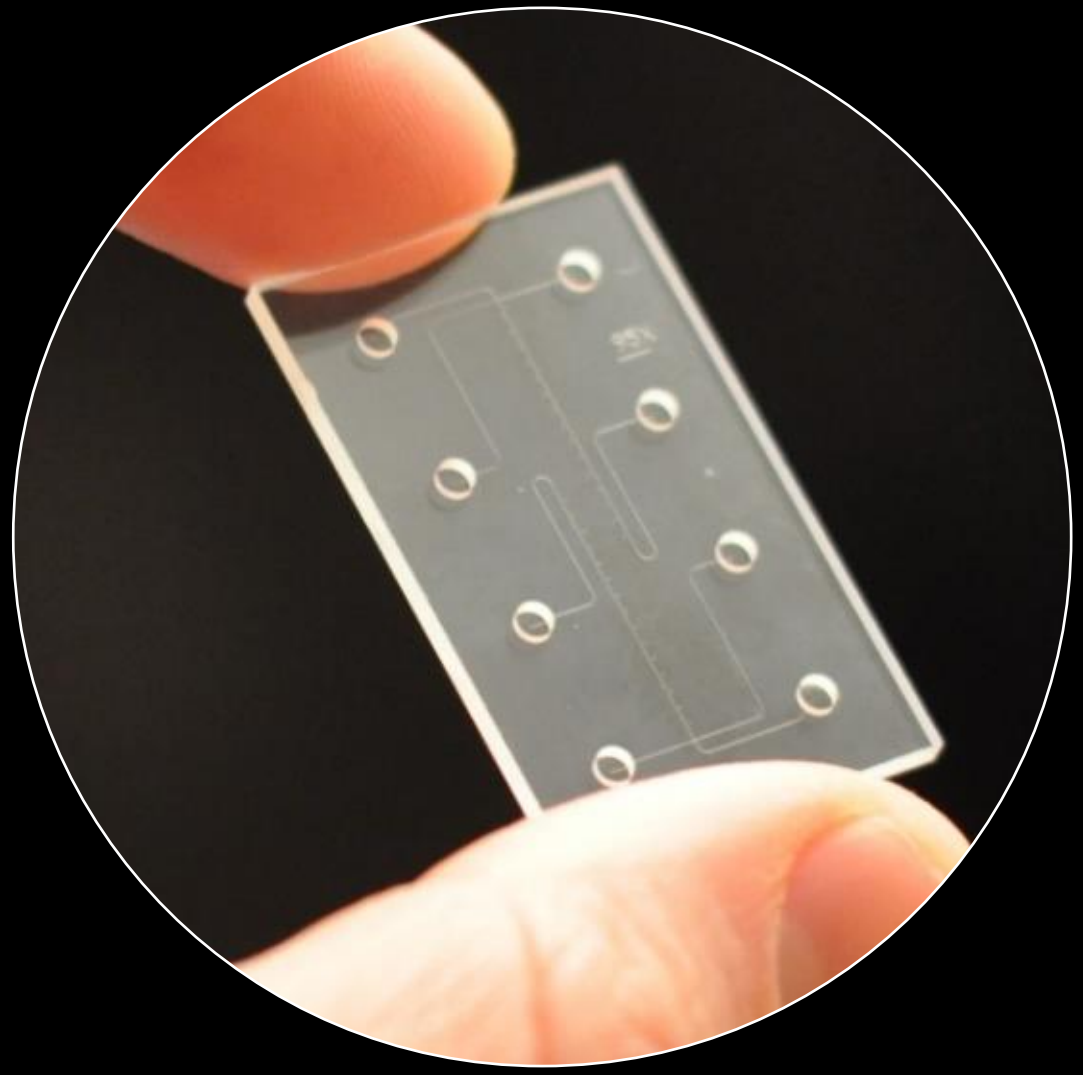
FLUTE

Fluidic Telescope Experiment

Edward Balaban, NASA Ames Research Center

~1-10 m



~1-10 μm

Optical Components

How it is done today

- Current methods for fabricating lenses rely on mechanical grinding, machining and polishing.

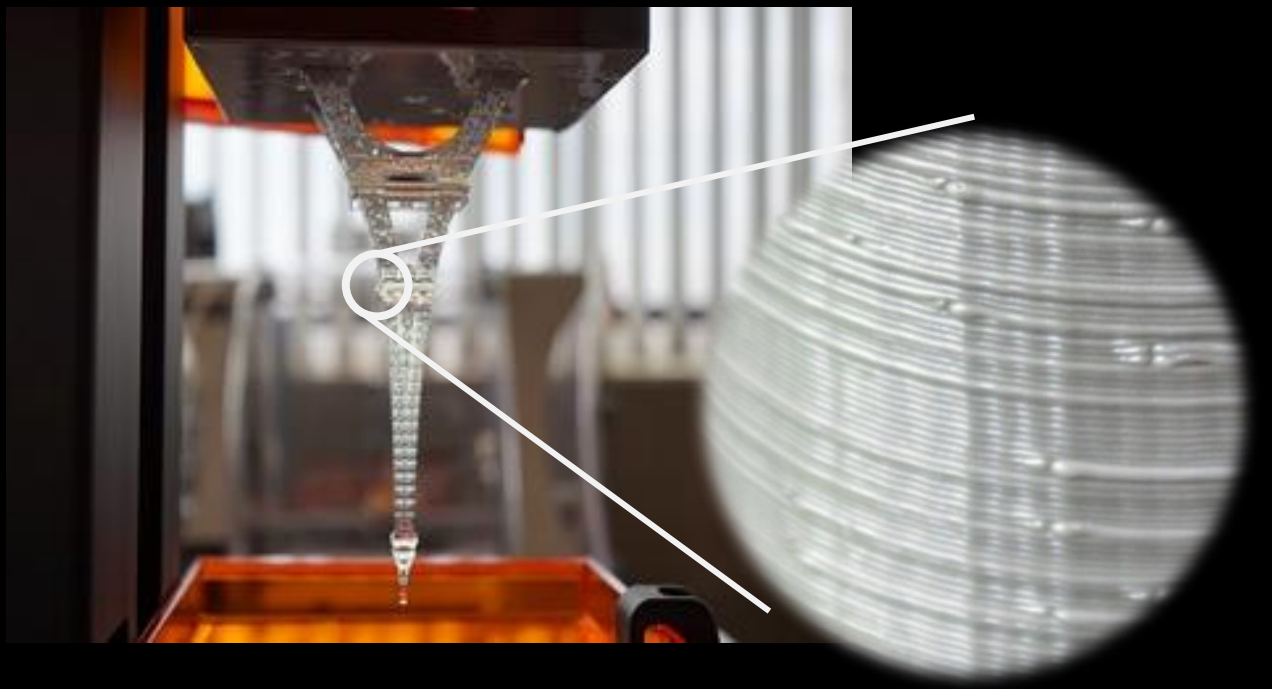
- These are complex processes that require specialized equipment, thus prohibiting rapid prototyping of optical components.

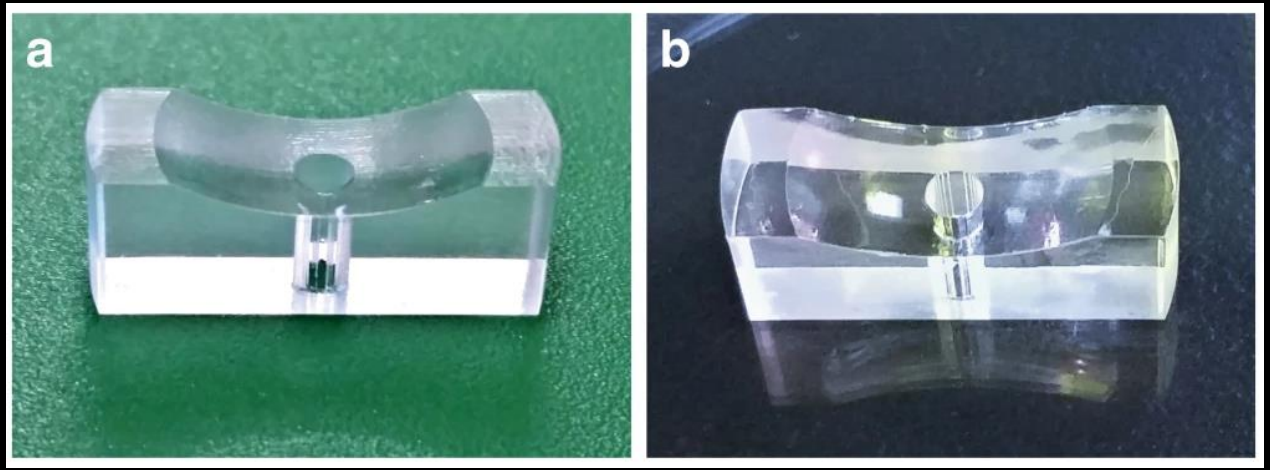
Laramy-K Optical

https://youtu.be/yL_02Cxkmxk

3D printing?

- 3D printing has revolutionized rapid prototyping and fabrication methods but cannot produce optical quality surfaces.
- Surface roughness typically on the scale of micro-meters. Can be improved by post processing, such as polymer coating.
- Printing time is long and scales with volume.





Vaidya, N., Solgaard, O. 3D printed optics with nanometer scale surface roughness. *Microsyst Nanoeng* **4,** 18 (2018).

This pesky, pesky gravity…

Capillary length

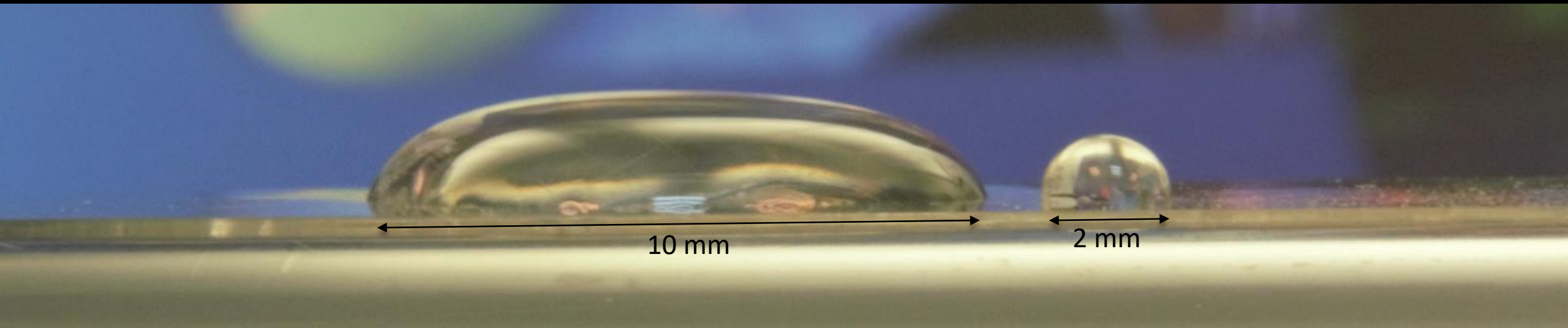
$$\ell_c = \sqrt{\gamma / \rho g}$$

Surface tension — γ; density — ρ; gravity — g

When droplet diameter is much smaller than ℓ_c, the droplet remains **spherical**.

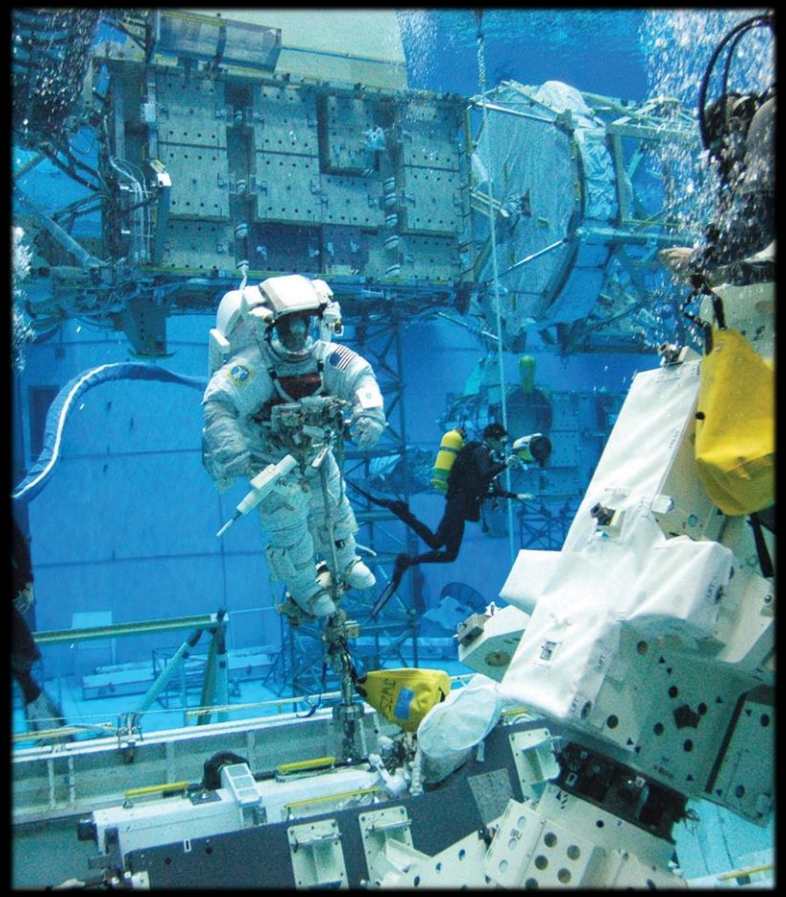
As the size approaches ℓ_c, the droplet becomes **squashed** by gravity.

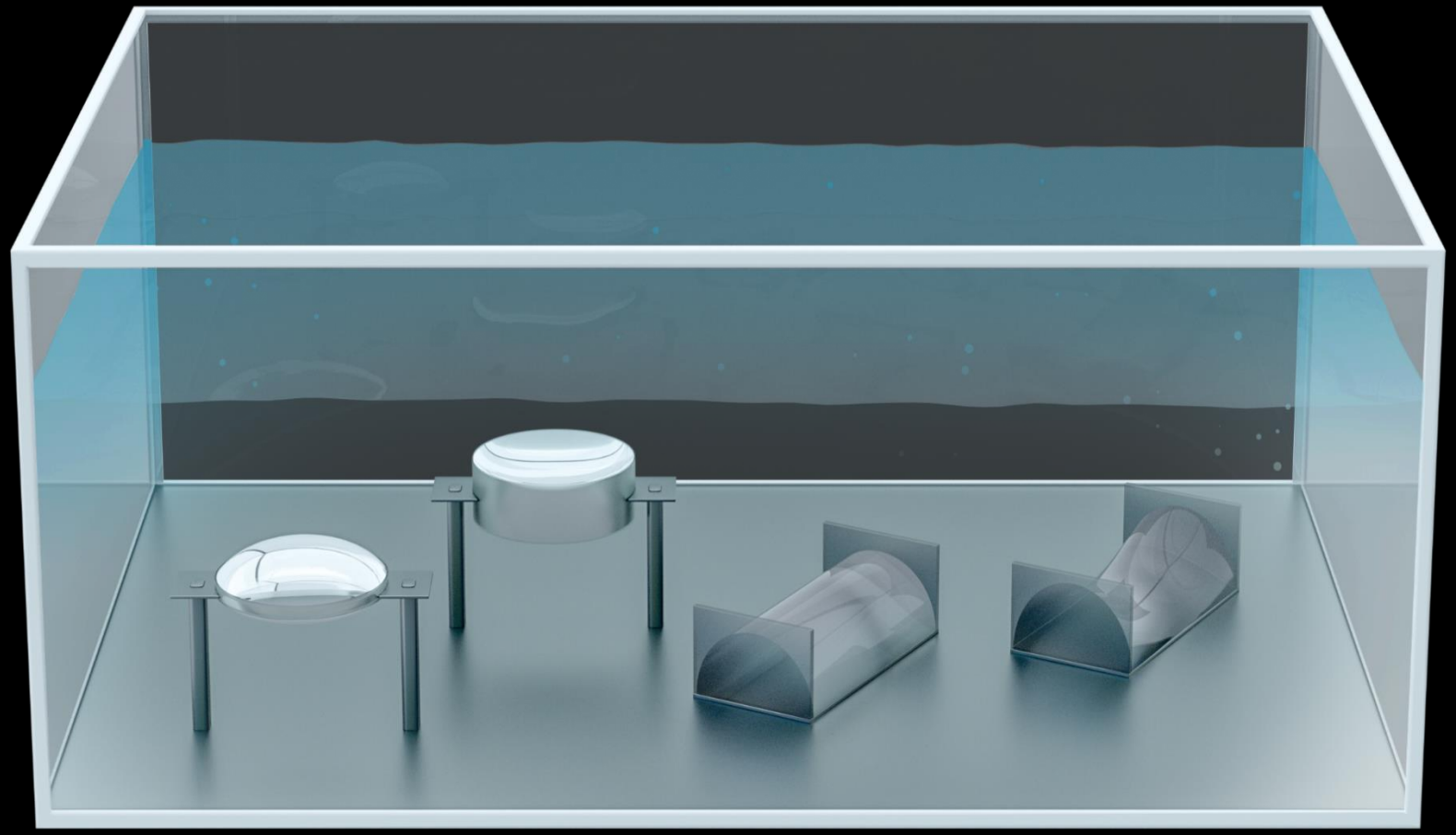
For most liquids $\ell_c < 2.5$ mm, so only tiny lenses can be made using this approach.



Our approach

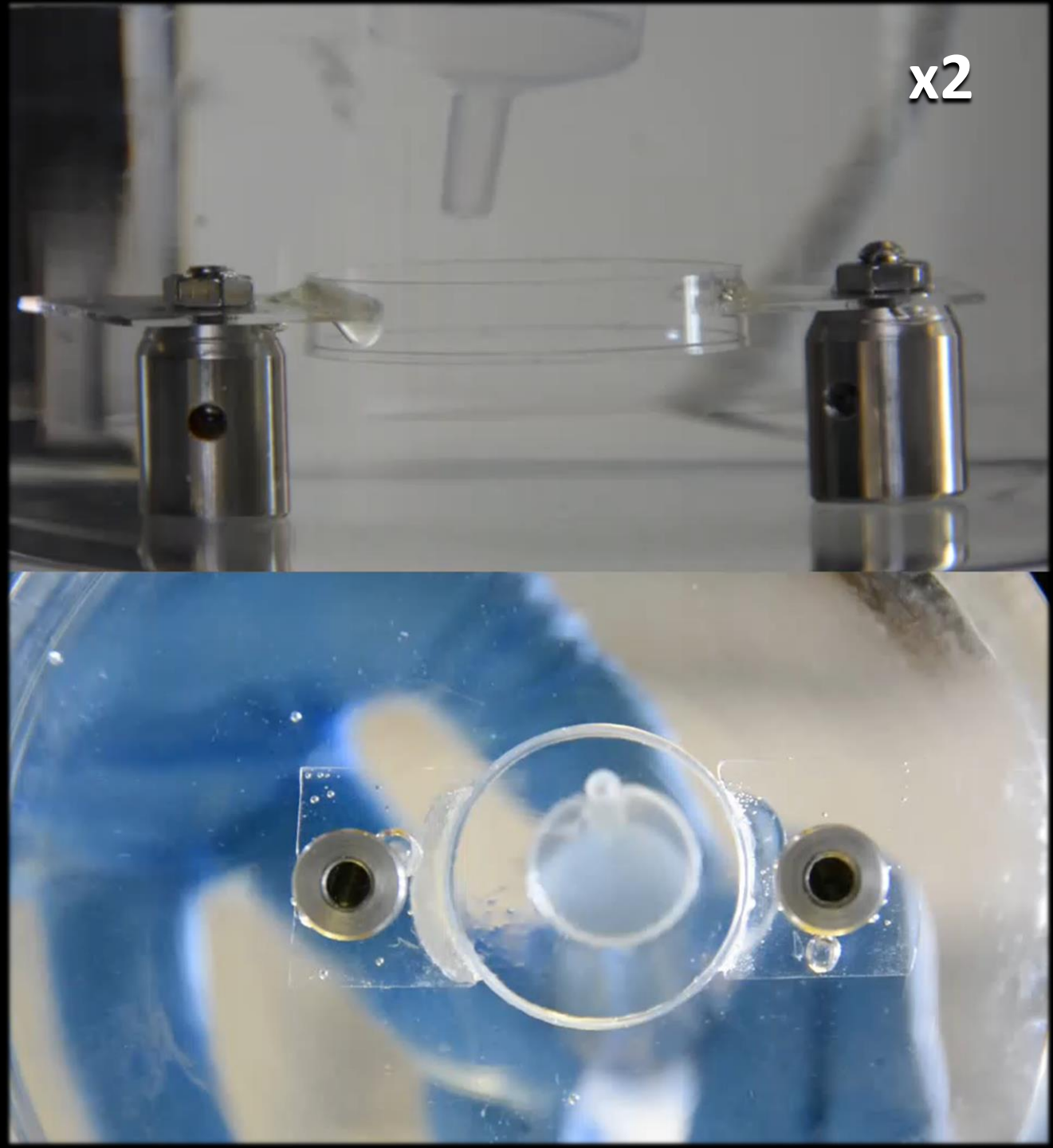
- We control the shape of the liquid lens by using a bounding surface, such as a ring, or a pad.
- At neutral density, the boundary condition dictates the resulting **constant mean curvature** surface.

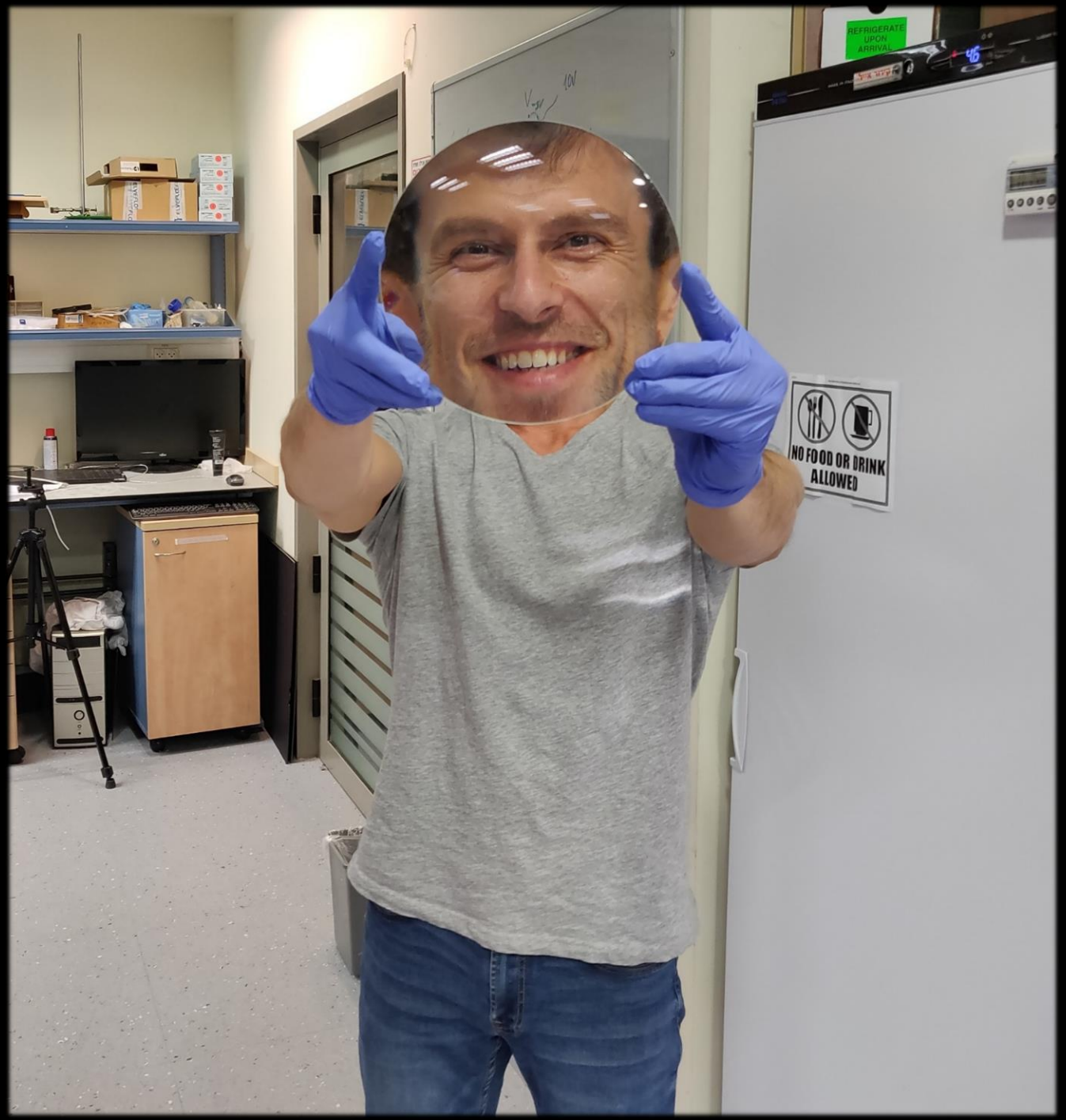




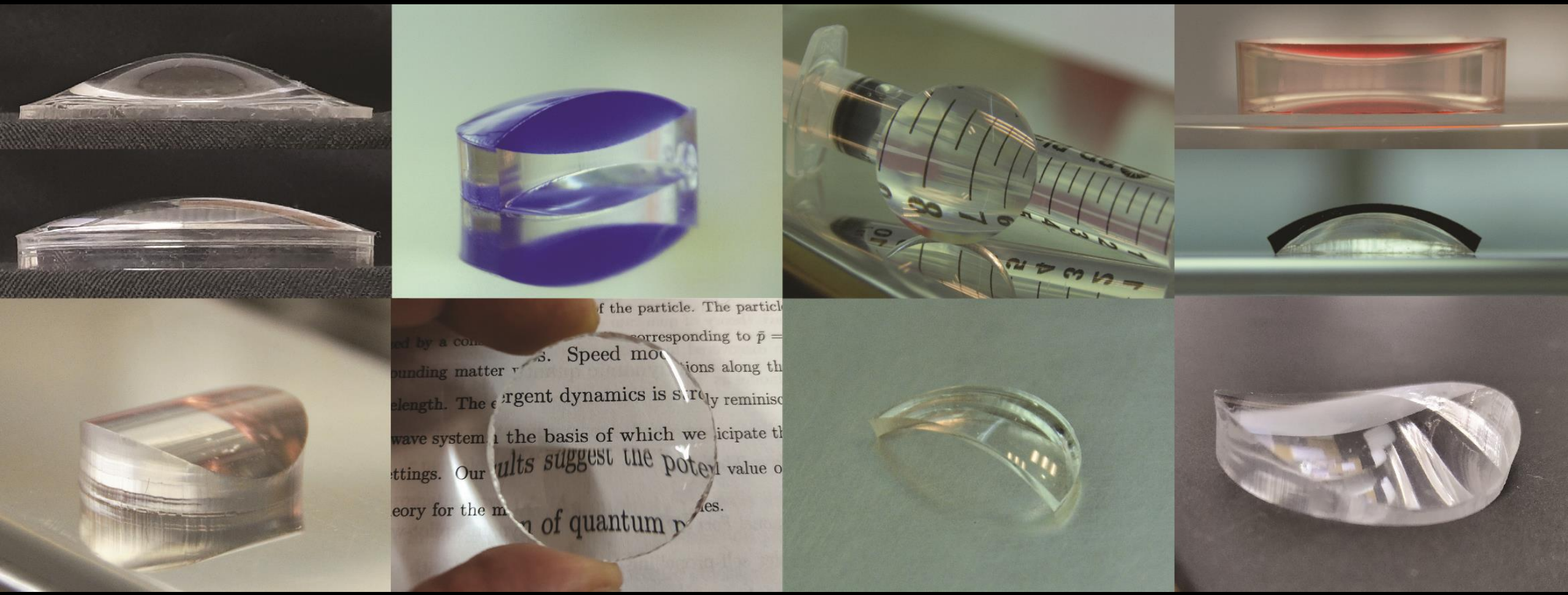
What does it look like?

- We inject a liquid polymer into a **bounding frame**, submerged in an immersion liquid environment.
- The material of the bounding frame is chosen such as to have **high affinity** to the injected polymer.
- After the injection, the polymer can be cured (**solidified**) to produce a high-quality solid lens.



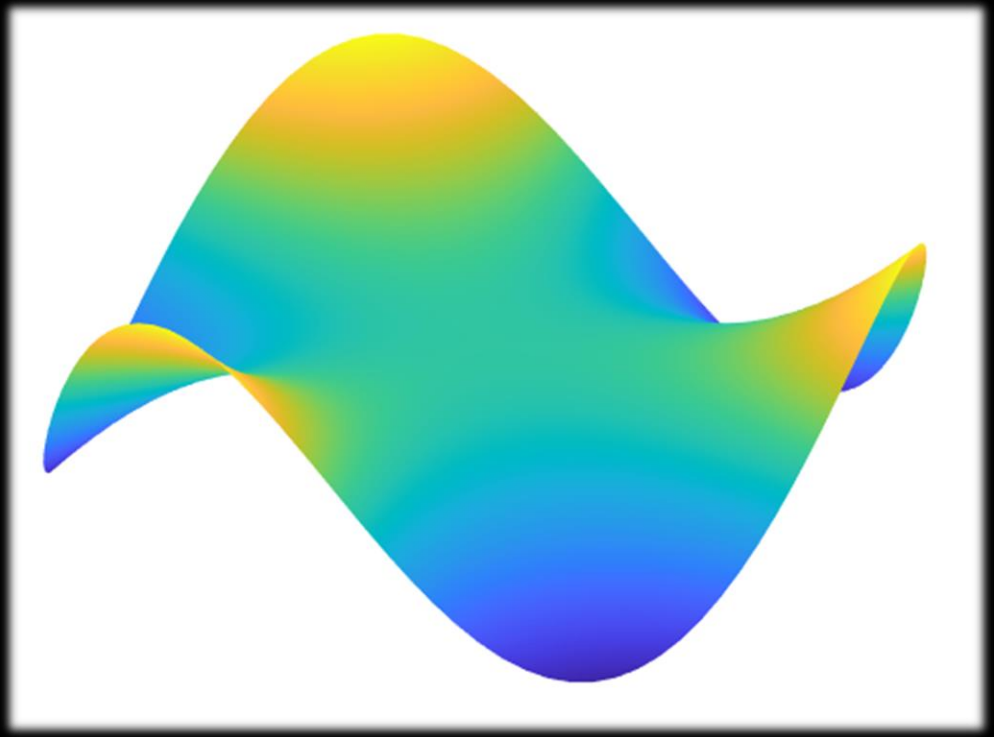

REFRIGERATE UPON ARRIVAL
NO FOOD OR DRINK ALLOWED

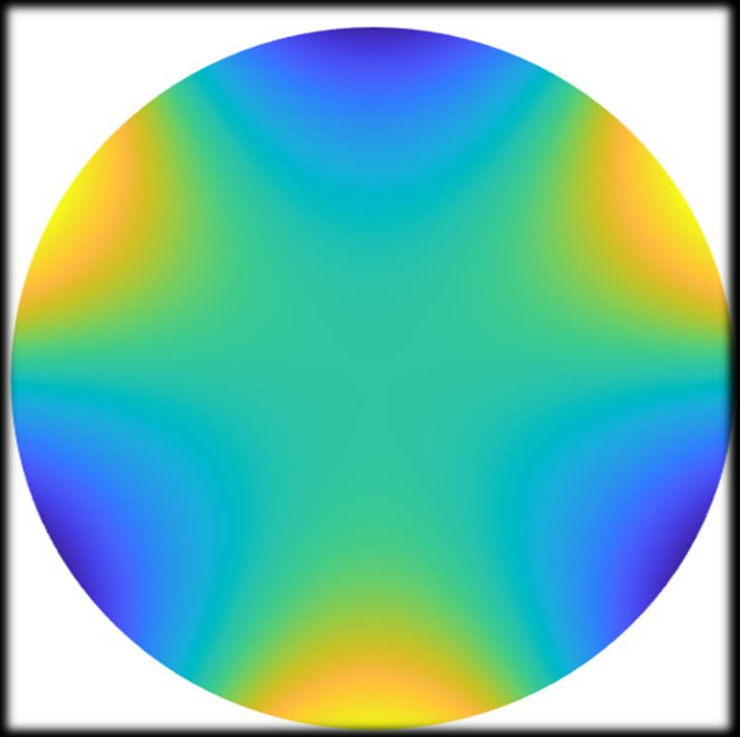
Examples of other optical geometries



Freeform optics – example

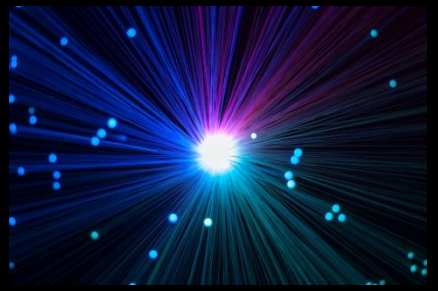
Theory and experiment at neutral buoyancy, for a non-axisymmetric solution given the boundary function: $f(\Theta) = b_0 + b_1 \sin(3\Theta)$



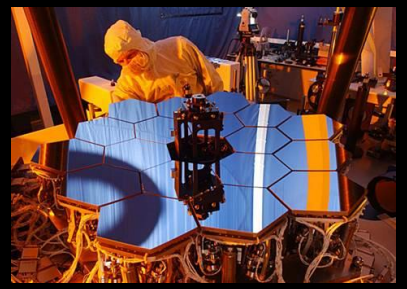


Surface quality

- Due to the natural smoothness of liquid interfaces, the resulting lenses are of excellent surface quality. DHM surface roughness of ~~RMS = 5.5 nm~~. RMS=0.75 nm (AFM 20 µm x 20 µm)
- Fabrication in a clean room will likely further improve surface quality.
- A wide variety of suitable polymers already exists, more can be engineered.



High power lasers < 1nm



JWST mirror 20 nm

Precision optics 3-5 nm

Eyeglasses 100 nm

Going big

The method is scale invariant

- Large optical components for **telescopes.**
- The 1.57 m diameter lens in the Large Synoptic Survey Telescope (LSST) fabricated at Lawrence Livermore National Lab (LLNL), cost ~$20 M, and took 5 years.
- Our method can potentially produce larger lenses at a fraction of their current price and in a fraction of the current manufacturing time.

https://www.llnl.gov/news/world%E2%80%99s-largest-optical-lens-shipped-slac

Photo by Farrin Abbott / SLAC National Accelerator Laboratory.

Let's go to space!

Capillary length $\ell_c = \sqrt{\frac{\gamma}{|\Delta\rho| g}}$

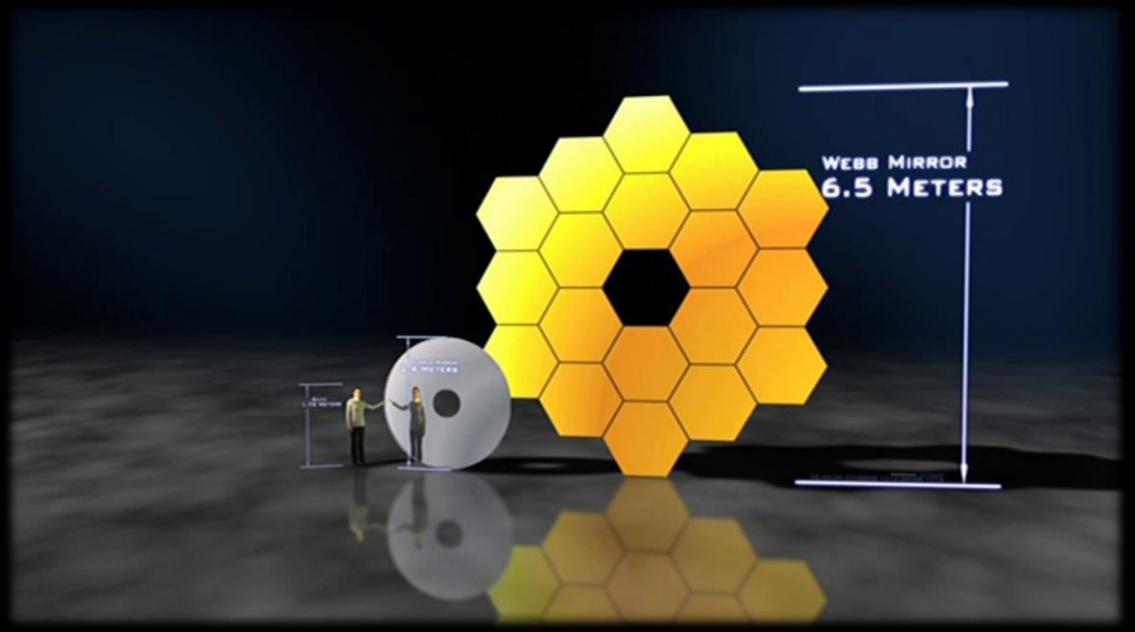
Neutral buoyancy

Eliminating the effect of gravity

- Can be solidified.
- Can remain in its liquid form.
- This allows for dynamic control of the focal length (by changing the volume of the lens liquid) or overall geometry and may result in an even better surface quality.

Technology need – space telescopes

- Performance of space telescopes directly depends on the size (aperture) of their optical components.
- NASA's long-term astrophysics goals require ever-larger apertures in space.
- Current approaches are expensive (JWST: ~$10B), result in long development times (JWST: 20+ years), and are generally reaching their limits.



The team

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Technion / MIT

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Valeri Frumkin

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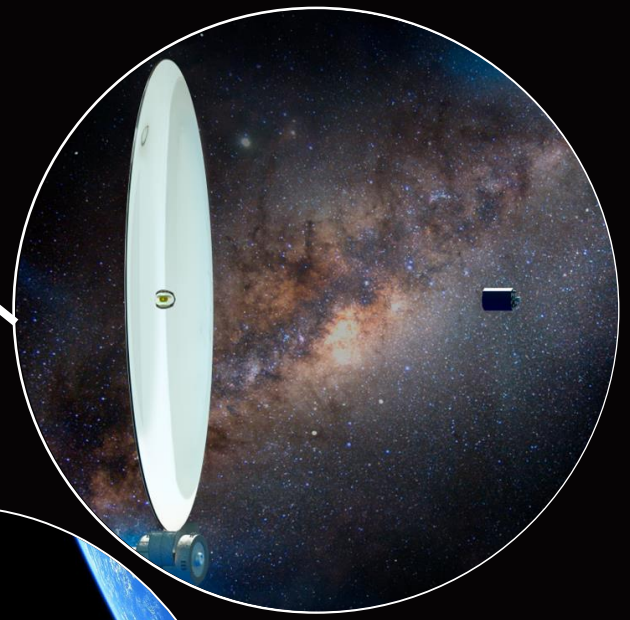
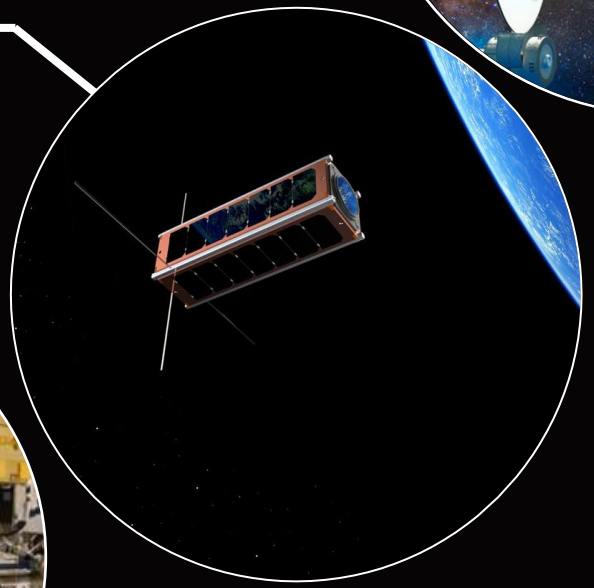
From lab to space — technology maturation steps

Large space observatory



Smallsat demo



ISS

Parabolic flights

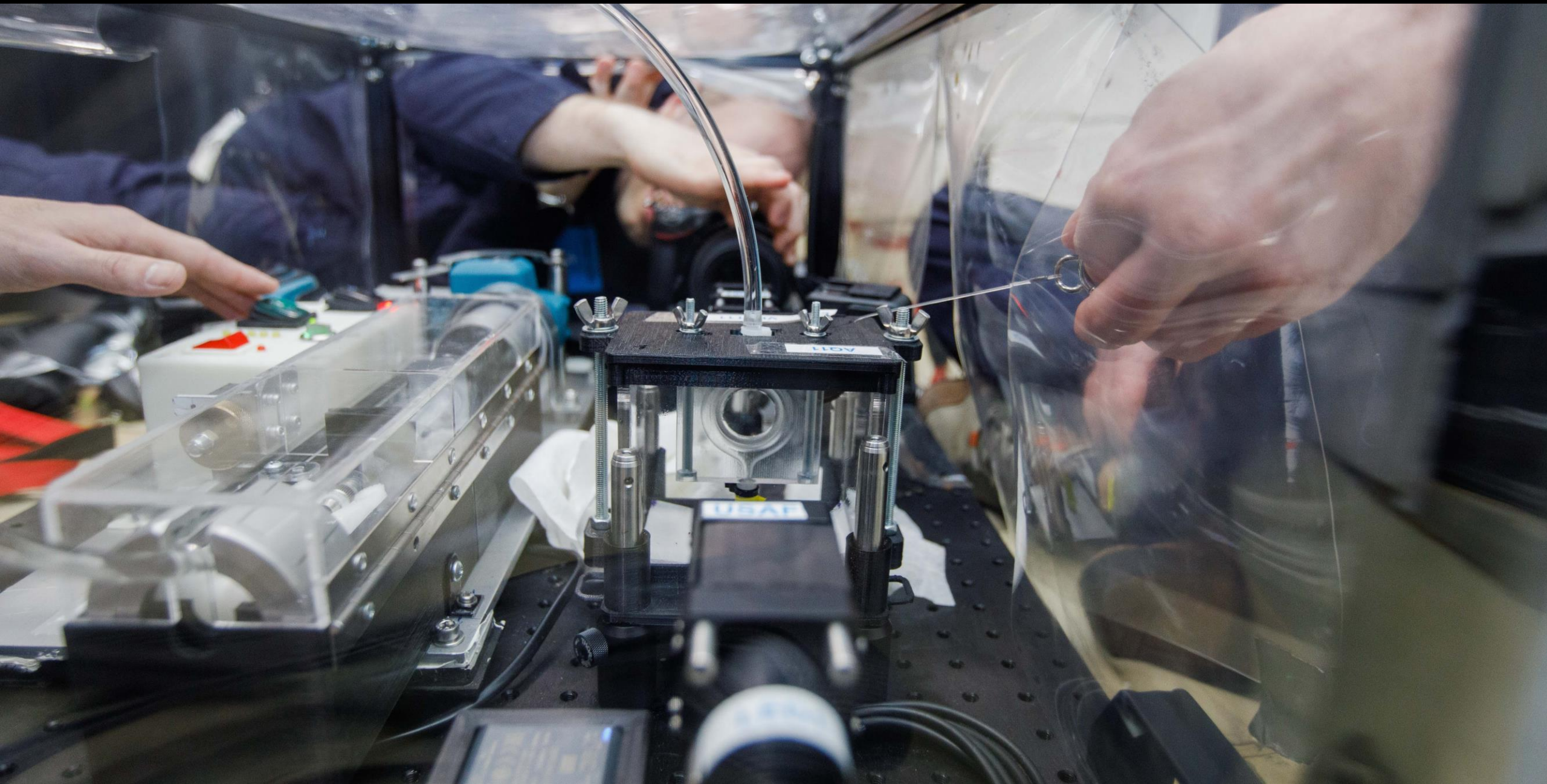
Lab

December 2021 parabolic flight tests

The crew

fluidic.technology
BERCOVICI FLUIDIC TECHNOLOGIES
NASA
Faculty of Mechanical Engineering
zero G

Lens formation

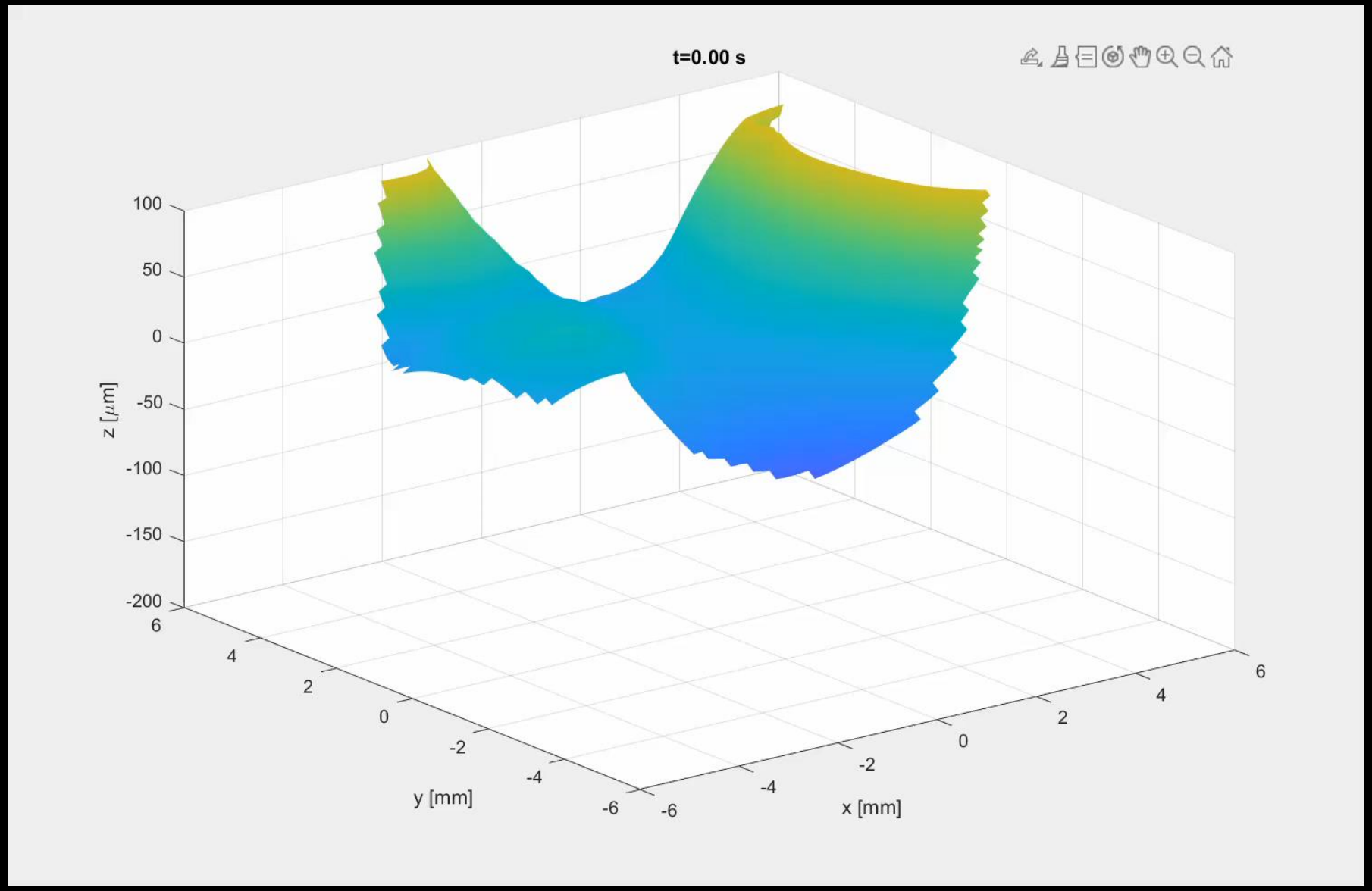


“WE HAVE AN IMAGE !”

Image of an illuminated target, taken through the liquid lens.

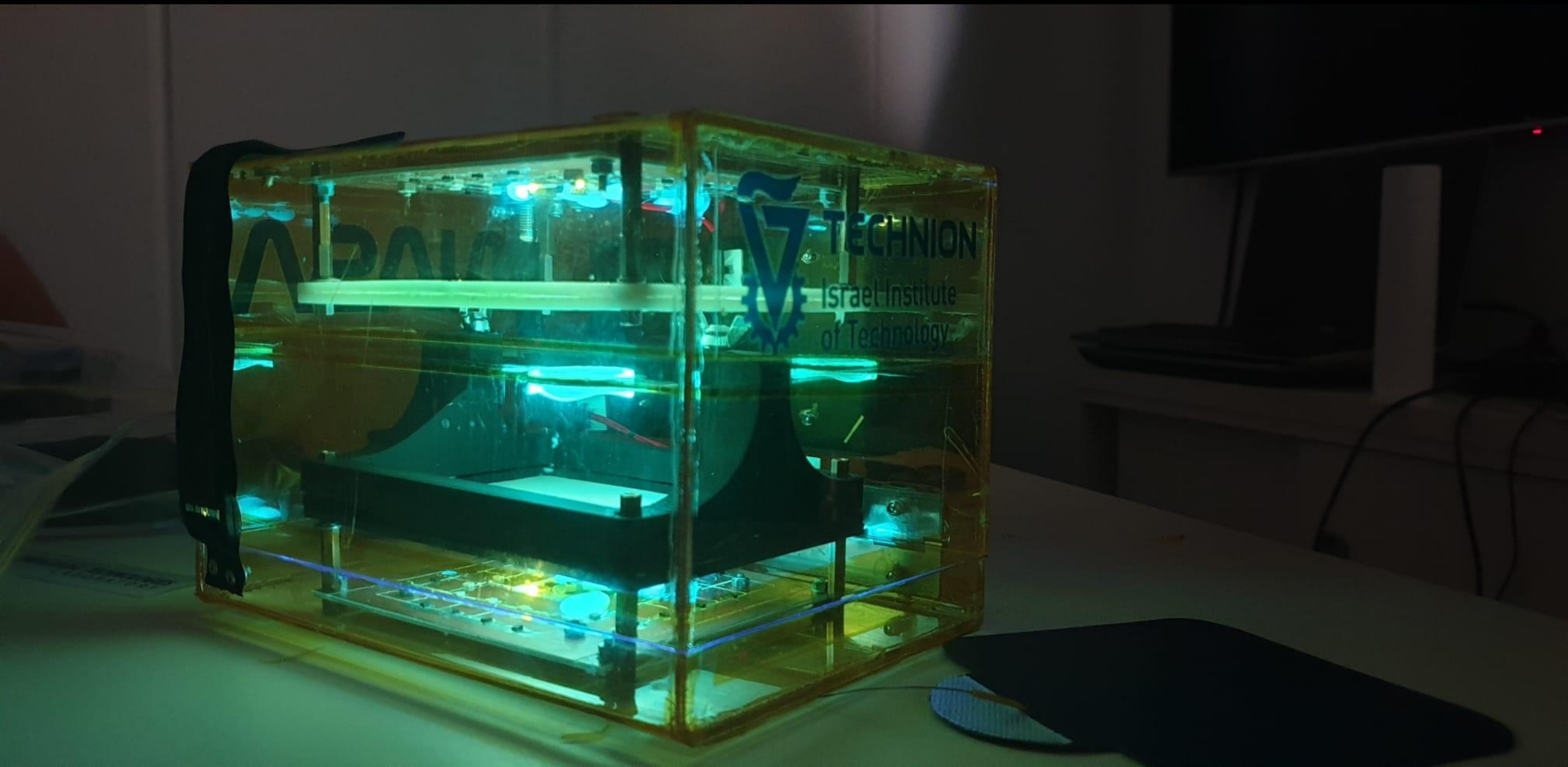
125 μm

Lens wavefront measurements



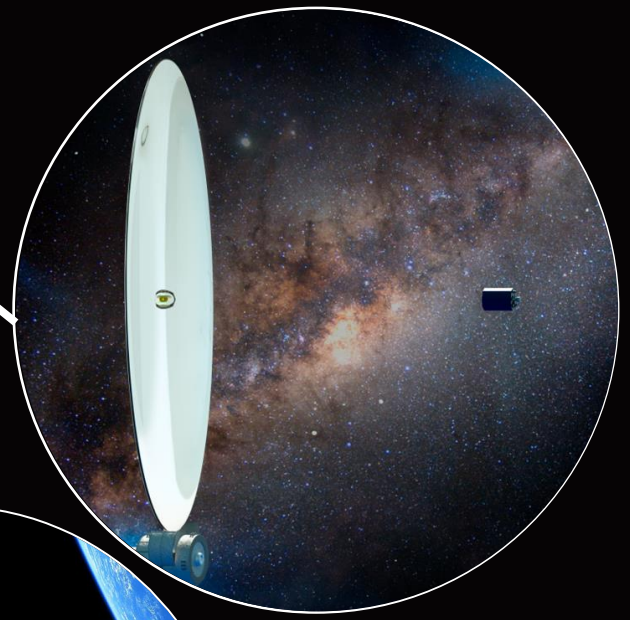
ISS Experiments

Experimental hardware



From lab to space — technology maturation steps

Large space observatory



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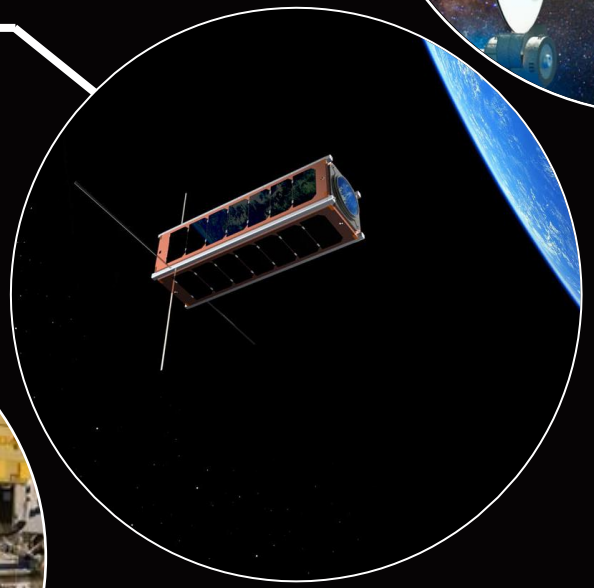
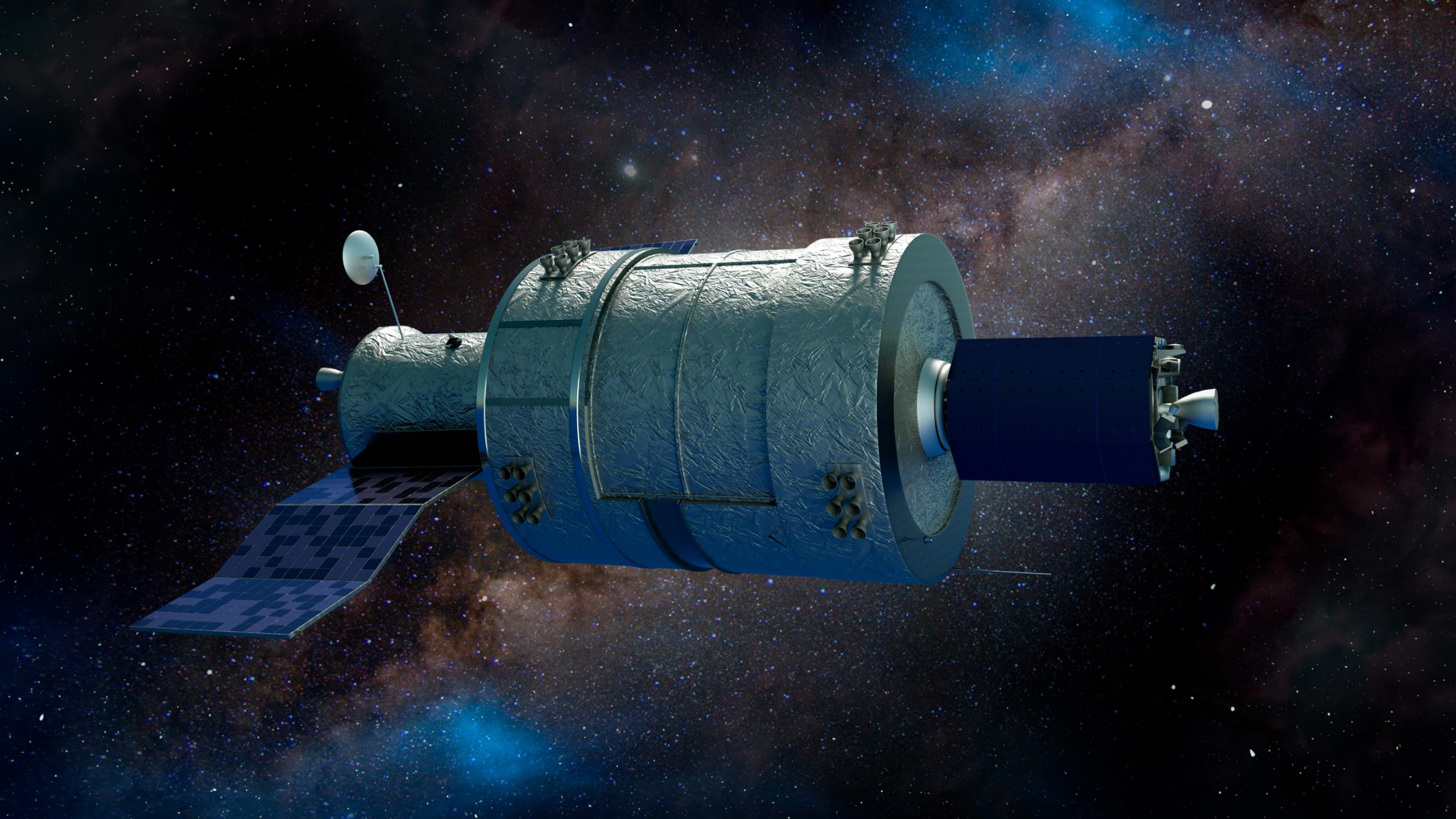
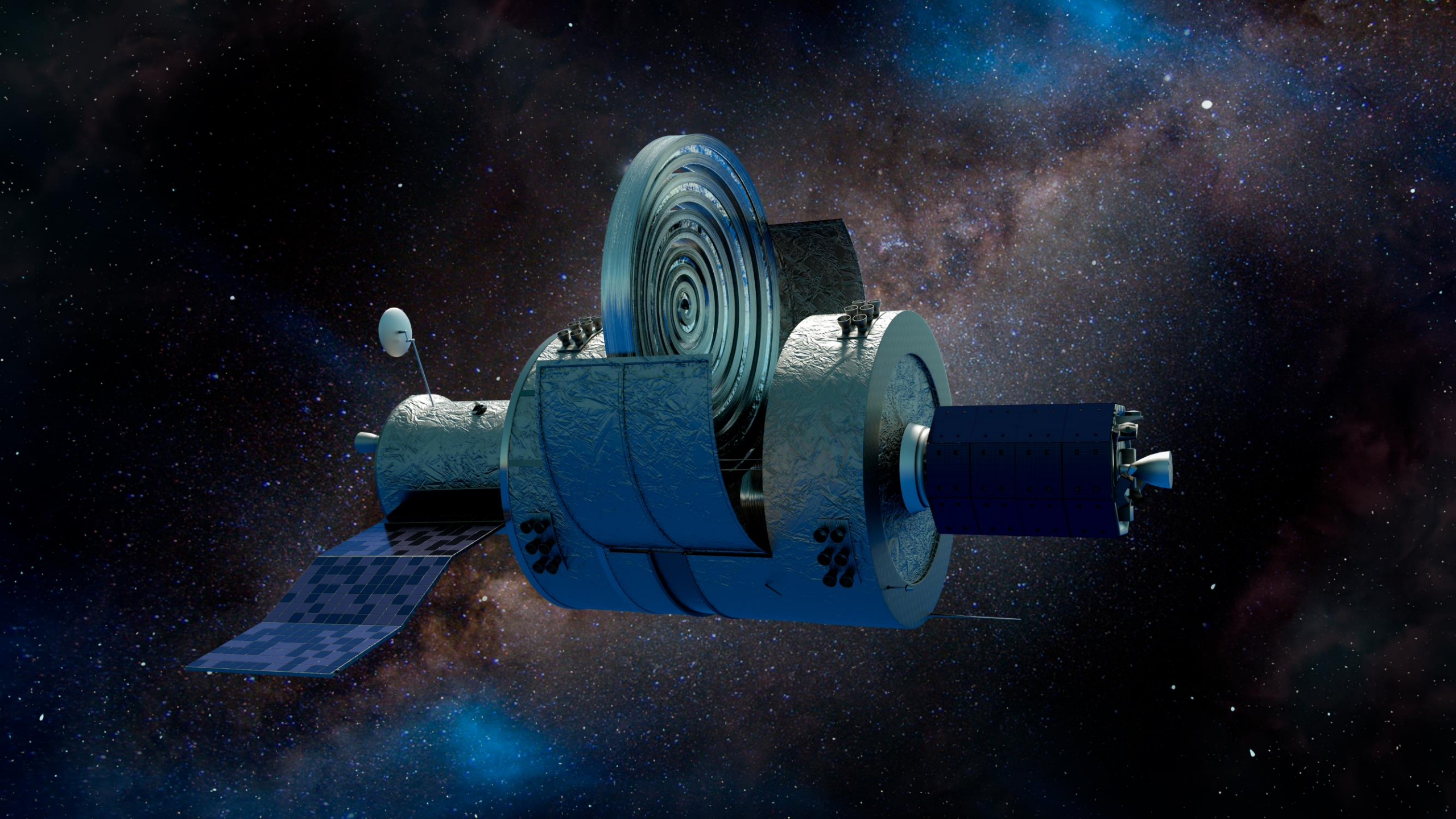


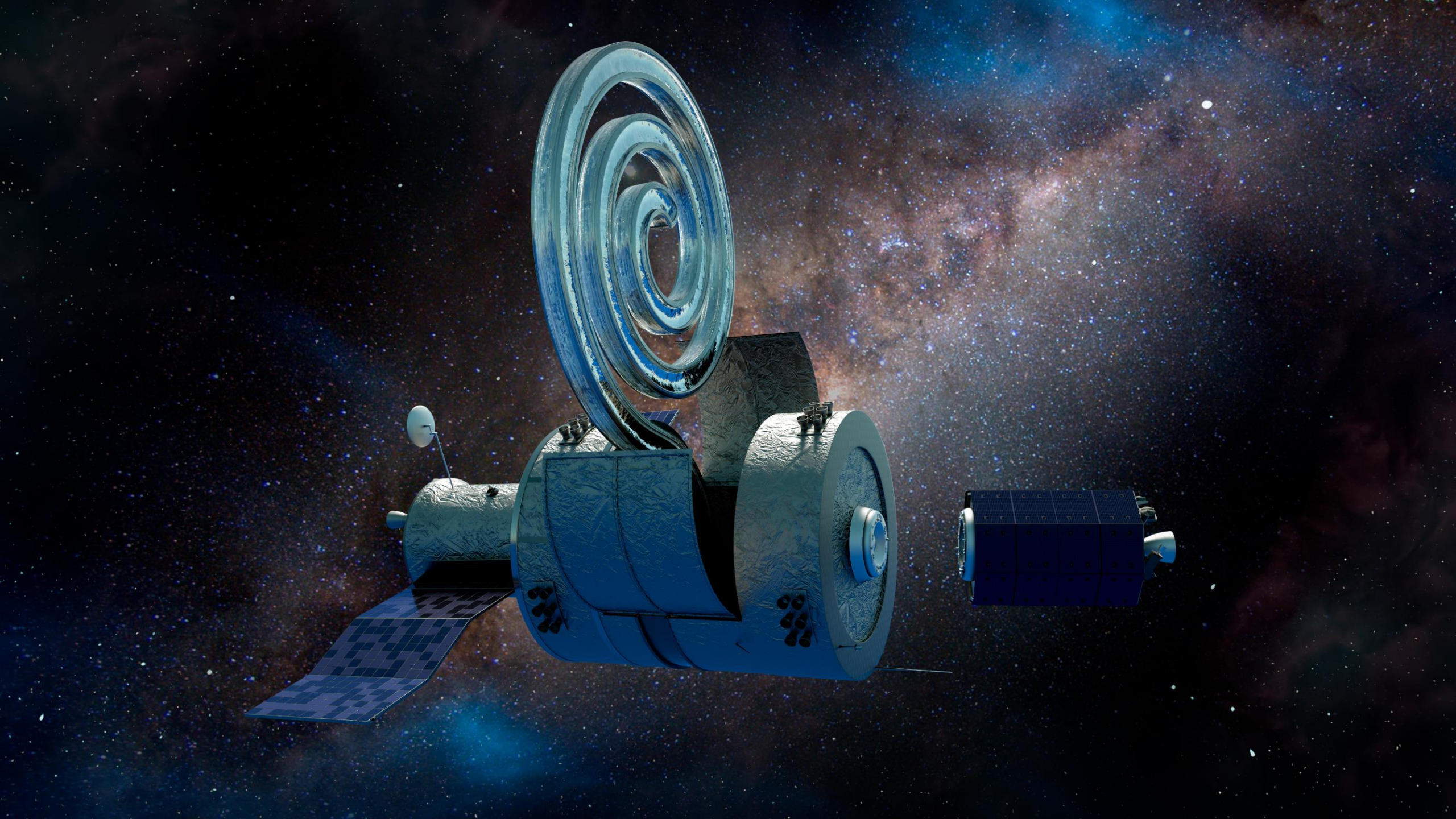
ISS

Parabolic flights

Lab







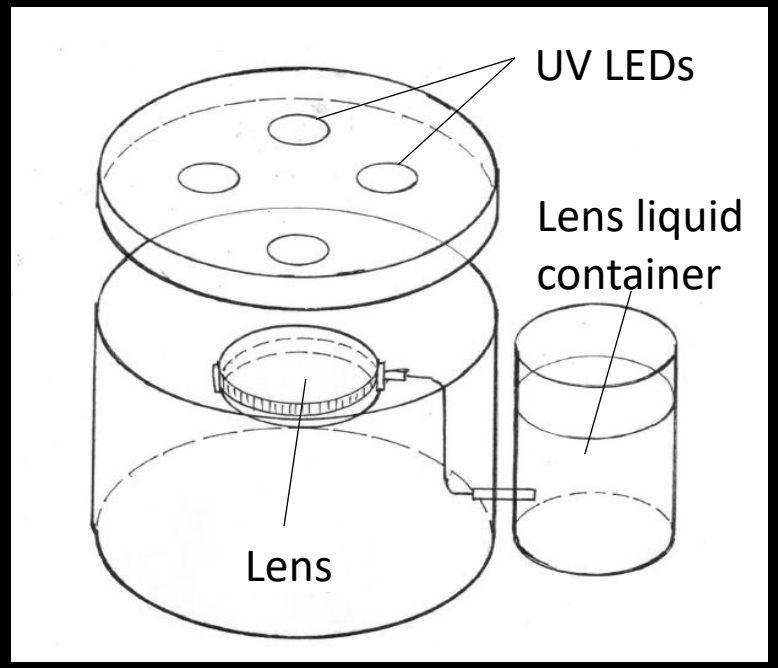
Other potential applications

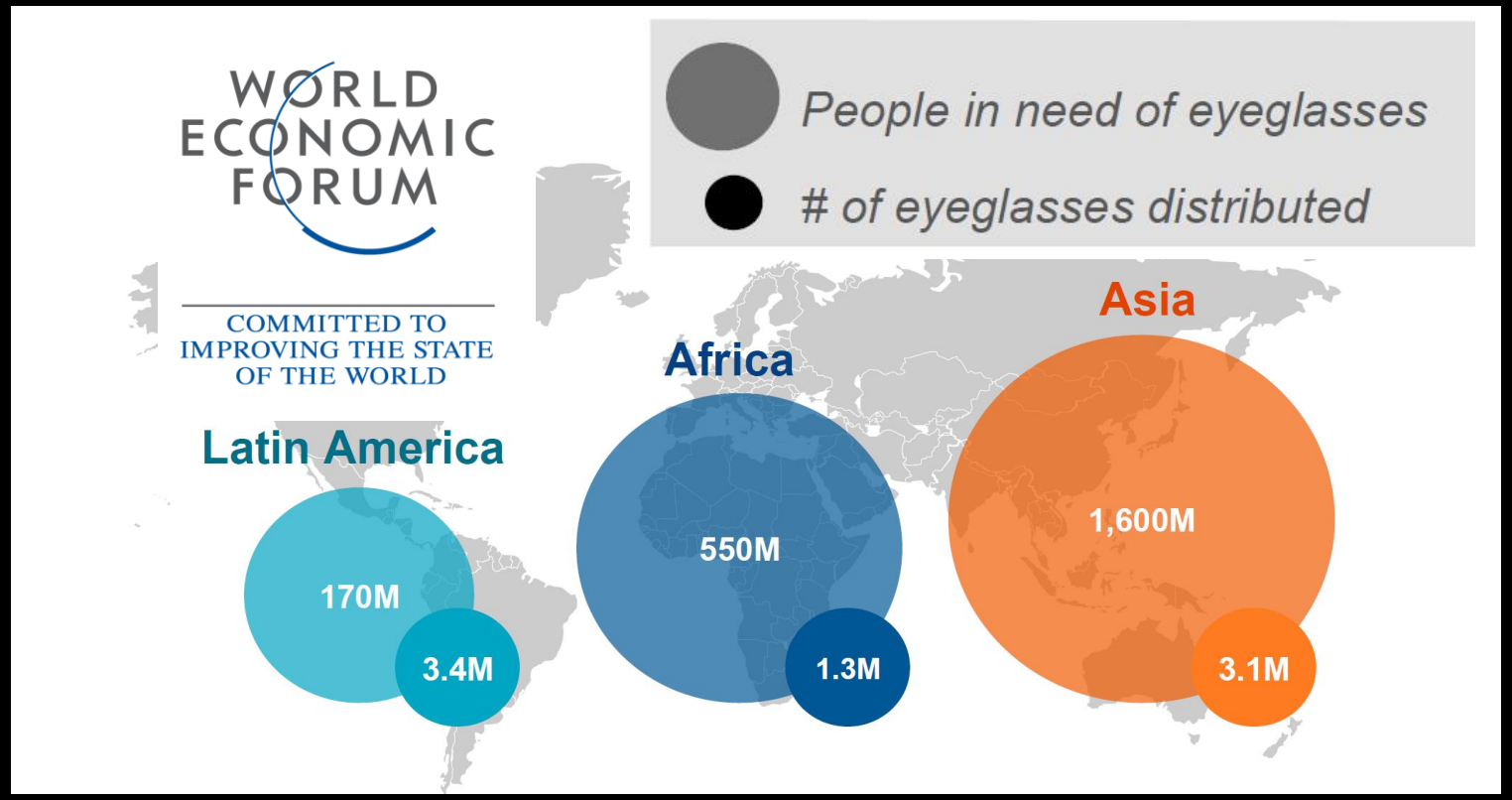
- On orbit manufacturing of high-quality optics for
  - Power collection and transmission equipment
  - Lasers
  - Optical communication equipment

- On orbit manufacturing of thermal control components
- Can be complementary to 3D printing and other additive manufacturing techniques

On Earth

- The LensMaker – a device able to fabricate lenses on demand in a matter of minutes.
- Create lenses with spherical and cylindrical corrections, and in the future even multifocal lenses (freeform).
- Enable accesses to prescription eyeglasses in low resource settings.





Funding

US:

- ARC Center Innovation Fund (STMD)
- GFRC Center Innovation Fund (STMD)
- Flight Opportunities Program (STMD)
- ISS National Laboratory

Israel:

- Technion CSST Fund
- The Ramon Foundation
- The Israeli Space Agency
- The Israeli Ministry of Innovation, Science and Technology
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Thank you!

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