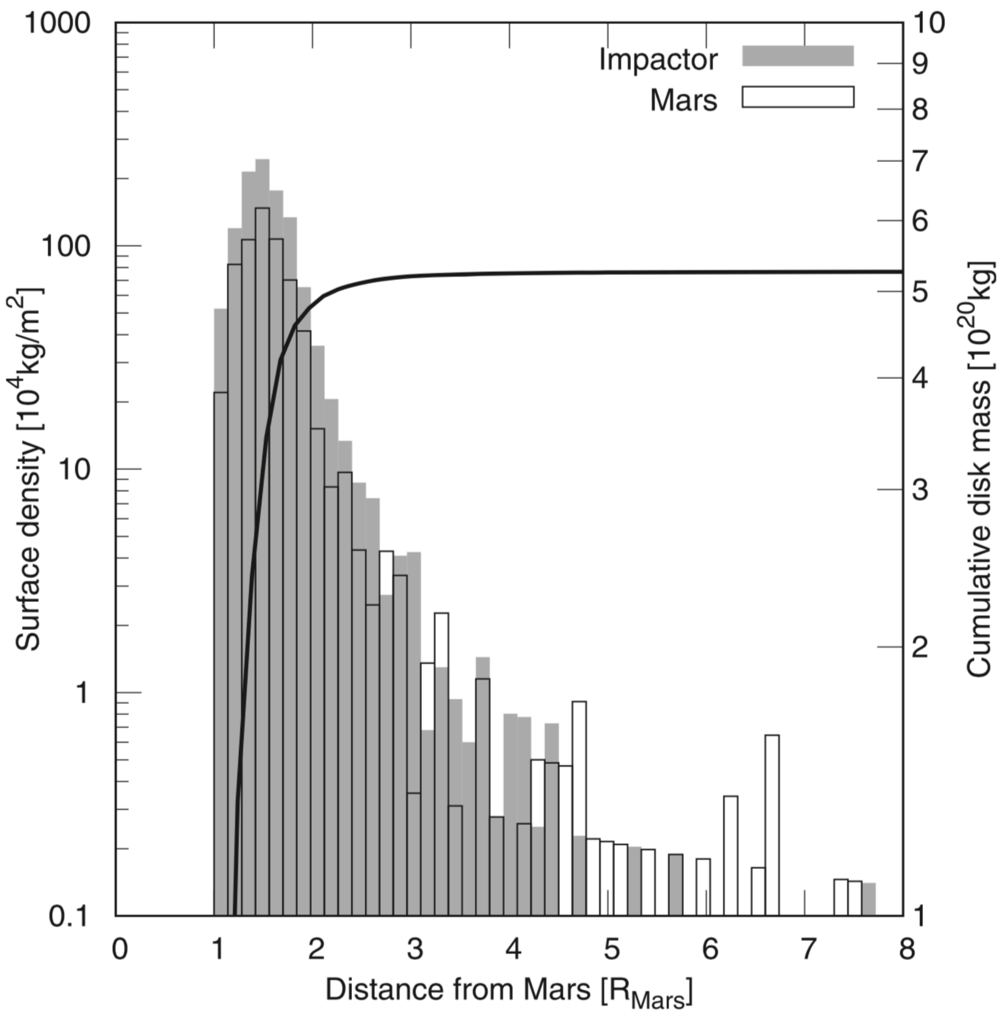
Marinova et al. (2008) Nature

Sweet Spot

Impactor mass : 3% of M_{Mars}
Impact velocity : ~ 6 km/s
Impact angle: ~ 45 deg



Inner Massive and Outer Light Disk



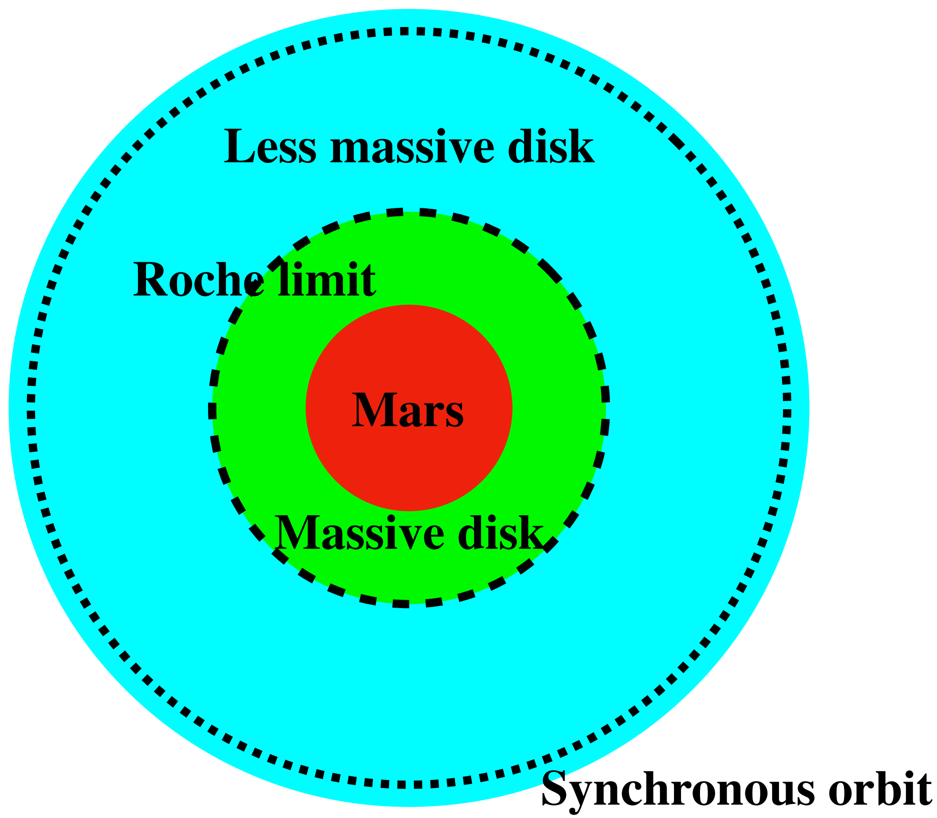
Hyodo, et al. (2017) ApJ

Impact simulation (SPH method)

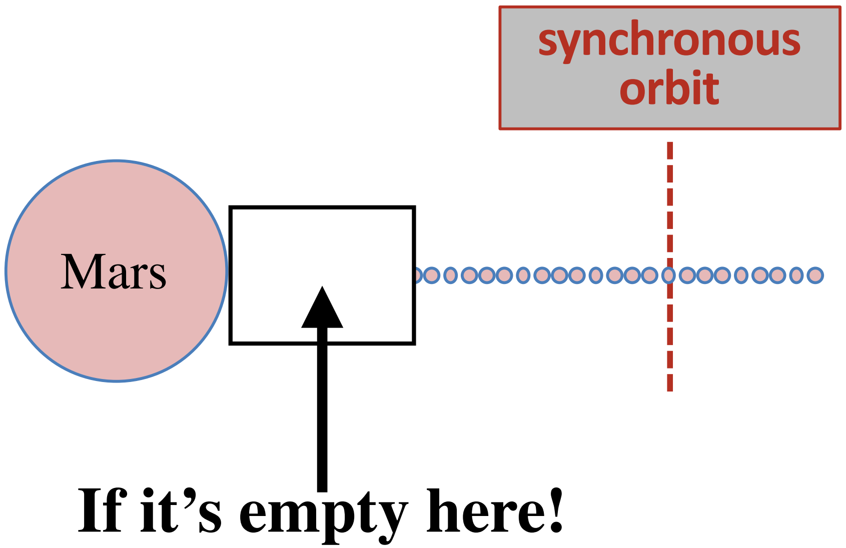
Smoothed Particle Hydrodynamics

Formed disk is relatively massive.

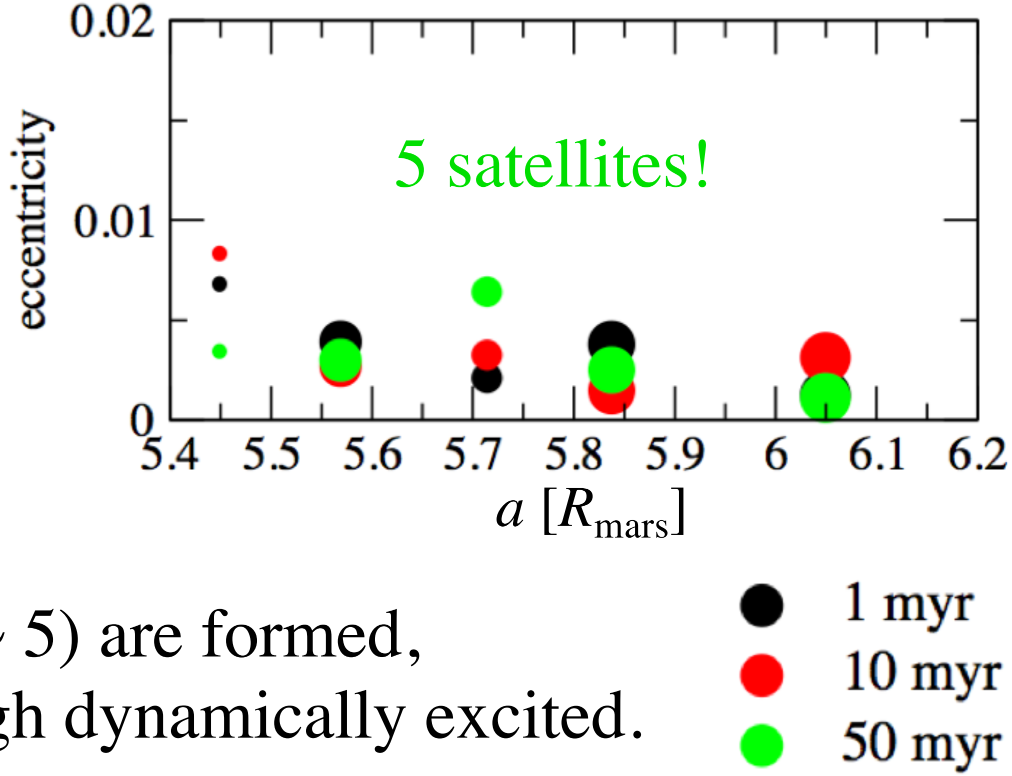
~ 10^{20} kg : 10,000 × Phobos



Accretion in Outer Light Disk



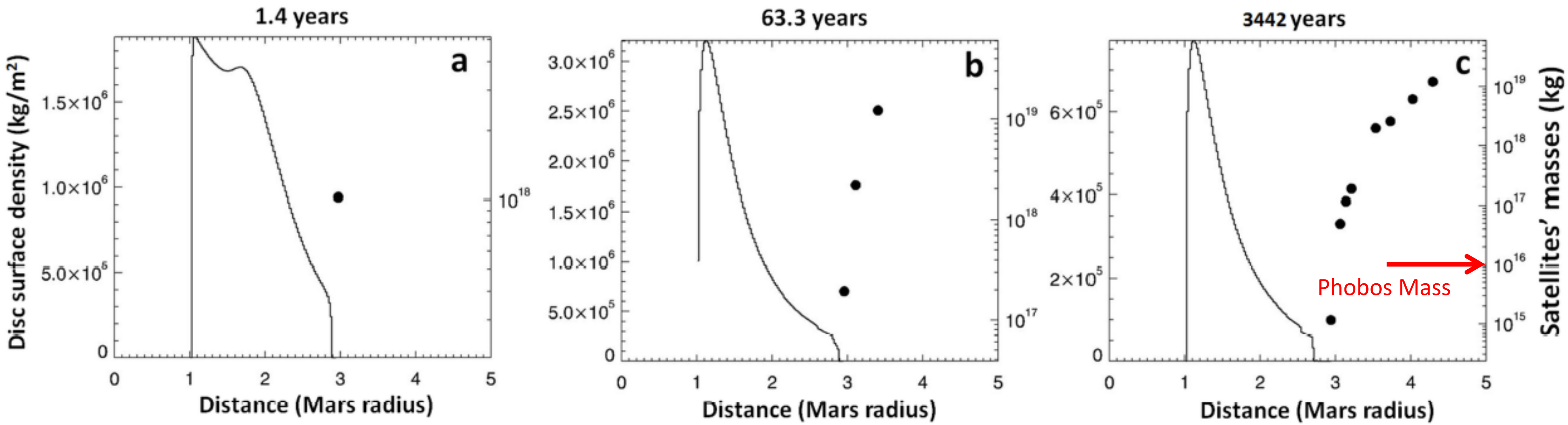
An example result of N-body simulation



✔ More than 2 satellites (typically ~ 5) are formed, because the system is NOT enough dynamically excited.

We need a trick which can enhance or force the accretion of satellites in the outer disk.

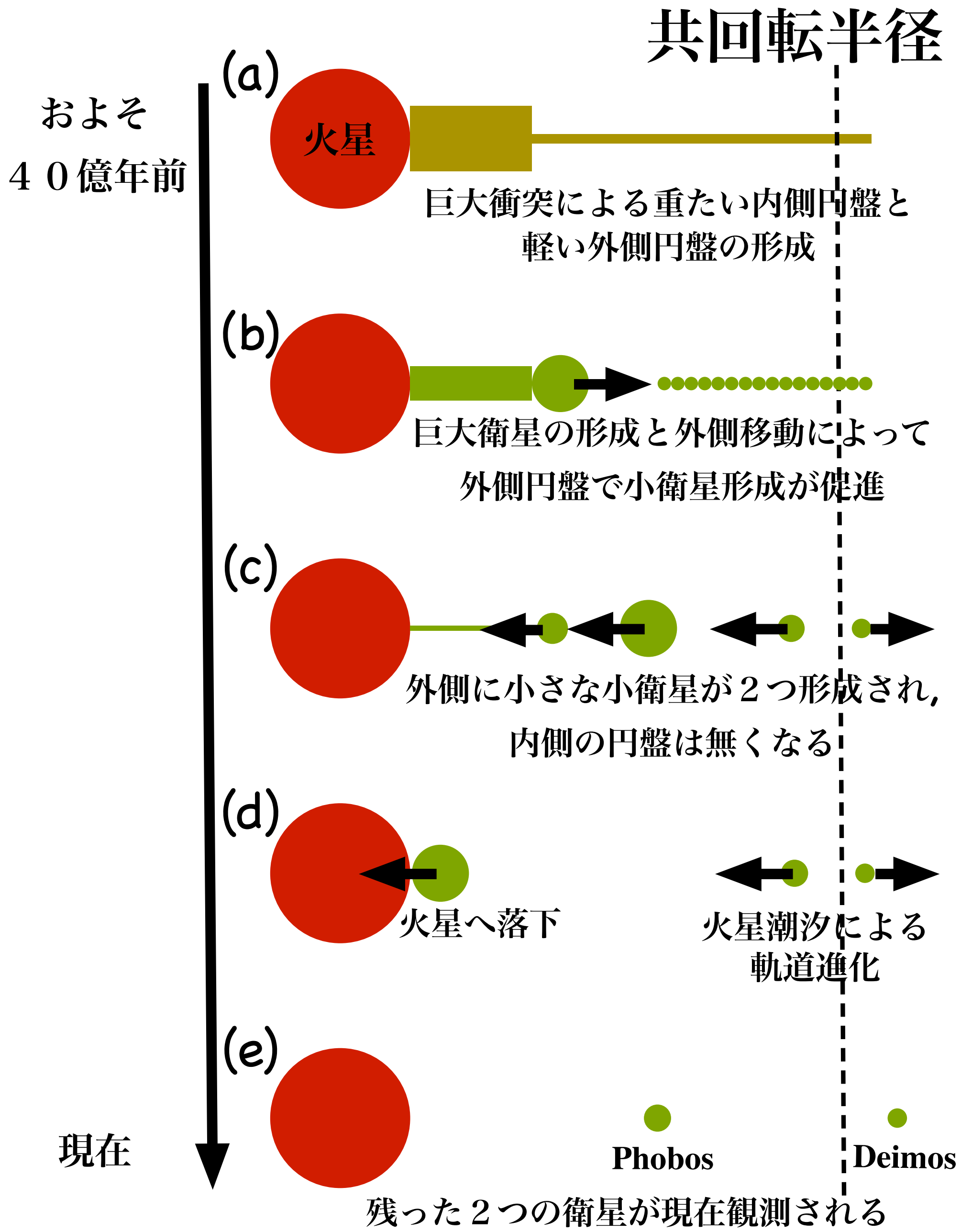
Formation of Big Moons from Inner Massive Disk



✔ From massive inner disk (10,000 × Phobos), a huge satellite (~ 1000 x Phobos) can be formed.

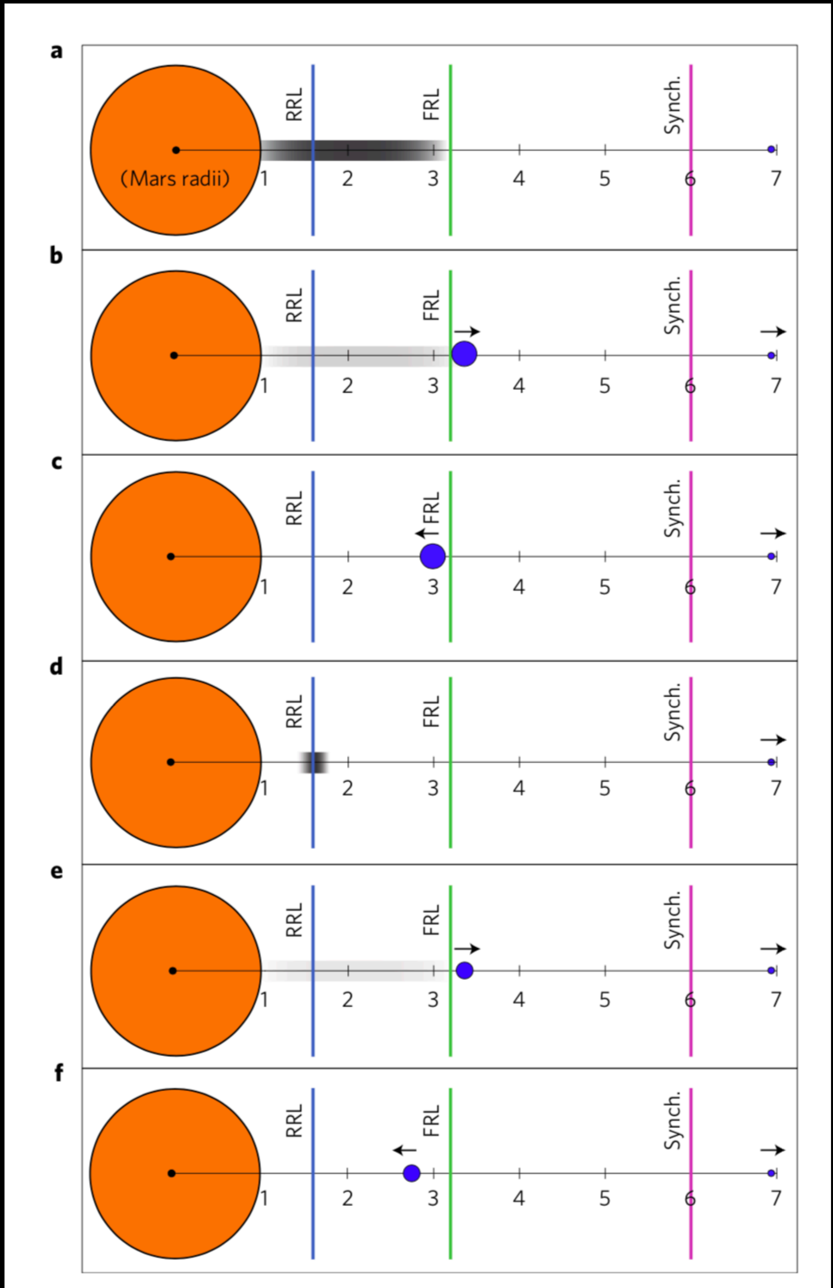
✔ This huge satellite moves outward up to $4.4R_{\rm mars}$ due to the gravitational interaction with the disk.

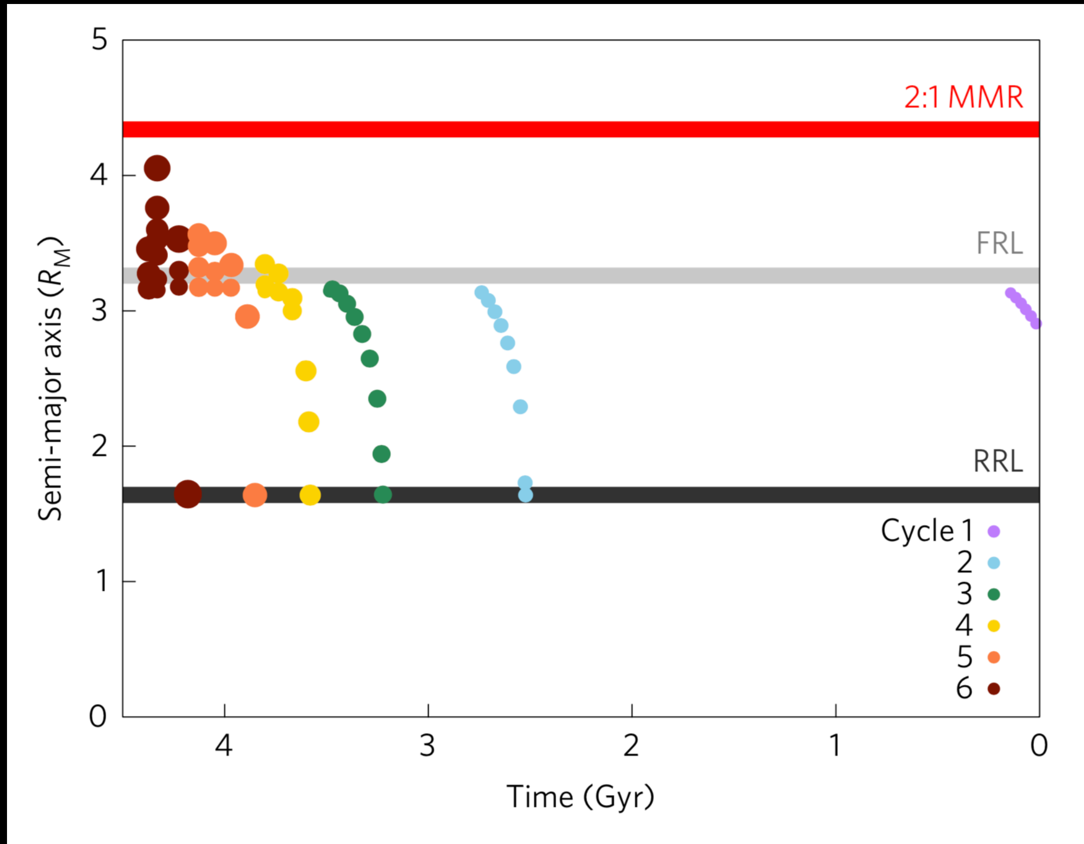
Rosenblatt, Charnoz, … Hyodo, Genda et al. 2016, Nature Geo.



Rosenblatt, Charnoz　　Hyodo, Genda et al. 2016, Nature Geo

Creations and Destructions of Phobos?

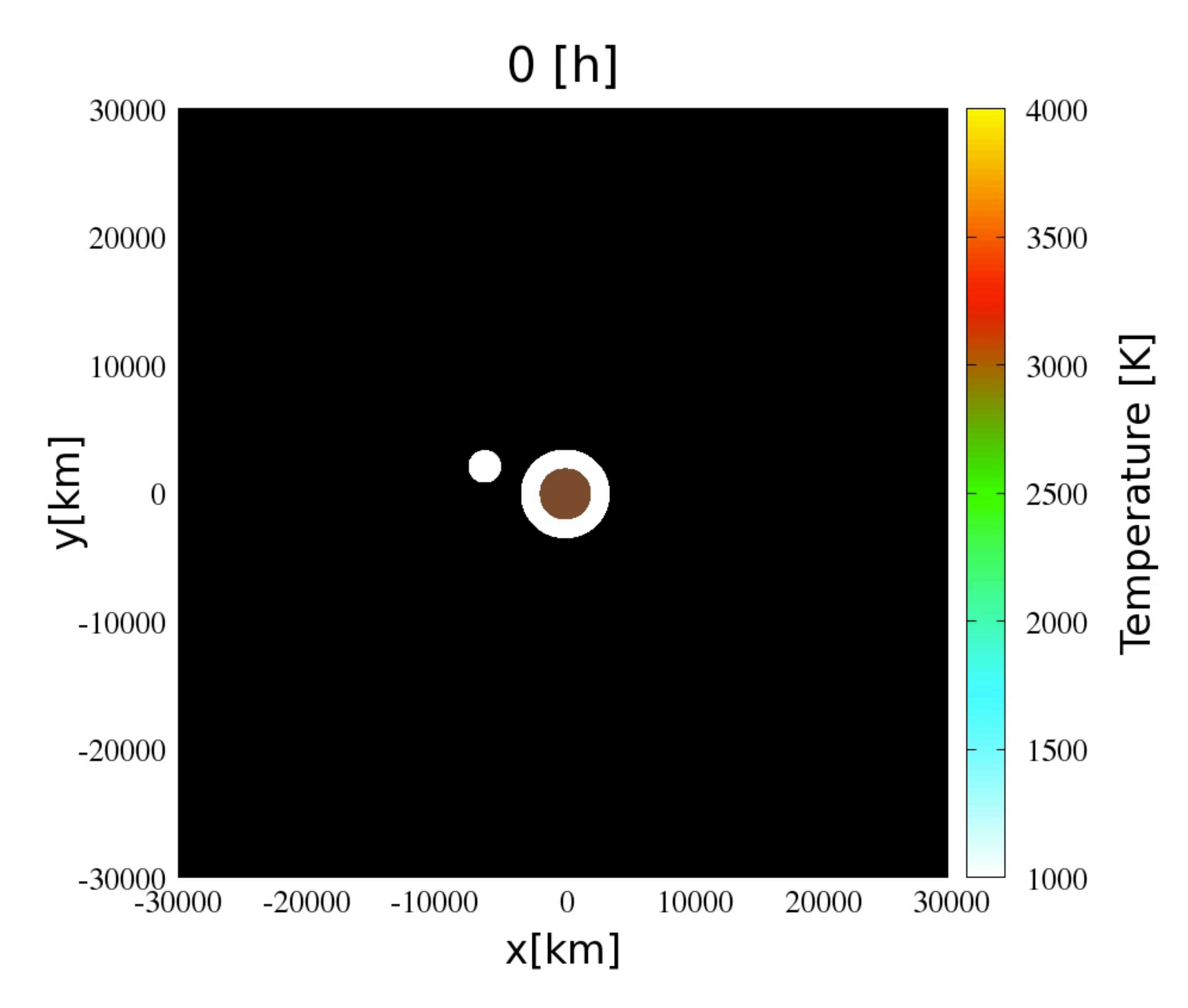




Hesselbrock & Minton 2017

Physical & chemical properties of Martian moons

High-Resolution SPH Simulations



Conditions:

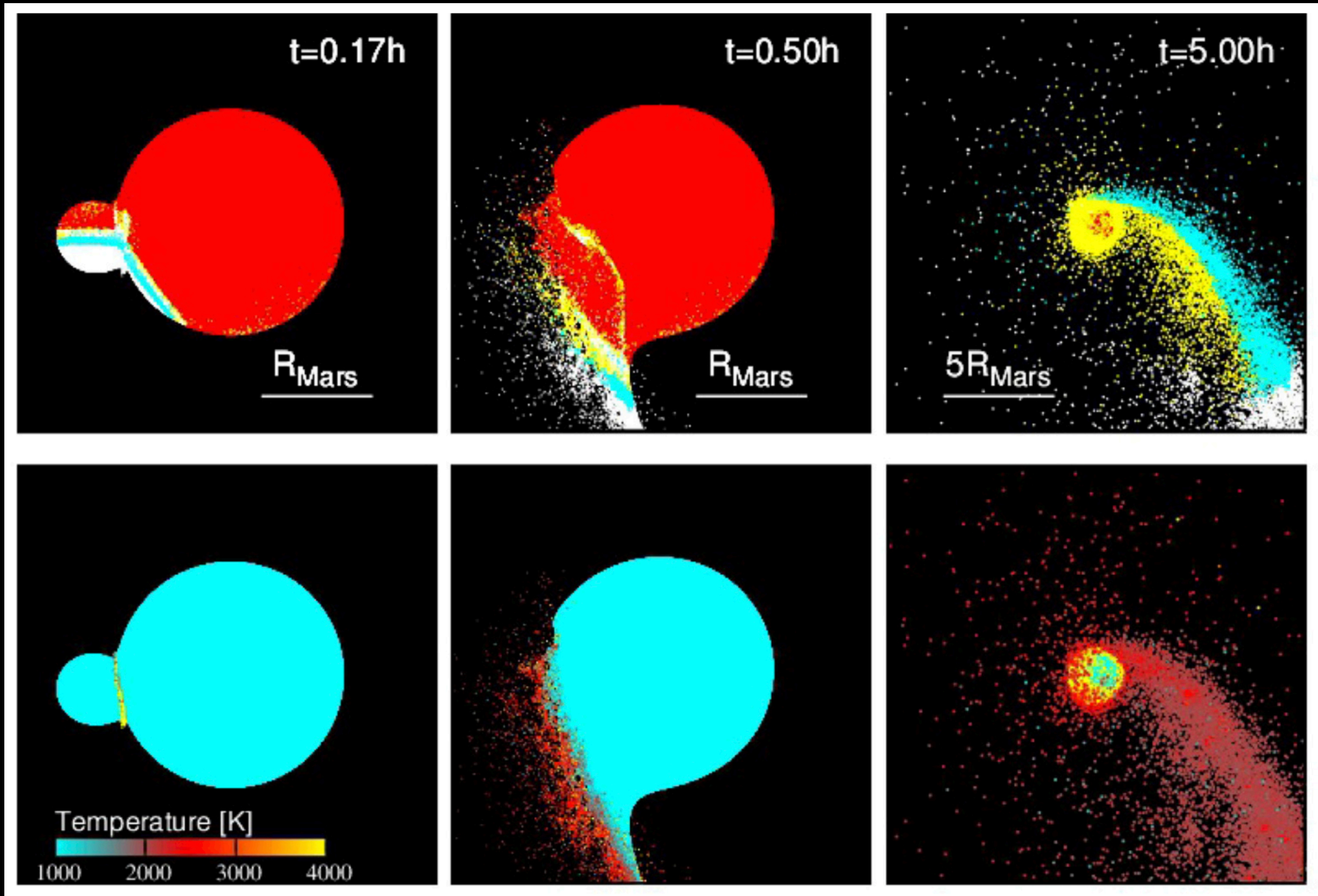
- N_{SPH}=3×10^6
- M-ANEOS
- θ_{imp}=45degs
- V_{imp}=6km/s
- m_{imp}=0.03M$_{Mars}$

Outcome:

- M_{disk}=5×10^{20}kg

Hyodo, et al. (2017) ApJ

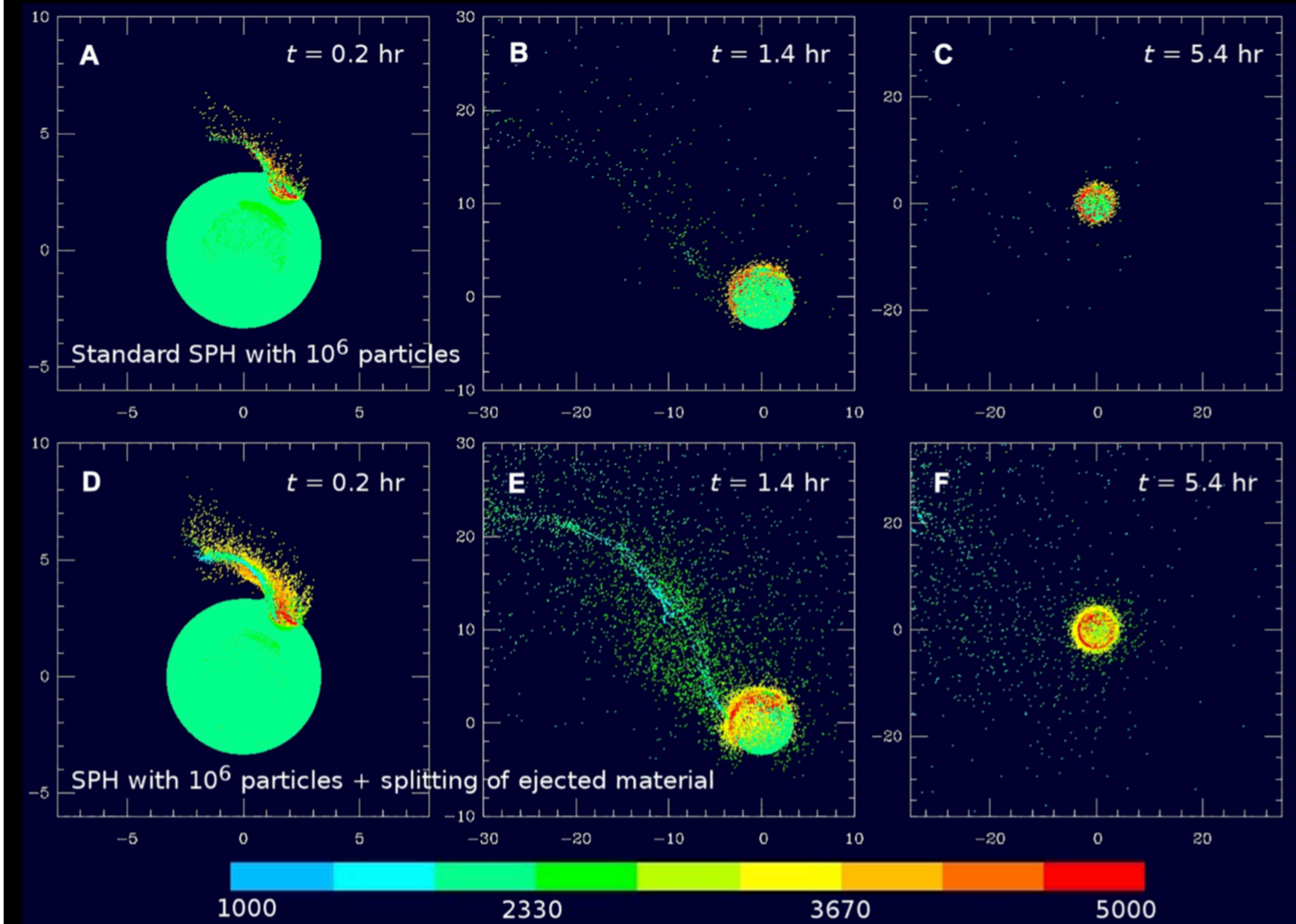
Debris just after the Ginat Impact



Hyodo, et al. (2017) ApJ

Giant impact by Vesta-to-Ceres impactor?

Physical, thermodynamical & compositional properties are similar to Hyodo et al. 2017



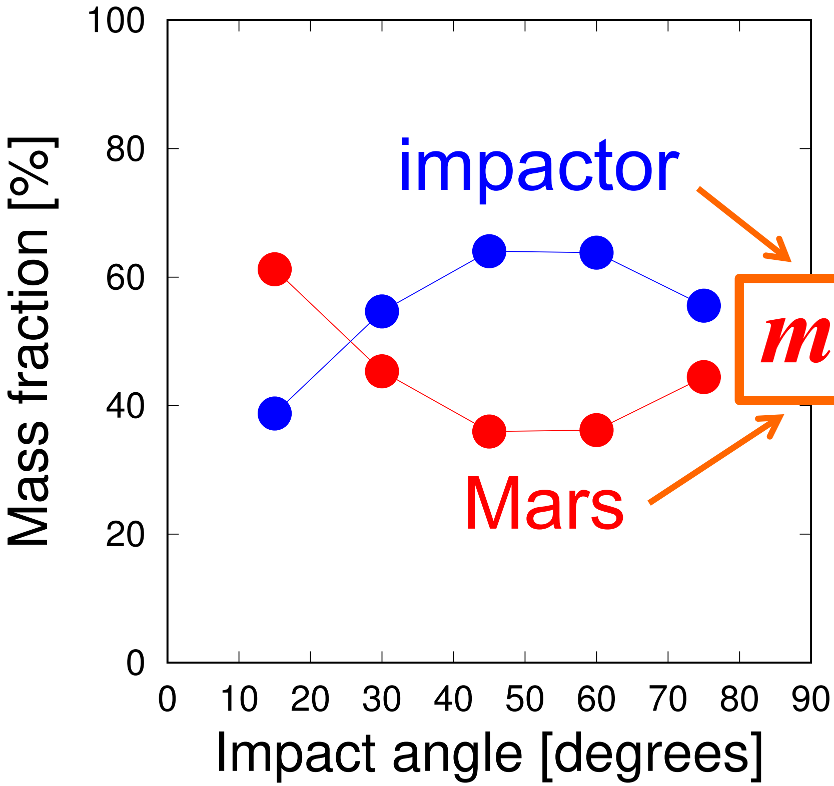
- θ_{imp}=45degs
- V_{imp}=7km/s
- $m_{imp}=5\times10^{-4}M_{Mars}$
- $M_{disk}=5\times10^{18}$kg

Canup & Salmon 2018

Building Blocks

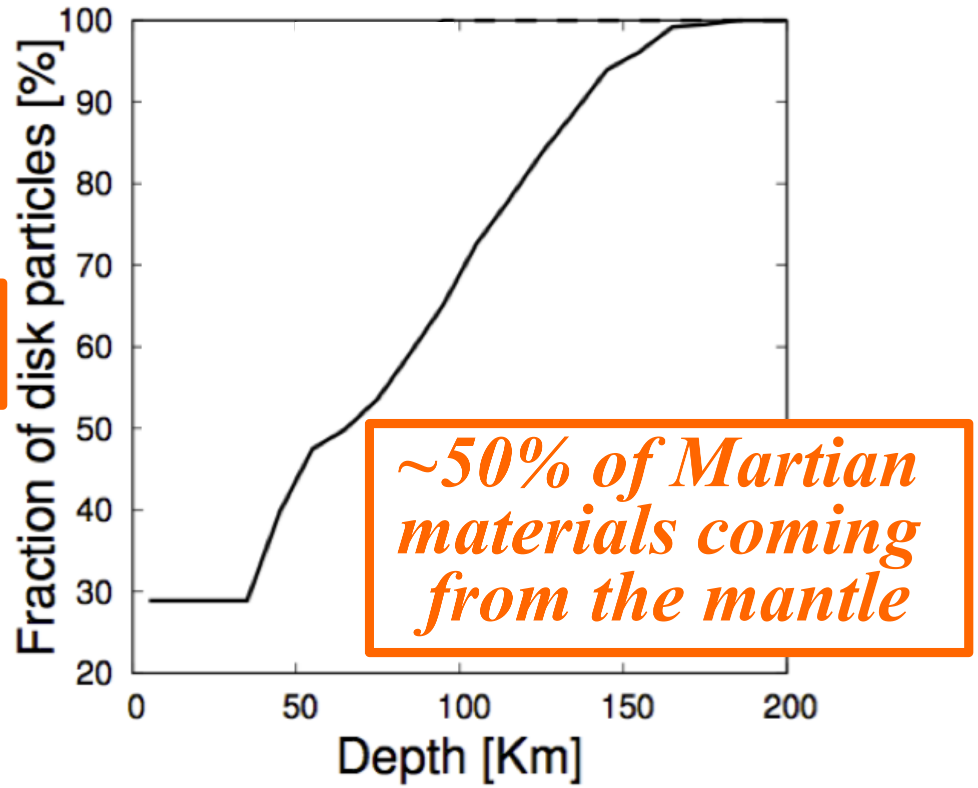
Phobos and Deimos contain Martian mantle materials

disk composition



mixture

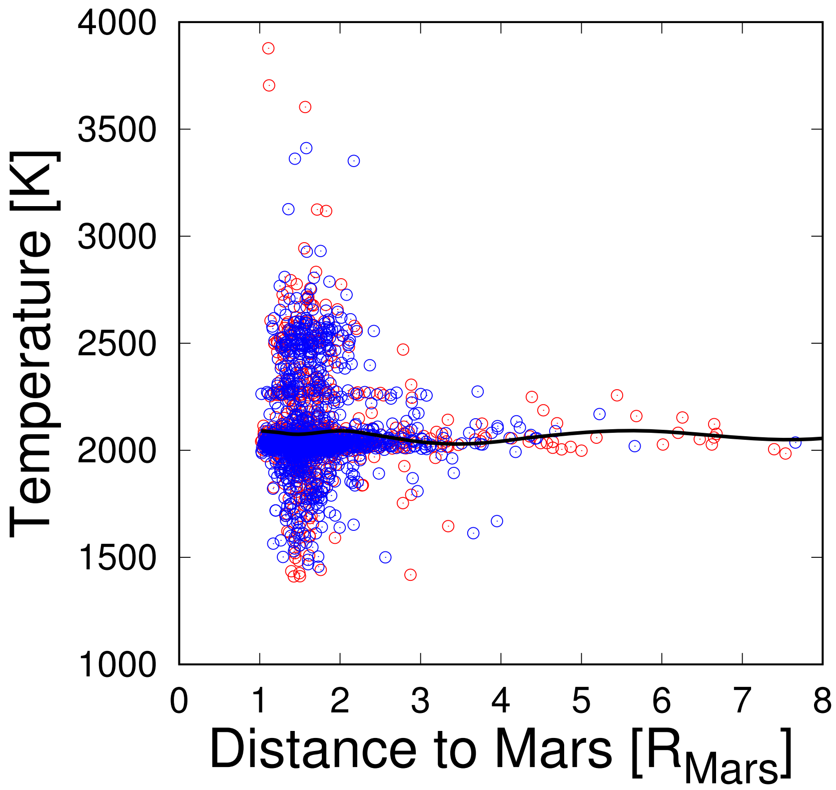
ejected depth



Hyodo, et al. (2017) ApJ

Thermal and Physical Aspects

disk's temperature



disk materials:

almost fully molten

low vapor fraction (< 5%)

particle sizes: *Melosh & Vickery (19991) Nature*

melt fragmentation: ~ 1 m

vapor condensation: ~ 0.1μm

very dark (FeS, C)

*Pignatale, ..., **Hyodo** (2018) ApJ*

featureless

Ronnet et al. (2016) ApJ

space-weathered Anorthosite

Yamamoto et al. (2018), GRL

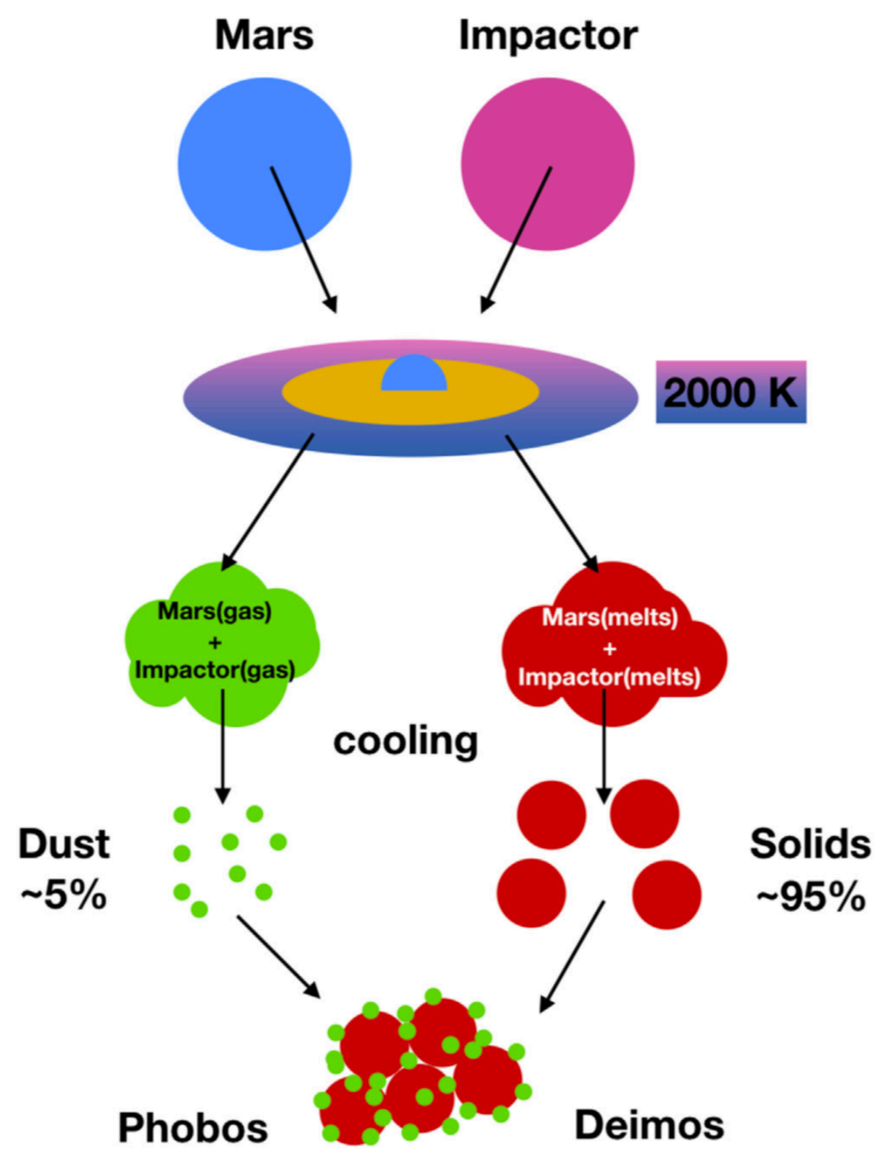
disk evolution:

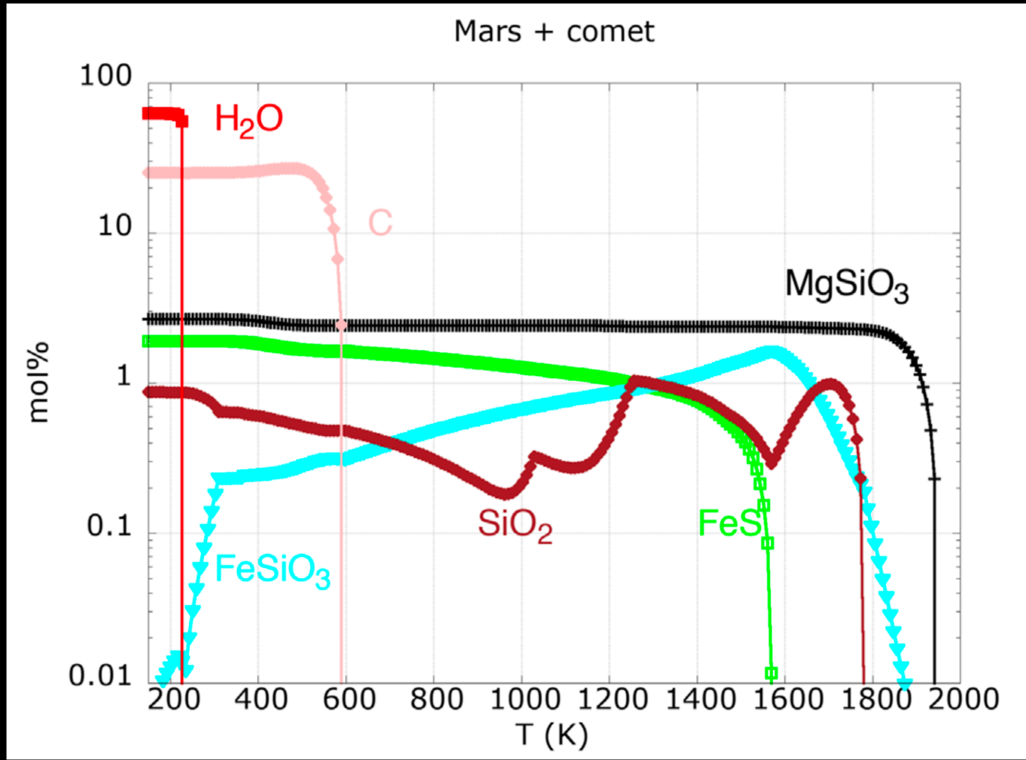
further fragmentation

from ~ 1 m to 100 μm

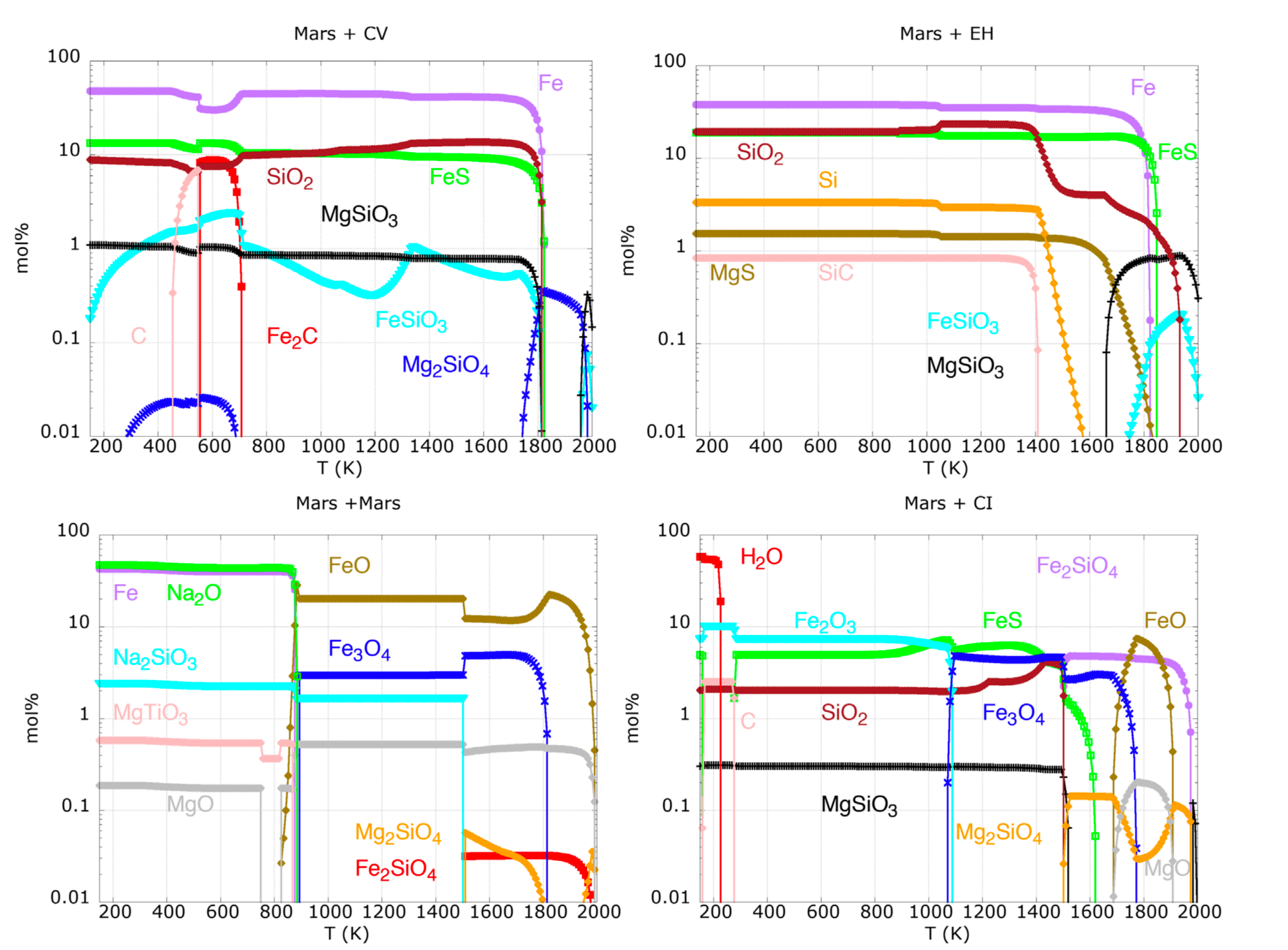
Hyodo, et al. (2017) ApJ

Chemistry in the Disk



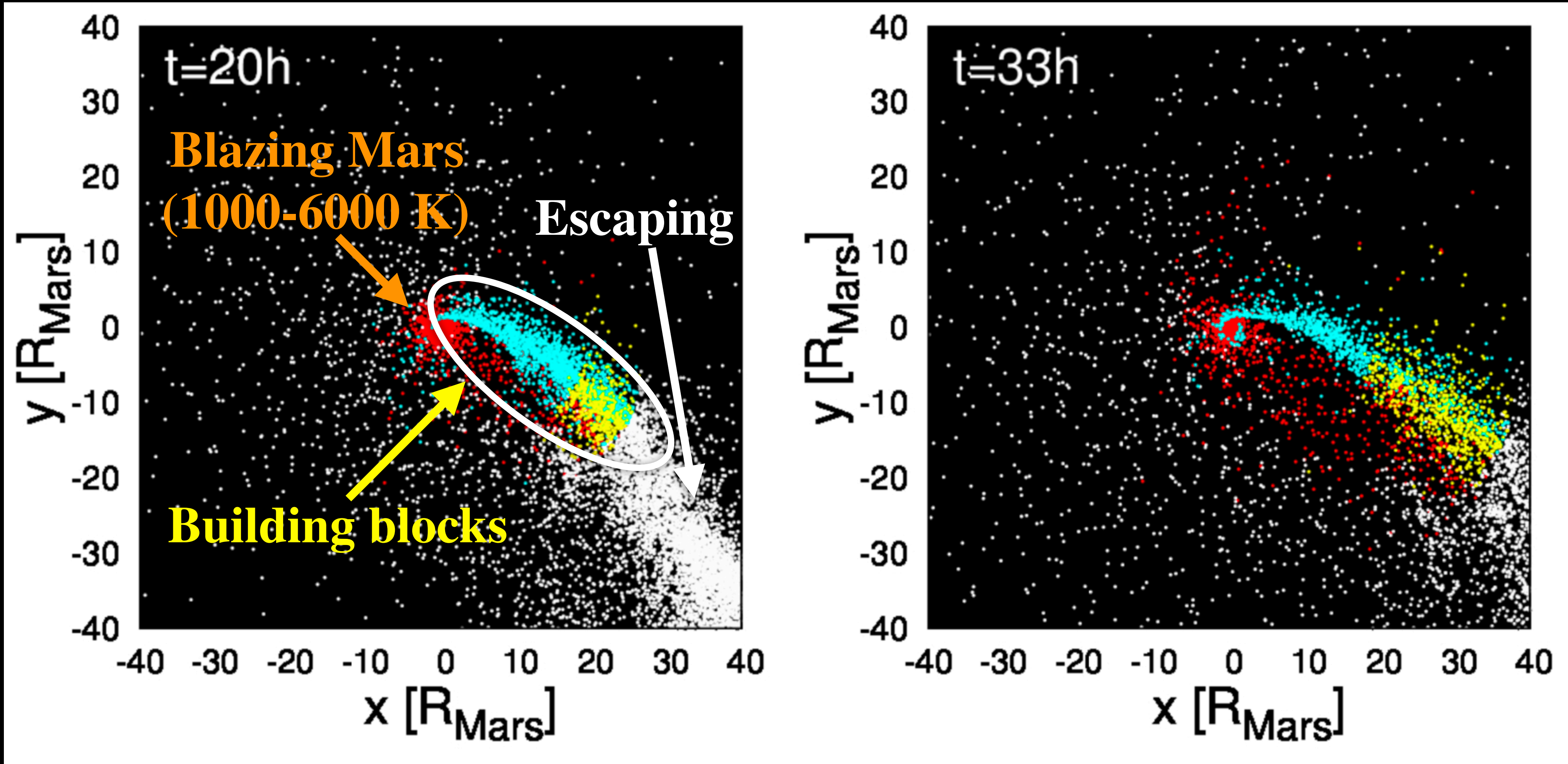


Dust Chemistry depends on impactor



Volatile Loss from Building Blocks

Hydrodynamic Escape & Radiation Pressure may remove volatiles?



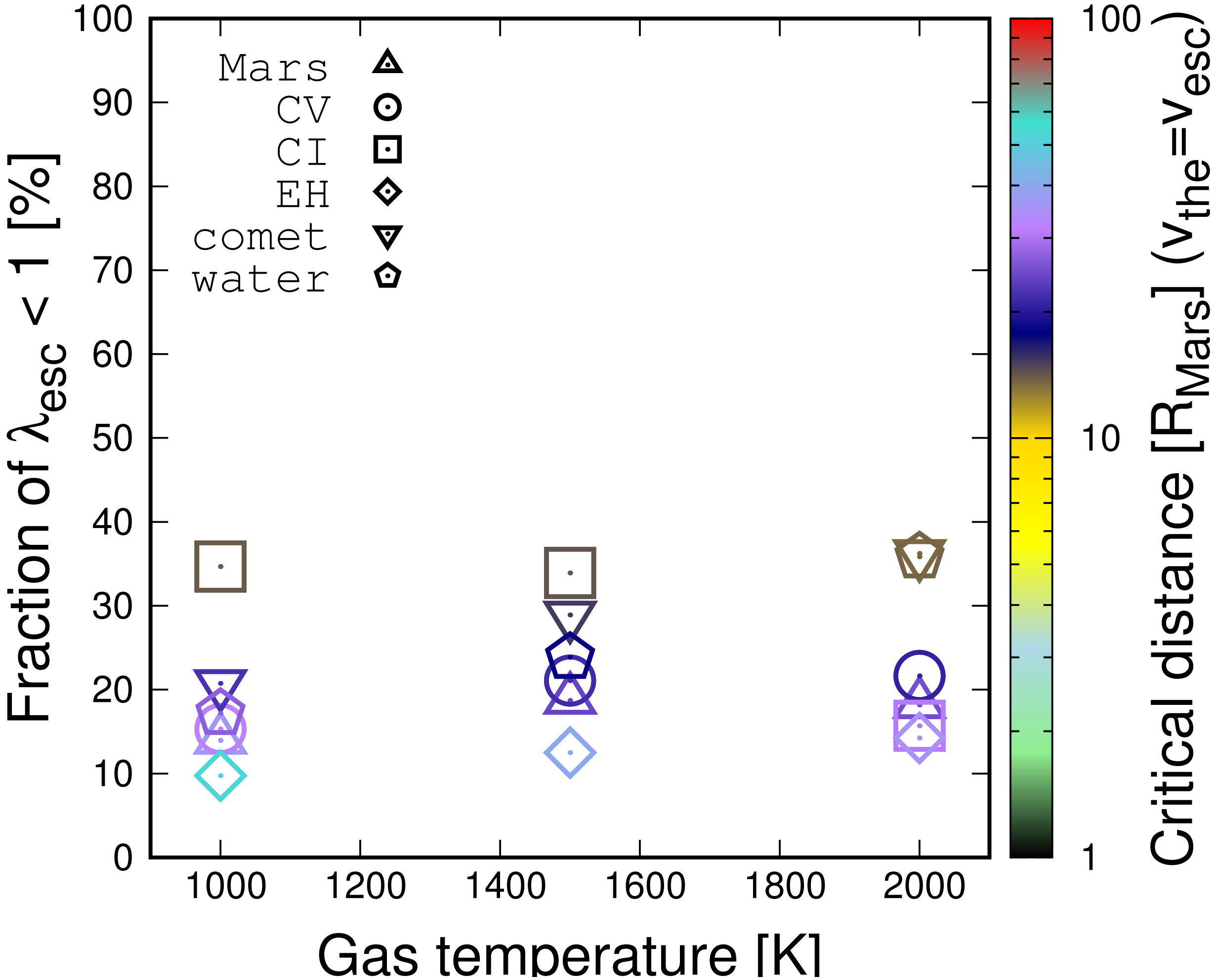
Outer parts of the building blocks: Opacity tau < 1 (yellow points)

Hyodo, et al. ApJ submitted

Volatile Loss from Disk

$$\lambda_{esc} = \frac{GM_{Mars}m_{vap}}{kT_{vap}r}$$

M_{Mars}: Mars mass, m_{vap}: mean molecular weight of vapor,
k: the Boltzmann constant, T_{vap}: vapor temperature, r: distance to Mars



Hydrodynamic Escape

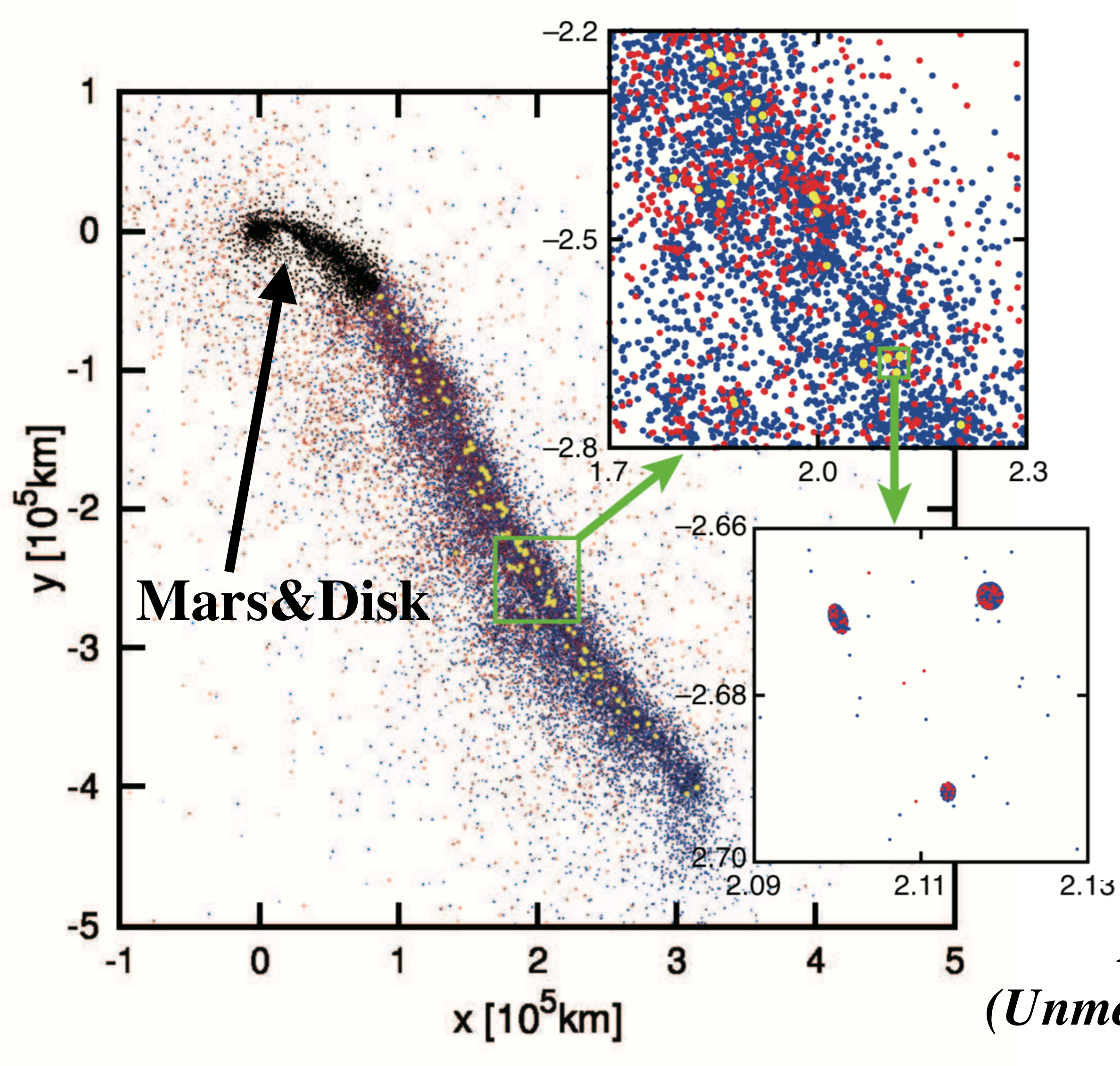
~ 30% of vapor can escape
→ ~ 70% of volatile elements can survive

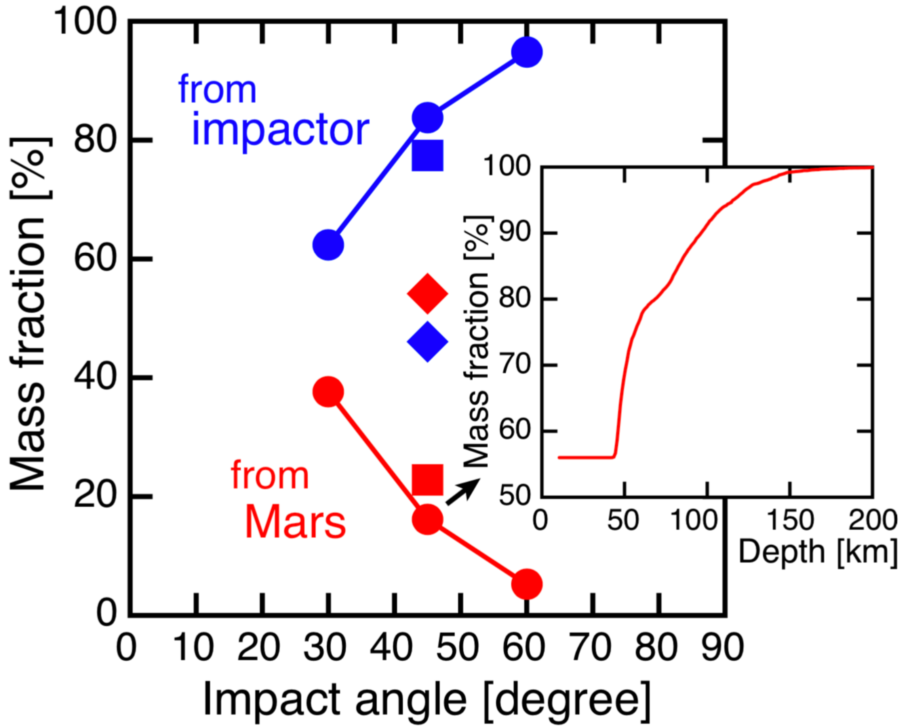
Radiation Pressure

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

***Hyodo*, et al. *ApJ* submitted**

Distribution of the Debris within the Inner Solar System



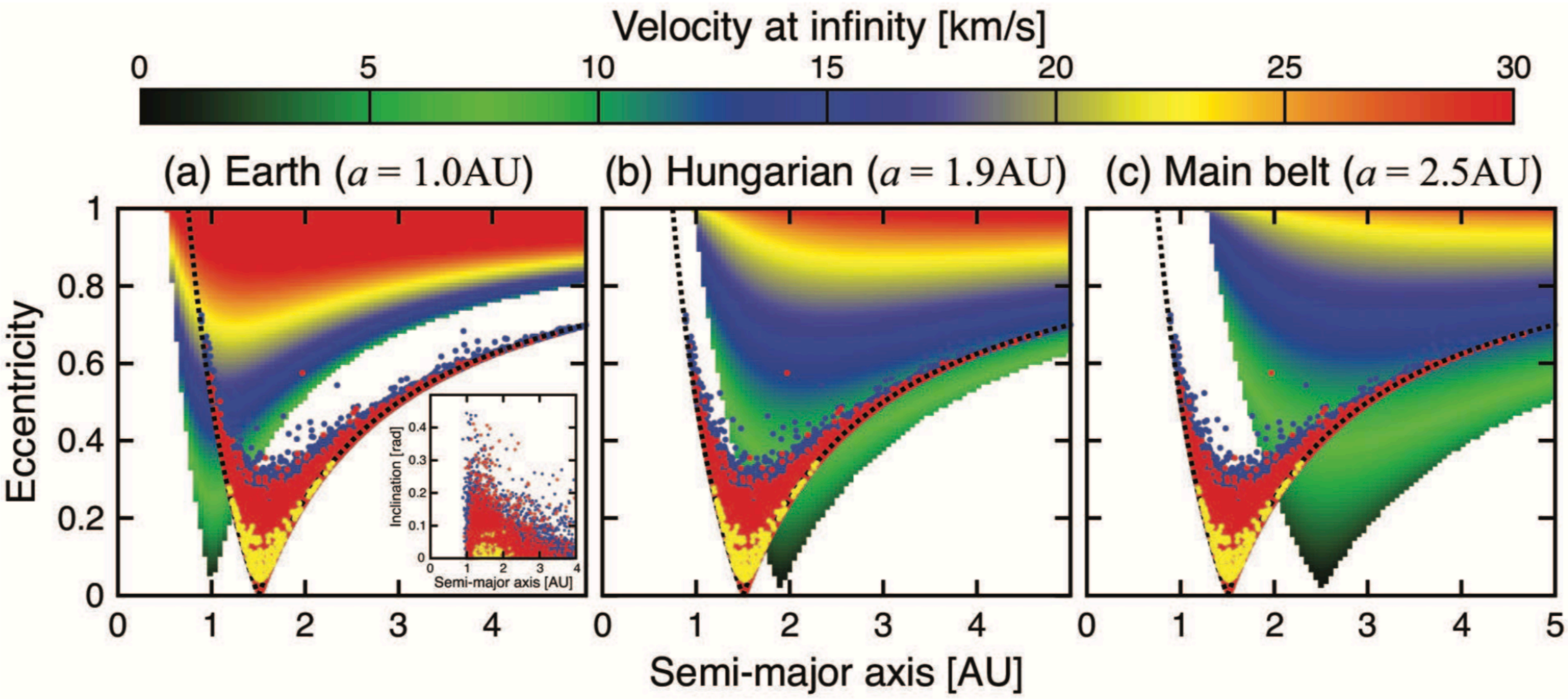


Debris mass M_{debris} ~ 2% of M_{Mars}

(Unmelted Martian Mantle ~ 0.02% of M_{Mars})

***Hyodo, & Genda* ApJL 2018**

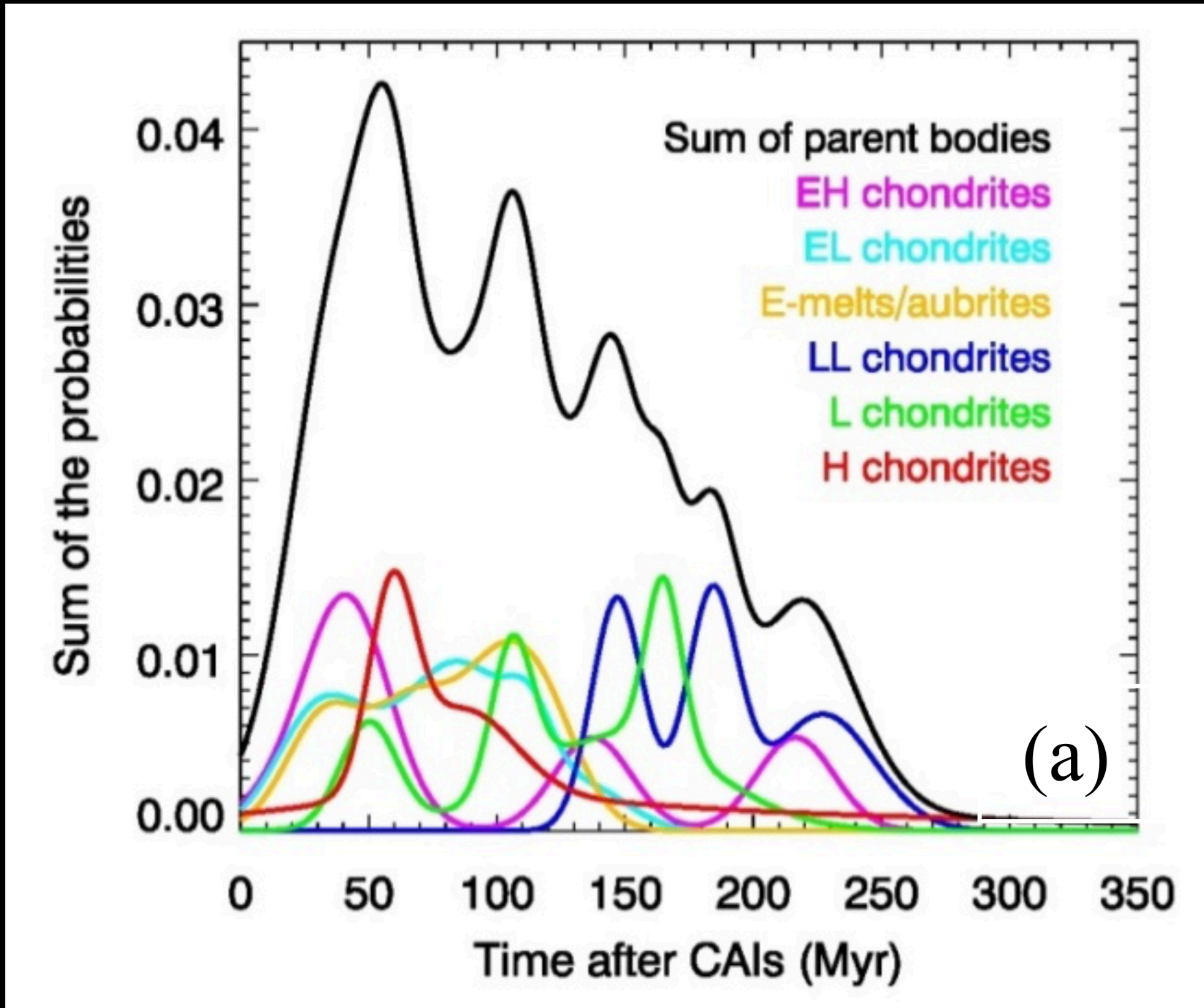
Distibution of Impact Debris within the inner Solar System



- <u>Impacting asteroids would reset ^{40}Ar-^{39}Ar age and/or cause impact melts</u>
- <u>Unmelted Martian mantle debris (~0.02% of M_{Mars}) can be the source of</u>
  - ☆ *Martian Trojan (Olivin-rich)*
  - ☆ *Rare A-type asteroids (Olivin-rich) in Hungarian and Main belt*

<u>Hyodo</u>, & Genda **ApJL 2018**

^{40}Ar-^{39}Ar Resetting Age Distribution



Bottke et al. 2015, Science

Take Home Message

A giant impact on Mars can

- produce Phobos and Deimos *(Rosenblatt, … Hyodo et al. 2016)*
- create the Borealis basin *(Marinova et al. 2008, Hyodo, et al. 2017b)*
- produce the current Mar's spin period *(Hyodo, et al. 2017b)*
- distribute debris as Martian Trojan & A-type asteroids *(Hyodo,&Genda 2018, ApJL)*

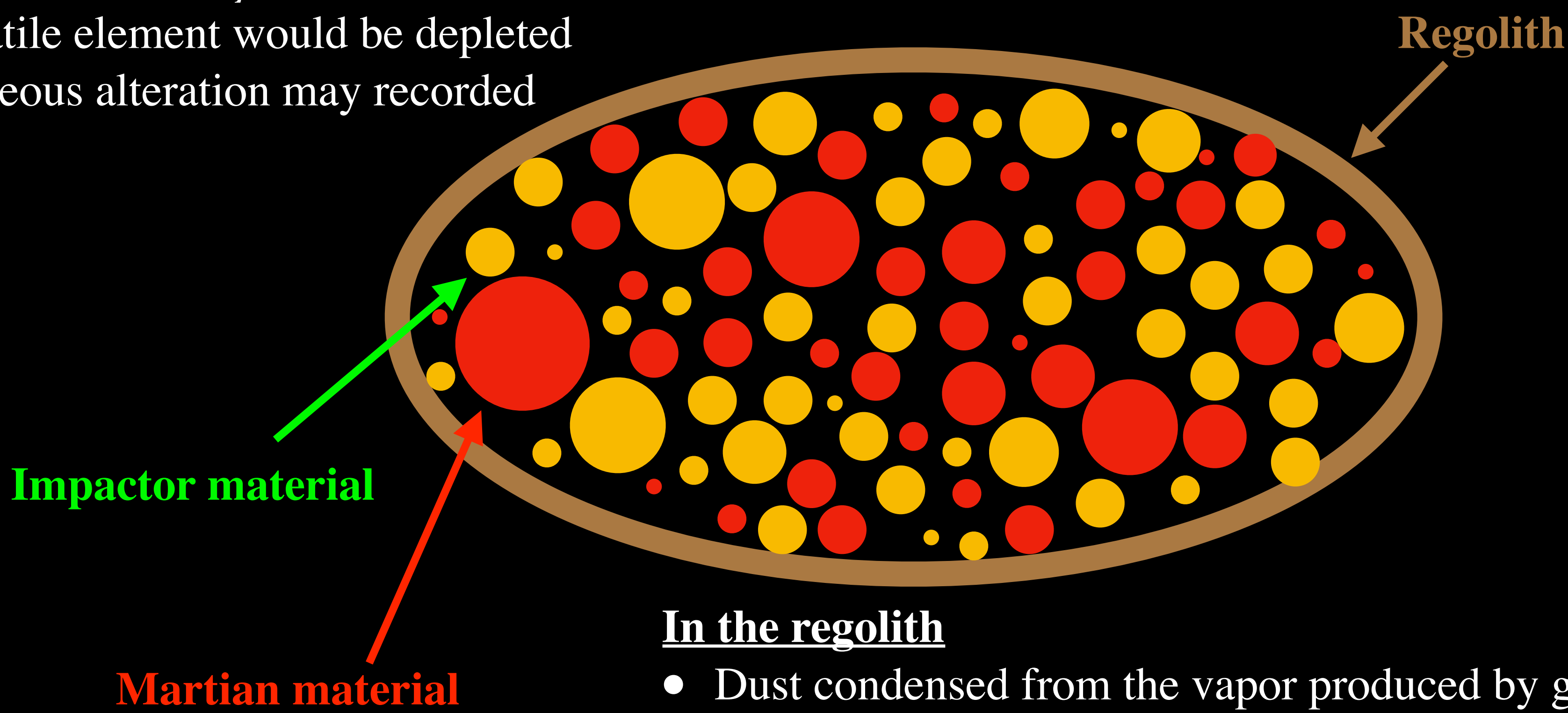
Building blocks of Phobos and Deimos:

- Mixture of impactor's and Martian materials
  crust & mantle *(Hyodo, et al. 2017a)*
- Mixture of 0.1 μm and 100 μm – 1 m sized particles
  Featureless & maybe dark (FeS, C) *(Pignatale, … Hyodo et al. 2018)*
- Volatile loss is limited *(Hyodo, et al. ApJ submitted)*

Summary (Expected Phobos & Deimos)

Bulk composition (rubble-pile object):

- ~50% Martian material (at the time of impact: ~4 Gyr ago)
  - ◆ Martian crust and mantle (up to150km in depth)
- ~50% impactor material
- Particle size: 100μm-10m
- Volatile element would be depleted
- Aqueous alteration may recorded



In the regolith

- Dust condensed from the vapor produced by giant impact
- Recently delivered material
  - ◆ Martian surface material
    - * ~150 ppm delivered within recent 10 Myr
    - * ~1500 ppm delivered within recent 500 Myr
  - ◆ Impactor material