Validating Aerosol Dispersal for Mars Atmospheric Warming as a First Step Toward Terraforming Mars: A Mission Concept Prototype

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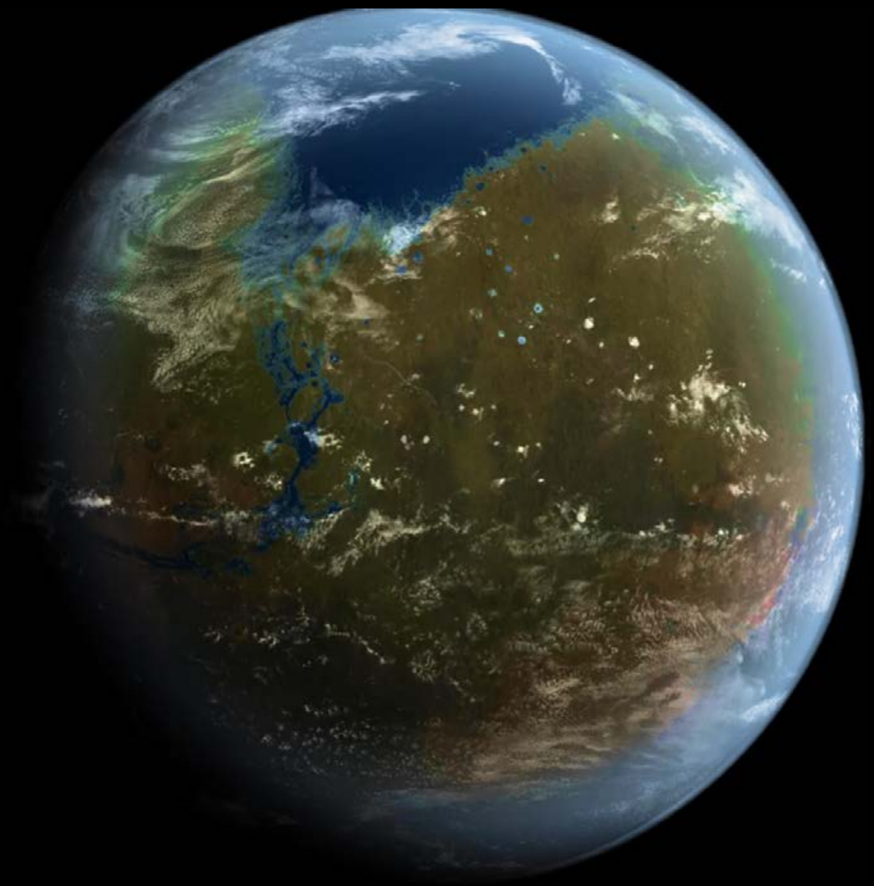
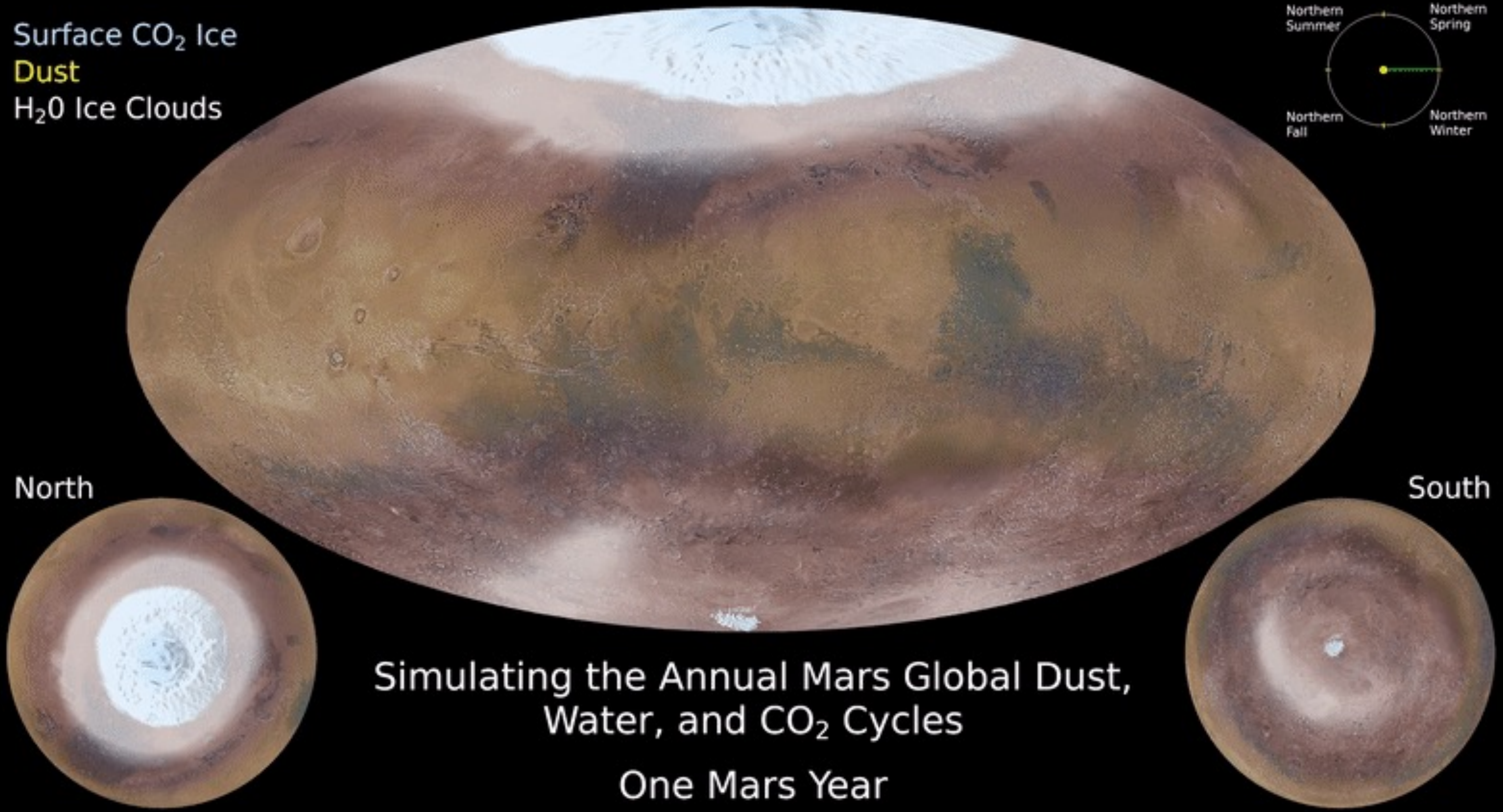
1. Astera Institute
2. University of Chicago
3. Stanford University

(open-science non-profit)

** Now at CU Boulder*



Mars today - a frozen desert



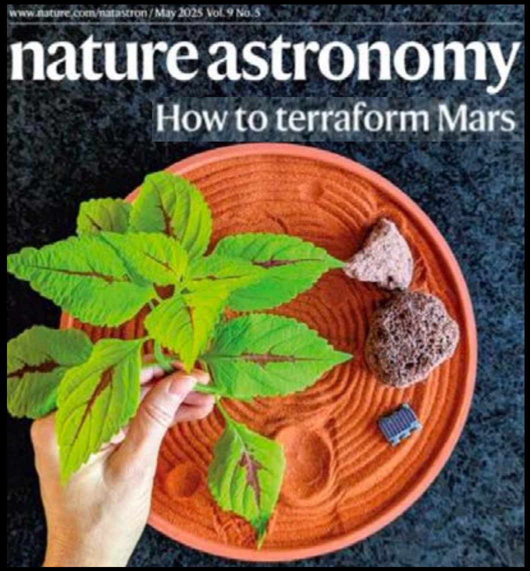
NASA Ames / Alex Kling

Creating sustainable habitats and biospheres beyond Earth: “applied astrobiology”

Post-2024 acceleration in Mars-warming research

Carl Sagan

- 1970s: Sagan’s proposal, first NASA summer study
- 1990s/2000s: super-greenhouse gases
- Post-2024 developments: Engineered aerosols, solar sails, aerogel warming, exponential production of bioplastic greenhouses …



Sagan Icarus 1973, Averner et al. NASA SP-414 1976, McKay et al. Nature 1991, Marinova et al. JGR-Planets 2005
Jakosky & Edwards Nat. Astron. 2018, Ansari et al. Science Advances 2024, DeBenedictis et al. Nat. Astron. 2025, Wordsworth et al. Science Advances 2025, Richardson et al. GRL 2026, Wordsworth et al. Nature Astronomy 2019 …

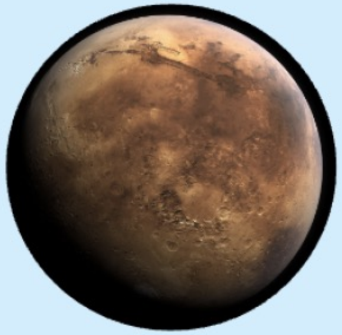
THIS TALK

First step would be warm Mars to enable a photosynthetic biosphere.

Near-term

Today Mars is too cold and dry for Earth–like life to flourish. The first step is abiotic engineering to heat the planet.

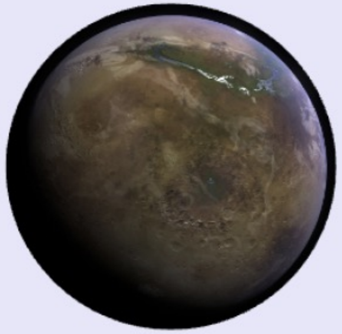
Method: abiotic engineering
GOAL: ⬆ Temperature



Mid-term

A future, warmer Mars would be suitable for non–human life. A planetary ecosystem would begin producing oxygen.

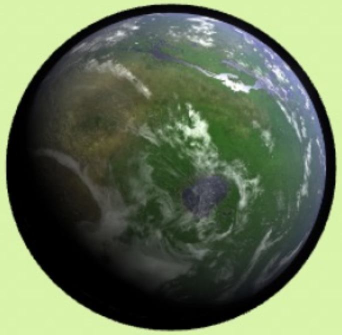
Method: photosynthesis
GOAL: ⬆ O2



Long-term

In the long term, Mars would accumulate more atmosphere and have a stable, favorable climate.

Method: abiotic + biotic
GOAL: ⬆ pressure, stabilize climate



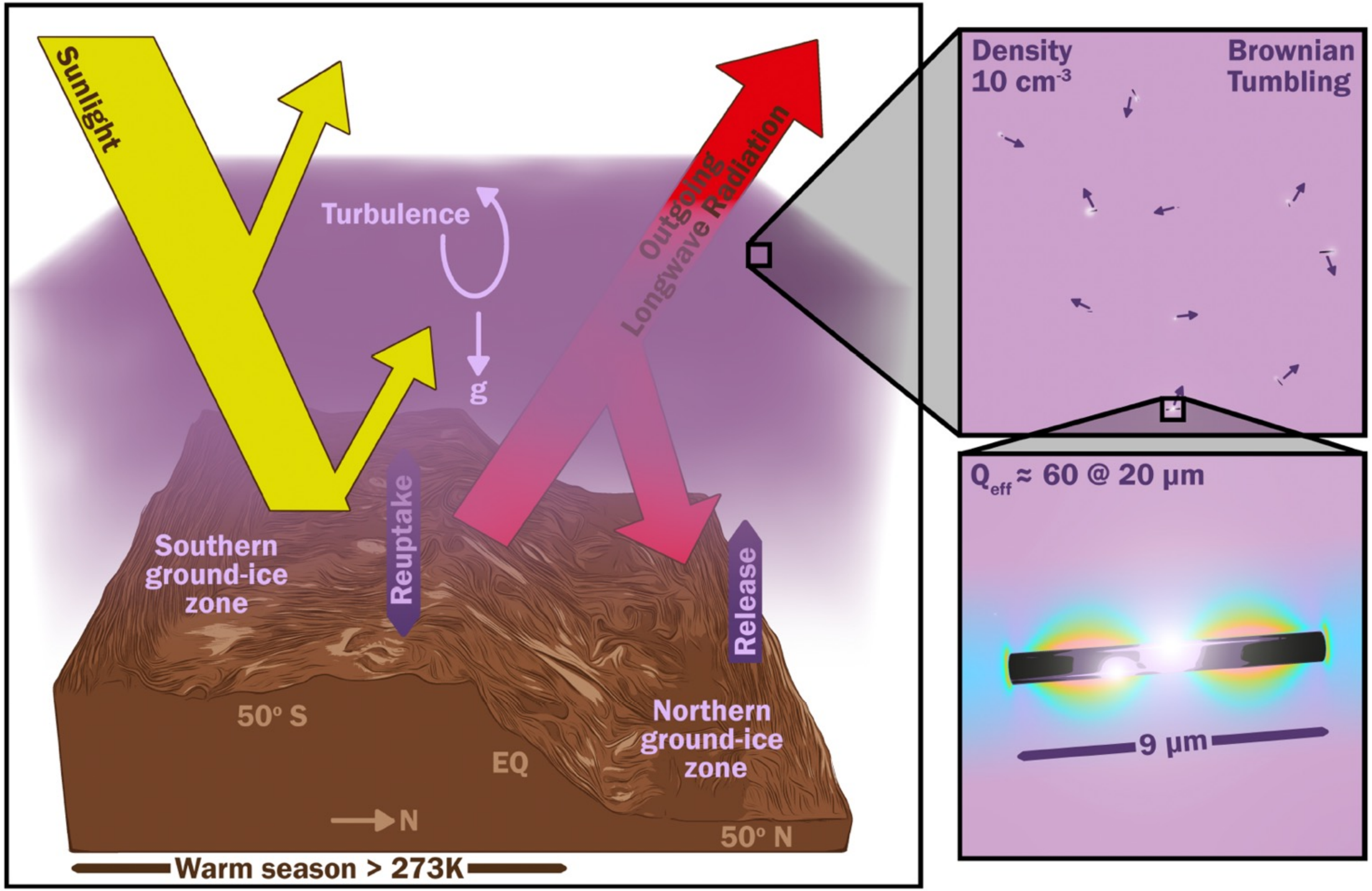
DeBenedictis et al.
Nature Astronomy 2025

1. Warming Mars.

2. Prototyping progress.

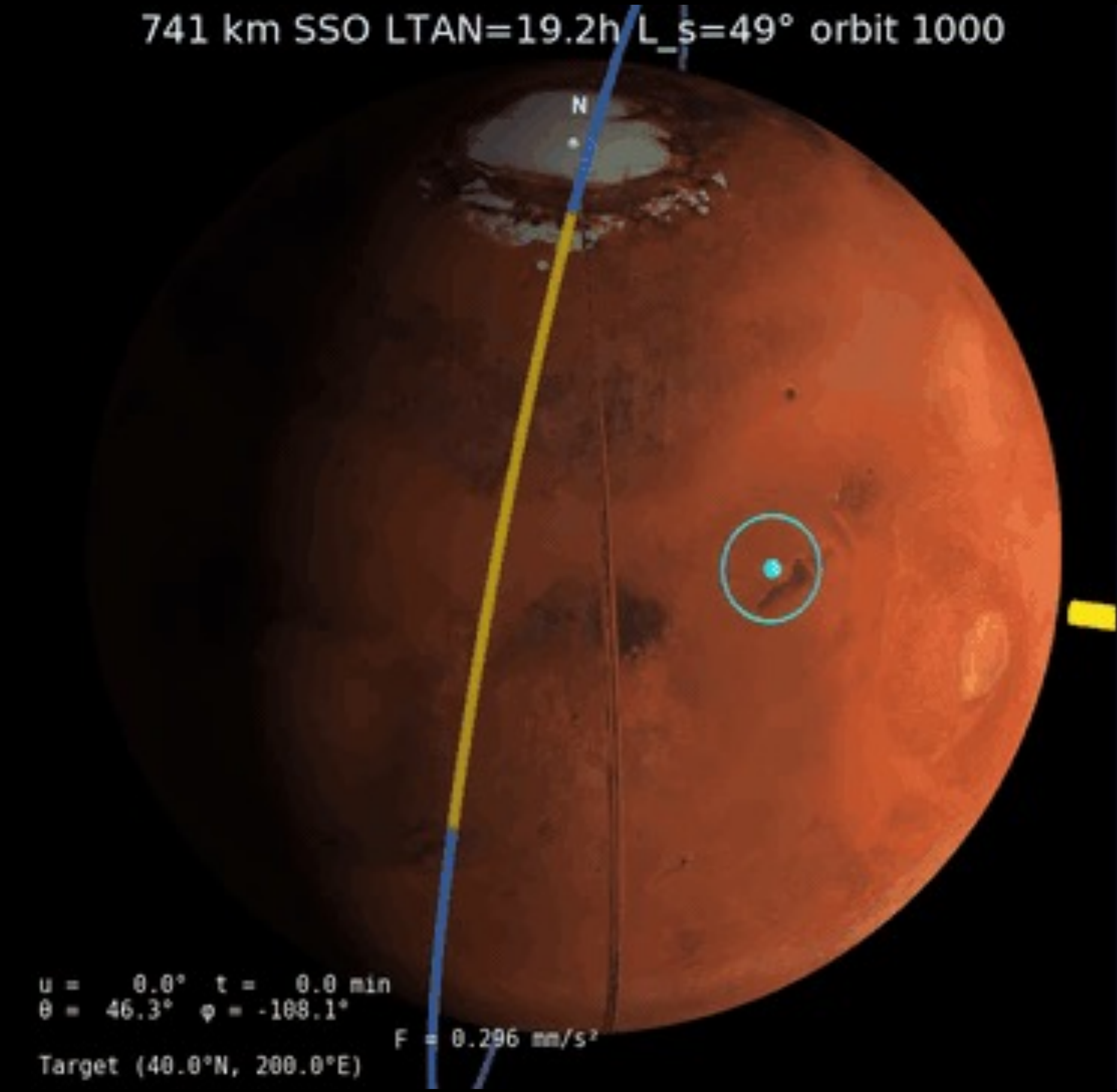
3. What’s next.

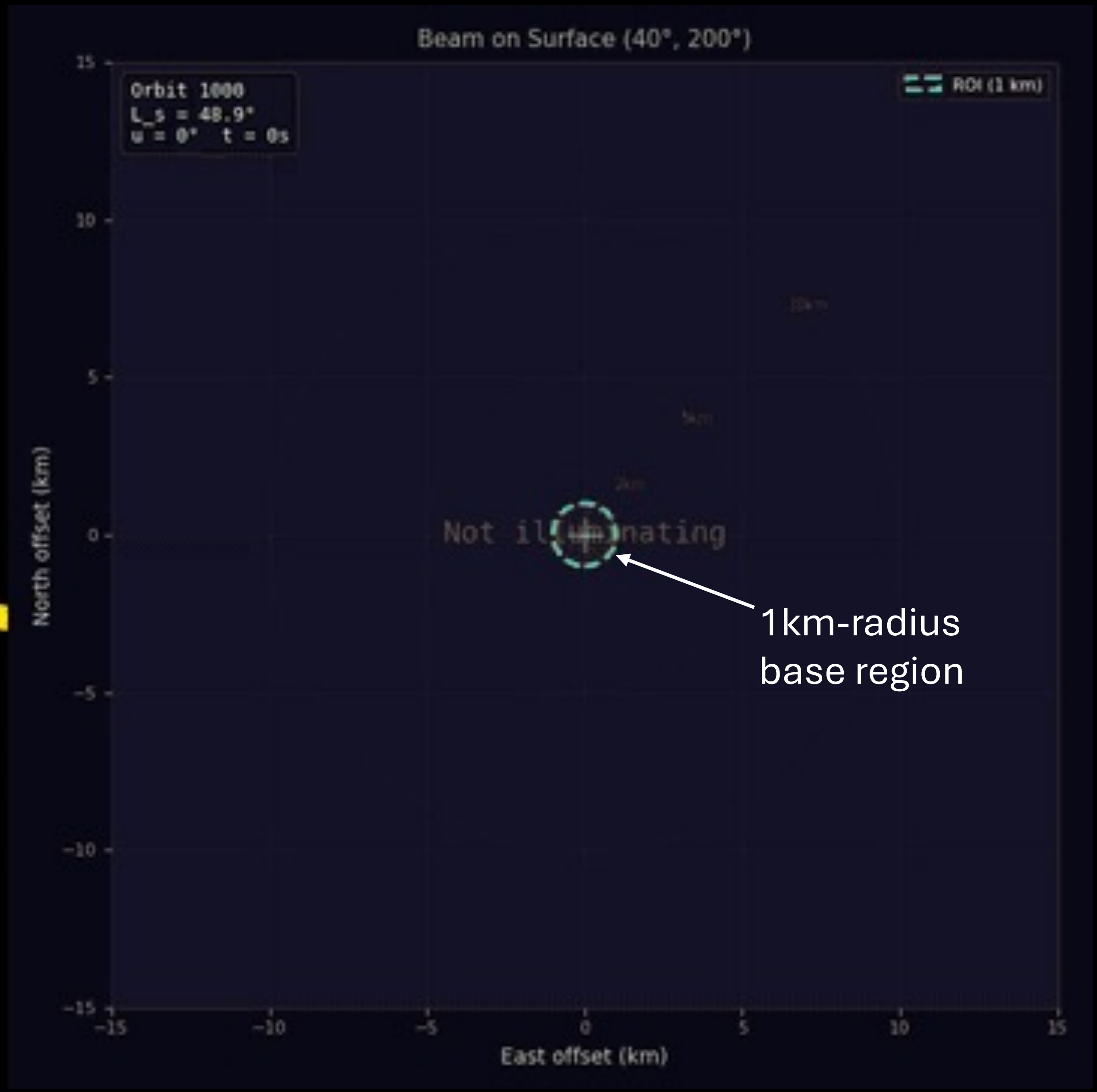
Engineered aerosols forward-scatter sunlight, but trap infrared, warming Mars



Ansari et al. Sci. Adv. 2024
Richardson et al . GRL 2026

Other options not covered today: super-greenhouse gases (CO_2 alone insufficient – Jakosky & Edwards 2018), adding volatiles, local warming (Wordsworth et al. 2019), orbiting reflectors (Handmer 2024)



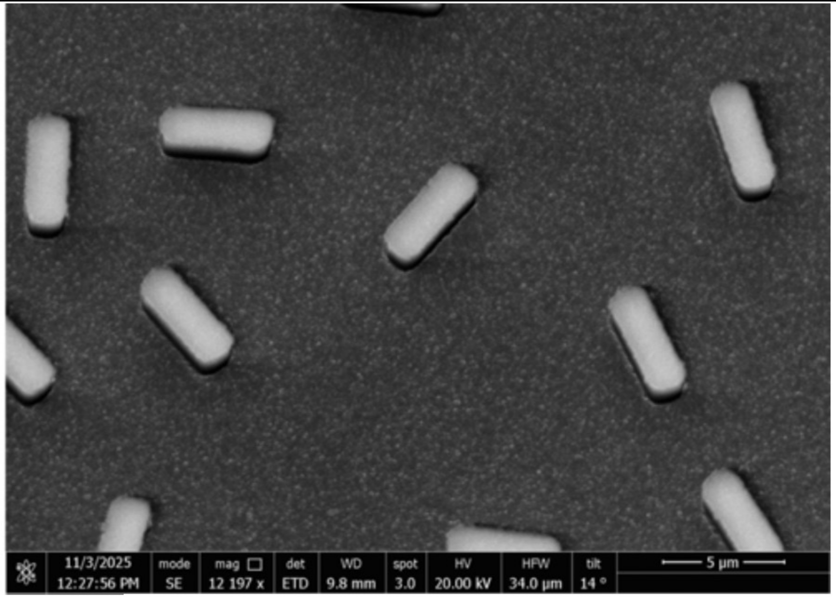


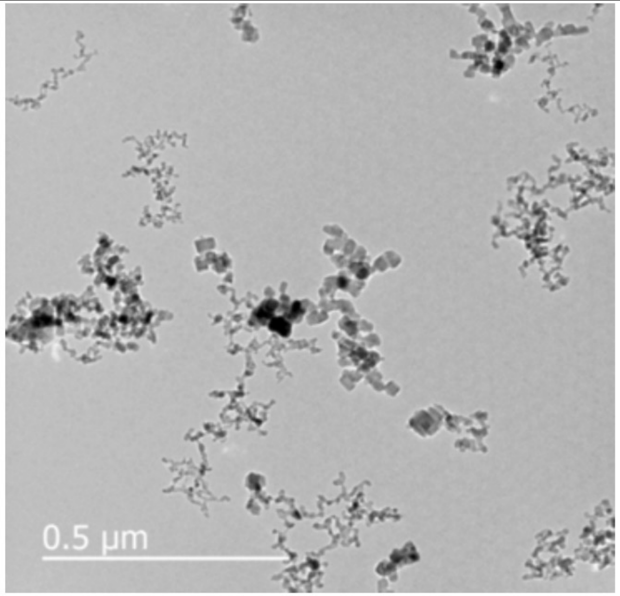
work by Ari Essunfeld (Astera)

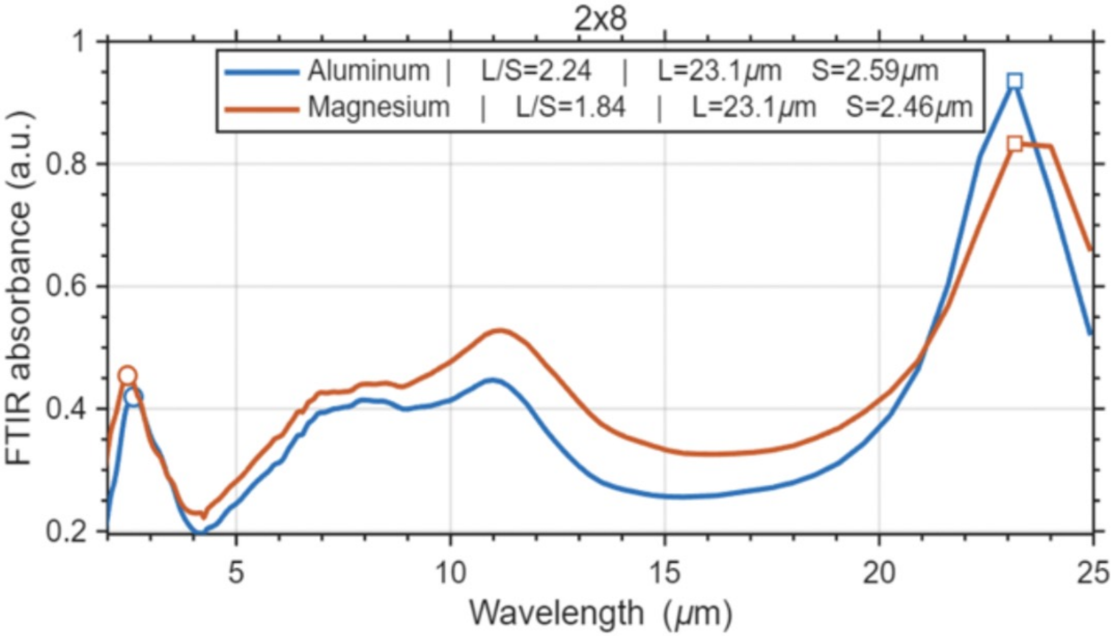
Engineered aerosols forward-scatter sunlight, but trap infrared, warming Mars

Ansari et al. Sci. Adv. 2024
Richardson et al . GRL 2026

a)







Shapes that are mass-efficient include rods, disks, rings, and fractal aggregates

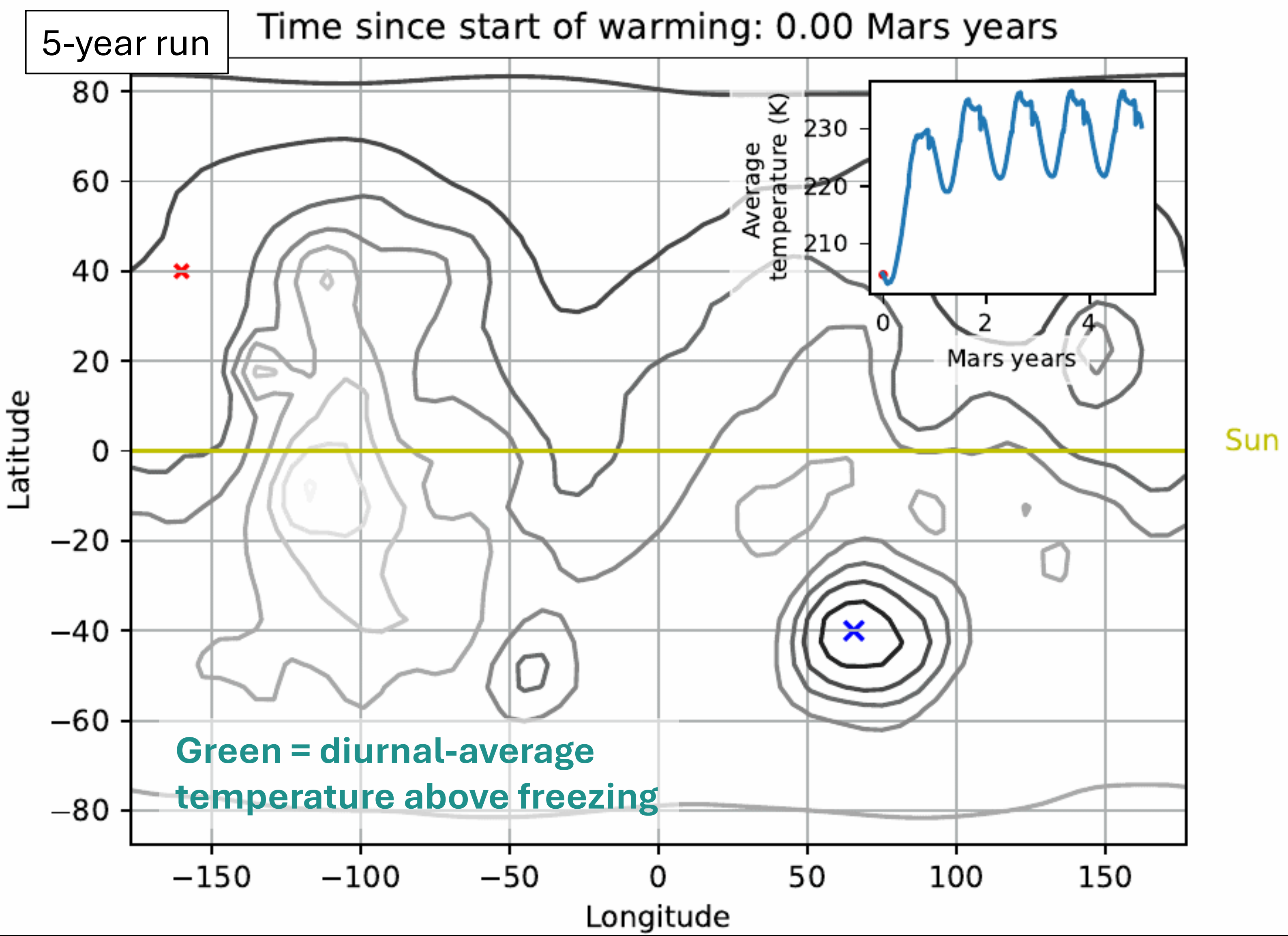
1. Warming Mars. 2. Prototyping progress. 3. What's next.

work by C. Jourdain (Stanford) & A. Bamba (Northwestern)

Mars warms fast: first seasonal-melting zones are in S midlatitudes

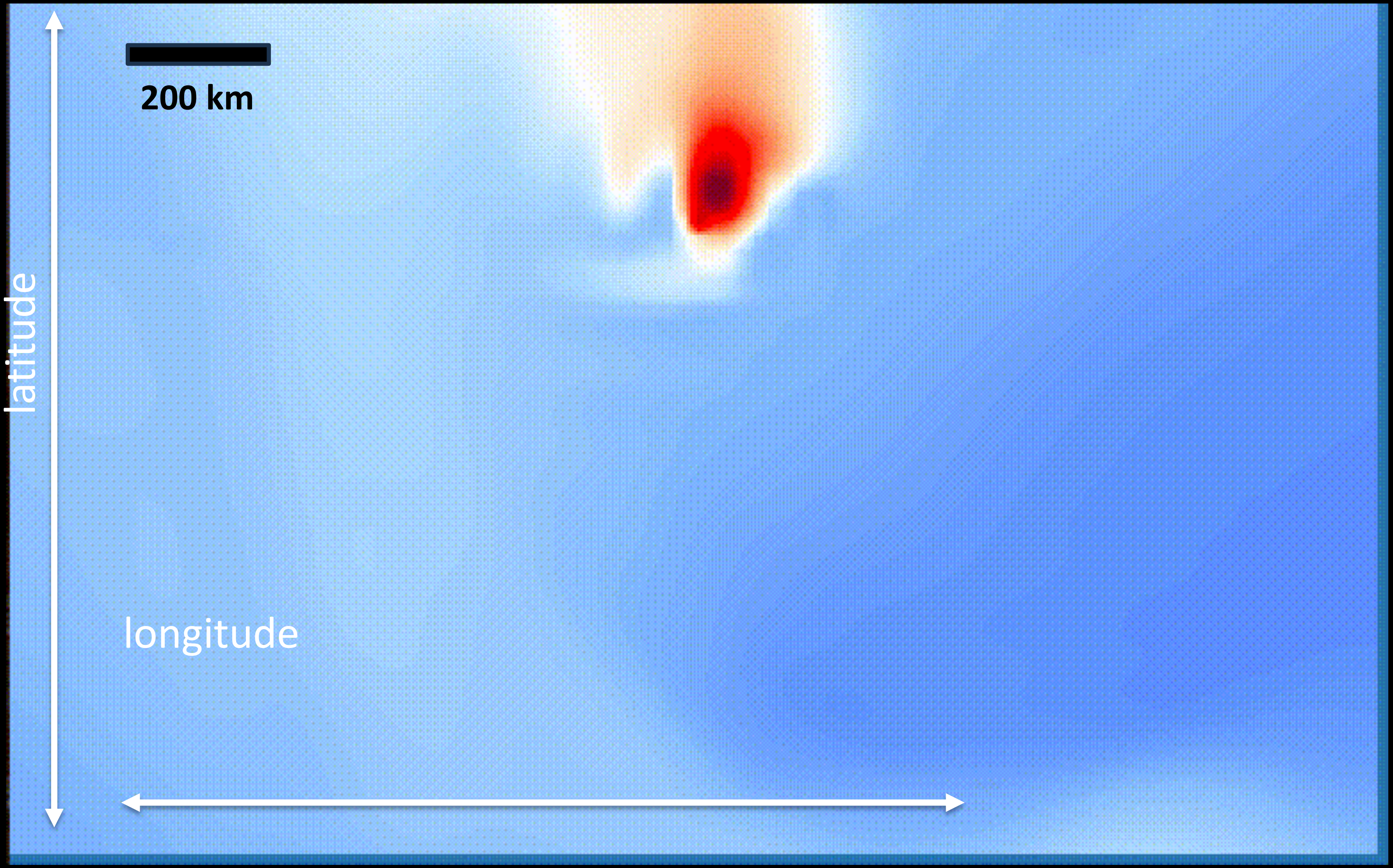
Braude et al. arXiv:2604.01539

- Not needed for initial human missions.
- Required to melt ice (where shallow-subsurface ice is present, ~1/3 of planet surface area).
- Supports ecosystem tests.
- Needed (but insufficient) to allow simple forms of life.



MarsWRF climate model.

Plume modeling shows self-lofting positive feedback



Richardson et al.
Geophysical Research Letters
2026

work by Michael Mischna

dx = 13km mesh of the plume over ~2 days - total warming-particle optical depth, rotation is the tide. Inmost grid of a nested GCM.

Large ISRU rough order of magnitude requirements for warming Mars globally by 35 °C

ISRU scale: 10^3 m^3 soil / hour
(or use Mars air)

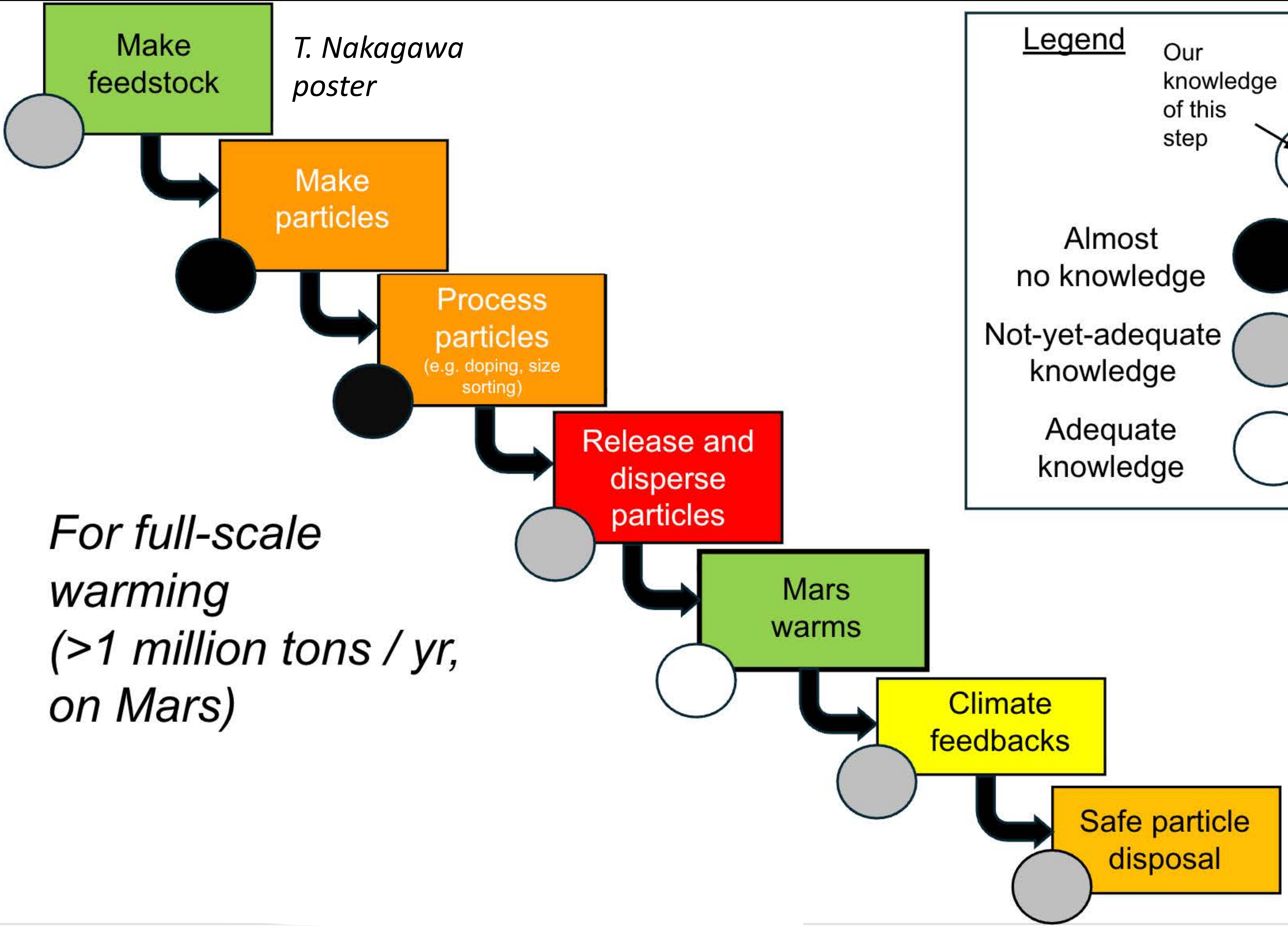
Richardson et al.
Geophysical Research Letters 2026

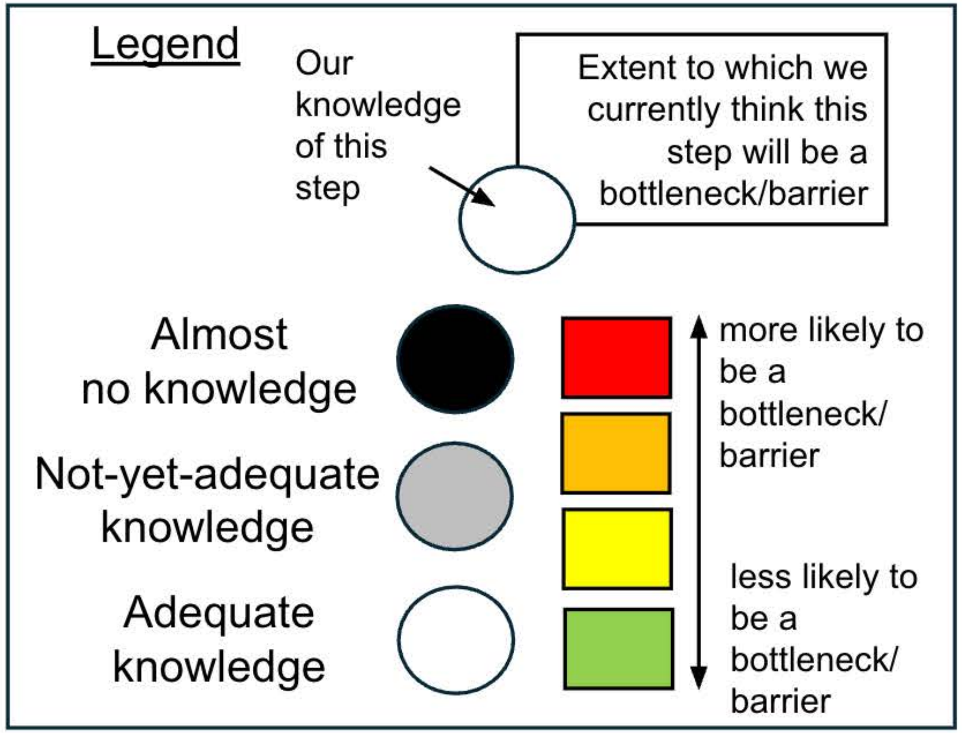
Particle composition	Feedstock production method	Mass in atmosphere needed	Lower limit on power requirement (*)	Particle flux
Metal	Molten regolith electrolysis, or carbothermal	~ 10^{10} kg	~10 GW	**45 L/s**
Carbon	CO_2 electrolysis	~ 10^{10} kg	4 GW	**20 L/s**

(*) Assumes 400-sol particle lifetime.

Major ISRU challenges remain

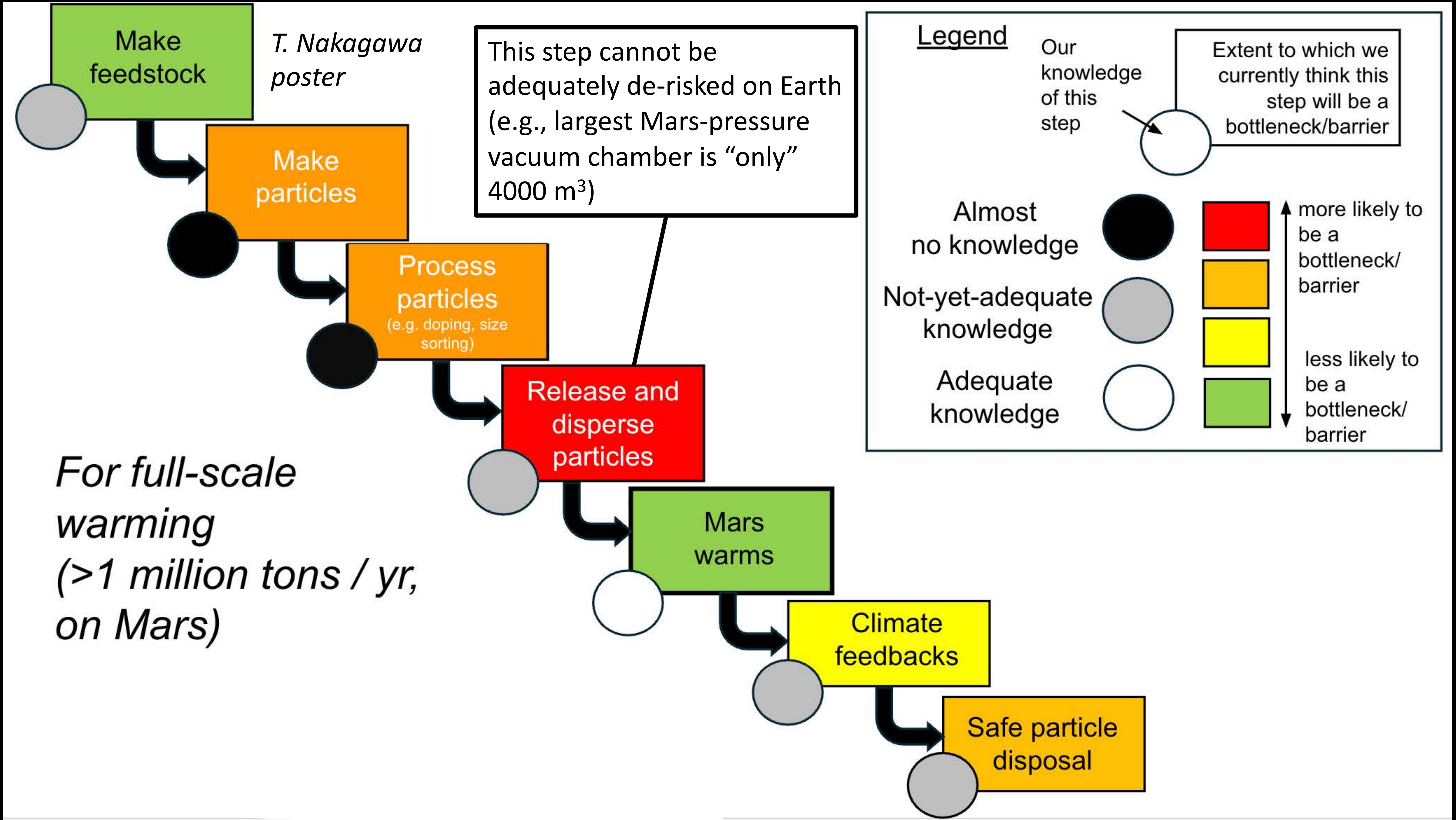
T. Nakagawa poster





For full-scale warming (>1 million tons / yr, on Mars)

Major ISRU challenges remain – and de-risking particle release and dispersal requires an on-Mars test

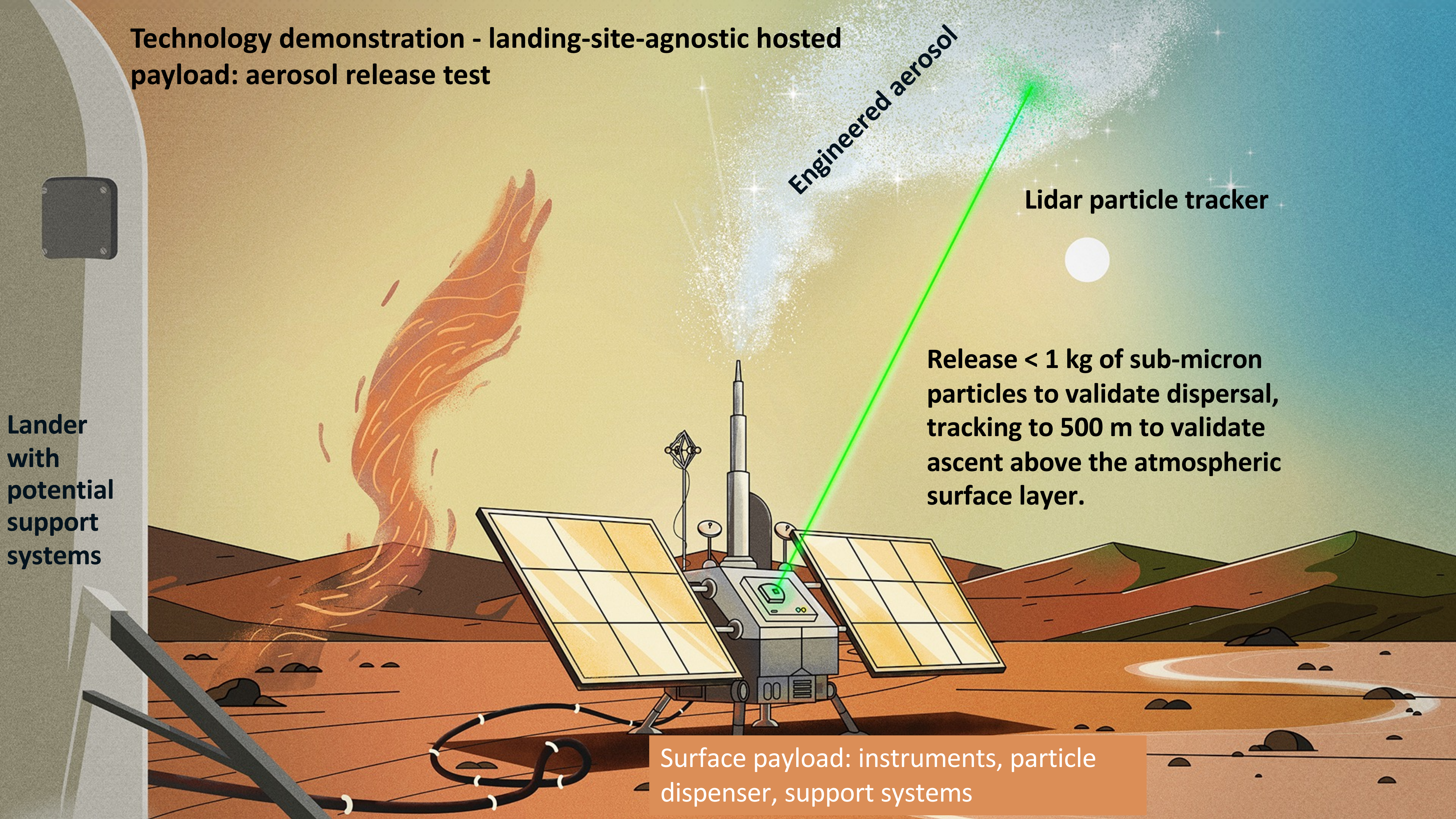


Technology demonstration: a landing-site-agnostic Mars aerosol release hosted payload

Mission Goal	Mission Sub Goals
De-risk key dispersal aspects of the engineered aerosol approach to warming Mars which require access to the surface of Mars, in order to stay on the critical path to fostering a photosynthetic ecosystem on the planet	Goal A: **Demonstrate that warming engineered aerosols can disperse** over regional-to-global distances in the Martian atmosphere.
	Goal B: **Constrain key dust fluxes** such as dry deposition, vertical transport in the Planetary Boundary Layer and lifting, needed for Mars dust storm forecasting for human exploration.

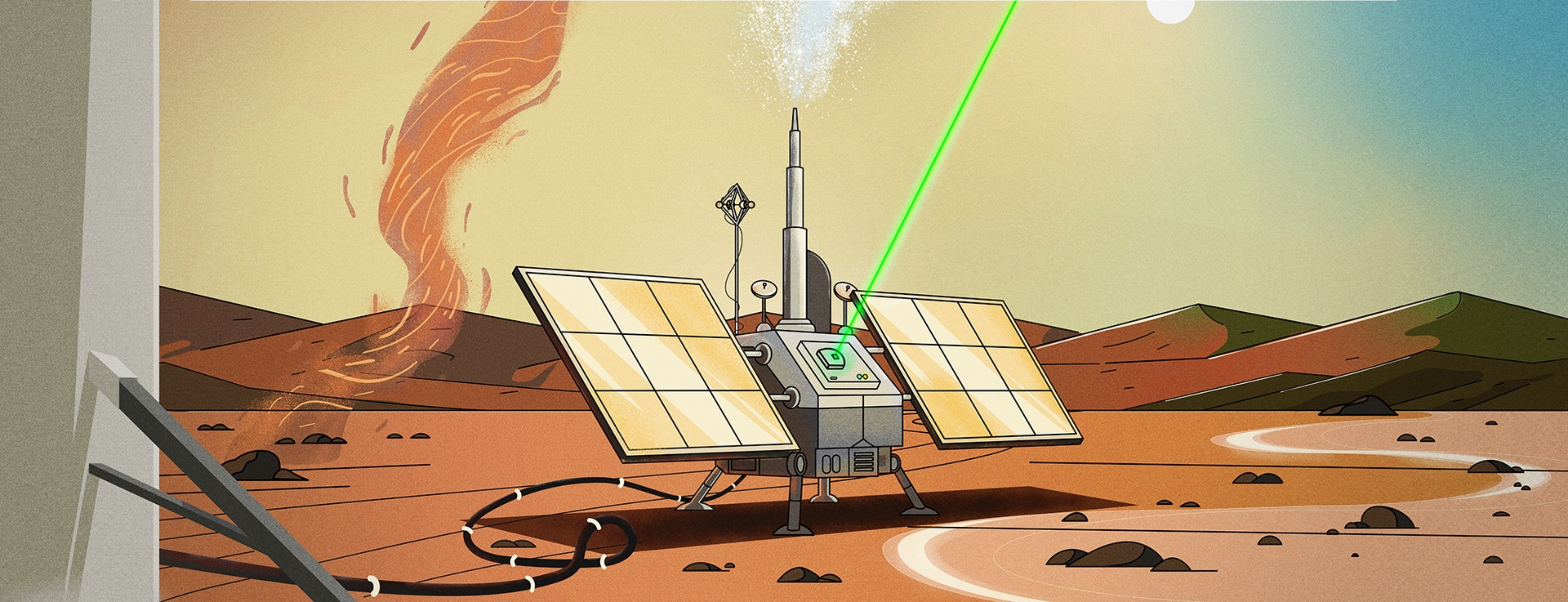
Dumitrescu et al. ASCEND 2026

Previous aerosol release tests (by NASA) include CRRES and the Charged Aerosol Release Experiments


Technology demonstration - landing-site-agnostic hosted payload: aerosol release test
Engineered aerosol
Lidar particle tracker
Release < 1 kg of sub-micron particles to validate dispersal, tracking to 500 m to validate ascent above the atmospheric surface layer.
Lander with potential support systems
Surface payload: instruments, particle dispenser, support systems

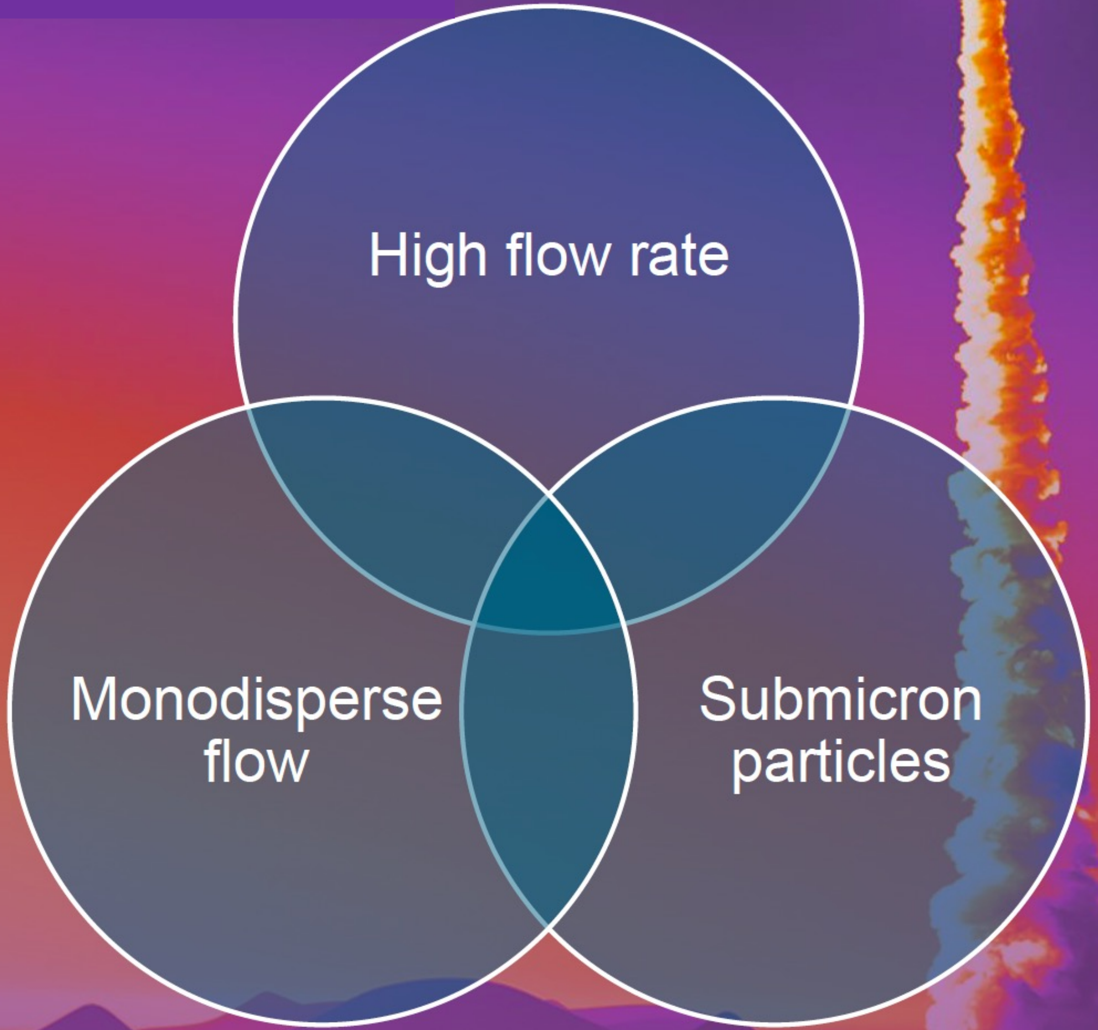
Key requirements for technology demonstration

- **Release** at 10 g/s; lose <25% of particles to clumping and dry deposition.
- **Track** plume to 500 m in range (~100 m in altitude).
- **Image** the 3D structure of convective updrafts.
- Determine the **dry deposition rate** for natural and engineered dust.
- Use 3D wind data to determine **surface fluxes**.



Dispenser requirements are particularly challenging: need to show it works on Earth before demonstrations at Mars

When combined, the expected operational conditions for the particle dispenser system are outside traditional industrial design envelopes:



1. Warming Mars.

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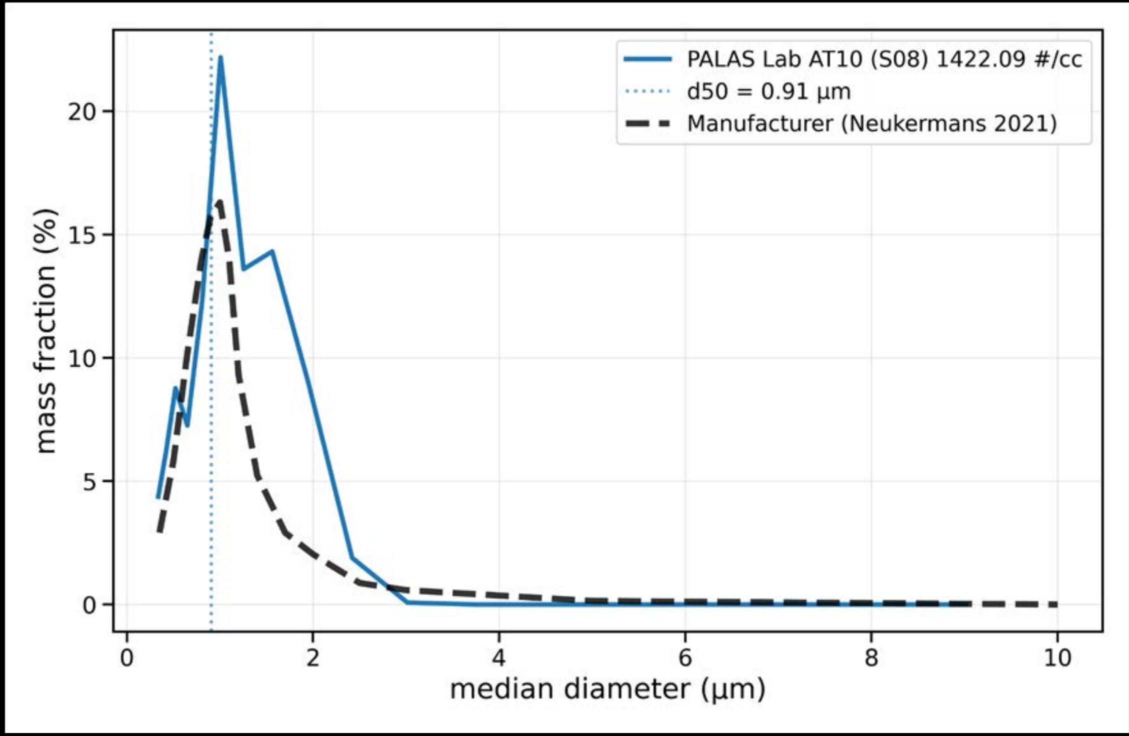
Experimental Setup is Designed for Rapid Deployment

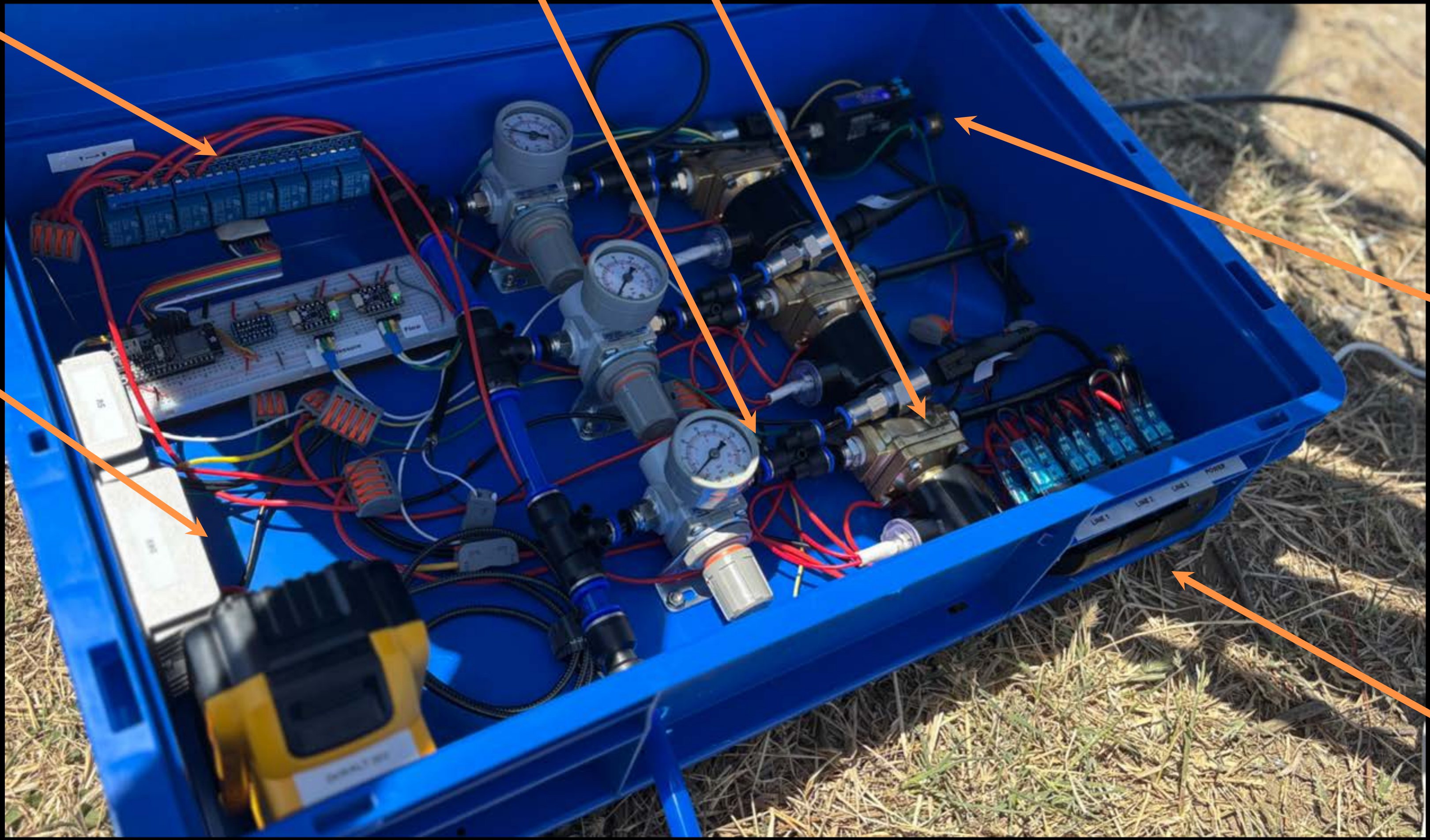
- Test particle: non toxic Calcium Carbonate in 70nm & 700nm varieties

How Do We Dispense Monodisperse Nanopowder at High Flow Rates?

1. Vibration Assisted Venturi Nozzle
2. Brush Impaction
3. Liquid Droplet Dispersion



Modular Flow Control Box Streamlines Test Setup



Instrument Box Prevents Instrument Overheating

Dilution Bridge

Fan with HEPA Filter

Windows OS w/ Bluetooth HDMI

Condensation Particle Counter

Battery

Optical Particle Sizer

Saturates at 3000 #/cm3

Vibration Assisted Venturi Nozzle

Instrument Box

Gimbaled Sample Line

Atomizing Nozzle

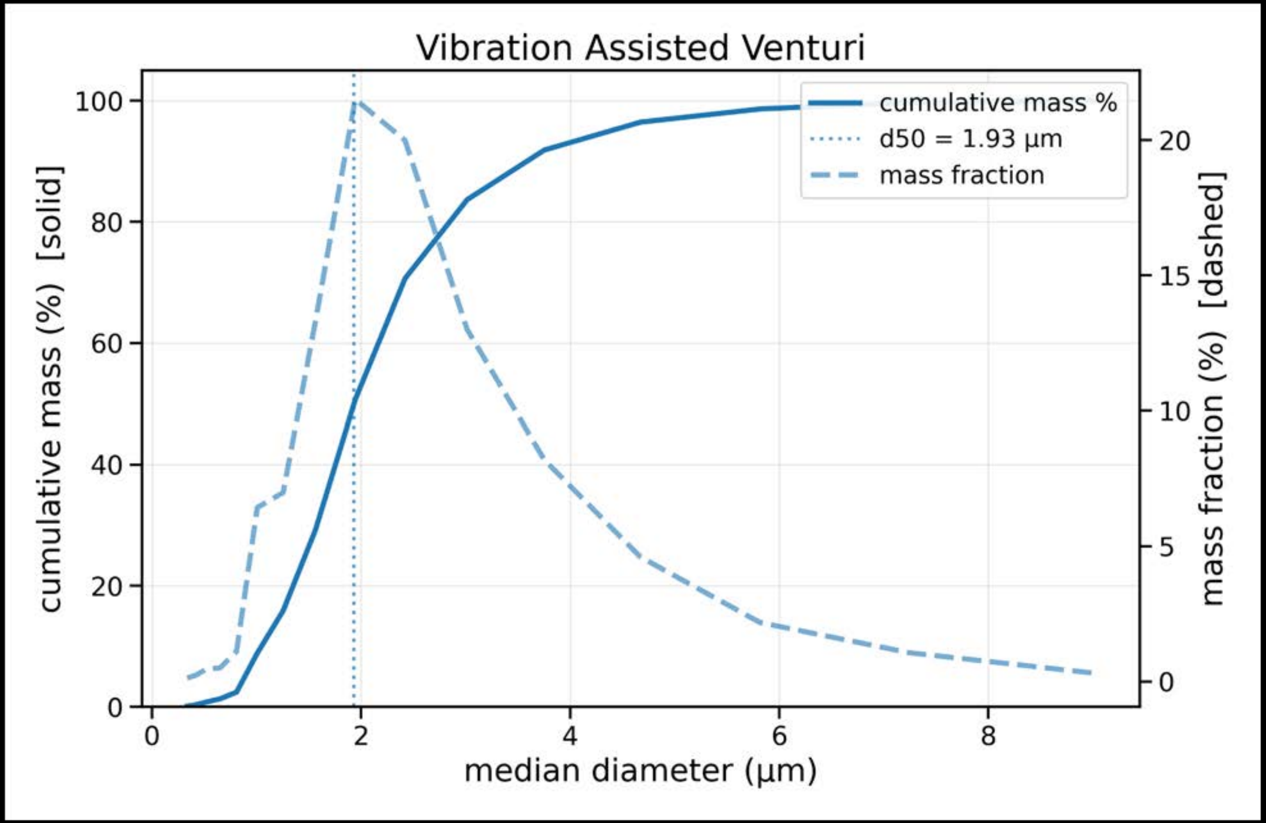
Eccentric Vibrating Motor

Flow Control Box (measures air flow rate)

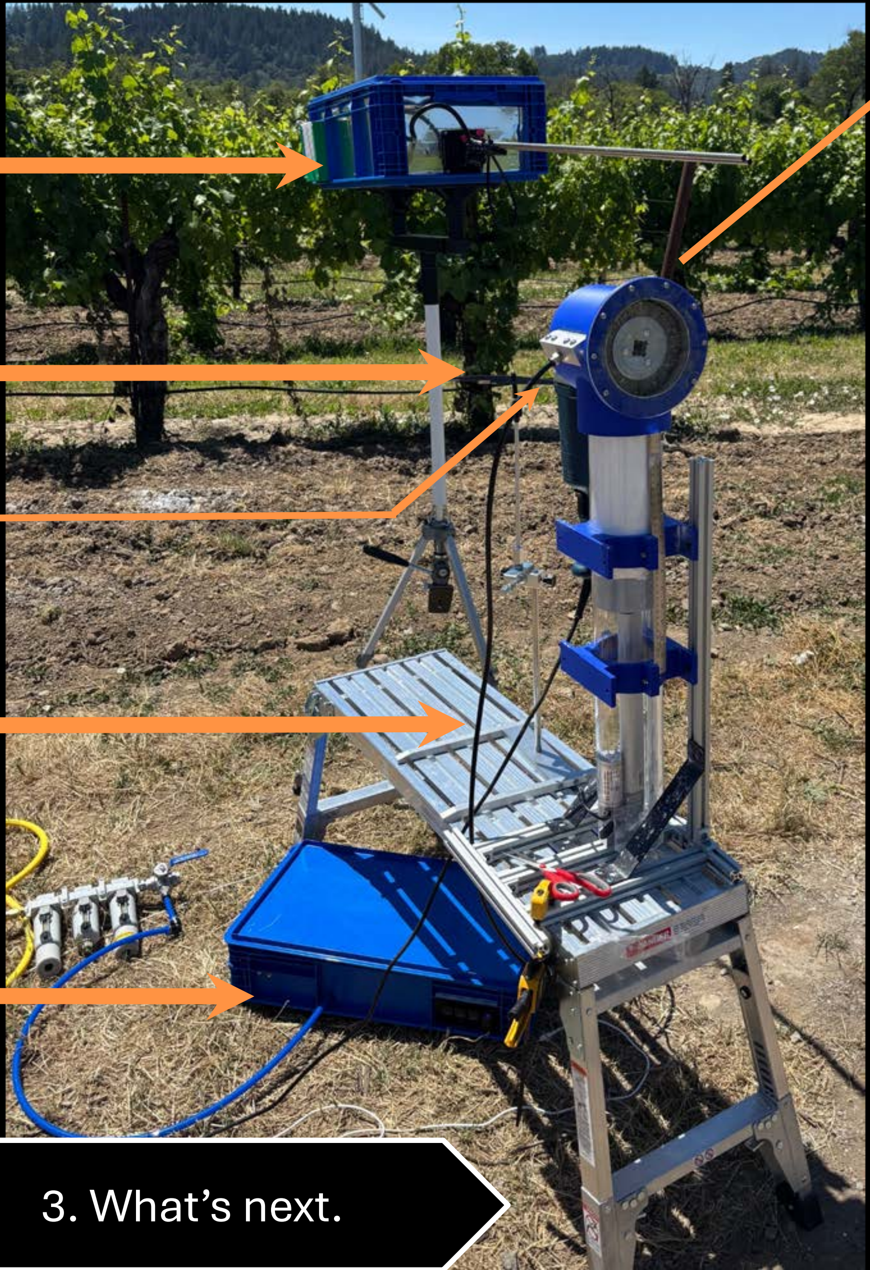
Linear Actuator Powder Feed

Vibration Assisted Venturi Nozzle Yields Powder:Air mass ratio of 1:5

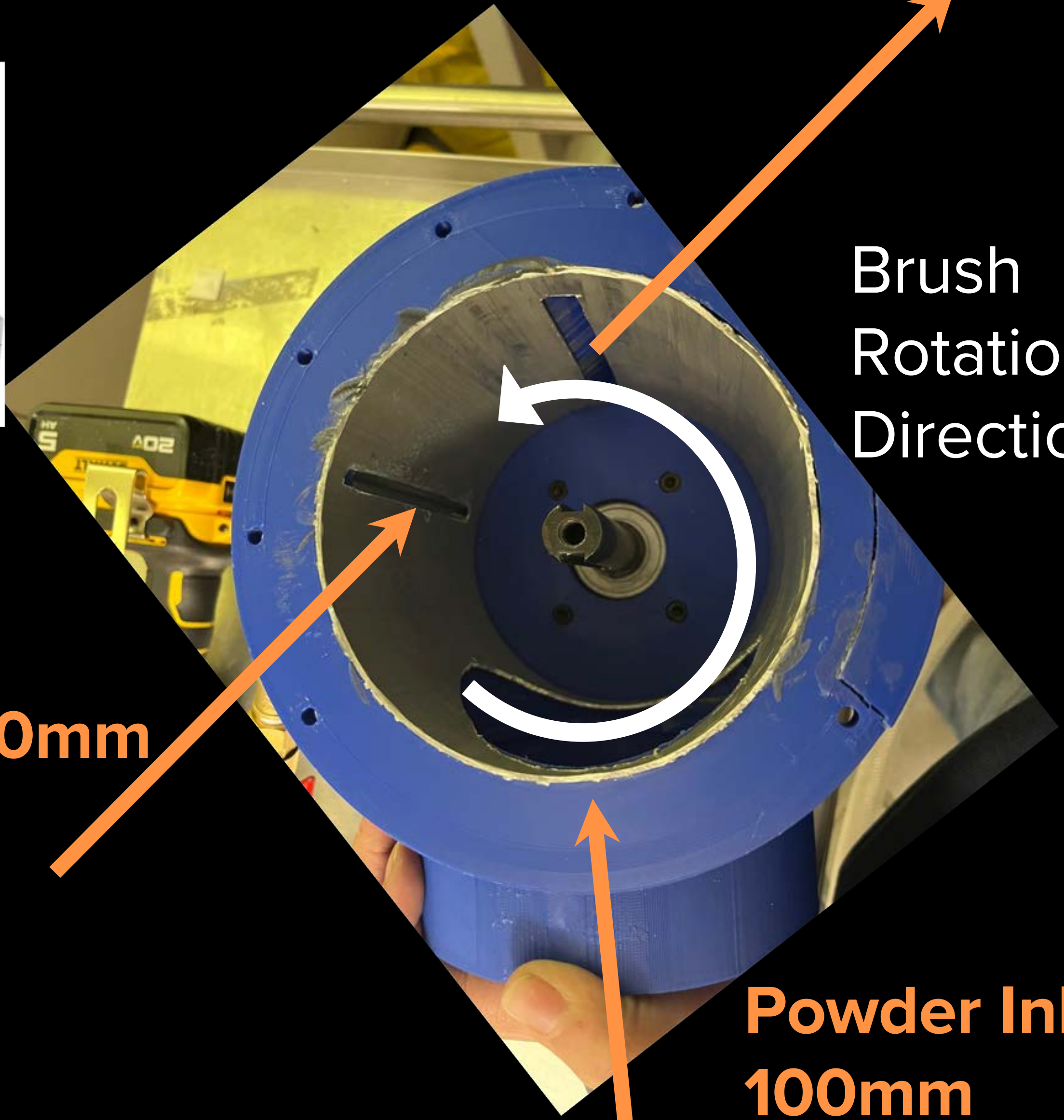
Powder Flow Rate	80 g/min
Air Flow Rate	450g/min



Brush Impaction

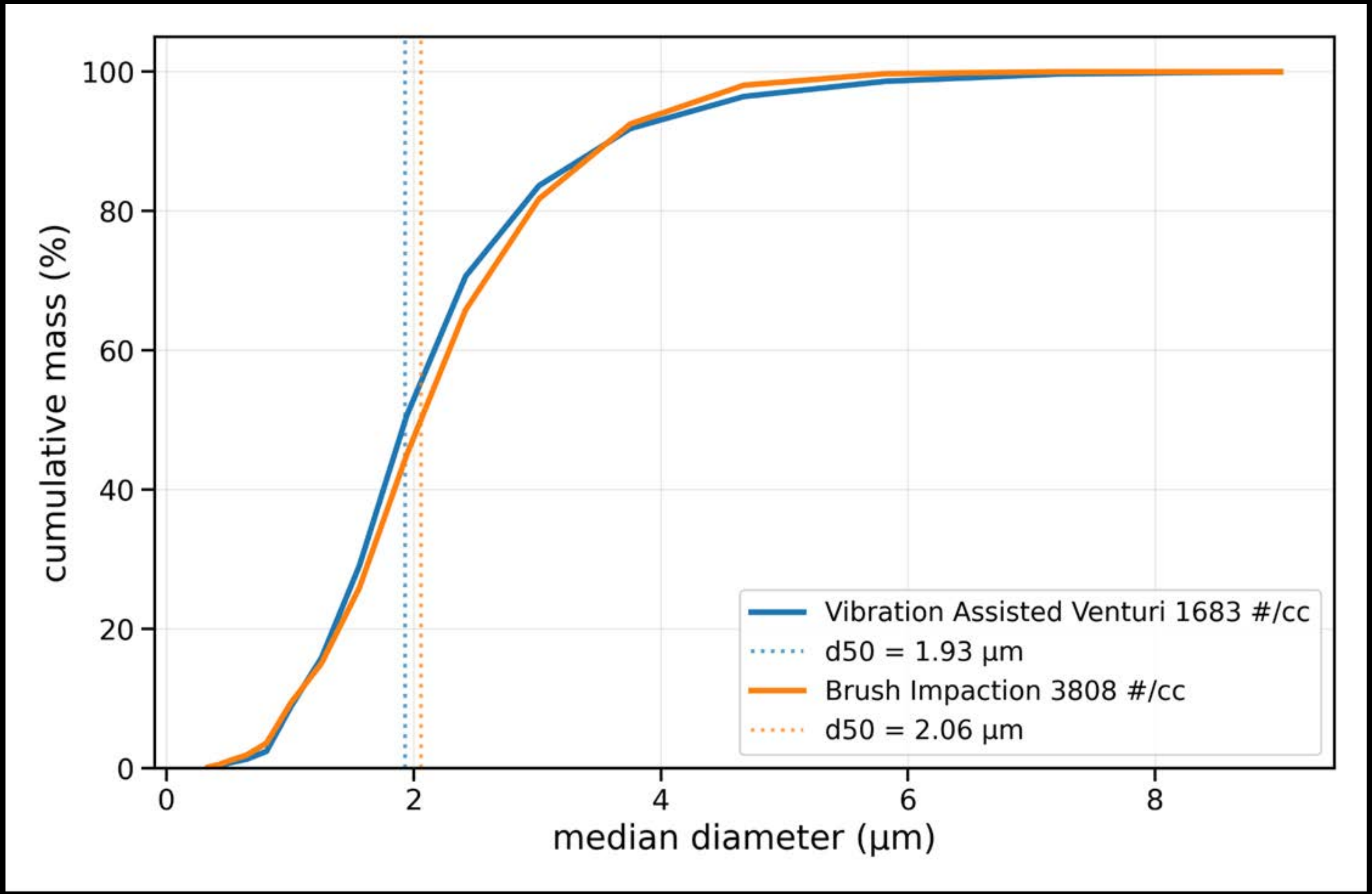


Brush Impaction



Brush Impaction Method Yields Powder:Air mass ratio of 2:1

Powder Flow Rate	950 g/m
Air Flow Rate	480 g/min

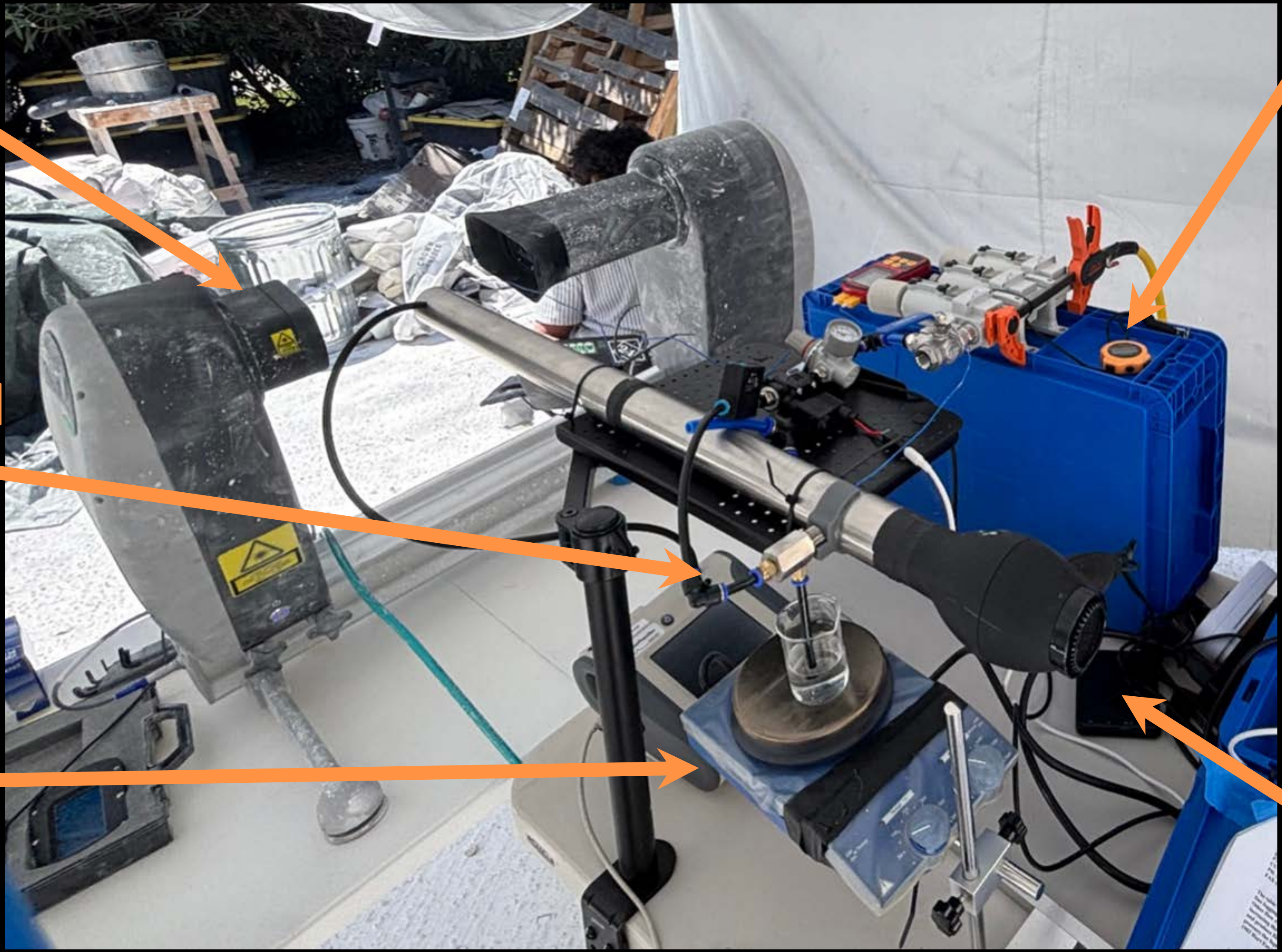


Liquid Droplet Dispersion

Spraytec Particle Sizer

Atomizing Nozzl

Scale (to measure the mass flow rate)

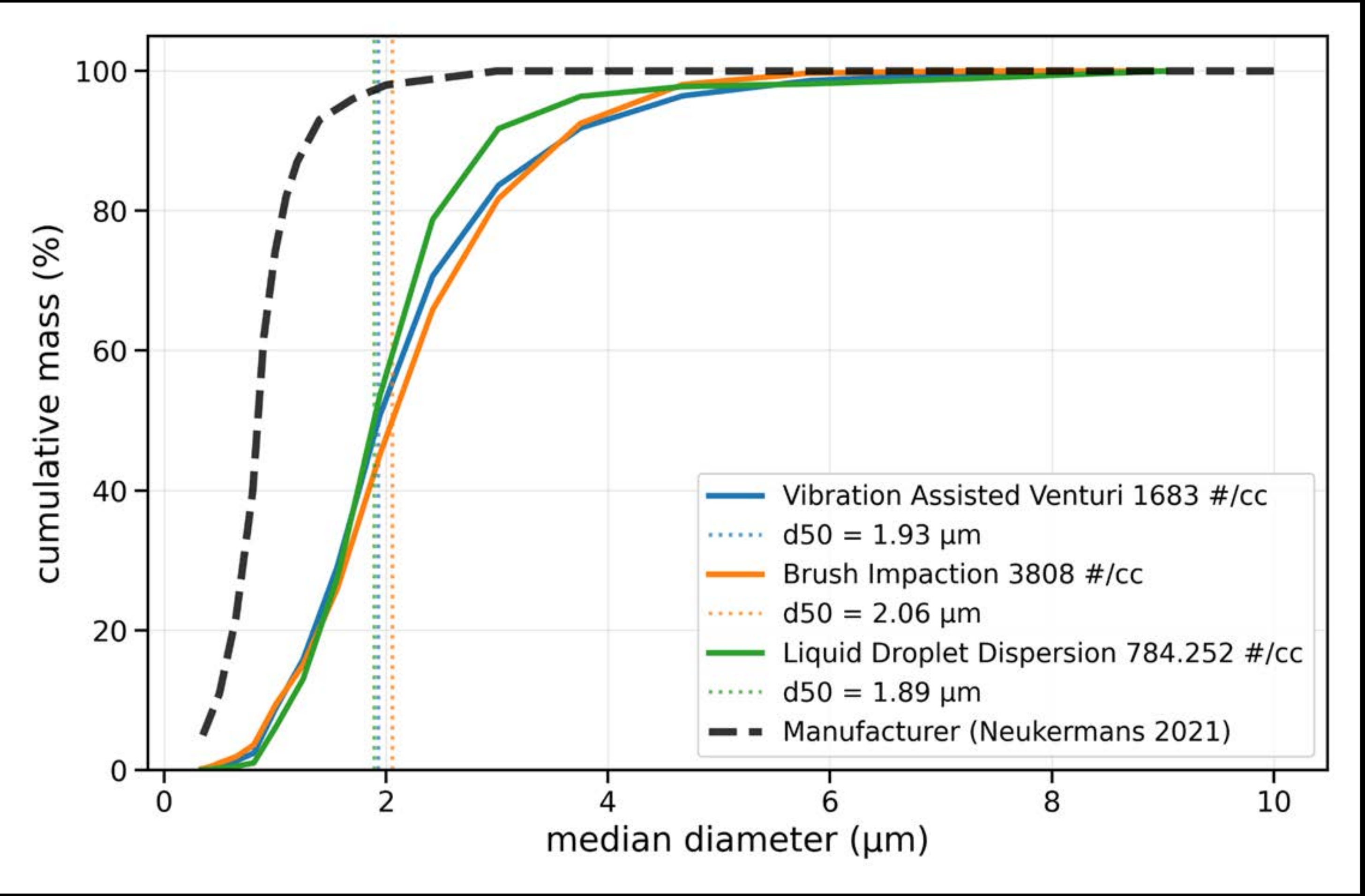


Flow Control Box (measures air flow rate)

Hair Dryer Tube (to evaporate droplets)

All Three Proposed Methods are Similarly Effective

	Venturi	Brush	Liquid
Powder Flow Rate	80 g/m	950 g/m	6.3 g/m
Air Flow Rate	450 g/min	480 g/min	53 g/min
Ratio	1:5	2:1	1:8



1. Warming Mars.
2. Prototyping progress.
3. **What’s next.**

Next steps for prototyping

- Exploring particle coatings to reduce particle clumping
- Integrating LIDAR with field testing for plume tracking development
- Further Characterization of liquid dispersion

Upcoming Milestones

- Testing particle dispersal + plume tracking in NASA Ames Planetary Aeolian Laboratory by October 2026
- Approaching Technology Readiness Level 5 by March 2027

Research roadmap for assessing the feasibility of warming Mars

arXiv:2604.02242

Interdisciplinary needs: Needed measurements on Earth and Mars

- Dry deposition rate for submicron particles over rough desert surfaces. 🔵/🔴
- Radiative properties of clumped aerosols. 🔵
- Safe particle disposal (degradation rate in Mars environment). 🔵
- Mars-chamber tests of in-situ research utilization. 🔵
- Search for deep groundwater on Mars. 🔴
- Small aerosol release test (validate dispersal). 🔴
- Ice mapping (e.g., International Mars Ice Mapper, IMIM). 🔴
- Climate monitoring. 🔴
- Soil sample return (e.g., Tianwen-3). 🔴
- Model intercomparison studies. 🔵
- International co-operation. 🔵/🔴

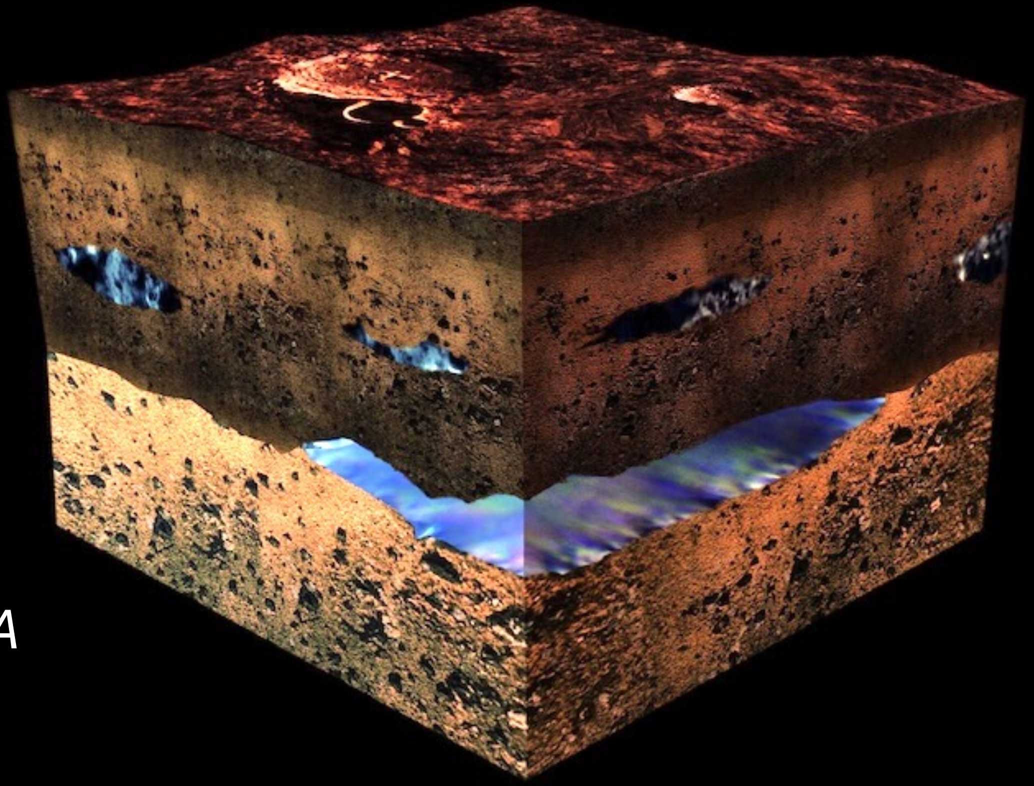
Consolidated roadmap tasks, expressed using a decision relevance / uncertainty research prioritization / cost framework.

arXiv:2604.02242

Impact on program viability if this uncertainty resolves negatively	*Existential*	Detailed TEA Climate feedback analysis	Mass production of Mars-warming aerosol	Hosted payload process experiments on commercial Mars payload services	Decision made for a human base on Mars	Integrated ecosystem tests	Create ice-covered lake
	Major	End-point modeling Biocompatibility research	Solar sail space deployment test (cislunar) Earth in situ resource utilization testing	Solar sail flight test (interplanetary)			Pilot factory Support human bases w/orbiting reflectors
	Minor	Mars chamber testing		Climate monitoring from orbit		Climate monitoring network	
		<$300k	*$3M*	*$30M*		*$300M*	*$3B*
		Approximate cost to retire this uncertainty					

Synergies with basic science needs

Look for deep liquid water



ESA

Improve maps of shallow water ice

See Roadmap for synergies with human needs on Mars

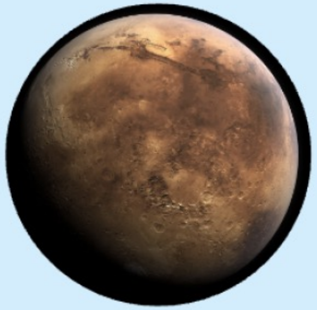
THIS TALK

First step would be to warm Mars to enable a photosynthetic biosphere.

Near-term

Today Mars is too cold and dry for Earth–like life to flourish. The first step is abiotic engineering to heat the planet.

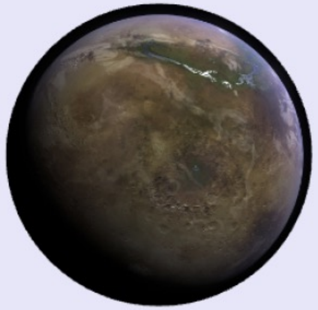
Method: abiotic engineering
GOAL: ⬆ Temperature



Mid-term

A future, warmer Mars would be suitable for non–human life. A planetary ecosystem would begin producing oxygen.

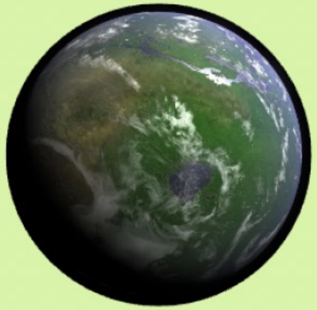
Method: photosynthesis
GOAL: ⬆ O2



Long-term

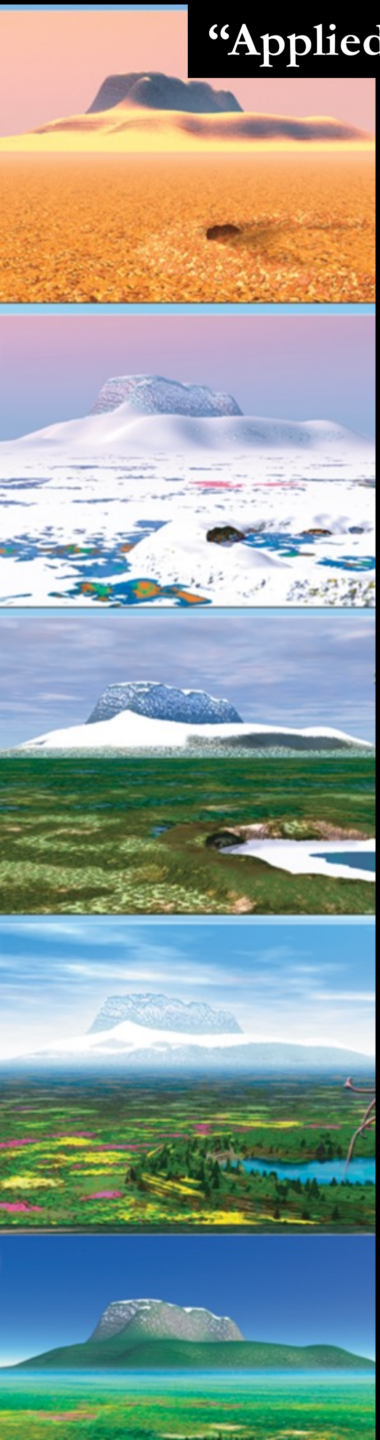
In the long term, Mars would accumulate more atmosphere and have a stable, favorable climate.

Method: abiotic + biotic
GOAL: ⬆ pressure, stabilize climate



DeBenedictis et al. Nature Astronomy 2025

"Applied astrobiology": creating sustainable habitats and biospheres beyond Earth



Graham 2004 Astrobiology

Warming Mars is a necessary (but insufficient) condition for surface habitability.

Green Mars community interest sign-up form

Recent progress includes:

- Warming Mars with artificial aerosol appears feasible - $10^4\times$ more mass-efficient than gases (Ansari et al., Sci. Adv. 2024).
- Small-batch production + FTIR spectra validate Mars-warming effects.
- Prototyping of particle dispersal system.
- A new case for Mars terraforming research (DeBenedictis et al. Nat. Astron. 2025)
- Workshops on Green Mars and applied astrobiology. (DeBenedictis and Stork 2025, Wordsworth et al. Astrobiology 2025).
- Plume-tracking simulations (Richardson et al. GRL 2026).

Astera is an open-science non-profit, happy to share details.

Prototyping team

2nd Green Mars workshop

THE UNIVERSITY OF CHICAGO

ASTERA

marsterraforming.org
edwin.kite@astera.org

Bonus slides

Warming Mars globally requires ~10^{10} kg of particles in the atmosphere and a correspondingly high particle release rate

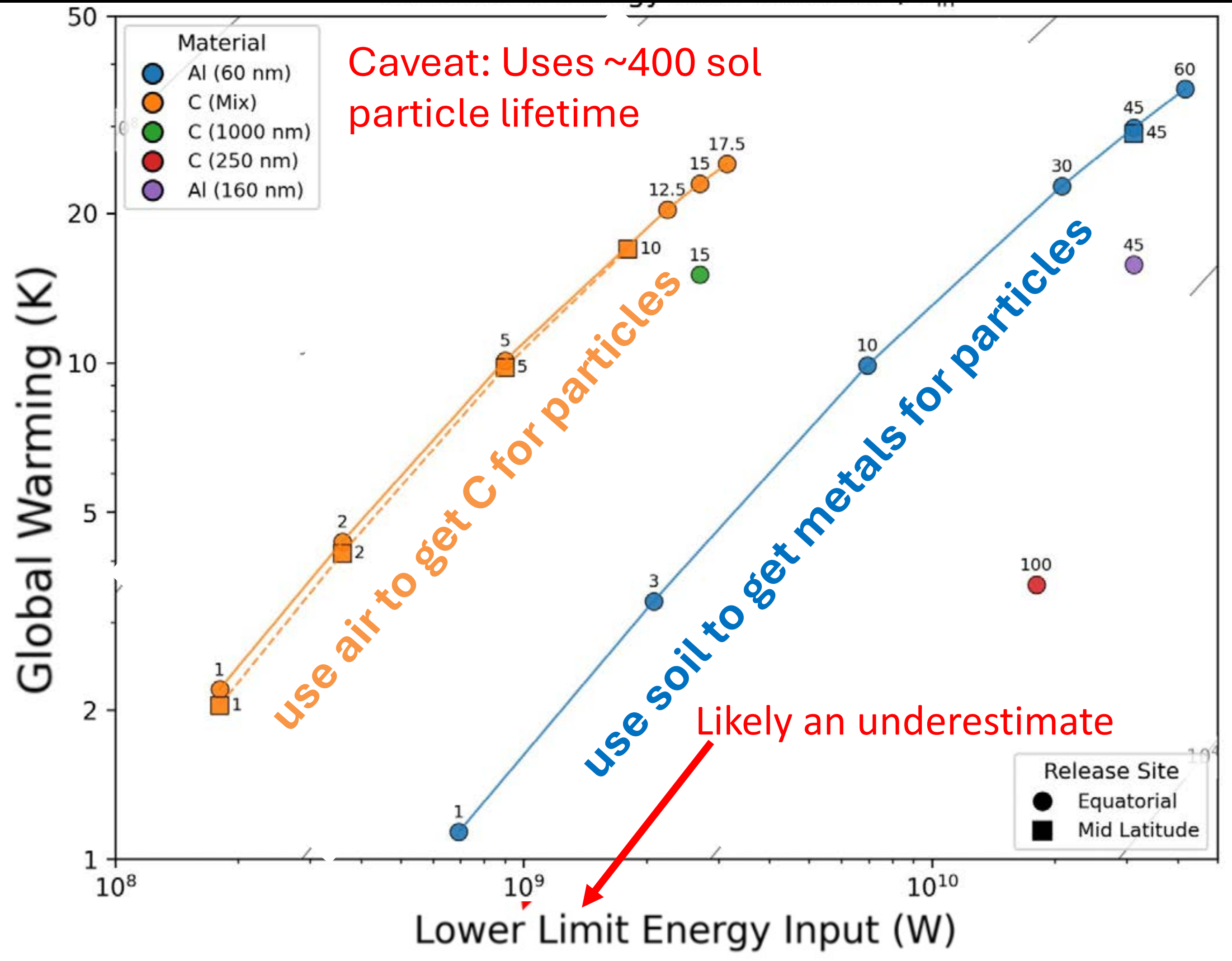
REPLACE WITH TABLE

Warming needed: ≥ 35 °C
Warming response time: months

Mass of warming particles: ~6 million tons

molten regolith electrolysis or CO_2 electrolysis

scale: 10^3 m^3 soil / hour (or use Mars air)

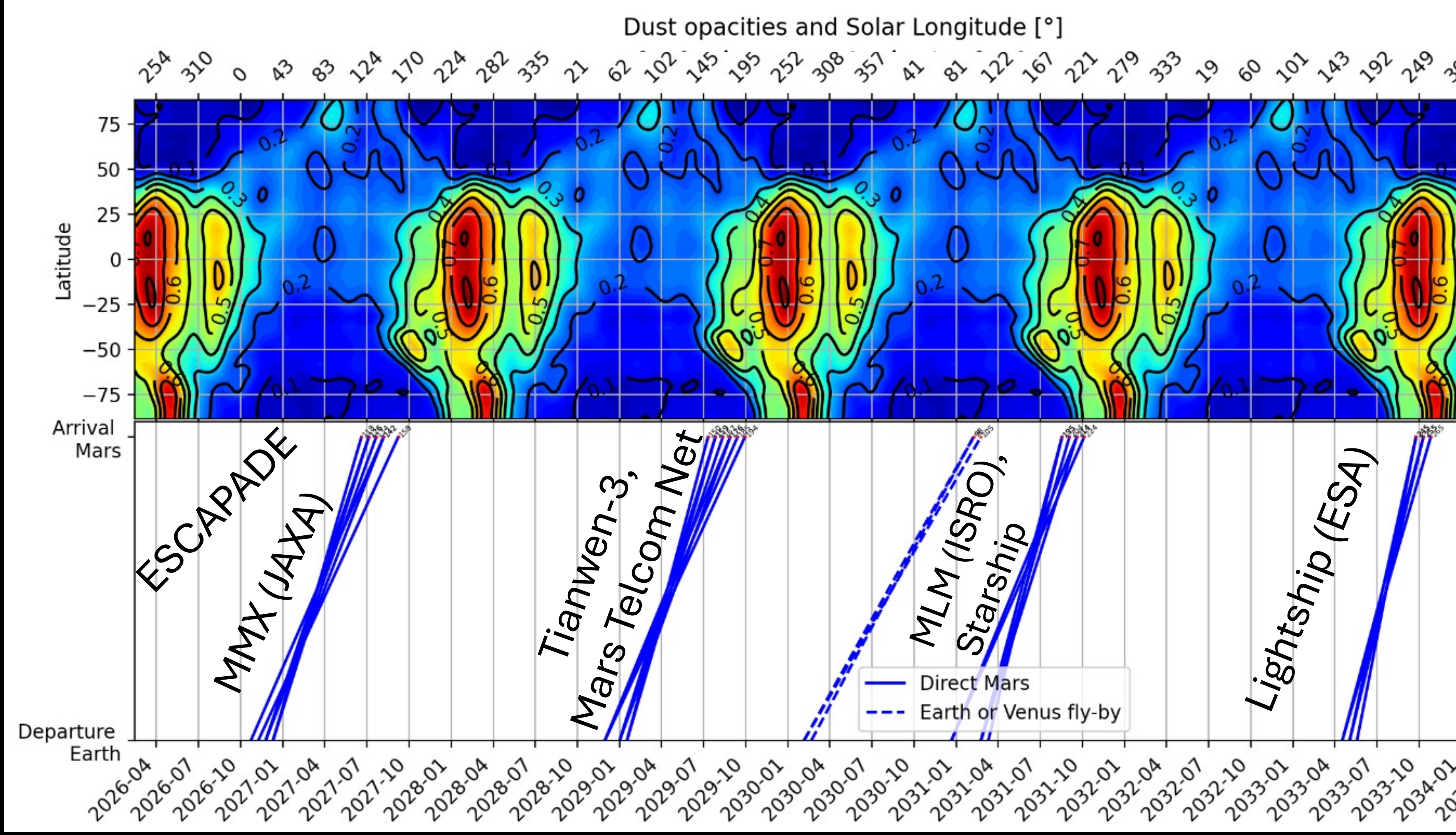


modified after Richardson et al. Geophysical Research Letters 2026

Mars-launch opportunities are infrequent, mission needs are many

Mission needs include:

- Mars aerosol-release test
- Deep-water search
- Ice mapper
- Climate monitoring
- Soil sample return



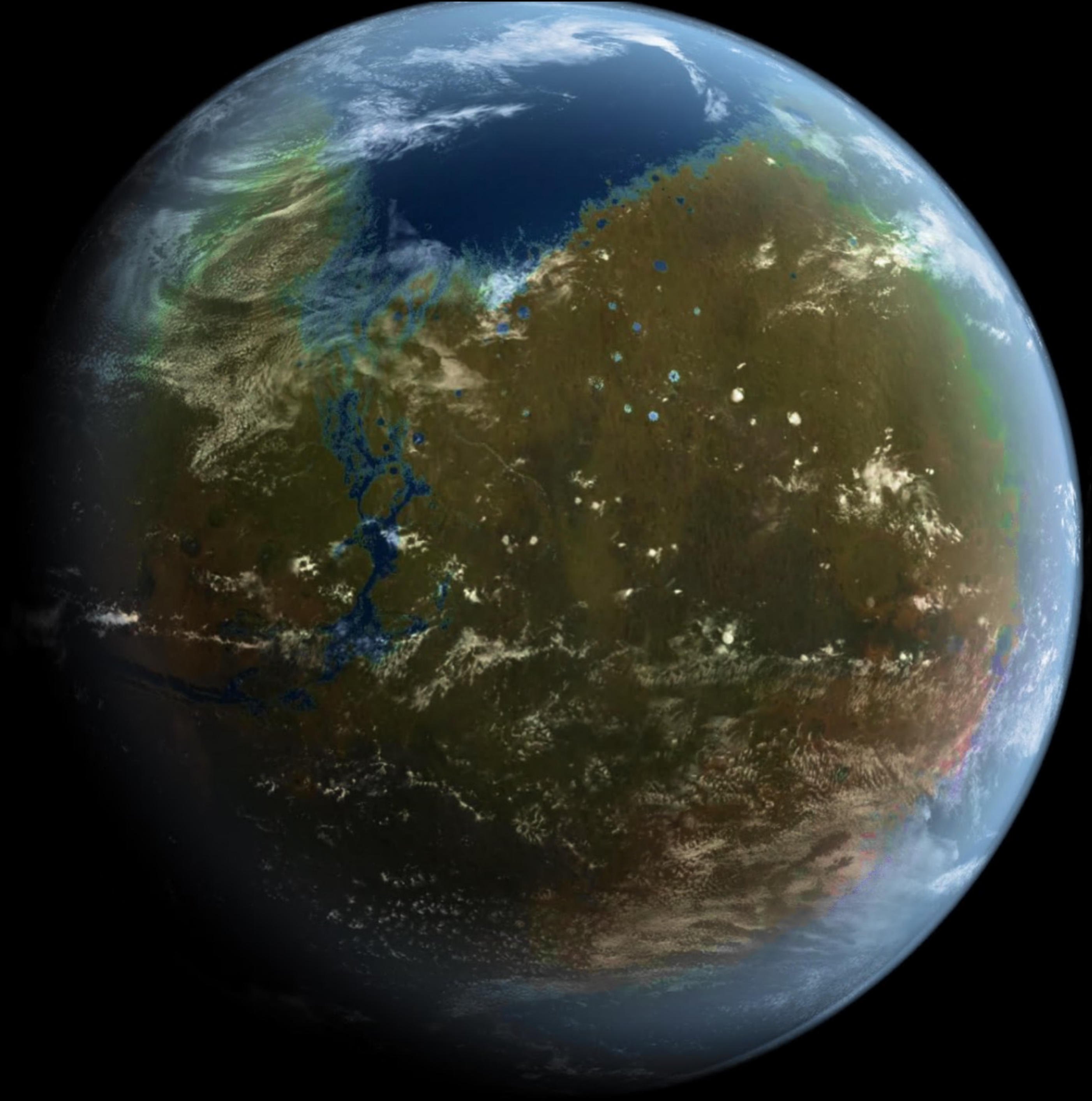
1. Warming Mars.
2. Prototyping progress.
3. What's next.

Living planets are better than dead ones

Expand our numbers

Protection

Base-camps for exploration



Thanks to collaborators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Adrian Dumitrescu
(Astera)


Nina Lanza
(Los Alamos)


Abdul Bamba
(Northwestern)


Liam Steele
(ECMWF)


Hooman Mohseni
(Northwestern)


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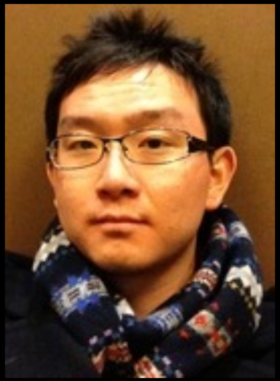
Ramses Ramirez
(UCF)


Mingyi Wang
(UChicago)


Michael Mischna
(JPL)


Mike Hecht
(MIT Haystack)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(Stanford)

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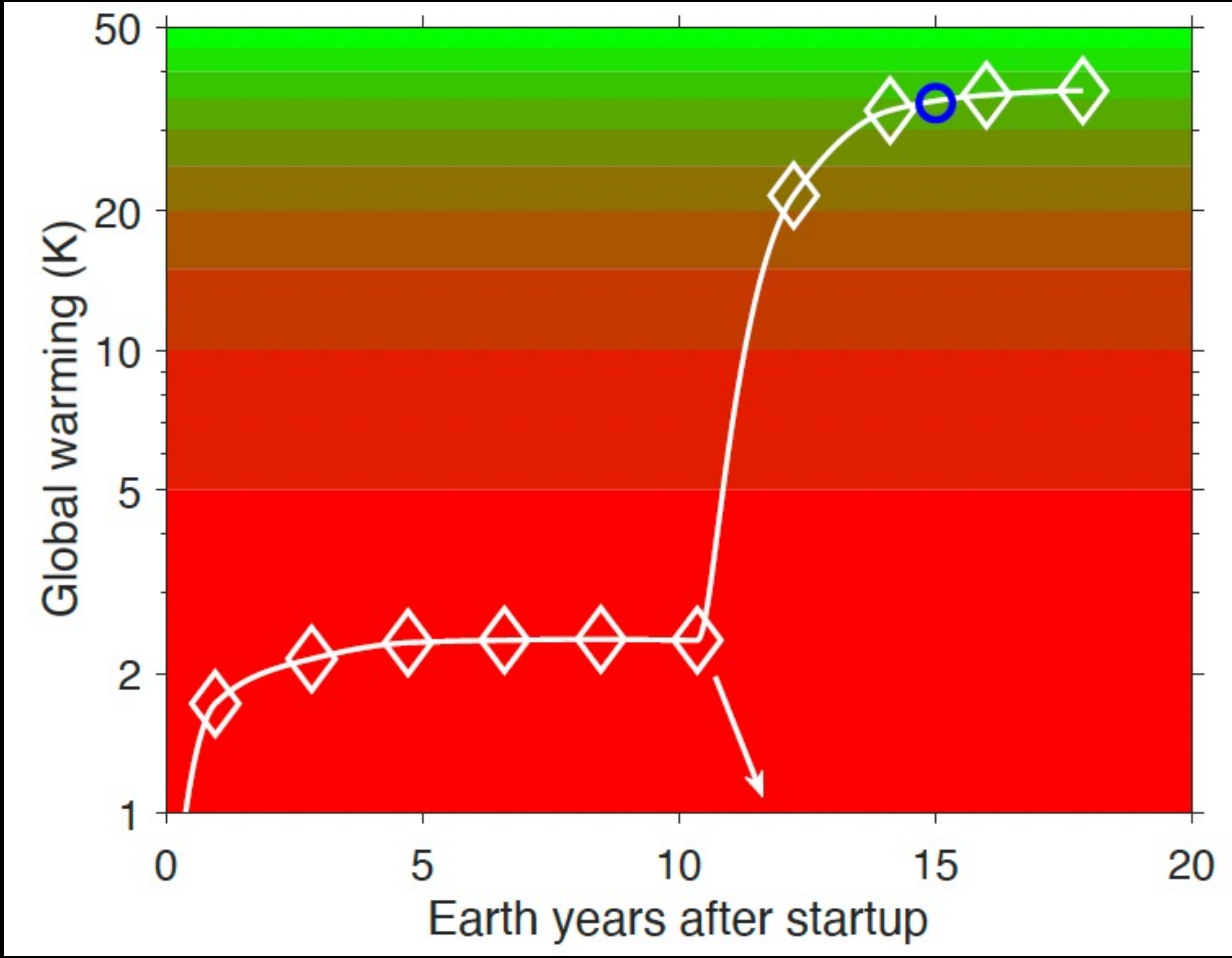
JPL

THE UNIVERSITY OF CHICAGO CLIMATE SYSTEMS ENGINEERING INITIATIVE

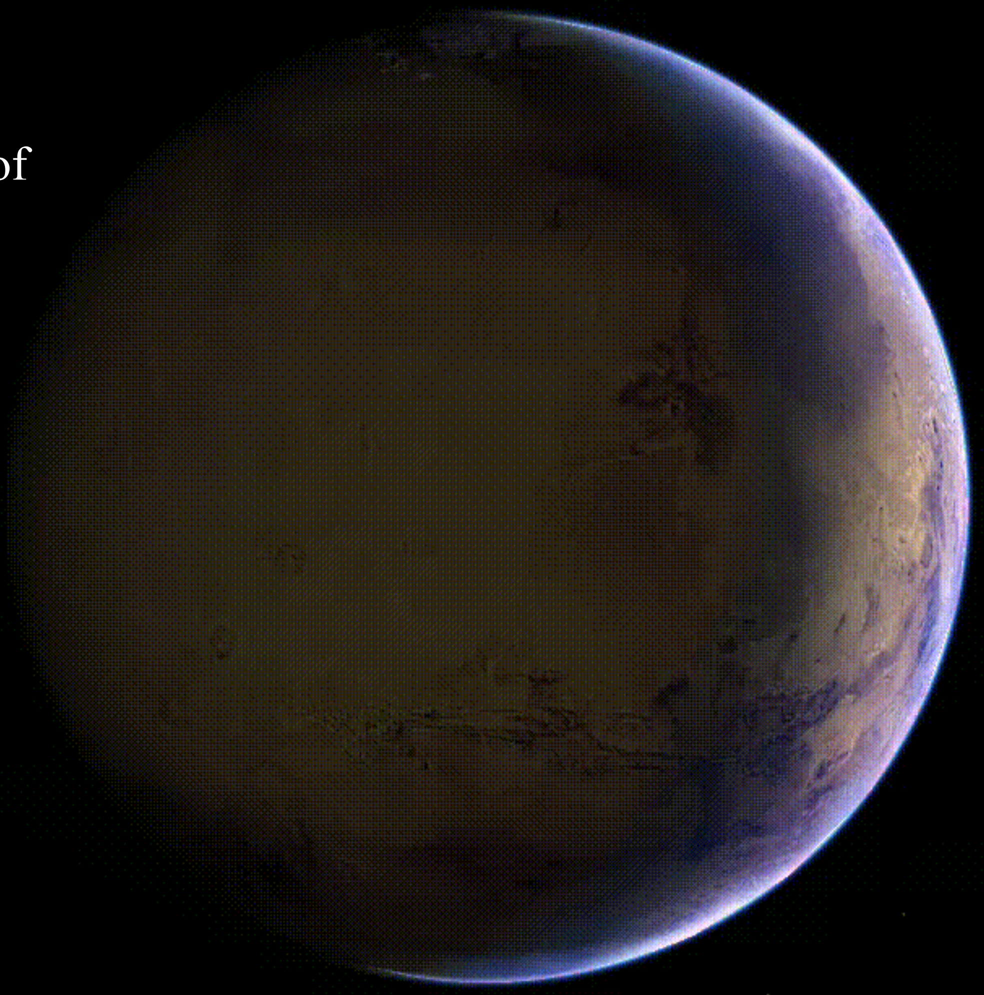
Ansari et al. Science Advances 2024, Richardson et al. arXiv 2025, DeBenedectis et al. Nature Astronomy 2025, Kite & Wordsworth Asterisk 2025

Richardson et al. arXiv:2504.01455



Time evolution of surface temperature, assuming a 3 L/s global warming test for the first 10 Earth years, followed by a choice to increase to 60 L/s. Al particles assumed. A smooth line is interpolated between the annual averages (diamonds).

To warm Mars using engineered nanoparticle aerosol, particles that are released locally must disperse globally. However, the winds that transport the aerosol respond to the aerosol's radiative forcing. Using a plume-tracking Mars global circulation model, we investigate the atmospheric dynamics of aerosol warming from point-source surface release of two particle types: graphene disks and metal rods.



Credit: Casey Handmer

Warming Mars: next steps/tests

- Simulation

Unexpected weather in dispersal area

- Batch manufacture + lab tests

Uncontrolled clumping, no reuptake

- Precursor 1-spacecraft mission (2031?)

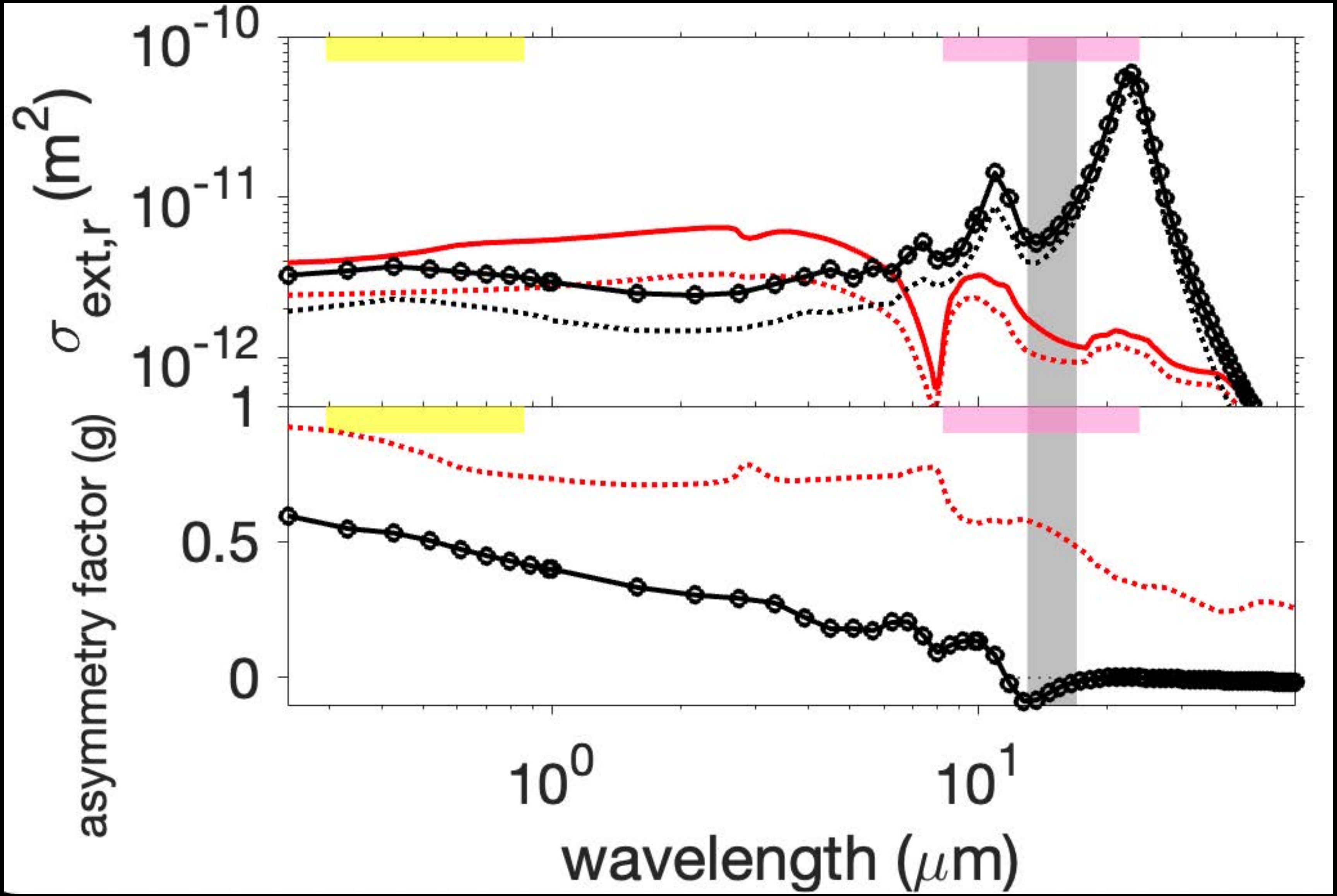
Full-scale behavior not captured in the lab

- Warm Mars by (2-5)°C *(measure climate feedbacks)*

Assess natural climate feedbacks

Nanoparticles have the desired properties

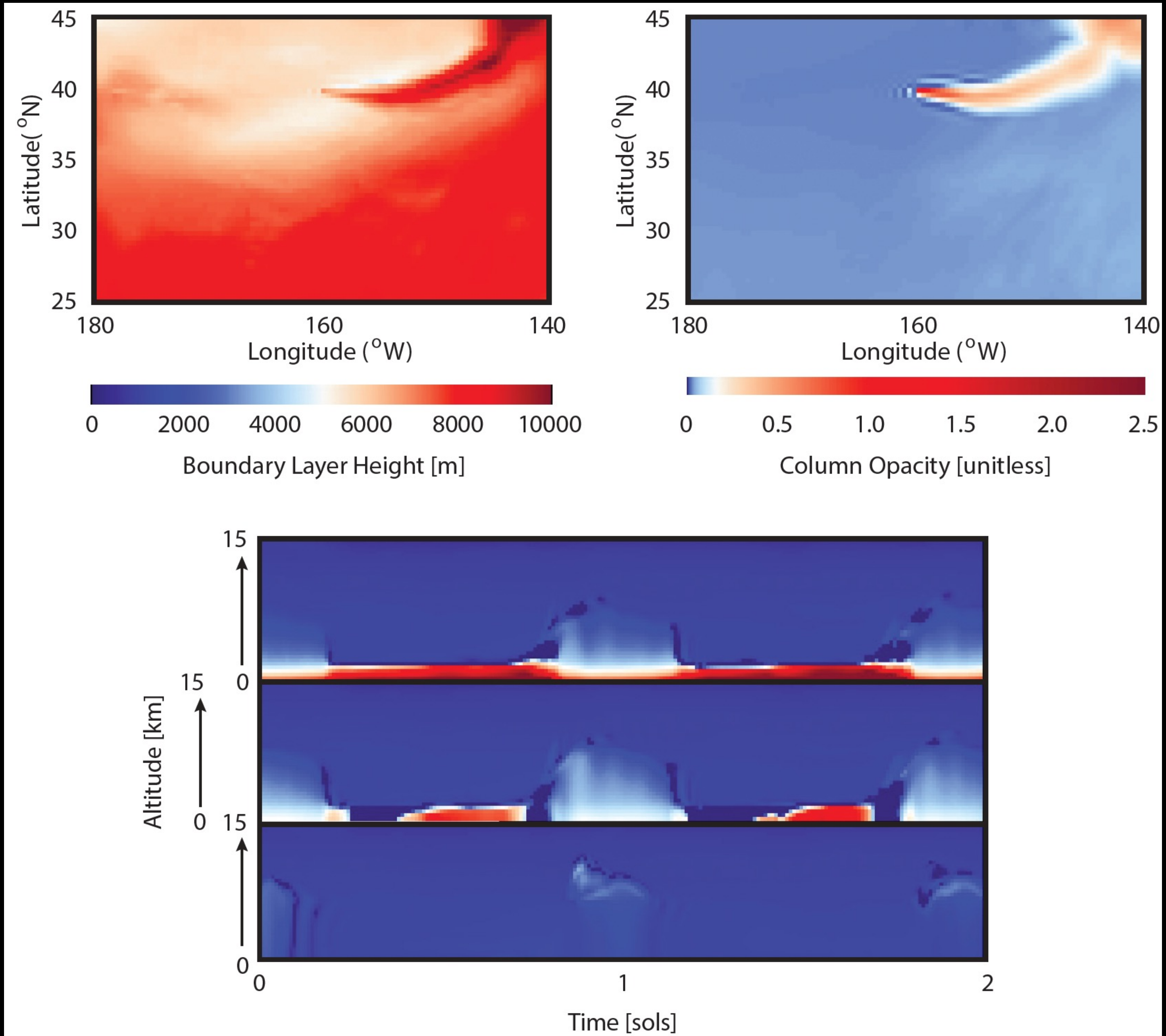
Ansari et al. Science Advances 2024



9 µm long, 0.16 µm diameter Fe rods (Al rods behave similarly)
- effective radius 80 nm, settle much more slowly than dust. (randomized geometric x-section 1.0×10^{-12} m^2)

Atmospheric dynamics of first steps in terraforming Mars

Richardson et al. arXiv:2504.01455



Many microbial species can proliferate at 7 mbar

ASTROBIOLOGY
Volume 16, Number 12, 2016

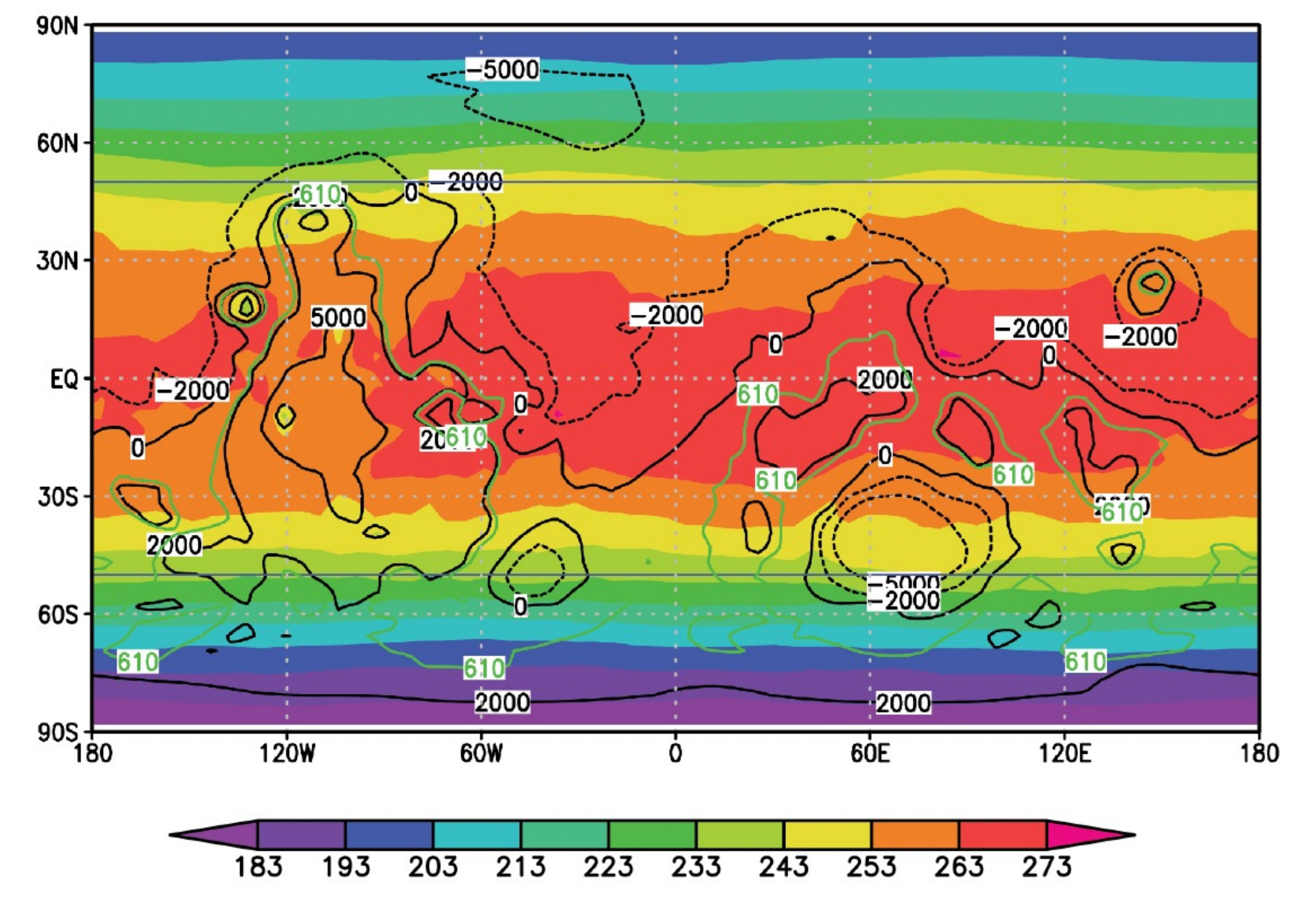
DOI: 10.1089/ast.2016.1587

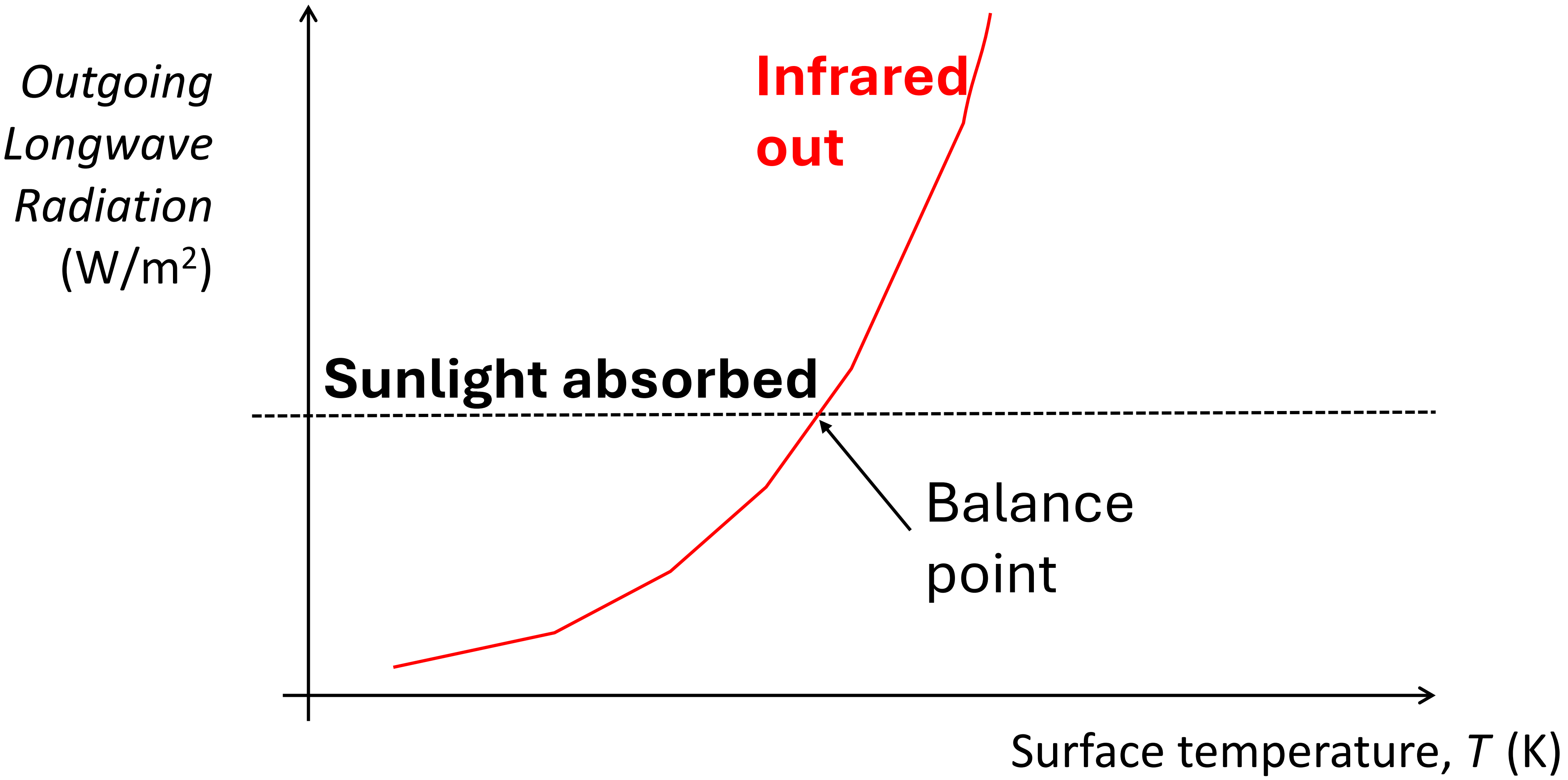
Twenty Species of Hypobarophilic Bacteria Recovered from Diverse Soils Exhibit Growth under Simulated Martian Conditions at 0.7 kPa

Andrew C. Schuerger[1] and Wayne L. Nicholson[2]

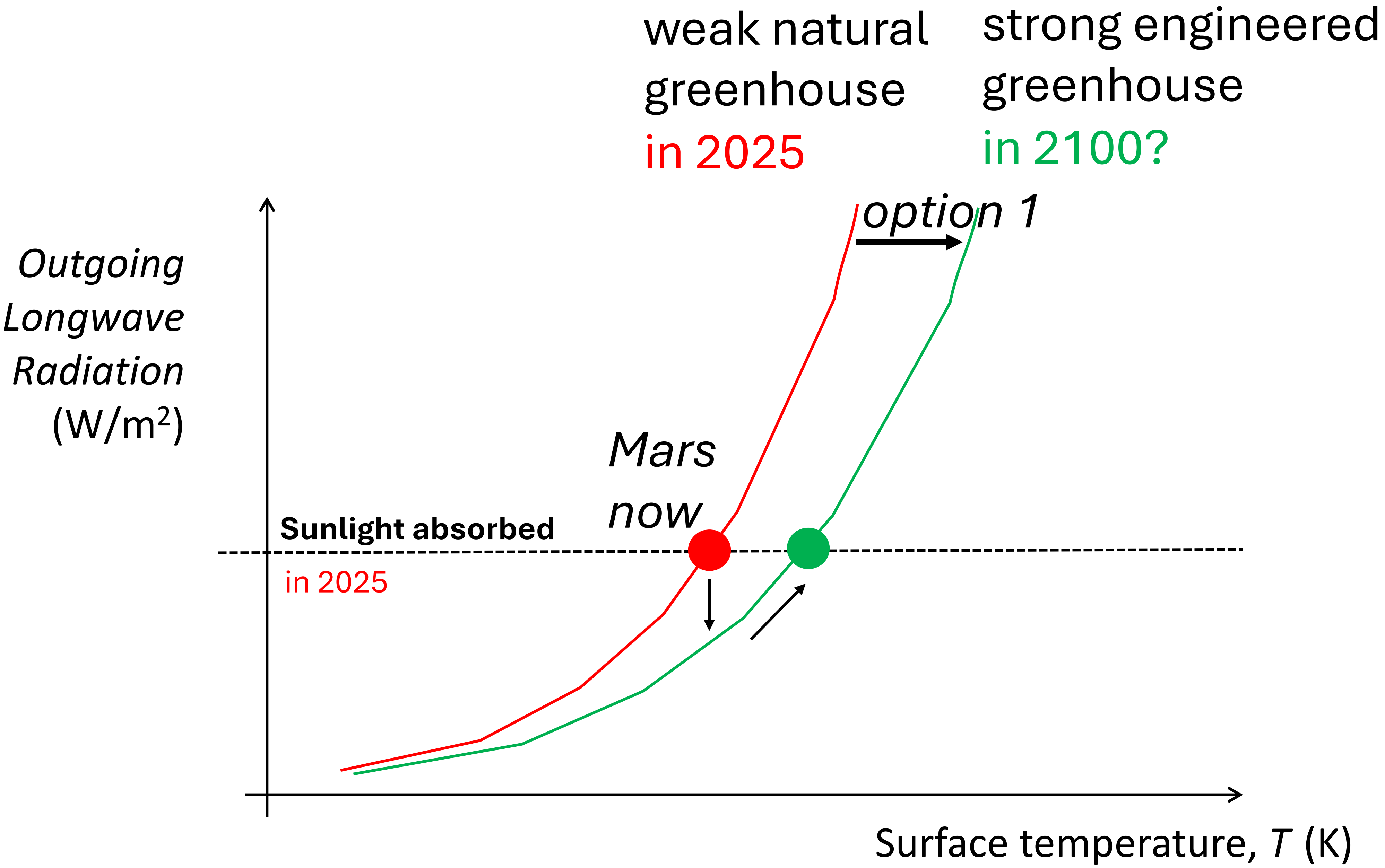
Annual average temperatures (warmed state)

Ansari et al.
Science Advances 2024

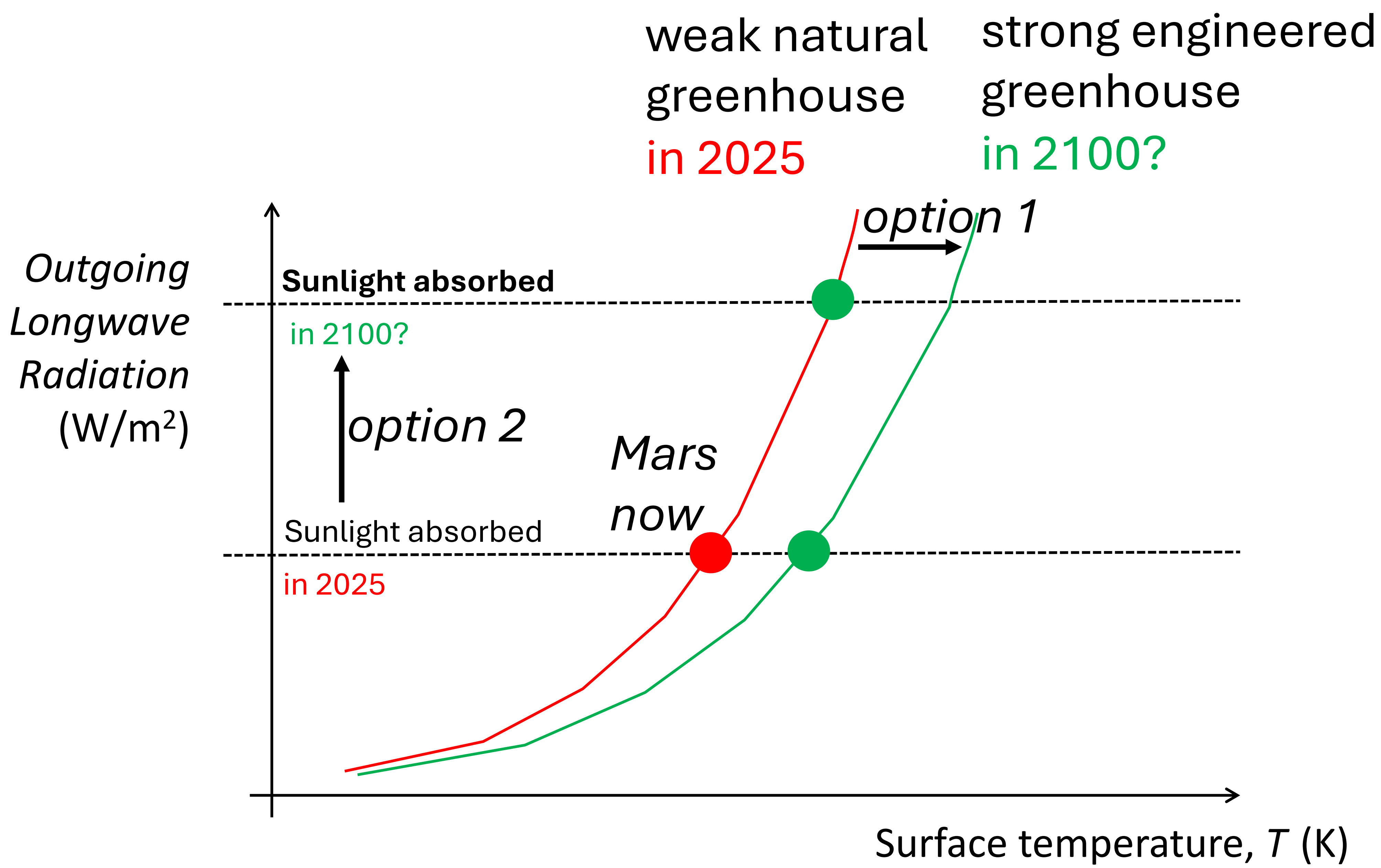




Pierrehumbert, *Principles of Planetary Clima*

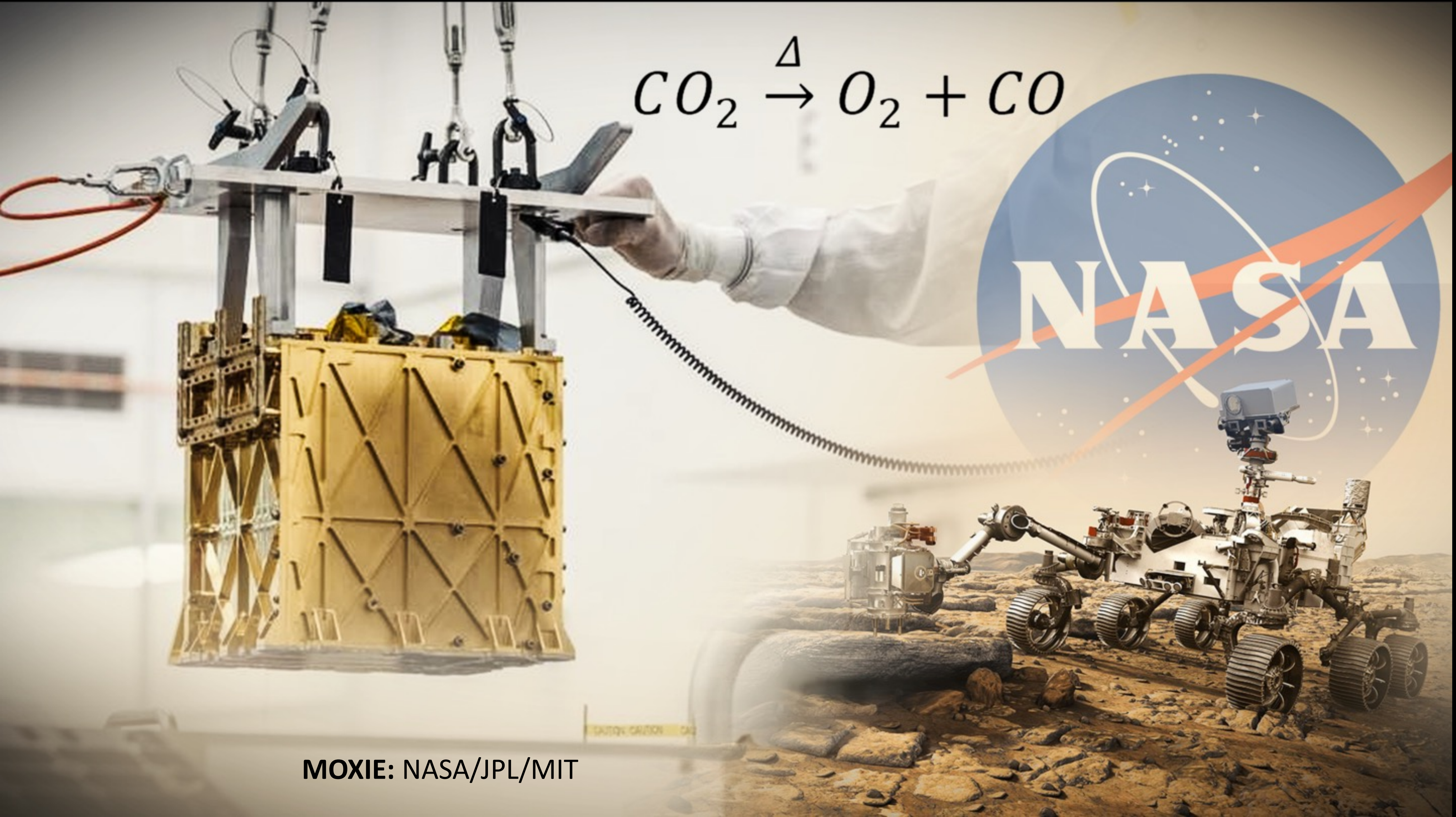


Pierrehumbert, *Principles of Planetary Clima*



Pierrehumbert, *Principles of Planetary Clima*

Successful demonstration of $CO_2 \rightarrow 2\ CO + O_2$ at Mars



MOXIE: NASA/JPL/MIT

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PERSPECTIVE
https://doi.org/10.1038/s41550-018-0529-6

nature astronomy

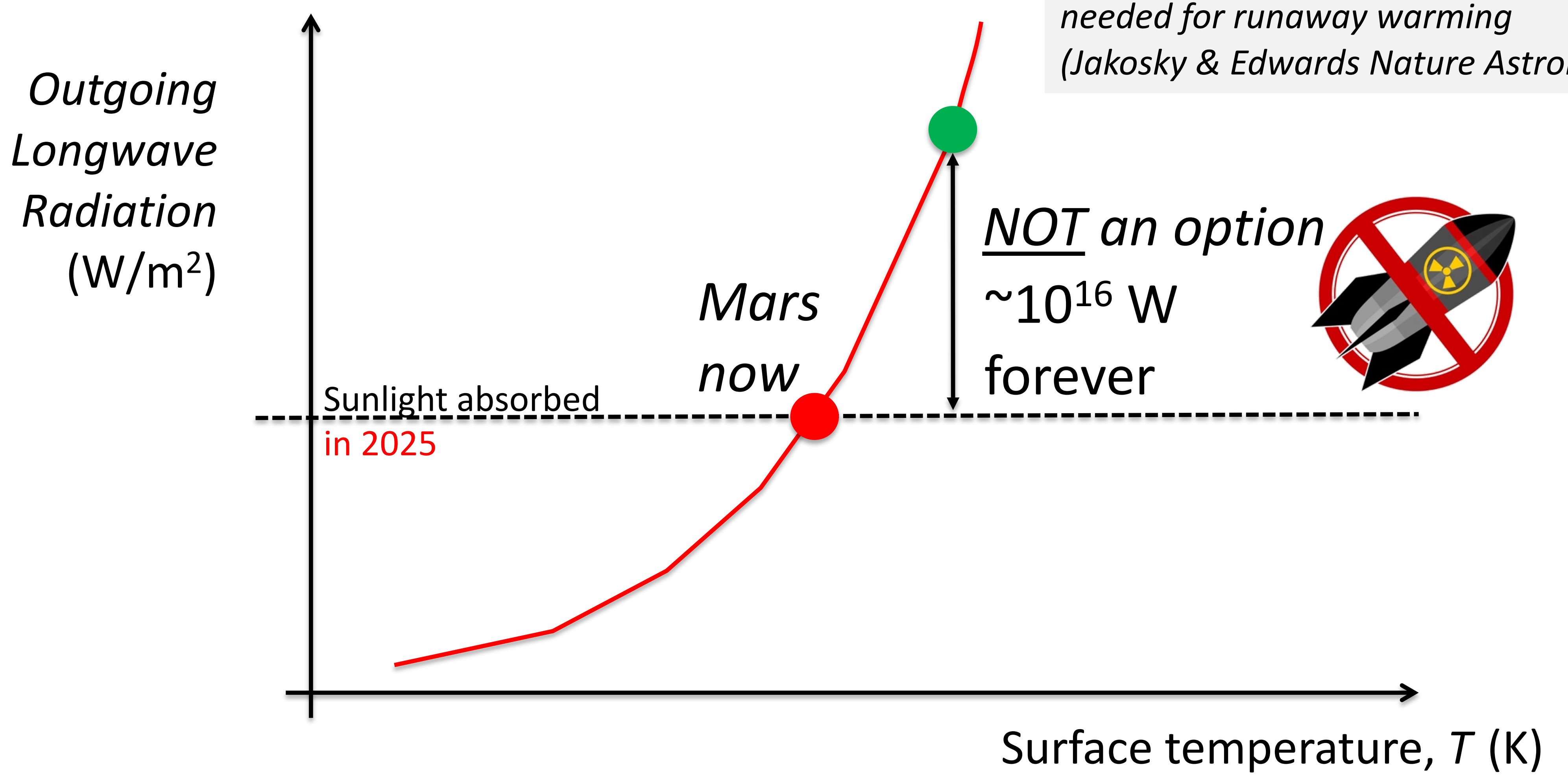
Inventory of CO_2 available for terraforming Mars

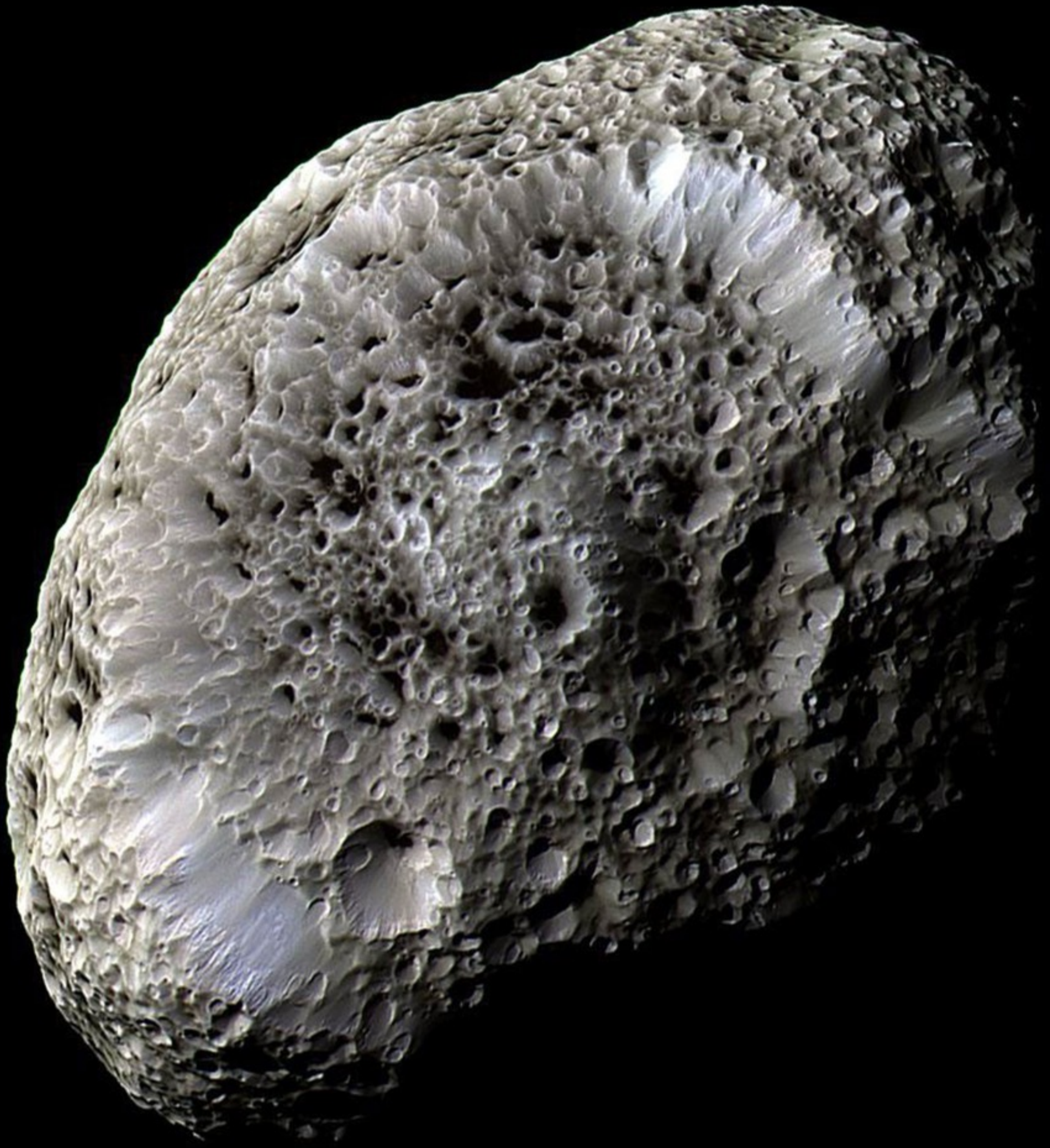
Bruce M. Jakosky[1,2*] and Christopher S. Edwards[3]

We revisit the idea of 'terraforming' Mars — changing its environment to be more Earth-like in a way that would allow terrestrial life (possibly including humans) to survive without the need for life-support systems — in the context of what we know about Mars today. We want to answer the question of whether it is possible to mobilize gases present on Mars today in non-atmospheric reservoirs by emplacing them into the atmosphere, and increase the pressure and temperature so that plants or humans could survive at the surface. We ask whether this can be achieved considering realistic estimates of available volatiles, without the use of new technology that is well beyond today's capability. Recent observations have been made of the loss of Mars's atmosphere to space by the Mars Atmosphere and Volatile Evolution Mission probe and the Mars Express spacecraft, along with analyses of the abundance of carbon-bearing minerals and the occurrence of CO_2 in polar ice from the Mars Reconnaissance Orbiter and the Mars Odyssey spacecraft. These results suggest that there is not enough CO_2 remaining on Mars to provide significant greenhouse warming were the gas to be emplaced into the atmosphere; in addition, most of the CO_2 gas in these reservoirs is not accessible and thus cannot be readily mobilized. As a result, we conclude that terraforming Mars is not possible using present-day technology.

Nuclear explosives are inelegant and unneccessary for the purpose of warming Mars

Sustained nuclear energy input would be needed, because Mars today lacks the CO_2 needed for runaway warming (Jakosky & Edwards Nature Astronomy 2018).





10^{19} kg