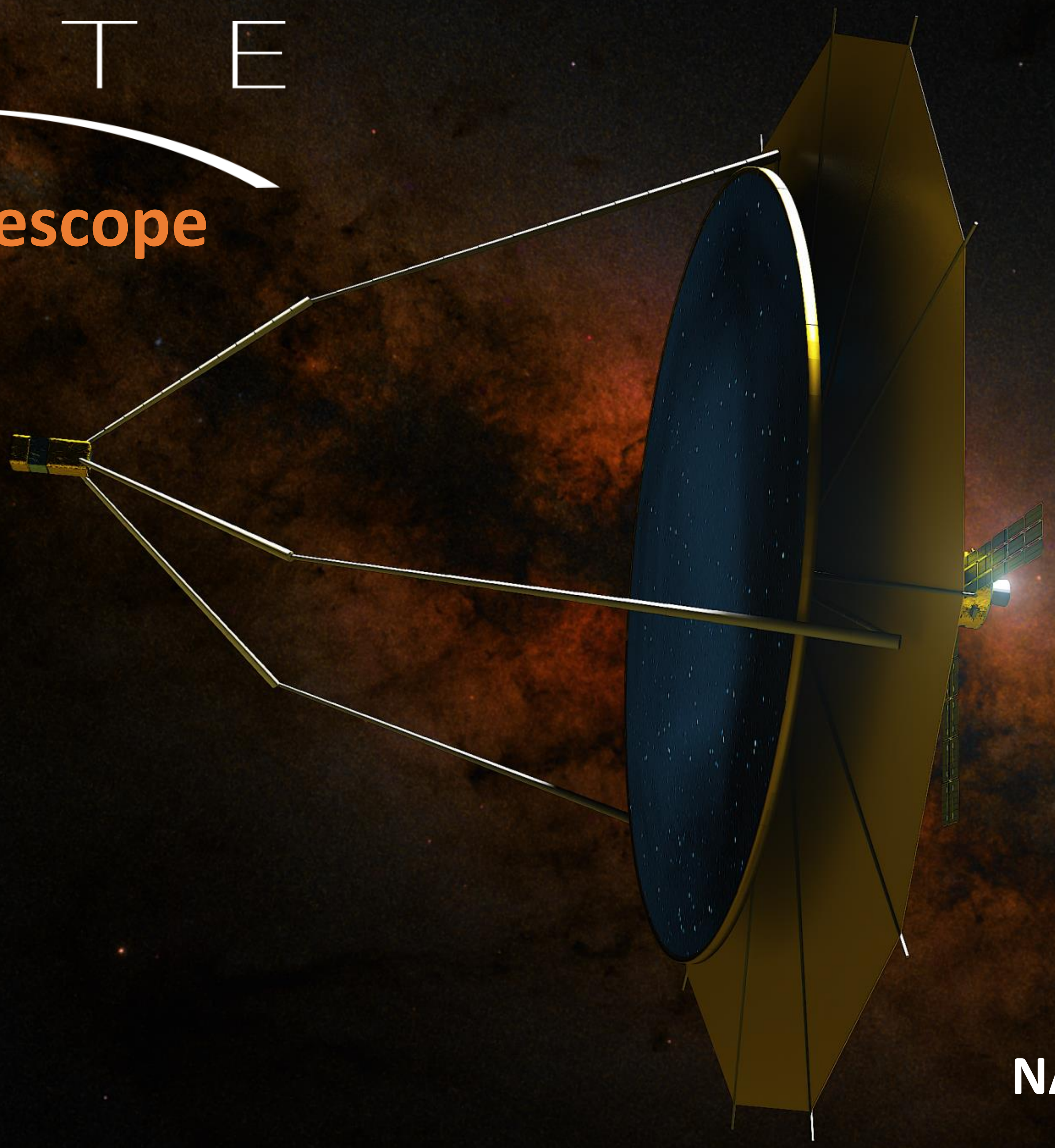
F L U T E

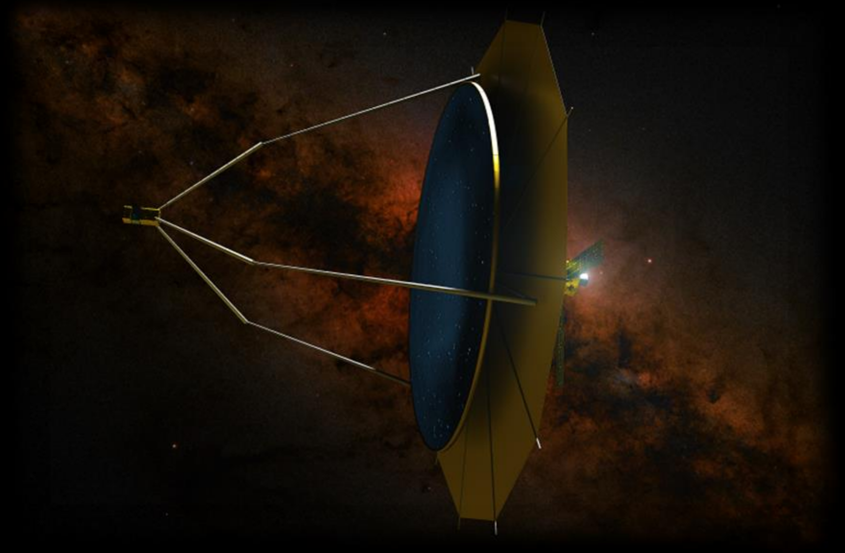
Fluidic Telescope



Edward Balaban
NASA Ames Research Center
edward.balaban@nasa.gov

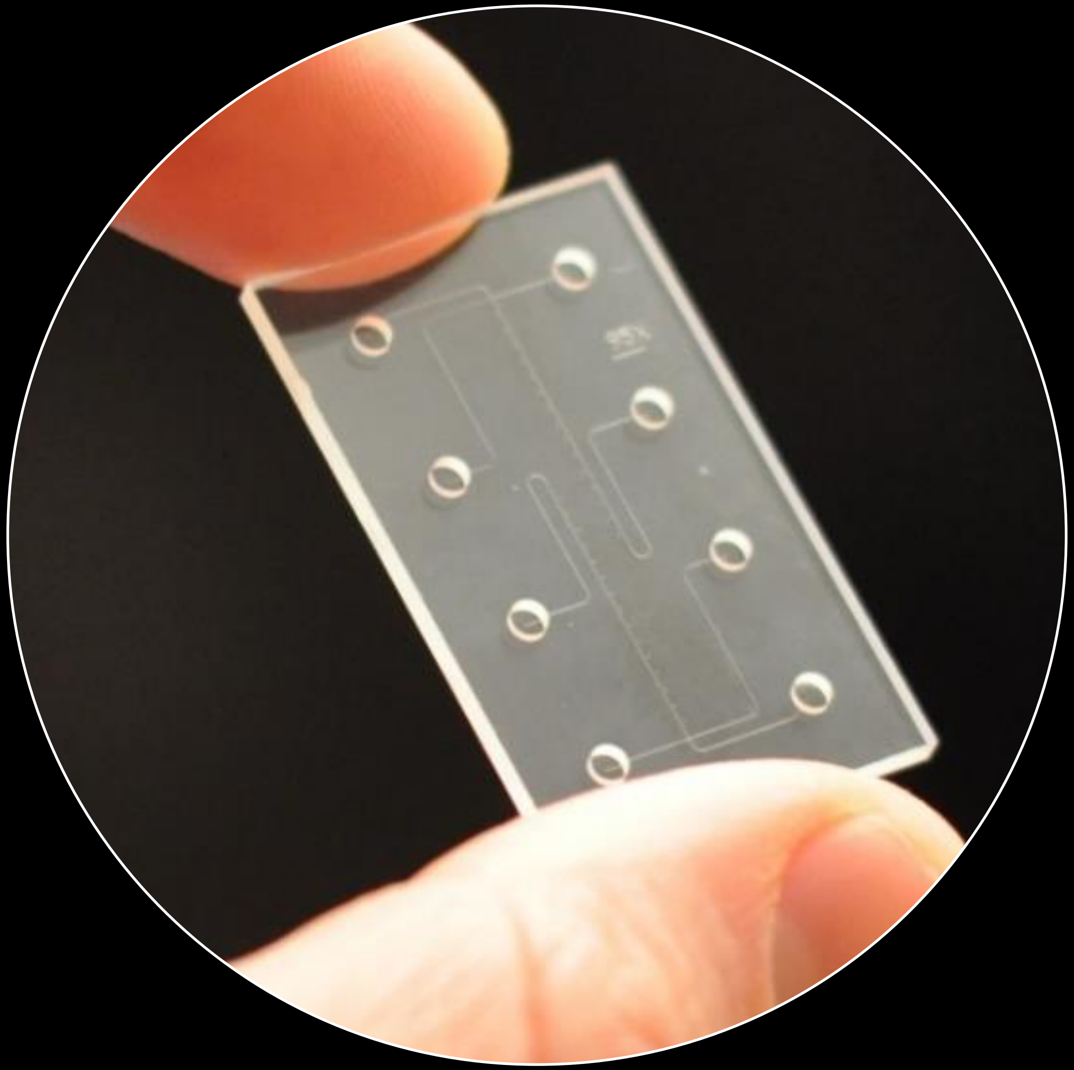
What is FLUTE?

- FLUTE is a concept for a space-based observatory with a large-aperture, unsegmented liquid primary mirror.
- The mirror is created via a novel approach based on fluidic shaping in microgravity.
- The approach enables a molecularly smooth, self-healing mirror surface and can lead to telescope mirrors measuring in tens or even hundreds of meters in diameter.
- FLUTE can help address some of the highest priority objectives of the Astro2020 survey: Earth-like exoplanets, first generation stars, and early galaxies.
- FLUTE is a joint effort between NASA and Technion — Israel Institute of Technology



How it started

~1-10 m



~1-10 μm

This pesky, pesky gravity…

Capillary length

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

Surface tension

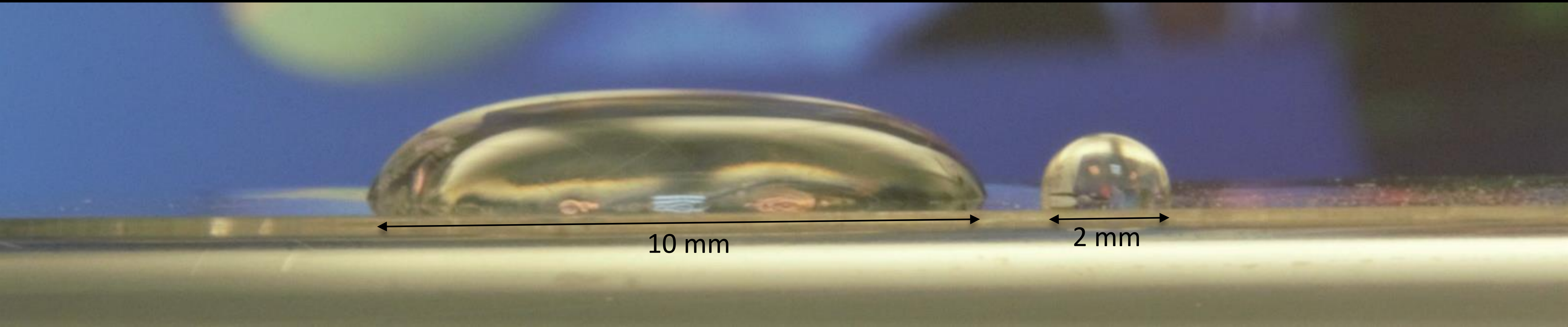
gravity

density

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

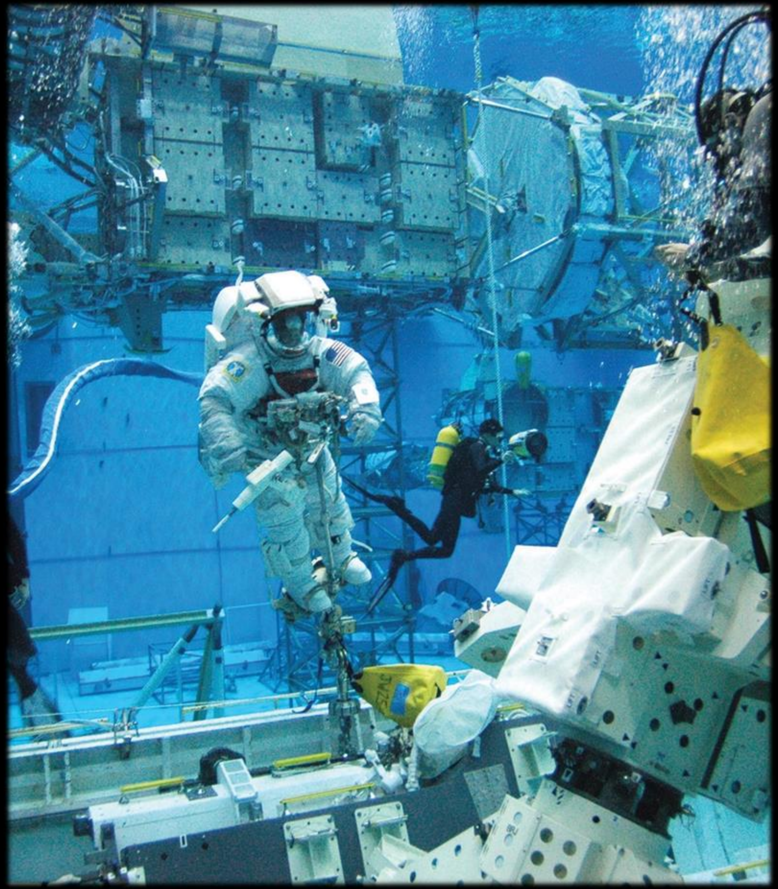
As the size approaches ℓ_c, the droplet becomes **squashed** by gravity.

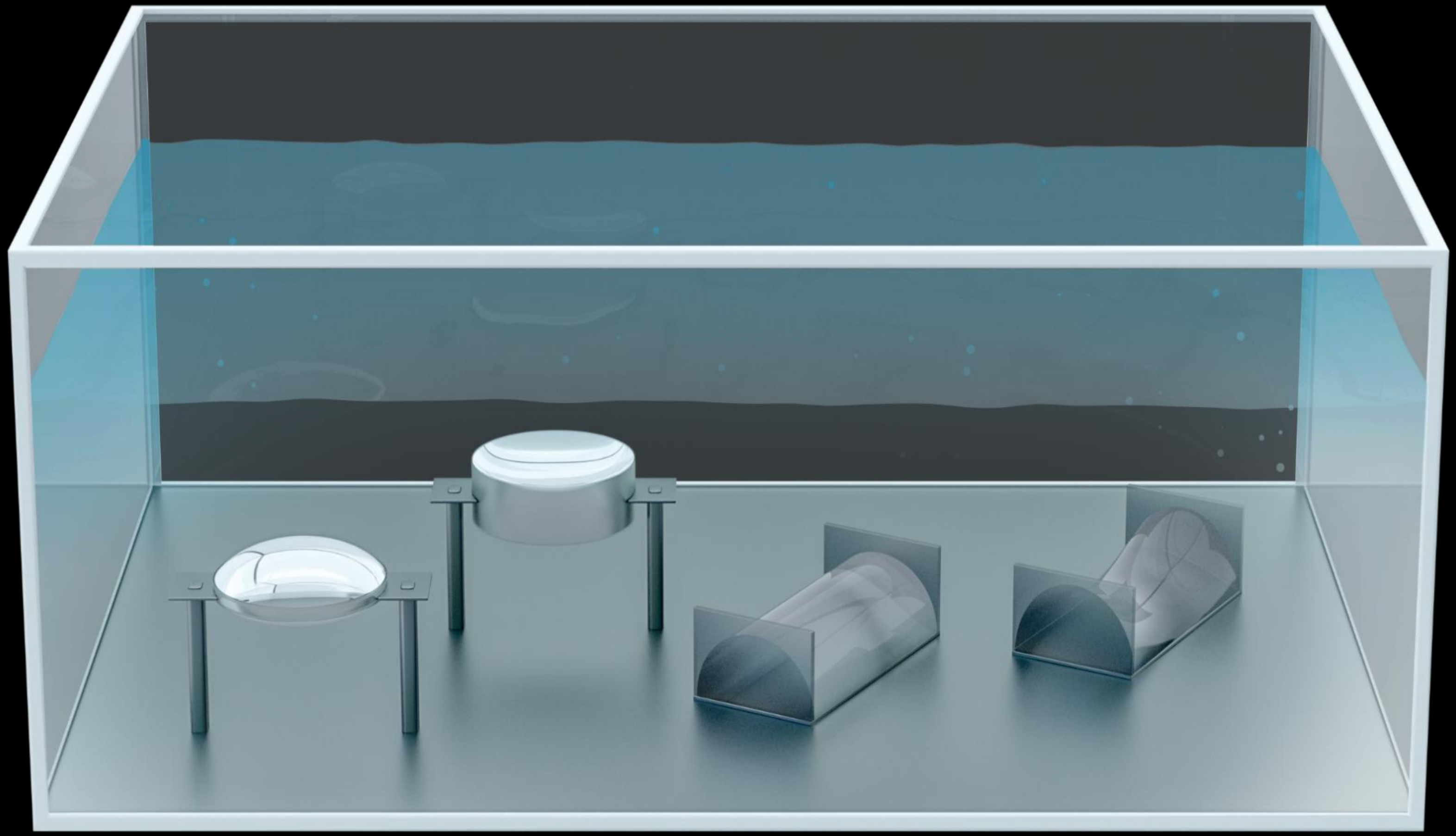
For most liquids $\ell_c < 2.5$ mm, so only tiny lenses can be made using this approach.



Our approach

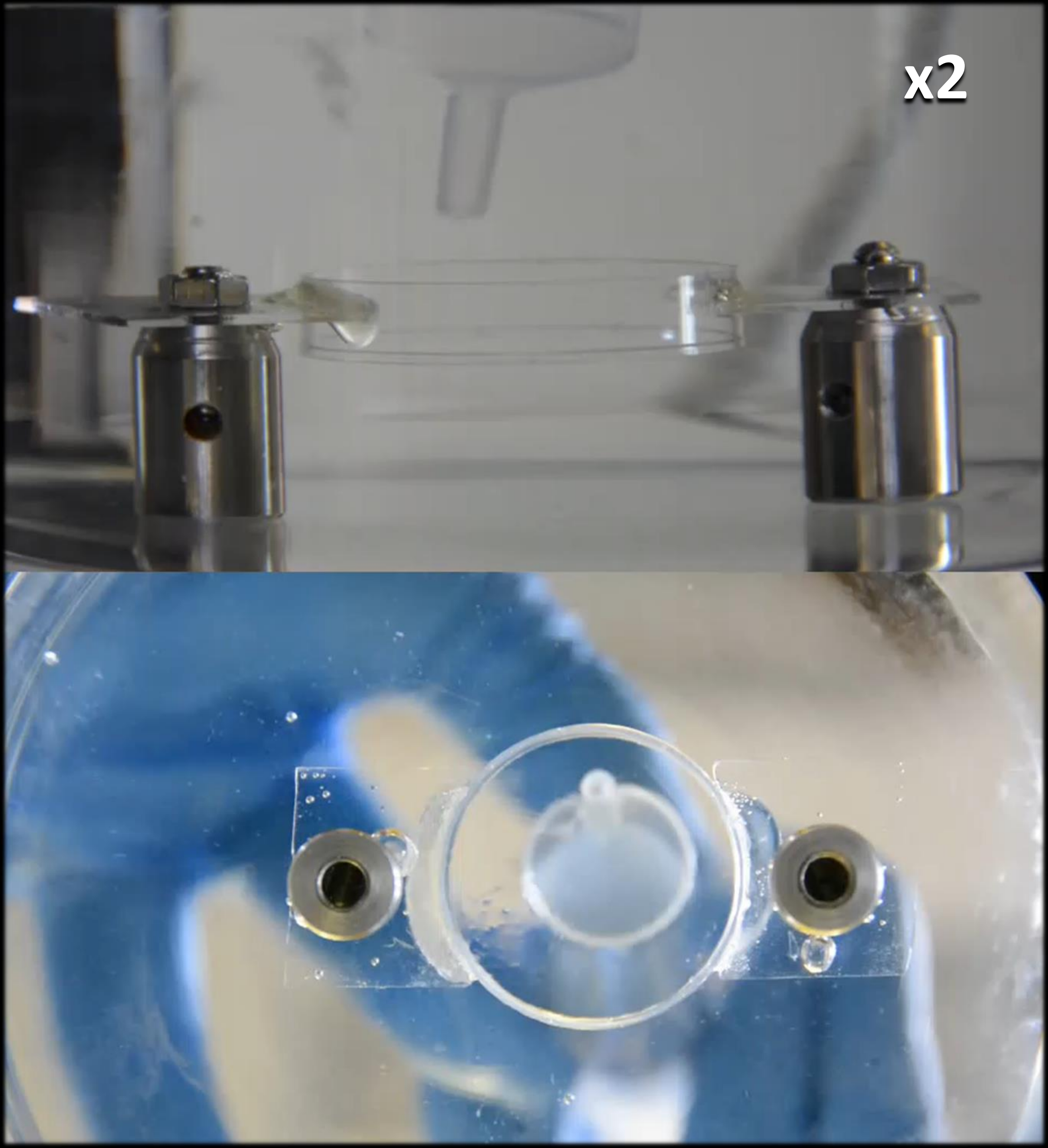
- We control the shape of the liquid lens by using a **bounding surface**, such as a ring, or a pad.
- At **neutral density**, the boundary condition dictates the resulting **constant mean curvature** surface.

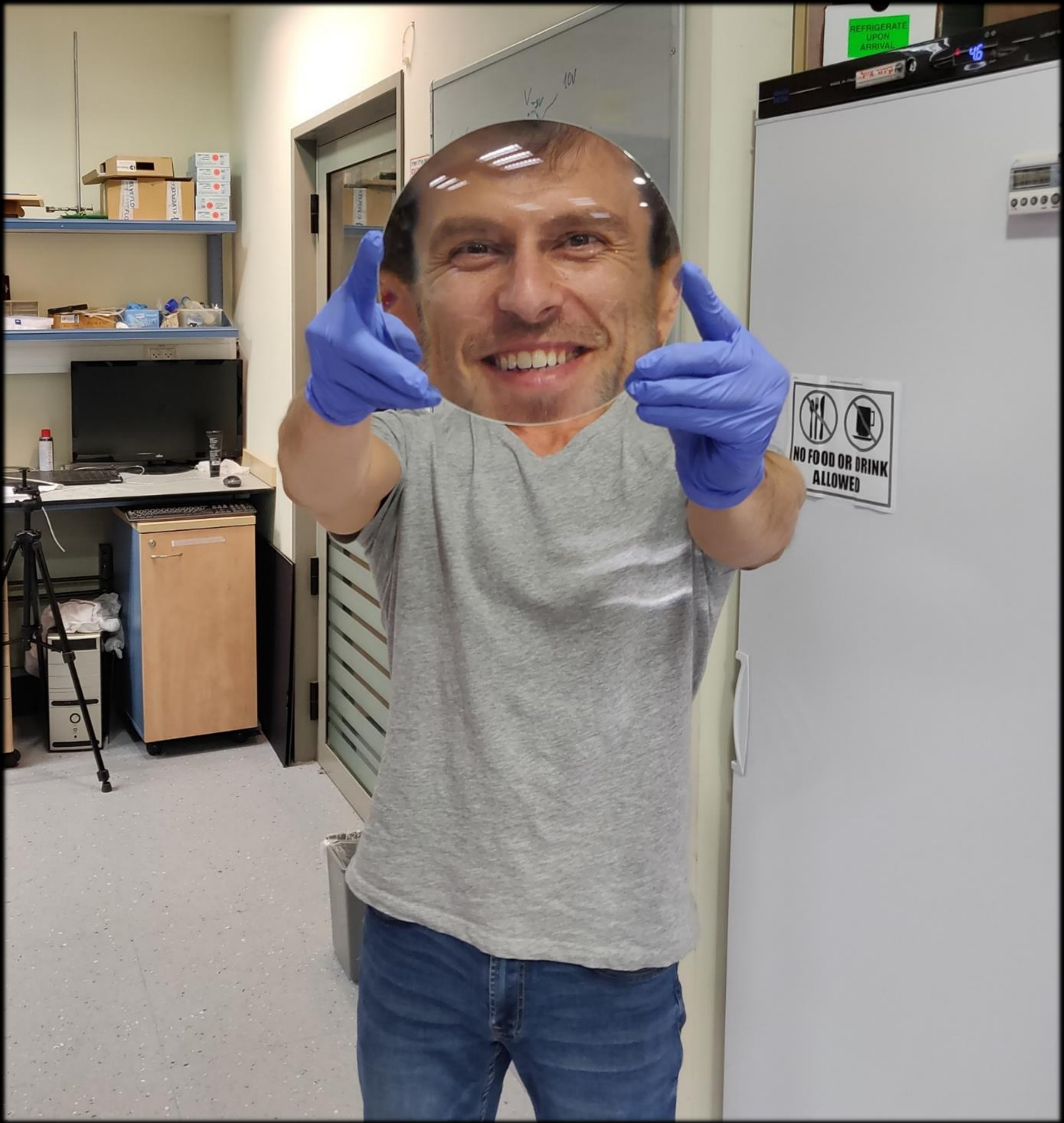




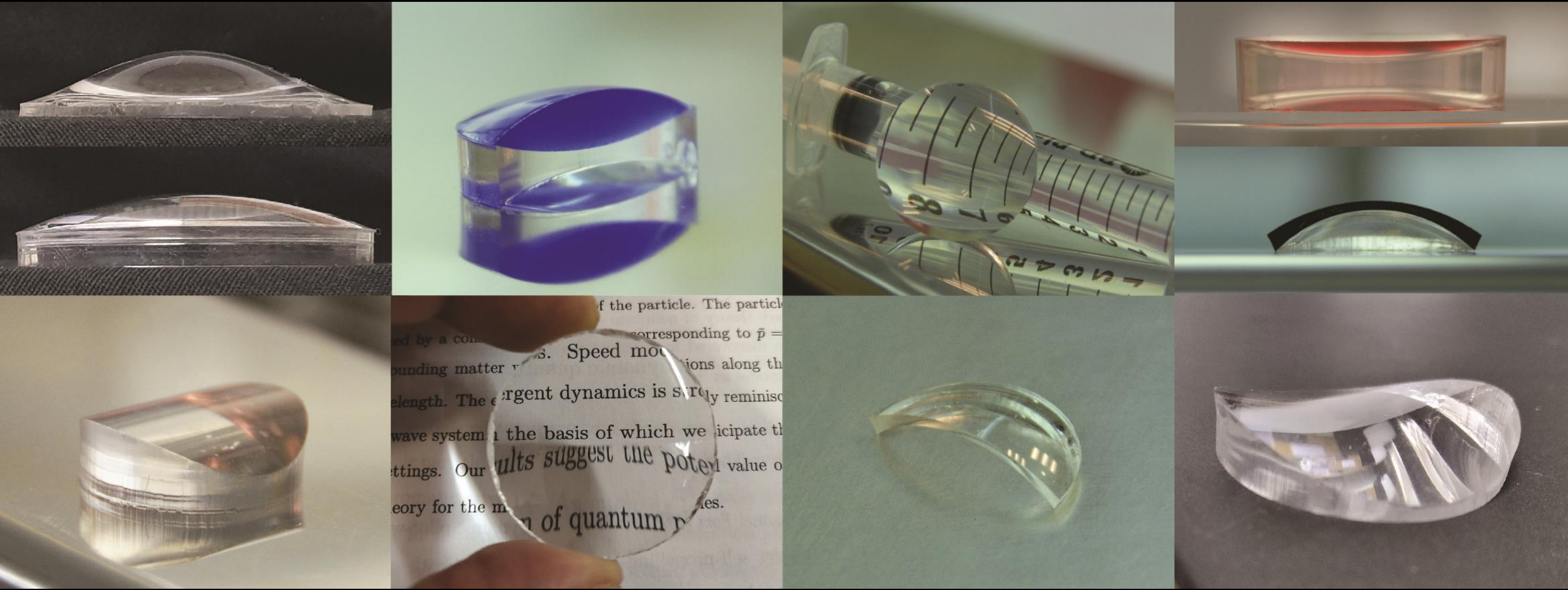
What does it look like?

- 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.



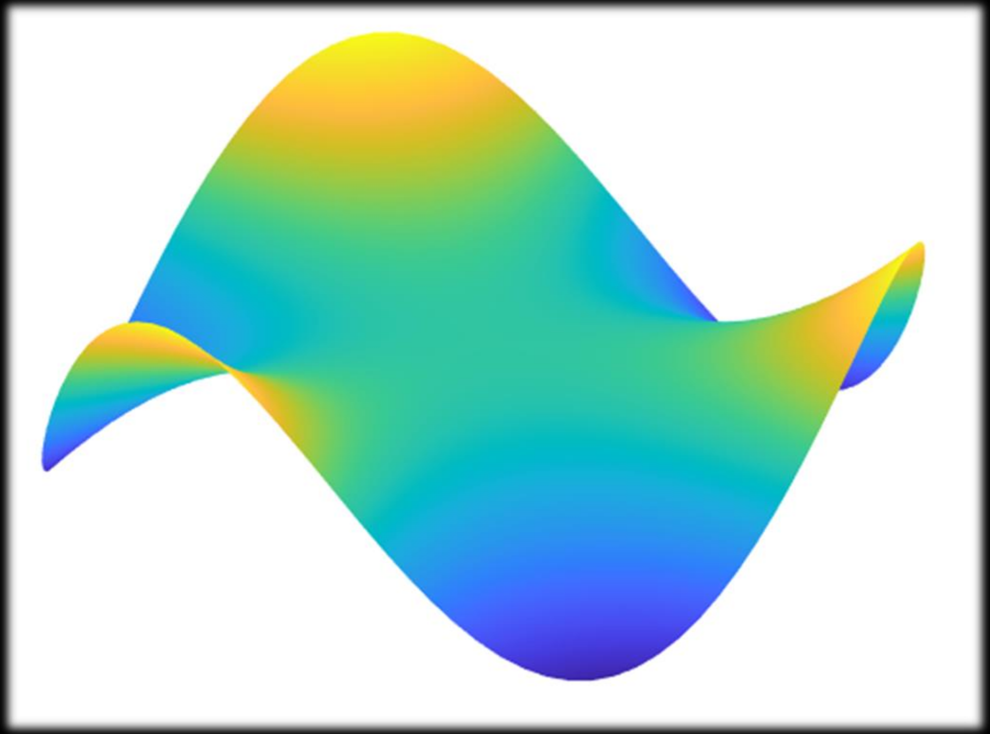

REFRIGERATE
UPON
ARRIVAL
NO FOOD OR DRINK
ALLOWED

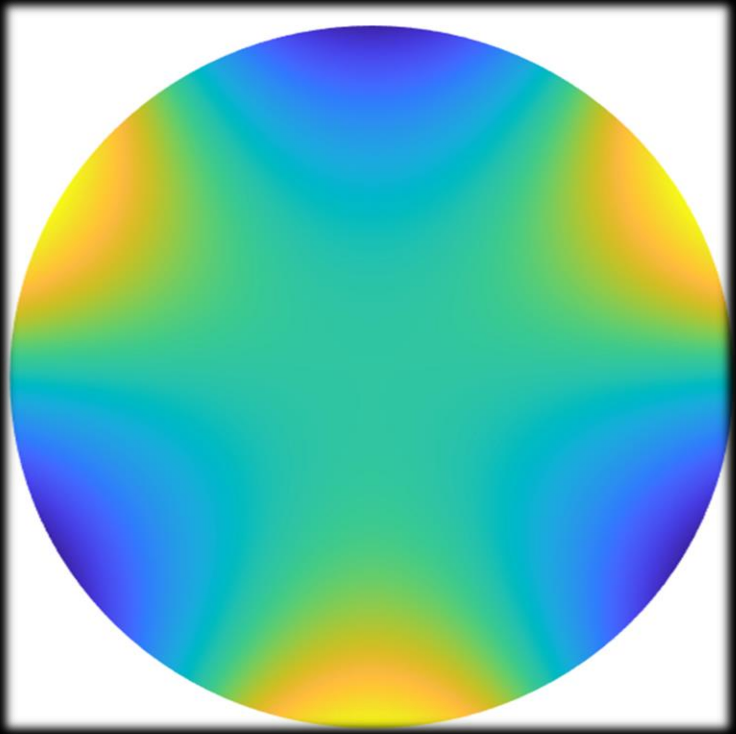
Examples of other optical geometries



Freeform optics – example

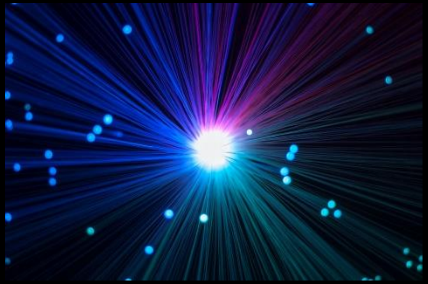
Theory and experiment at neutral buoyancy, for a non-axisymmetric solution given the boundary function: $f(\Theta) = b_0 + b_1 \sin(3\Theta)$

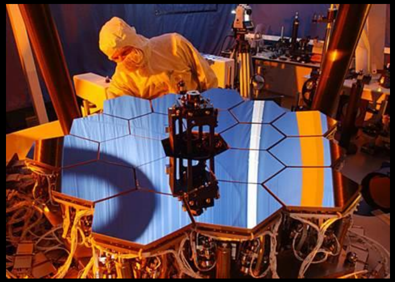




Surface quality

- Due to the natural smoothness of liquid interfaces, the resulting lenses are of excellent surface quality. DHM surface roughness of ~~RMS = 3.5 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

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.

How it’s going

Team

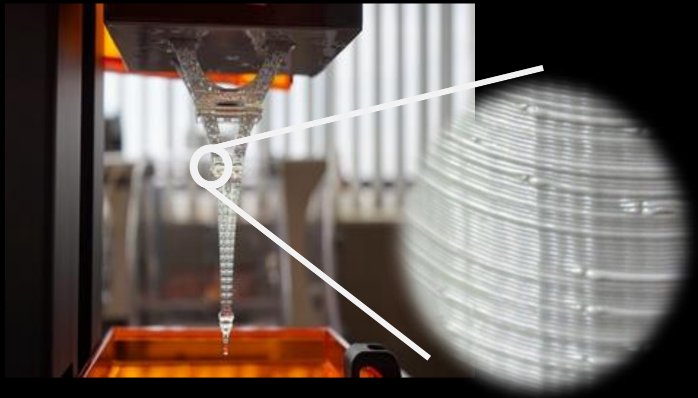
- Edward Balaban (NASA ARC, PI-NASA)
- Moran Bercovici (Technion, PI-Technion)
- Rus Belikov (NASA ARC, astronomy/optics)
- Enrico Biancalani (UMD, instruments)
- Jay Bookbinder (NASA ARC, astronomy / optics)
- Penny Boston (NASA ARC, astrobiology / ionic liquids)
- Howard Cannon (NASA ARC, project manager)
- Kevin Carrico (NASA ARC, visualization)
- Alan Cassell (NASA ARC, mission design)
- Shintaro Chofuku (NASA ARC / JAXA, mission design)
- Anthony Colaprete (NASA ARC, instruments)
- Michael Dickey (NCSU, gallium alloys / ionic liquids)
- Vivek Dwivedi (NASA GSFC, mirror coatings / ionic liquids)
- Mor Elgarisi (Technion, fluid mechanics)
- Jonathan Erickson (Technion, experiment design)
- George Fiedziuszko (NASA ARC, thermal analysis)
- Valeri Frumkin (Technion, fluid mechanics)
- Israel Gabay (Technion, modeling)
- Khaled Gommed (Technion, experiment design)
- Christine Gregg (NASA ARC, structures)
- Jessica Koehne (NASA ARC, measurements)
- Omer Luria (Technion, optics / experiment design)
- Dylan Morrison-Fogel (NASA ARC, mission design)
- Duy Nguyen (NASA ARC, mission cost analysis)
- Collin Payne (NASA ARC, mission design)
- Titus Szobody (NCSU, IL reflectivity)
- Rachel Ticknor (NASA ARC, mission design)
- Daniel Widerker (Technion, experiments)

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.

In-space manufacturing of optical components



- In-space manufacturing of high-quality optics with current methods is highly challenging due to the infrastructure required.
- 3D printing, which can be used for just about anything else, cannot achieve optical surface quality without extensive post-processing. Also, does not scale well to large sizes.

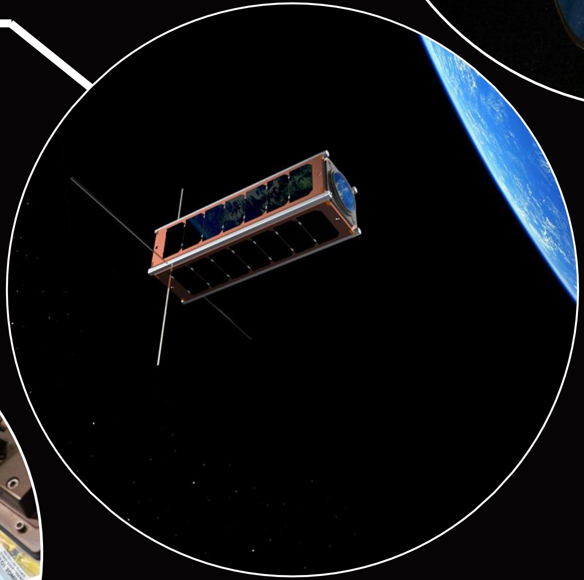
From lab to space — technology maturation steps

Lab

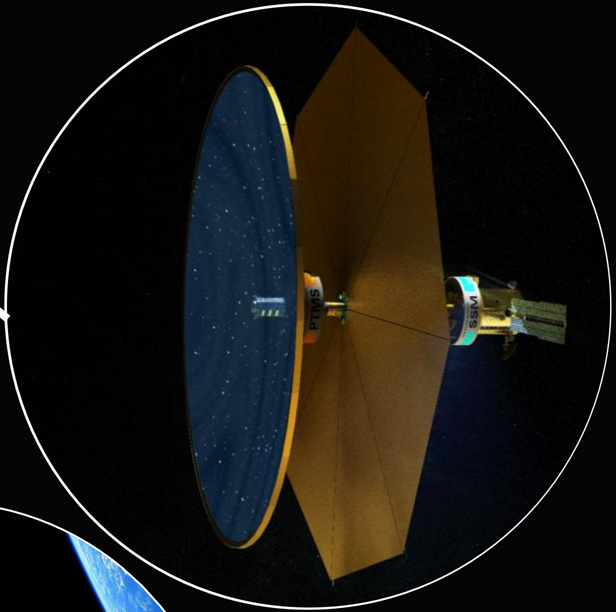
Parabolic flights

ISS

Smallsat demo



Large space observatory



Big-picture plan

- Main mid-term goal: small-sat demo mission of an end-to-end fluidic telescope with reflective optics (by 2030).
- Key near-terms goals:
    1. Develop mission design
    2. Identify and retire tall-pole risks through flight and laboratory experiments
- Key near-term tasks:
    1. Validate fundamentals of the approach in a relevant environment (done)
    2. Identify suitable mirror liquid
    3. Identify and test suitable frame architecture and liquid deployment method
    4. Create a modeling pipeline that predicts mirror surface response to external disturbances (e.g., slewing/station-keeping accelerations, micrometeorite impacts, gravitational forces)

Technology maturation through flight-testing

Test campaign	Objectives	Status
Zero-G parabolic flights, Dec 2021 • 2 x 25 microgravity parabolas • Technion-led	• Focus on liquid lenses • Confirm fundamental principles and physics • Collect real-time data on lens surface quality and geometry	• Experiments successfully completed — first freestanding liquid lenses created in microgravity • Excellent surface and optical quality observed
ISS experiments, Apr 2022 • 2 x 25 microgravity parabolas • Technion-led execution • NASA-led analysis	• Focus on solidified components • Test both UV and thermal curing approaches • Analyze component geometry and surface quality	• Experiments successfully completed — first optical components created in space • Also fit in a bonus experiment with large liquid lenses • Lenses returned on CRS-25 • Currently being analyzed at Ames
Zero-G parabolic flights, Nov 2022 • 2 x 25 microgravity parabolas • NASA-led	• Focus on mirror surfaces and model validation • Test ALD equipment	• Experiments successfully completed • Equipment being completed and tested
Zero-G parabolic flights, Aug 2024 • 2 x 25 microgravity parabolas • NASA-led	• Focus frame-liquid interaction and surface disturbances models validation	• Frame-liquid interaction and surface disturbance models developed • HW and SW ready to go

December 2021 parabolic flight tests

The crew


fluidic.technology
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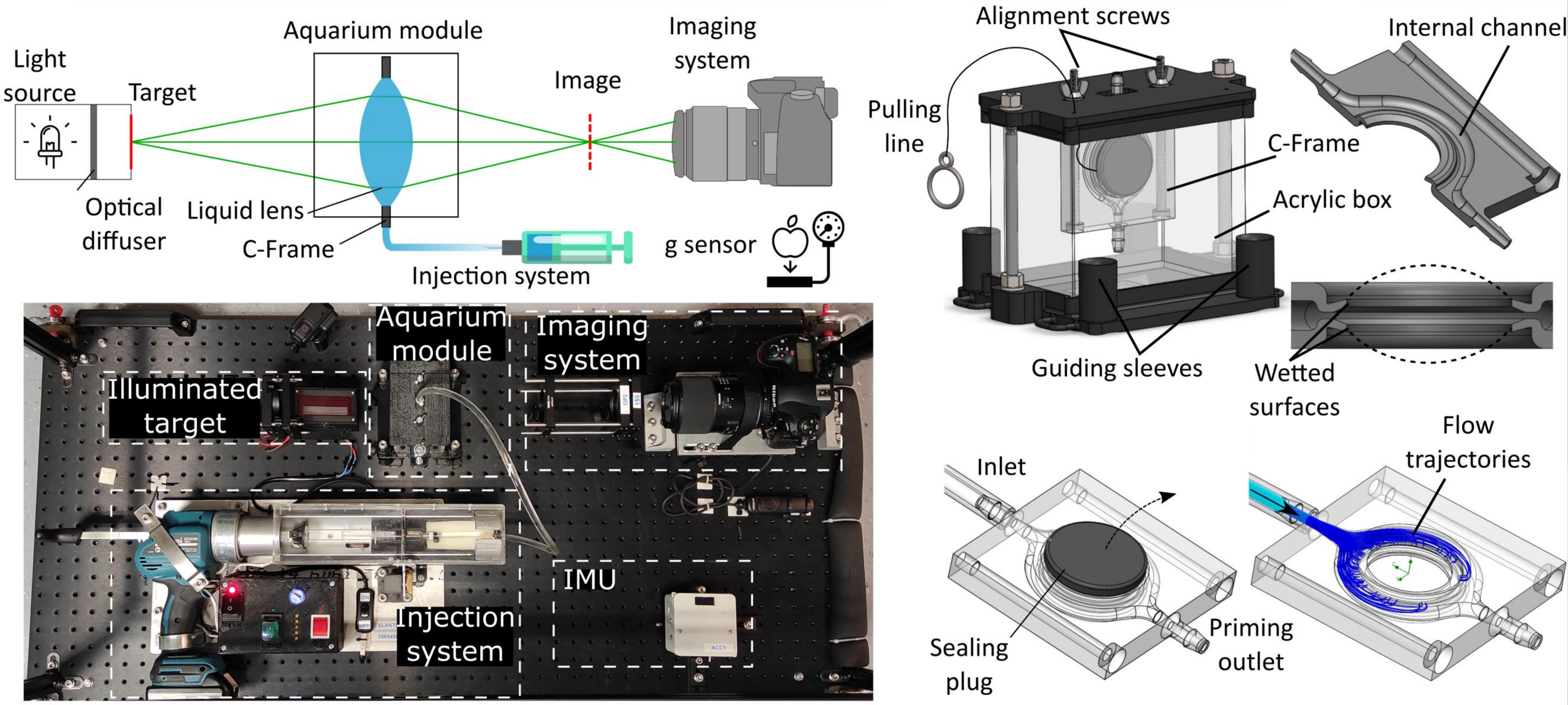
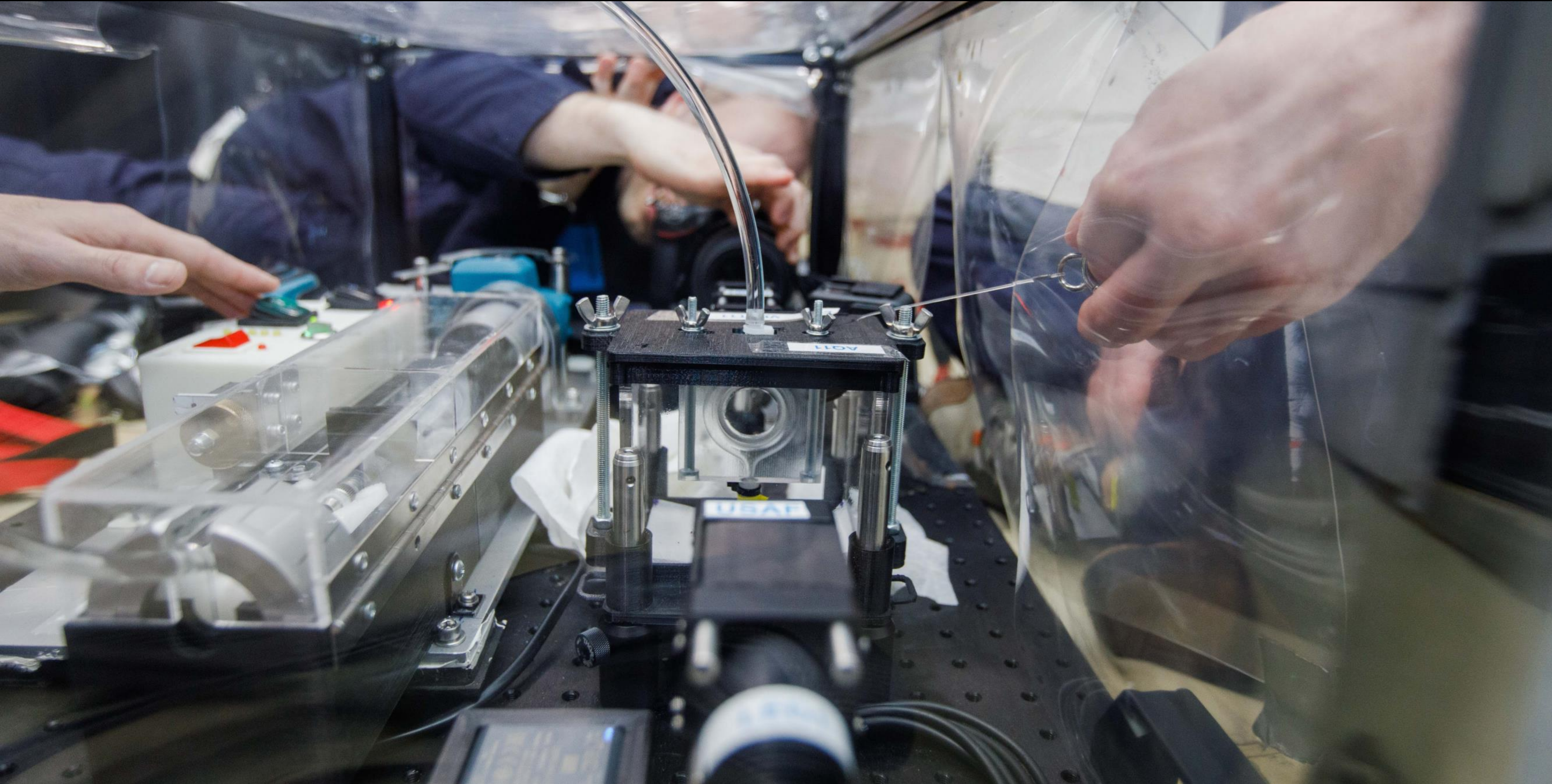
TECHNOLOGIES LAB
NASA
הפקולטה
להנדסת
מכונות
Faculty of
Mechanical
Engineering
TECHNION
zero G
TECHNION


Edward

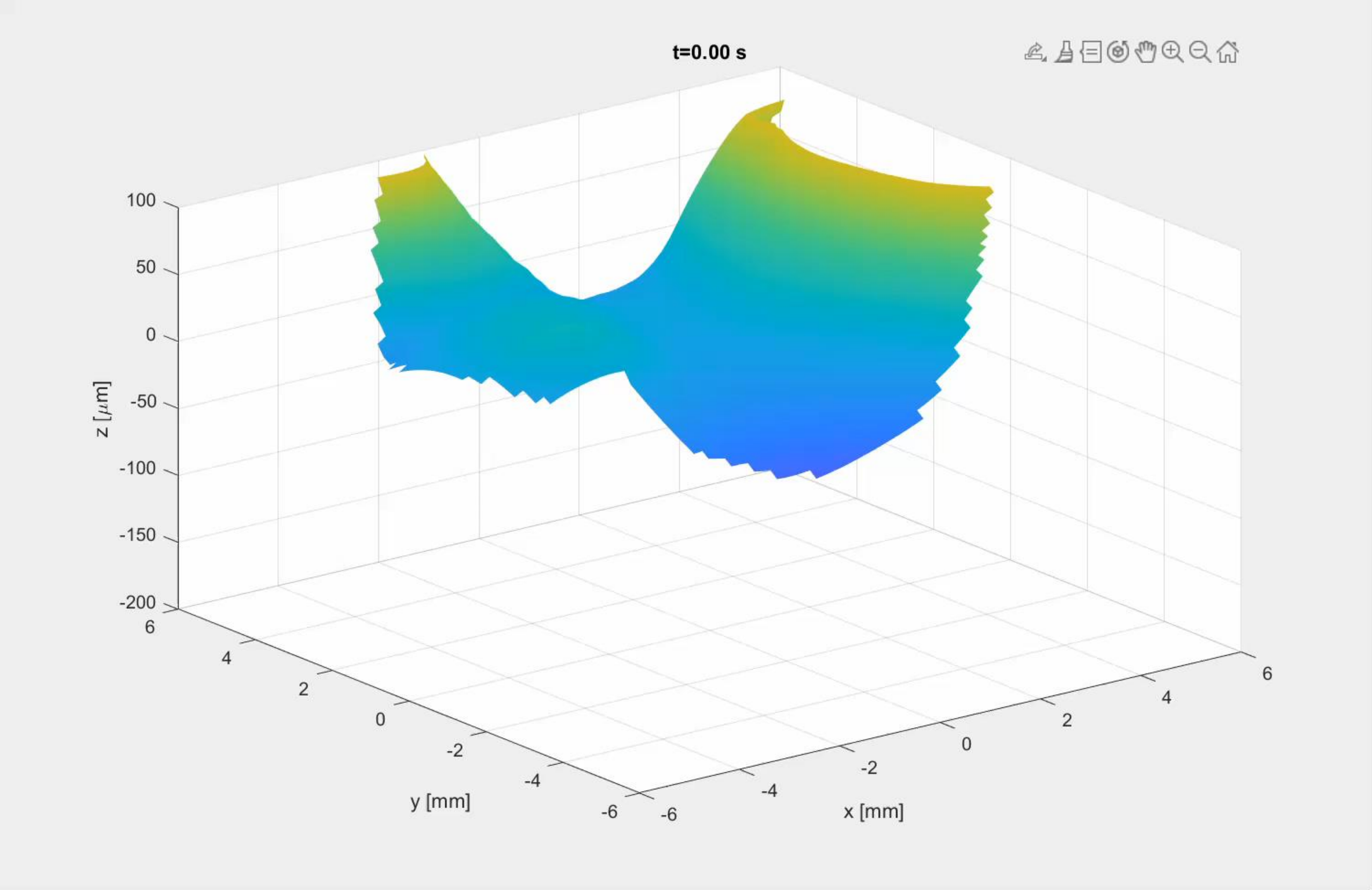
Experimental hardware



Lens formation

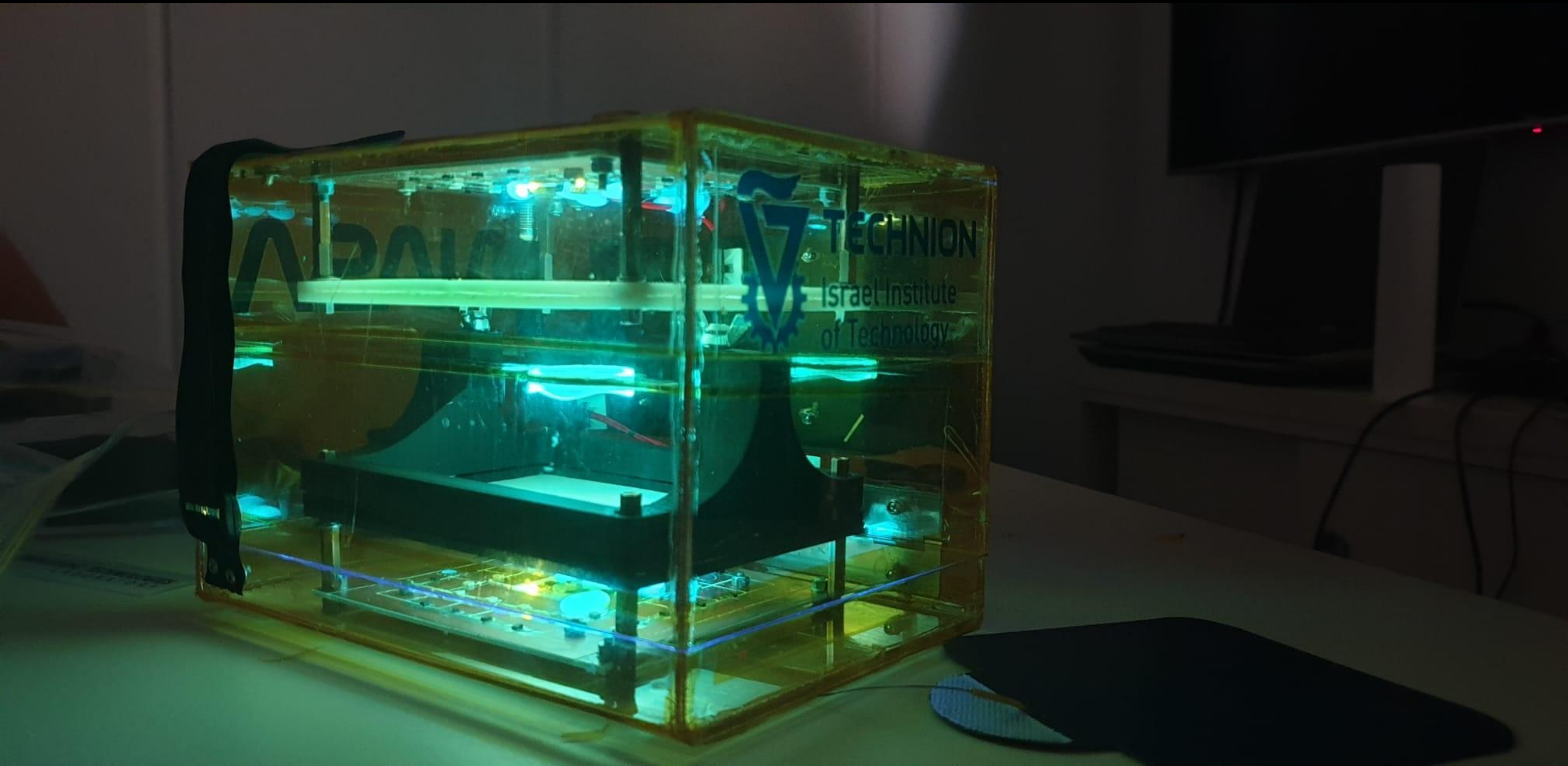


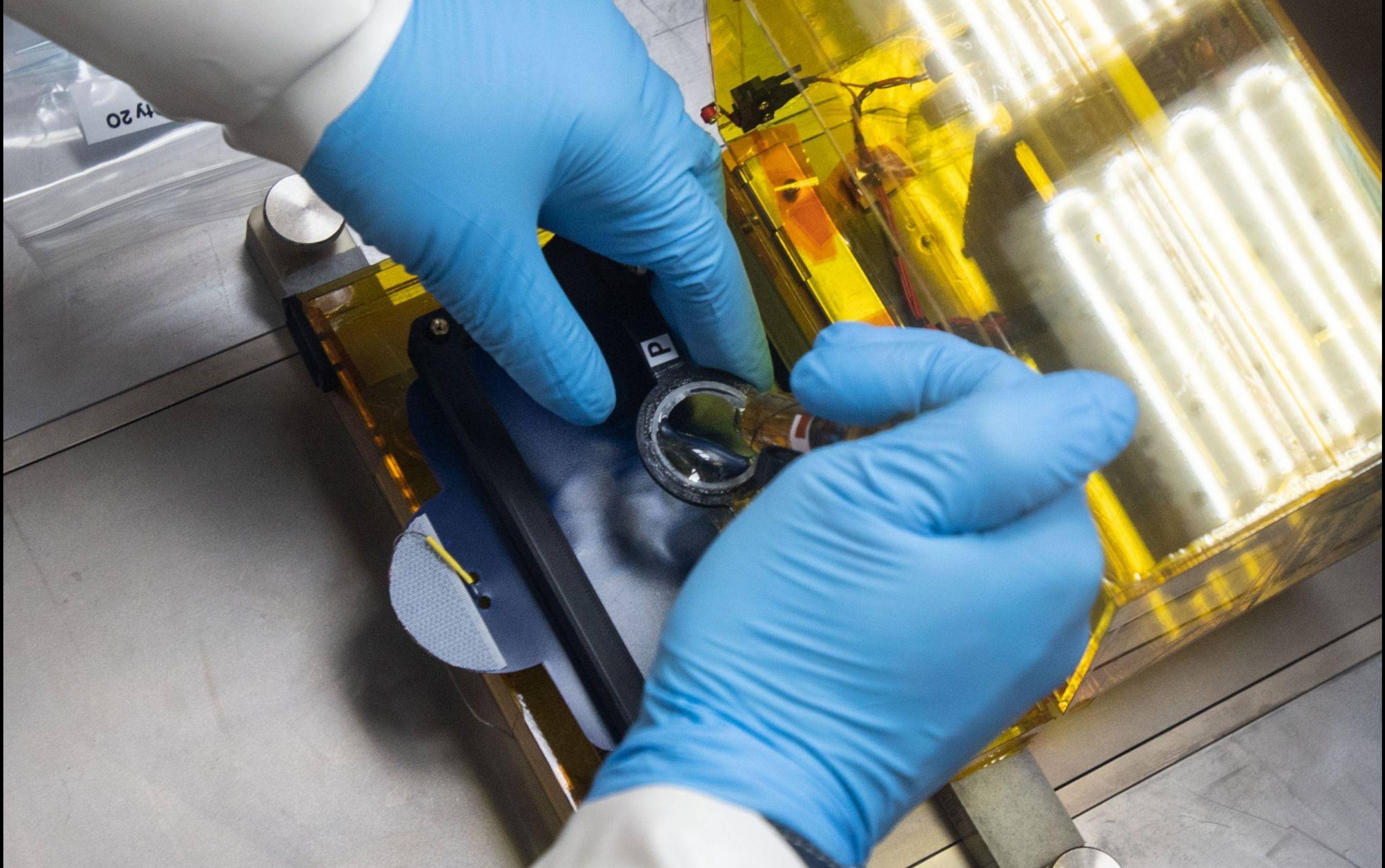
Lens wavefront measurements



ISS Experiments

Experimental hardware

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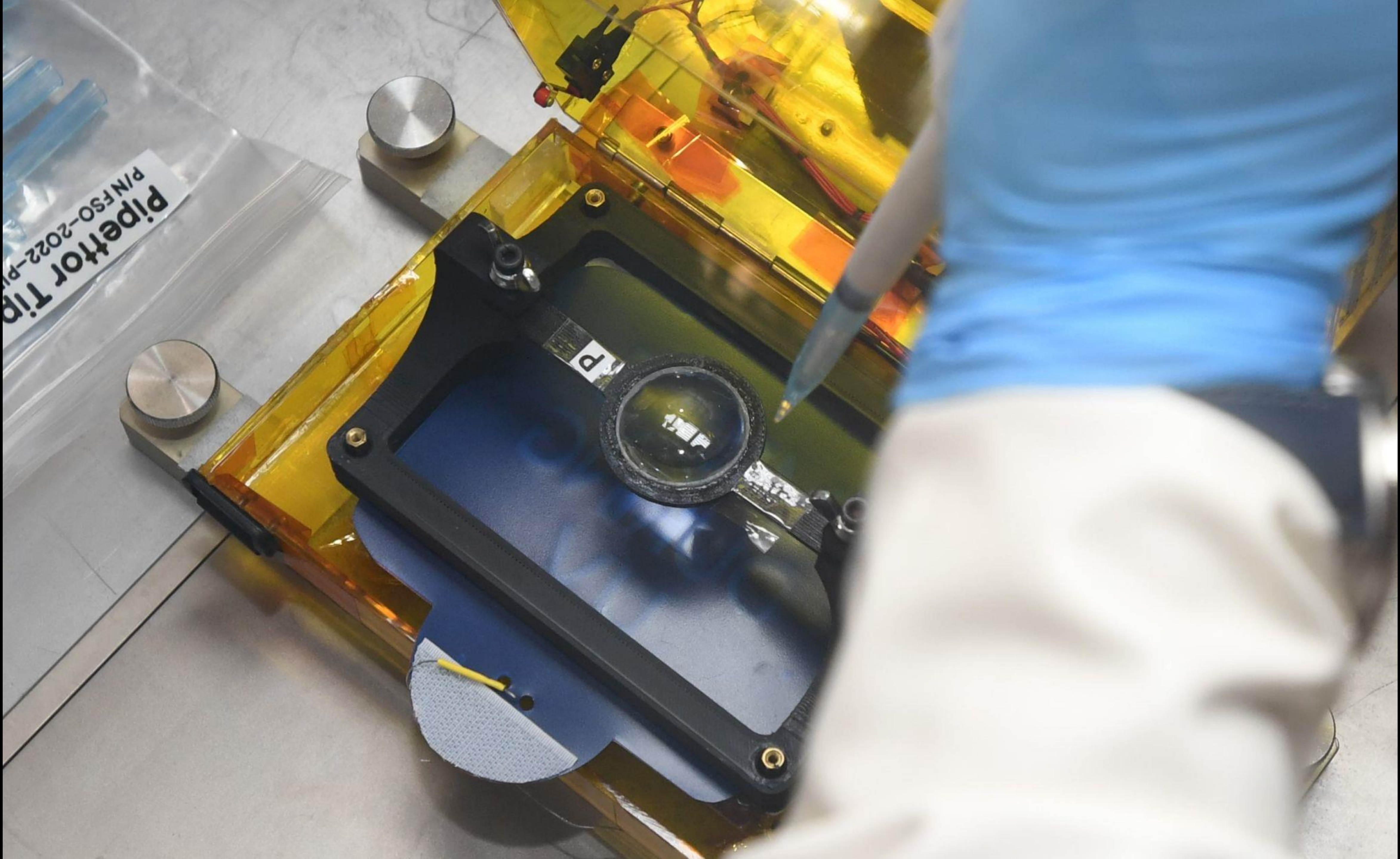
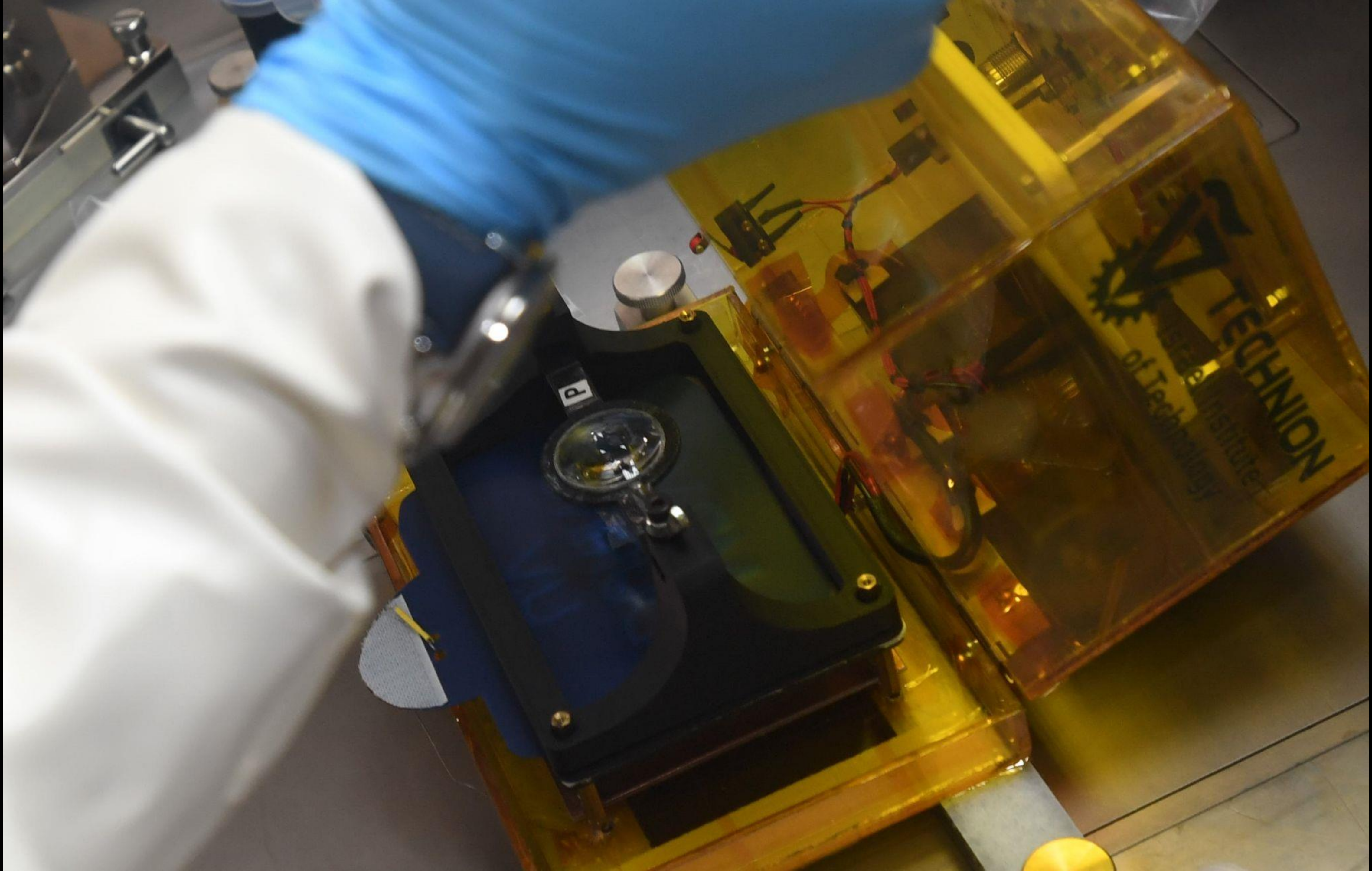
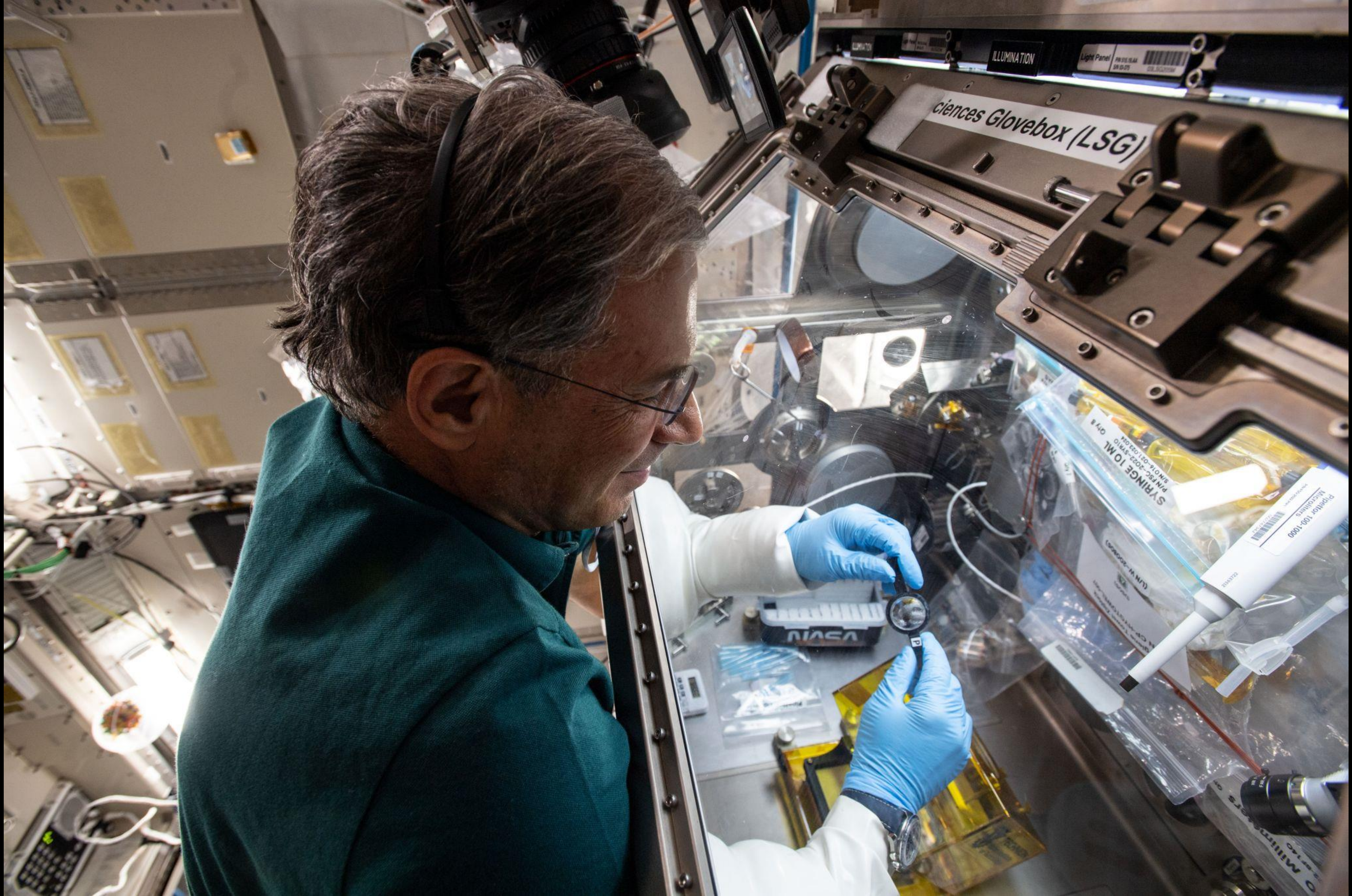
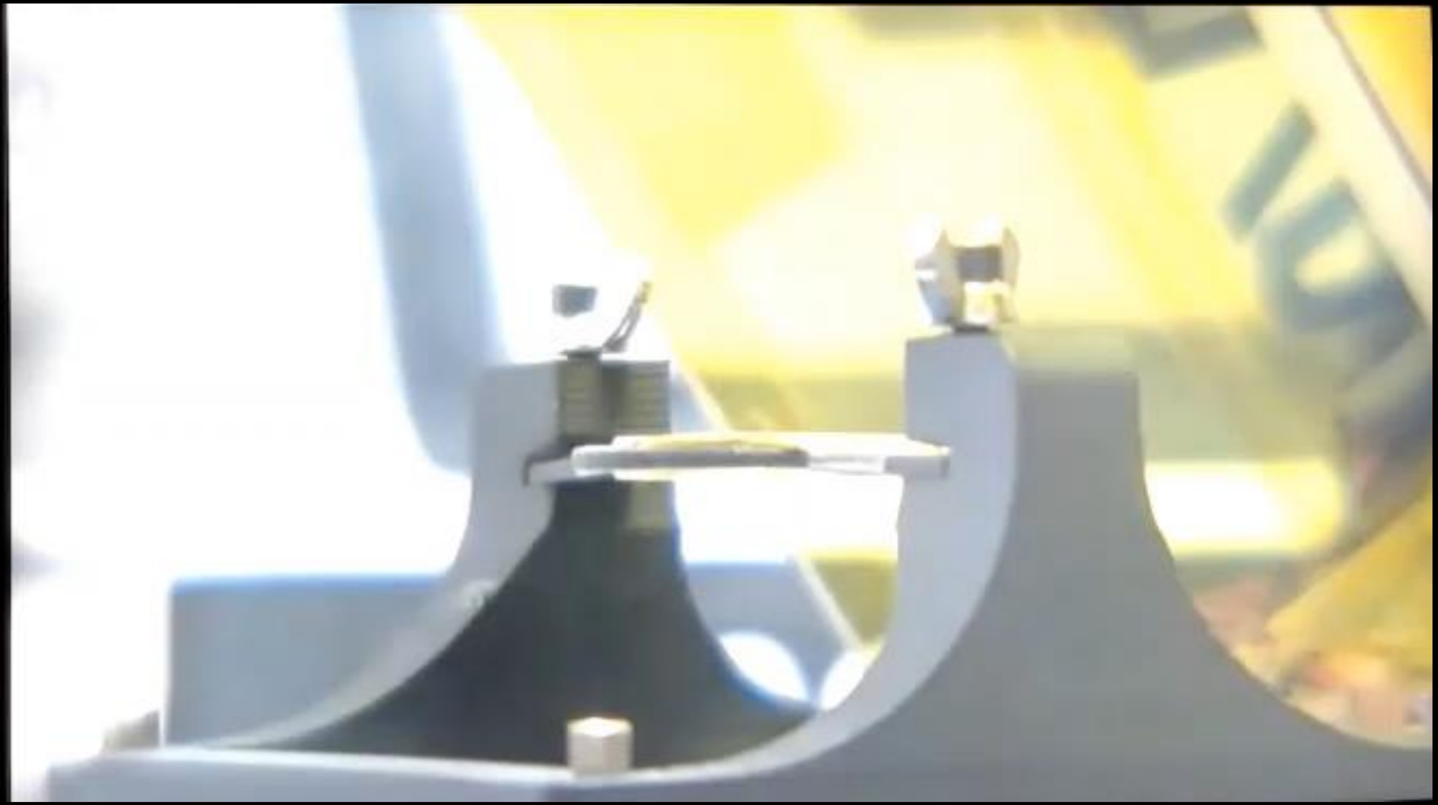

Pipettor
P/N FSO-2022-P
P

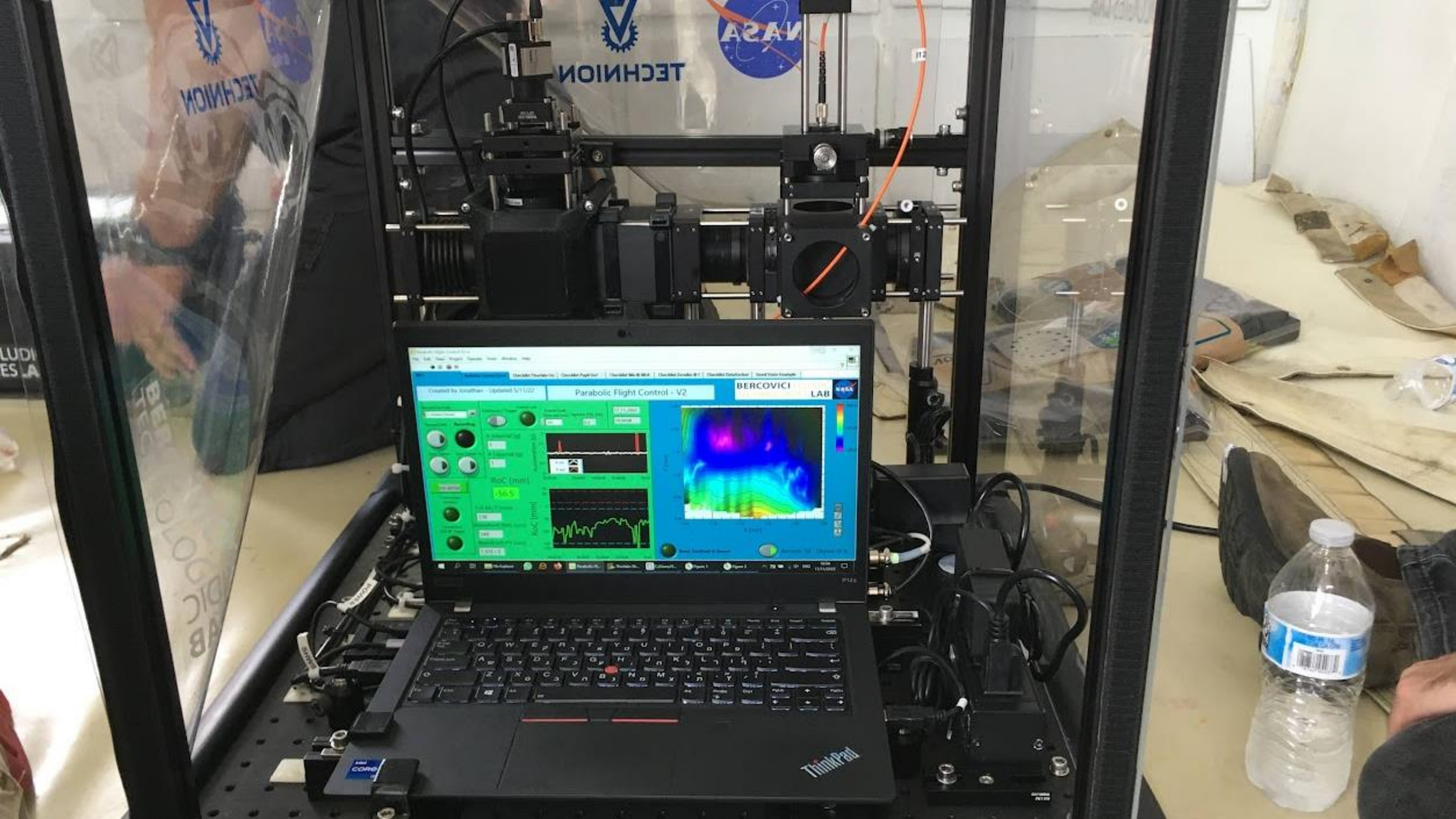

P
TECHNION

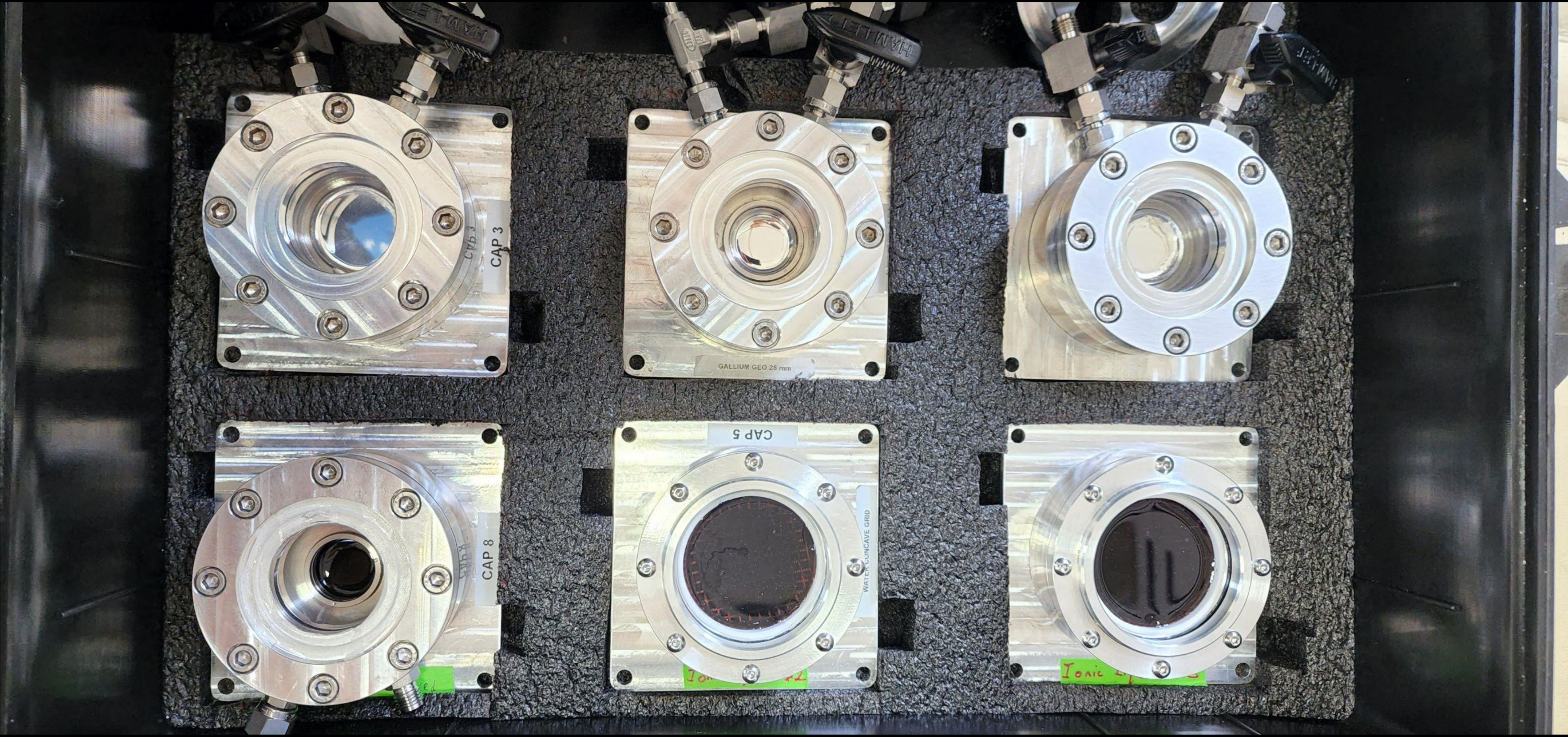

ILLUMINATION
ILLUMINATION
Light Panel
ciences Glovebox (LSG)
SYRINGE 10 ML
Pipettor 100-1000
Microliters
NASA

On-orbit lens creation

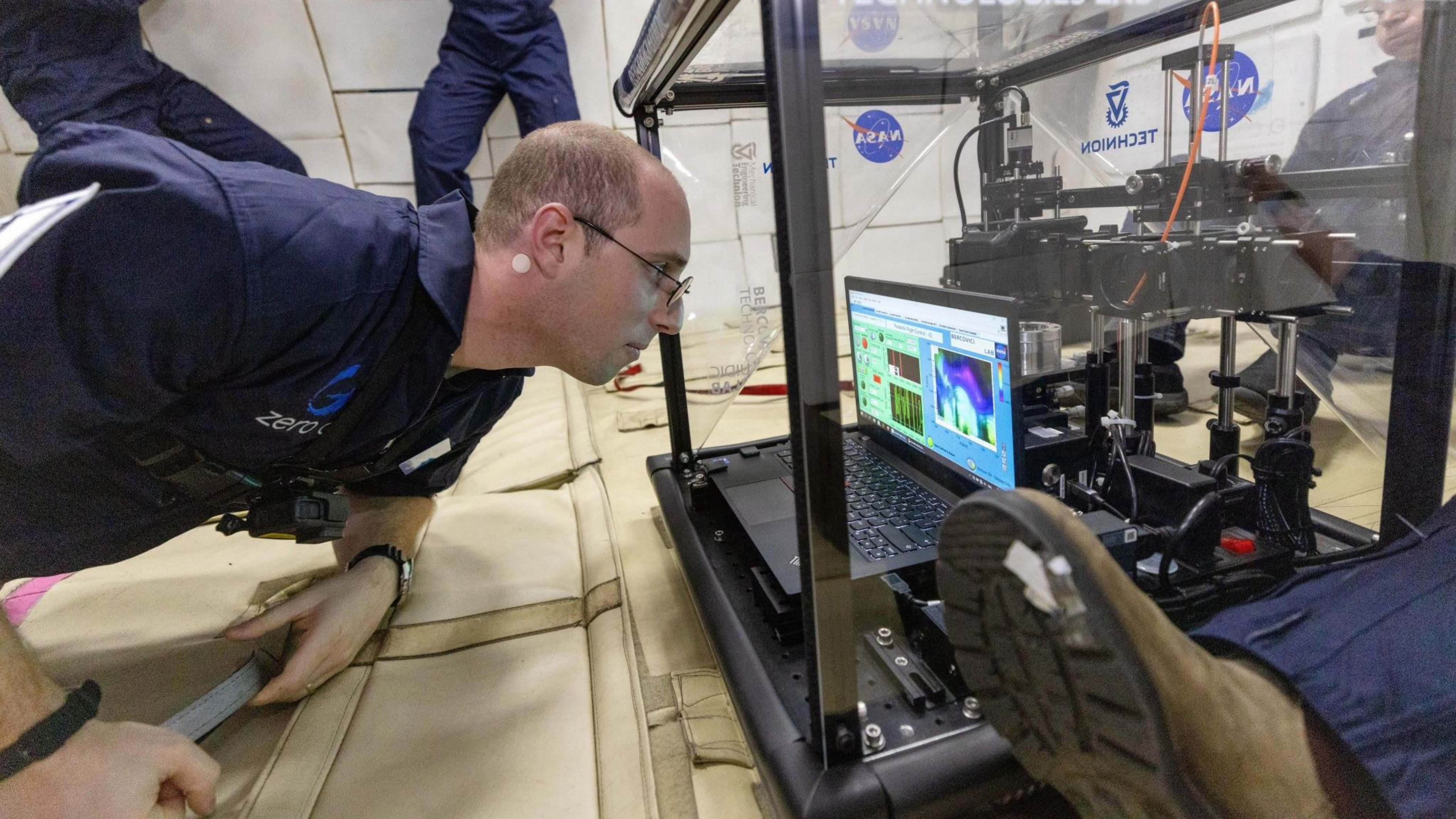


November 2022 parabolic flight tests

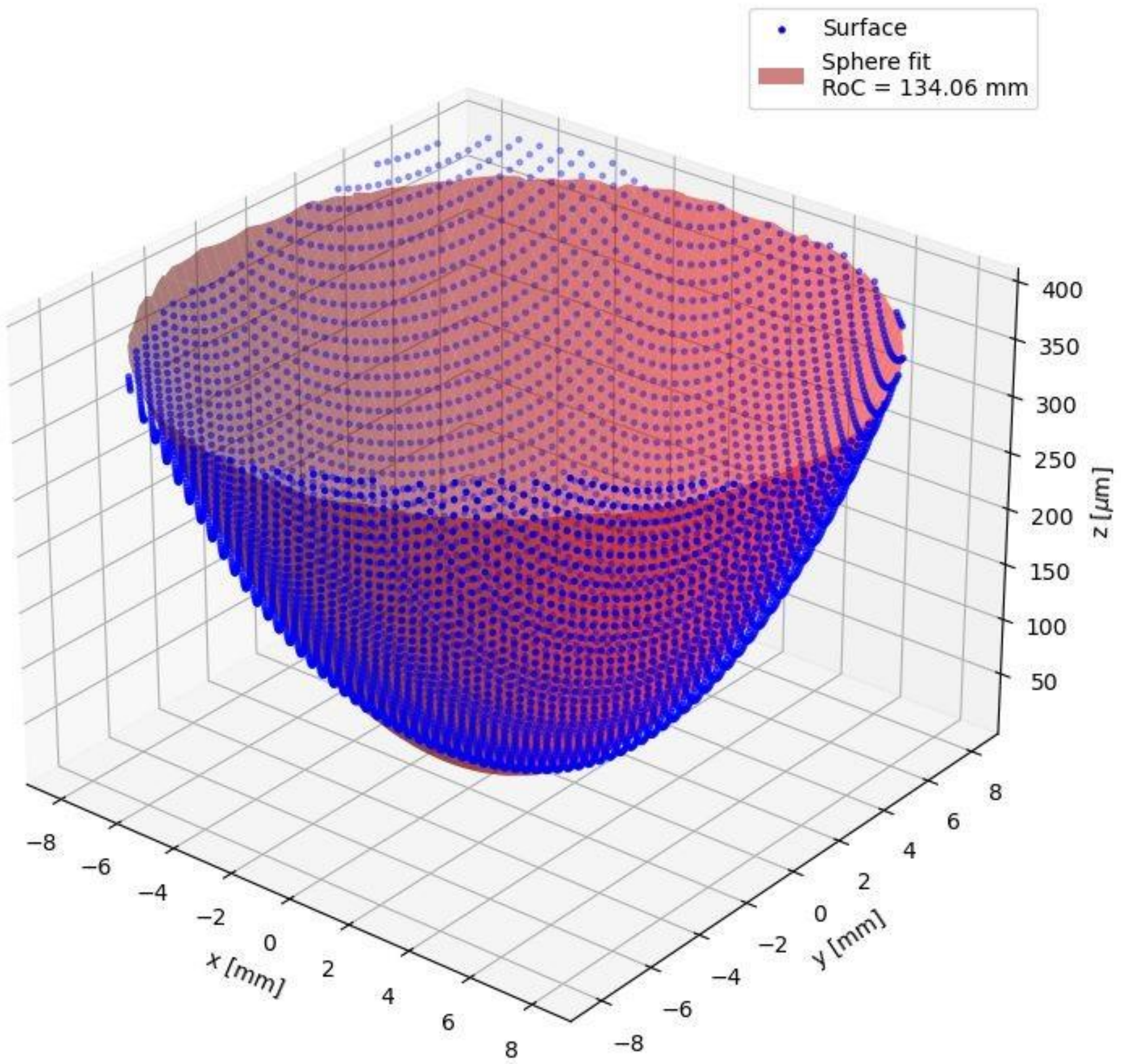

TECHNION
NASA
Created by Jonathan - Updated 5/11/22
Parabolic Flight Control - V2
BERCOVICI
LAB
RoC [mm]
ThinkPad

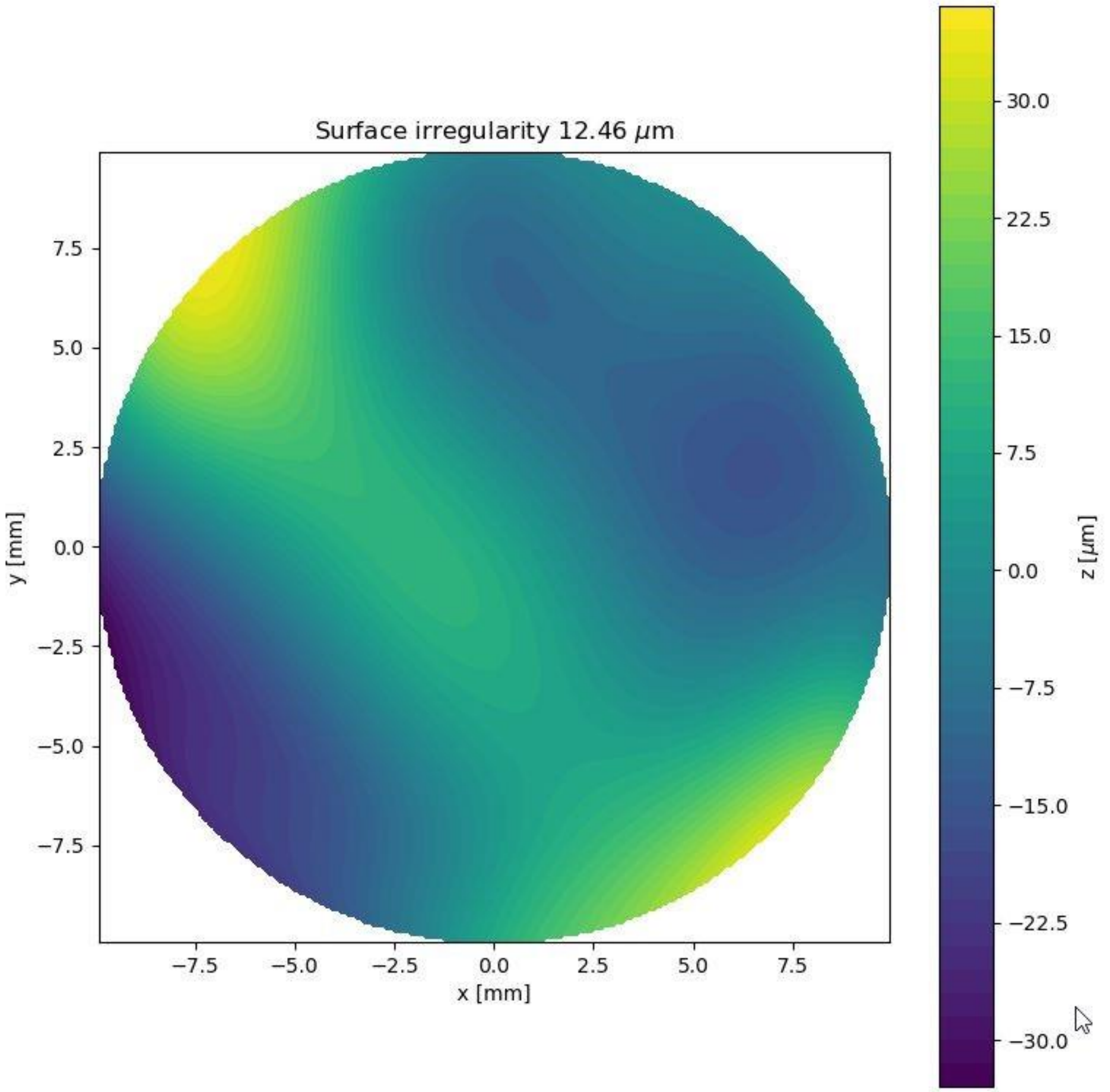


HAM-LET
CAP 3
GALLIUM GEO 28 mm
CAP 8
CAP 5
WATER CONCAVE GRID


NASA
TECHNION
BERCOVICI
LAB

Ionic liquid mirror example



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zero g
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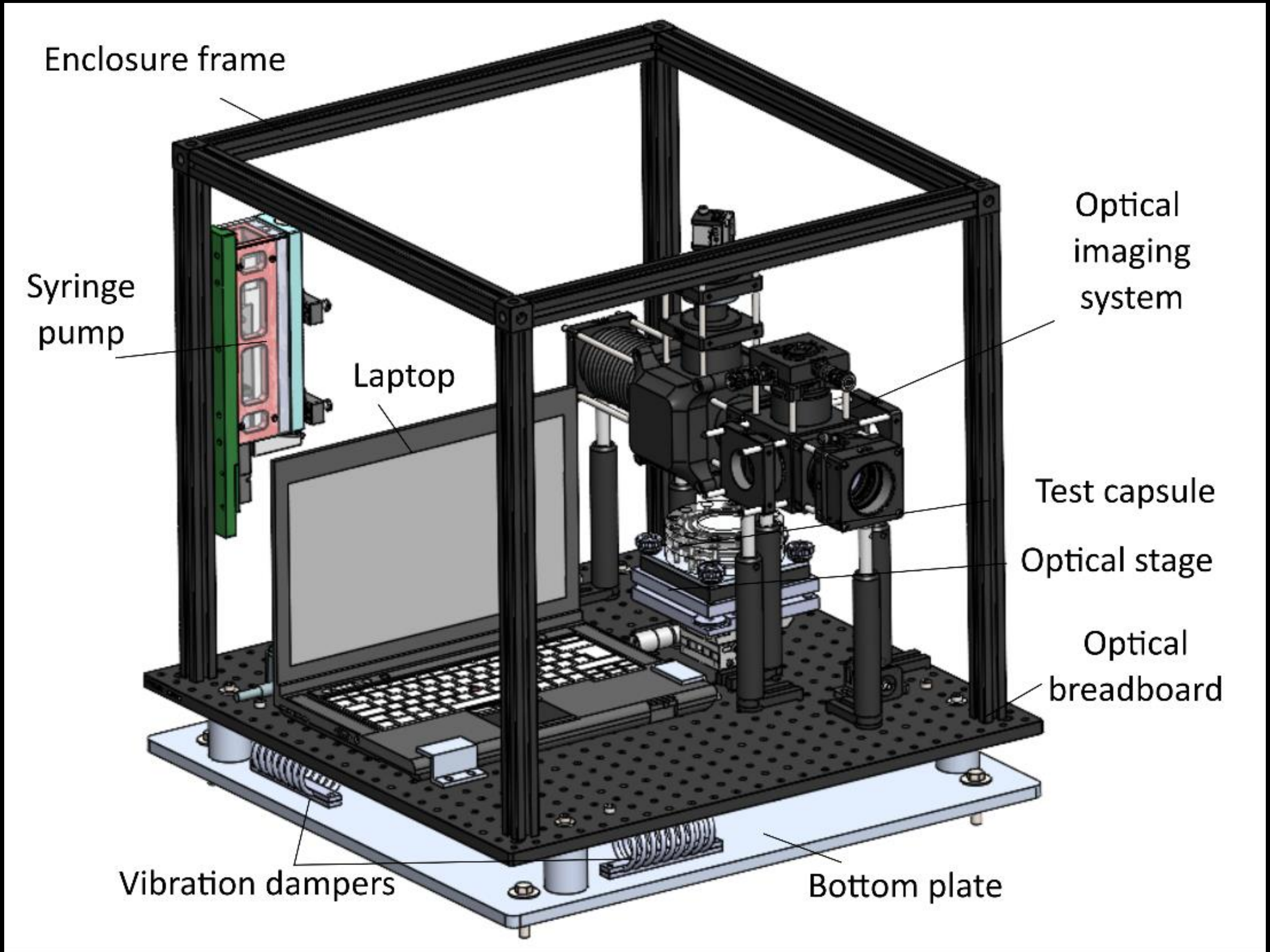
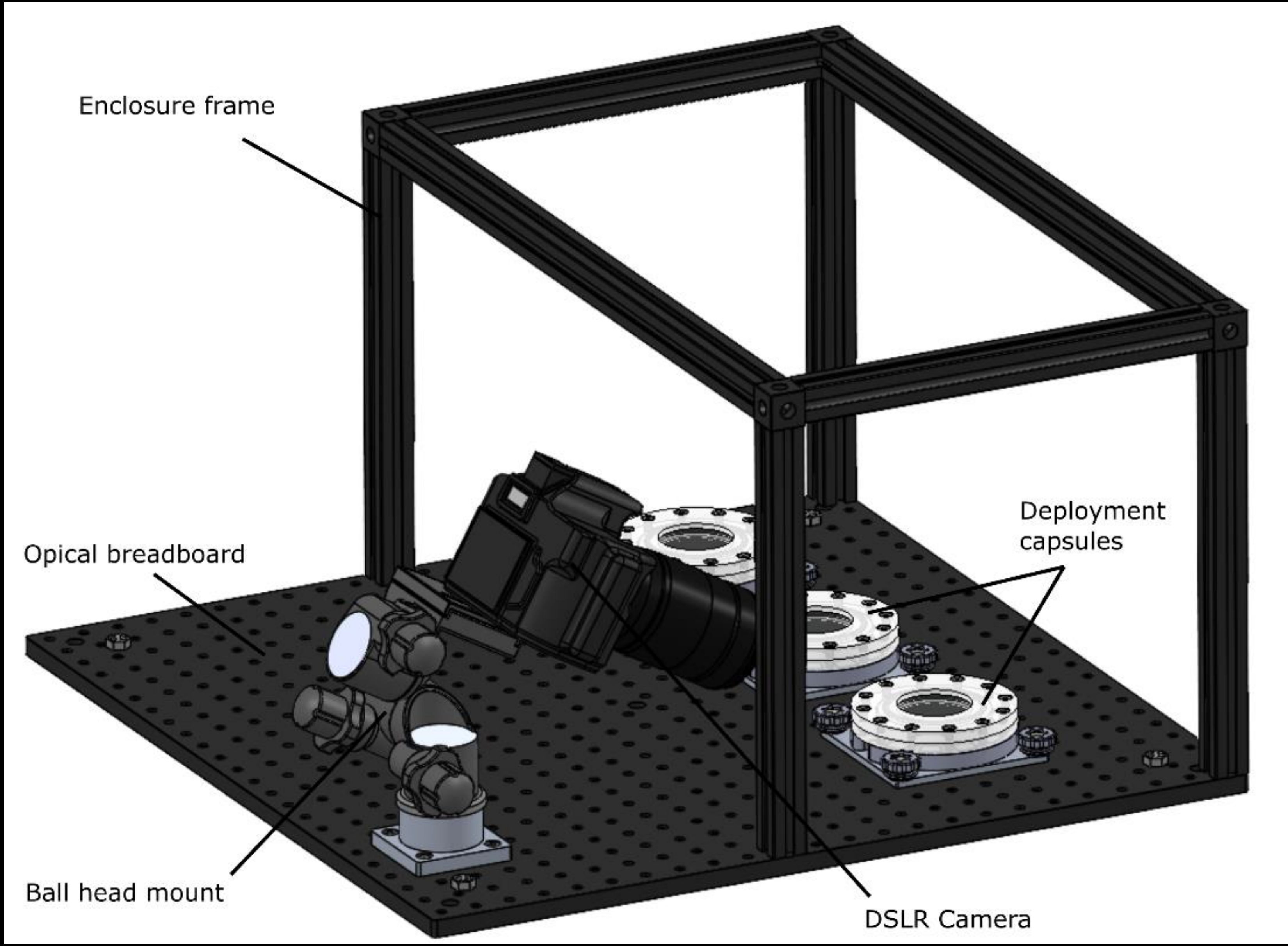
Ideal

December 2023 parabolic flight tests (postponed to 05/24)

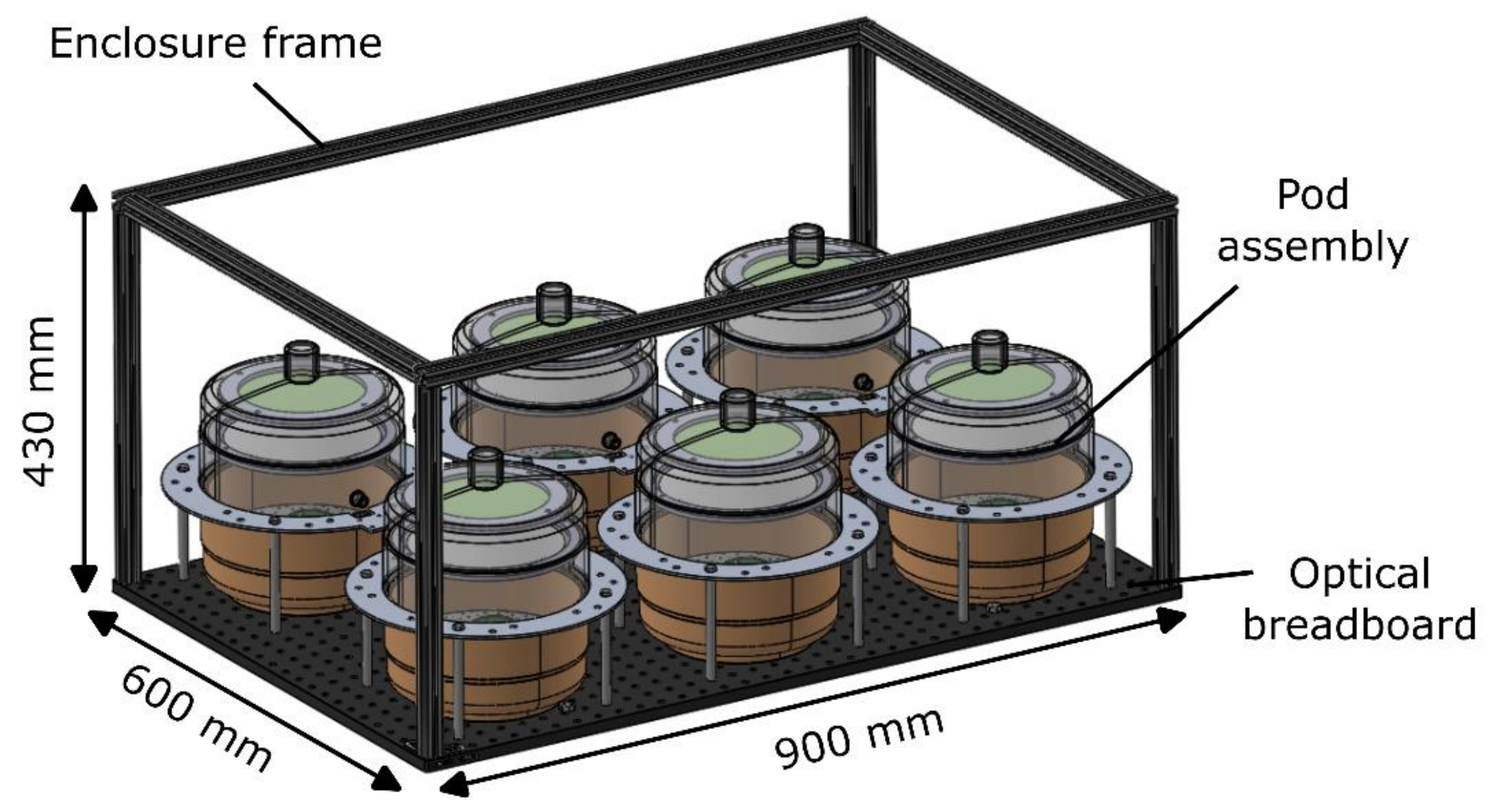
Liquid dynamics experiment



Liquid deployment experiment

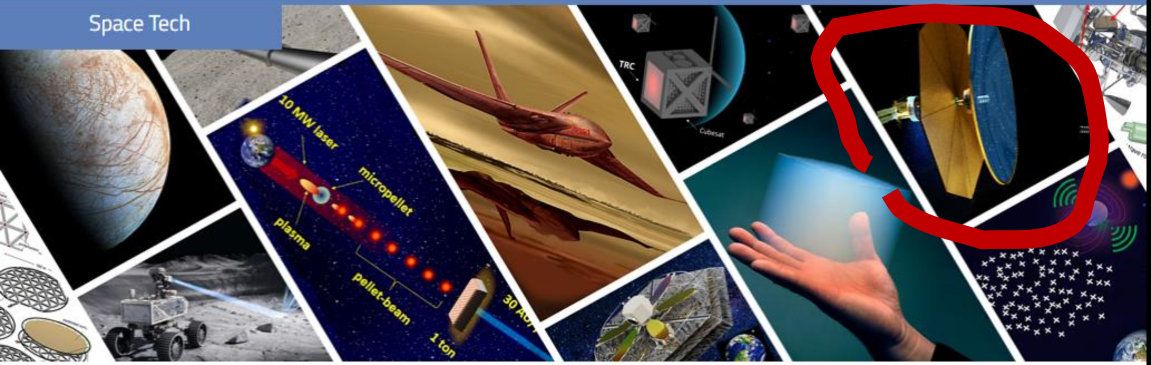


UV curing experiment



Other current work

Space Tech



Jan 9, 2023

RELEASE 23-003

NASA Selects Experimental Space Technology Concepts for Initial Study

Imagine a future in space where pellet-beam propulsion systems speed up travel to other worlds, pipelines on the Moon transport oxygen between settlements, and Martian bricks grow on their own before being assembled into homes. Researchers will delve into these ideas and more using NASA grant funding.

The NASA Innovative Advanced Concepts (NIAC) program fosters innovation by funding early-stage studies to evaluate technologies that could support future missions. The latest round of awards will provide $175,000 grants to 14 visionaries from nine states. Ten of the selected researchers are first-time NIAC recipients.

"NASA dares to make the impossible possible. That's only achievable because of the innovators, thinkers, and doers who are helping us imagine and prepare for the future of space exploration," said NASA Administrator Bill Nelson. "The NIAC program helps give these forward-thinking scientists and engineers the tools and support they need to spur technology that will enable future NASA missions."

NIAC

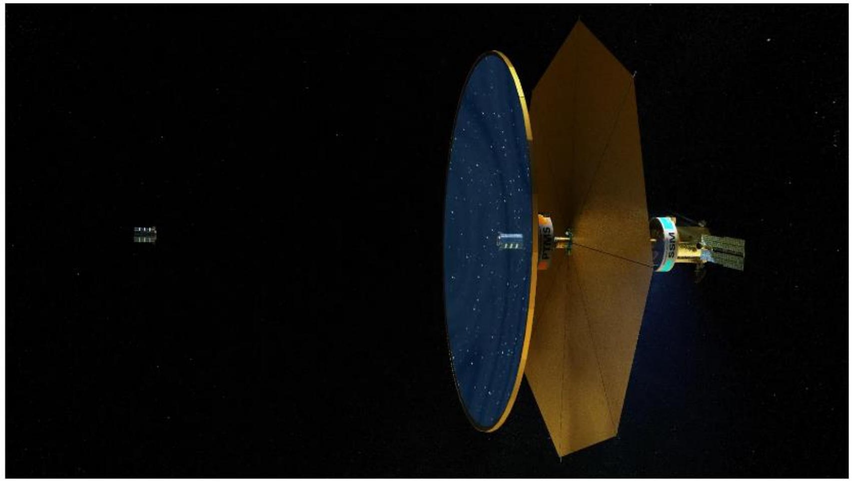
Sci-fi ideas that could change the future of space exploration

By Ashley Strickland, CNN

Updated 10:26 AM ET, Sat February 4, 2023

It's Not Sci-Fi—NASA Is Funding These Mind-Blowing Projects

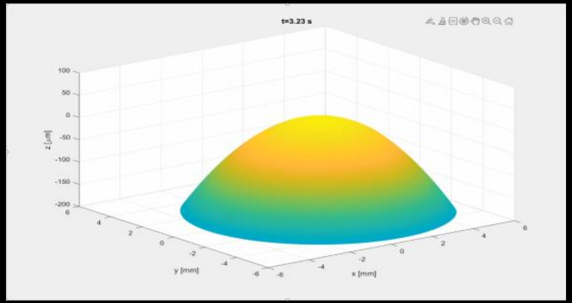
The space agency gave money to researchers working on liquid telescope mirrors, a lunar oxygen pipeline, and Martian building blocks made of fungi.

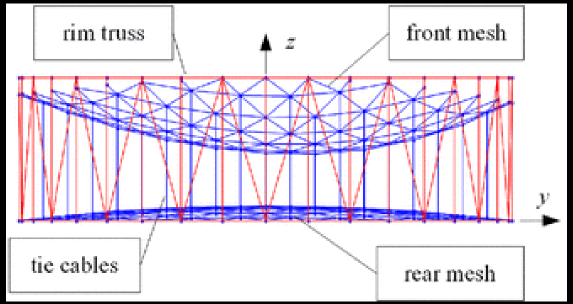


Fluidic Telescope (FLUTE). COURTESY OF EDWARD BALABAN/NASA

Fluidic Telescope Sounds Like Something Out of Terminator, NASA Seriously Considering It

Modeling pipeline





Adaptive optics requirements ⇔ Necessary fluid surface accuracy ⇔ Structural requirements

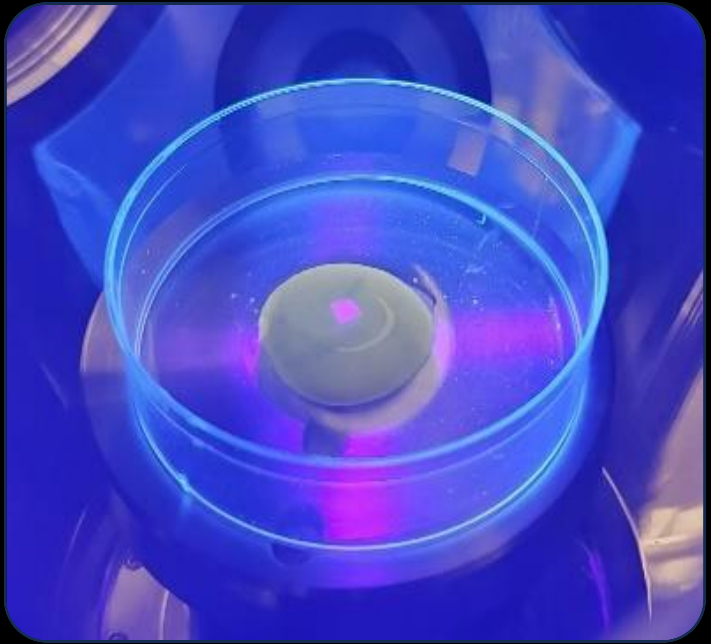
Model relating surface deformations in main mirror to requirements on adaptive optics

Structure/Fluid Model relating disturbances/ structural performance to surface deformation

Mirror liquid candidates trade study

- Based on the experience gained in laboratory and parabolic flight experiments, decided to deprioritize gallium alloys and focus more on ionic liquids.
- Identified properties of ionic liquids important to FLUTE; performing a wide-ranging literature review of existing ionic liquids to identify those possessing as many favorable properties as possible.
- Conducting modeling and experiments on enhancing reflectivity of ionic liquids through the formation of a surface layer with reflective nanoparticles (with NCSU, co-funded by GSFC and Ames Center Innovation Funds).

Precursor formulation

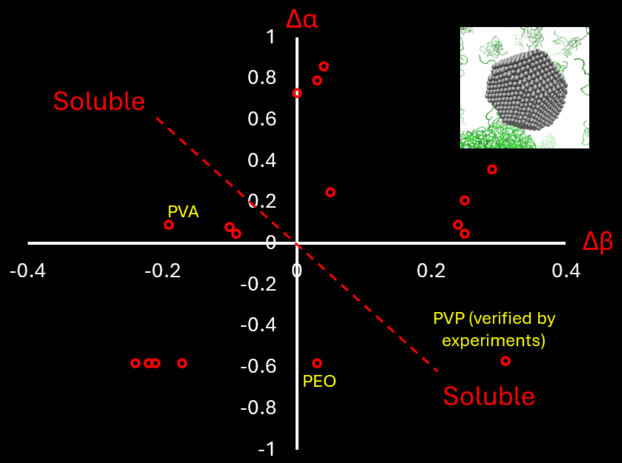


Formulation exposed to UV
in a vacuum chamber

Final liquid mirror surface

Multiscale Modeling of Ionic Liquid Mirror Properties

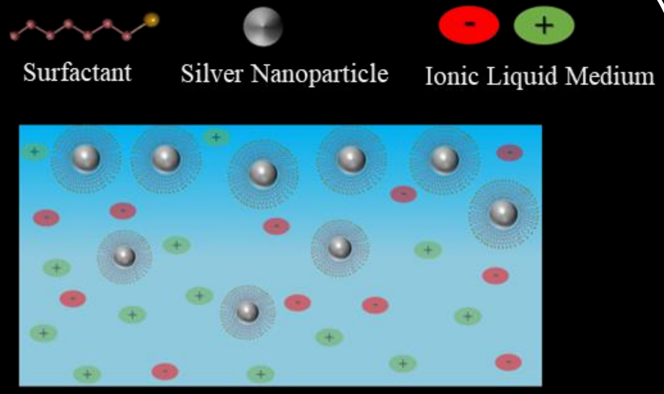
Predict nanoscale phenomena



Develop mechanisms to ***prevent*** reflective ***particle aggregation*** (e.g., nanoparticle encapsulation)

Molecular modeling

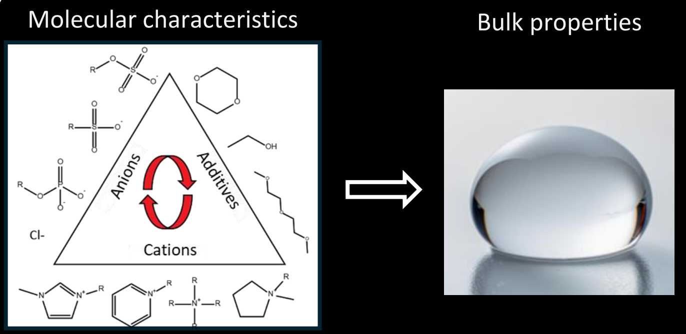
Model long-term stability



- Predict mirror ***response to external forces*** (e.g., mechanical perturbations, ***electric field***)

Computational Fluid Dynamics-Discrete Element models

Future directions

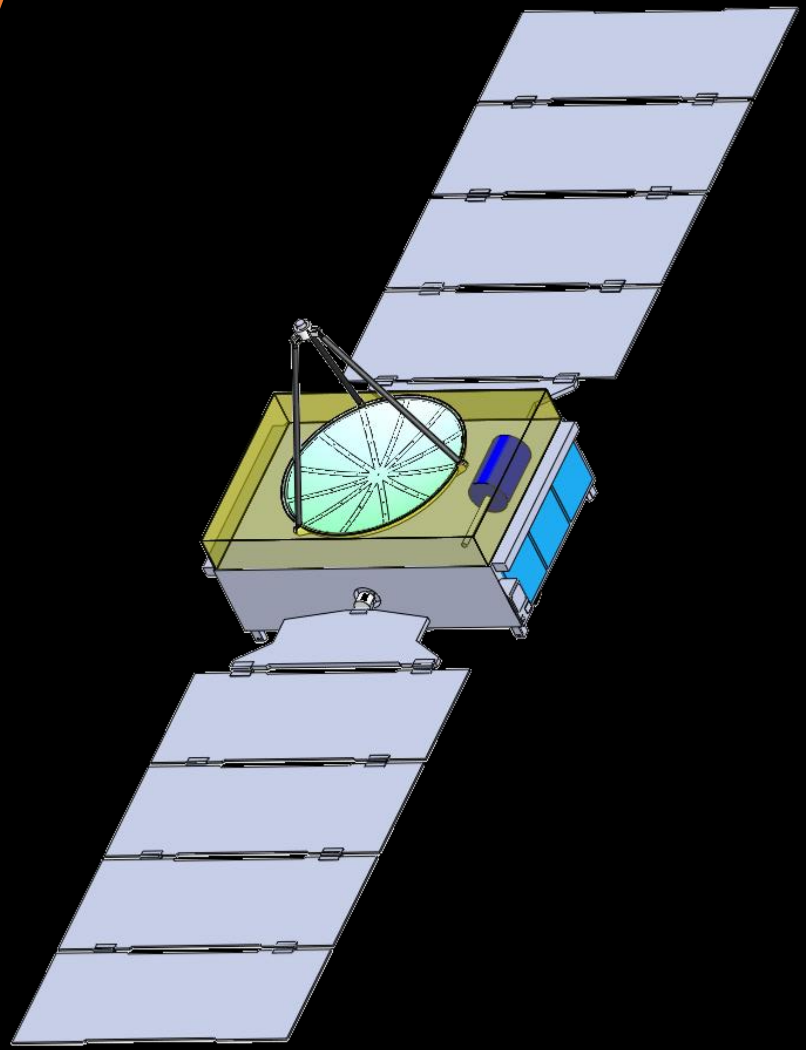


- Comprehensive ***modeling kit*** for property prediction (e.g., surface tension, wettability)

Liquid mirror modeling tool kit

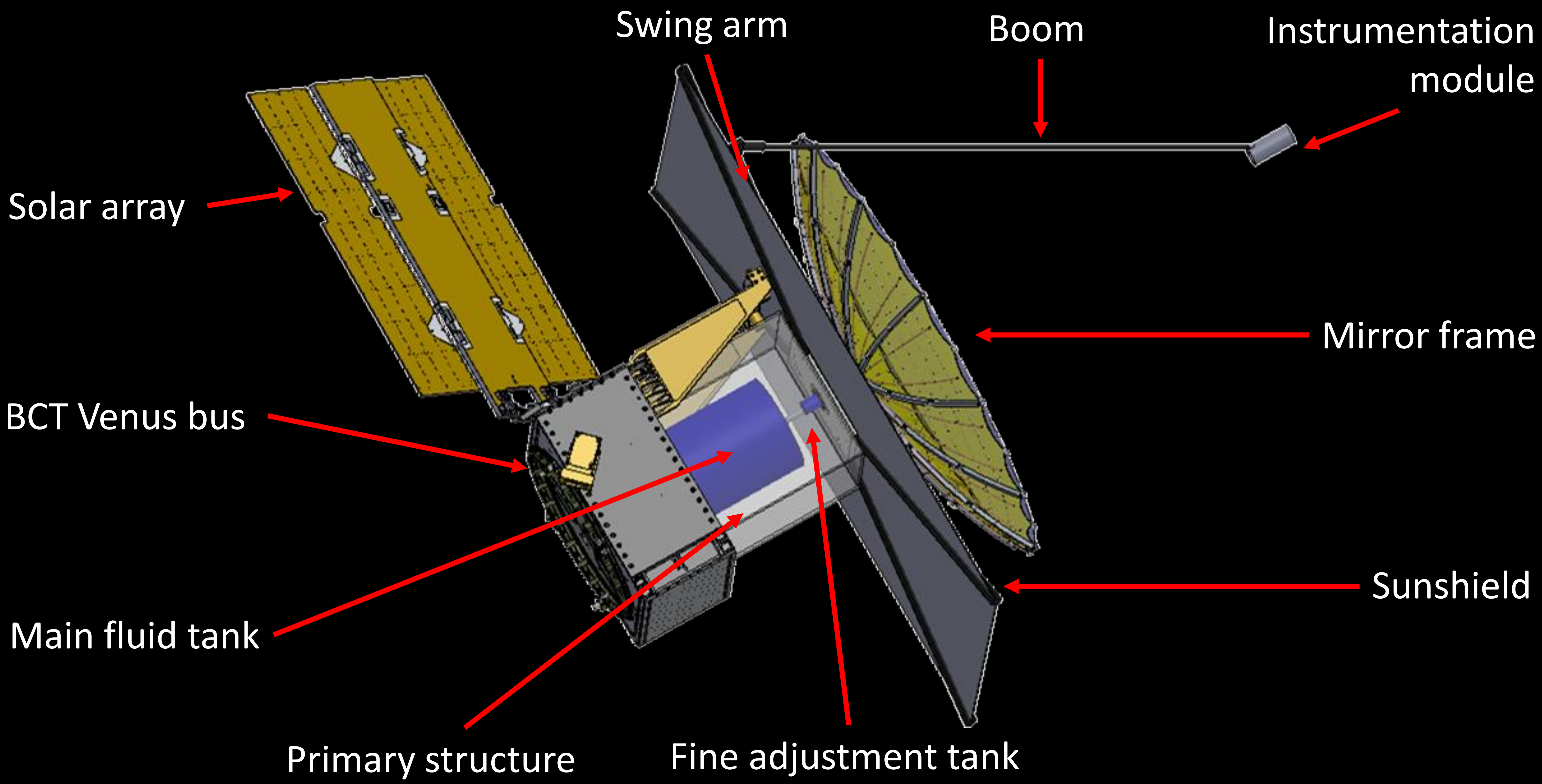
Technology demonstration mission study

- Subscale low Earth orbit mission (FLUTE-TD) to demonstrate the overall concept and reduce development risks for a large-scale observatory.
- Considered baseline as well as low-cost architecture options, both with a ~1-m liquid mirror.
- Performed analysis of key mission elements: orbits, flight dynamics, thermal factors, designs of the main subsystems (mirror frame, fluid management, and instrumentation package), and costs.
- Developed preliminary concepts of operations for baseline and low-cost options.
- Identified key risks and potential unit tests.

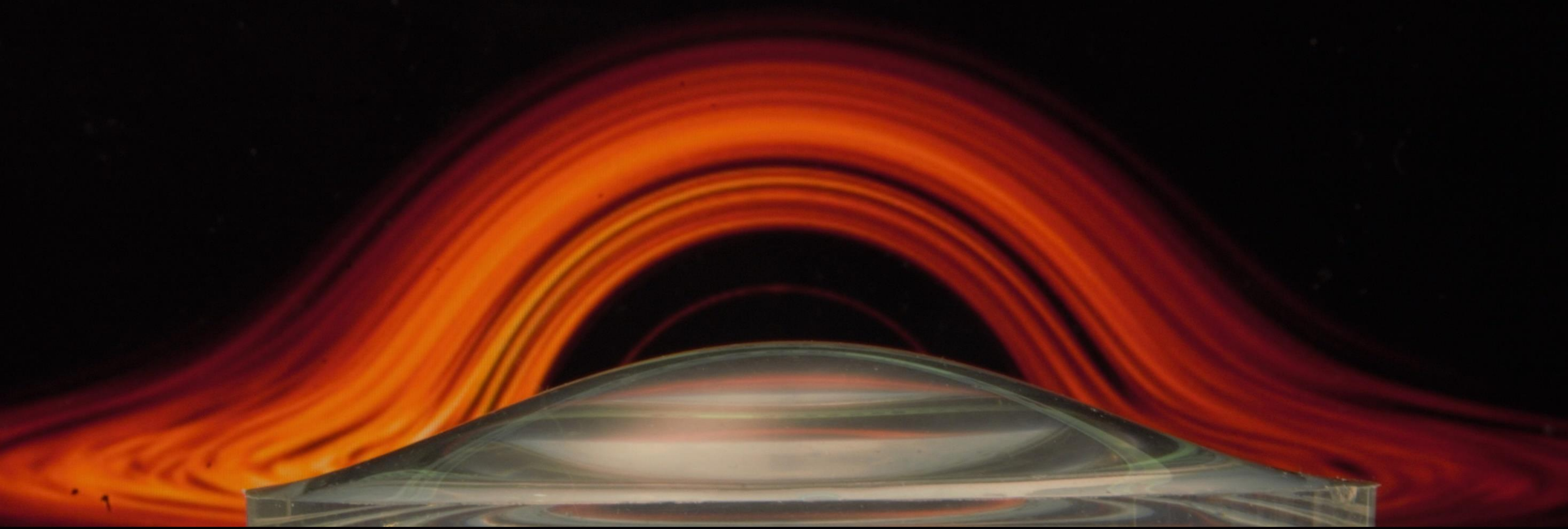


Example of a low-cost option as a payload on a shared Momentus Vigoride bus.

Example FLUTE demo mission option (baseline)



Thank you!



edward.balaban@nasa.gov