From granular rheology to 3D printing in space — and back

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Who is talking to you?

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Background
Materials science and engineering

Master thesis
ESA/EAC (Spaceship EAC)

PhD
German Aerospace Centre,
Institute for Material Physics in Space
Powder-based additive manufacturing for space


esa

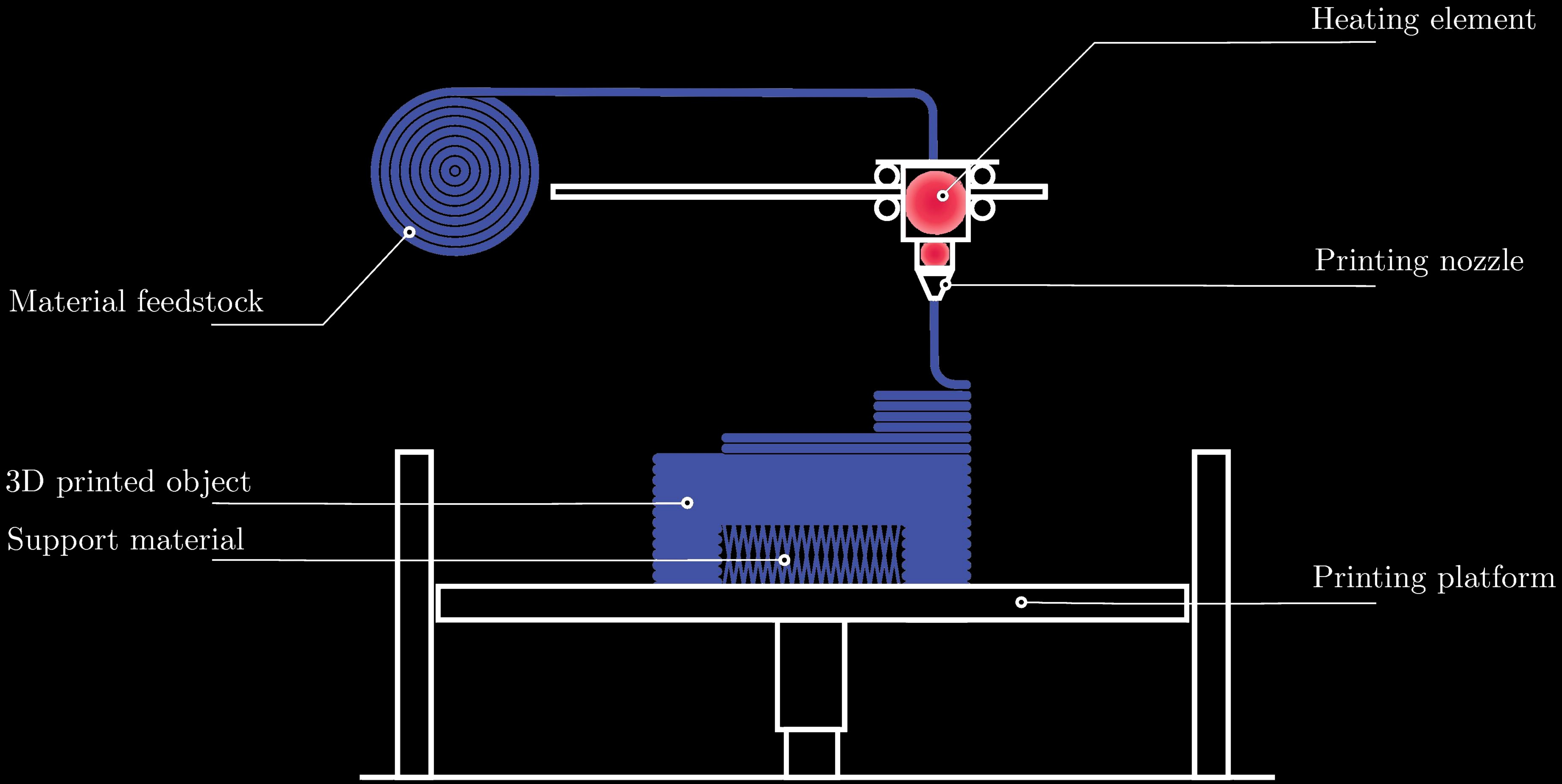
What is the near future of humans in space ?

Planetary exploration	Continuous human presence in space
Long endurance missions	Long duration missions
Low gravity	Microgravity
In-situ resource utilisation: sandy planetary surface (regolith)	Versatile (metals, polymers, ceramics) Material recycling

⟶ AM in low- and microgravity:
enabling technologies for future space missions

Additive manufacturing in space

Currently: filament-based (FDM) AM on board the ISS (since 2014)



Additive manufacturing in space

Currently: filament-based (FDM) AM on board the ISS (since 2014)

Small, low constrains parts

< 200 functional parts over two years

Limited size

Low quality parts (delamination, limited resolution)

Thermoplastics only

AMF (Additive Manufacturing Facility), 2016

Image © NASA / Made In Space

Image © NASA

Image © NASA

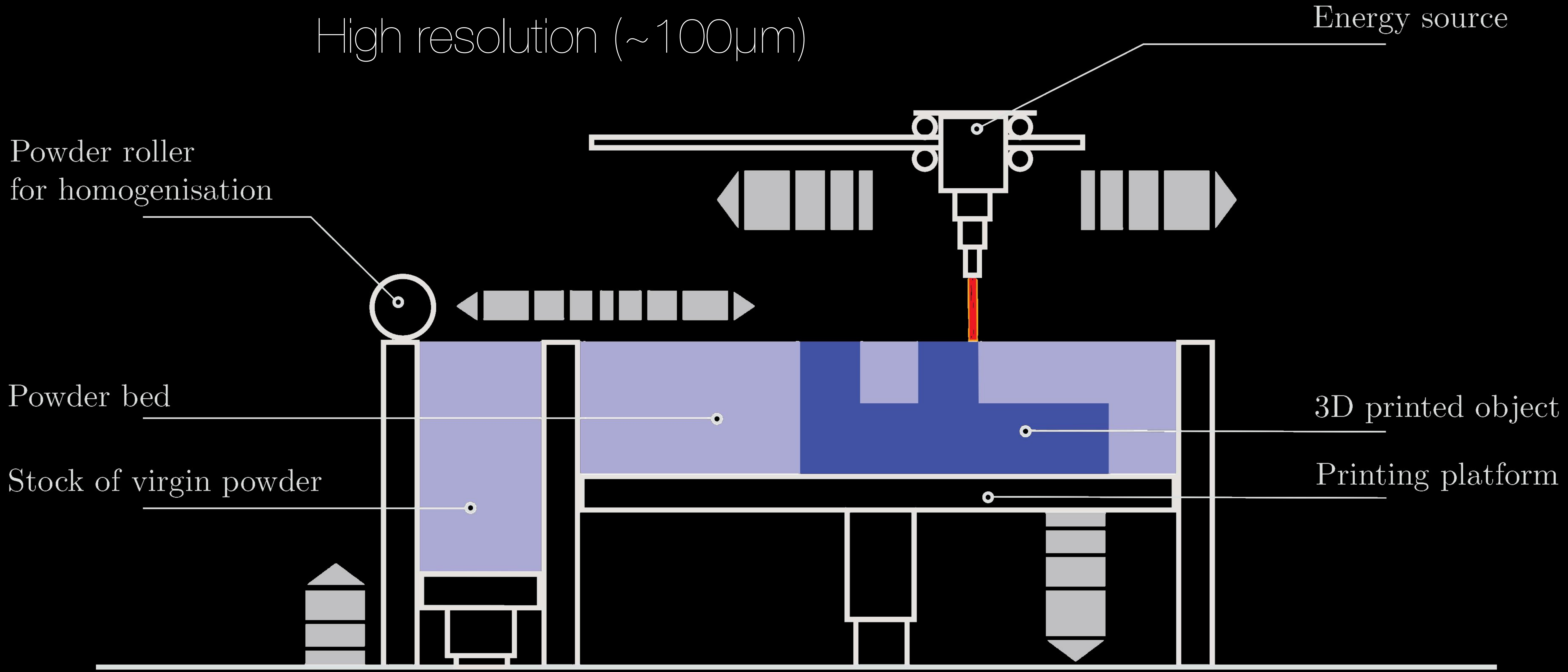
T. Prater, N. Werkheiser, F. Ledbetter, D. Timucin, K. Wheeler, and M. Snyder, “3D Printing in Zero G Technology Demonstration Mission: complete experimental results and summary of related material modelling efforts”, International Journal of Advanced Manufacturing Technology **101**, 391–417 (2018).

Additive manufacturing in space

Higher resolution Higher dimensional accuracy	Multimaterials fabrication: Polymers, metals, ceramics

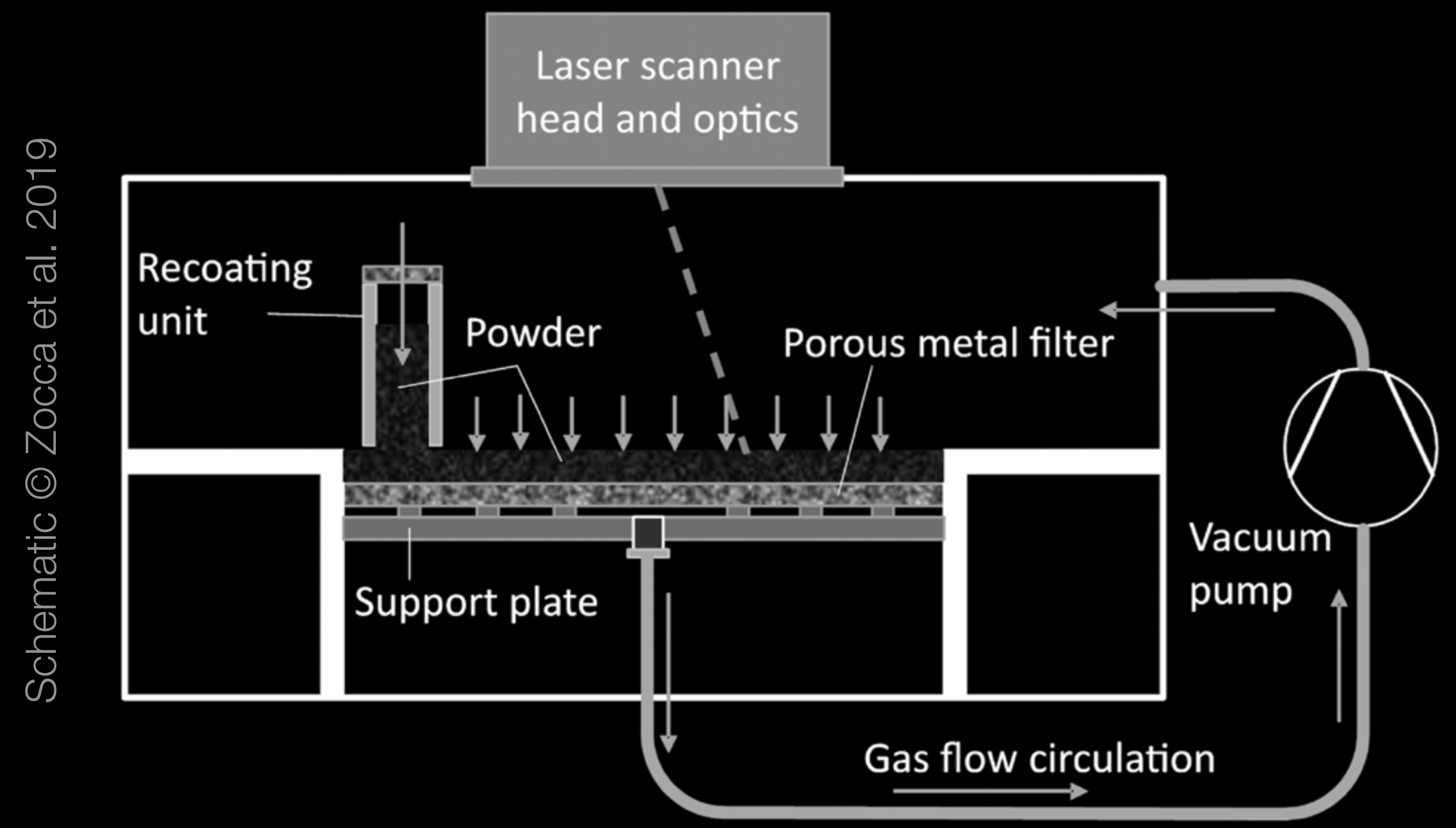
Powder-bed based

- Versatile (polymer, metal, ceramic powders)
- High resolution (~100µm)



Additive manufacturing in space

Powder-based AM for space: Gas-flow assisted powder-bed stabilisation



First parts 3D p. in µg from powder

From ceramic and metal powders

High resolution (~100µm)

Deposition relies on powder flowability
(i.e. limited recycling / powder batch reusing)

Bed thickness limited by pump power

Powder without fines

Vertical walls thickness < 2 mm

A. Zocca, J. Lüchtenborg, T. Mühler, J. Wilbig, G. Mohr, T. Villatte, F. Léonard, G. Nolze, M. Sparenberg, J. Melcher, K. Hilgenberg, and J. Günster, “Enabling the 3D printing of metal components in µ-gravity”, Advanced Materials Technologies **4**, 1900506 (2019).

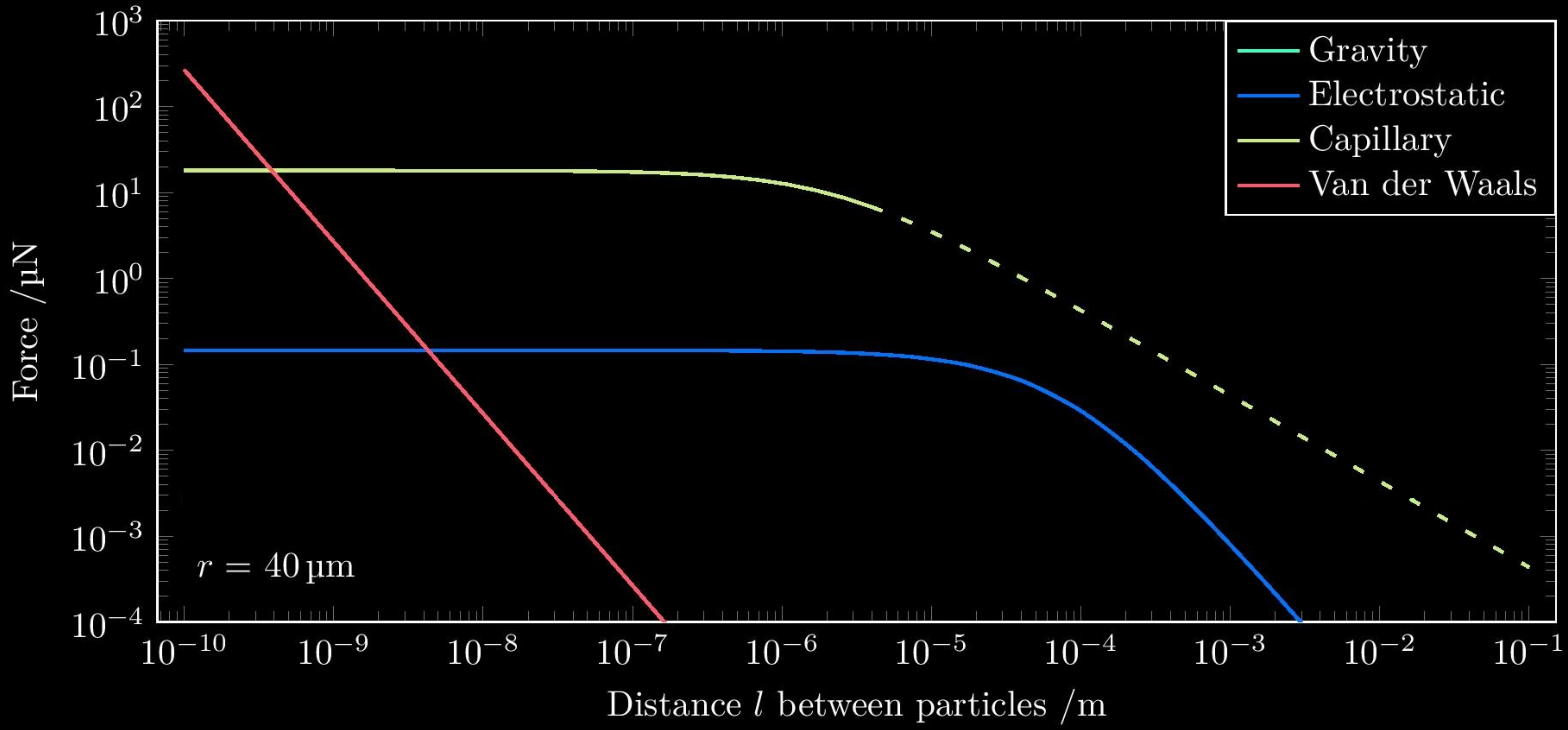
J. Günster, A. Zocca, C. M. Gomes, and T. Muehler, “Method for Stabilizing a Powder Bed by means of Vacuum for Additive Manufacturing”, United States Patent 9533452B2 (BAM, 2017).

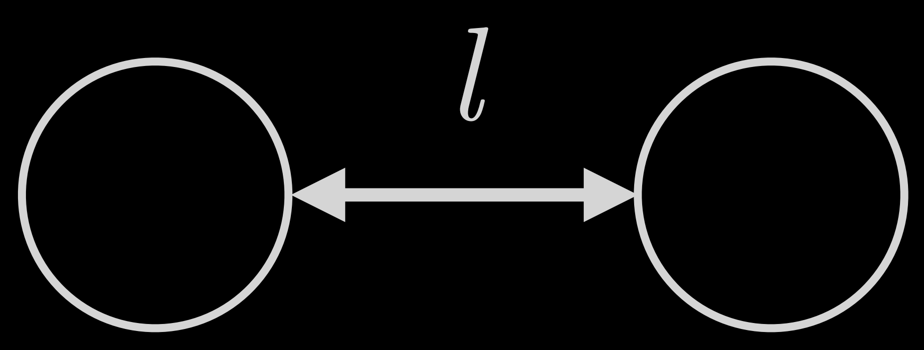
Powder flow in microgravity

Video courtesy of Plasma Ben, available on https://www.youtube.com/watch?v=Q0kteyMDnwE

Handling powders in microgravity

How to explain behaviour change of granular materials in microgravity?

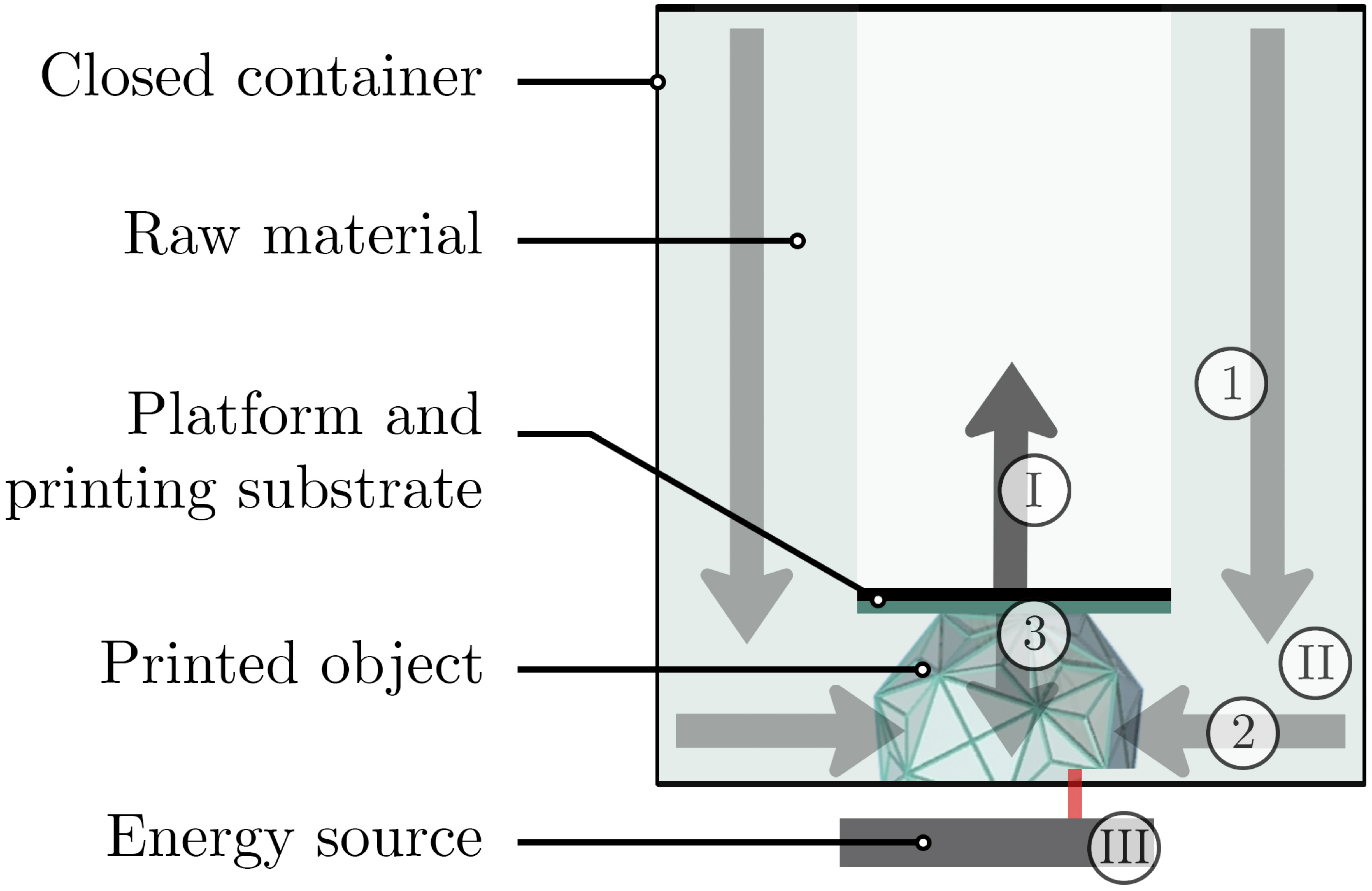




Material parameters (PS powder):
mass density $\rho = 1460\ kg.m^{-2}$
dielectric constant $\varepsilon = 3$
surface tension $\gamma = 72\ mN.m^{-1}$
$\theta = 5°$
aperture angle of capillary liquid bridges $\phi = 20°$
Hamaker constant $A = 8\ 10^{-19}\ J$
surface charge density $\sigma = 1.6\ 10^{-5}\ C.m^{-2}$

Handling & 3D printing powders independently of gravity

A process for 3D printing powders independently of gravity



(I) **Increment**

(II) **Deposition**

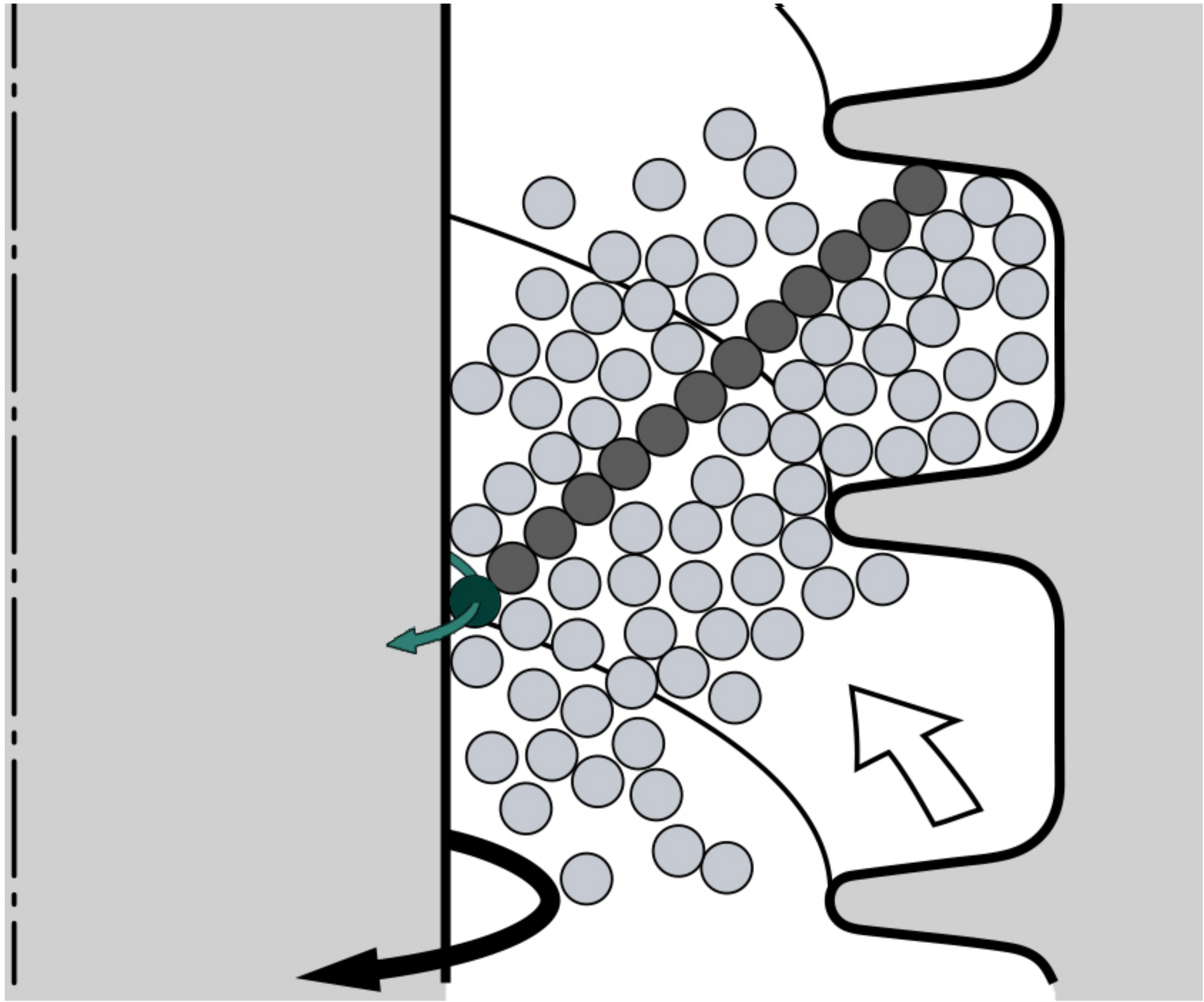
(1) Transport
(2) Homogenisation
(3) Compression

(III) **Solidification**

O. D’Angelo et al., A gravity-independent powder-based additive manufacturing process tailored for space applications, unpublished manuscript (2021) arXiv:2102.09815 [cond-mat.mtrl-sci]

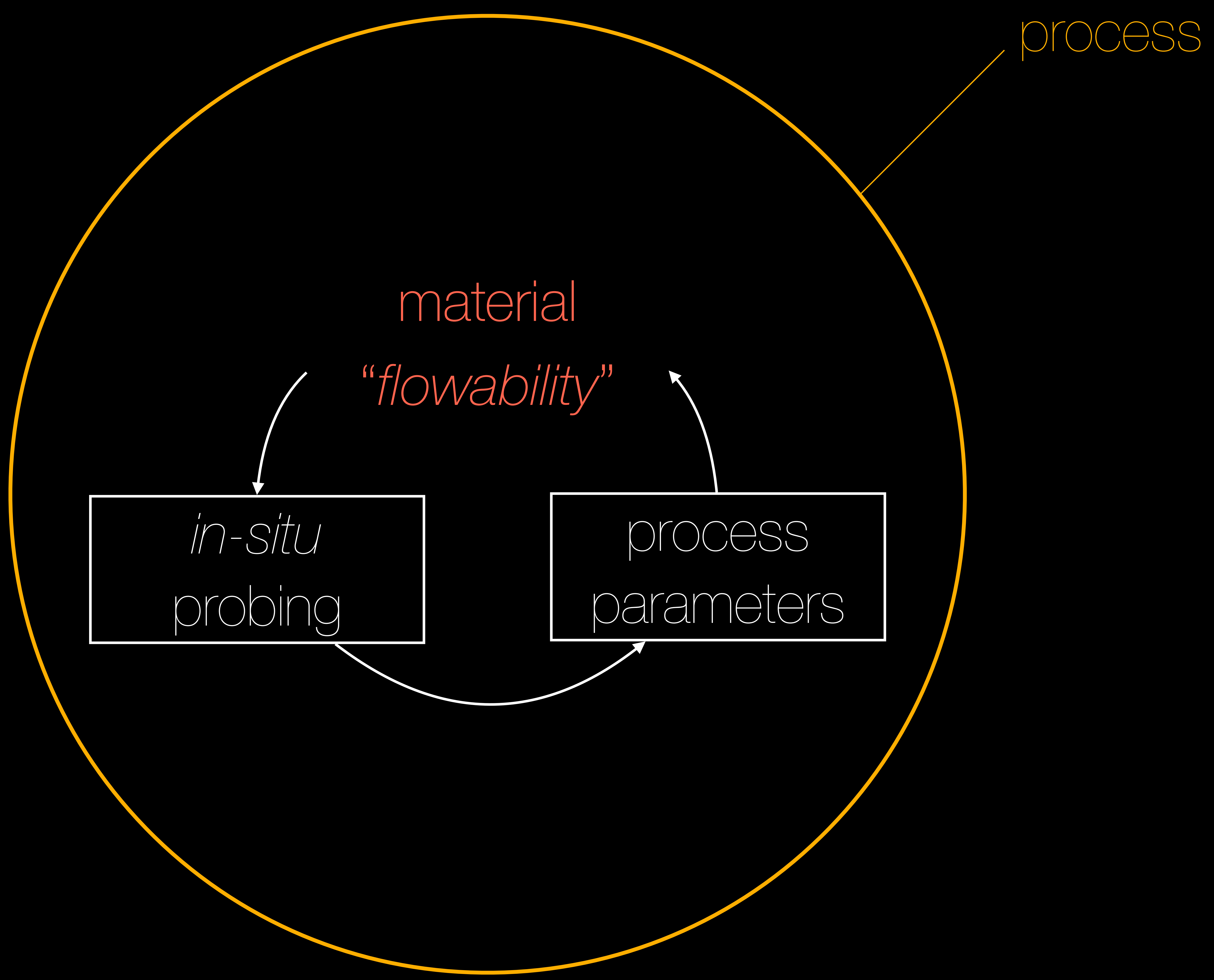
Patent application DE 10 2020 123 753.7 (2020)
Apparatus and Method for Additive Manufacturing of Components in Environments with Various Gravitation-levels and with Materials of Different Flowability

A process for 3D printing powders independently of gravity

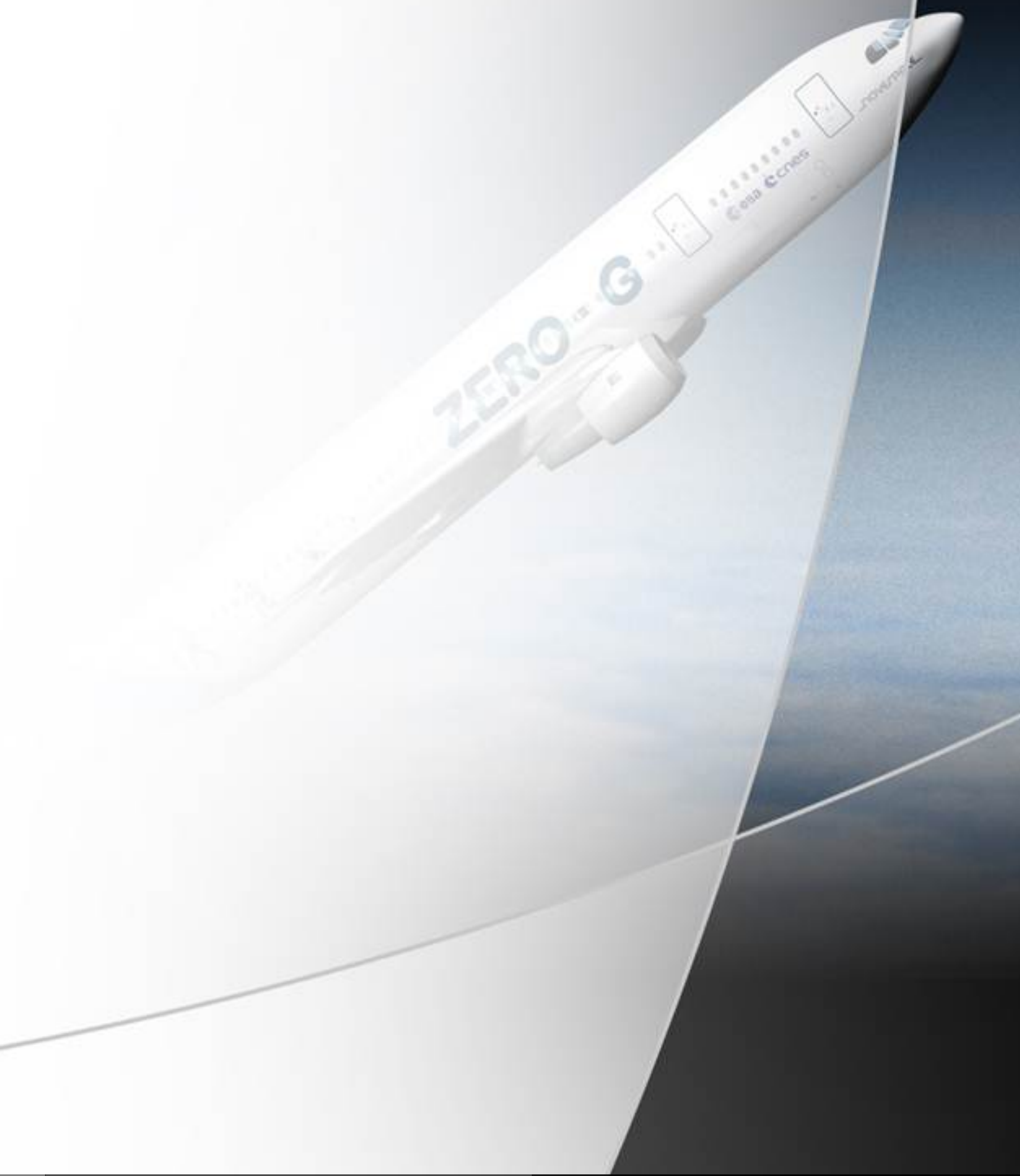


1. Screw conveyor rotation: blades rotation pushes material downwards
2. Force chains
3. Inner tube rotates: disruption of force chains by orthogonal force

Using rheology as a tool towards adaptability



Technology demonstration



Technology demonstration

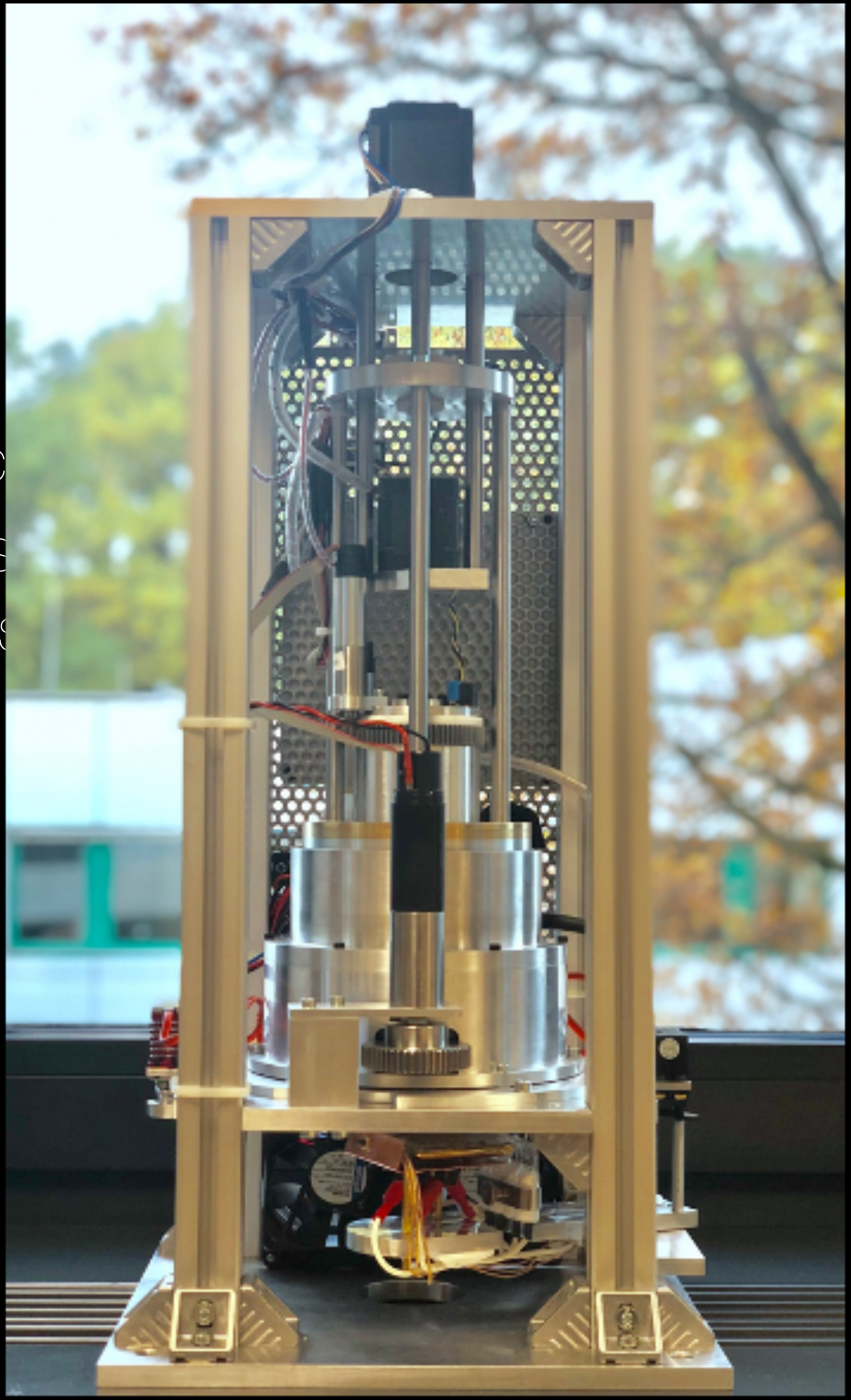
- Use simulation

  DEM simulation: number of particles limited by c

  Continuum approach: no constitutive equations
  encompassing all states

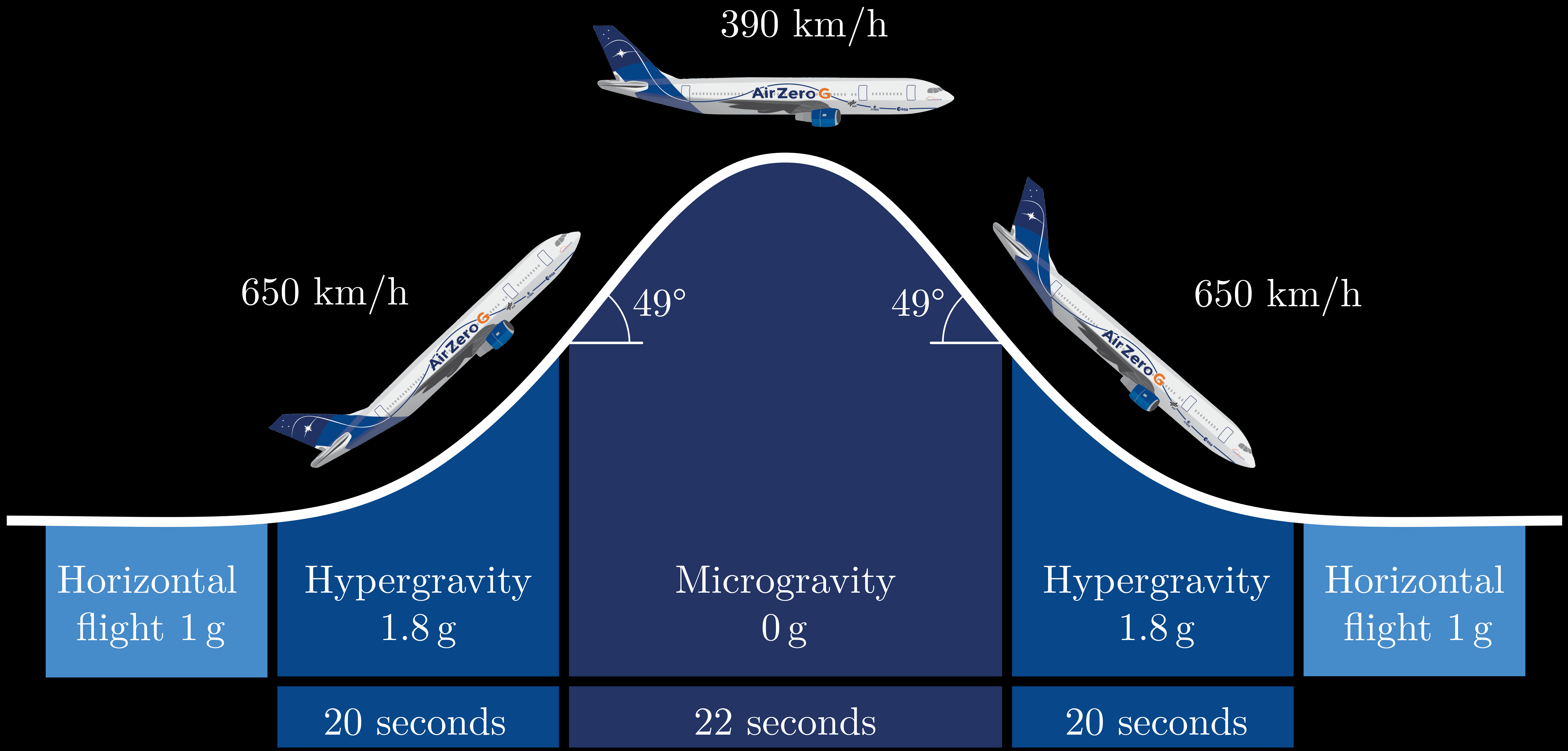
- Experimental proof of concept

  1. Build prototype(s)
  2. Experiment on-ground (1g)
  3. Experiment in weightlessness (µg)



Technology demonstration

Parabolic flight as a microgravity experimental platform

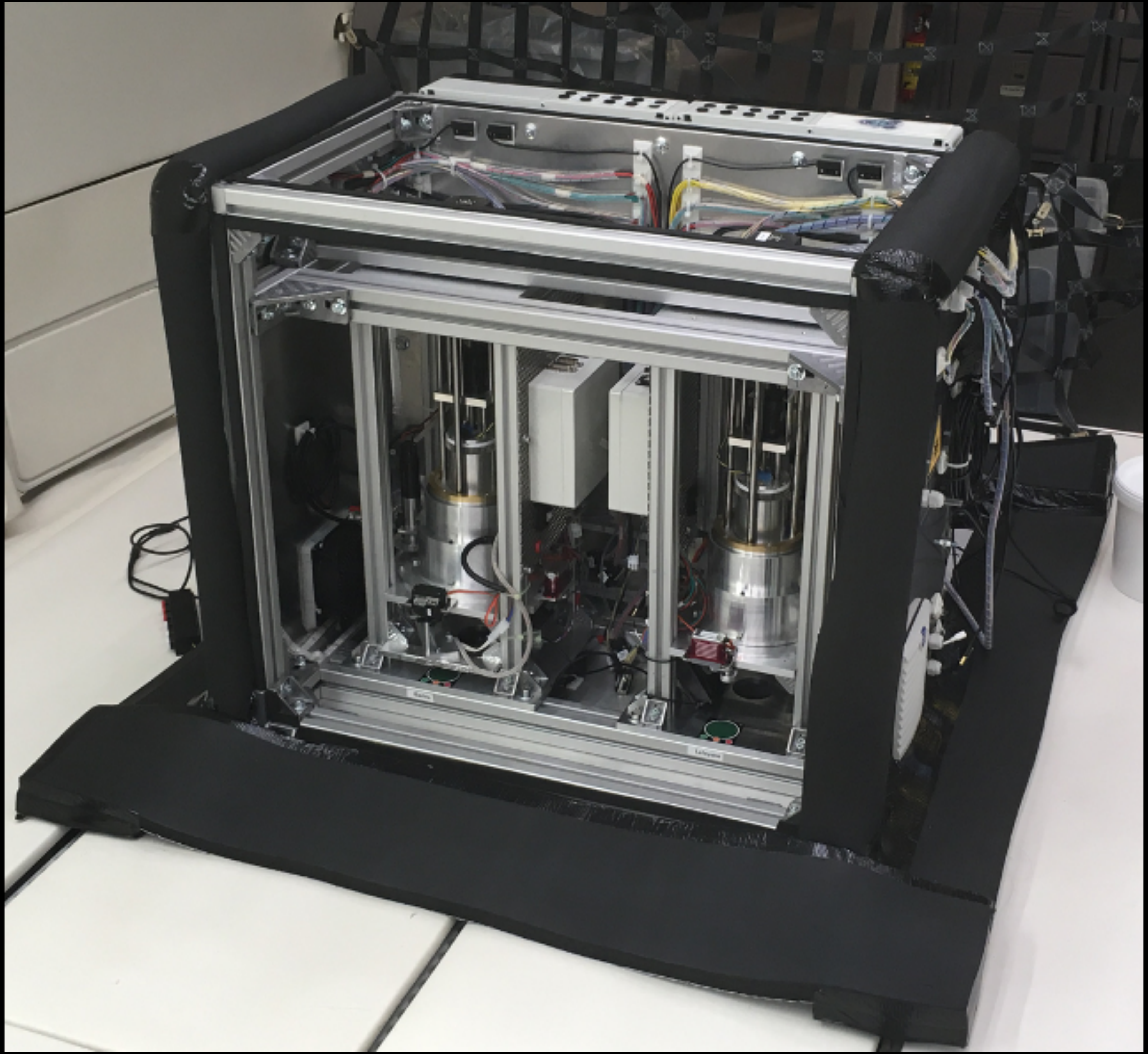


650 km/h
49°
49°
Horizontal flight 1 g
Hypergravity 1.8 g
Microgravity 0 g
Hypergravity 1.8 g
Horizontal flight 1 g
20 seconds
22 seconds
20 seconds

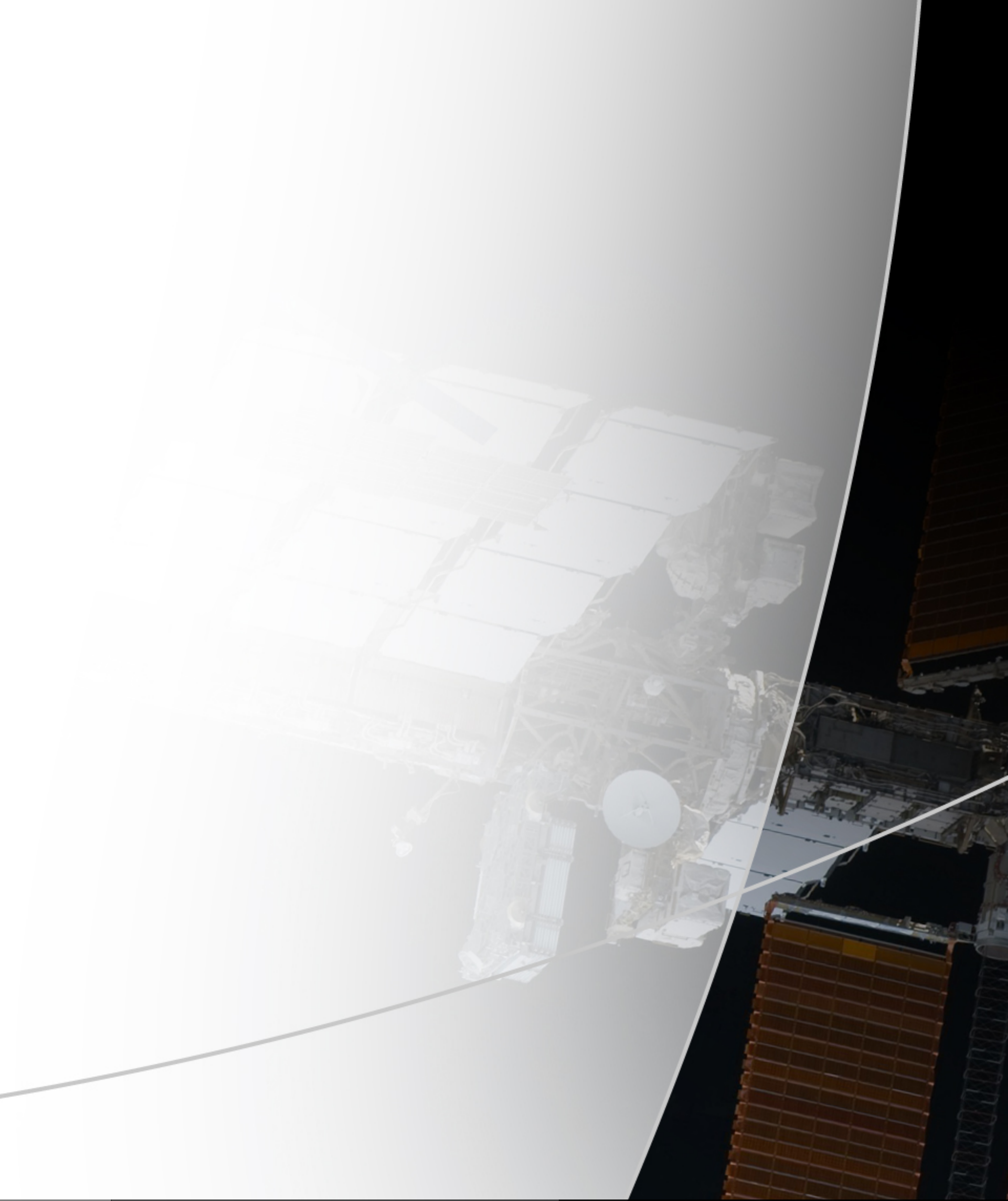
Technology demonstration

Parabolic flight as a microgravity experimental platform

Technology demonstration



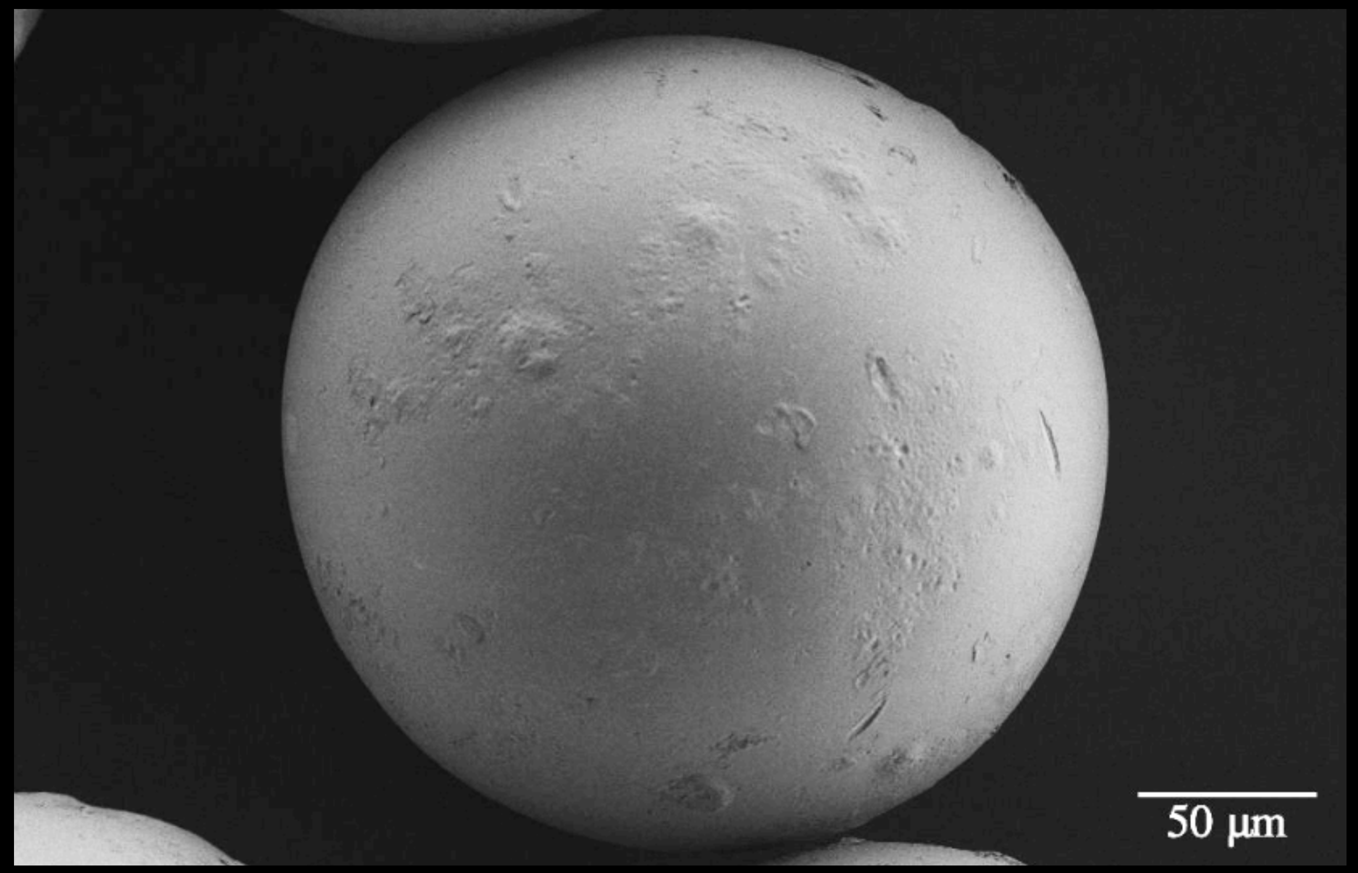
Results

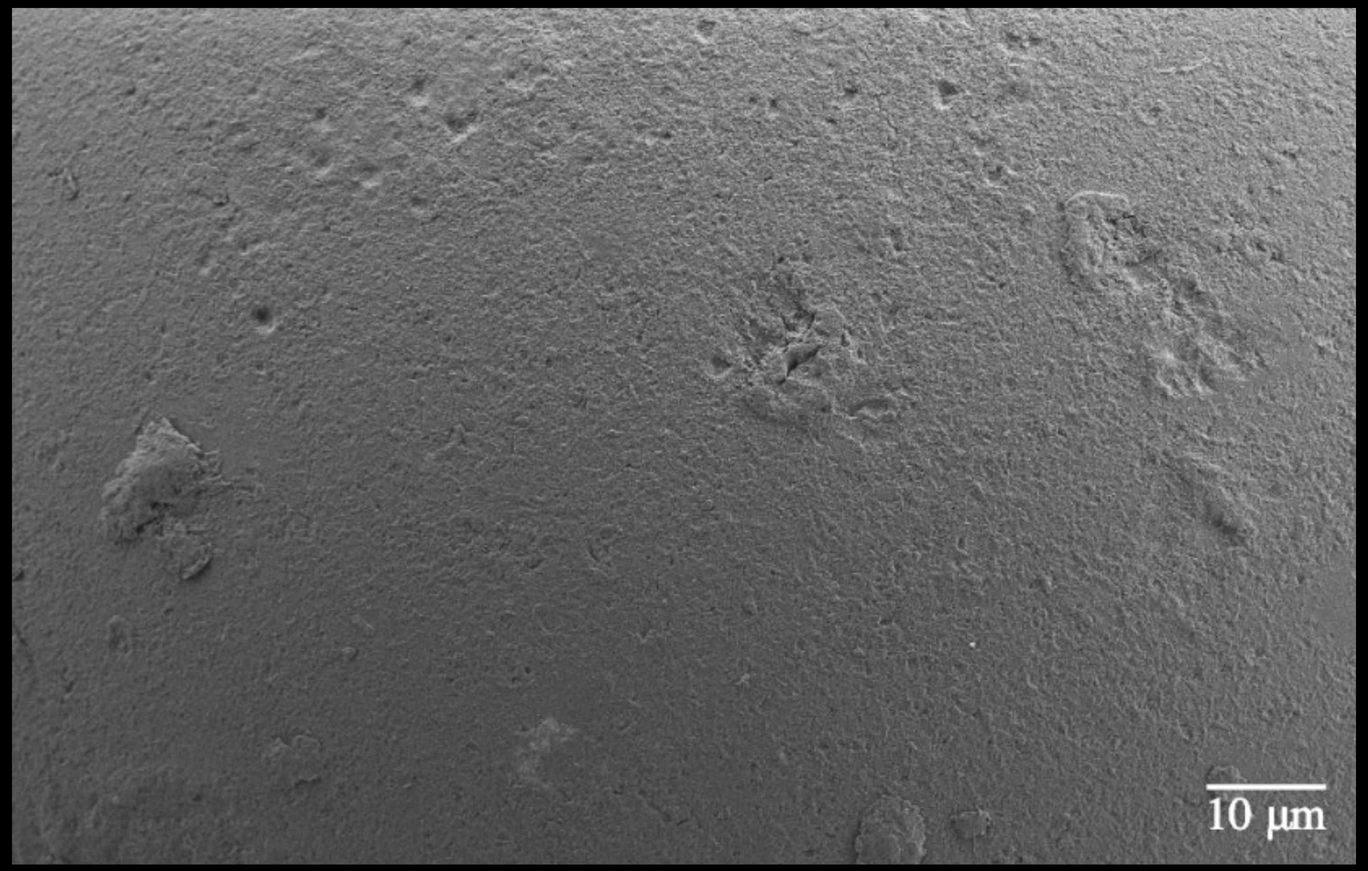


Technology demonstration

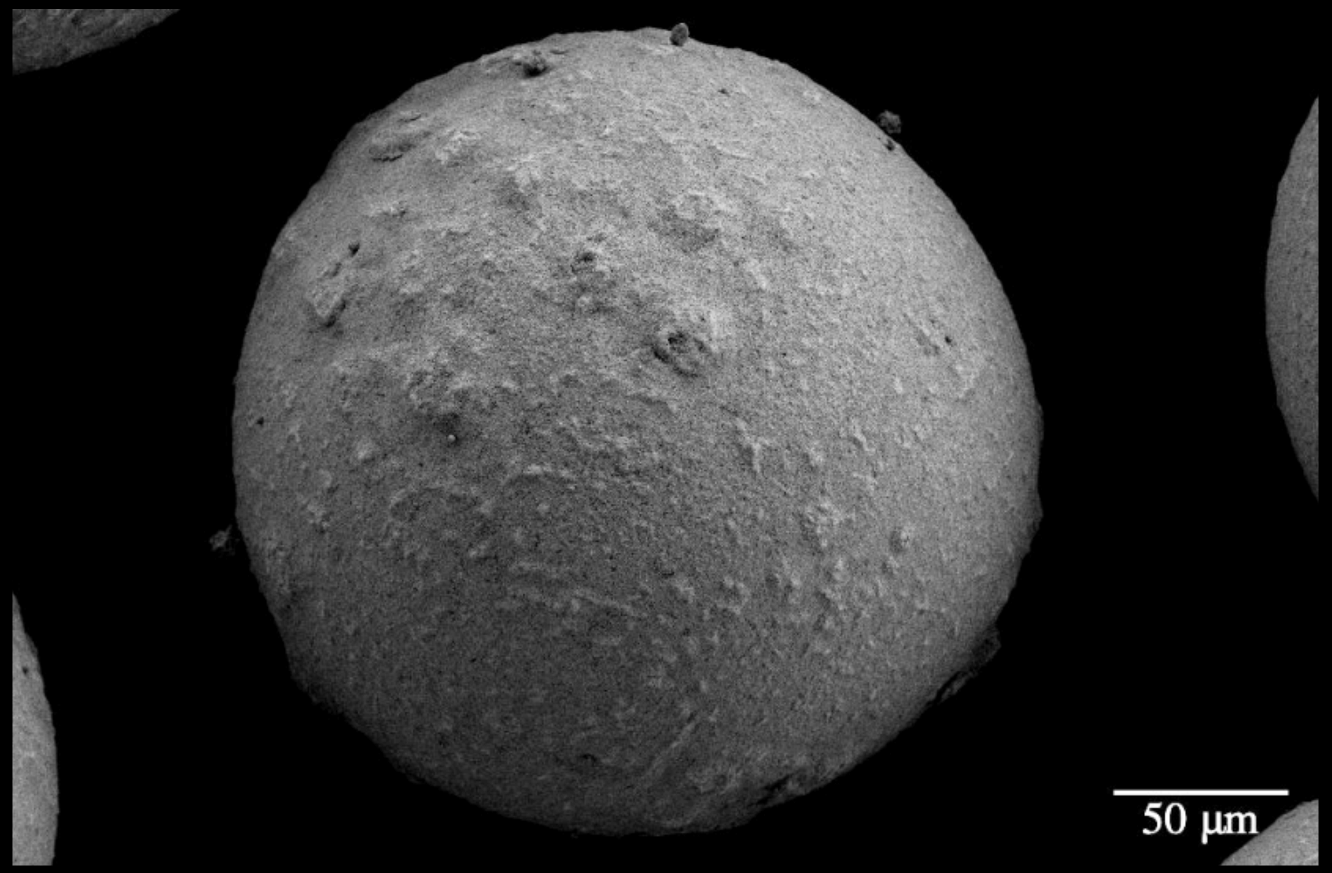
Demonstrator powders: two typical powders (PS 80µm), very different *flowability*…

- Smooth surface powder





- Rough surface powder



Results: powder rheology *vs.* gravity

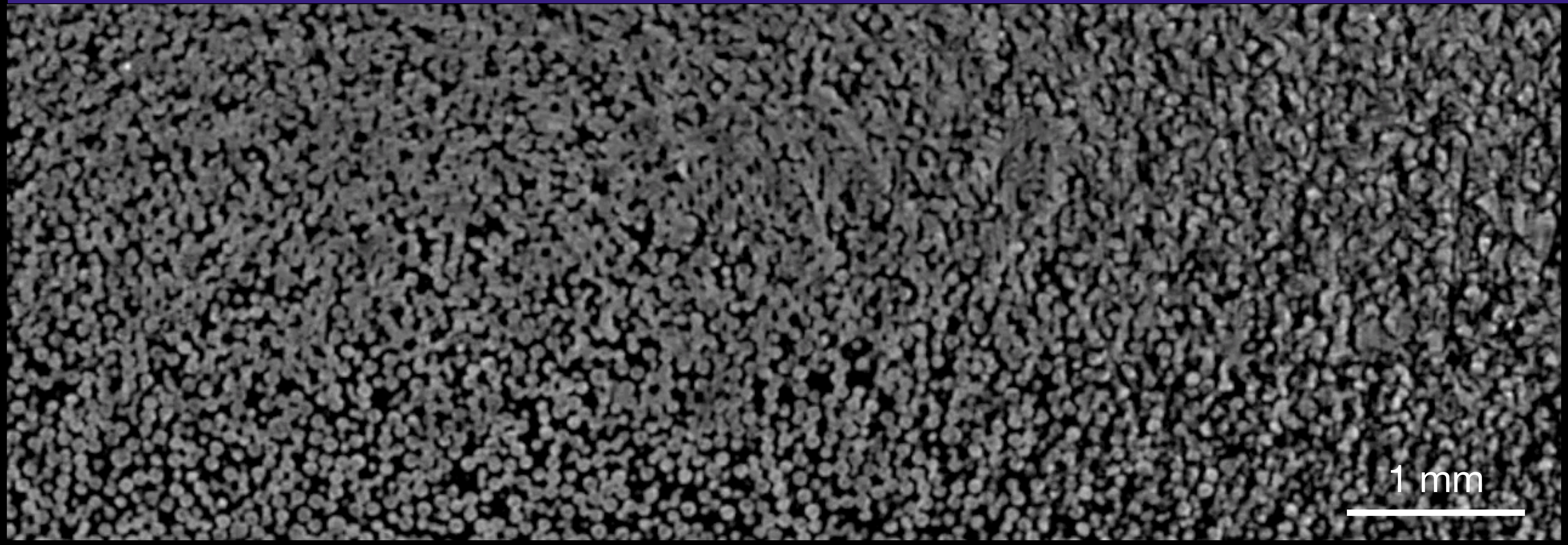
Results: powder-based 3D printing in weightlessness

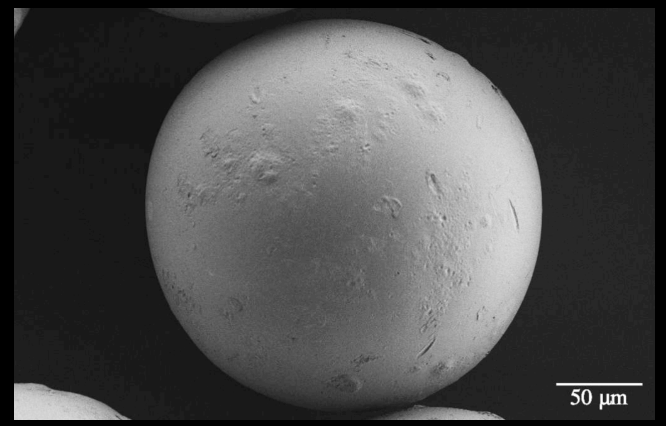
Smooth surface powder

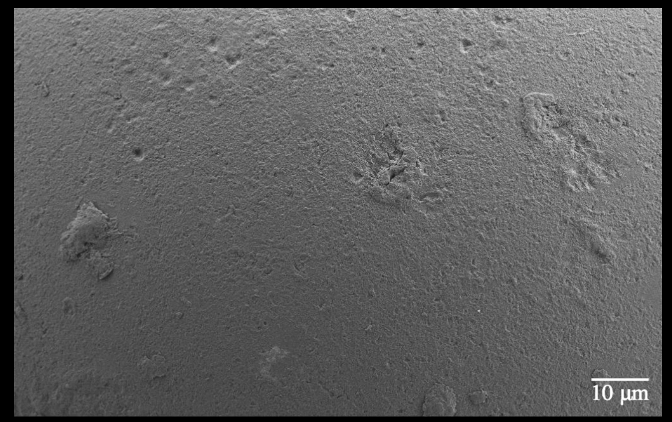
Rough surface powder

Results: powder-based 3D printing in weightlessness

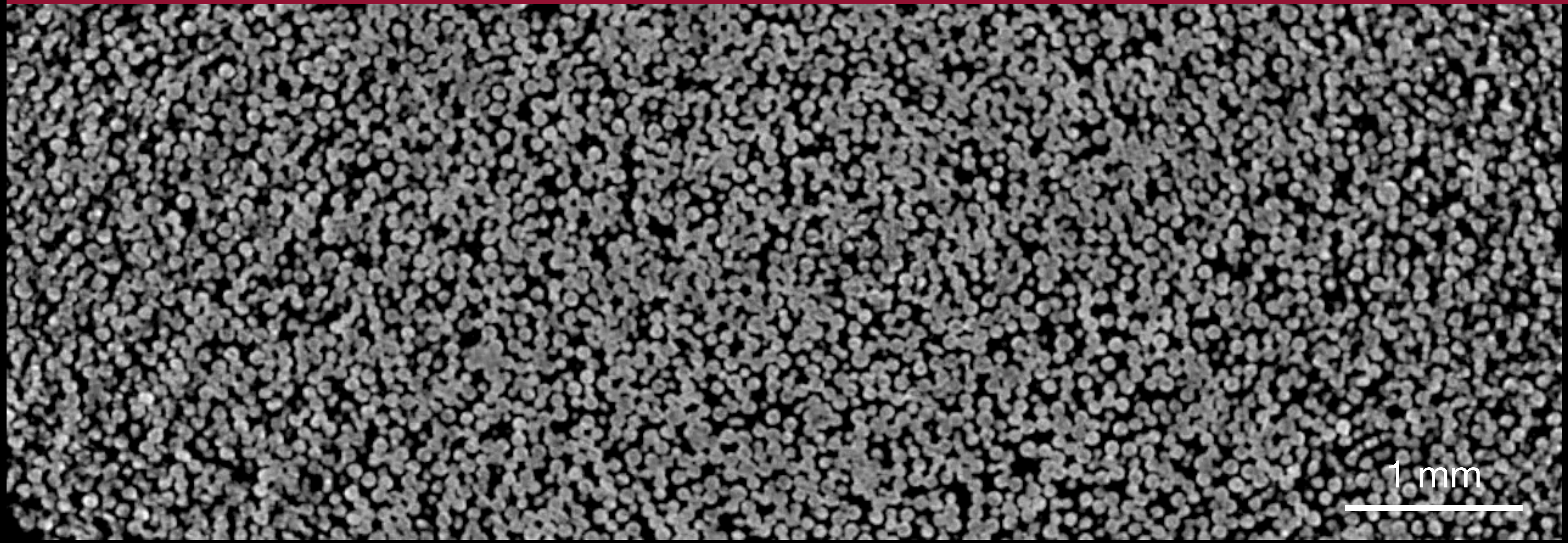
Smooth surface powder

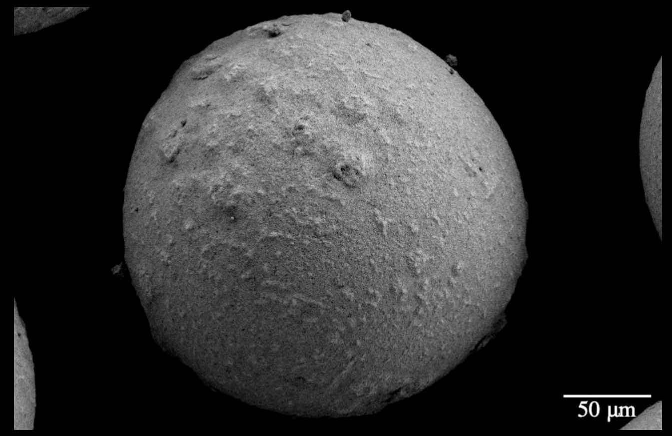






Rough surface powder





Conclusion

Conclusion

Additive manufacturing for space applications

- AM: enabling technology for space exploration
- New processes are yet to be developed

  3D printing metals
  with high precision
  and minimal waste

  Handling granular materials
  in extreme environments

Altered-gravity experimental platforms

Need for altered-gravity experimental platforms:

- To provide reliable proof of concept
- To work with materials difficult to simulate (e.g. granular materials)
- For technology demonstrations

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