Assessment of microbial contamination probability for sample return from Martian moons

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Takashi Mikouchi[4]
&
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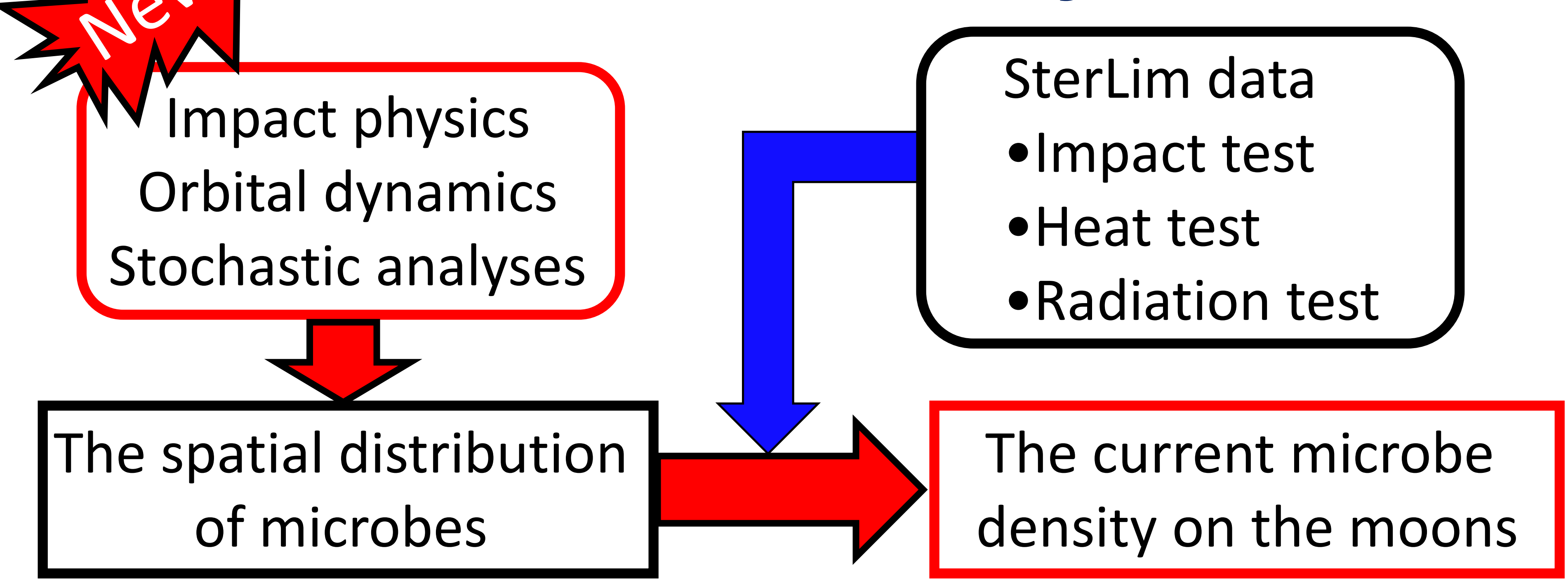
2018 9/19

Brief summary



☆The total survived fraction of microbes at the present is only ~2 ppm on Phobos and ~50 ppm on Deimos.

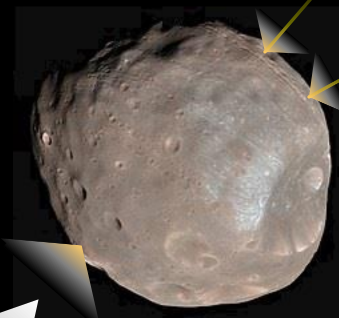
☆Heterogeneous distribution of the microbes on the Martian moons

☆Microbe contamination probability of collected samples can be below 10^{-6} by appropriately choosing the sampling approaches.

Each step considered in this study

5.Impact processes
on the moon's surface
-Sterilization by shocks
-Fragmentation
-Mixing with the regolith
-Dispersion

7. The formation of radiation
shield by natural meteoroids

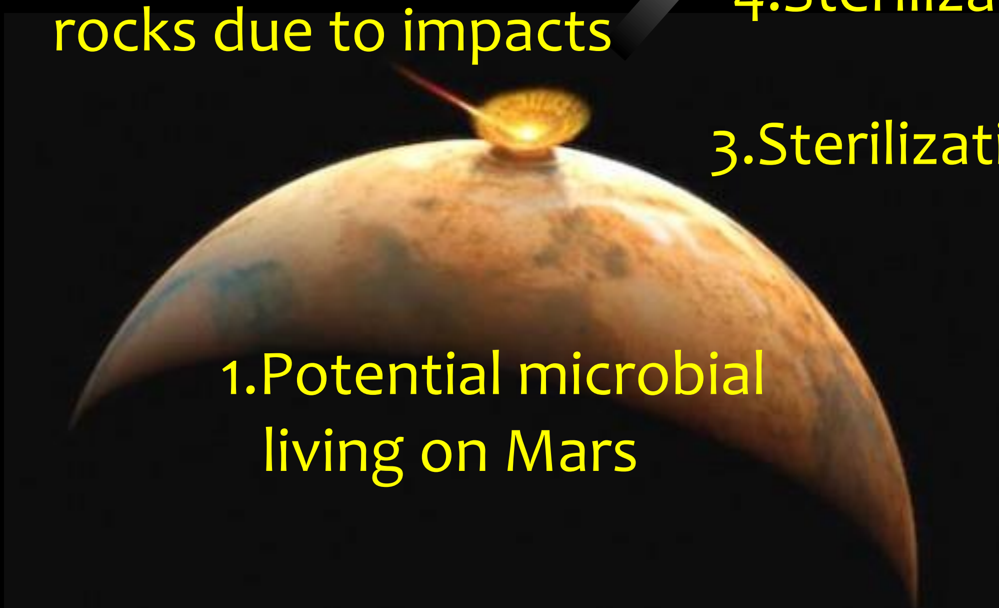


6. Sterilization
by radiation

2.The launch of Mars
rocks due to impacts

4.Sterilization by aerodynamic heating

3.Sterilization during the launch



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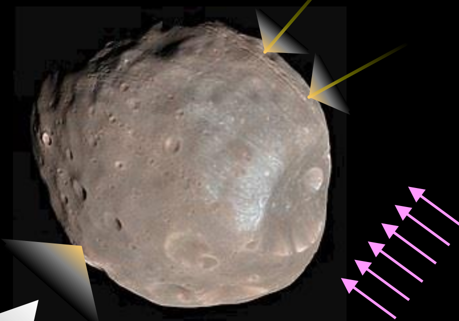

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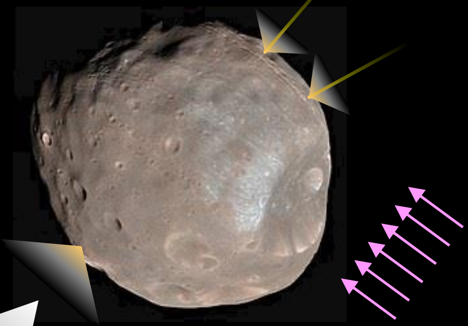

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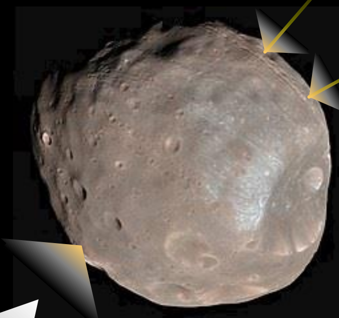

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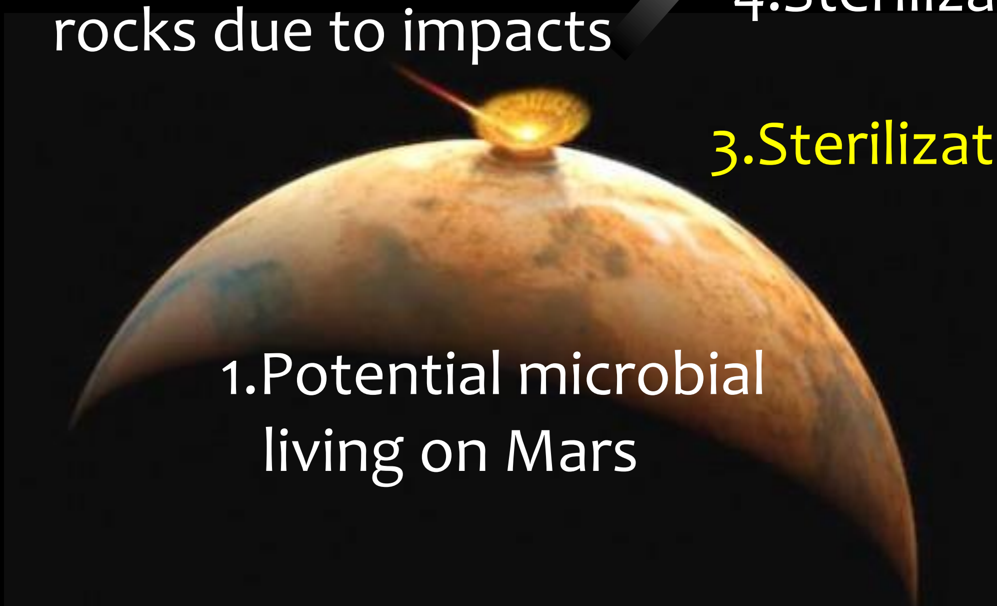

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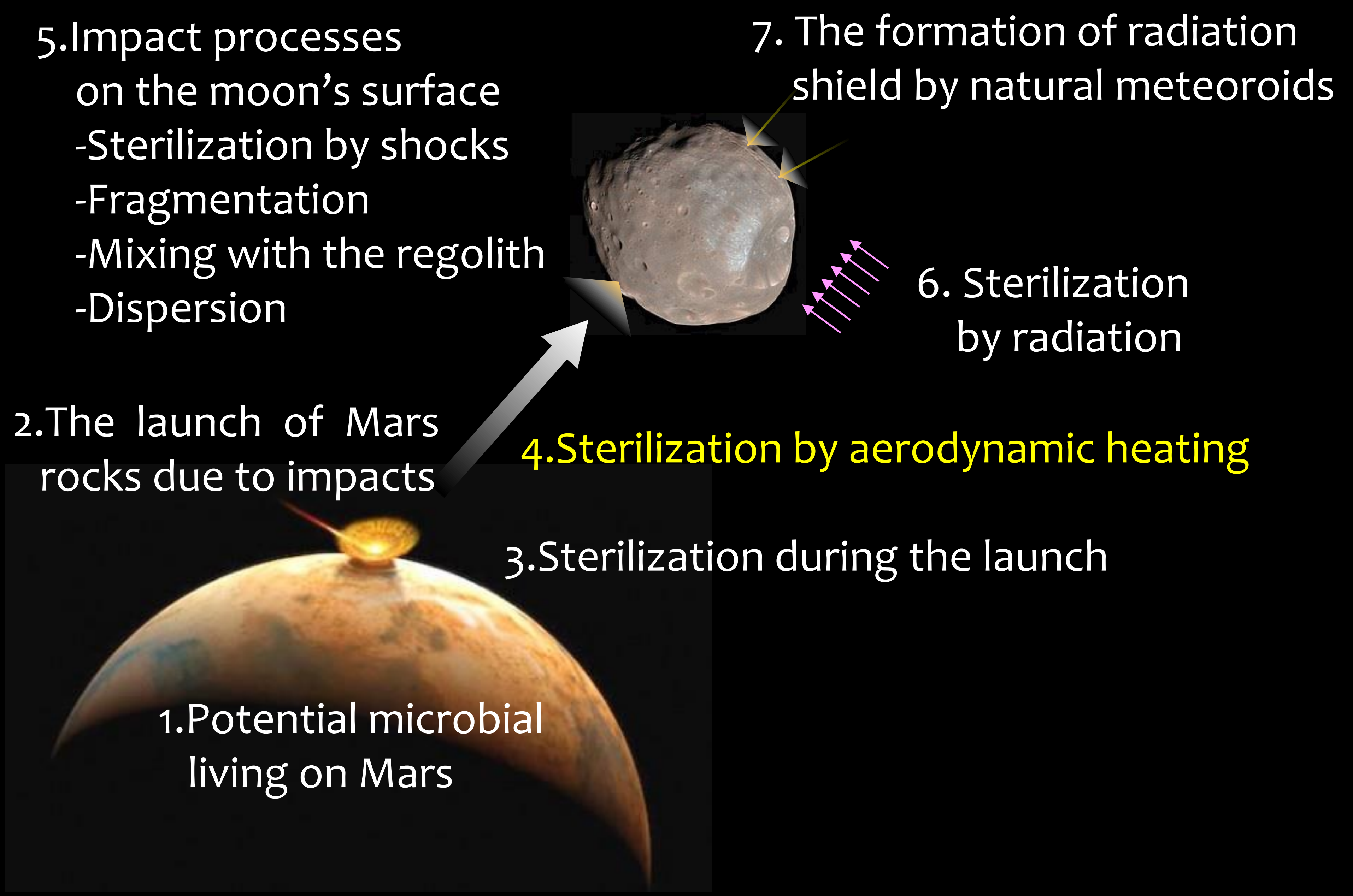

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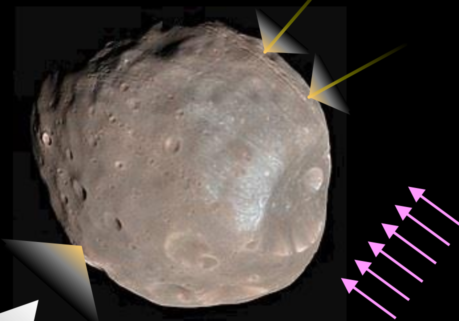

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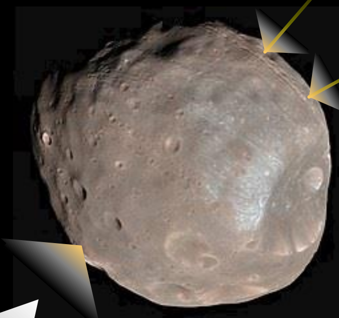

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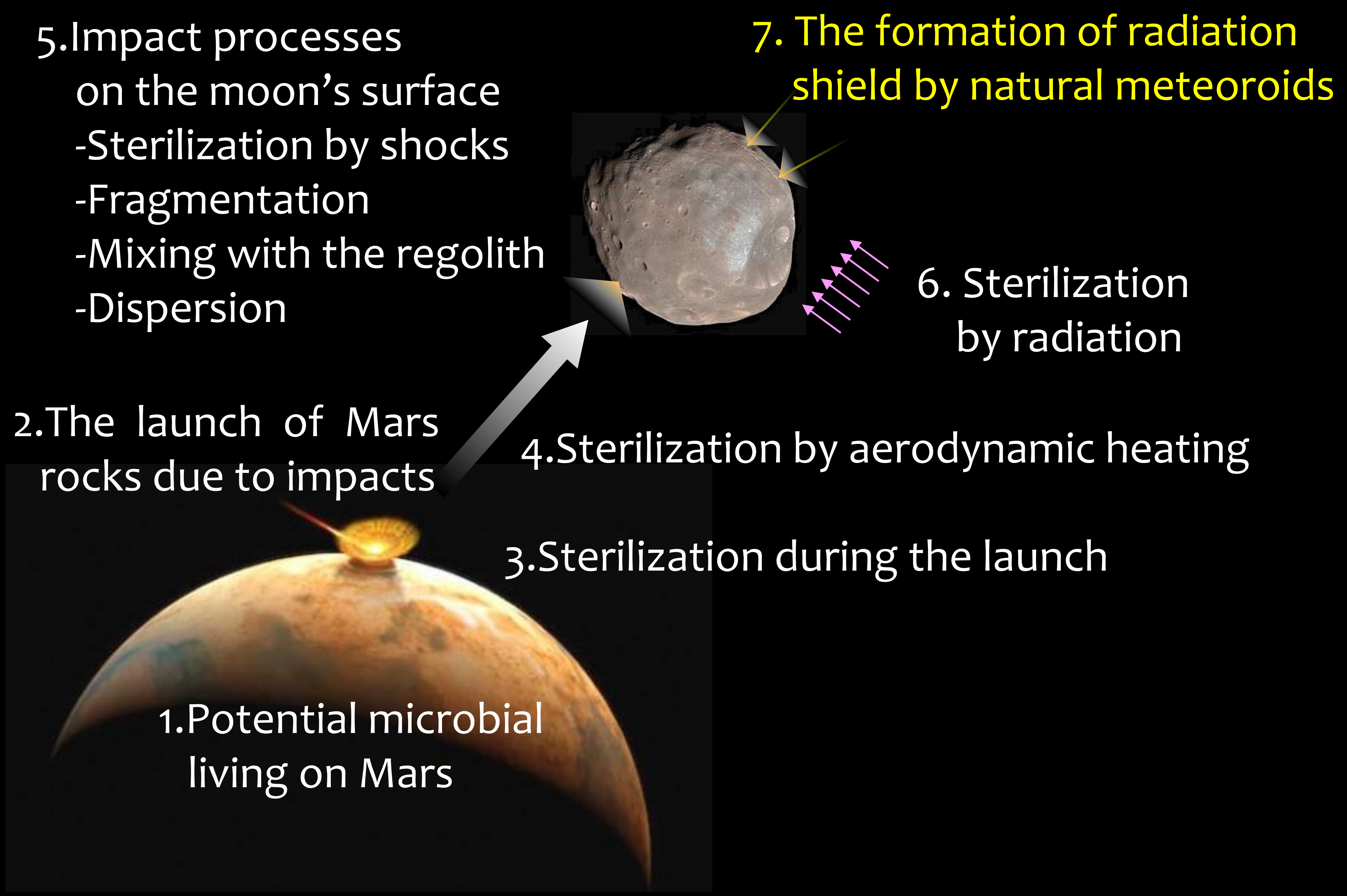
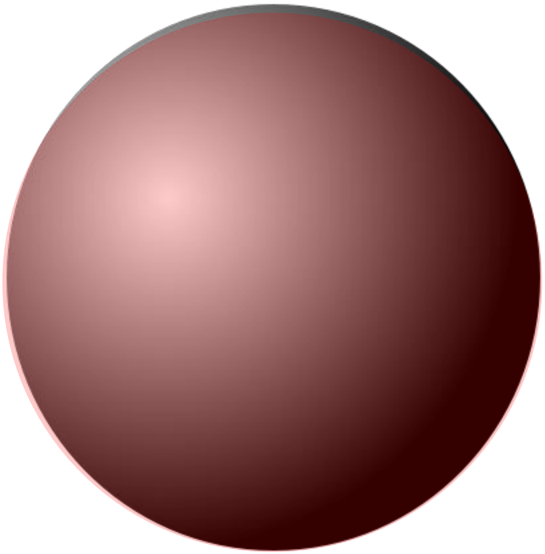


Difference from SterLim study

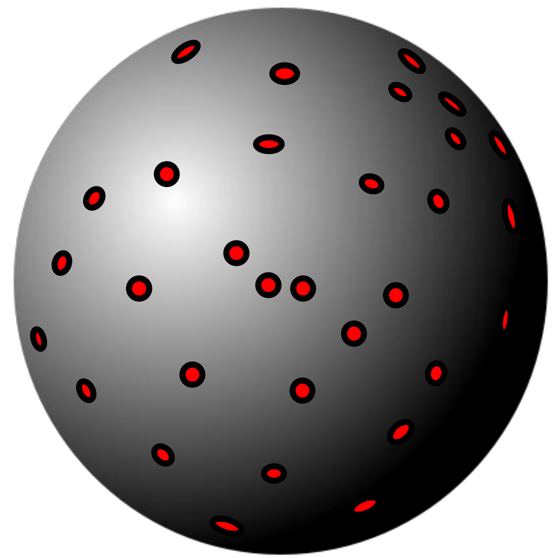
SterLim view

Homogeneous deposition by averaging incoming flux to the uppermost layer



Our view

“Mars-rock bombardment” & Impact physics



Microbe distribution
- -Patchy in the horizontal direction
- -Depth-dependent

Significant/Moderate/Minor effects	***SterLim***	***Our work***
1. Potential microbes living on Mars	Assuming same microbial density as Atacama Desert	Similar to SterLim, but a downward revision is introduced.
2. The launch of Mars rocks due to impacts	Analytic model given by the point-source theory (The same used by Melosh)	3-D hydrodynamic simulations to obtain appropriate initial conditions for the trajectory analyses
3. Sterilization during the launch	Not considered	Sterilization during the launch based on the data compilation of Martian meteorites and recent finding on shock heating
4. Sterilization by aerodynamic heating	Not considered	Thermal analysis of Mars ejecta conducted along trajectories
5-1. Impact sterilization on the moon's surface	Microbe survival rate ~ 0.1 regardless of impact velocity	A revised-impact sterilization model to treat v_{imp} dependence
5-2. Impact processes on the moon's surface	Homogeneous deposition by averaging the incoming flux	Crater formation by Mars ejecta with retention & scattering of Mars ejecta fragments taken into account
6. Sterilization by radiation	Sterilization model constructed by experiments	Same as SterLim, but the effects of the depth is also considered.
7. The formation of radiation shield by natural meteoroids	Not considered	A new stochastic model

Outline

1. General assumptions
2. Transportation to the moons
3. Mars-rock bombardment on the moon
4. Background impact flux by natural meteoroids
5. The change in the microbe density with time
6. Microbe contamination risk assessment
7. Conclusions

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General assumptions

- Potential microbe density on Mars
- Supporting data (SterLim data)
- Source crater

Potential microbe density on Mars

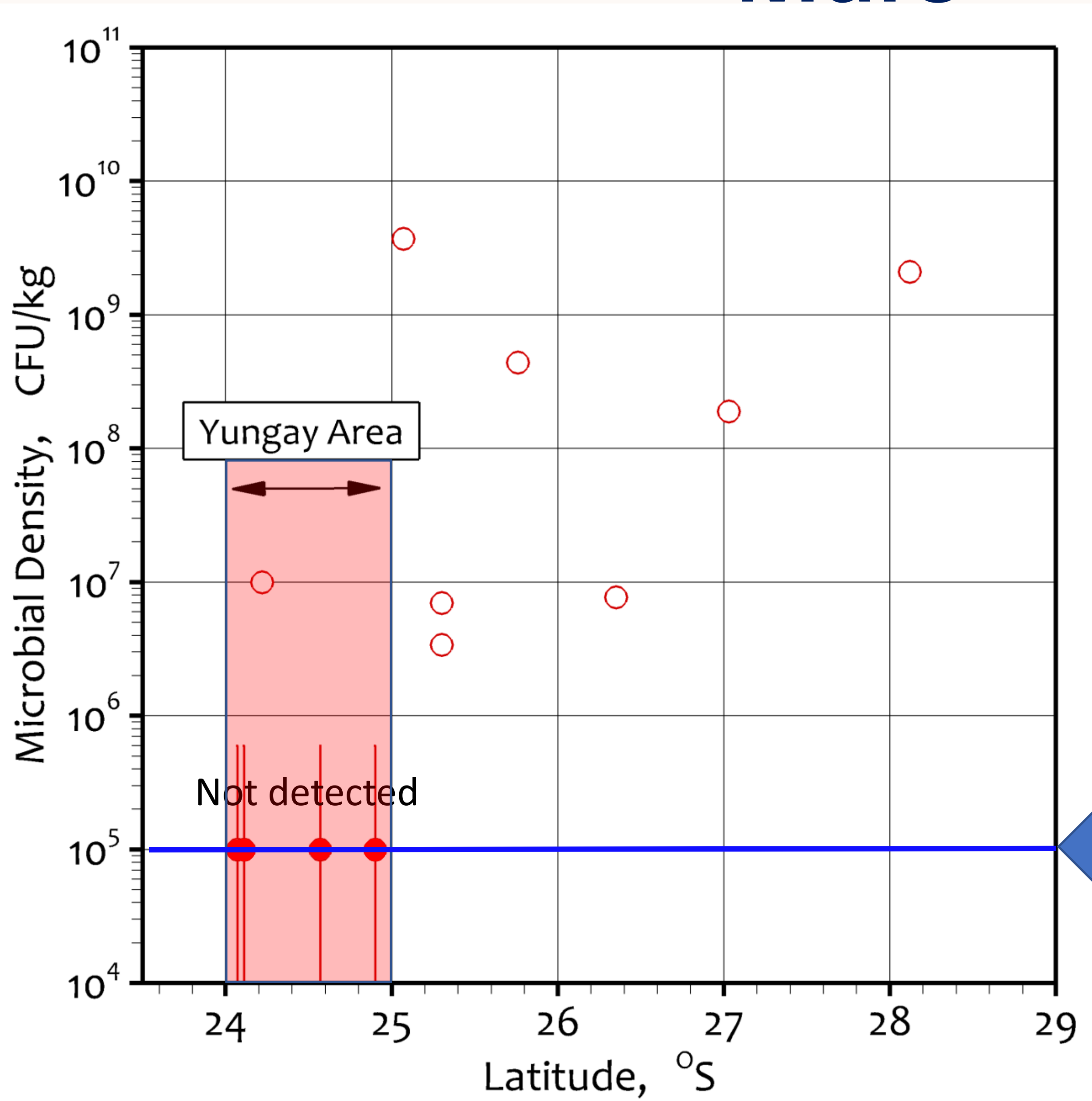
Terrestrial Mars analog

Condition	Location	Microbe concentration
Hyperarid	Yungay (Atacama Desert)	$10^6 – 10^8$ CFU/kg [Navarro-González+03; Maier+04] $10^8 – 10^{10}$ cells equivalent/kg [Glavin+04; Drees+06; Lester+07; Connon+07]
Cold & Arid	McMurdo Dry valley (Antarctic permafrost)	$10^6 – 10^7$ cells equivalent/kg [Goordial+16]

Initial microbe density $n_{\mathrm{Mars}} = 10^8$ CFU/kg

※1 CFU/kg ~ 10^2 cells/kg

Potential microbe density on Mars



[Data are taken from Navarro-González+03]

McMurdo Dry valley (Antarctic permafrost)
[Goordial+16]

※1 CFU/kg ~ 10^2 cells/kg was assumed.

Potential microbe density on Mars

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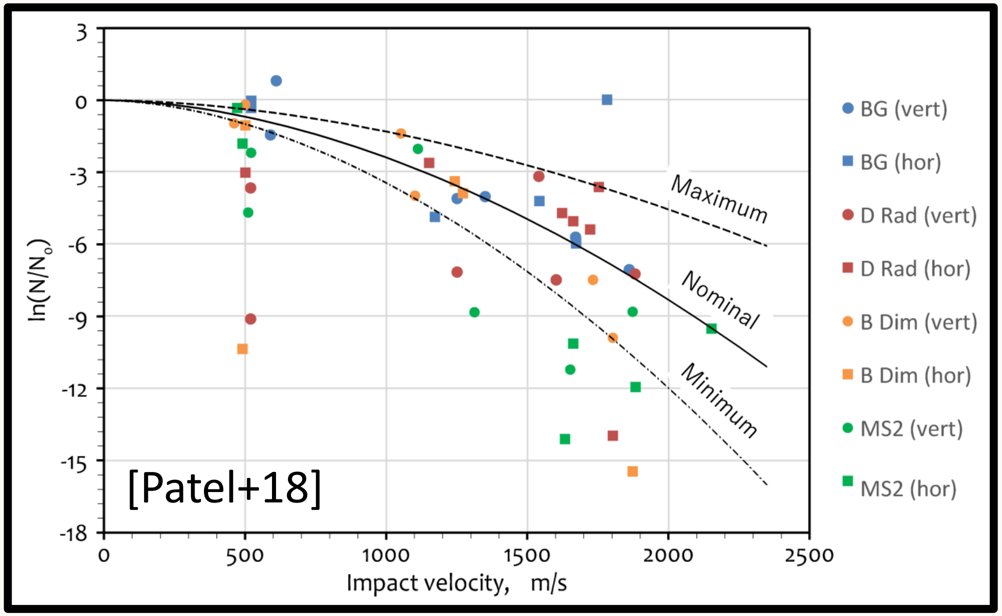
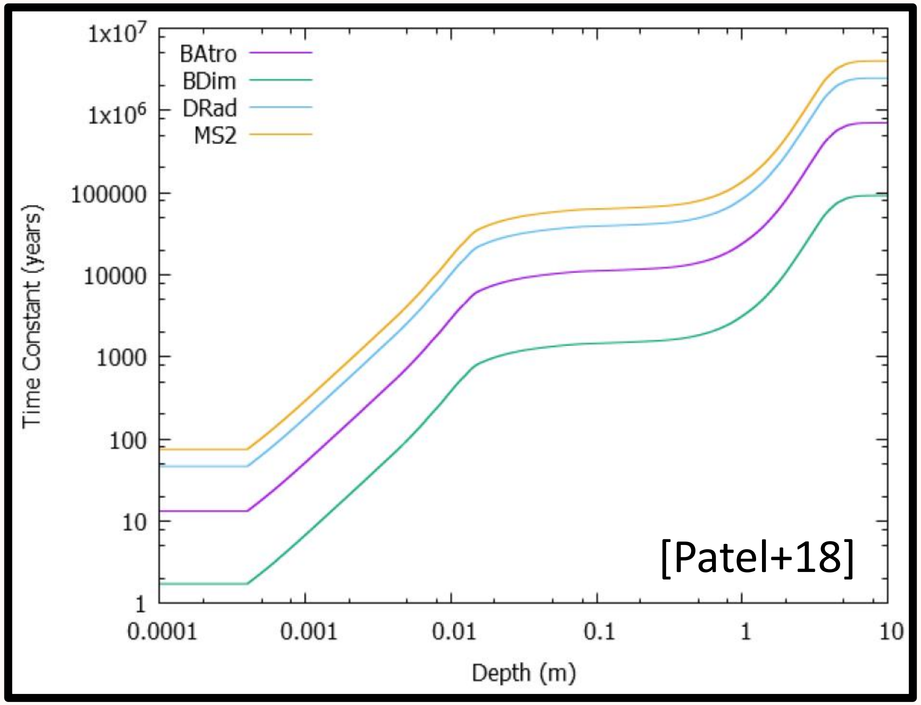
Supporting data on sterilization

The best systematic dataset to consider the case of Martian moons.

SterLim impact test



SterLim radiation test

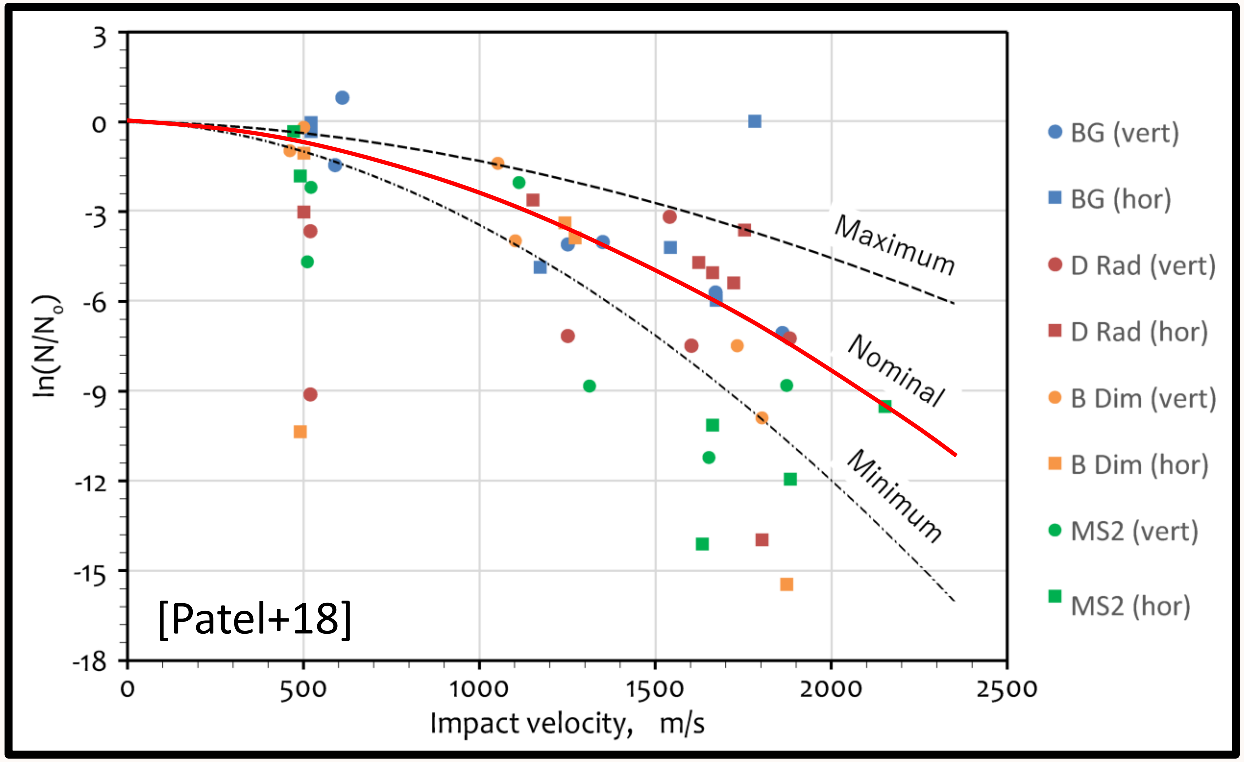


A different empirical model based on the dataset was used. (Next slide)

Time constant of MS2 was used for conservative estimate.

Impact survival rate

The SterLim study assumed the survival rate is ~0.1.



Physical constraint: Survival rate must be decrease with increasing v_{imp} because post shock temperature $\propto v^2$

An empirical model

$$N/N_0 = \exp\left[-(9.5 \pm 4.3) \times 10^{-6} V_{imp}{}^{1.8}\right]$$

Main source crater

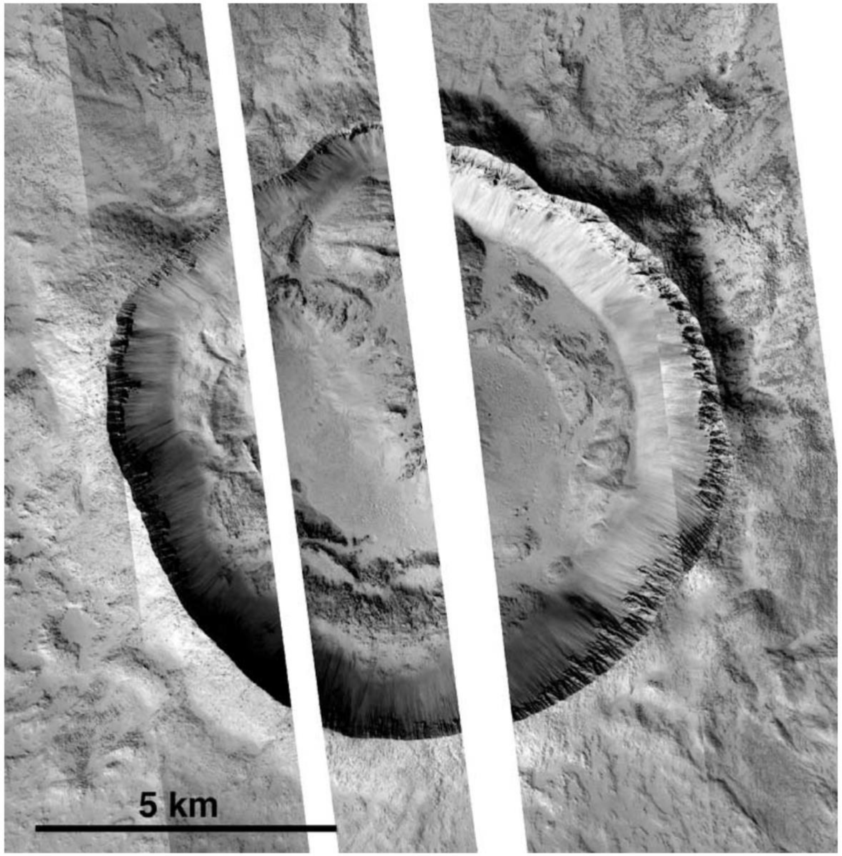


Figure 5. Mosaic of Zunil using 5 MOC images at 3–5 m/pixel. No impact craters superimposed on Zunil have been found. The unit covering the flat bottom of the crater is densely pitted, but these pits do not have raised rims or other characteristics of impact craters. The largest blocks in the near-rim ejecta are ~10 m diameter. North is up.

[Preblich+07]

Zunil crater

Diameter: 10.1 km
Longitude: 166 deg. East
Latitude: 7.7 deg. North
(Near the equator)

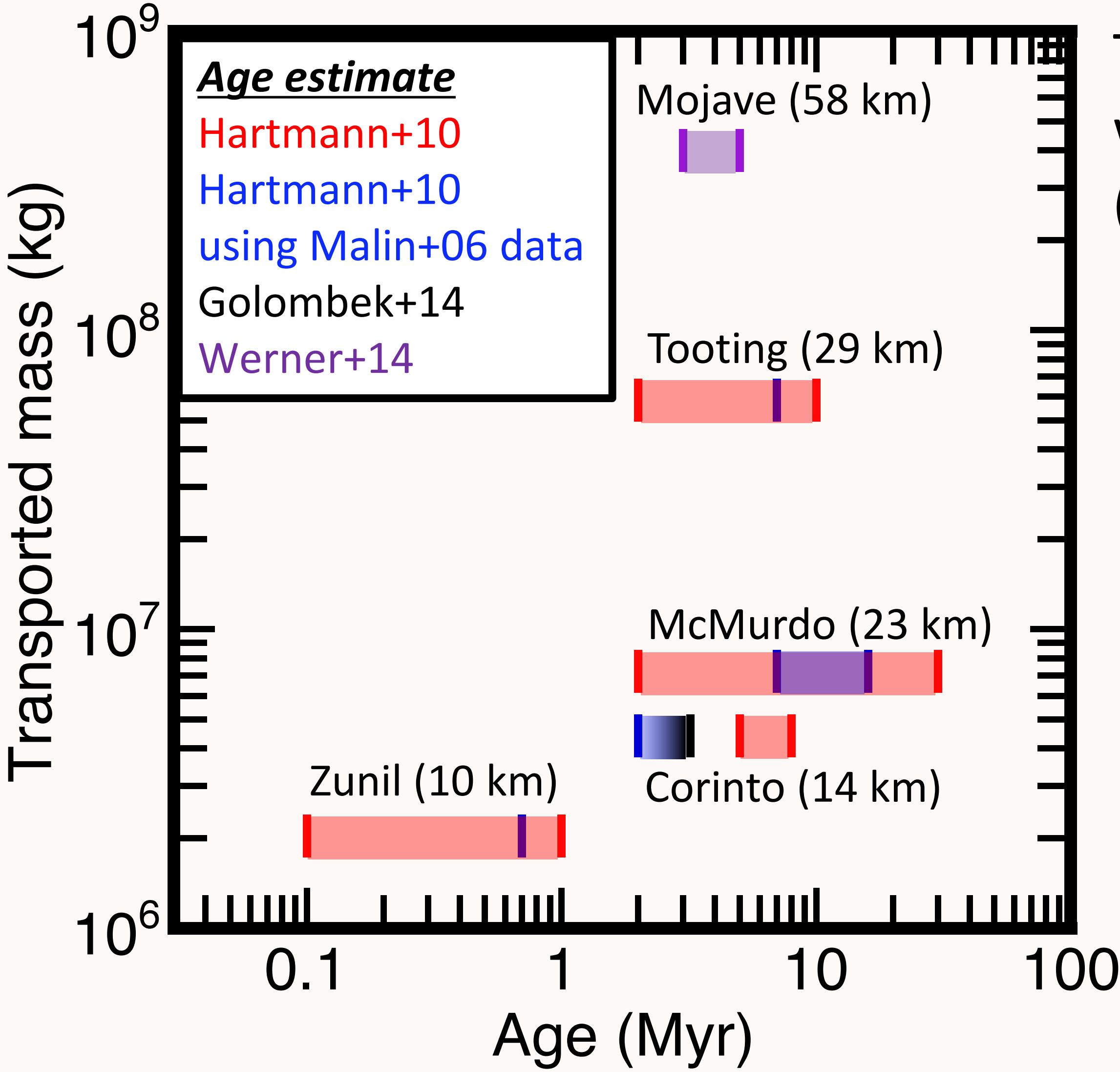
Impact direction: East-NorthEast
[Preblich+07]

Formation age: 0.1–1 Myr ago
[Hartmann+10]

The youngest-ray crater on Mars with a diameter of >10 km

The other craters

Transported mass to Phobos vs Formation age



Transported mass $M_{\text{transported}}$ was estimated in this study. (discuss later)

[Hyodo+, to be submitted]

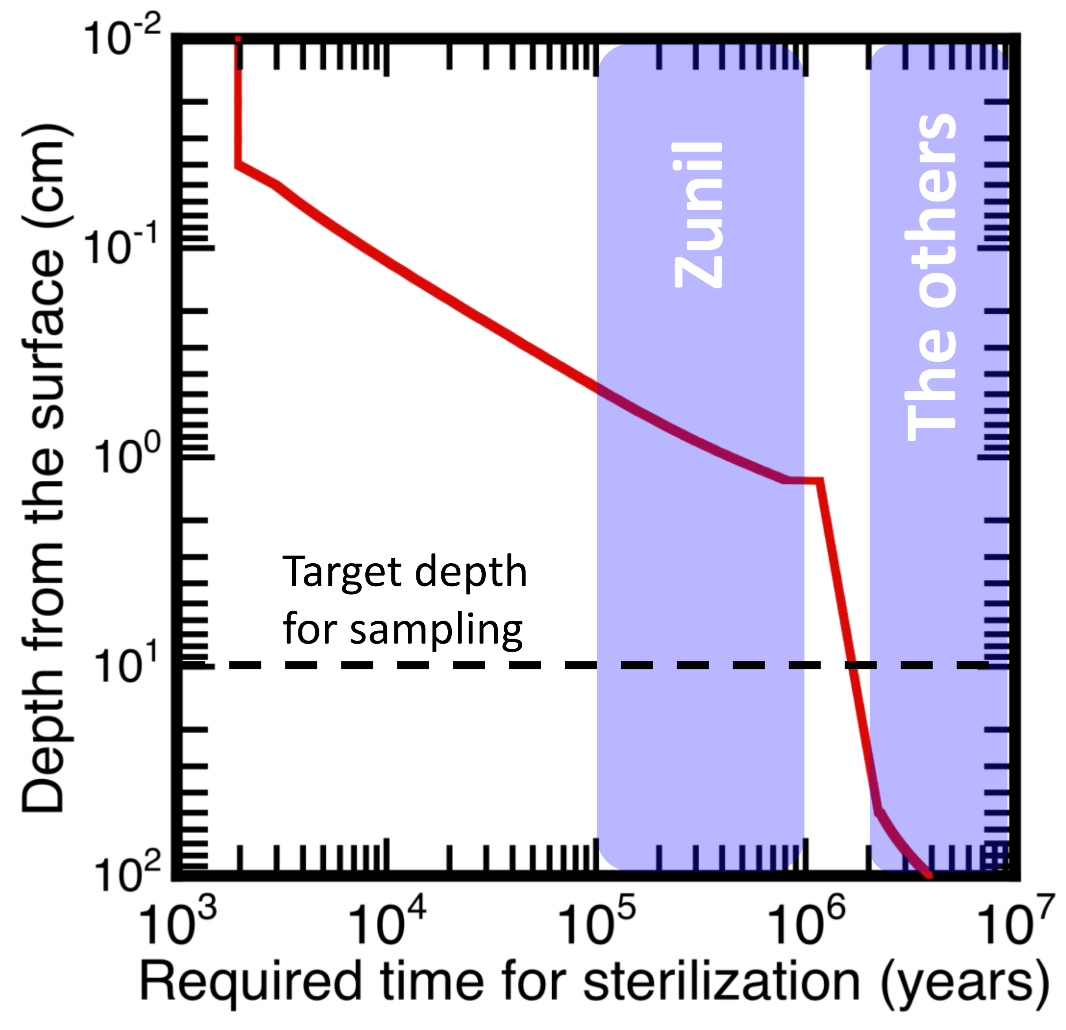
$M_{\text{transported}}$ strongly depends on D_f.

-> The smaller craters are not important.

The other large craters are much older than Zunil.

-> The microbes must be sterilized at the present. (Next slide)

Required time t_{req} for radiation sterilization



$$t_{req} = TC(H) \ln \left(\frac{N_0}{N_{th}} \right)$$

For conservative estimate,

$N_0 = 10^7$ (CFU/kg)

$N_{th} = 10^{-5}$ (CFU/kg)

(Req-10 for 100 g sampling)

Depth (cm)	t_{req} (years)
<0.04	2.0×10^3
1	4.4×10^5
10	1.7×10^6
30	2.0×10^6

The microbes from the other craters must be sterilized until now.

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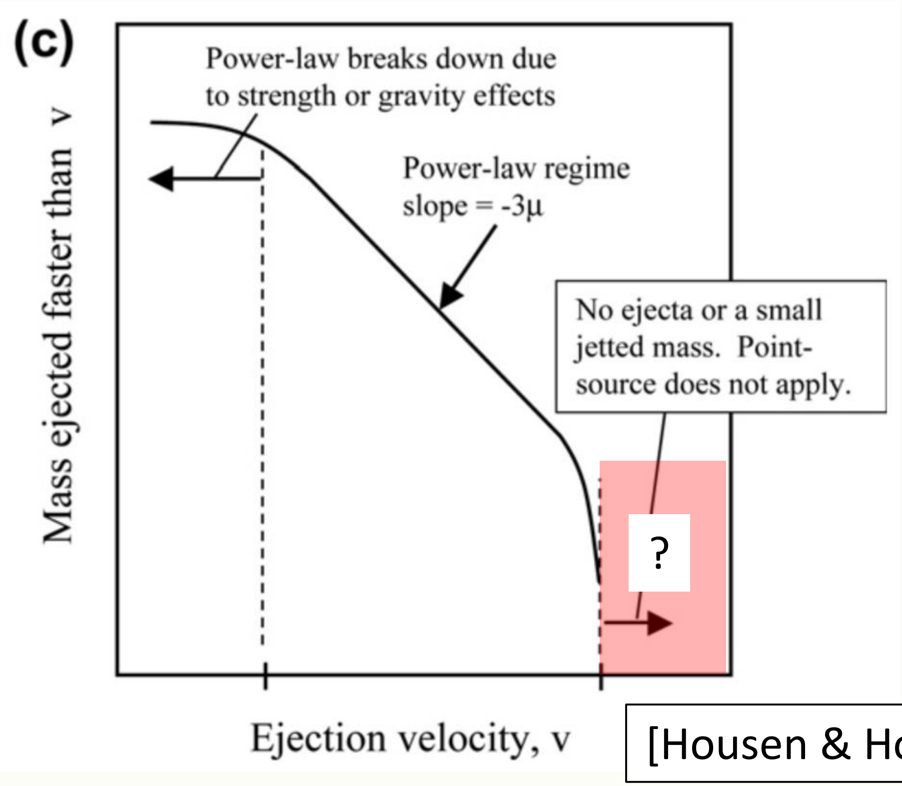
Launch

Difficulties in the estimation of the mass of high-speed ejecta

High-speed ejection at velocities higher than ~20% of v_{imp} cannot be treated by the widely-used point-source theory

[Melosh84; Kurosawa&Takada19]



[Housen & Holsapple11]

<-Velocity-volume behavior in the point-source theory

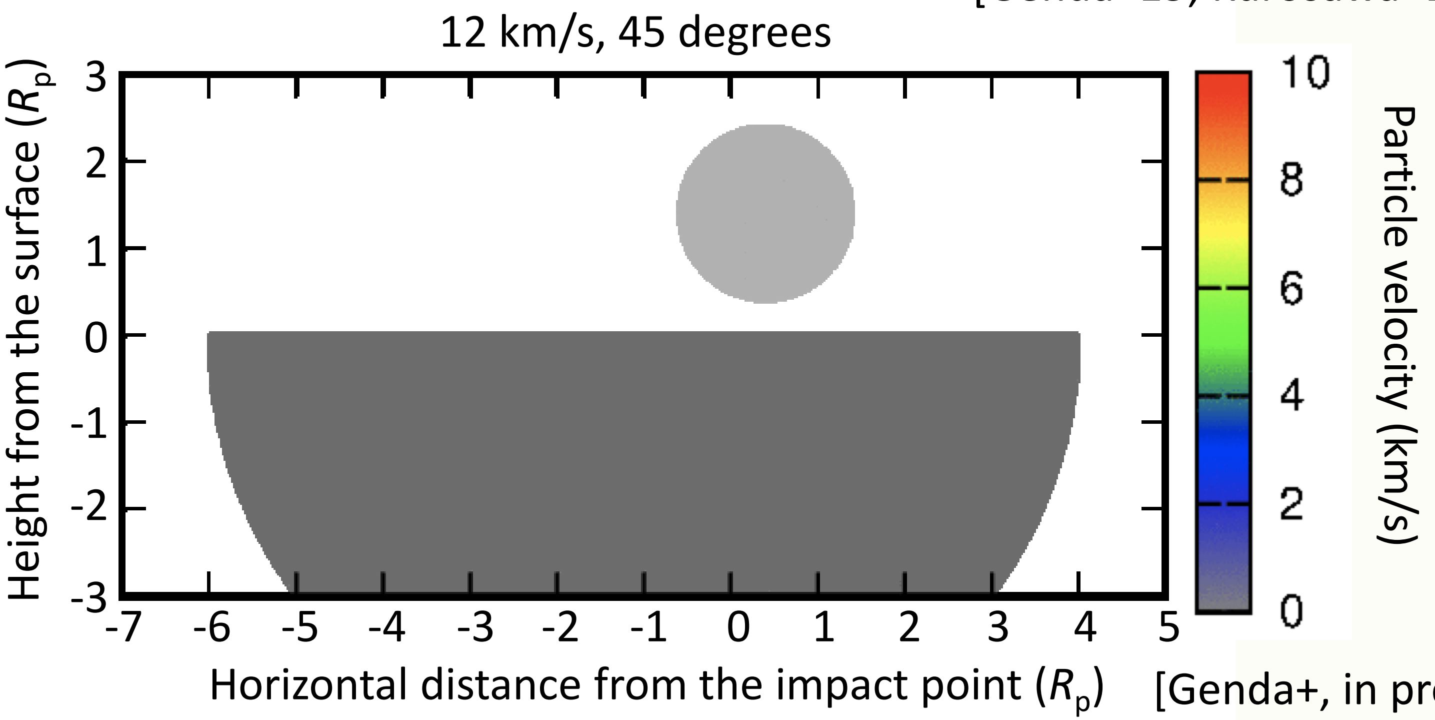
※The previous studies used the point-source theory

[Chappaz+13; SterLim study]

Numerical simulations are necessary to address the total mass of high-speed ejecta M_{ej}.

3-D SPH simulation

A three-dimensional Smoothed Particle Hydrodynamics code was used.
[Genda+15; Kurosawa+18; Genda+, in prep.]



[Genda+, in prep.]

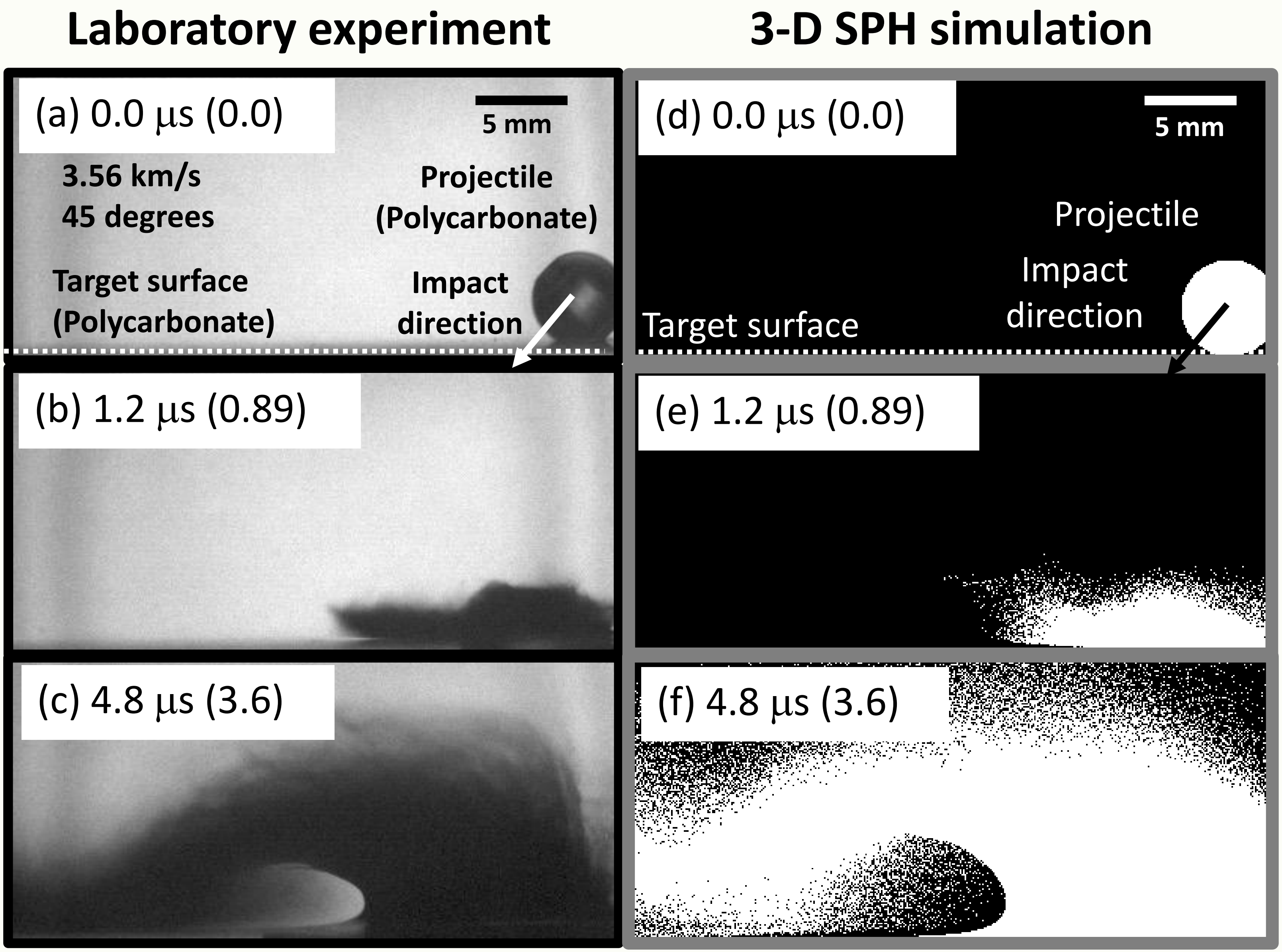
Calculation conditions

- Granite projectile onto Granite target (Tillotson EOS)
- Impact velocity v_{imp}: 6, 9, 12, 15, 18 km/s
- Impact angle θ_{imp}: 15, 30, 45, 60, 75, 90 degrees
- No gravity and strength (Scale-free calculation)

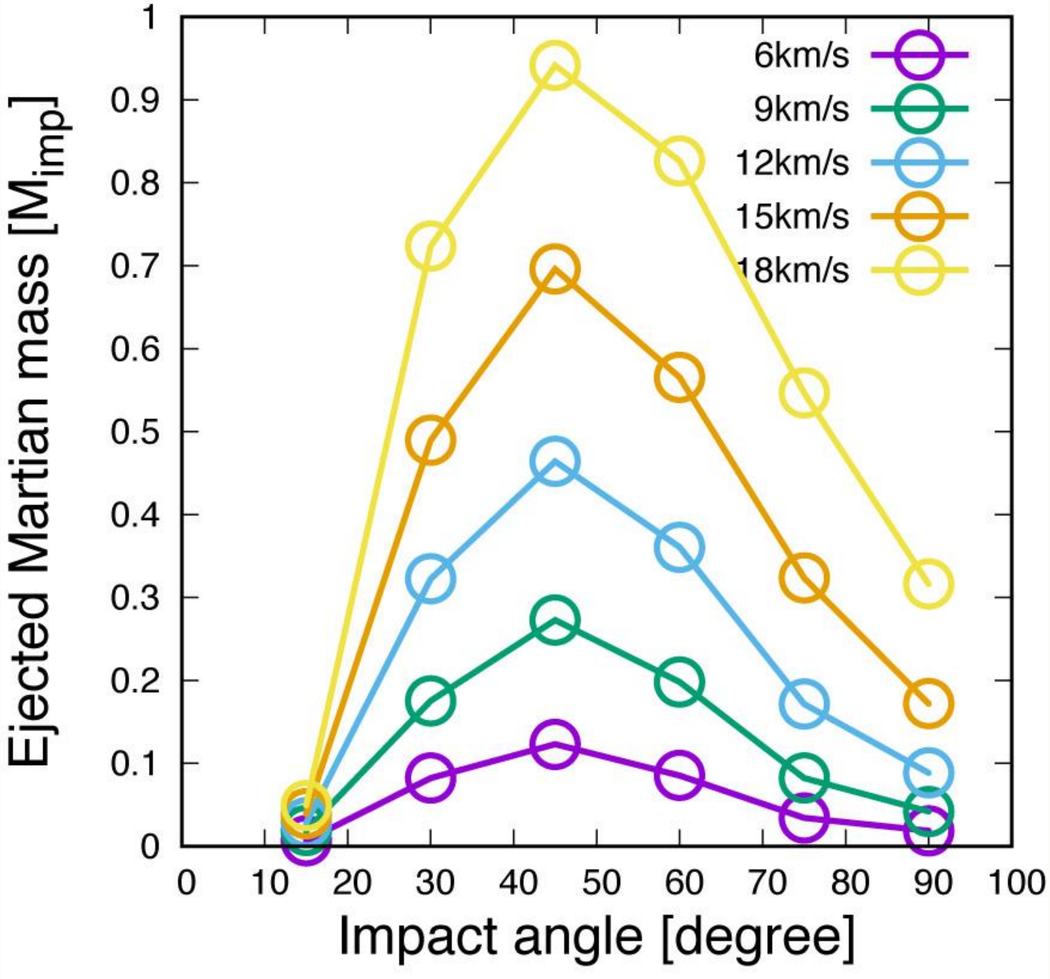
→ Total 30 runs

Experimental validation

[Okamoto, Kurosawa, Genda & Matsui, to be submitted]



High-speed ejecta mass M_{ej}(>3.5 km/s)



Strongly depends on both v_{imp} and θ_{imp}

Consistent with Artemieva&Ivanov04

Zunil-forming impact conditions

Given that we know the projectile size,
the absolute value of M_{ej} can be obtained.
-> We searched for the impact conditions that reproduce
the observed crater diameter D_f of the Zunil crater (10.1 km)

Crater scaling laws [Schmidt & Housen87]

$$D_{tr} = \left(\frac{\pi}{6}\right)^{\frac{1}{3}} C_D \left(\frac{4\pi}{3}\right)^{-\frac{\beta}{3}} \left(\frac{\rho_p}{\rho_t}\right)^{\frac{1}{3}} D_p^{1-\beta} g^{-\beta} \left(v_{imp} \sin\theta_{imp}\right)^{2\beta}$$

$C_D = 1.4$
$\beta = 0.17$
(Dry sand)

An empirical law for crater collapse [McKinnon+91]

$$D_f = 1.2 D_c^{-0.13} D_{tr}^{1.13}$$

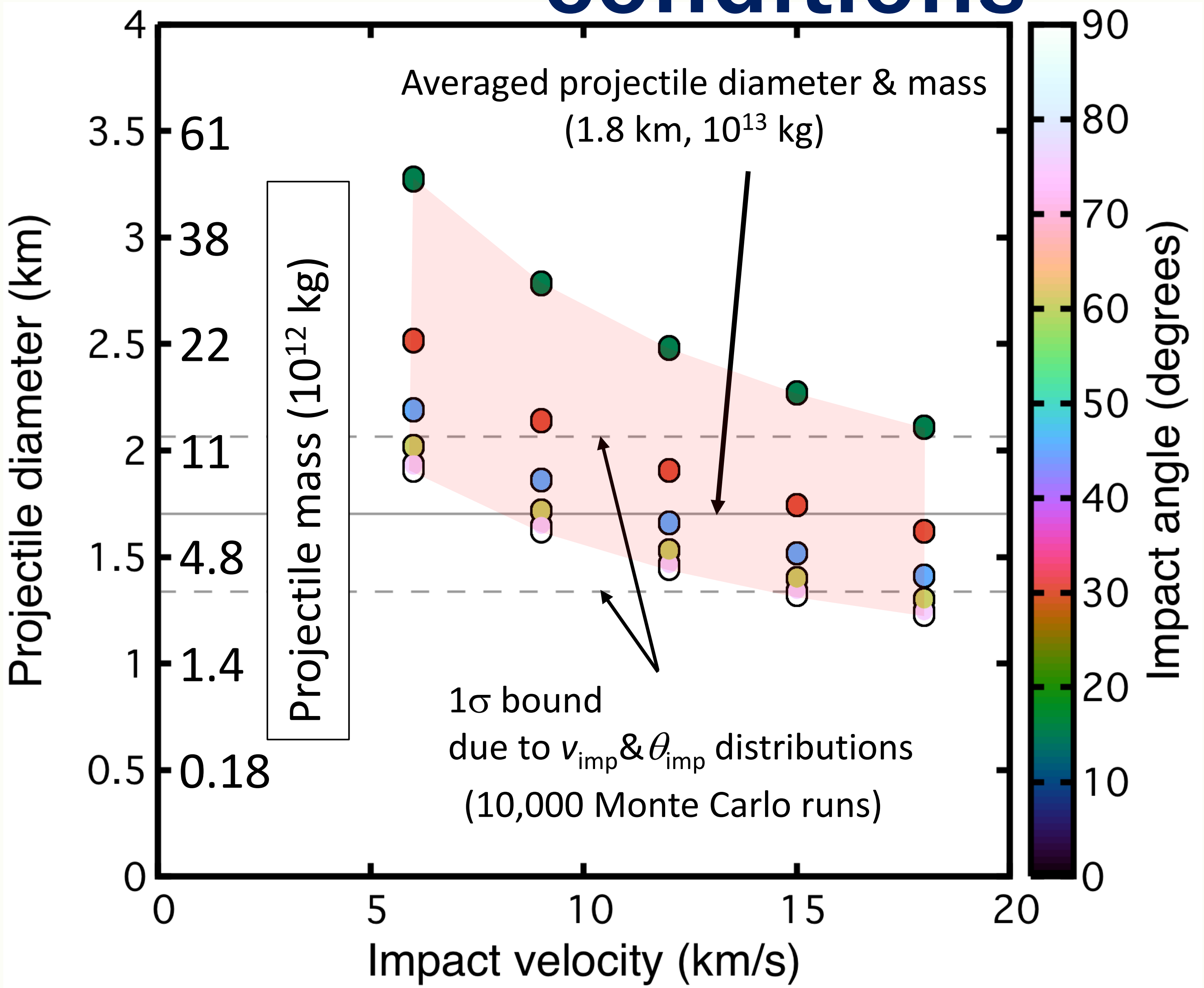
D_c = 7 km for Mars [Pike88]

Impact velocity distribution: Rayleigh [Zahnle+03]

Averaged impact velocity onto Mars = 14 km/s
[Ito&Malhotra06]

Impact angle distribution: $\sin(2\theta_{imp})$ [Shoemaker62]

Zunil-forming impact conditions



Sterilization during ejection

Sterilization during the launch

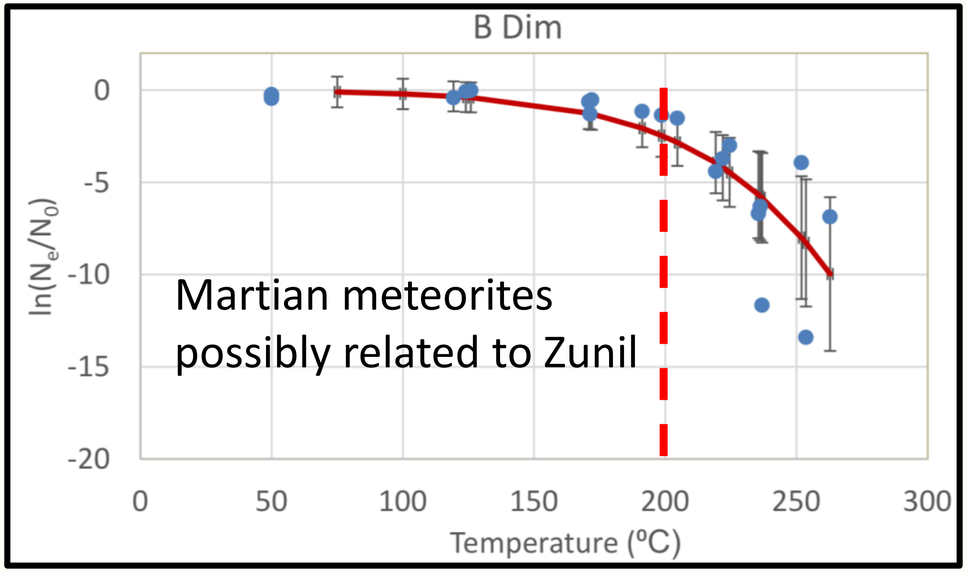
Major (>1 kg) Martian meteorites having young ejection ages (~1 Myr)

Name	Ejection age (Myr)	Mass (kg)	P_{peak} (GPa)	$T_{post\_calc} - T_0$(K)
EETA79001	0.73 ± 0.15	7.94	34 ± 2	**250 ± 50**
Tissint	0.7 ± 0.3	7-11		
DaG 476	1.24 ± 0.12	2.02	35–40	**400 ± 50**
SaU 005	1.5 ± 0.3	1.34	35–40	**400 ± 50**

Same event (EETA79001 and Tissint) [e.g., Chennaoui Aoudjehane+12]

[Nyquist+01; Chennaoui Aoudjehane+12]

The estimated temperature are from thermodynamic calculations, *NOT* from any measurements.



$\ln(N/N_0) \sim -2.5$

$\rightarrow N/N_0 \sim 0.1$

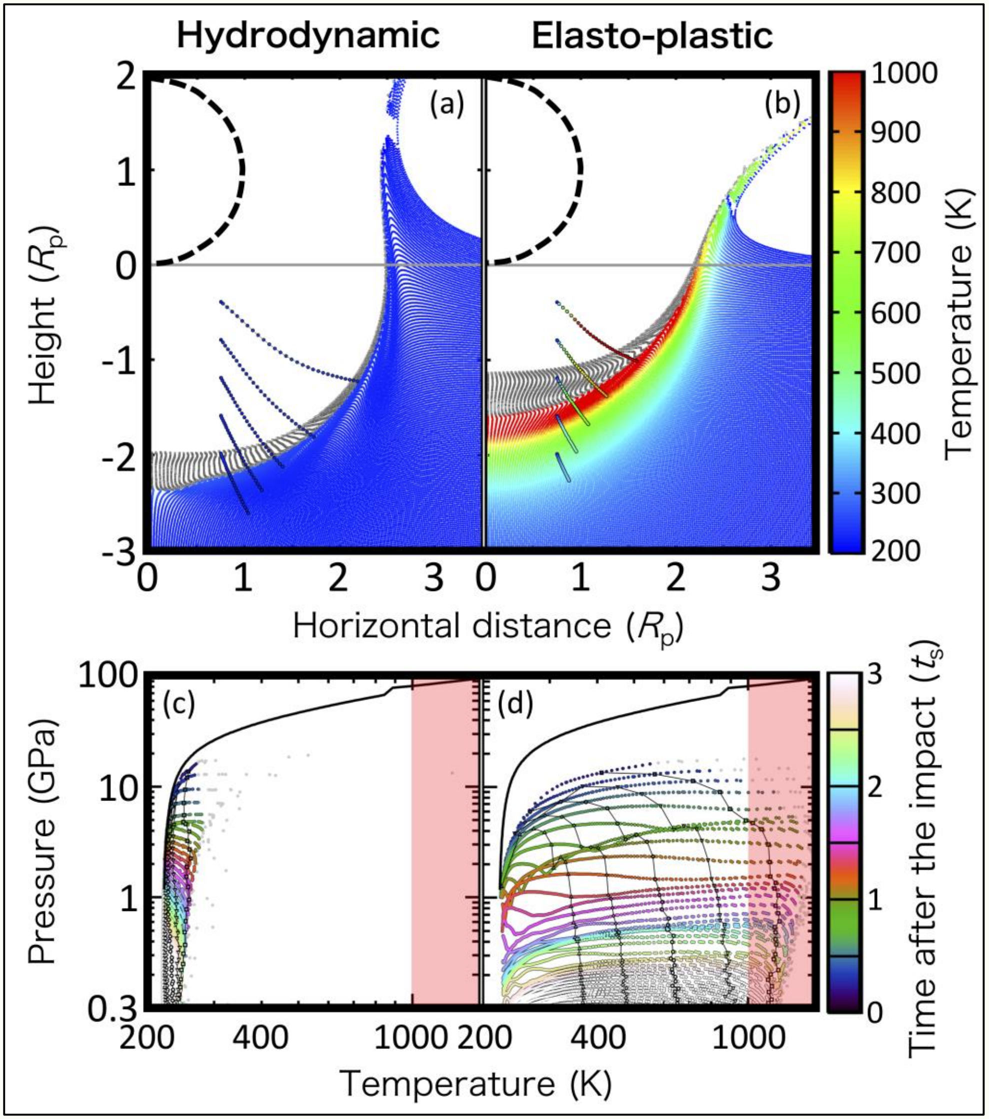
The survival rate immediately after the launch is likely to be ~0.1.

SterLim Heat test [Patel+18]

Roles of Plastic deformation

[Kurosawa & Genda18]

The estimated-post-shock temperatures are likely to be underestimated.



2-D iSALE calculations

Dunite->Dunite (ANEOS)

v_{imp} = 3 km/s

θ_{imp} = 90 degrees

The degree of shock heating is significantly higher than the case of purely hydrodynamic.

"This heat source has surprisingly escaped explicit attention for decades"

[Comments by Melosh & Ivanov18, GRL]

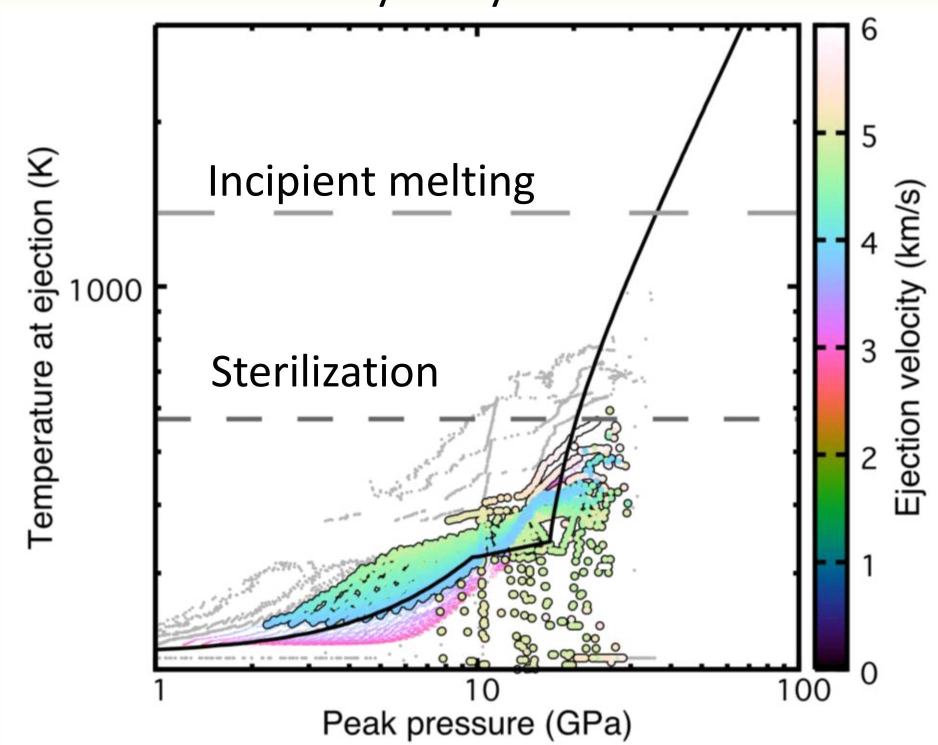
High-resolution numerical model

2-D iSALE shock physics code allows us to address
the degree of shock heating during impact spallation.

[Kurosawa+18]

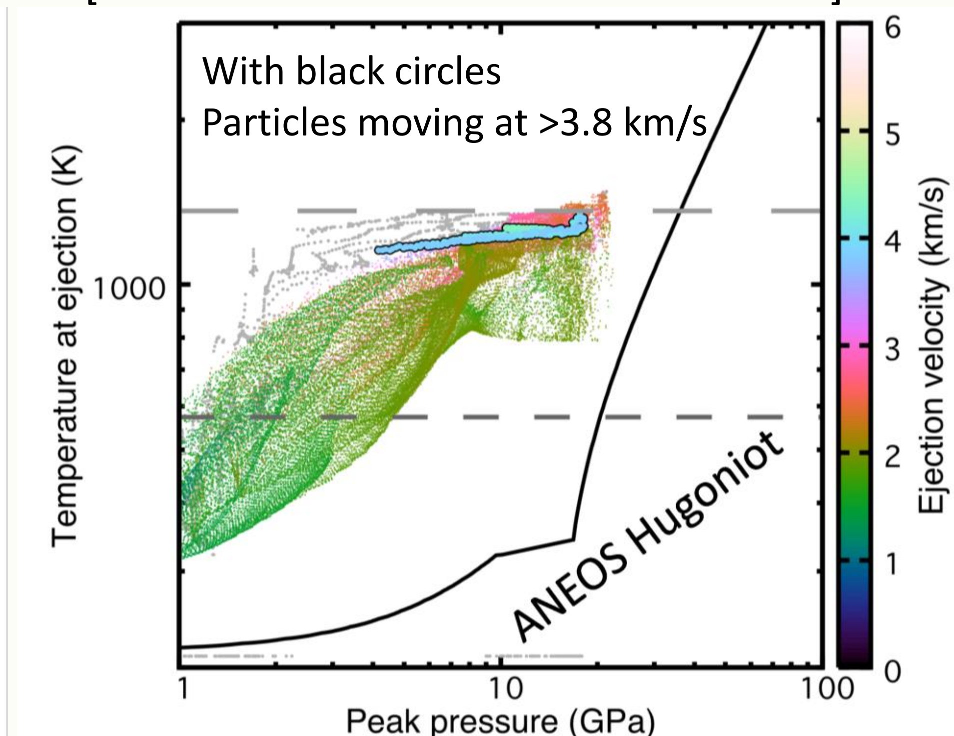
Basalt -> Basalt (ANEOS)
v_{imp} = 3.5 km/s (The normal component of 5 km/s at 45 degrees)
1000 cells per projectile radius

Hydrodynamic



Consistent with Artemieva & Ivanov04

Elasto-plastic
[Parameters are taken from Ivanov+10]



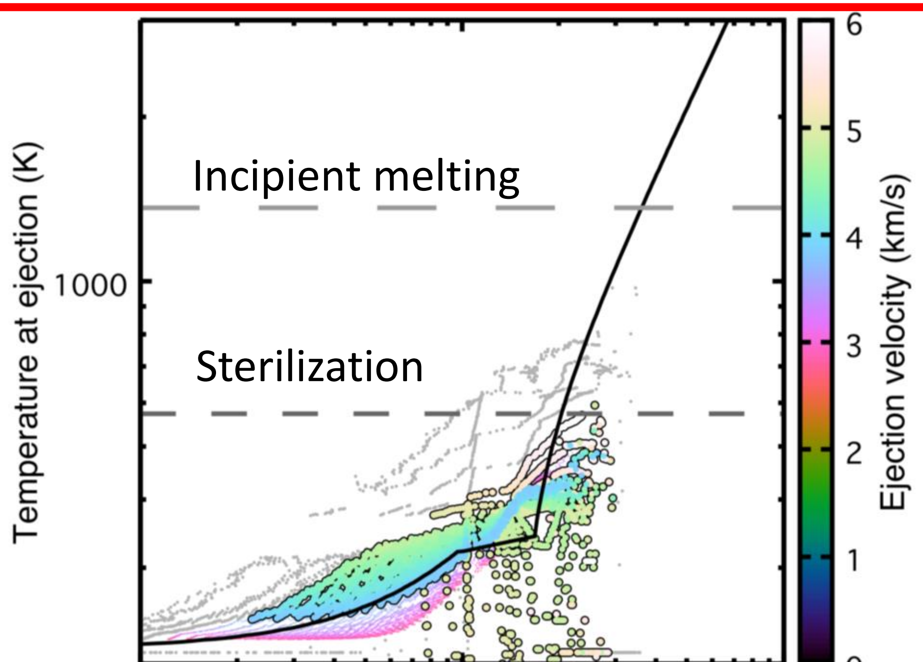
High-resolution numerical

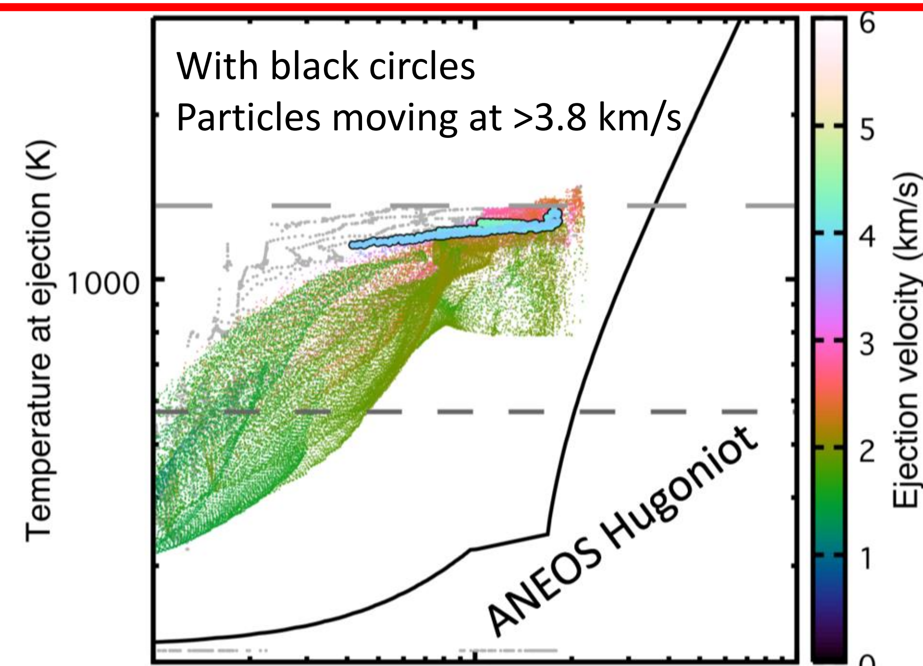
Low-temperature ejection is hard to be explained by impact physics.

Unknown special condition(s) is required for ejecting high-speed materials with the low degree of heating.

The impact-survival rate during the launch is likely to be << 1.

Survival rate after the launch 0.1 is expected to be highly conservative.



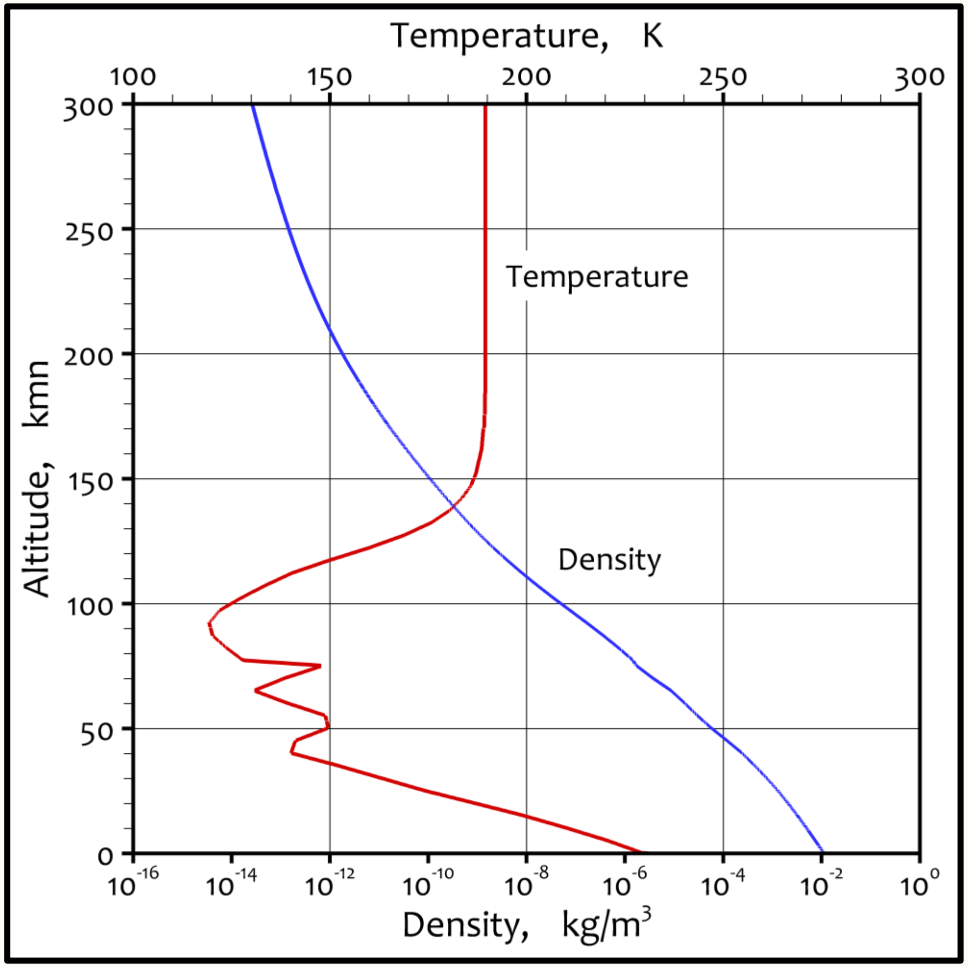


Acknowledgements:

We thank the developers of iSALE, including G. Collins, K. Wünnemann, B. Ivanov, J. Melosh, and D. Elbeshausen.

Aerodynamic heating

Aerodynamic heating



The standard atmospheric model for Mars
[Duvall+05; Justus+05]

Atmospheric condition

Composition: 95% CO_2, 5% N_2

T & ρ profile: Mars-GRAM 2005 v1.3
[Duvall+05; Justus+05]

Mars rocks

Perfect sphere

Density: 2.8×10^3 kg/m^3

Specific heat: 10^3 J/K/kg

Thermal conductivity: 2.3 W/m/K

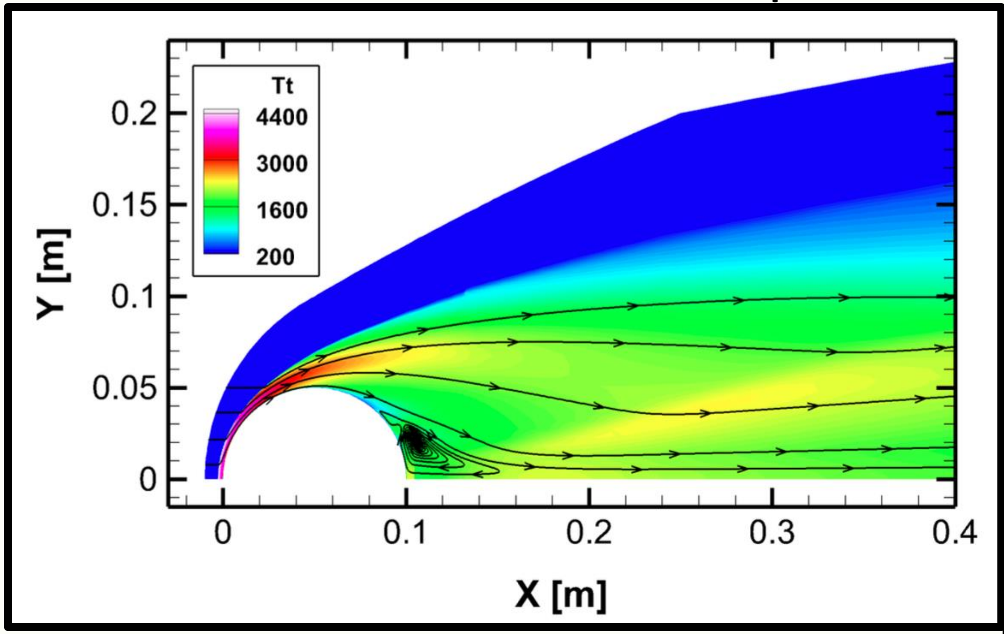
Emissivity: 0.95

A compressible flow solver

JAXA Optimized Nonequilibrium Aerodynamic Analysis code (JONATHAN)

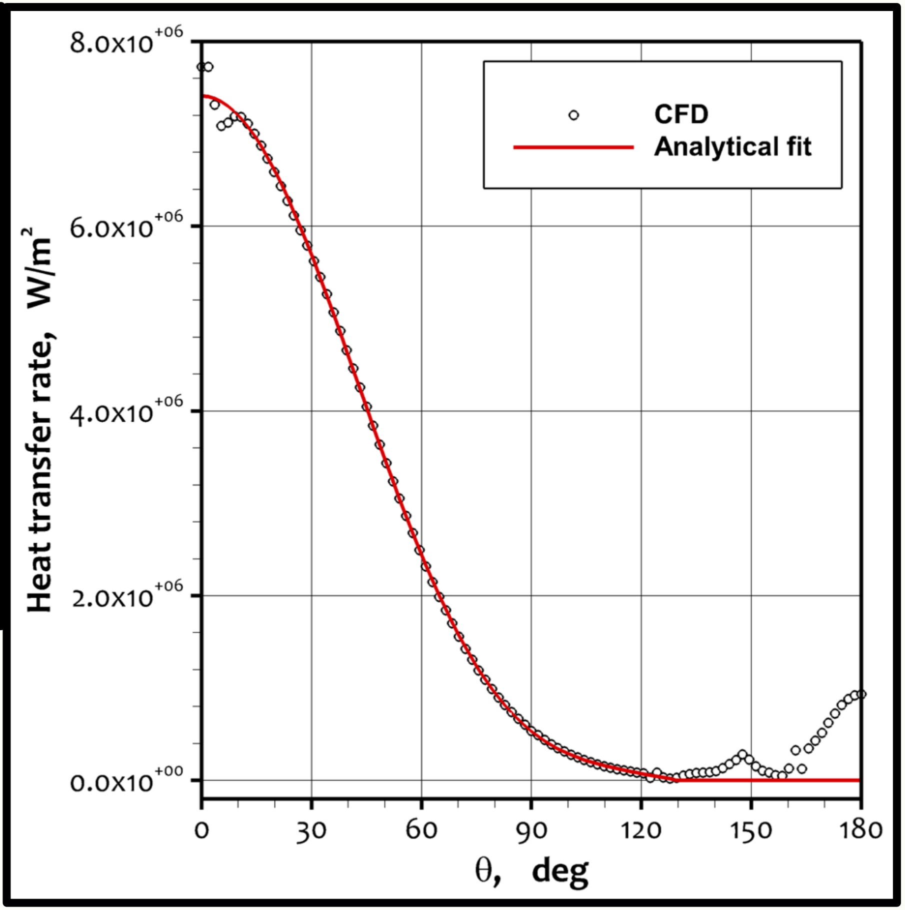
[Fujita+06]

Gas flow around 10 cm sphere



3.8 km/s at the ground condition

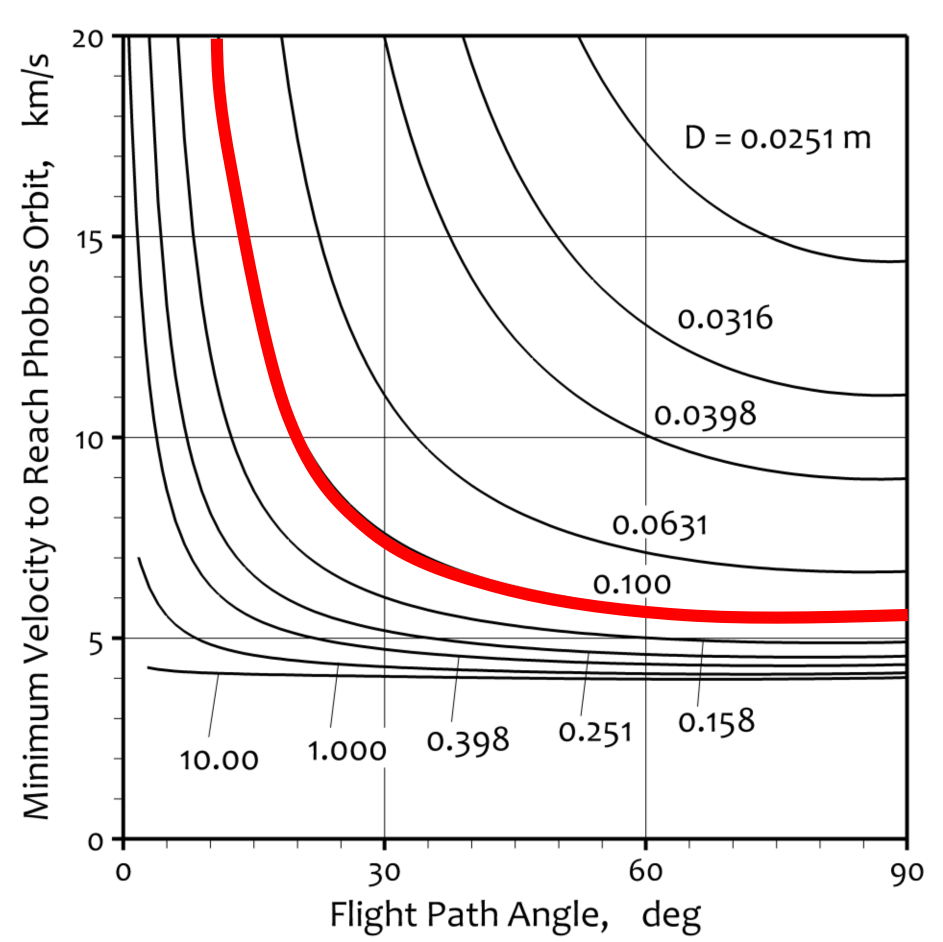
Heat transfer rate



Trajectory analyses code[Fujita+12]

-> The minimum size required for the penetration into the atmosphere is ~10 cm.

Minimum size of Mars ejecta

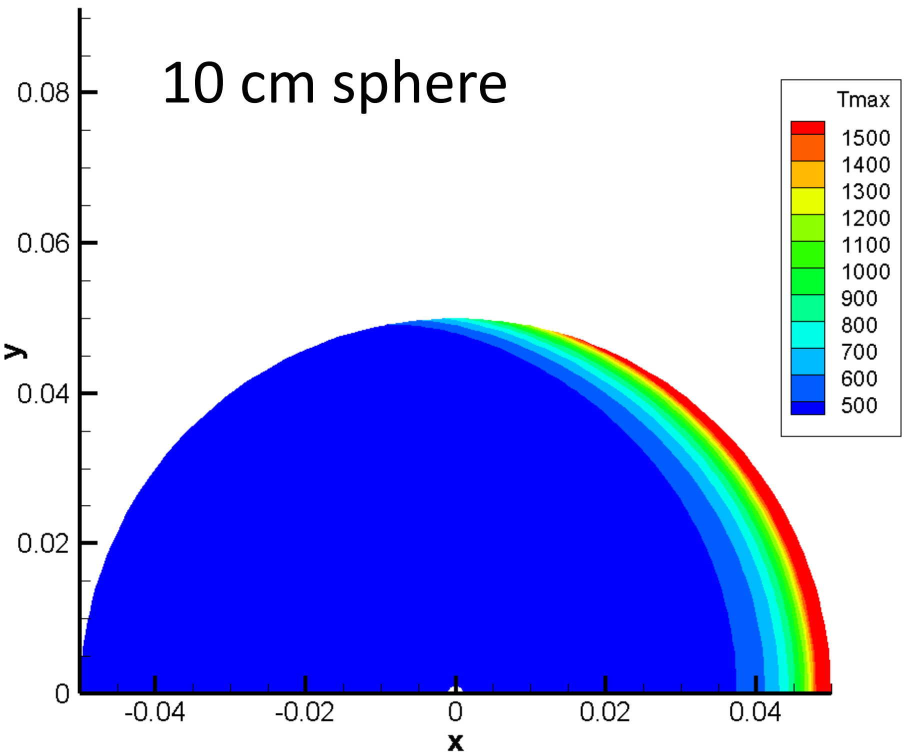


<10 cm particles are largely affected by aerodynamic effects during the atmospheric passage.

We set the minimum size of Mars ejecta to be 10 cm.

Thermal conduction

Maximum temperature distribution



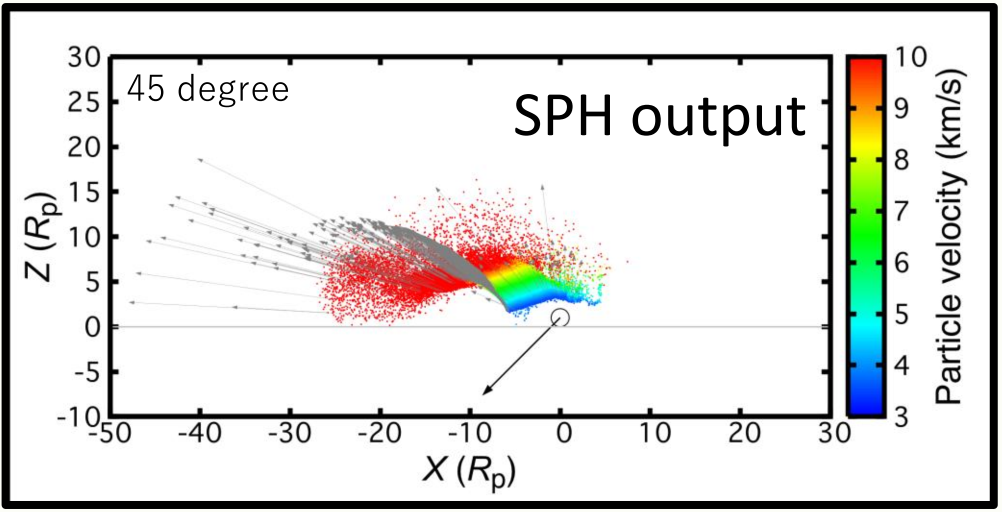
Flight path angle (deg)	Survival rate (N/N_0)
45	0.87
60	0.89
75	0.90
90	0.90

Sterilization condition:
773 K, >0.5 s

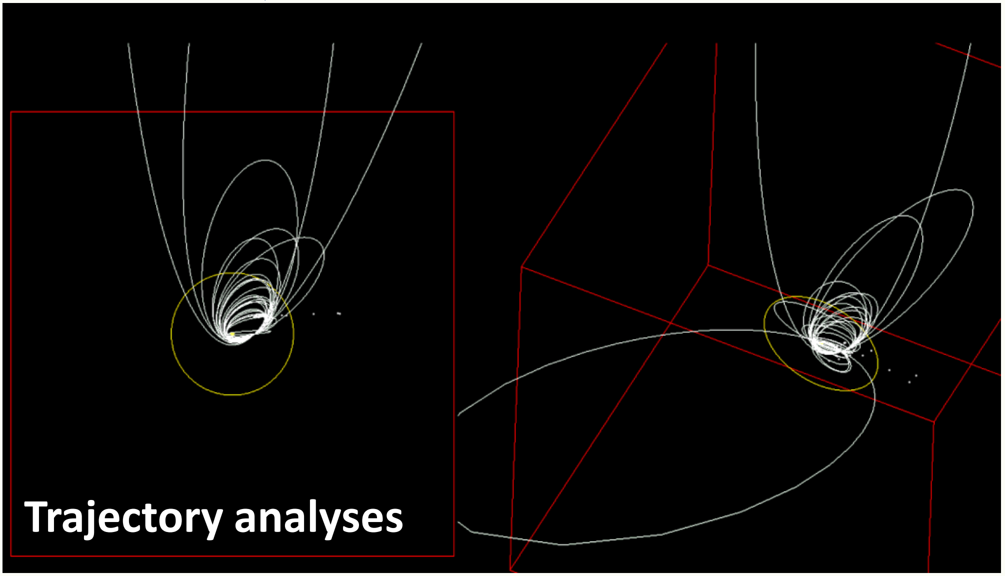
The effects of aerodynamic heating on the microbe sterilization is minor.

Orbital evolution

Orbital calculation



By assuming ballistic flight under Mars gravity



Impact conditions: were chosen to match D_f of 10 km. (previous slide)

v_{imp}: Rayleigh (6–18 km/s, 3 km/s step)

θ_{imp}: $\sin(2\theta_{imp})$ (15–90 deg., 15 deg. step)

Impact location: The Zunil location (7.7N, 166E)

Impact direction: NorthEast – East

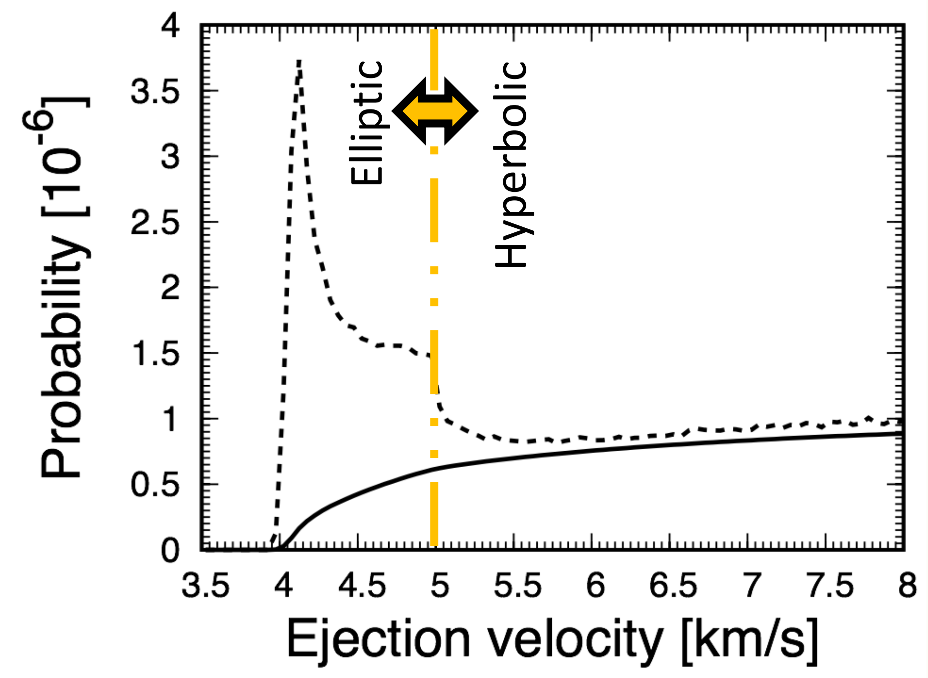
※ Mars rocks are injected into the retrograde orbits, leading to frequent high-speed collisions.

Phase angle of the moons: Random

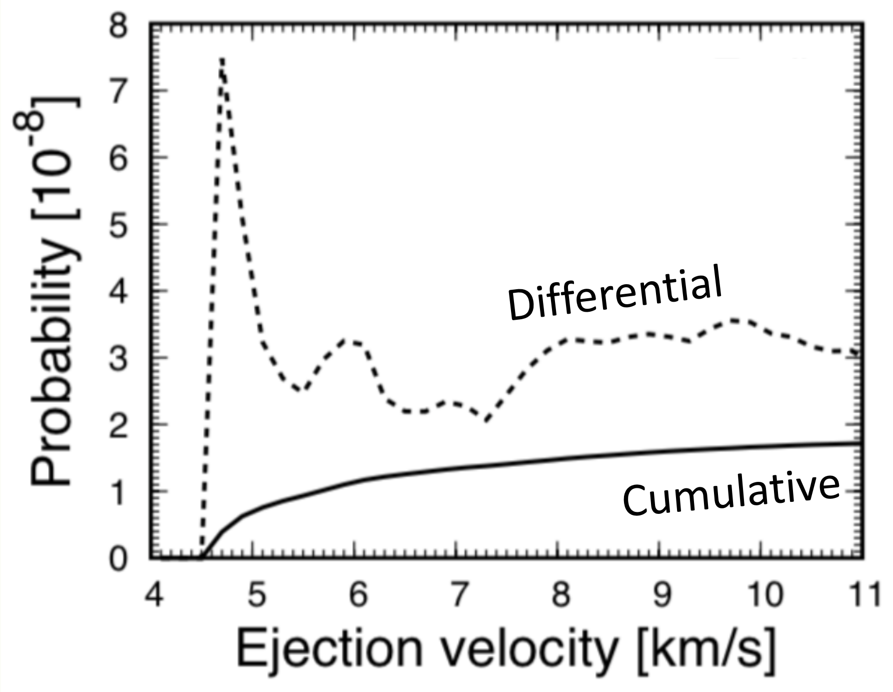
Total 10,000 Monte Carlo runs

Transport probability

To Phobos



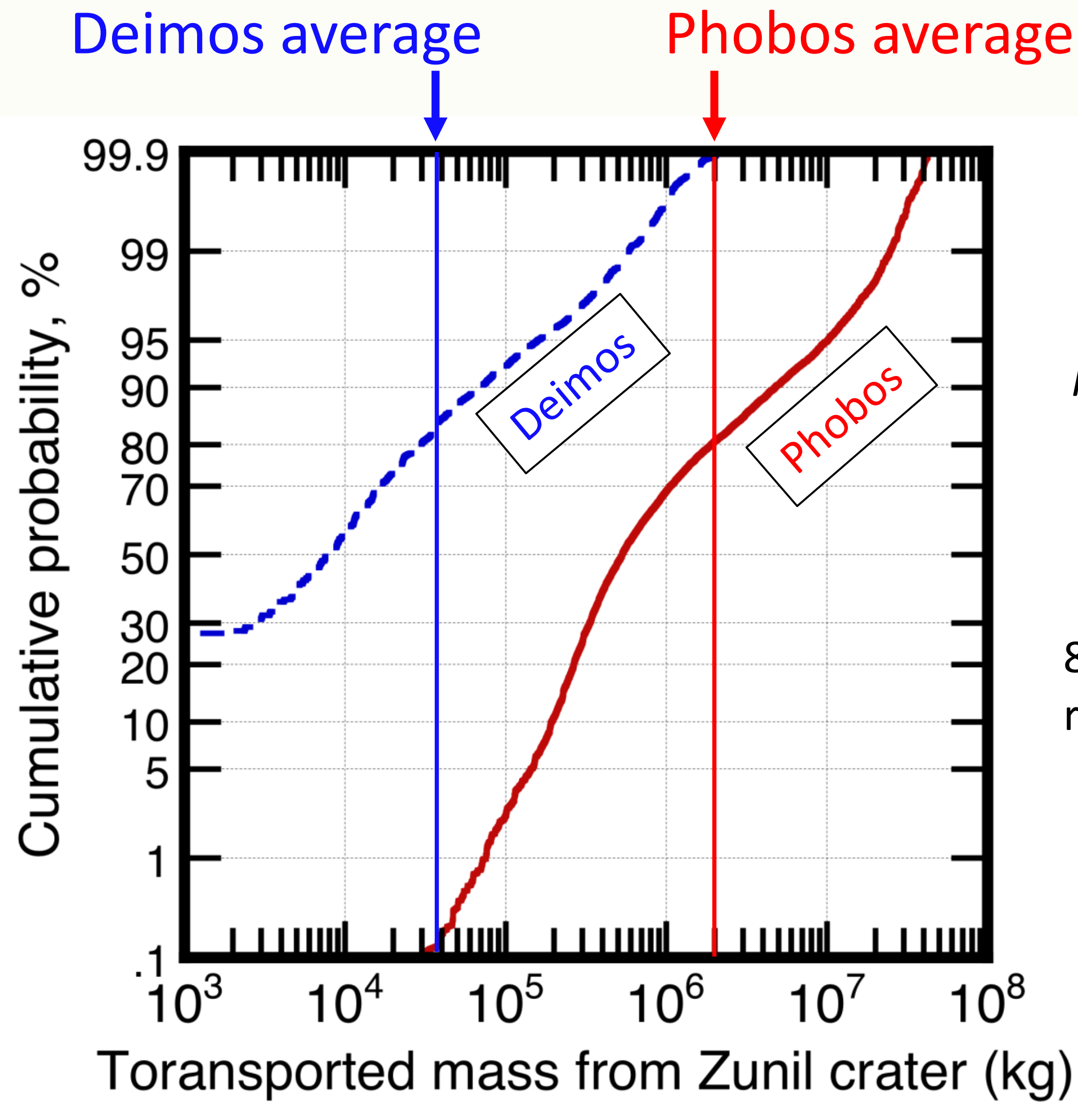
To Deimos



Total transported mass from Mars to Martian moons

$$M_{\mathrm{transported}} = \begin{cases} 2.0 \times 10^{6}\ \mathrm{kg} & \text{(Phobos)} \\ 3.8 \times 10^{4}\ \mathrm{kg} & \text{(Deimos)} \end{cases}$$

Transported mass distribution



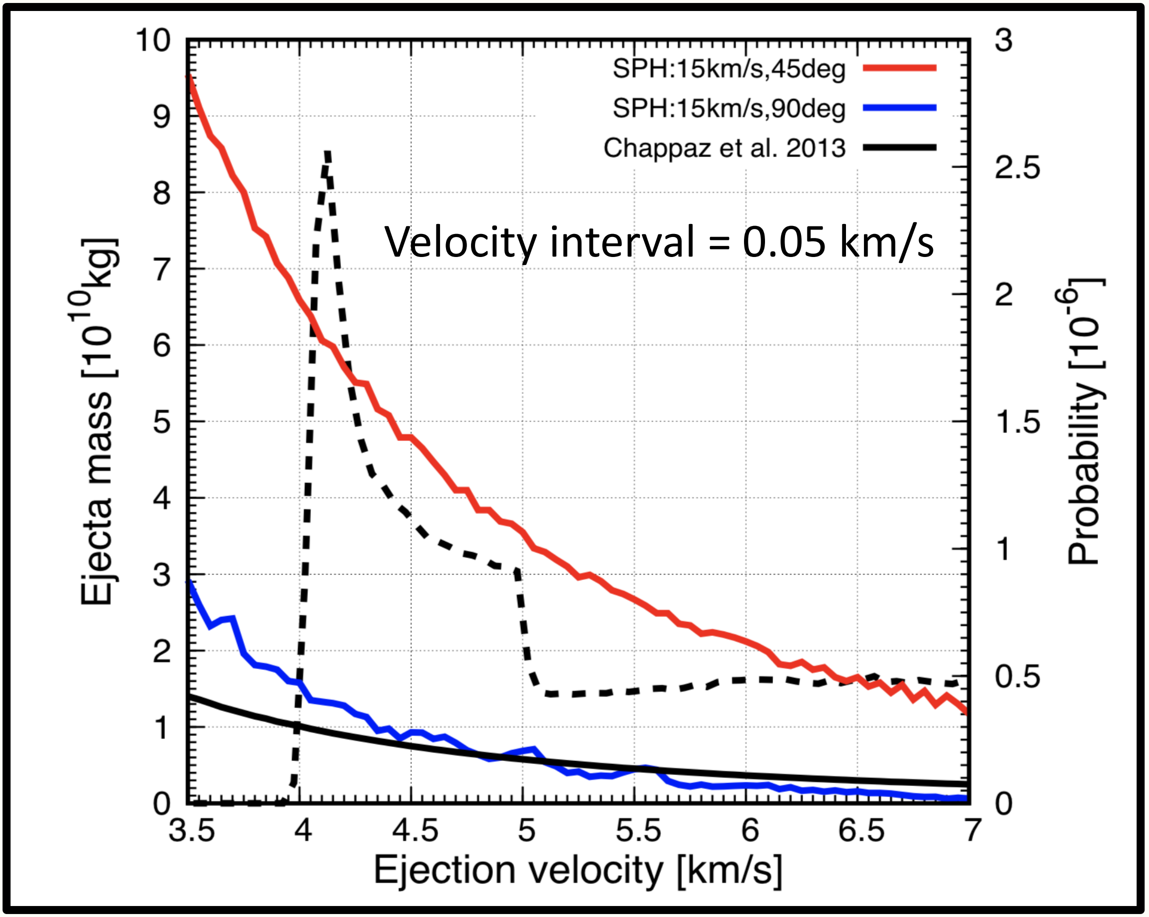
The averaged values were employed.

$$M_{\text{transported}} = \begin{cases} 2.0 \times 10^6 \text{ kg (Phobos)} \\ 3.8 \times 10^4 \text{ kg (Deimos)} \end{cases}$$

80% of Monte Carlo runs (8000 runs) result in the smaller mass transportation.

A 10-times mass transportation could occur. But, it is statistically rare.

Difference from Chappaz+13
v_{ej}-M_{ej} distribution



The Mars rocks launched at 4–5 km/s are efficiently transported to Phobos.

Oblique impacts produce Mars ejecta
with the mass several times than vertical impacts.

Total transported microbes N_{total}

Initial microbe density on Mars n_{Mars} = 10^8 CFU/kg

Survival rate after the launch = 0.1

Survival rate due to aerodynamic heating = 1

Total transported mass $M_{transported}$ = $\begin{cases} 2.0 \times 10^6 \text{ kg} & \text{(Phobos)} \\ 3.8 \times 10^4 \text{ kg} & \text{(Deimos)} \end{cases}$

Total transported microbes N_{total} = $\begin{cases} 2.0 \times 10^{13} \text{ CFU} & \text{(Phobos)} \\ 3.8 \times 10^{11} \text{ CFU} & \text{(Deimos)} \end{cases}$

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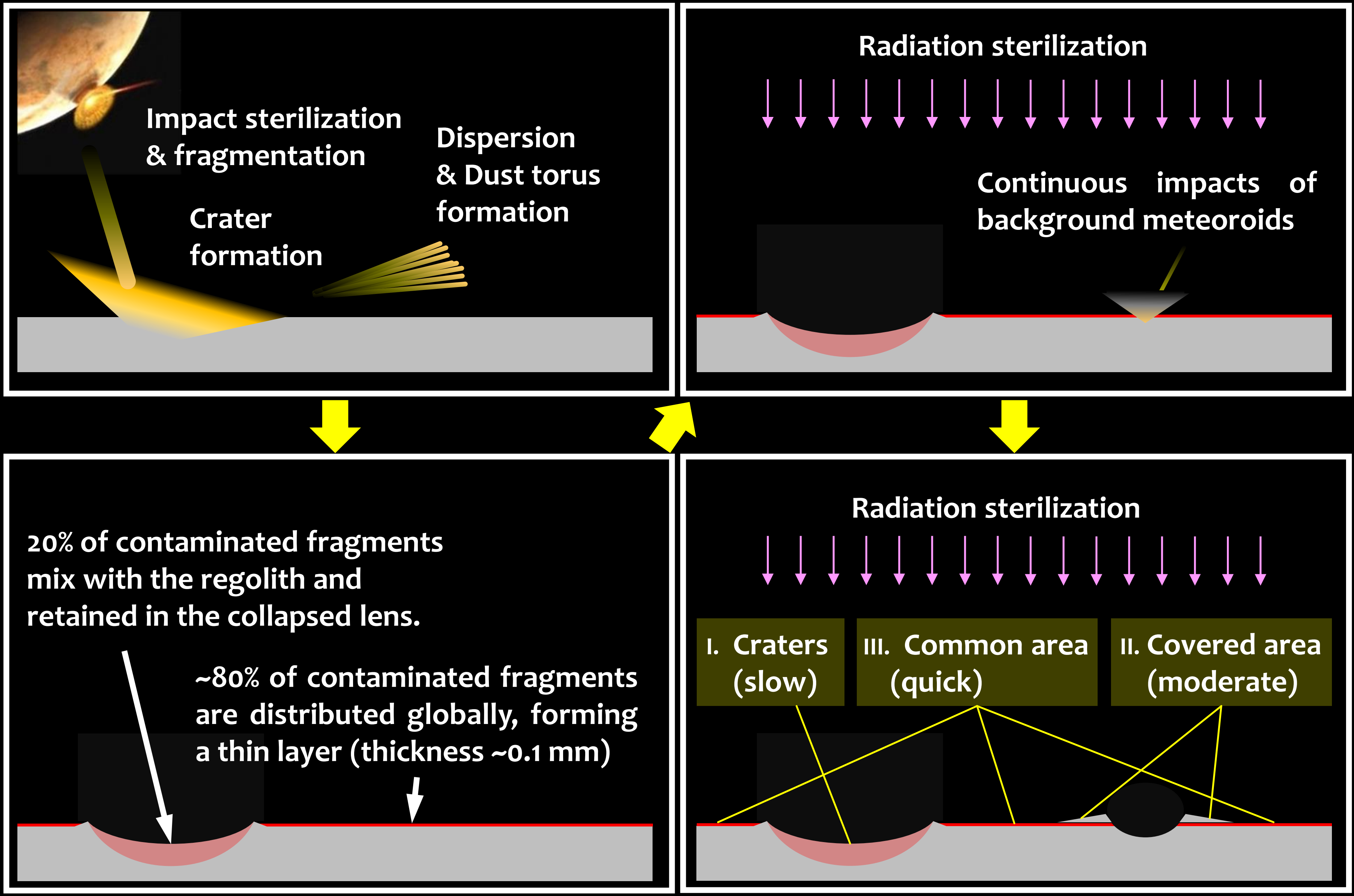
Processes considered in this work

Time sequence



Characterization of Mars rocks

-Size

-v_{imp} & θ_{imp} distributions

Size & Total number

The size-frequency distribution of high-speed ejecta is highly uncertain.
[Melosh11; Chappaz+13; Melosh+17]

For conservative estimate, “10 cm-assumption” was employed.
-> All Mars rocks were assumed to be spheres with a diameter of 10 cm.

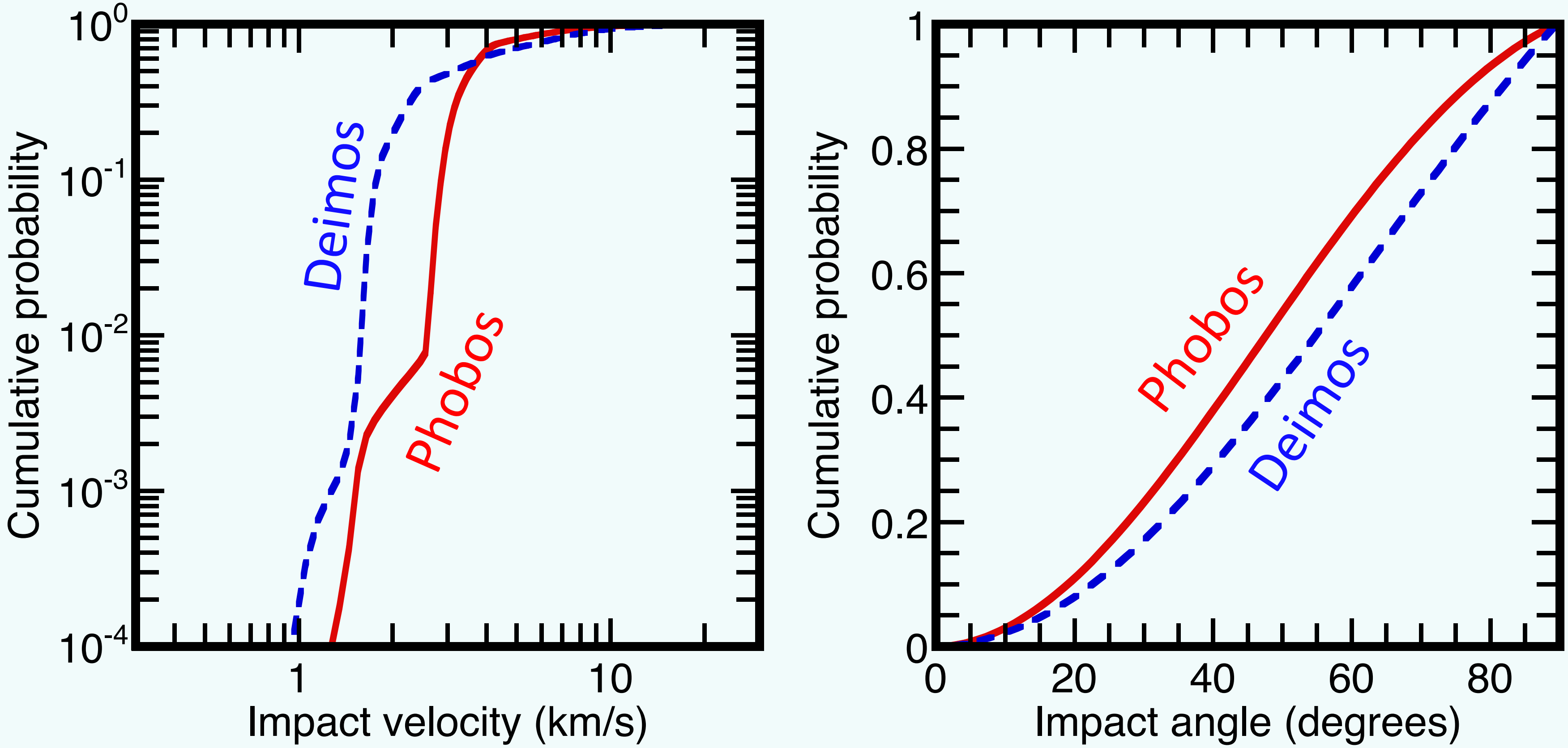
※The minimum size required for the penetration of the Martian atmosphere is ~10 cm.
[Artemieva & Ivanov04; Our aerodynamic analysis]

$$\text{The total number of Mars rocks} = \begin{cases} 1.4 \times 10^{6} & \text{(Phobos)} \\ 2.7 \times 10^{4} & \text{(Deimos)} \end{cases}$$

The assumption yields the maximum contaminated area.

v_{imp} & θ_{imp} distributions

Obtained in the orbital calculations



We extracted v_{imp} & θ_{imp} for each Mars rock from the distributions by a Monte Carlo method.

[e.g., de Niem+12; Kurosawa15; Kurokawa+18]

The fate of projectiles

1. Fragmentation
2. Projectile retention or dispersion

Fragmentation

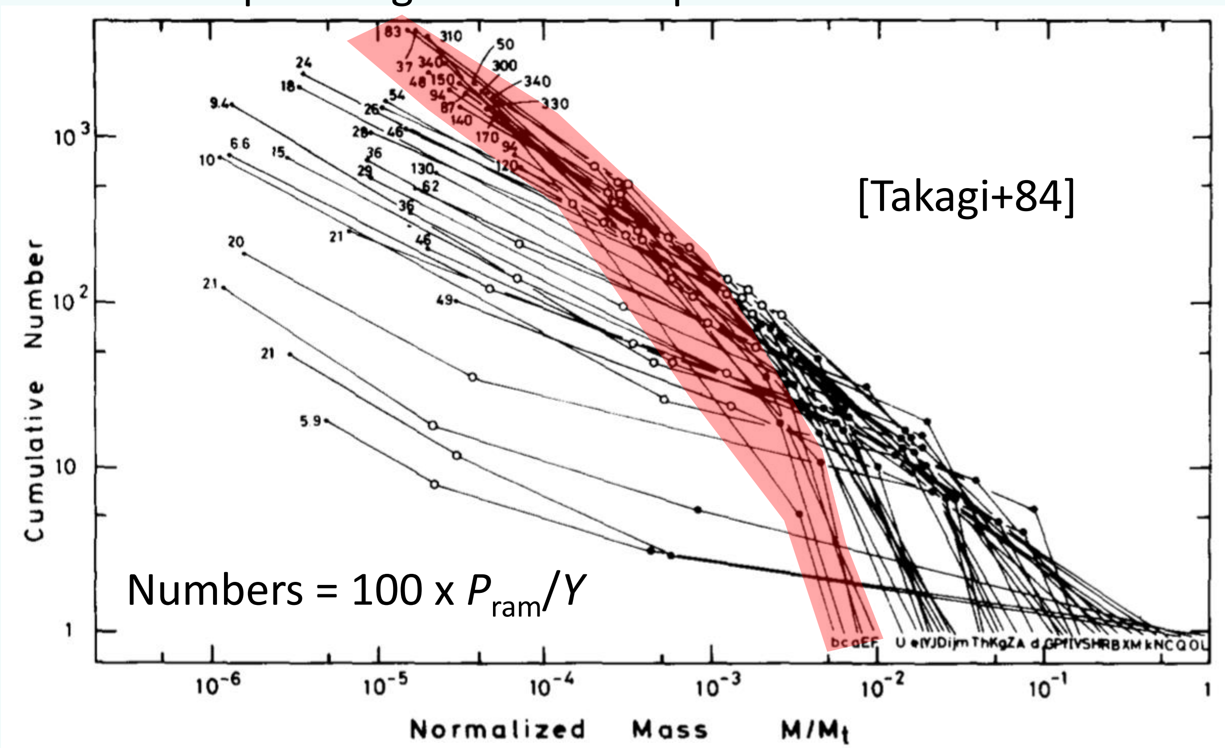
Longitudinal stress pulse in a penetrating Mars rock into the regolith $P_{ram} \sim \rho_t v_{imp}^2/2 \sim$ 4 GPa (at v_{imp} = 2 km/s)

$\rho_t = 2 \times 10^3$ kg/m^3

cf., Compressive strength of intact basaltic rocks Y = 0.17-0.48 GPa

[e.g., Mizutani+90]

Impact fragmentation experiments of Basalt

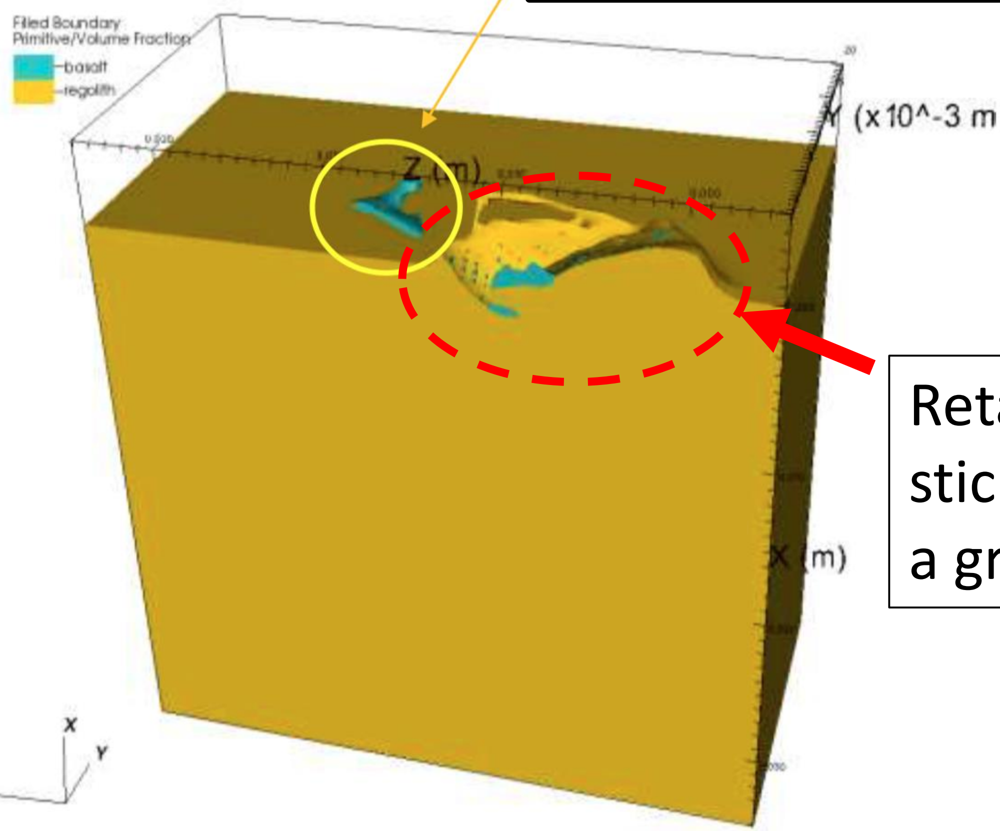


The largest fragment has ~1% of M_p.
(~1 cm fragment)

Projectile retention or dispersion

SterLim impact modeling

A much higher $v_{translational}$ compared to v_{esc} of the moons (~10 m/s).
But, $v_{translational}$ would be lower than v_{esc} from the Mars system (~3 km/s)



-> Dust torus formation around Mars

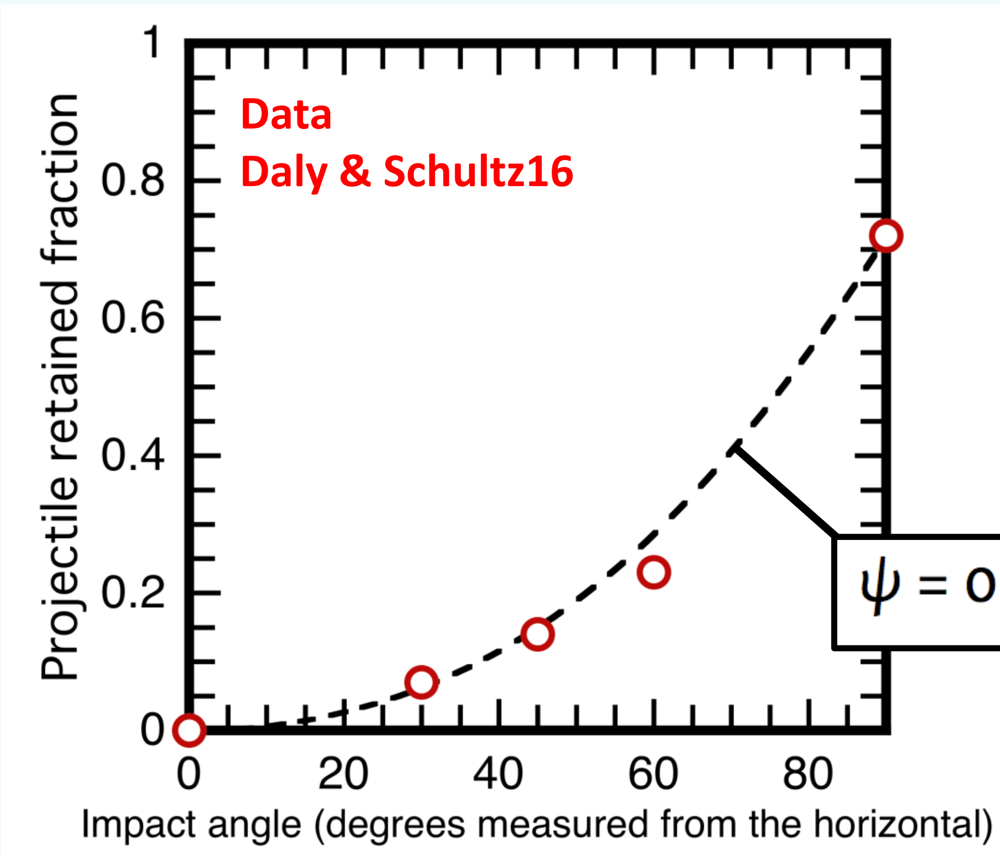
Retained Mars-rock fragments stick around the wall of a growing crater.

[Patel+17, The meeting in the last year]

Projectile retained fraction

The dynamics of projectile deformation has not been fully understand.

We employed the experimental data by Daly & Schultz (2016)



A basalt sphere impacting onto an asteroidal regolith analog at 4.5–5 km/s

Projectile retained fraction ψ

$$\psi = 0.718 - 1.01\cos\vartheta_{imp} + 0.294\cos^2\vartheta_{imp}$$

By convolving with the θ_{imp} distribution $\psi_{ave} = \begin{cases} 22\% & \text{(Phobos)} \\ 29\% & \text{(Deimos)} \end{cases}$

Crater formation

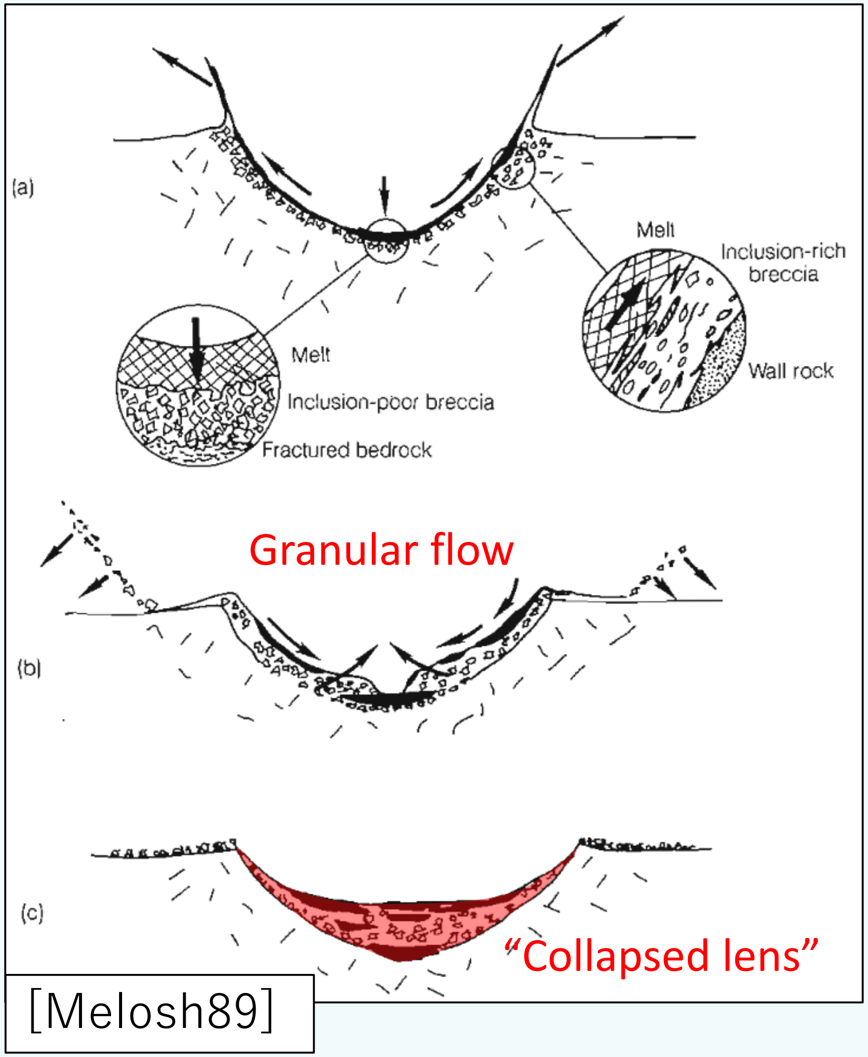
Mars-rock craters

Regolith thickness of Martian moons ~ 20 m [Thomas98]

much thicker than the Mars-rock diameter (10 cm)

-> All the Mars-rock impacts occur on a granular layer.

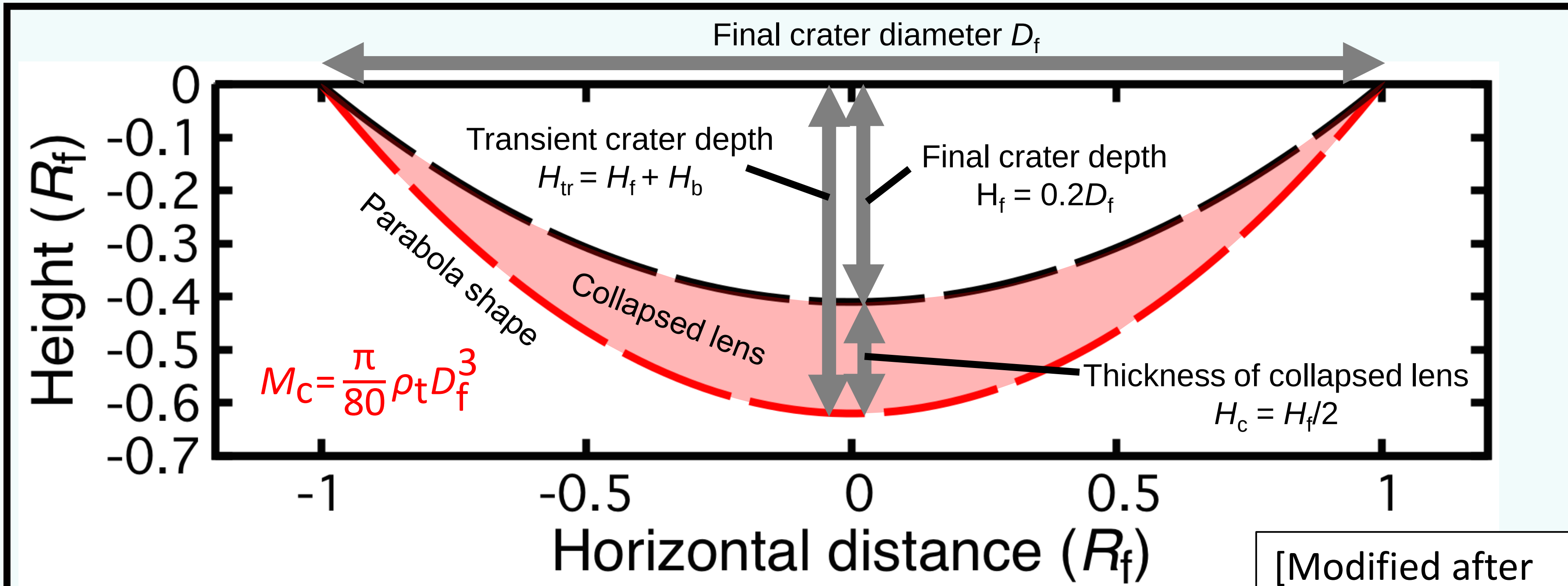
Mars rock mixing with the regolith



1. The slope of a transient wall is steeper than the angle of repose of granular materials in general.
2. The wall of the transient crater collapses due to the gravity.
3. A granular flow directed to the crater center is produced.
4. The retained Mars-rock fragments efficiently mix with the regolith.
5. A "collapsed lens" is deposited on the floor of a Mars-rock crater.

A thick regolith layer works as "a radiation shield" of the microbes.

Mars rock mixing ratio in a collapsed lens



[Modified after Melosh89, Fig8.3]

The π-group scaling law

$$D_{tr} = \left(\frac{\pi}{6}\right)^{\frac{1}{3}} C_D \left(\frac{4\pi}{3}\right)^{\frac{\beta}{3}} \left(\frac{\rho_p}{\rho_t}\right)^{\frac{1}{3}} D_p^{1-\beta} g^{\beta} \left(V_{imp} \sin\vartheta_{imp}\right)^{2\beta}$$ [Schmidt & Housen87]

An empirical relation between D_{tr} & D_f

$$D_f = 1.25 D_{tr}$$ [Melosh & Vickery89]

$C_D = 1.4$, $\beta = 0.17$, $\rho_p = 2.7 \times 10^3$ kg/m^3
and $g = 0.0057$ m/s^2 for Phobos,
0.003 m/s^2 for Deimos

Typical values from Monte Carlo runs

Typical final crater diameter ~10 m (~100 D_p)

Typical thickness of collapsed lenses ~1 m (~10 D_p)

Typical mixing ratio of a Mars rock in a collapsed lens ~10^{-5} (~10 ppm)

Access probability to the Mars-rock craters P_{crater} = 3.4% (Phobos), 0.28% (Deimos)

(= Total coverage of the final craters on the moon's surface)

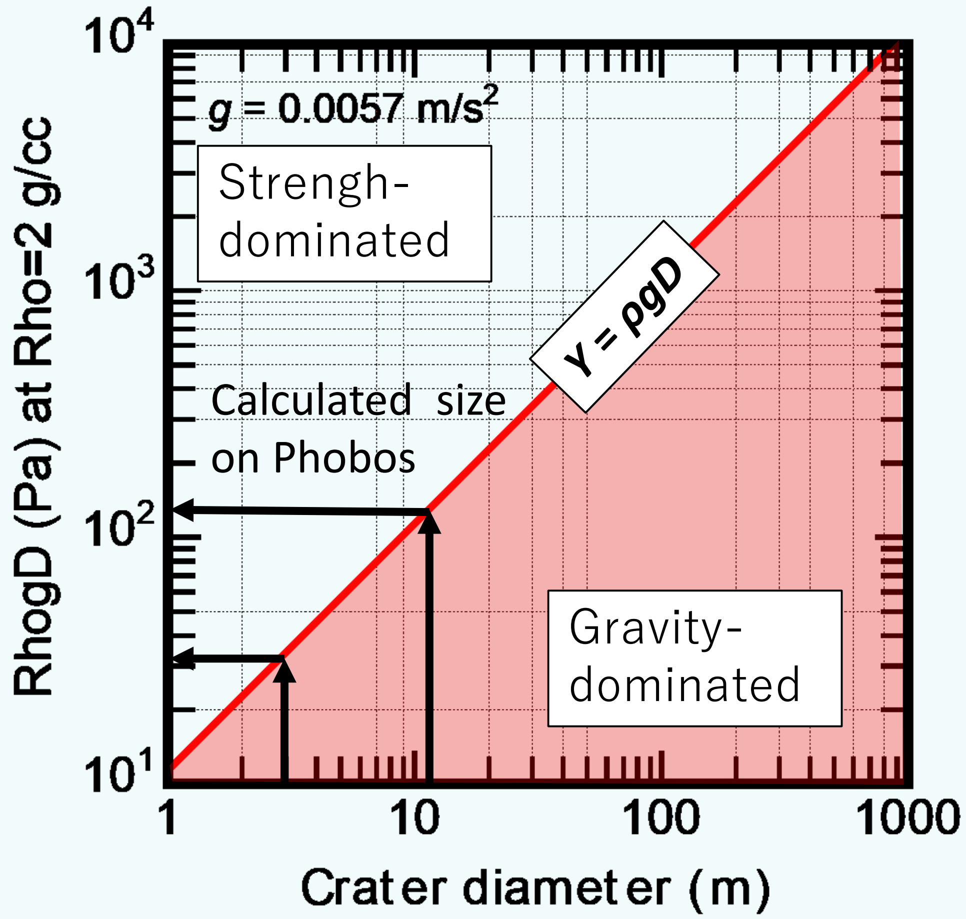
$$P_{crater} = \sum \pi D_f^2 / S_{moon}$$

Gravity vs Strength

Two cratering regime

Gravity: $Y \ll \rho g D$

Strength: $Y \gg \rho g D$

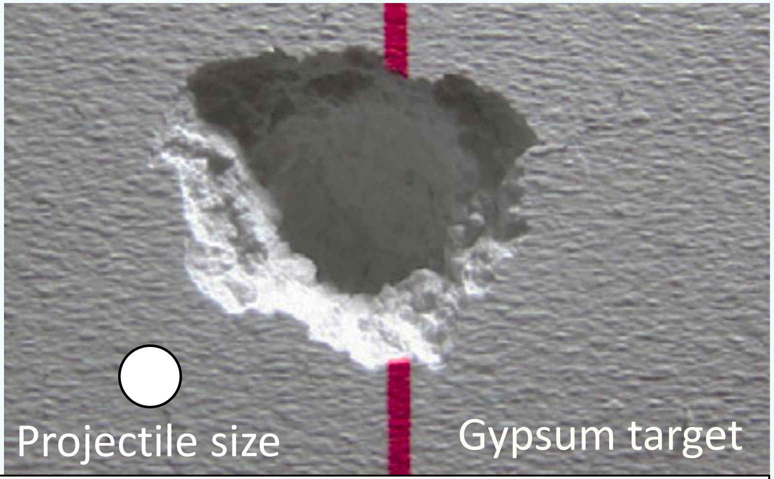


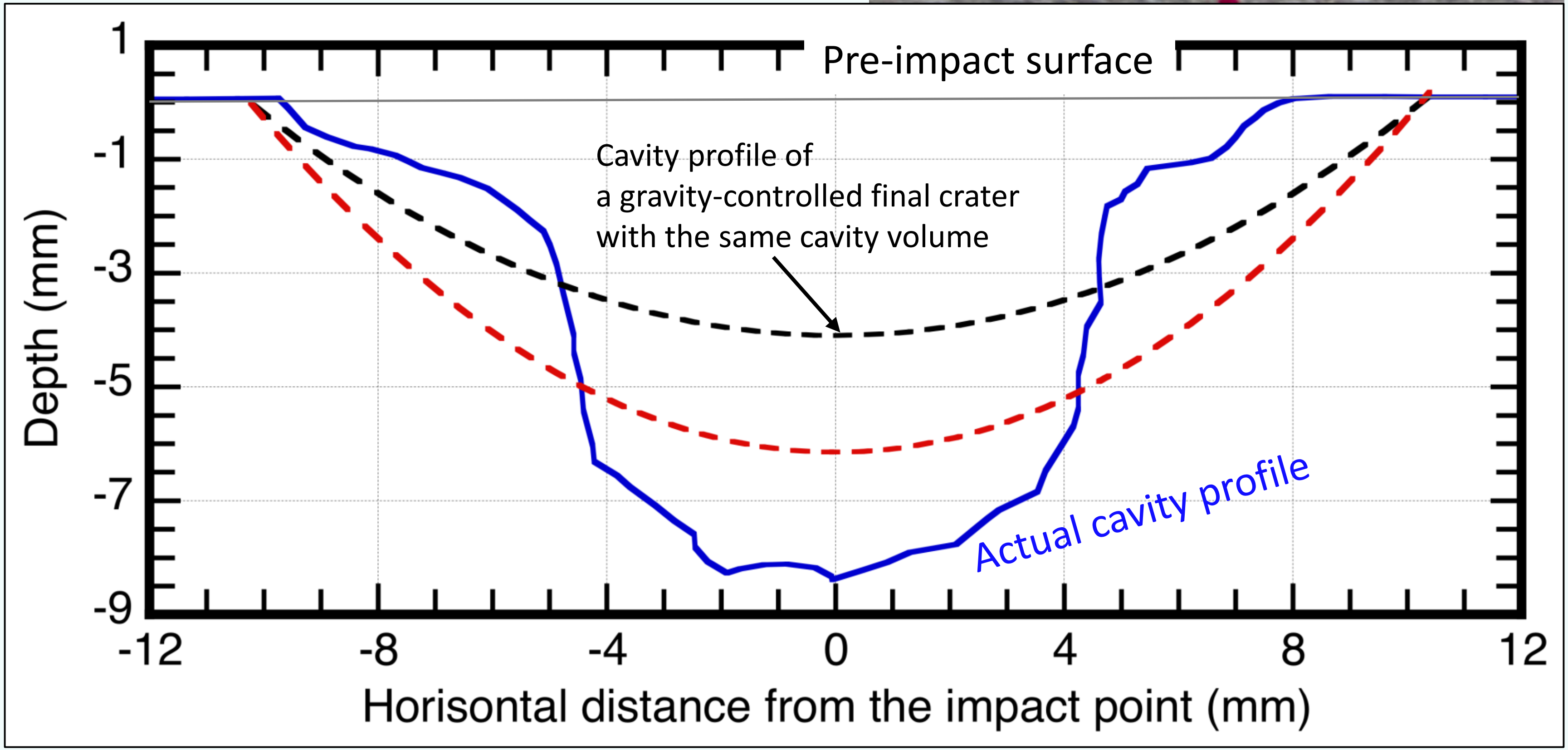
If the strength of the regolith on the moons less than 30–100 Pa, the cratering process is controlled by the gravity.

Strength-dominated craters

An impact experiment using Gypsum block target
[Suzuki+18]

Nylon (3.2 mmϕ) -> Gypsum
v_{imp} = 3.4 km/s
θ_{imp} = 90 deg
Target tensile strength = 2.3 MPa



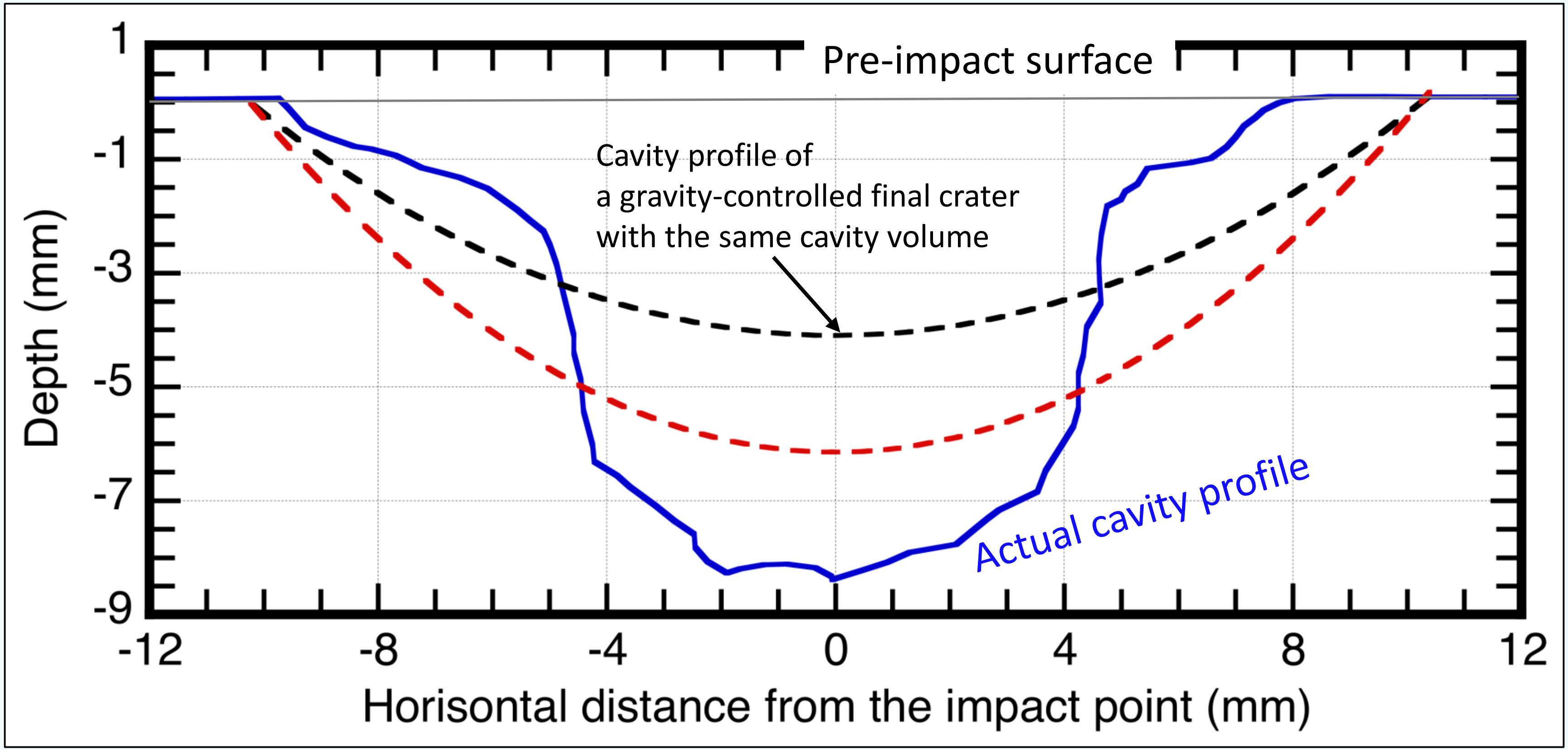


Strength-dominated craters

Target strength prevent the crater collapse or reduce the degree of the collapse, resulting in the steep crater wall.

The thickness of a collapsed lens under the strength-dominated regime is likely to be much thinner than the case of the gravity-dominated one.

The “gravity-dominated cratering” assumption gives an upper limit pertaining to the survived number of the microbes.

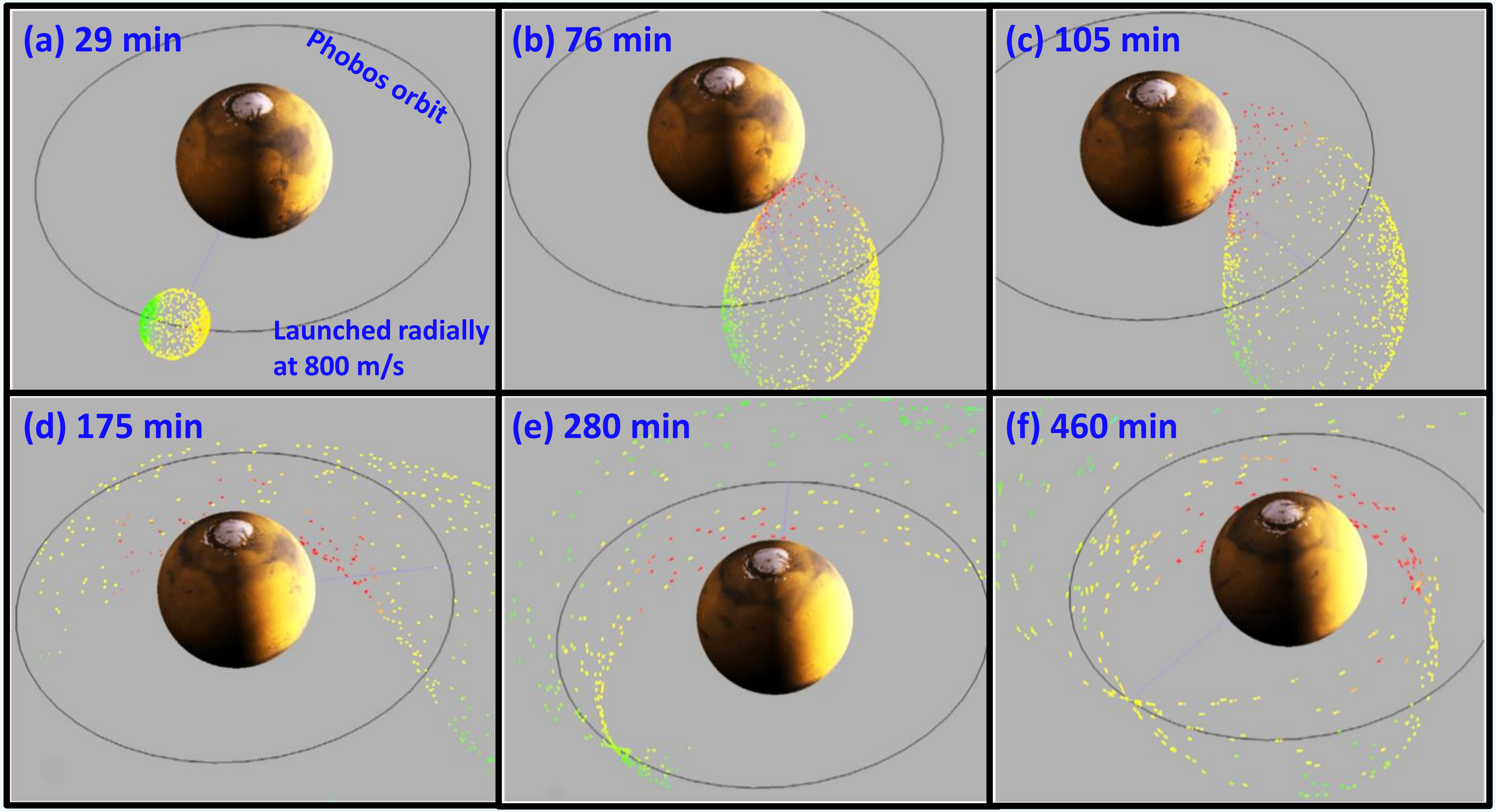


Scattered fragments

Dust torus

Dispersed Mars-rock fragments and escaped regolith particles produce a dust torus around Mars.

[Modified after Ramsley & Head13]



Nearly all ejecta fragments that remain in orbit of Mars return to Phobos within ~ 10^3 years [Hamilton and Krivov, 1996]

The mass of dust torus

The mass of dispersed projectile

$$M_{\mathrm{dis,p}} = (1-\psi)M_{\mathrm{p}}$$

~1 kg

The escaped mass of the regolith particles

$$M_{\mathrm{dis,t}} = C_{\mathrm{V}}\rho_{\mathrm{t}}R_{\mathrm{tr}}^{3}\left(\frac{v_{\mathrm{esc}}}{\sqrt{gR_{\mathrm{tr}}}}\right)^{-3\mu}$$

~10^2 kg

Given by the point-source theory
[Holsapple & Housen82; Housen+83]

$C_{\mathrm{v}} = 0.32$, $R_{\mathrm{tr}} = 0.5D_{\mathrm{tr}}$, and $m = 0.4$

cf., Total excavated mass $M_{\mathrm{exc}} = \frac{\pi}{6}\rho_{\mathrm{t}}R_{\mathrm{tr}}^{3}$
[e.g., Croft80]

~2×10^4 kg

The mixing ratio of the Mars-rock fragments in a dust torus ~1%

$$\text{The mass of dust torus } M_{\mathrm{torus}} = \begin{cases} 1 \times 10^{8}\,\mathrm{kg} & \text{(Phobos)} \\ 3 \times 10^{6}\,\mathrm{kg} & \text{(Deimos)} \end{cases}$$

A global thin layer

The dust particles are expected to be re-accumulated into the uppermost surface of the moons within several orbital periods.

(~100 hours)

The thickness of the global layer $L_{\mathrm{global}} = \dfrac{M_{\mathrm{torus}}}{\rho_{\mathrm{t}} S_{\mathrm{moon}}} = \begin{cases} 30\ \mu\mathrm{m} & \text{(Phobos)} \\ 1\ \mu\mathrm{m} & \text{(Deimos)} \end{cases}$

Infinitesimal dust particles are assumed.

The small particles (1–10 μm) are removed from the Mars system due to radiation pressure within several hours. [Ramsley & Head13]

We assumed L_{global} = 0.1 mm.

This assumption does not change the conclusion of this study unless the thickness is thicker than 0.3 mm because the time constant *TC* for radiation-induced sterilization is nearly constant (71 years) for the layer with a thickness of < 0.3 mm.

Rapid sterilization of the microbes in the thin layer

More than 70% of Mars rocks are concentrated into the global thin layer.

Required time for radiation-induced sterilization

$$t_{\mathrm{req}} = 71\ln\left(\frac{0.1\xi_{ave}N_{Mars}}{N_{th}}\right) = \begin{cases} 1.2 \times 10^3 \text{ years (Phobos)} \\ 1.4 \times 10^3 \text{ years (Deimos)} \end{cases}$$

The major fraction of the transported microbes must be extinct until now.

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4. **Background impact flux by natural meteoroids**

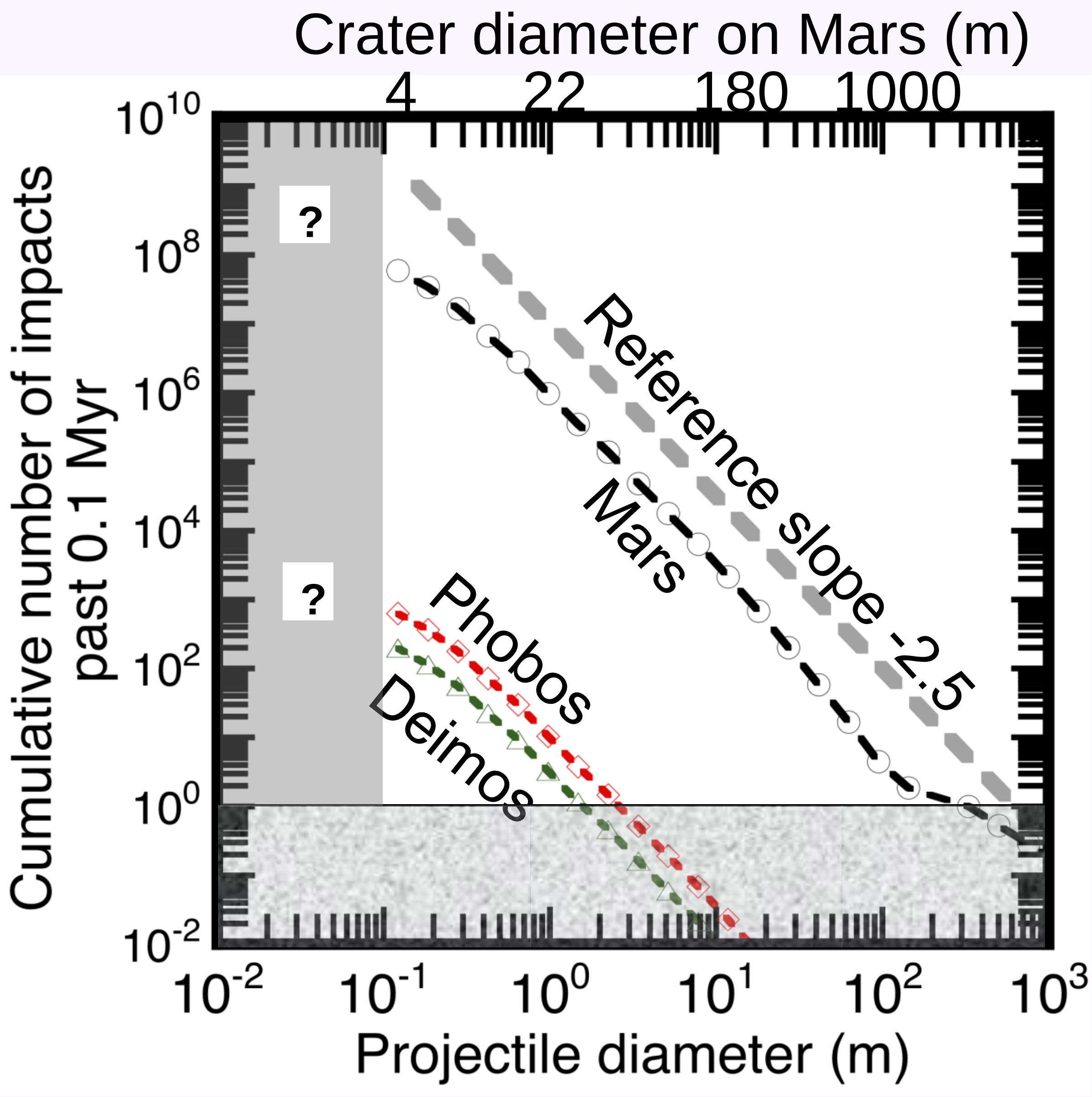
5. The change in the microbe density with time

6. Microbe contamination risk assessment

7. Conclusions

Background impact flux of natural meteoroids

Impact flux of natural meteoroids



$$D_{pmax} = \begin{cases} 2.6\ \text{m (Phobos)} \\ 1.6\ \text{m (Deimos)} \end{cases}$$

From crater SFD to Impactor SFD

The π-group scaling law

$$D_{tr} = \left(\frac{\pi}{6}\right)^{\frac{1}{3}} C_D \left(\frac{4\pi}{3}\right)^{\frac{\beta}{3}} \left(\frac{\rho_p}{\rho_t}\right)^{\frac{1}{3}} D_p^{1-\beta} g^{\beta} \left(V_{imp} \sin\vartheta_{imp}\right)^{2\beta}$$

[Schmidt & Housen87]

Empirical laws between D_f and D_{tr}

$$D_f = \max(1.25 D_{tr},\quad 1.2\, D_c^{-0.13}\, D_{tr}^{1.13})$$

For simple crater

For complex crater

D_c = 7 km for Mars [Pike88]

D_c is the transition diameter from simple to complex craters

We employed averaged values on Mars.

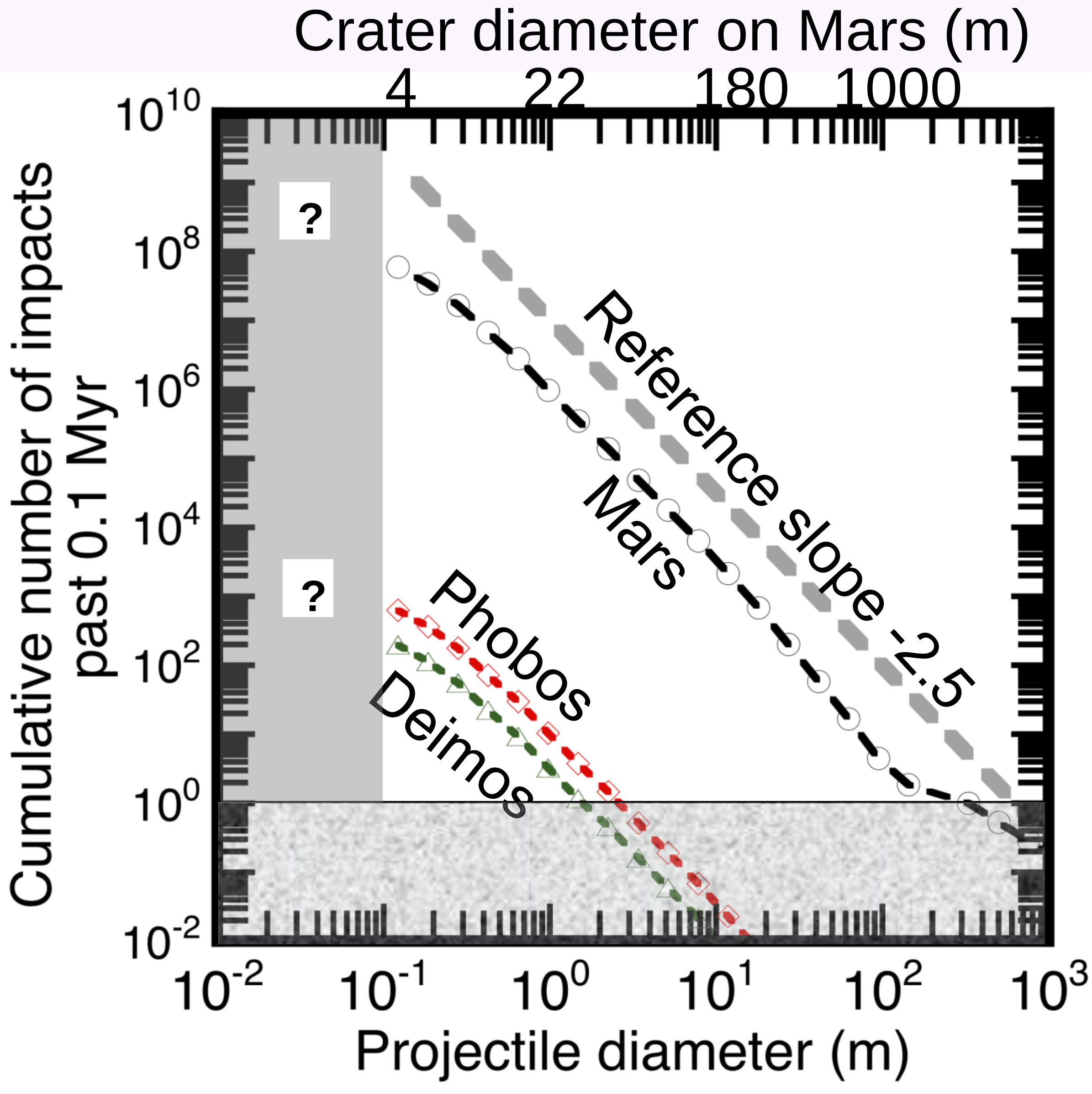
V_{imp} = 14 km/s

[Ito & Malhotra06]

θ_{imp} = 45 degrees

[Shoemaker62]

Impact flux of natural meteoroids



$$D_{pmax} = \begin{cases} 2.6\ \text{m (Phobos)} \\ 1.6\ \text{m (Deimos)} \end{cases}$$

$$N(>D_p) = D_{pmax}^{2.5} D_p^{-2.5}$$

v_{imp} & θ_{imp} distributions of natural meteoroids

Impact velocity distribution: Rayleigh [Zahnle+03]

Averaged impact velocity = $v_{imp,ave}$

$$= \sqrt{v_{imp,ave,Mars}^2 - v_{esc,Mars}^2 + v_{esc,moons}^2}$$

[Schmedemann+14]

$$= \begin{cases} 13.4 \text{ km/s} & \text{(Phobos)} \\ 13.2 \text{ km/s} & \text{(Deimos)} \end{cases}$$

Impact angle distribution: $\sin(2\theta_{imp})$ [Shoemaker62]

Ejecta thickness

The mass of ejecta at a velocity interval (v_{ej}, v_{ej}+dv_{ej}) [Housen+83]

$$m_{ej}\left(v_{ej}\right)dv_{ej} = 3\mu C_V \rho_t R_{tr}^3 (gR_{tr})^{\frac{3\mu}{2}} v_{ej}^{-3\mu-1} dv_{ej}$$

The ballistic range of the ejecta at the velocity interval R_b [Melosh89]

$$R_b = 2\ R_{moon} \tan^{-1}\left[\frac{\left(\frac{v_{ej}^2}{gR_{moon}}\right)\sin\vartheta_{ej}\cos\vartheta_{ej}}{1-\left(\frac{v_{ej}^2}{gR_{moon}}\right)\cos^2\vartheta_{ej}}\right]$$

The surface area of the ejecta landing site for the velocity bin S_{ej}

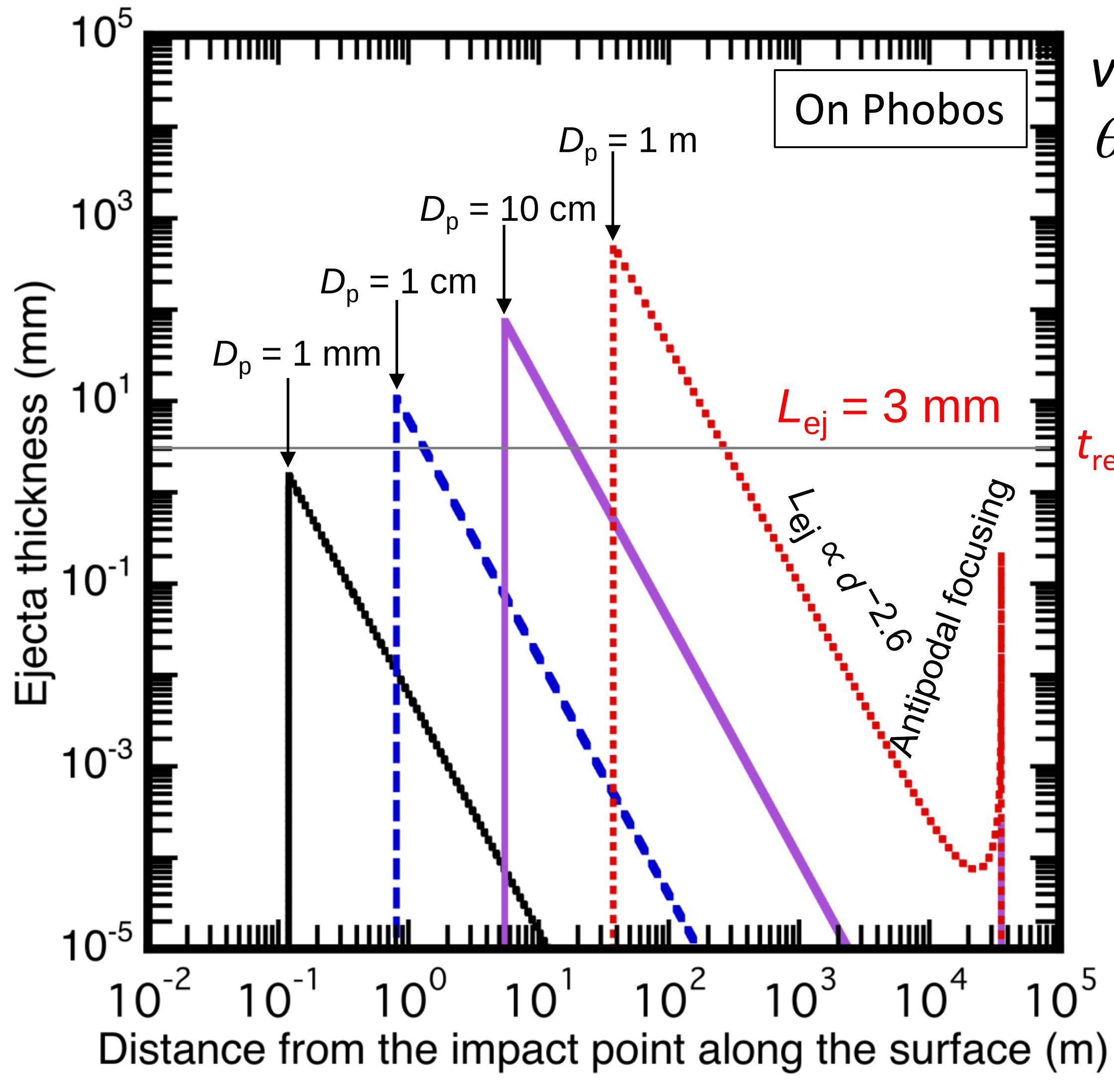
$$S_{ej} = 2\pi R_{moon} \sin\lambda d\lambda, \text{ where } \lambda = \frac{R_b}{R_{moon}}$$

λ is the arc angle between the impact point and the ballistic range measured from the center of the moon.

Thickness of the ejecta deposit launched at the velocity interval L_{ej}

$$L_{ej} = \frac{m_{ej} dv_{ej}}{S_{ej} \rho_t}$$

Ejecta thickness vs distance



v_{imp} = 13.4 km/s
θ_{imp} = 45 deg

t_{req} ~ 0.1 Myr

L_{ej} decrease with distance by follow the power law with an exponent -2.6

Consistent with the previous studies [e.g., Melosh89]

The minimum size of impactor D_{pmin}~1 mm

Total number of impacts prior to complete sterilization

$$N_{\mathrm{total,BG}} \sim \left(\frac{2\times10^3\ \mathrm{years}}{0.1\ \mathrm{Myr}}\right) D_{\mathrm{pmax}}^{2.5} D_{\mathrm{pmin}}^{2.5} = \begin{cases} 6.7\times10^6 & \text{(Phobos)} \\ 2.0\times10^6 & \text{(Deimos)} \end{cases}$$

The ratio of t_{req} to the time after the Zunil-forming event.

※The impact rate on the Mars system in the past 3 Gyr is roughly constant.
[e.g., Neukum et al., 2001; Schmedemann et al. 2014]

For conservative estimate, we used $t_{req} = 2 \times 10^3$ years.
This t_{req} was obtained by assuming $N_0 = 10^7$ CFU/kg.

Cumulative surface area of the thick ejecta-deposit layer

$N_{\mathrm{total,BG}}$, v_{imp} & θ_{imp} distributions -> The same Monte Carlo model for Mars-rock bombardment

The surface area of the thick ejecta-deposit layer $S_{\mathrm{shield}} = \pi\left(R_{\mathrm{b,3mm}}^2 - R_{\mathrm{f}}^2\right)$

$R_{\mathrm{b,3mm}}$ is the distance from the impact point covered by the thick ejecta-deposit layer along with the surface

The possible covered fraction by the ejecta deposit

$$P_{\mathrm{layer}} = \frac{\sum S_{shield}}{S_{moon}} = \begin{cases} 0.11\% & \text{(Phobos)} \\ 0.097\% & \text{(Deimos)} \end{cases}$$

99.9 % of the microbes in the global thin layer should be sterilized within ~2 x 10^3 years after the Zunil-forming impact event.

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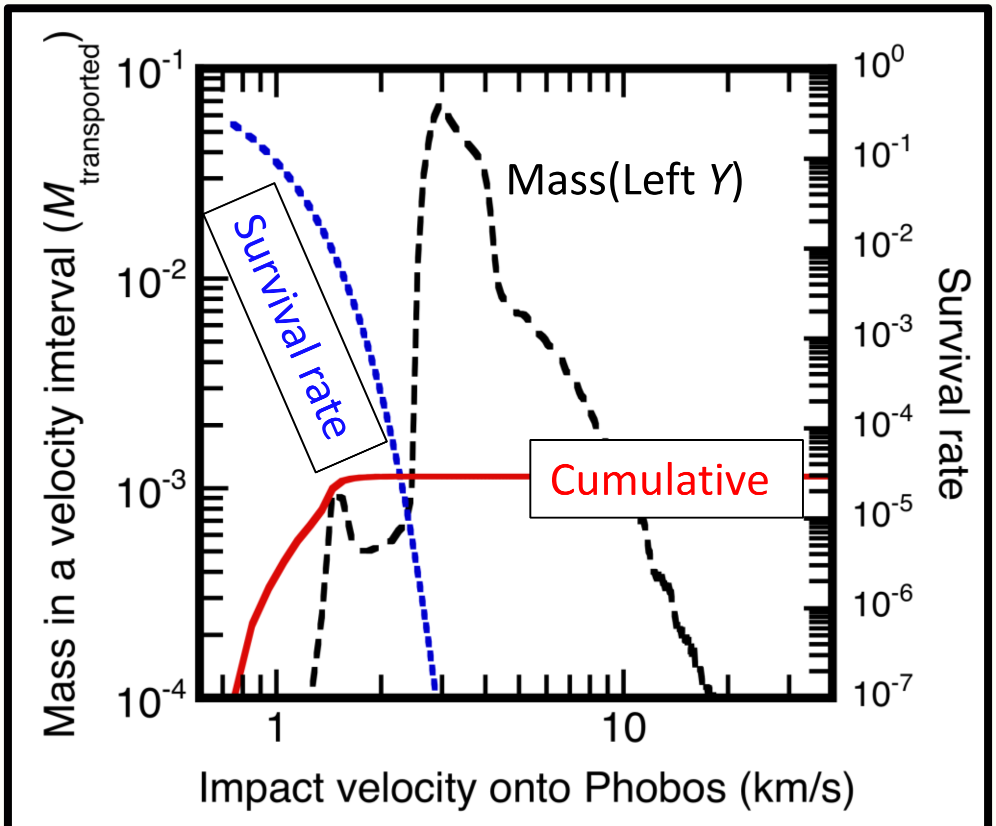
Impact sterilization of Mars rocks

Survival rate $\xi \equiv N/N_0 = \exp\left[-9.5\times10^{-6} v_{imp}{}^{1.8}\right]$

By convolving with the v_{imp} distribution, $\xi_{ave} = \begin{cases} 2.9\times10^{-5}\ \text{(Phobos)} \\ 5.6\times10^{-4}\ \text{(Deimos)} \end{cases}$



v_{imp} – Mass distribution

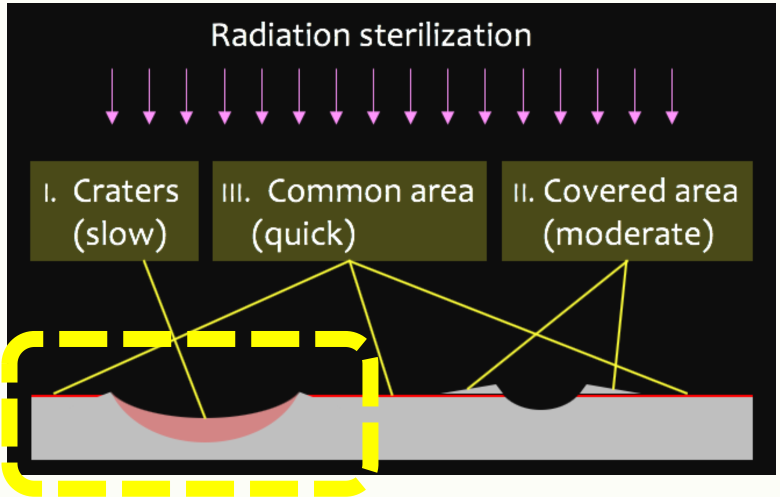
Velocity interval = 0.1 km/s

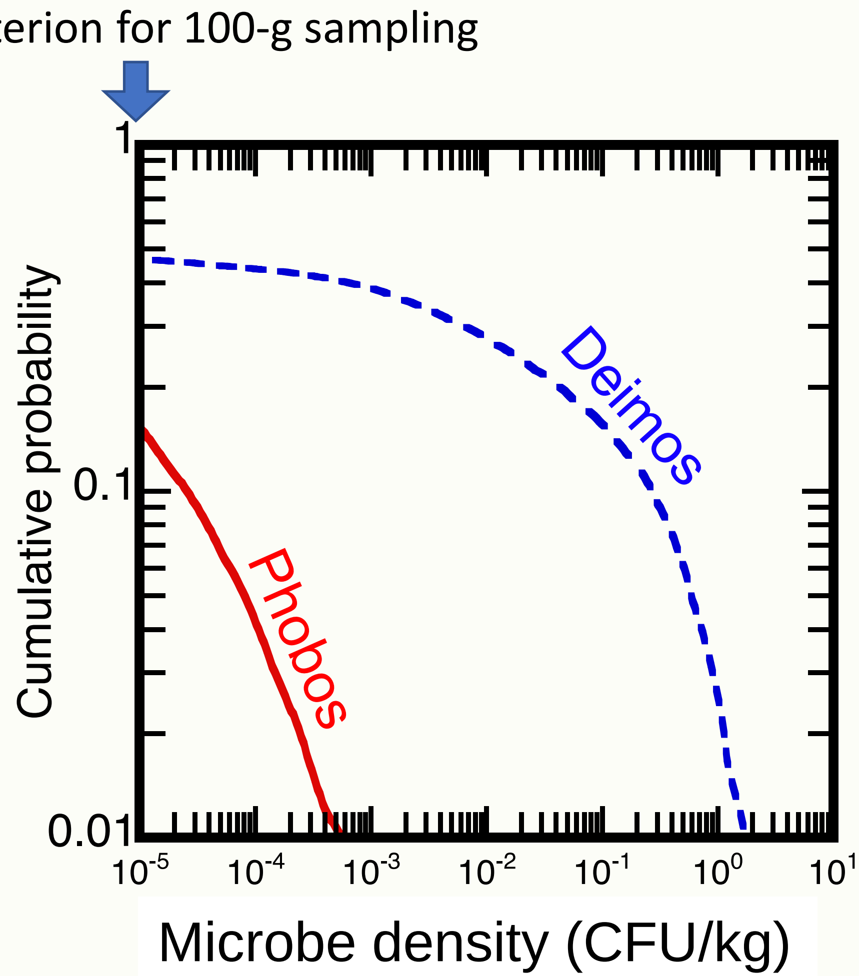
The most part of the Mars rocks have v_{imp} > 3 km/s.

[Hyodo+, to be submitted; Our trajectory analyses]

First collisions with the moons leads to significant sterilization.

Microbe density in a collapsed lens



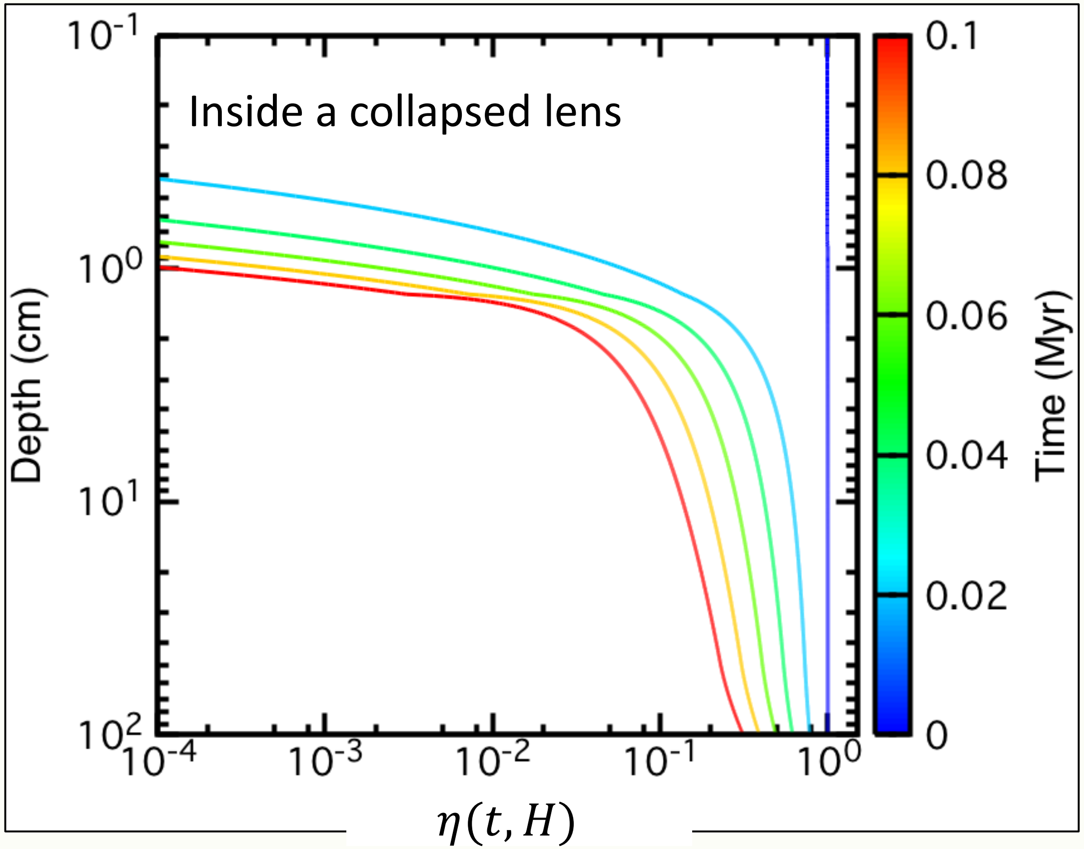


$$n_{\mathrm{crater0}} = 0.1\xi n_{\mathrm{Mars}}\psi \frac{M_{\mathrm{p}}}{(M_{\mathrm{c}}+M_{\mathrm{p}})}$$

$$n_{\mathrm{crater0,ave}} = \begin{cases} 3.1 \times 10^{-3}\ \mathrm{CFU/kg\ (Phobos)} \\ 4.8 \times 10^{-2}\ \mathrm{CFU/kg\ (Deimos)} \end{cases}$$

Radiation-induced sterilization in Mars-rock craters

Radiation survival rate integrated over a given depth *H* at time *t*

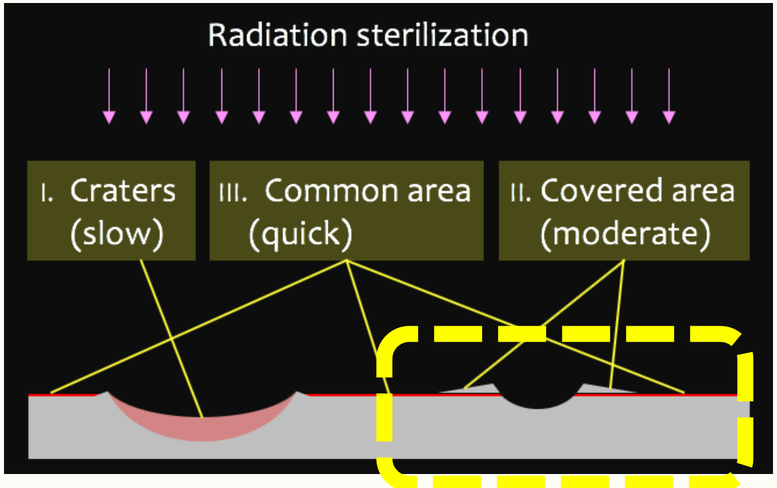


$$\eta(t, H) = \frac{\int_0^H \exp\left(-\frac{t}{TC(h)}\right) dh}{H}$$

At t = 0.1 Myr

Depth (cm)	Survival rate
0.3	3.1×10^{-27}
1	1.2×10^{-4}
3	6.6×10^{-2}
6	0.11
10	0.14
30	0.2
60	0.24
100	0.31

Microbe column density beneath the ejecta blanket



The microbial column density immediately after the formation of the global thin layer

$$\sigma_{\mathrm{thin0}} = \frac{0.1\xi_{\mathrm{ave}} n_{\mathrm{Mars}} (1-\psi_{\mathrm{ave}}) M_{\mathrm{transported}}}{S_{\mathrm{moon}}}$$

The change in the column density during 2 x 10^3 years

$$\sigma_{\mathrm{thin}}(t) = \sigma_{\mathrm{thin0}} \exp\left(-\frac{t}{71\ \mathrm{years}}\right)$$

where $t = i\Delta t$ is the time at the i-th impact and Δt = 2 x 10^3 years/$N_{\mathrm{total,BG}}$.

The number of microbes protected by the ejecta-deposit layer N_{layer} at the i-th impact

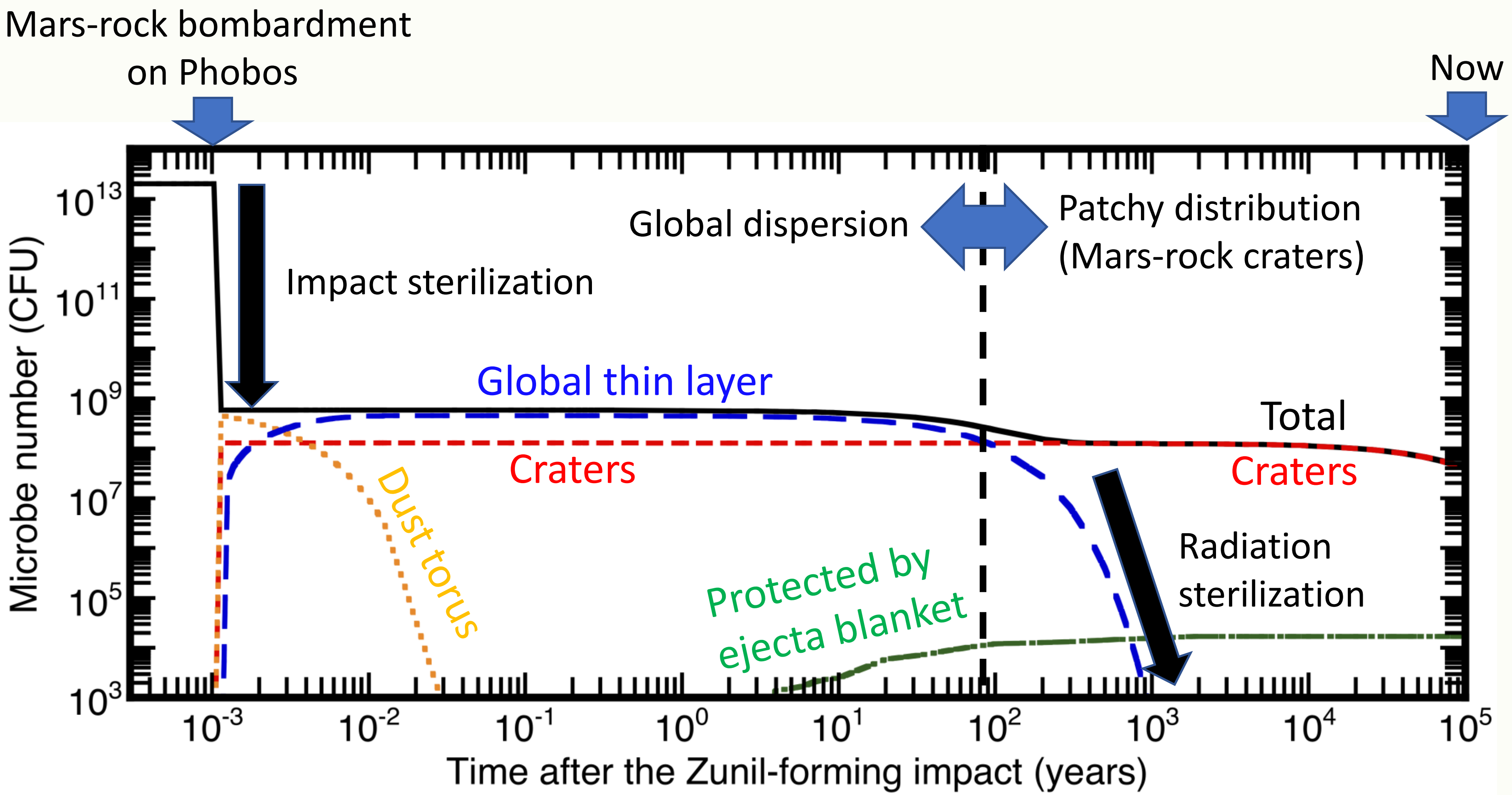
$$N_{\mathrm{layer}} = \sigma_{\mathrm{thin}}(t) S_{\mathrm{shield}}$$

Averaged-microbial-column density of the covered-microbial thin layer

$$\sigma_{\mathrm{thin,ave}} = \frac{\Sigma N_{\mathrm{layer}}}{\Sigma S_{\mathrm{shield}}} = \begin{cases} 1.0 \times 10^{-6}\ \mathrm{CFU/cm^2}\ \text{(Phobos)} \\ 1.1 \times 10^{-6}\ \mathrm{CFU/cm^2}\ \text{(Deimos)} \end{cases}$$

※ For conservative estimate, further sterilization during 0.1 Myr is not considered.

The change in survived microbe numbers on Phobos



Total number of transported microbes = 2×10^{13} CFU

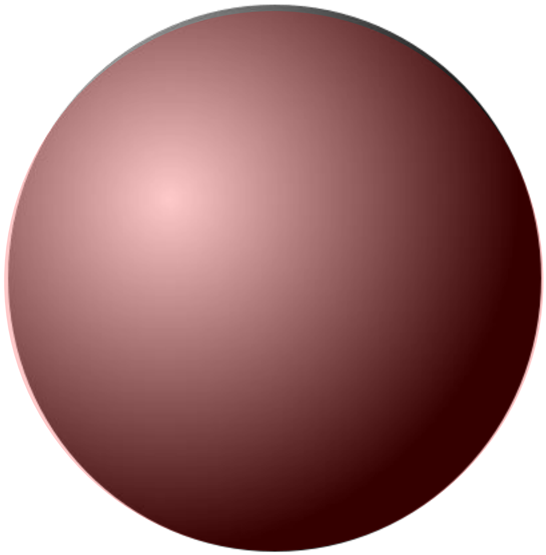
Total number of survived microbes up to the present = 4×10^{7} CFU (2 ppm)

Outline

1. General assumptions
2. Transportation to the moons
3. Mars-rock bombardment on the moon
4. Background impact flux by natural meteoroids
5. The change in the microbe density with time
6. **Microbe contamination risk assessment**
7. Conclusions

Microbe distribution

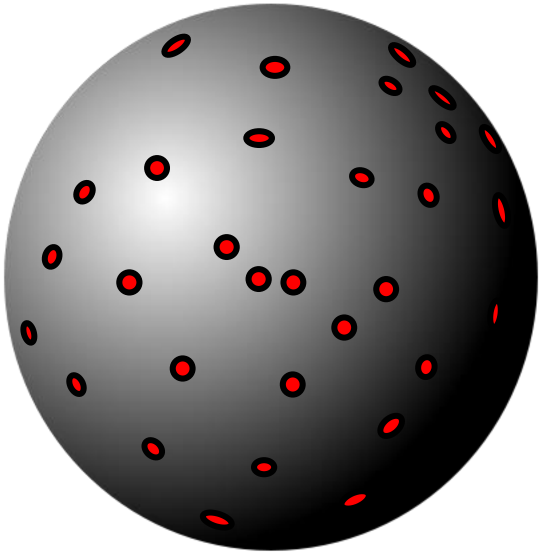
SterLim view



Homogeneous deposition by averaging incoming flux to the uppermost layer

c.f.,
Microbe column density
10^{-8}–10^{-3} CFU/cm^2

Our view



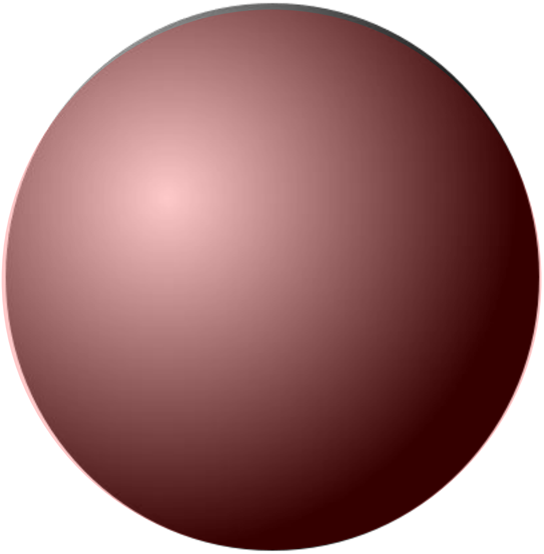
Mars rock bombardment
-Patchy in the horizontal direction
-Depth-dependent

Total survived microbes $= \begin{cases} 4.0 \times 10^7 \text{ CFU} \\ 1.9 \times 10^7 \text{ CFU} \end{cases}$

Access probability $P_{crater} = \begin{cases} 3.4\% \\ 0.28\% \end{cases}$

Microbe distribution

SterLim view



Homogeneous deposition by averaging incoming flux to the uppermost layer

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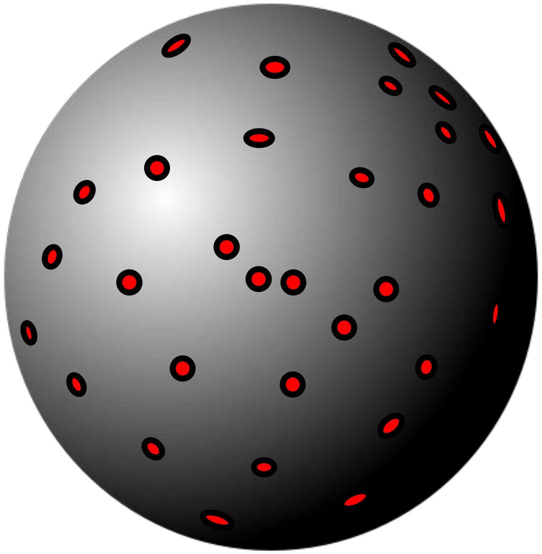
Microbe column density
10^{-8}–10^{-3} CFU/cm^2

Our view



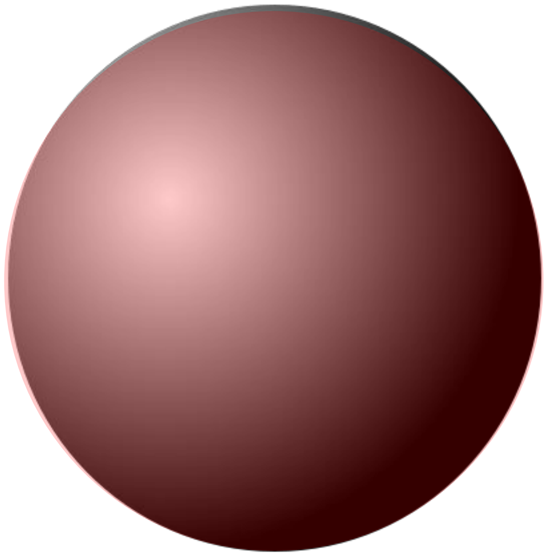
Mars rock bombardment
-Patchy in the horizontal direction
-Depth-dependent

Total survived microbes $= \begin{cases} 4.0 \times 10^{7}\ \text{CFU} \\ 1.9 \times 10^{7}\ \text{CFU} \end{cases}$

Equivalent microbe column density $= \begin{cases} 2.6 \times 10^{-6}\ \text{CFU/cm}^2 \\ 4.0 \times 10^{-6}\ \text{CFU/cm}^2 \end{cases}$

Microbe distribution

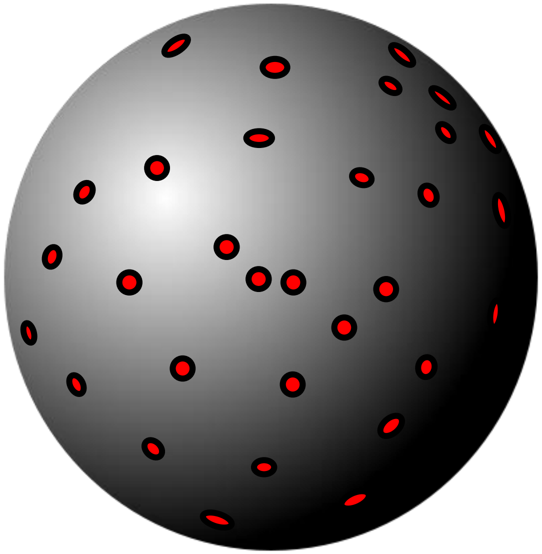
SterLim view



Homogeneous deposition by averaging incoming flux to the uppermost layer

c.f.,
Microbe column density
10^{-8}–10^{-3} CFU/cm^2

Our view



Mars rock bombardment
-Patchy in the horizontal direction
-Depth-dependent

Total survived microbes $= \begin{cases} 4.0 \times 10^7 \text{ CFU} \\ 1.9 \times 10^7 \text{ CFU} \end{cases}$

Access probability $P_{\text{crater}} = \begin{cases} 3.4\% \\ 0.28\% \end{cases}$

Sampling probabilities

The sampling probabilities of the microbes from the Mars-rock craters

$$P_{s,crater} = P_{crater} n_{crater}(t,H) M_s$$

※ $n_{crater}(t,H) = \eta(t, H) n_{crater0}$

The sampling probabilities of the microbes from the covered-microbial thin layer

$$P_{s,layer} = P_{layer} \sigma_{thin,ave} S_s$$

Note:

The unit of $n_{crater}(t,H)$ is CFU/kg.

The unit of $\sigma_{thin,ave}$ is CFU/cm^2

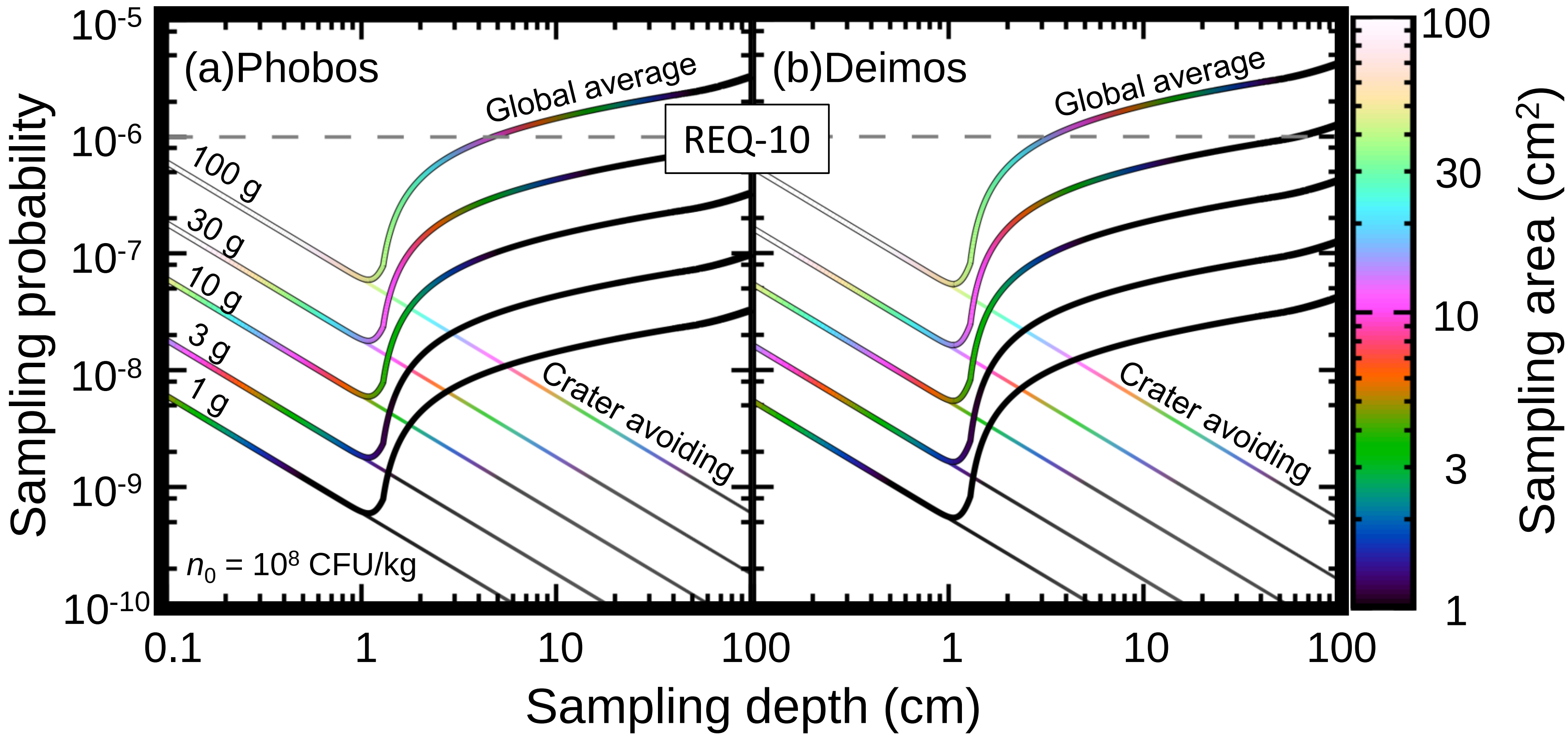
$M_s = \rho_t S_S H_s$	Sampling mass
S_s	Sampling area
H_s	Sampling depth

Sampling probabilities

Global average: $P_s = P_{s,crater} + P_{s,layer}$

Crater-avoiding: $P_s = P_{s,layer}$

$\rho_t = 2 \times 10^3$ kg/m^3 was assumed.

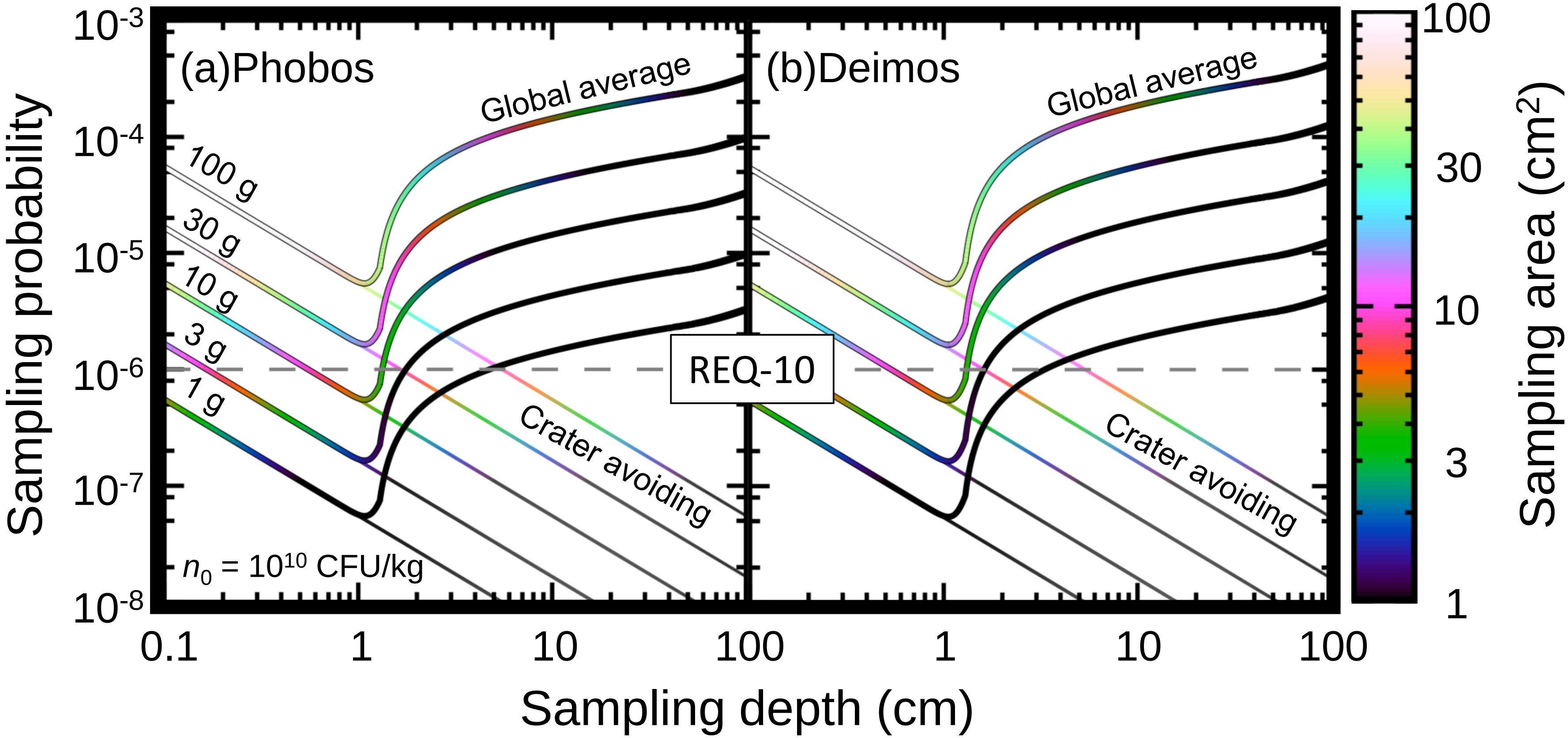


Allowable sampling depth for the Unrestricted Earth return = { 5 cm (Phobos); 3 cm (Deimos) } (100 g-sampling)

There is no limit for 30 g-sampling.

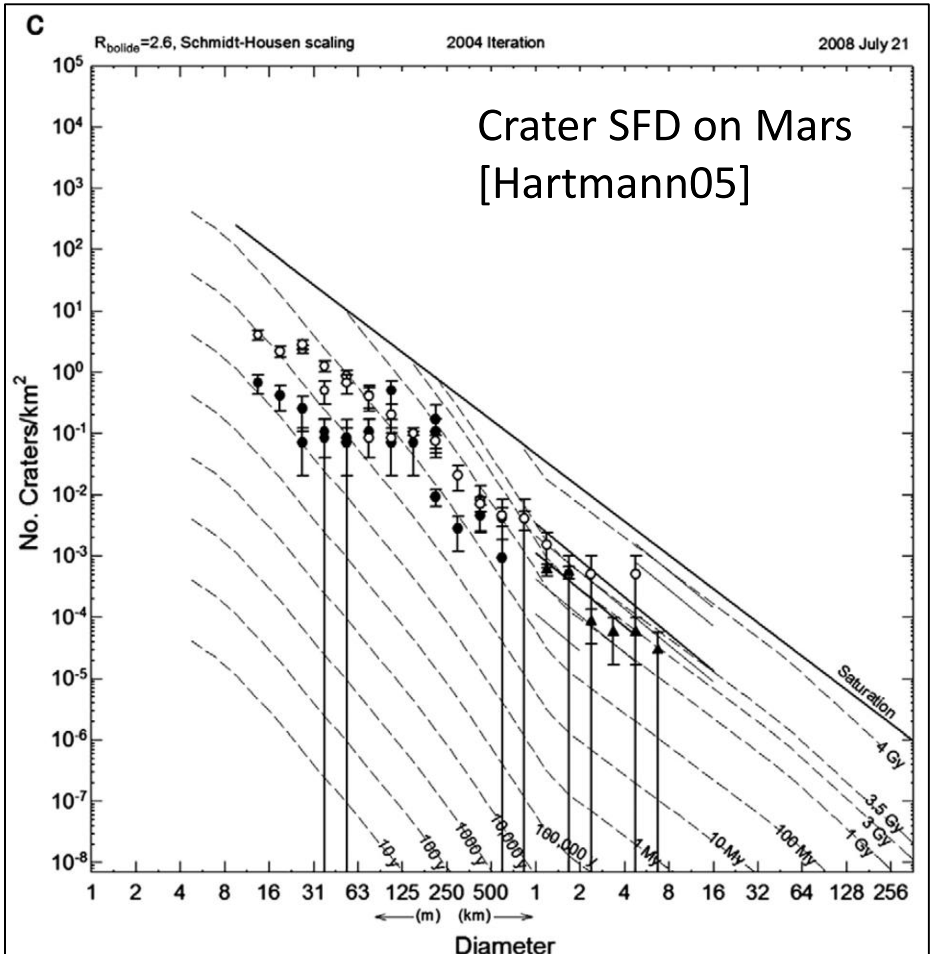
Sensitivity analysis

If we used n_{Mars} = 10^{10} CFU/kg, the curves of P_s 2-orders shift to the upward.



We could also collect the regolith sample up to ~10 cm^2 by crater-avoiding operations.

Contamination risk from unrecognized craters

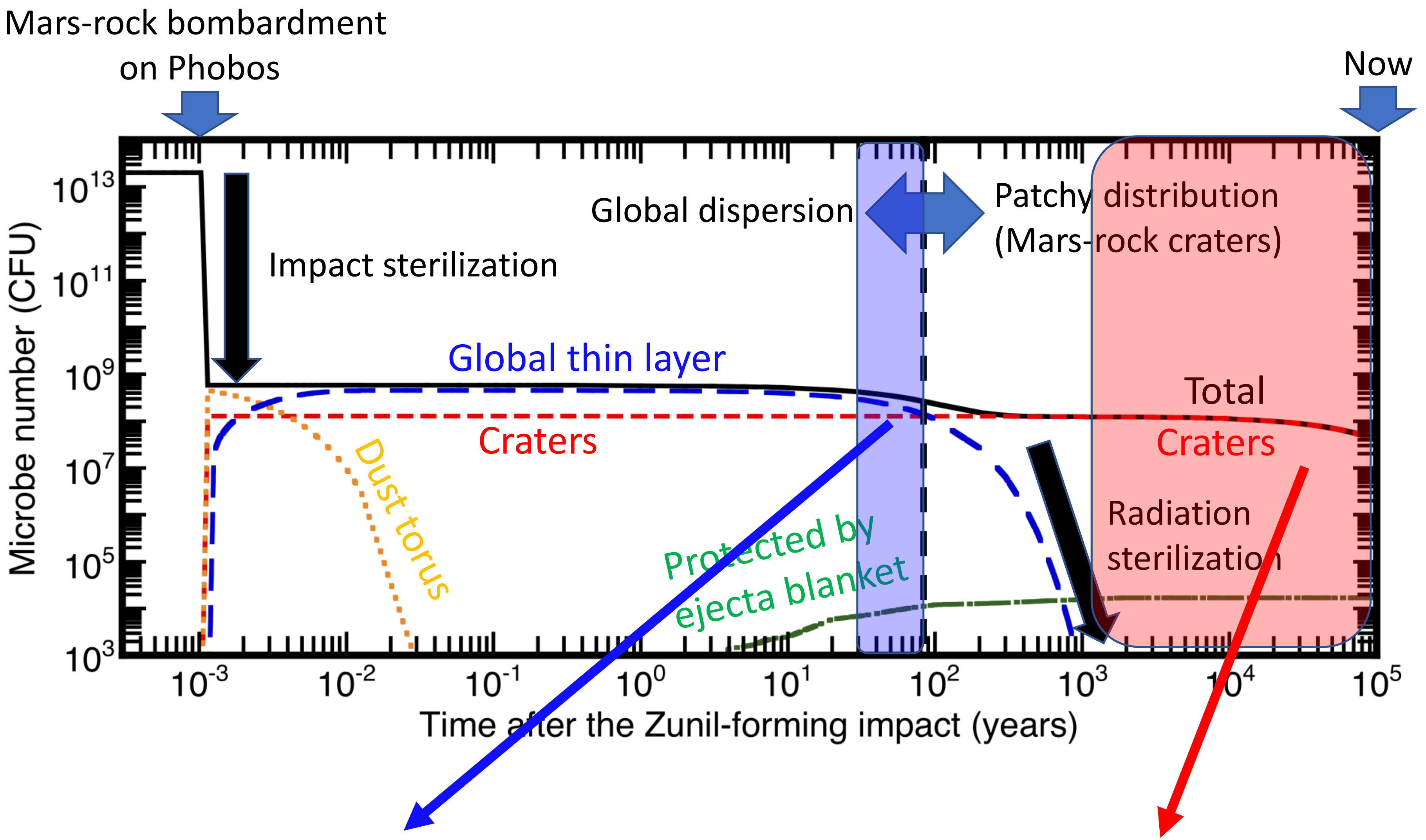


By introducing "event probability" P_{event}, we can address the risk by unfound craters.

Formation age (years)	P_{event}
10^6	1
10^5	0.1
10^4	0.01
10^3	0.001
10^2	0.0001

v_{imp} & θ_{imp} distributions from the unfound crater were obtained by assuming fully-randomized impact locations and directions.

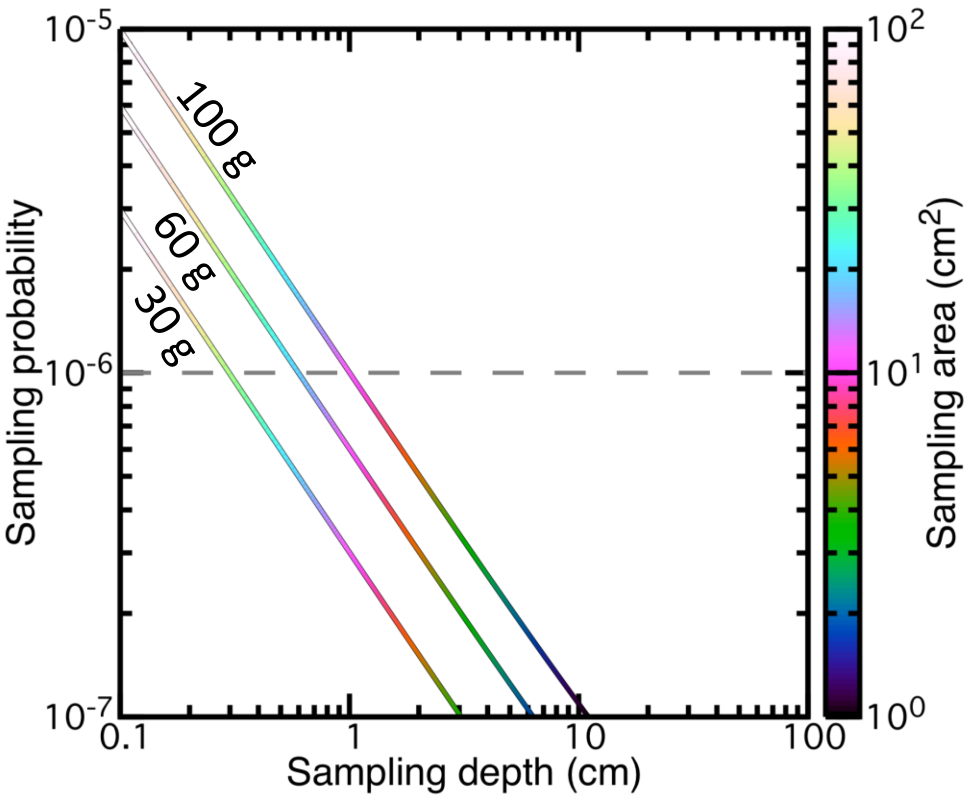
The change in survived microbe numbers on Phobos



$P_s = P_{event}(P_{s,crater} + P_{s,layer})$

$P_s = P_{event}P_{s,crater} + P_{s,layer}$

Contamination risk from unrecognized craters (100 years)



$$P_S = P_{event}(P_{s,crater} + P_{s,layer})$$
$$\sim P_{event} P_{s,layer}$$
$$= P_{event}\,\xi_{ave} N_{total} S_S$$

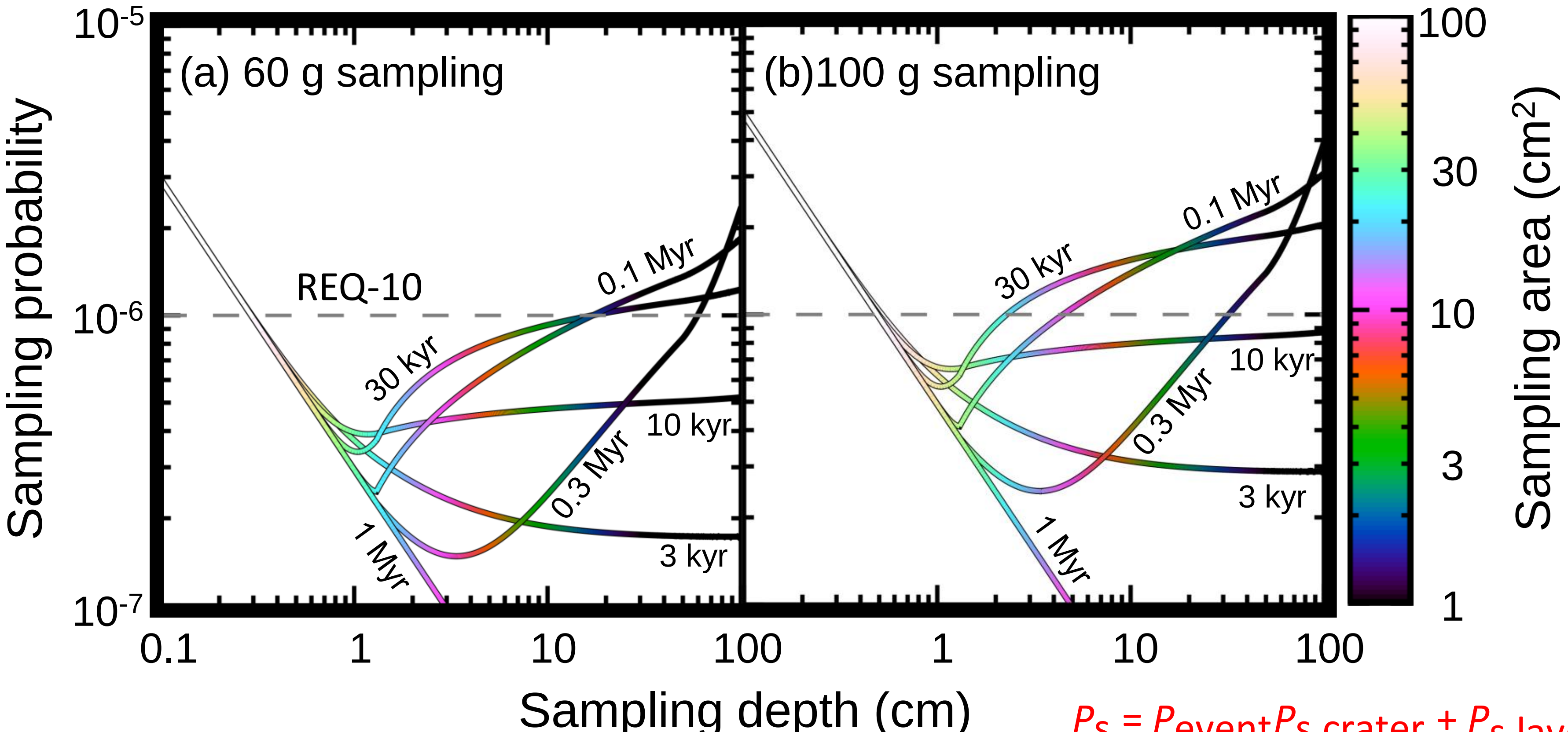
ξ_{ave} : Impact survival rate = 2.9×10^{-5}

N_{total} : Transported microbes = 2×10^{13} CFU

Zunil-sized unfound craters with the formation age of 100 years are highly unlikely.

-> The contamination risk by the young unfound crater can be negligible.

Contamination risk from unrecognized craters (>10 kyr)



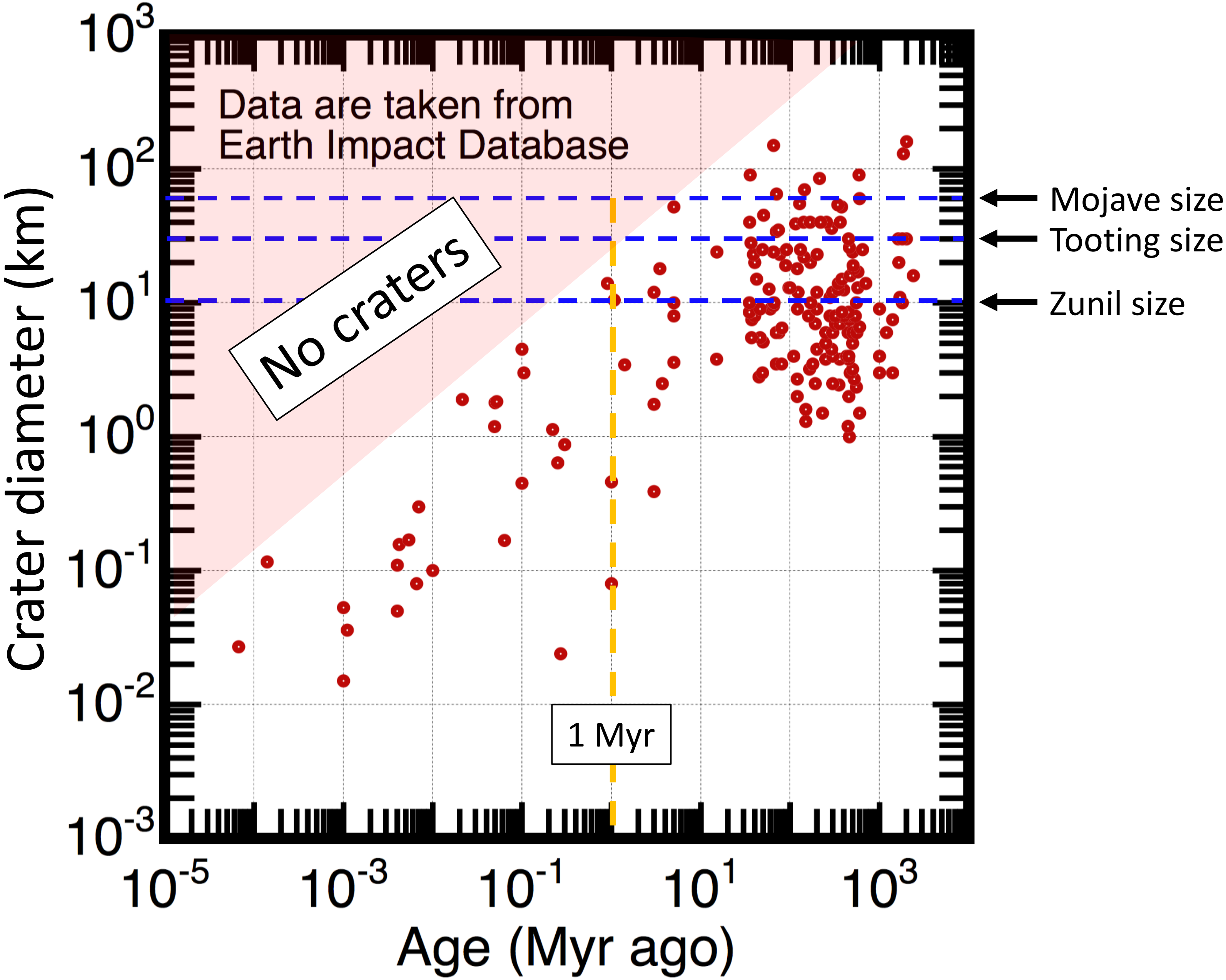
$P_s = P_{event} P_{s,crater} + P_{s,layer}$

$\sim P_{event} P_{s,crater}$

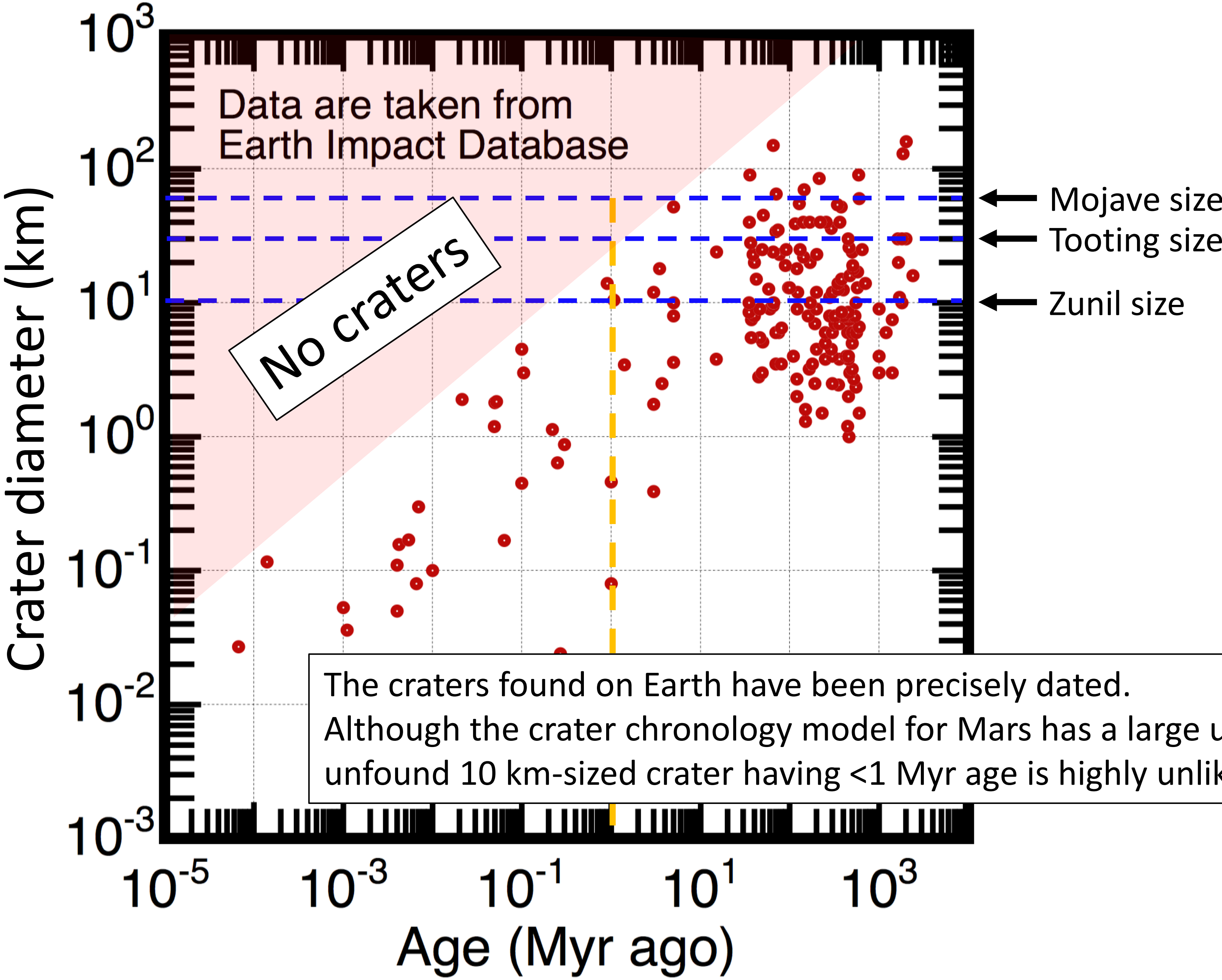
$\eta(t,H)$ and $P_{event}(t)$ are competitive. -> Complex behavior in P_s against the changing depth.

We could rule out the contamination risk from unfound craters down to ~10 cm from the surface of Phobos if the sampling mass could be limited to <60 g.

Known craters on Earth



Known craters on Earth



The craters found on Earth have been precisely dated.
Although the crater chronology model for Mars has a large uncertainty, unfound 10 km-sized crater having <1 Myr age is highly unlikely.

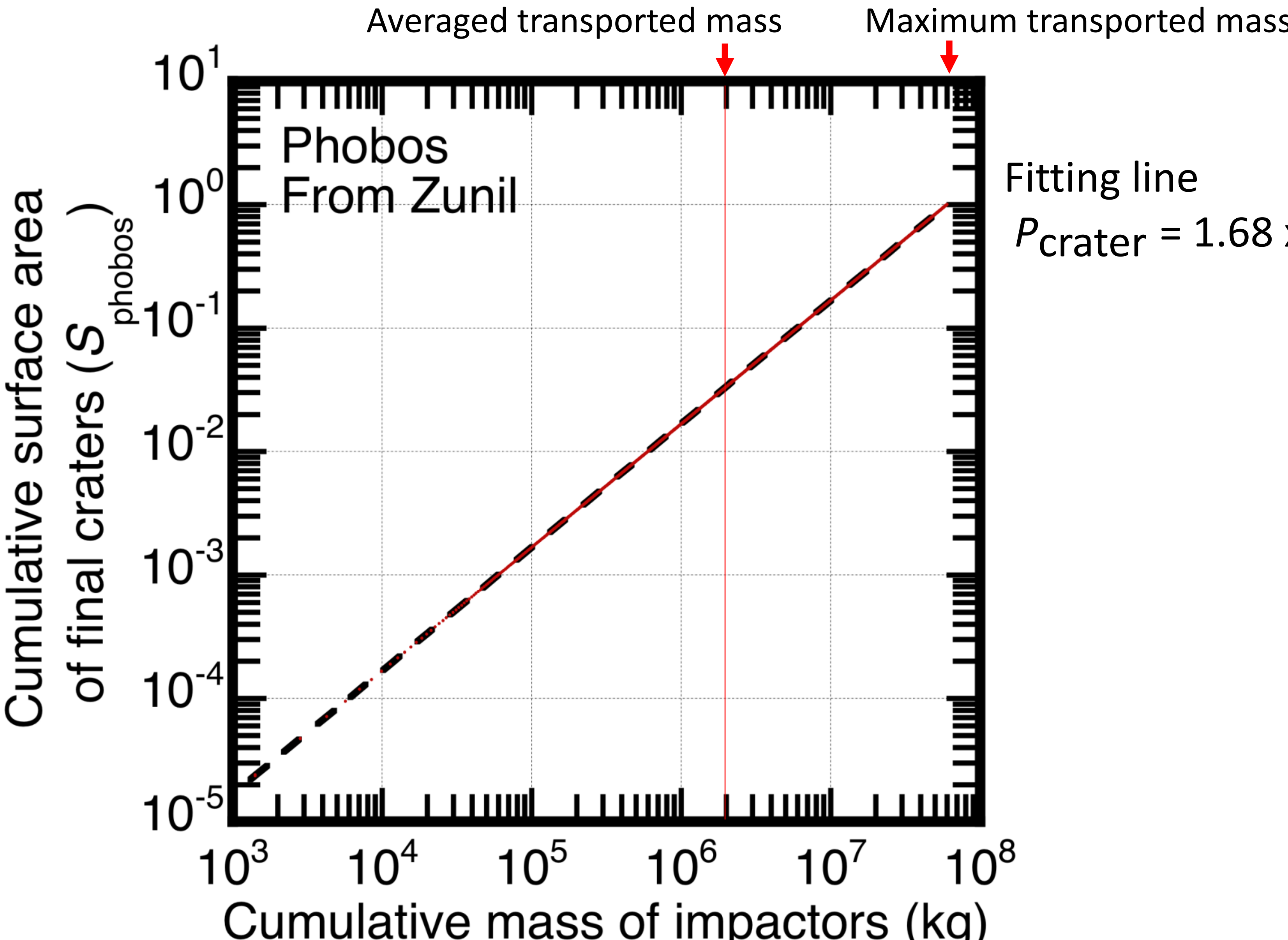
Propagation of uncertainties

$$P_s = P_{s,crater} + P_{s,layer} \sim P_{s,crater}$$

$$P_{s,crater} = P_{crater} n_{crater}(t,H) M_s$$
$$\propto M_{transported} \eta(t,H) \alpha \beta \xi_{ave} \psi_{ave} n_{Mars} \rho_t S_s H_s$$

	Current analyses
α: Survival rate during the launch	0.1
n_{Mars} : Potential microbe density on Mars	10^8 CFU/kg
β: Mixing ratio of Mars rocks to collapsed lens	~10 ppm
ξ : Impact survival rate	2.9×10^{-5}
ψ: Projectile retained fraction	0.22
η: Radiation survival rate	

$$\eta(t,H) = \frac{\int_0^H \exp\left(-\frac{t}{TC(h)}\right) dh}{H}$$



Fitting line

$P_{crater} = 1.68 \times 10^{-8} \times M$

Propagation of uncertainties

$$P_s = P_{s,crater} + P_{s,layer} \sim P_{s,crater}$$

$$P_{s,crater} = P_{crater} n_{crater}(t,H) M_s$$

$$\propto M_{transported} \eta(t,H) \alpha \beta \xi_{ave} \psi_{ave} n_{Mars} \rho_t S_s H_s$$

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ψ: Projectile retained fraction	0.22
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$$\eta(t,H) = \frac{\int_0^H \exp\left(-\frac{t}{TC(h)}\right) dh}{H}$$

Conclusions

☆ We re-visited the launch of Mars rocks and their orbital evolution by using advanced numerical methods.

☆ We constructed the spatial distribution of the Mars rocks based on our best knowledge about impact physics.

☆ The microbe density is patchy in the horizontal direction and depth-dependent.

☆ The survived fraction of the transported microbes is only ~2 ppm for Phobos and ~50 ppm for Deimos.

☆ Microbial contamination probability of collected samples can be easily made below 10^{-6} by choosing appropriate sampling approaches.

Sample return missions from the Martian moons can be classified as Unrestricted Earth return.

Q6

TR 2018-00-17C

Comparative Risk Assessment between Samples from Martian moons & Natural Influx

September 19, 2018 Rev.C

September 14, 2018

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Phobos/Deimos Microbial Contamination Assessment Team
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Document Revision History

Revision	Status and Description	Date	Author
	First release	14/09/2018	Fujita, K. et al.
A	Data of Martian meteorites are updated. Detailed descriptions about aerodynamic heating in the terrestrial atmosphere are added.	16/09/2018	Fujita, K.
B	Descriptions about the Martian meteorite with a 0.2-m diameter are added.	18/09/2018	Fujita, K. and Kurosawa, K.
C	Comparison to direct sample return from Mars is added.	19/09/2018	Fujita, K.

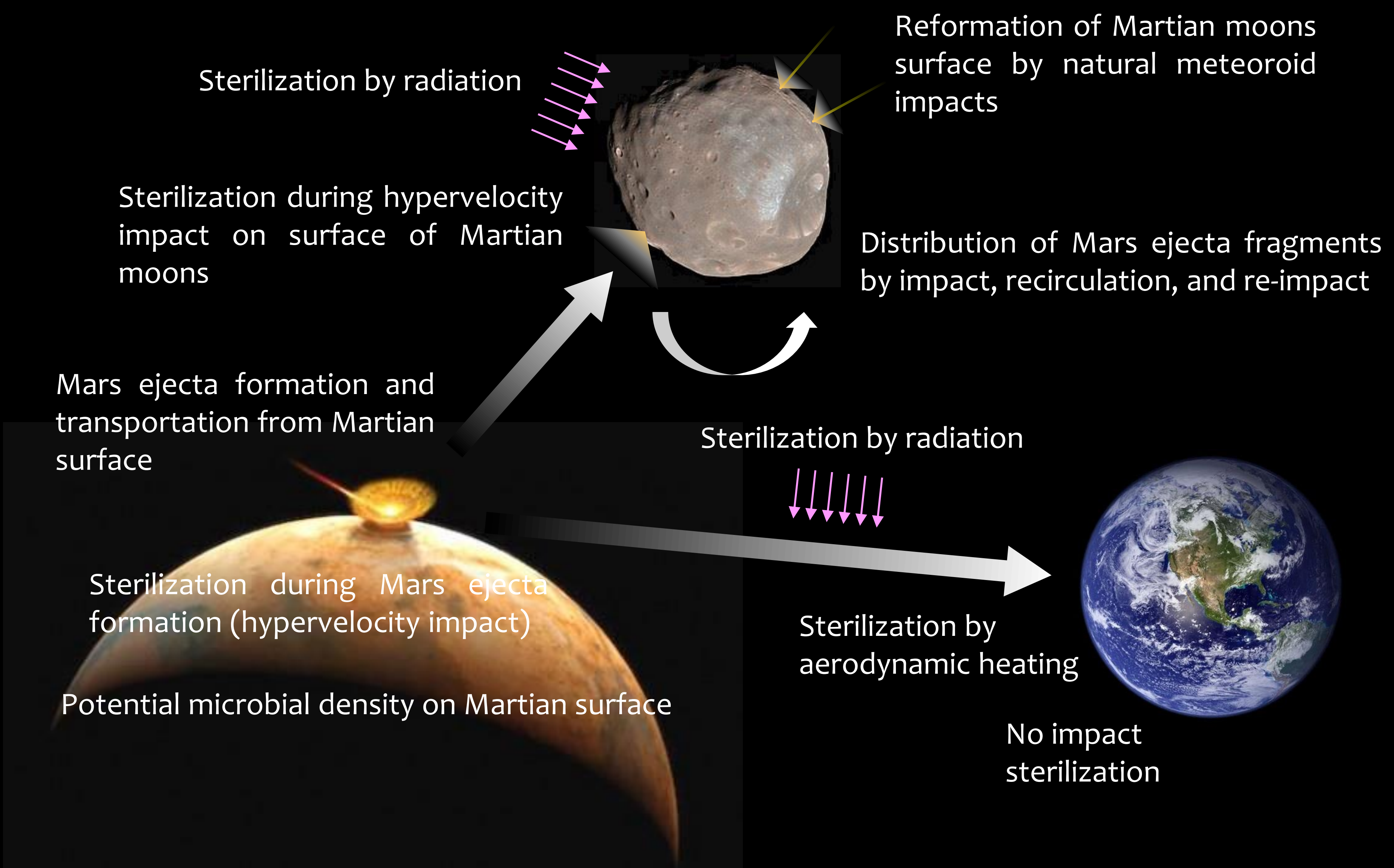
Summary

- According to COSPAR planetary protection policy (PPP), determination as to whether a sample return mission is classified "Restricted Earth return" or not shall address the six questions, the sixth of which goes

  Does the preponderance of scientific evidence indicate that there has been a natural influx to Earth, e.g., via meteorites, of material equivalent to a sample returned from the target body?

- Based on the estimation of microbial contamination probability of Martian meteorites obtained by Fujita et al. (2018), and on the preceding study of Mileikowsky et al. (2000a, 2000b) and Horneck et al. (2002), it is clearly proven that the answer to the sixth question is ***Yes***.
- Martian meteorites transported from Mars in the past 1 Myr have microbial contamination probability much higher by order of magnitude (**10^3 or more**) than that of 100-g samples taken from Martian moons. This means that natural influx equivalent to samples from Martian moons is continuously transported to the surface of Earth.
- For this reason, it is considered that sample return from the Martian moons is classified as ***Unrestricted Earth Return***, provided that total mass of samples is limited within 100 kg.

Physical Processes



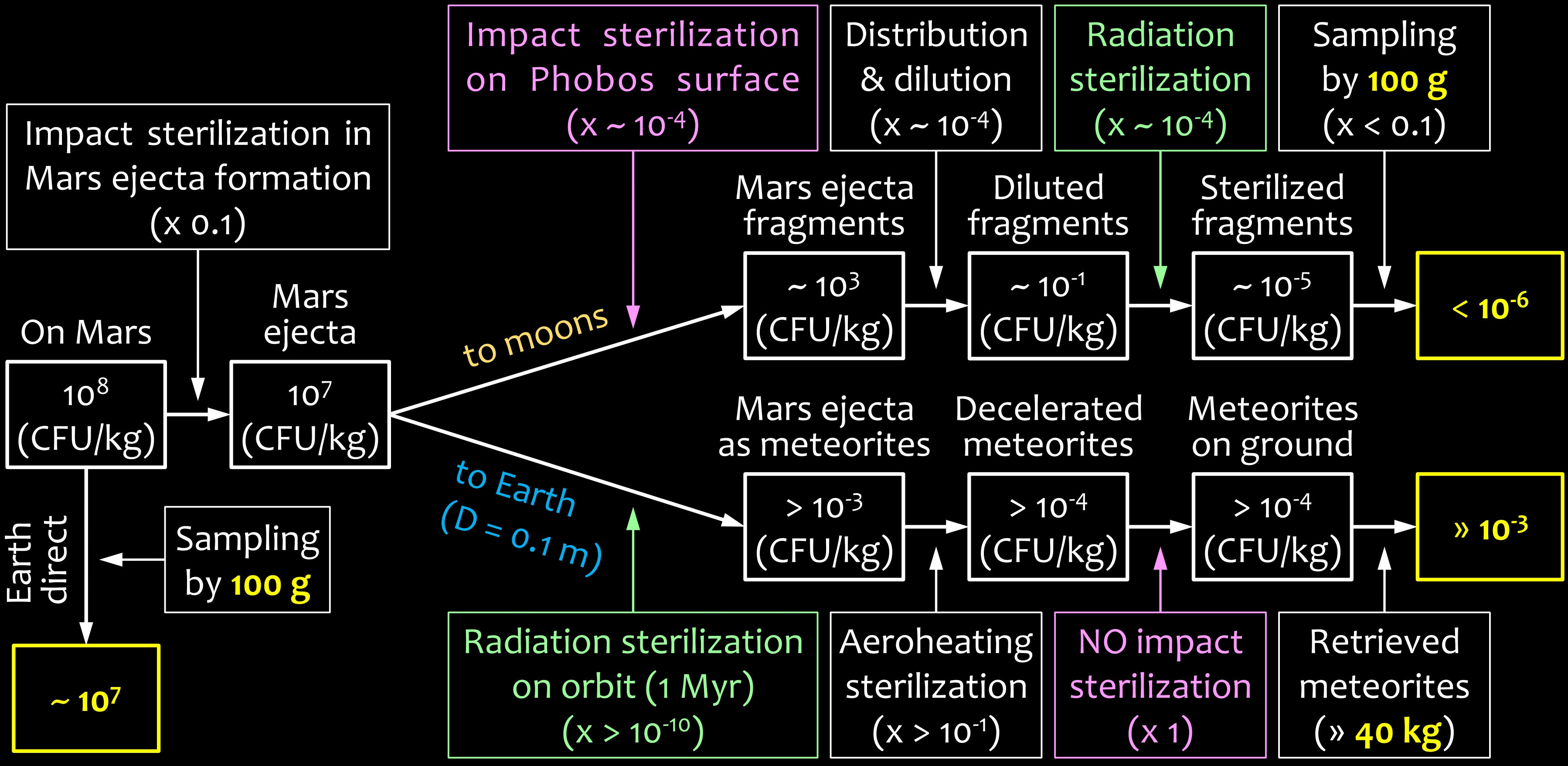
Identified Martian Meteorites in the Past 1 Myr

- List of latest Martian meteorites having cosmic-ray exposure ages less than 1 Myr
  - Cosmic-ray exposure ages are taken from Aoudjehane et al. (2012), Nishiizumi et al. (2011), Park et al. (2003), Schwenzer et al. (2007), and Wieler et al. (2016). Ejection age is expected to be a sum of cosmic-ray exposure age and terrestrial age.
  - Total mass of Martian meteorites collected on the terrestrial surface amount to **40 kg**, which is expected to be only the tip of the iceberg.

Martian meteorite	Mass (kg)	Cosmic-ray exposure ages (Myr)	Ejection age (Myr)
EETA 79001	7.94	~ 0.6	~ 0.6
NWA 4925	0.282	~ 0.7	~ 1.1
Sayh al Uhaymir 005-150	11.21	~ 1.0	~ 1.0
NWA 1195	0.315	~ 1.0	~ 1.2
NWA 5789	0.049	~ 1.0	~ 1.0
NWA 6162	0.089	~ 1.0	~ 1.0
Tissint	7-11	~ 1.0	~ 1.0
NWA 2046	0.063	~ 1.0	~ 1.2
NWA 2626	0.0311	~ 1.0	~ 1.3
Dar al Gani 476-1051	10.45	~ 1.0	~ 1.0

Comparison between Sample Return & Natural Influx

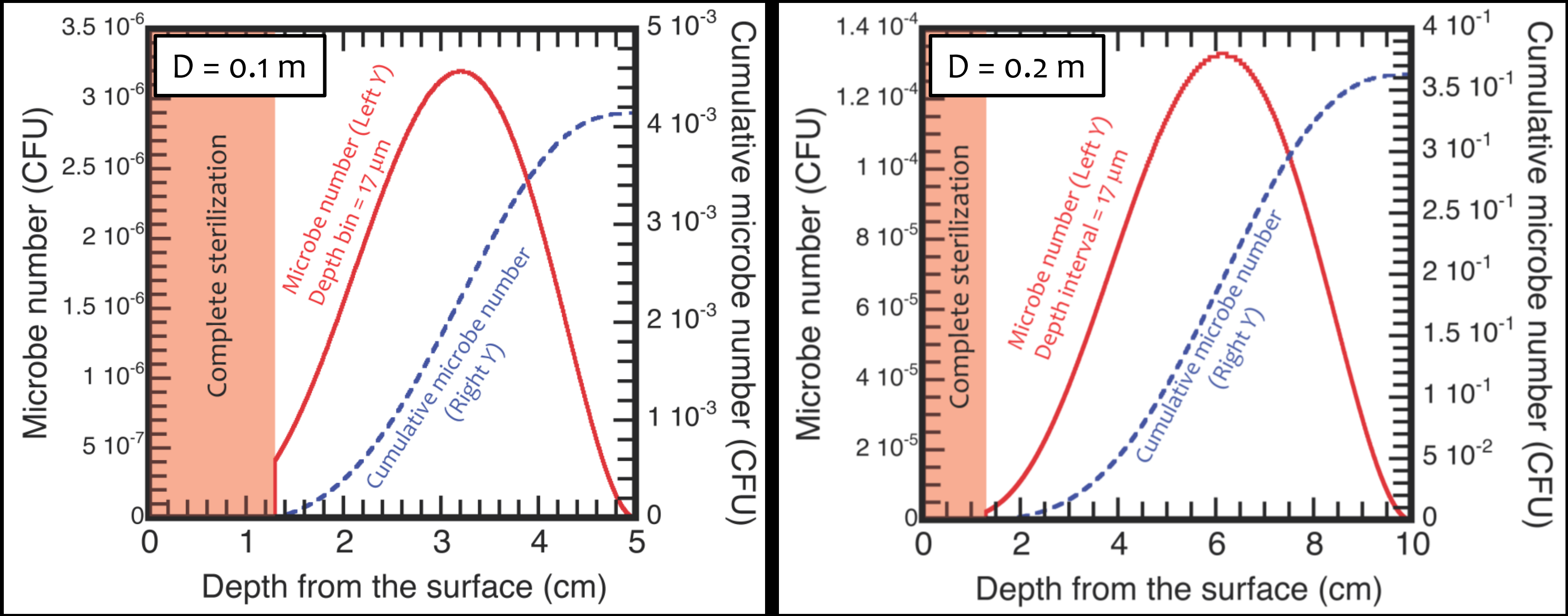
- If microbial survival rate (MSR) against radiation is higher than expected, contamination probabilities are higher in both cases by the same order of magnitude.
- Even if MSR against hypervelocity impact may is higher than expected, it may be improbable to exceed a 10^3 times prediction, according to past impact experiments in the literature.
- MSR of Martian meteorites quickly increases with diameter.



Radiation Sterilization of Martian Meteorite

Essential Characteristics

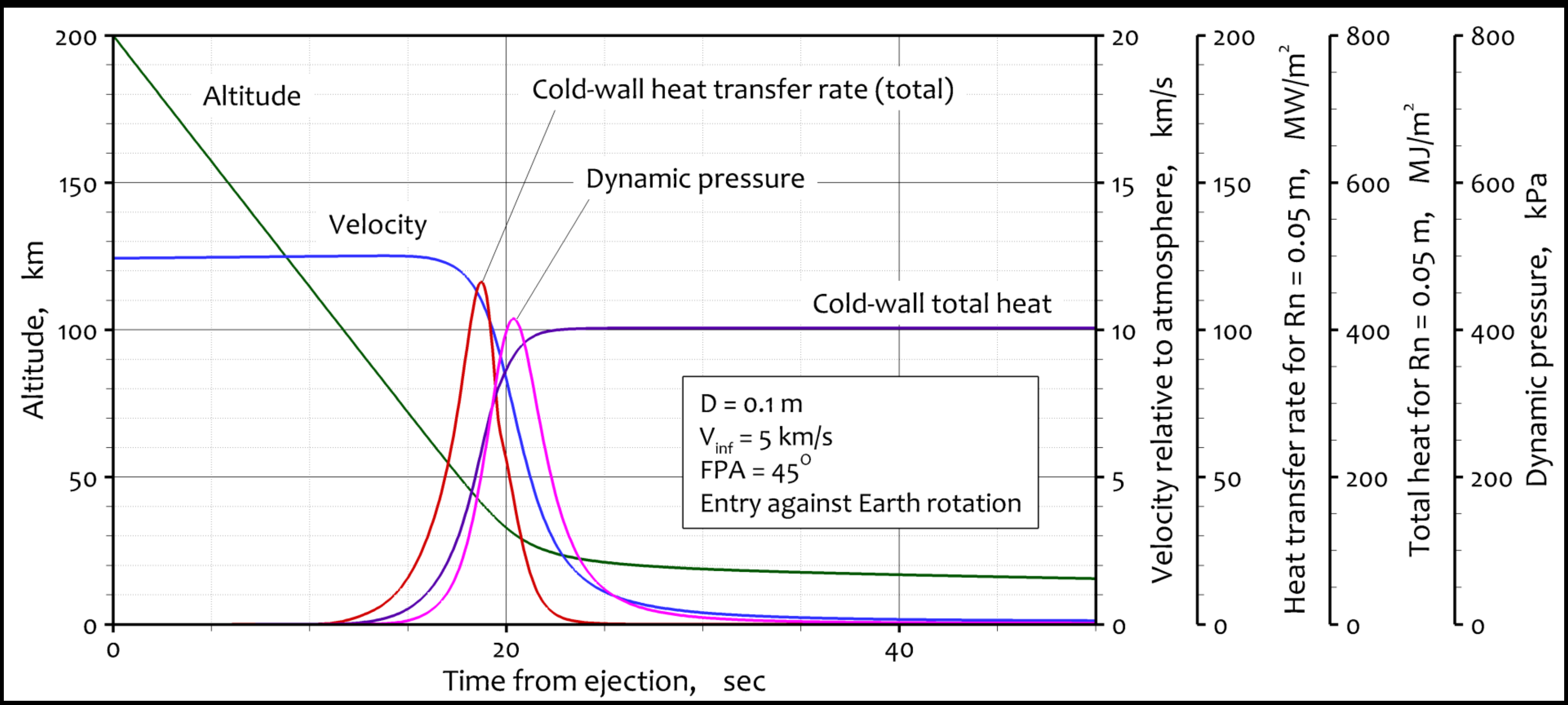
- According to radiation sterilization model (see Sec. 7 of Fujita et al., 2018), total microbes surviving after 1 Myr amount to 4.1×10^{-3} CFU (MSR = 4.1×10^{-10}) for a meteorite having a 0.1-m diameter (1 kg in weight) , which is a threshold diameter for escape from Mars.
- Martian meteorites having larger diameters, which are more likely to arrive at Earth, have much higher MSR because of slower radiation sterilization in the deep region (3.6×10^{-8} for D = 0.2 m) . Above all, **MSR > 10^{-10}** for all Martian meteorites generated in the past 1 Myr.



Aerodynamic Deceleration &Heating on Earth Entry

Characteristics of Terrestrial Aerodynamic Heating

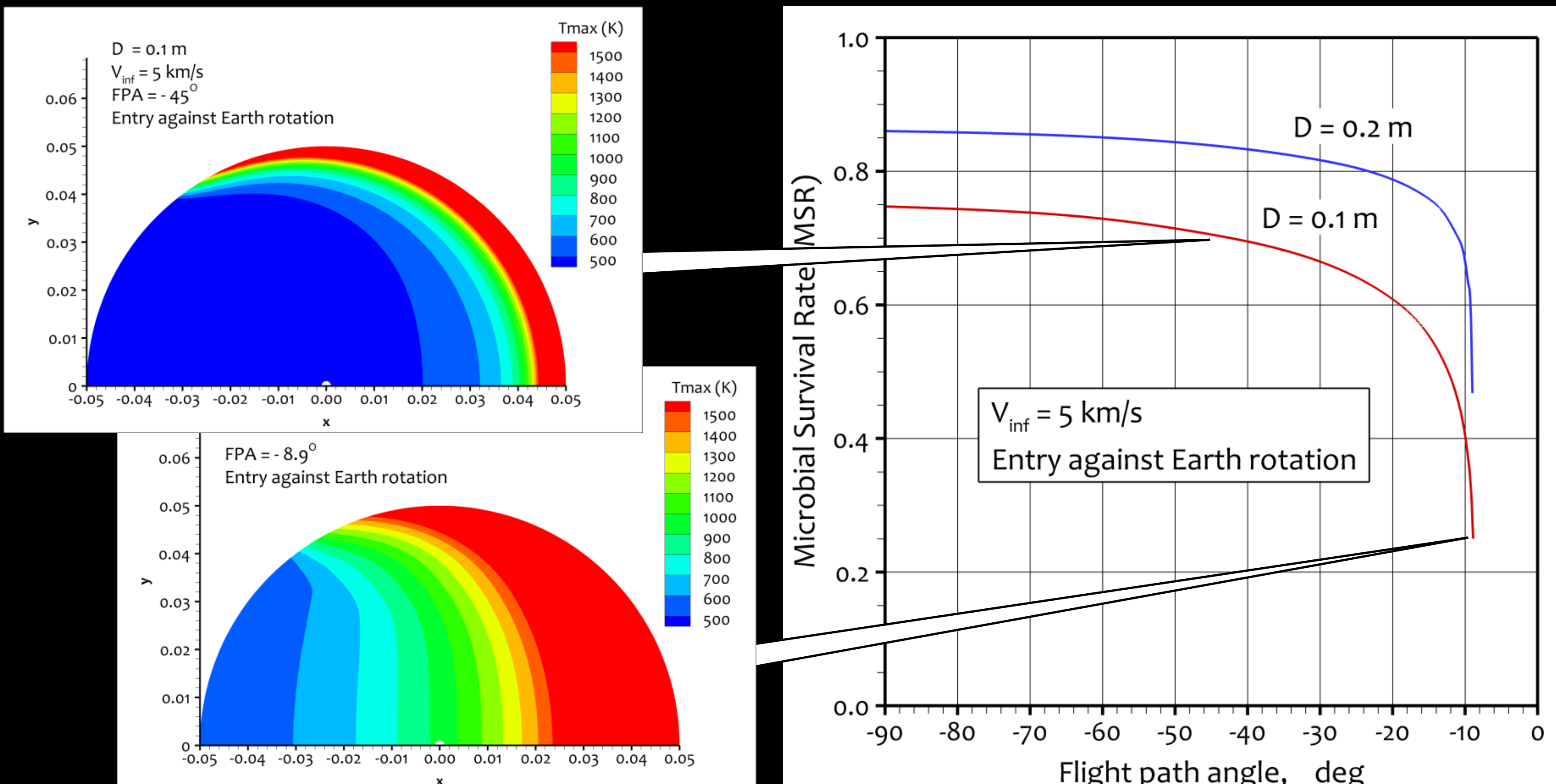
- Because of a dens atmosphere, Martian meteorites arriving at Earth undergo much higher aerodynamic heating than they did during the Mars escape phase in the Marian atmosphere (see Sec. 5 of Fujita et al., 2018).
- Martian meteorites are completely decelerated by aerodynamic drag to terminal velocities (< 100 m/s for D < 0.4 m), resulting in **no impact sterilization** on the ground.



Aerodynamic Heating Sterilization on Earth Entry

Characteristics of Terrestrial Aerodynamic Heating

- Heat conduction analysis of Martian meteorites along the atmospheric entry trajectory (with an assumption of V_{inf} = 5 km/s) shows that **MSR > 0.1** for meteorites larger than 0.1 m in diameter (based on 500ºC x 0.5 sec sterilization), even though uncertainties originating from ablation, erosion, and fragmentation are taken into account.



Conclusions

- Martian meteorites transported from Mars to Earth in the past 1 Myr have microbial contamination probability much higher by order of magnitude (**10^3 or more**) than that of 100-g samples taken from Martian moons.
- Errors in radiation sterilization model do not change this conclusion because microbial contamination probabilities of samples and meteorites changes accordingly at the same order of magnitude.
- Errors in hypervelocity impact sterilization model do not change this conclusion, since the microbial survival rate against hypervelocity impacts is expected to remain below 0.1.
- Aerodynamic heating has minor contributions to sterilization of Martian meteorites on arrival at Earth.
- The above means that natural influx equivalent to samples from Martian moons is continuously and frequently transported to the surface of Earth.

- According to COSPAR planetary protection policy (PPP), since the preponderance of scientific evidence indicates that there has been a natural influx to Earth of material equivalent to a sample returned from the target body, sample return from the Martian moons is classified as ***Unrestricted Earth Return***.

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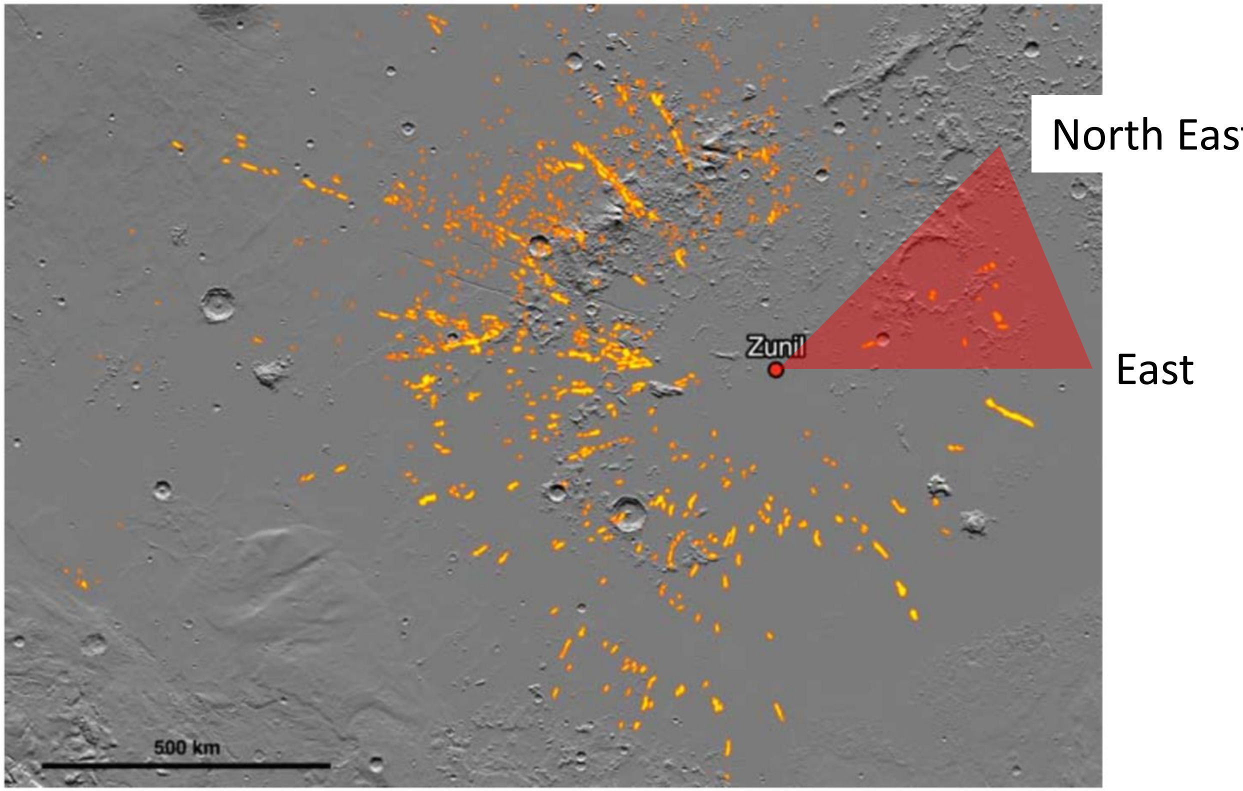
Items

Impact direction of the Zunil-forming impact

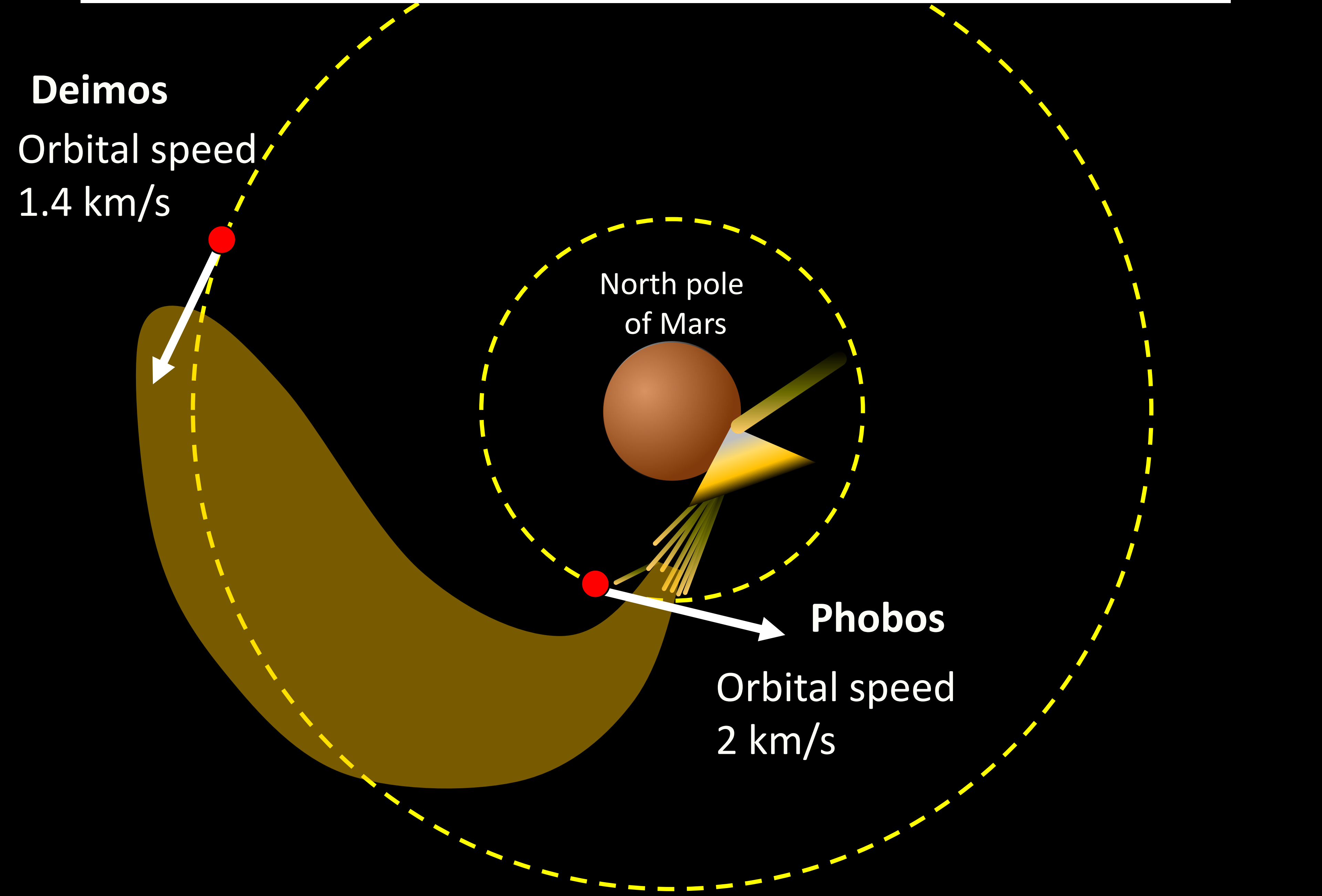


Our Monte Carlo model

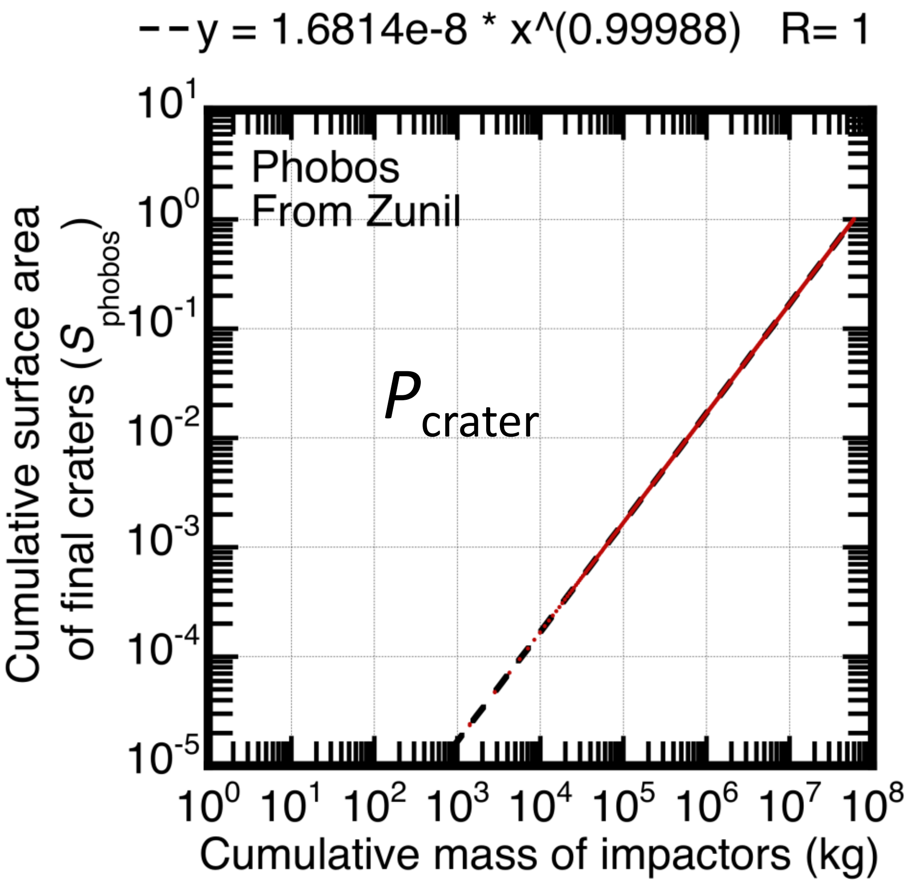
Figure 6. MOLA shaded relief map with Zunil's rays as seen in the nighttime thermal IR. Rays are mapped in yellow and outlined in orange to make them more apparent. The map extends from latitude 6°S to 18°N and longitude 148°–175°E. There are additional small ray segments to the west and south, beyond the edges of this map.

[Preblich+07, JGR]

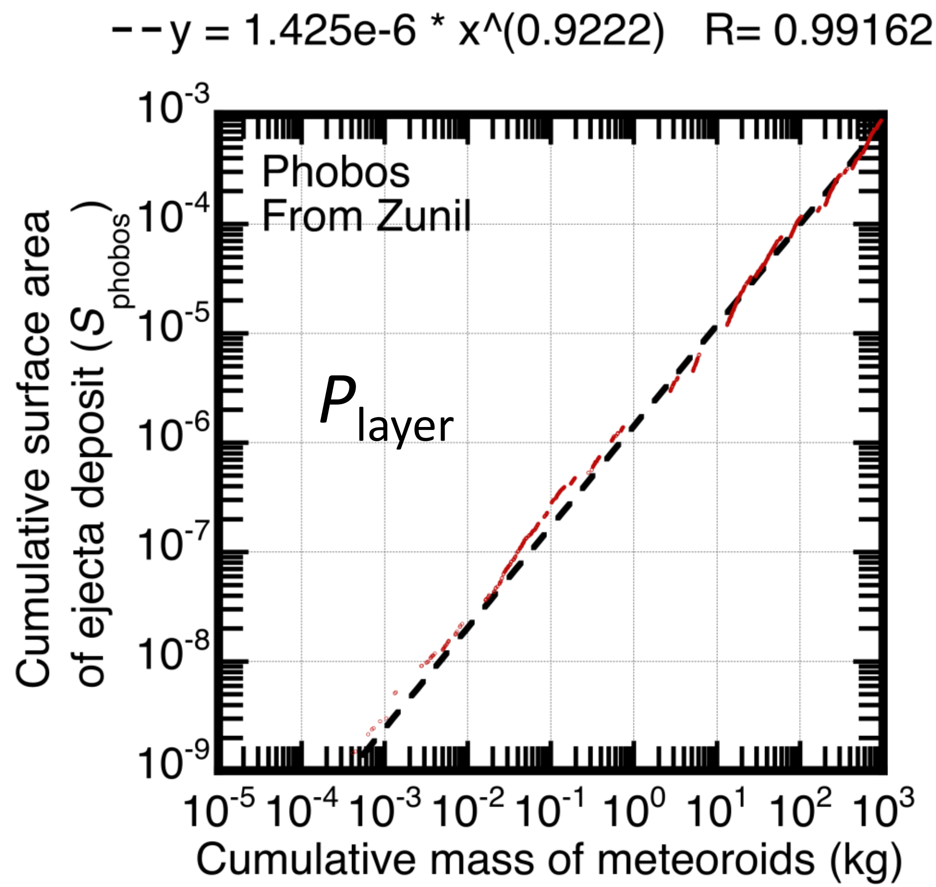
The ejecta having the retrograde orbits



P_{crater} vs Cumulative mass of Mars rocks

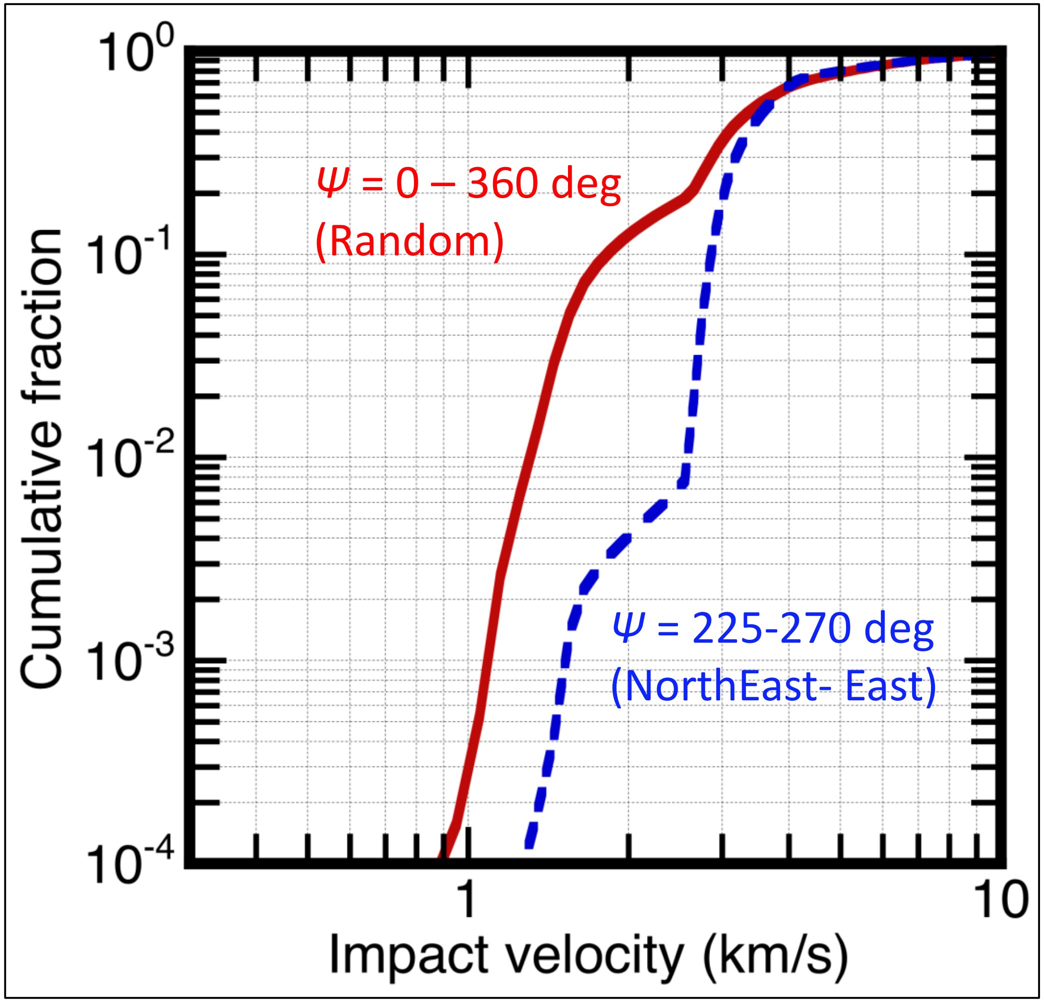


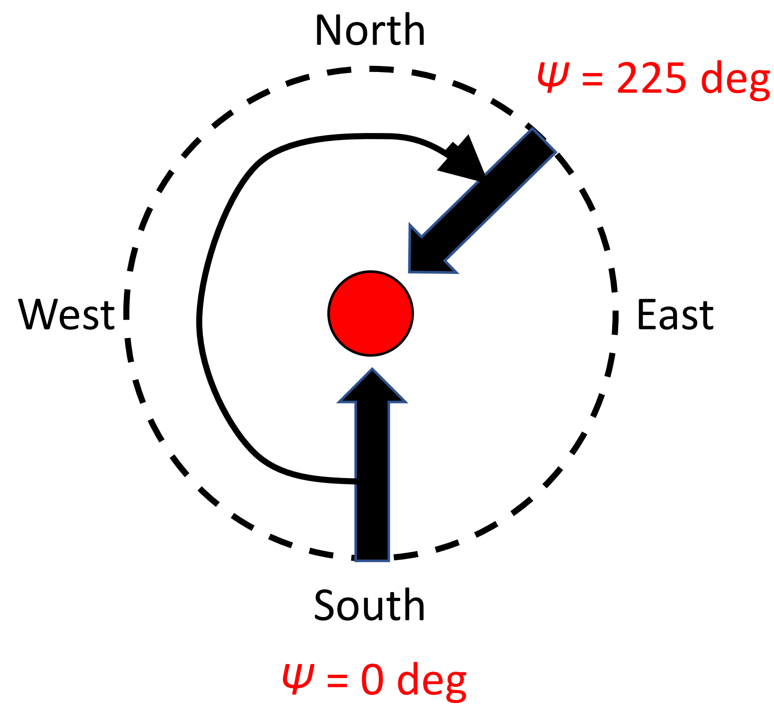
P_{layer} vs Cumulative mass of meteoroids



P_{crater} & P_{layer} are roughly proportional to Cumulative mass of impactors.

Effects of impact direction on $M_{transported}$ & v_{imp}





The mass fraction at v_{imp} < 2 km/s

Ψ : 0 – 360 deg -> 13%

Ψ : 225 – 270 deg -> 0.4%

$M_{transported}$

Ψ : 0 – 360 deg -> 1.46 x 10^6 kg

Ψ : 225 – 270 deg -> 2.04 x 10^6 kg

Mojave crater chronology

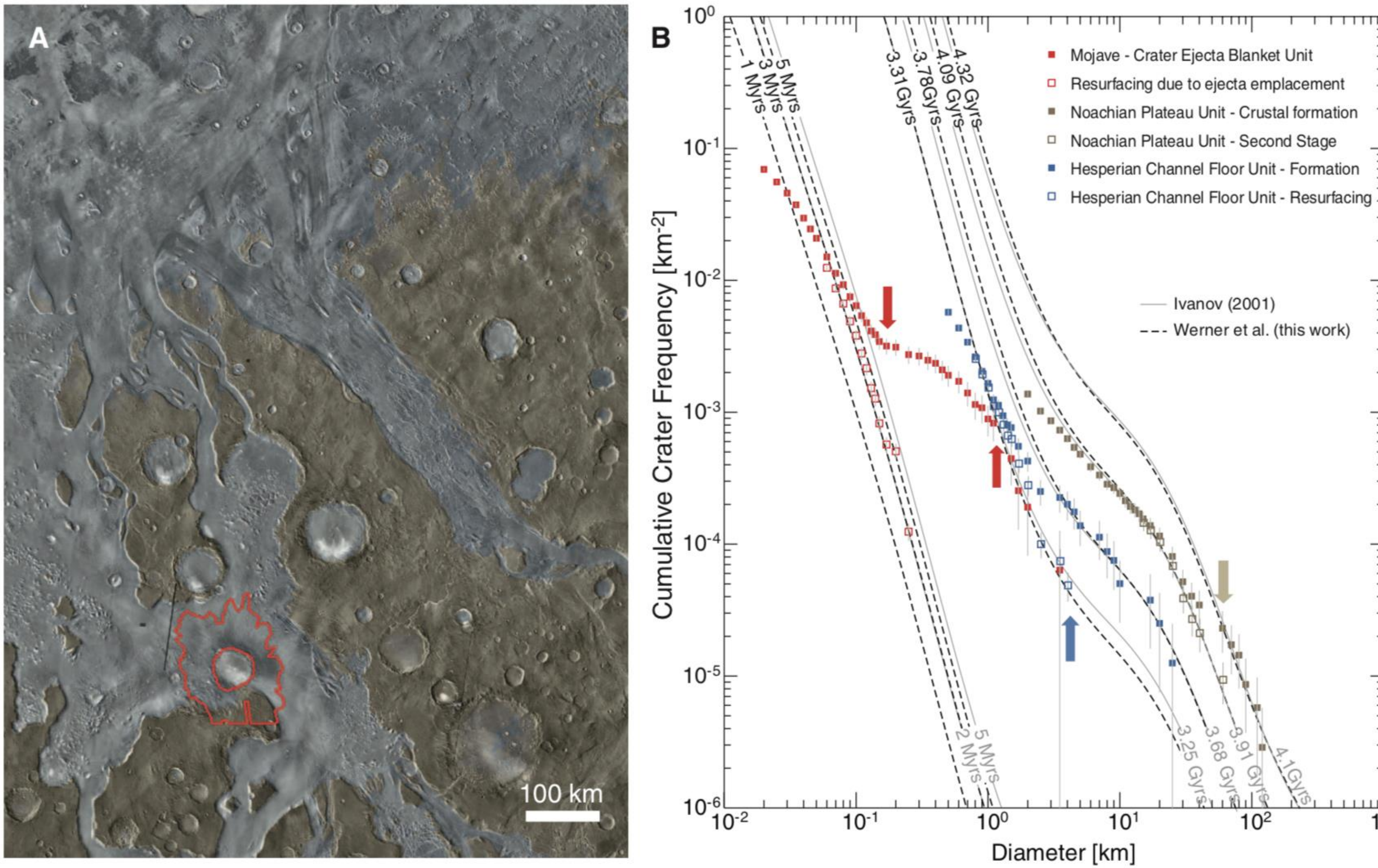
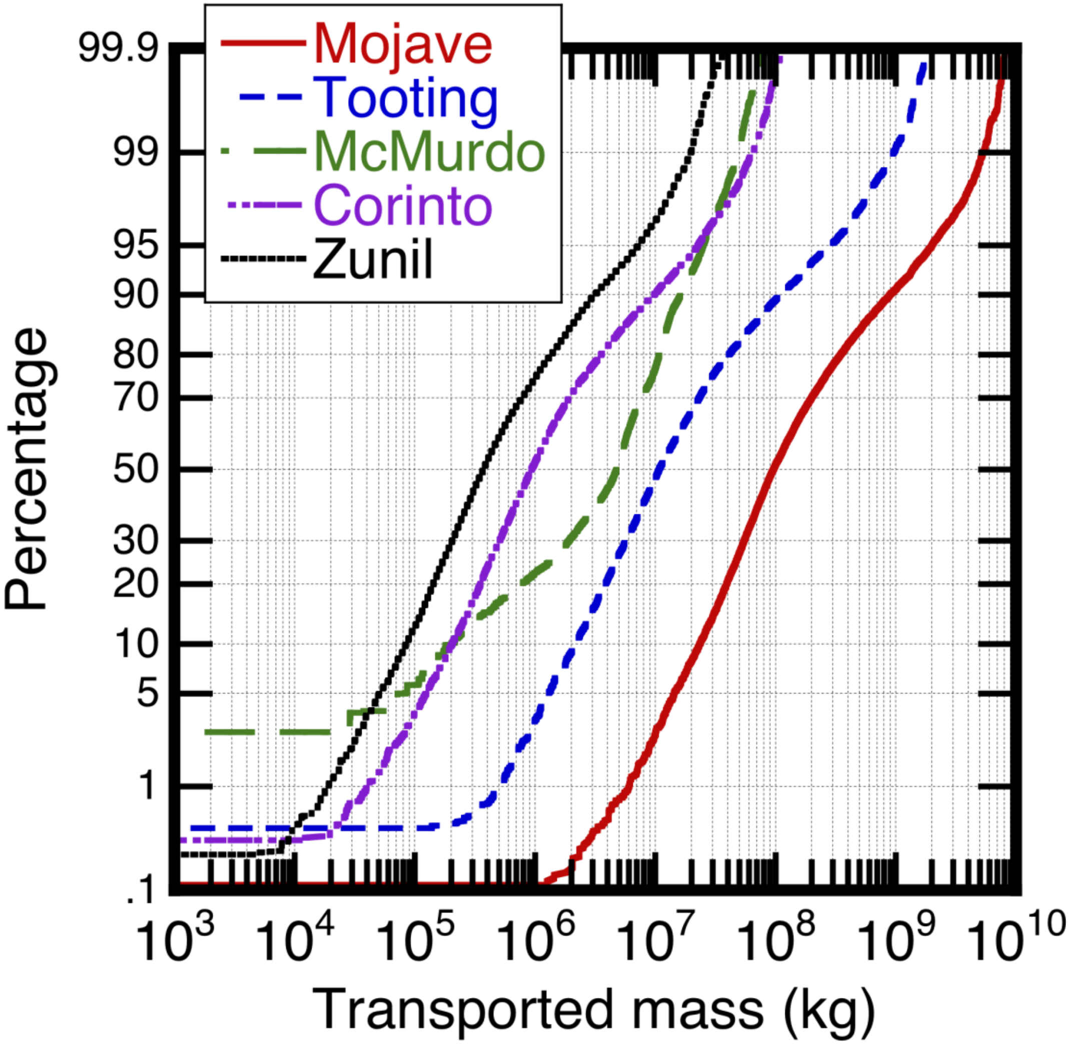


Fig. 2. Crater statistics of Mojave. (**A**) THEMIS daytime image mosaic overlain by Mars Orbiter Laser Altimeter color-coded topography. Craters were counted for the plateau units (brown), the channel units (blue-gray), and the continuous ejecta unit of Mojave Crater (red line). (**B**) Results of the crater count statistics [brown, blue-gray, and red refer to the units in (A)], displayed as cumulative crater frequency versus crater diameter. The age interpretation is based on our crater-production function and cratering chronology model (black dashed line) and is compared to a standard model [(*23*), light gray solid line]. Colored arrows indicate the onset crater diameter, at which resurfacing occurs or stops.

[Werner+14]

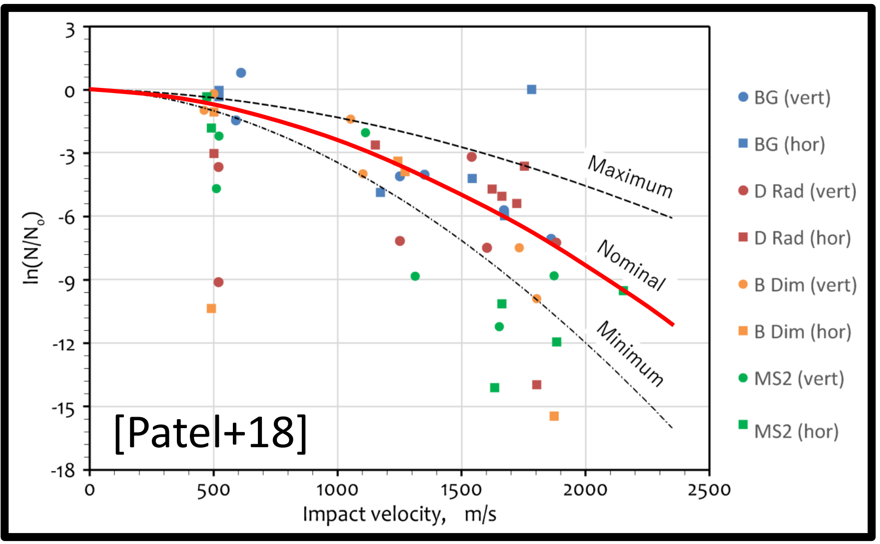
Transported mass to Phobos from five large craters on Mars

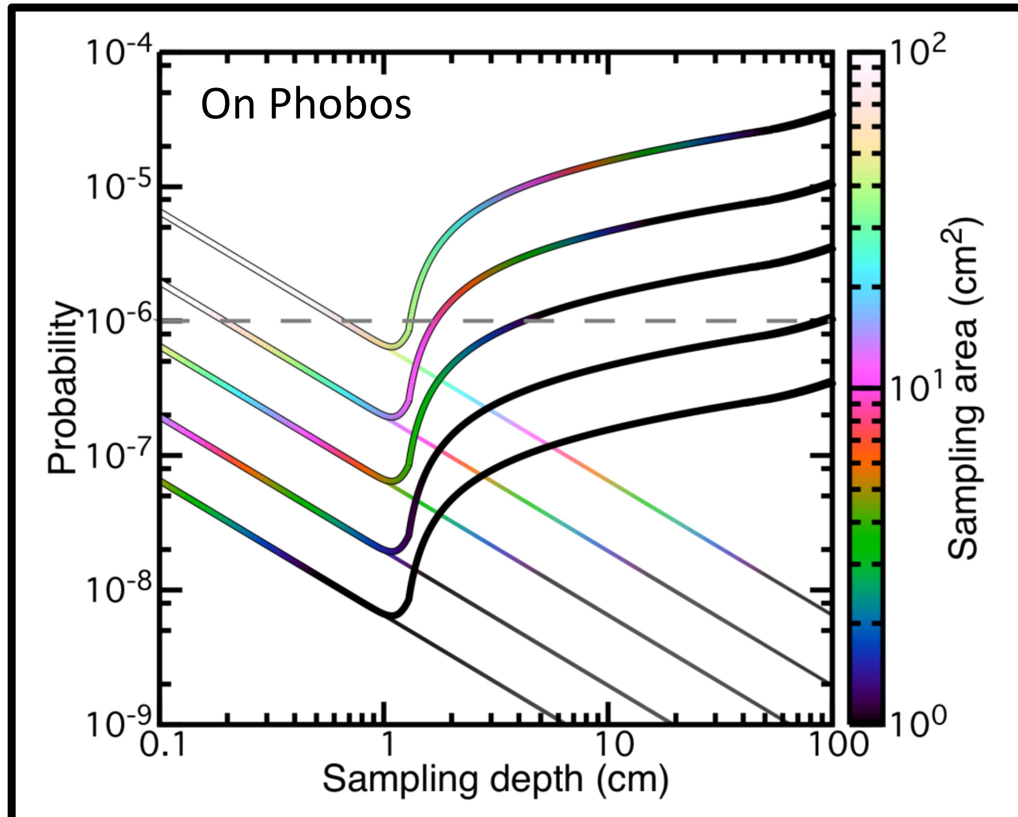


	Average
Mojave:	3.9914e+08
Tooting:	5.8380e+07
McMurdo:	7.2231e+06
Corinto:	4.4108e+06
Zunil:	1.4661e+06

Uncertainty in impact-survival rate

Sampling probability in the "Maximum case"





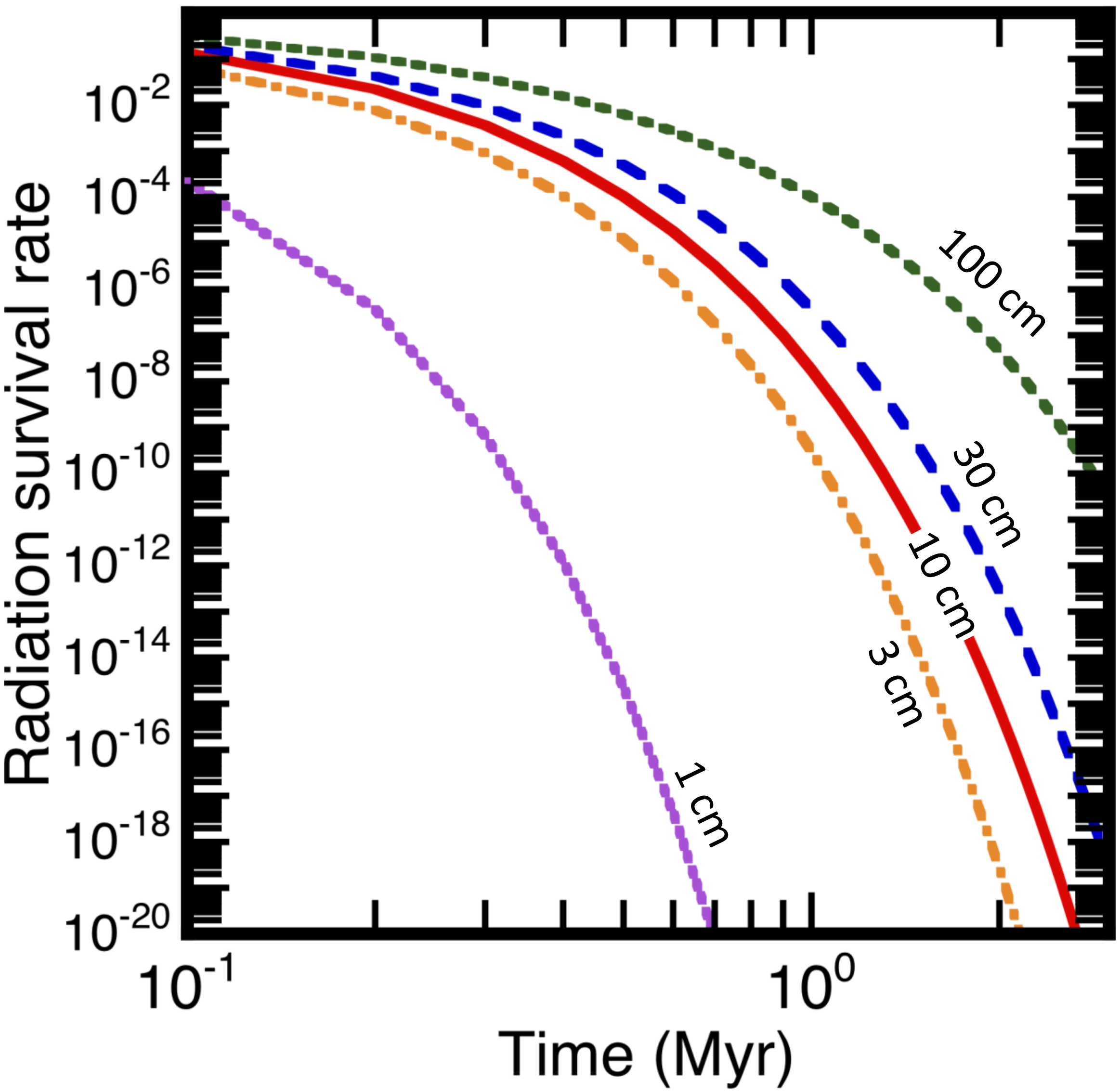
By convolving the v_{imp} distribution

Nominal: $N/N_0 = 2.9 \times 10^{-5}$

Maximum: $N/N_0 = 3.2 \times 10^{-4}$

(On Phobos)

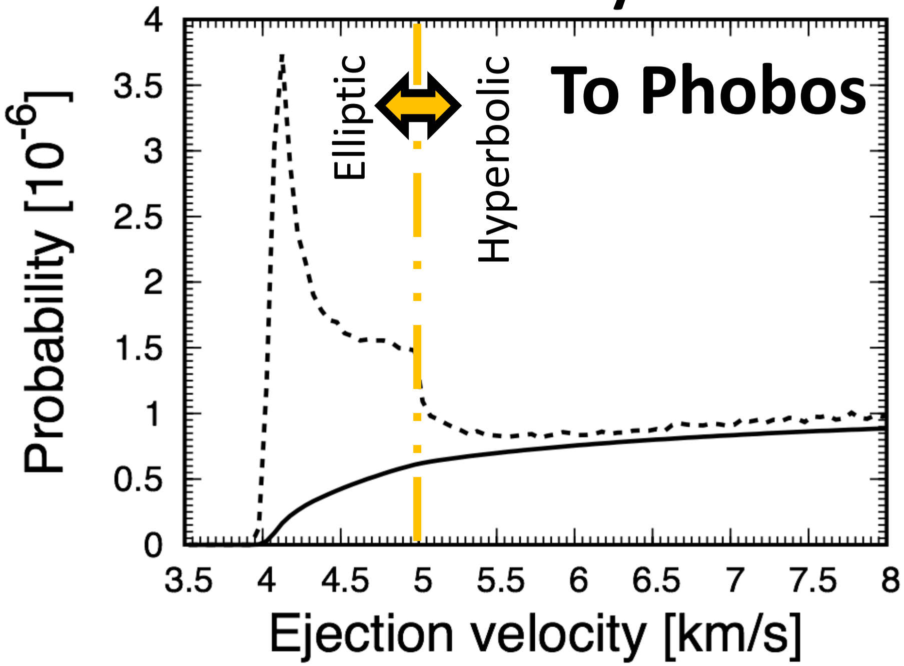
Radiation survival rate $\eta(t, H)$



$$\eta(t, H) = \frac{\int_0^H \exp\left(-\frac{t}{TC(h)}\right) dh}{H}$$

Transportation probability

Our study



Chappaz+13

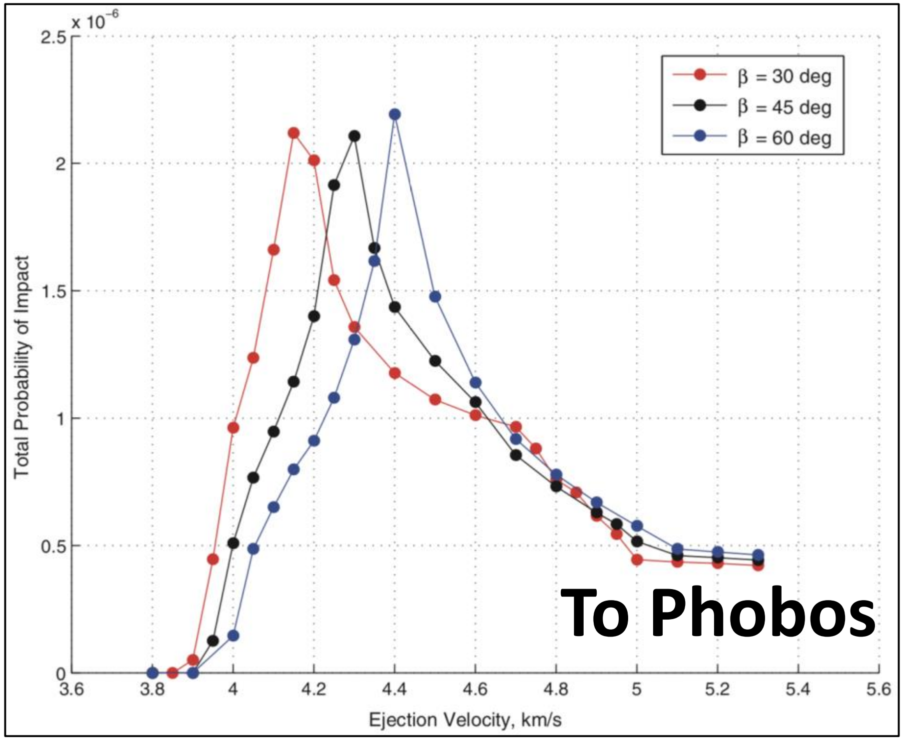
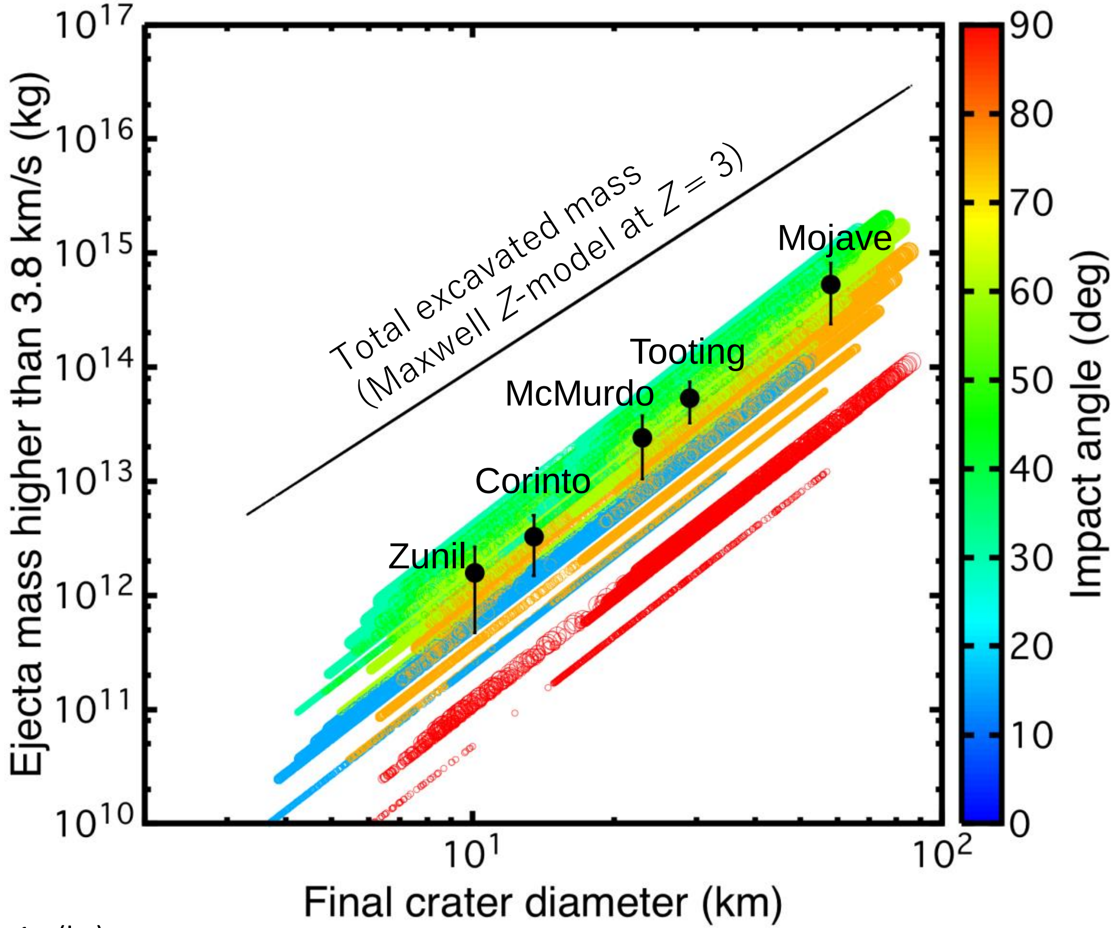


Table 1

	Phobos	Deimos
Transported mass (kg)	2.0E+06	3.8E+04
Transported microbes (CFU)	2.0E+13	3.8E+11
Number of impacts of Mars rocks	1.4E+06	2.7E+04
Median impact velocity (km/s)	3.6E+00	3.2E+00
Impact survival rate	2.9E-05	5.6E-04
Projectile retained fraction	2.2E-01	2.9E-01
Mars rock mixing ratio in crater	1.0E-05	1.1E-05
ncrater0 (CFU/kg)	3.1E-03	4.8E-02
Pcrater	3.4E-02	2.8E-03
Radiation survival rate at 1 m depth	3.1E-01	3.1E-01
sthin0 (CFU/cm2)	2.9E-05	3.3E-05
sthin (CFU/cm2)	1.0E-06	1.1E-06
Player	1.1E-03	9.4E-04
Nsurv,crater (CFU)	4.0E+07	1.9E+07
Nsurv,layer (CFU)	1.7E+04	4.9E+03
Survived fraction at the present	2.0E-06	5.1E-05

Table 2

Depth from the surface (cm)	Survival rate
0.3	3.1E-27
1	1.2E-04
3	6.6E-02
6	1.1E-01
10	1.4E-01
30	2.0E-01
60	2.4E-01
100	3.1E-01

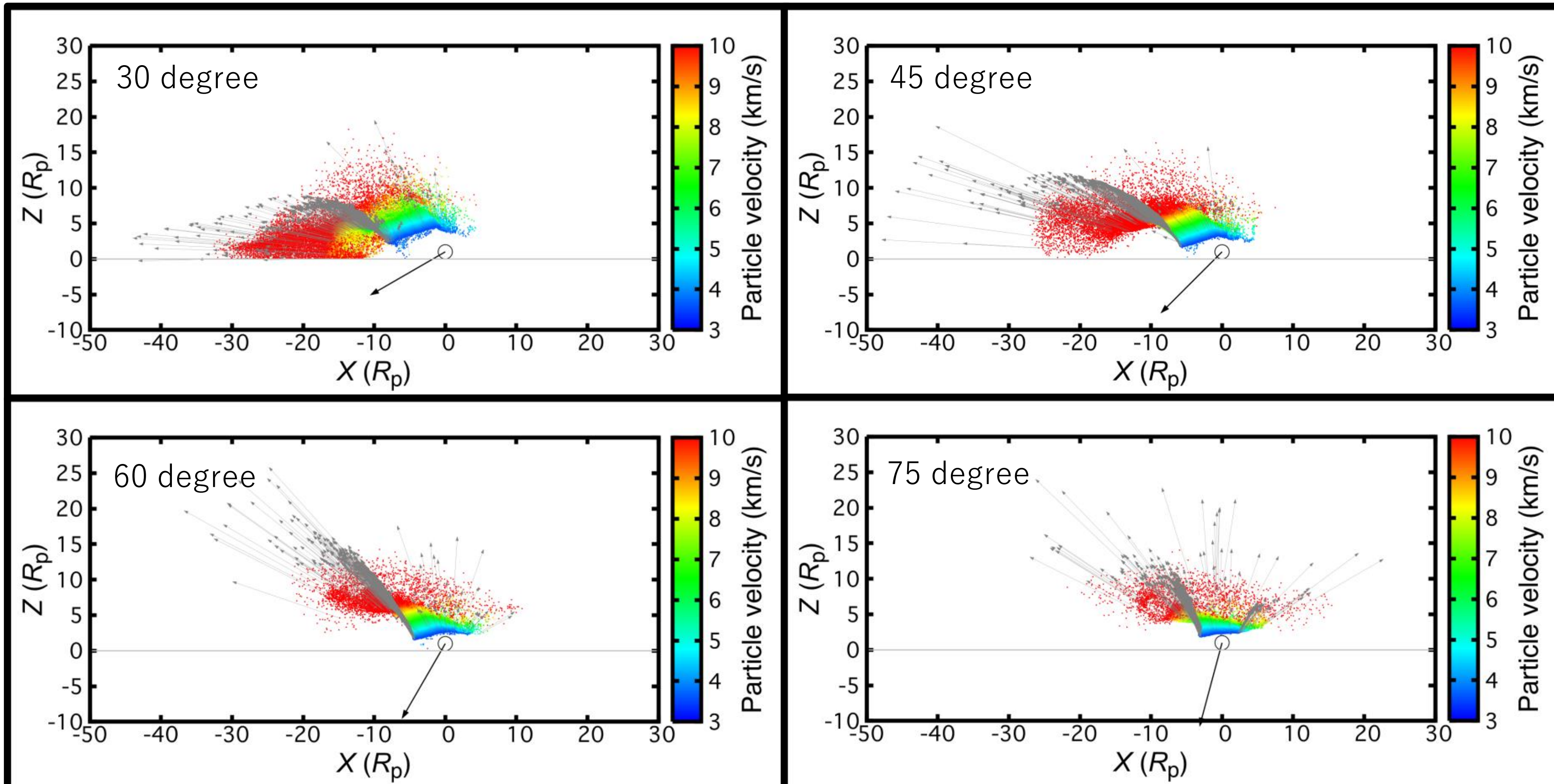


#Name	Diameter(km)	Ejecta_mass (kg)	1σ (kg)
Mojave	58	5.28E+14	2.90E+14
Tooting	29	5.34E+13	2.09E+13
McMurdo	23	2.41E+13	1.36E+13
Corinto	13.5	3.27E+12	1.79E+12
Zunil	10.1	1.57E+12	1.10E+12

$M_p \sim 1 \times 10^{13}$ kg

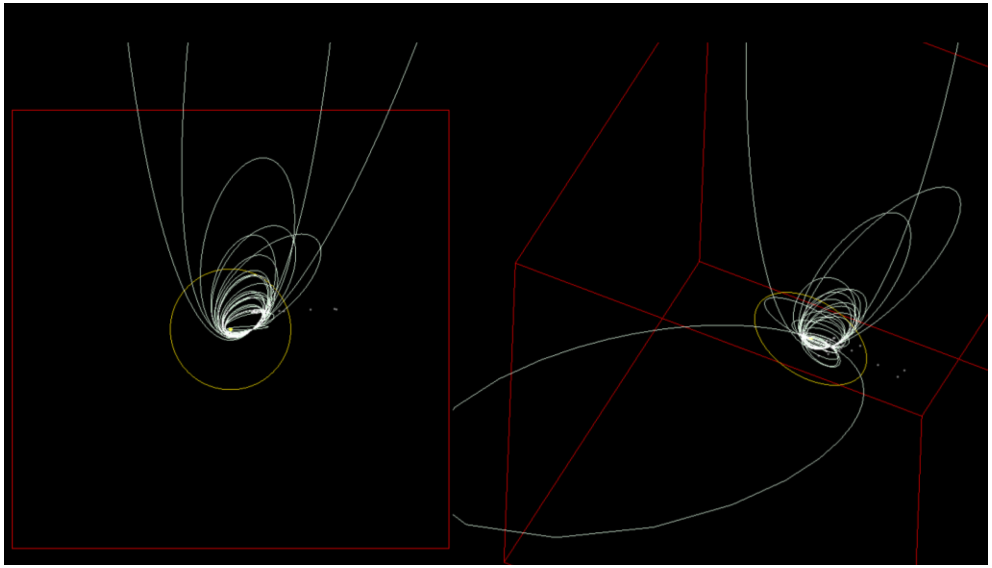
衝突放出計算(玄田)

12 km/s, Basalt -> Basalt



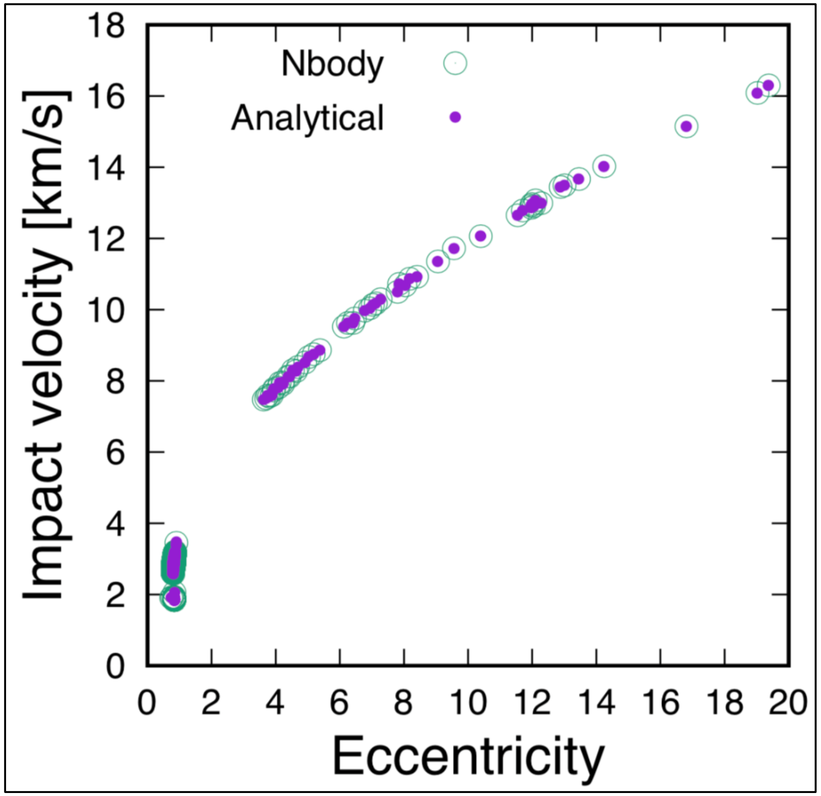
地表面より上空にあり, >3.5 km/sの速度で運動している粒子のデータを出力.

軌道計算(兵頭, 計算中)



SPH粒子の軌道をN体軌道計算, 解析計算で追跡し,
結果が一致することを確かめた.

計算の1例

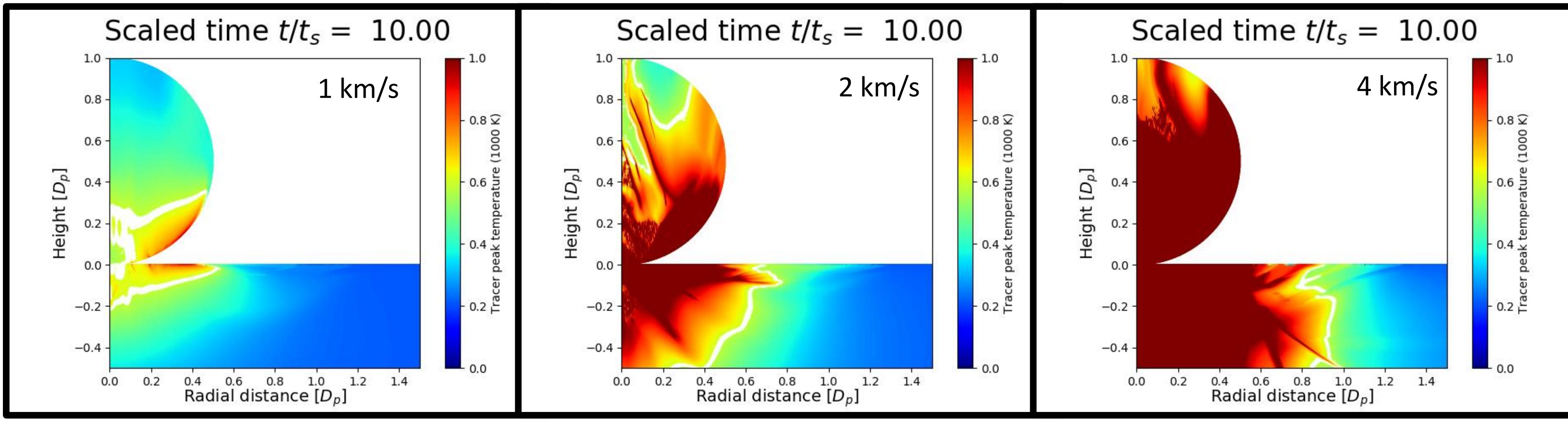


計算コードが概ね完成. 現在計算中. 計算出力待ち, 結果の解析, 吟味, まとめなど随時進める予定...

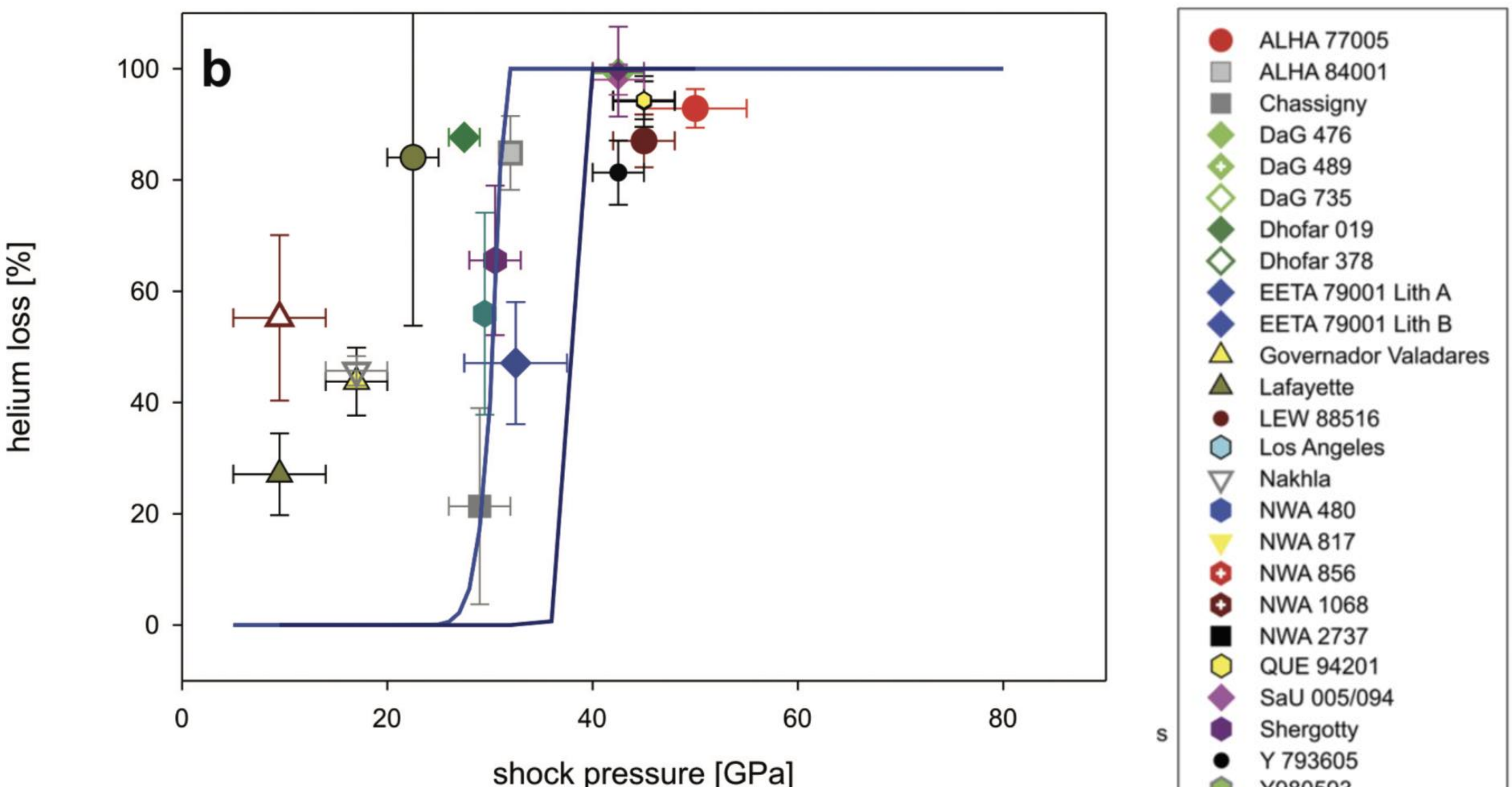
フォボスへの衝突時の加熱

強度モデルパラメータ
[Ivanov+10, GSA special paper]

Basalt->Basalt, 正面衝突, 250 CPPR



Projectileの裏面まで>600 Kまで加熱するには4 km/sの速度が必要か…?


b
helium loss [%]
100
80
60
40
20
0
0
20
40
60
80
shock pressure [GPa]
ALHA 77005
ALHA 84001
Chassigny
DaG 476
DaG 489
DaG 735
Dhofar 019
Dhofar 378
EETA 79001 Lith A
EETA 79001 Lith B
Governador Valadares
Lafayette
LEW 88516
Los Angeles
Nakhla
NWA 480
NWA 817
NWA 856
NWA 1068
NWA 2737
QUE 94201
SaU 005/094
Shergotty
Y 793605
Y980593
Y 000593
Zagami
s

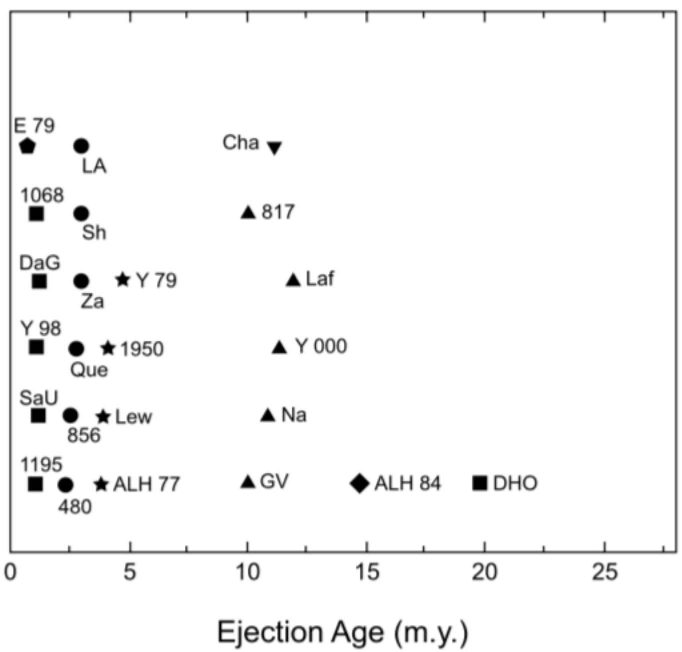
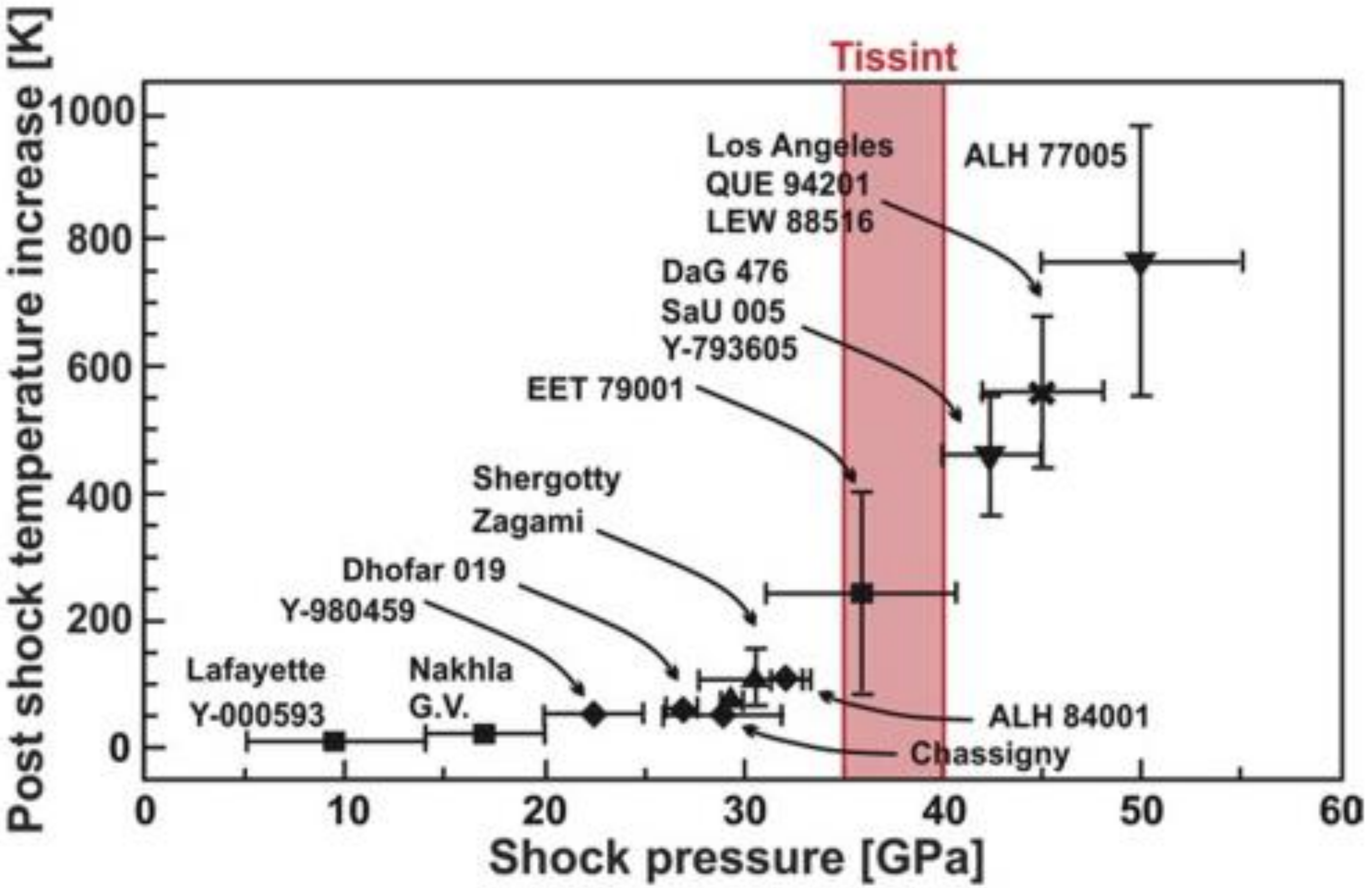


TABLE I

Estimates of the peak shock pressure (final equilibration shock pressure) and the overall post-shock temperature increase in Martian meteorites. Data from Stöffler *et al*. (1986) and Stöffler (2000) except for Sayh al Uhaymir 005, Los Angeles, and Dhofar (this paper).

Meteorite	Shock pressure (GPa)	Post-shock temperature*
Shergotty	29 ± 1	200 ± 20
Zagami	31 ± 2	220 ± 50
EETA 79001	34 ± 2	250 ± 50
QUE94201	∼30–35	∼200 – 350
Dar al Gani 467	∼35–40	∼350 – 450
Los Angeles	∼35–40	∼350 – 450
Dhofar 019	∼35–40	∼350 – 450
Sayh al Uhaymir 005	∼35–40	∼350 – 450
ALHA77005	43 ± 2	∼450 – 600
LEW88516	∼45	∼600
Y793605	∼45	∼600
ALH84001	∼35–40	∼300 – 400
Nakhlites	∼20 (±5)	∼100
Chassigny	∼35	∼300

*Relative to ambient pre-shock temperature.



Tissint
Los Angeles
QUE 94201
LEW 88516
ALH 77005
DaG 476
SaU 005
Y-793605
EET 79001
Shergotty
Zagami
Dhofar 019
Y-980459
Lafayette
Y-000593
Nakhla
G.V.
ALH 84001
Chassigny
Post shock temperature increase [K]
0
200
400
600
800
1000
0
10
20
30
40
50
60
Shock pressure [GPa]