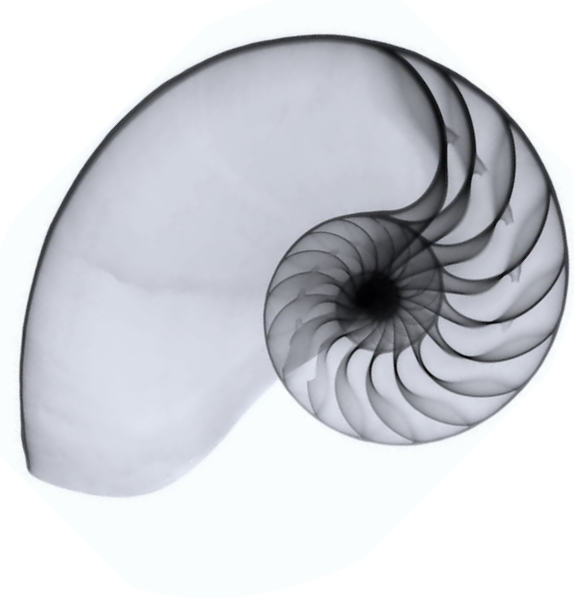




Nautilus Space Observatory

**Flagship Science with a Scalable, Modular, Sustainable,
Rapidly Deployable Architecture**

Dániel Apai (The University of Arizona)

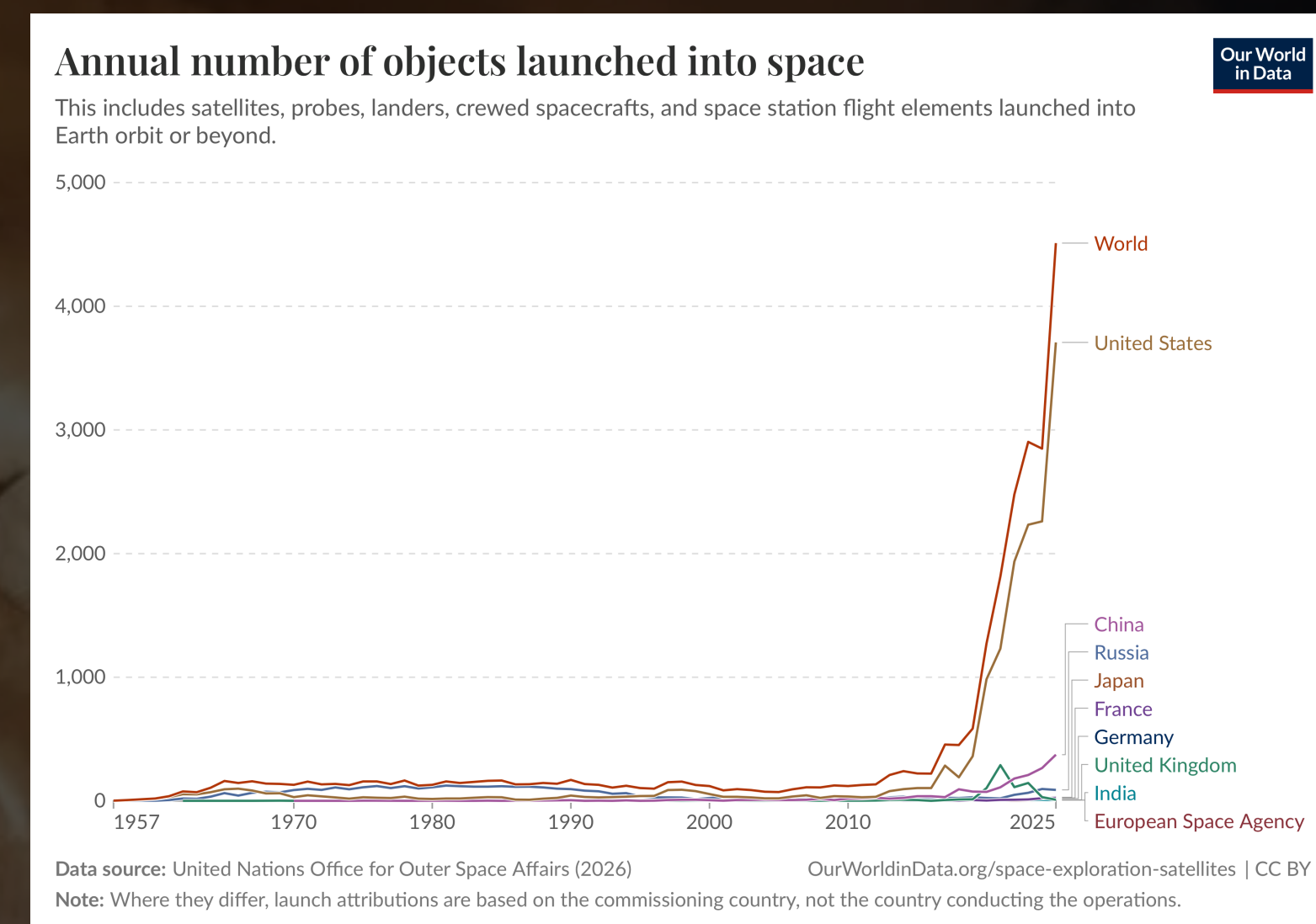
Tom Milster, Daewook Kim, Andre Wong, Young-Sik Kim, Nick Brar, Marcos Esparza, Kevin Wagner, Noah Tuchow, Cat Merrill, Heejoo Choi, Ilaria Pascucci, Chia-Lung Lin, Chaucer Langbert, Kylie Hall, Andras Gaspar (The University of Arizona), Allen Yi (OSU), Benjamin Rackham, Julien de Wit, Sara Seager, Prajwal Niraula, Ana Glidden, Artem Burdanov (MIT), Dan Goldin, Jonathan Arenberg (Northrop-Grumman); Yifan Zhou (U Virginia), Daniel Eisenstein, Robin Wordsworth (Harvard), Jeff Valenti, Mercedes López-Morales, Nestor Espinoza (STScl), Evgenya Shkolnik (ASU/Harvard), Alexander Shapiro (U Graz), Stephane Mazevet (OCA), Adina Feinstein (MSU), Luis Welbanks (ASU), Elisabeth Newton (Dartmouth), David W Miller (JPL/MIT), Valeriy Vasilyev (MPSF), Nadiia Kostogryz (MPSF), Peter Plavchan (GMU), Peter McGill (LLNL), Raymond Pierrehumbert (MIT/Oxford), Mitchell Yzer (Oxford), Kevin Hardegree-Ullman (Caltech), Hans-Walter Rix (MPIA), Stuart Shaklan (JPL); Elisa Quintana, Tom Barclay, John C. Mather, Eliad Perez (GSFC).





Space Sciences at a Turning Point

- Launch industry and access to shape completely different than a few years ago
- Space infrastructure and geopolitical landscape are disrupted
- New economical drivers, key players, new sources of funding, different goals
- Changes lead rapid innovation and competition
- Drives down costs and opens up new possibilities
- Advent of private space observatories
- Speed, Cost, Flexibility, Innovation, and Relevance Beyond NASA are important



New Science through New Mission Architectures and Approaches

Science Questions Include

What Processes Shape the Small Exoplanet Population?

A spectral library of 1,000 small exoplanets to understand the processes during the formation and evolution of Earth-sized and sub-Neptune exoplanets that shape their properties.

What are the nature of stellar explosions and black holes?

Nautilus' parallelized, rapid, sensitive, and high-precision imaging and spectroscopic follow-up of astrophysical transients will allow deeper understanding of massive stars and black holes.

How did the Universe expand? What is dark energy?

We will map the Universe's large-scale structure by surveying ~400 million galaxies with redshifts of $z=1.4-4.6$ through redshifted [OIII] and H α lines.

What is the nature of stellar activity and how does it impact planetary habitability?

We will sample stellar flares and outbursts with high-cadence, broad-band spectroscopy to refine the temperature evolution and energy released by flares.

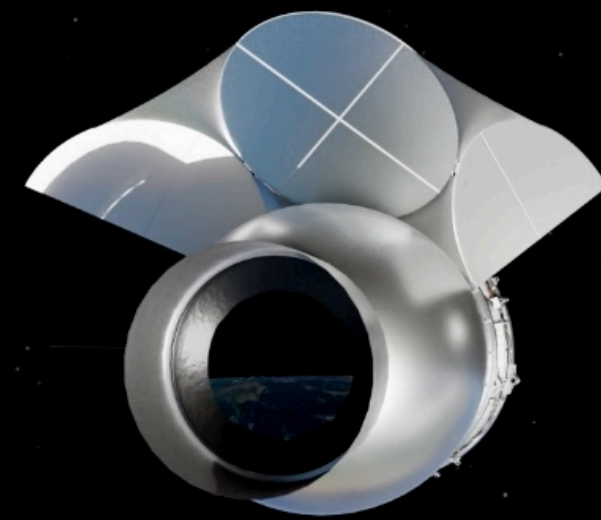
... and beyond



Two Telescopes, Two Instruments: Four Combinations

Nautilus Quattro D=4m telescope

>0.2 deg² FOV
f/6 beam, 0.3-2.8 μm



Wide FOV Imager and Slitless Spectrograph

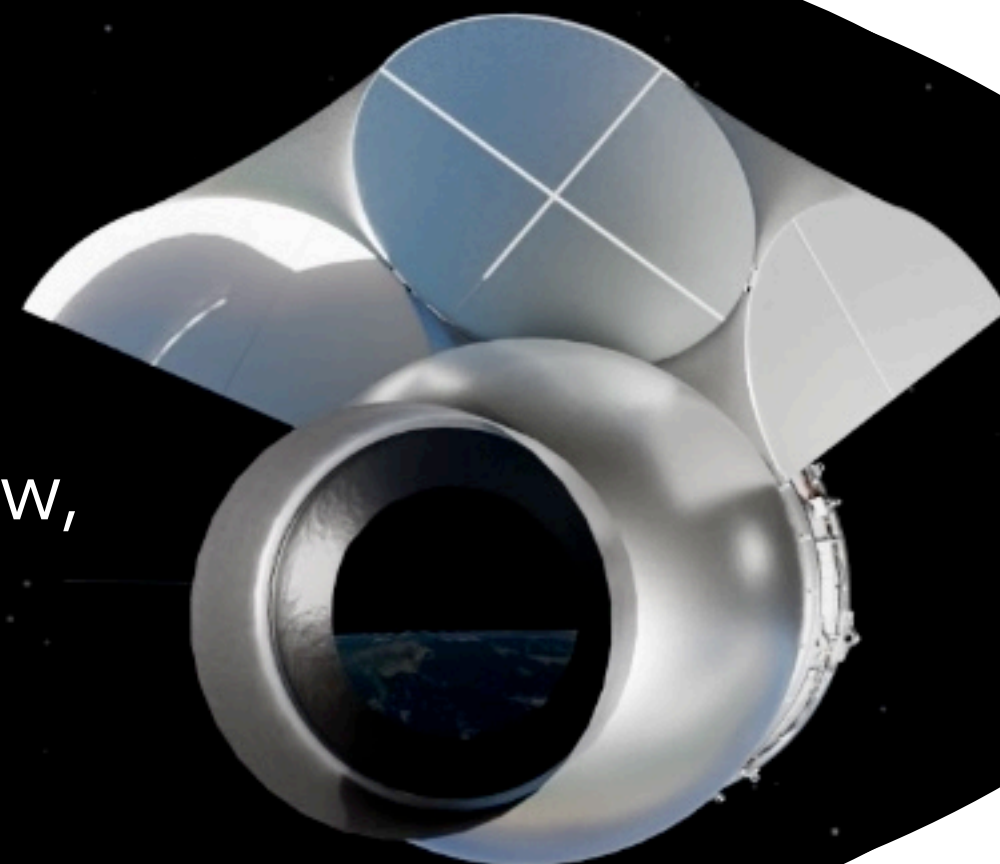
- 12 x 12 array of 4Kx4K NIR sensors
- 17 mas/pixel
- R~100 slitless imaging spectroscopy over 0.3-1.7 μm

Broadband Spectrograph

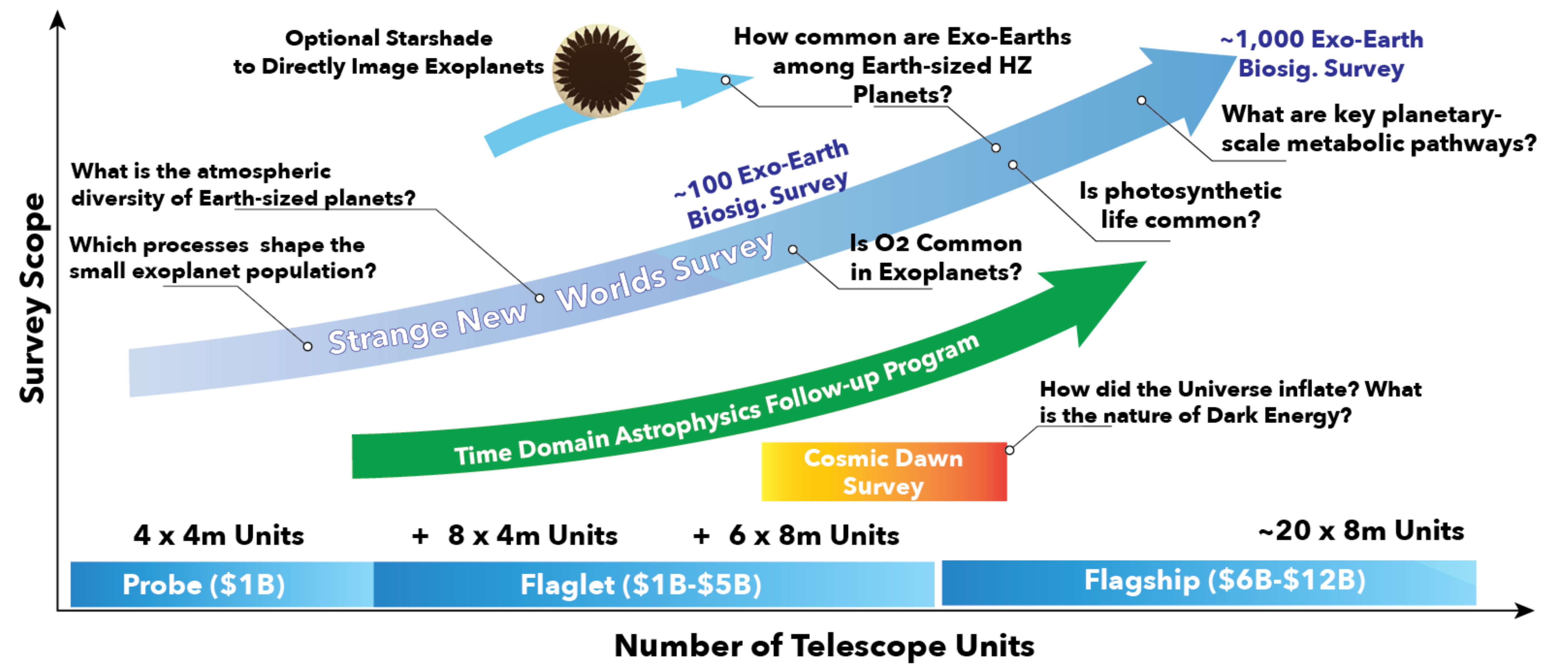
- R~1,000 single-shot slit spectroscopy over 0.3-2.8 μm
- Four separate arms with grism
- CMOS and cryogenic 4K x 4K HgCdTe sensors
- 1 ppm spectrophotometric precision (post processing)

Nautilus Otto D=8m telescope

>0.2 deg² Field of view,
f/6 beam, 0.3-2.8 μm



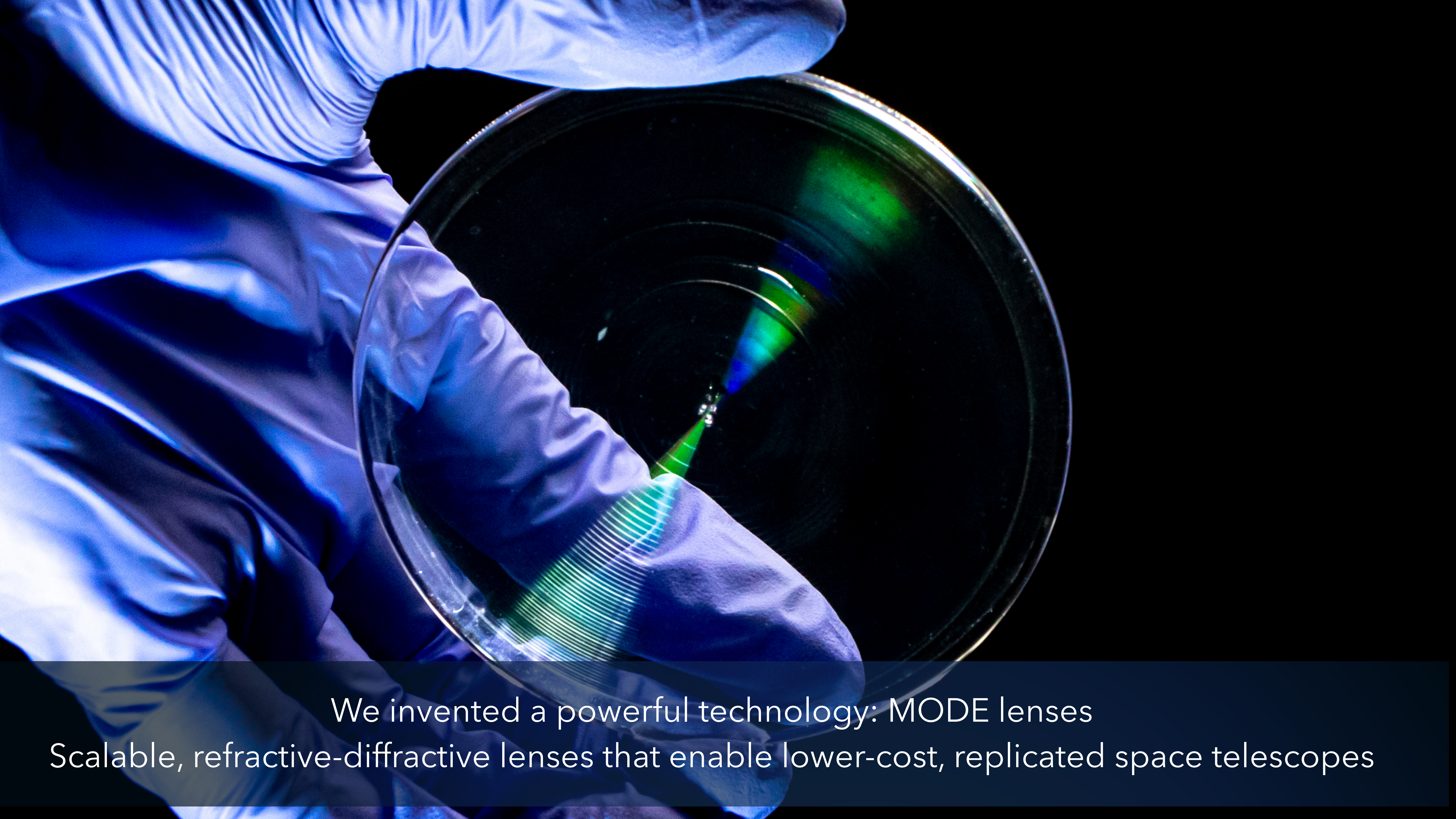
Representative Configurations and Surveys for Nautilus: A Modular, Scalable, Strategic Observatory



Nautilus is Scalable, Incrementally Deployable, and Expandable



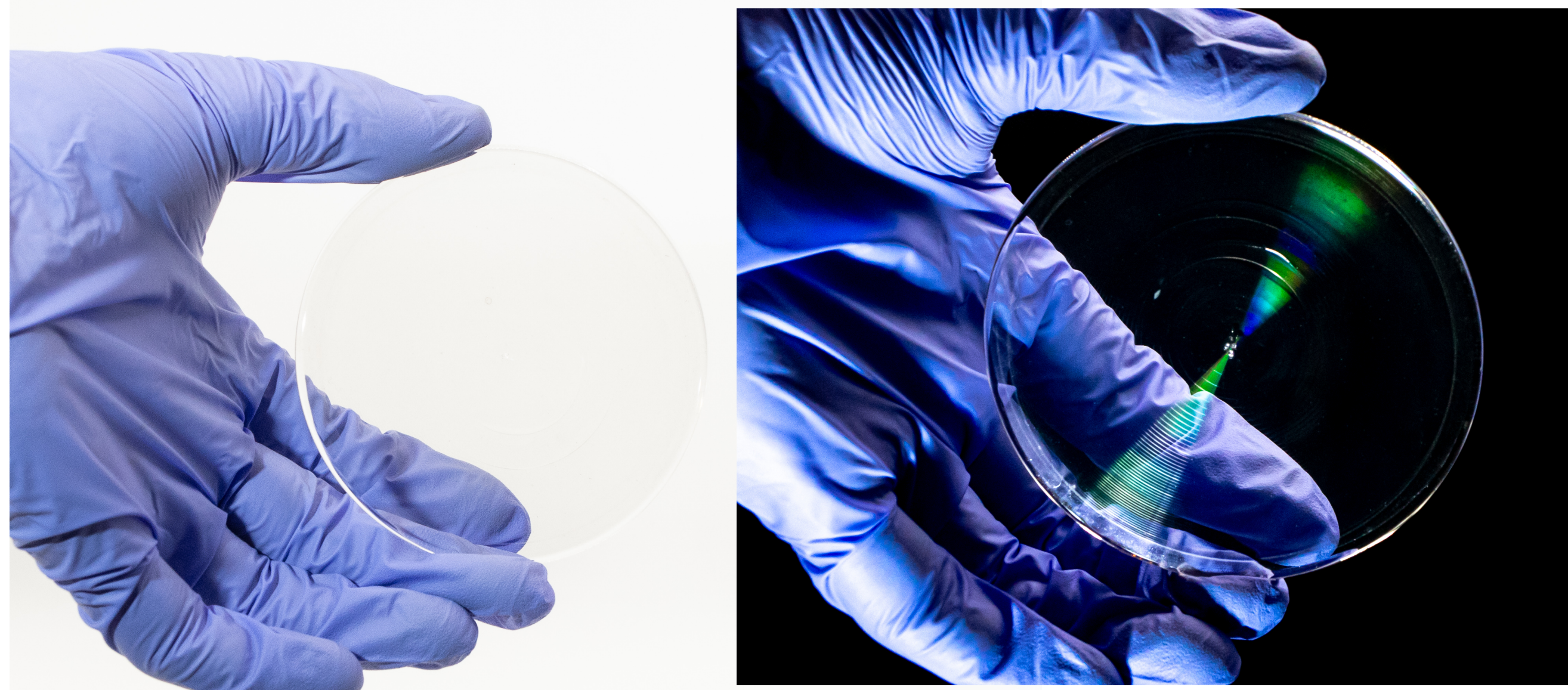
Large optics invented to allow low-cost, rapid fabrication
Just like how car windshields are produced



We invented a powerful technology: MODE lenses

Scalable, refractive-diffractive lenses that enable lower-cost, replicated space telescopes

New Technology: Hybrid, Flat Lenses



Rapid, Cost-Effective, High Quality

- Hybrid Diffractive-Refractive Lenses ("MODE")
- Mass producible alternatives to primary mirrors
- Ultra broad-band, high image quality ($\sim 0.25\text{-}3\mu\text{m}$)
- Ultra wide FOVs, low-cost systems
- Imaging, Spectroscopy, high-precision photometry
- 25+ publications, prototypes, passed TVAC/Vibe
- Space demonstration scheduled for 2028
- At UA: World's largest facility for rapid production of large space optics
- Goal: Hubble-like (2m) optics: One per day
- 5m lens: One per week
- 8m lens: Two per month



A dramatic photograph of a space shuttle launch. The shuttle is positioned vertically, with its white solid rocket boosters and orange external tank clearly visible. A massive, billowing plume of white smoke and fire erupts from the base, filling the lower half of the frame. The upper half shows the dark sky and the top of the shuttle's structure. The overall scene is one of immense power and technological achievement.

Funding through Partnerships

Fundable - High ROI Technology

Space economy projected to grow to
\$1.8T/year by 2035 (McKinsey Report)

Estimated Investment in space-based observations ~\$50B/yr

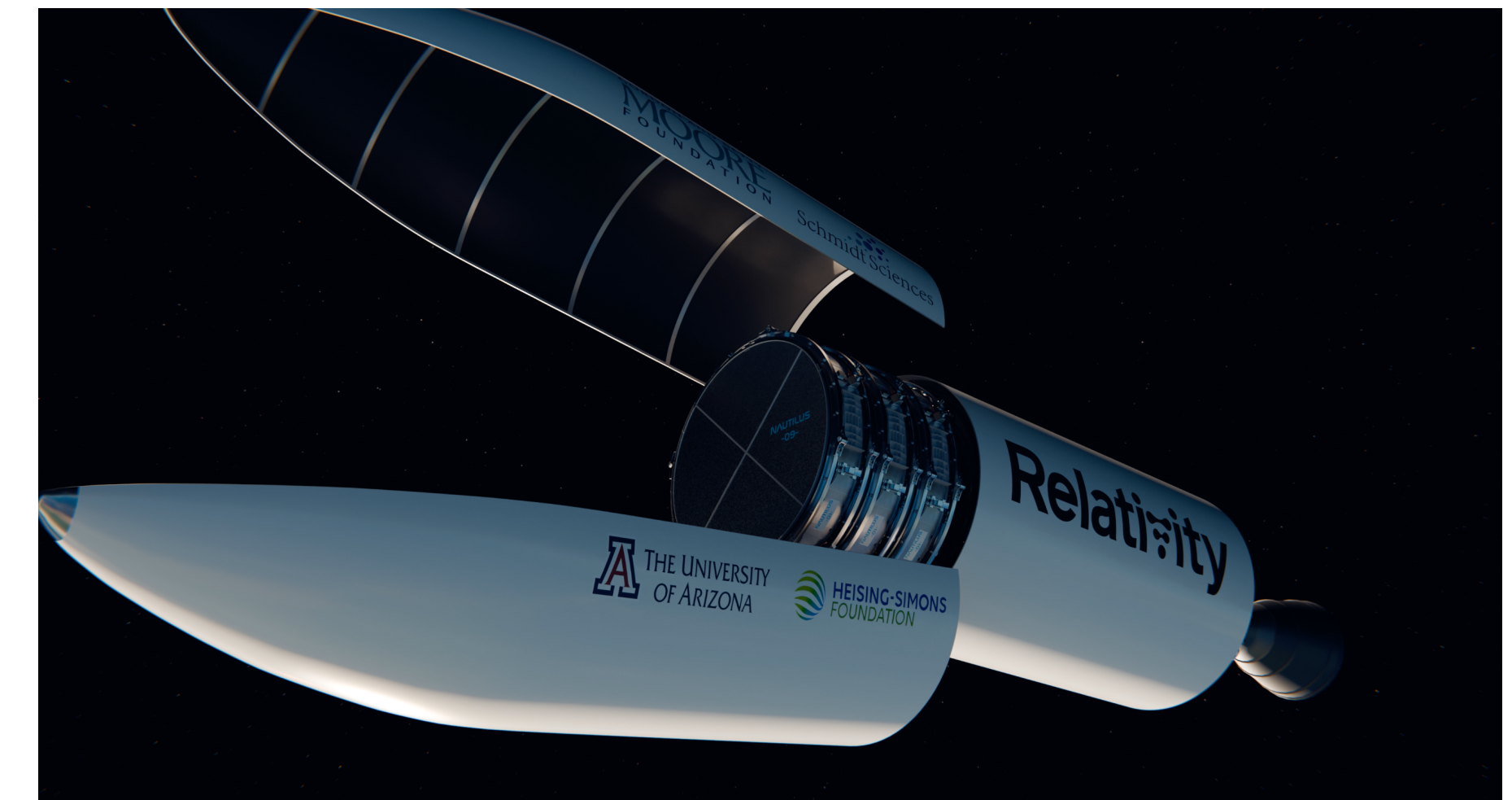
← Approx. NASA Flagship Budget (~\$400M/yr)

Estimated number of space-based imaging systems: > 1,000

Vast potential for innovative solutions: Huge amount of funding available, intense competition, rapidly expanding market, tech-savvy investors and donors

"Are you ready to launch?"

- Our technology development funded independently of NASA
- \$25M+ Raised from five sponsors (moved from TRL1 to TRL6)
- Spin-off to commercialize tech and fast-track TRL and MRL



Nautilus Science Case Workshop

MIT EAPS | May 11–13, 2026

Sponsored by the Heising-Simons Foundation



Strong Community Support

Already >40 papers citing Nautilus science
5 white papers on Nautilus Science on arXiv; 2 close to completion; 5 in prep.
>\$1M in funding for science case development

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<https://doi.org/10.3847/1538-3881/ab2631>



A Thousand Earths: A Very Large Aperture, Ultralight Space Telescope Array for Atmospheric Biosignature Surveys

Dániel Apai¹, Tom D. Milster², Dae Wook Kim², Alex Bixel³, Glenn Schneider³, Ronguang Liang⁴, and Jonathan Arenberg⁵

¹ Steward Observatory and the Lunar and Planetary Laboratory, The University of Arizona, Tucson, AZ 85721, USA; apai@arizona.edu

Unveiling the Diversity and Origin of Sub-Neptunes with the Nautilus Space Observatory

Luis Welbanks¹, Kylie E. Hall², Julien de Wit³, Ana Glidden^{3,4}, Noah Tuchow², Ilaria Pascucci⁵, Dániel Apai^{6,2,7}, Robin Wordsworth^{8,9}, Benjamin V. Rackham^{3,4}, Chia-Lung Lin⁶, Raymond Pierrehumbert³, Mercedes López-Morales¹⁰ and Adina D. Feinstein¹¹

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² Lunar and Planetary Laboratory, University of Arizona, 1629 E. University Boulevard, Tucson, AZ 85721, USA

³ Department of Earth, Atmospheric and Planetary Science, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge,

A Scalable Path to Astrometric Exomoon Discoveries with the Nautilus Space Observatory

Kevin Wagner¹, Sumin Seung^{1,2}, Dániel Apai^{3,4,5}, Enrico Biancalani^{6,7,8}, Eduardo Bendek⁹, Samantha Hasler⁵, Nadia Kostogryz¹⁰, Sowmya Krishnamurthy¹¹, Mercedes López-Morales¹², Peter McGill¹³, Peter Plavchan¹⁴, Benjamin V. Rackham¹⁵, Alexander Shapiro¹¹, Noah Tuchow¹, S. Pete Worden^{16,1} and Yifan Zhou¹⁷

¹ Steward Observatory, University of Arizona, Tucson, AZ, USA

² Department of Earth Science Education, Seoul National University, Seoul, Republic of Korea

Nautilus Space Observatory: The Evolution of Planets and their Atmospheres

Ilaria Pascucci^{1,2}, Noah Tuchow¹, Yifan Zhou³, Dániel Apai^{2,1,4,5}, Chaucer Langbert¹, Ana Glidden⁵, Luis Welbanks⁶, Chia-Lung Lin², Adina D. Feinstein⁷, Benjamin V. Rackham^{5,8}, Peter Plavchan⁹, Kevin Wagner¹⁰, Raymond Pierrehumbert¹¹ and Robin Wordsworth¹²

¹ Lunar and Planetary Laboratory, University of Arizona, 1629 E. University Boulevard, Tucson, AZ 85721, USA

² Steward Observatory, The University of Arizona, 933 N. Cherry Avenue, Tucson, AZ 85721, USA

Mapping Stellar Heterogeneities with the Nautilus Space Observatory

Adina D. Feinstein¹, Jeff Valenti², Julien de Wit³, Valeriy Vasilyev⁴, Chia-Lung Lin⁵, Dániel Apai^{5,6,7}, Ana Glidden^{3,8}, Prajwal Niraula^{3,8}, Peter Plavchan⁹, Benjamin V. Rackham^{3,8}, Noah Tuchow⁵ and Luis Welbanks¹⁰

¹ Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824 USA

² Space Telescope Science Institute, 3700 Charles St., Baltimore, MD 21218

Nautilus: Fast Time-Resolved Spectroscopy of GKM Stellar Flares and Their Implications for Planetary Habitability

Chia-Lung Lin¹, Adina D. Feinstein², Jeff Valenti³, Mark S. Giampapa^{1,4,5}, Dániel Apai^{6,7,8}, Julien de Wit⁹, Valeriy Vasilyev¹⁰, Alexander Shapiro^{10,11}, Prajwal Niraula^{9,12}, Benjamin V. Rackham^{9,12}, Noah Tuchow¹, Ana Glidden^{9,12} and Nadia Kostogryz¹⁰

¹ Steward Observatory, The University of Arizona, Tucson, AZ 85721, USA

² Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824 USA

New Paradigm: Constellation-based Observatory

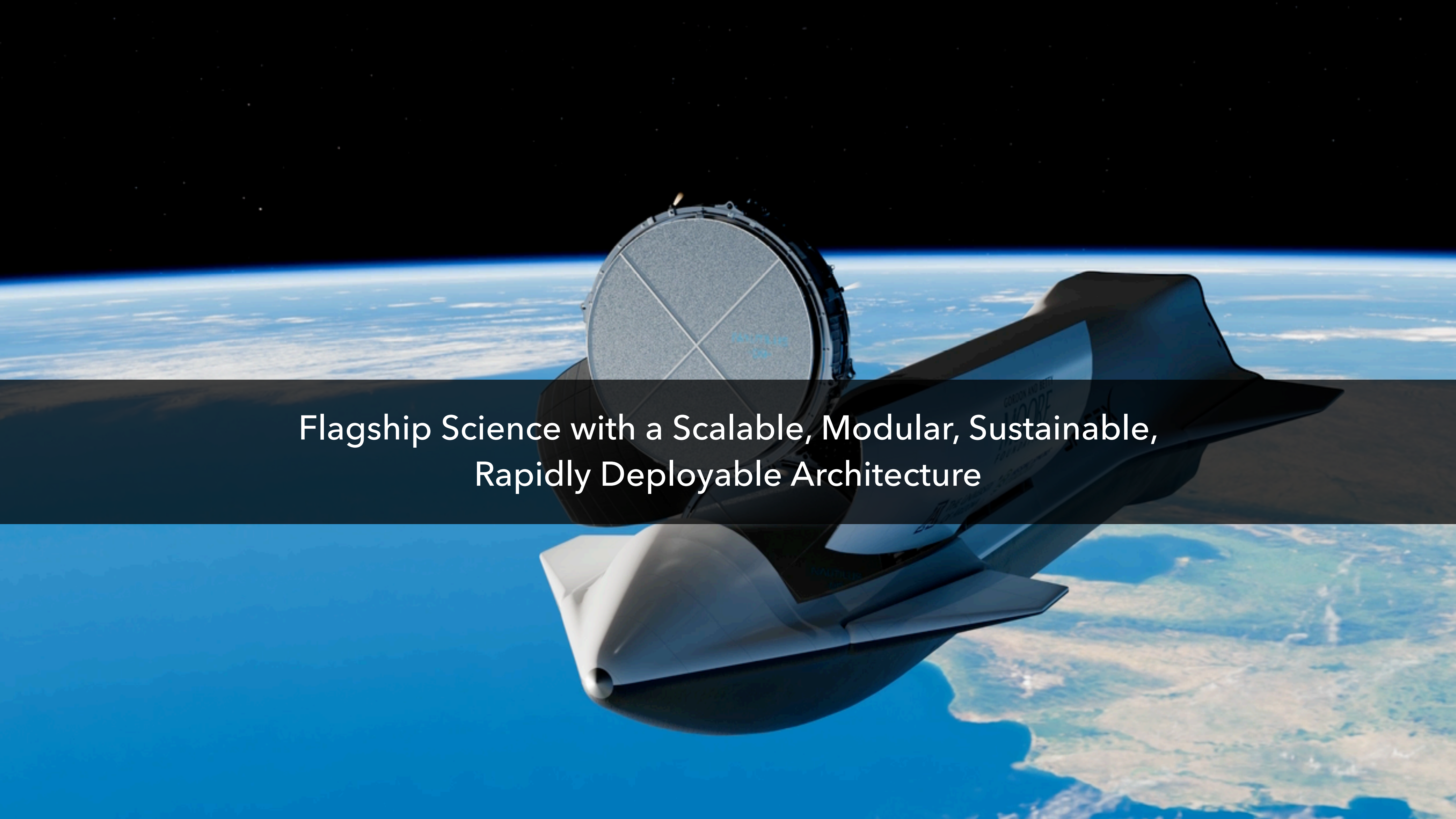


Constellation-based Observatory

- 10x-100x Greater Sensitivity
- 100x Greater Survey Efficiency
- Scalable: Probe - Small/Full Flagship
- Flexible, Modular Architecture
- Made for Mass-producibility
- Sustainable, Expendable, Redundant
- Operational Flexibility: Parallel or Coordinated Observations
- Ideal for Public-Private Partnerships

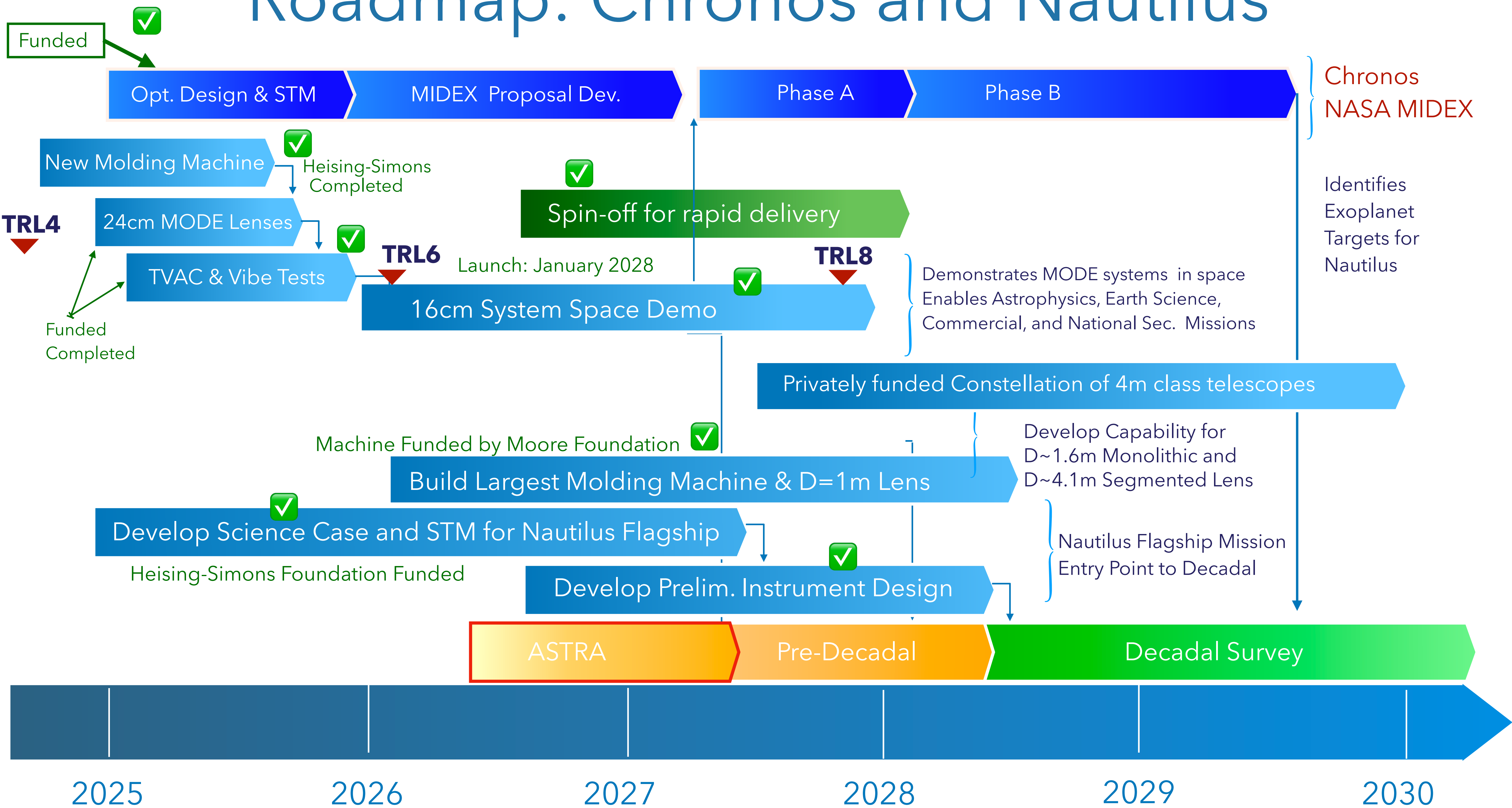
Nautilus Tech is Specifically Developed for Constellations

- \$9M raised, ~\$15M+ committed
- 25+ publications, multiple gen. of prototypes
- High optical quality
- Mass produceable at low cost
- Novel, Independently-funded Technology - at TRL6
- Rapid Execution Pathway
- Very Broad Science Scope
- Very high ROI on Technology Development
- Diverse funding streams

A hypersonic glide vehicle, identified as the Nautilus-class, is shown in a high-altitude orbit above Earth's atmosphere. The vehicle is white with a dark, conical nose and a large, circular sensor dish mounted on its side. The dish is divided into four quadrants and has the word "NAUTILUS" and the number "500" printed on it. The vehicle is angled towards the right, and the Earth's horizon is visible in the background. The text "Flagship Science with a Scalable, Modular, Sustainable, Rapidly Deployable Architecture" is overlaid on the image.

Flagship Science with a Scalable, Modular, Sustainable,
Rapidly Deployable Architecture

Roadmap: Chronos and Nautilus



MOORE
FOUNDATION

Schmidt Sciences

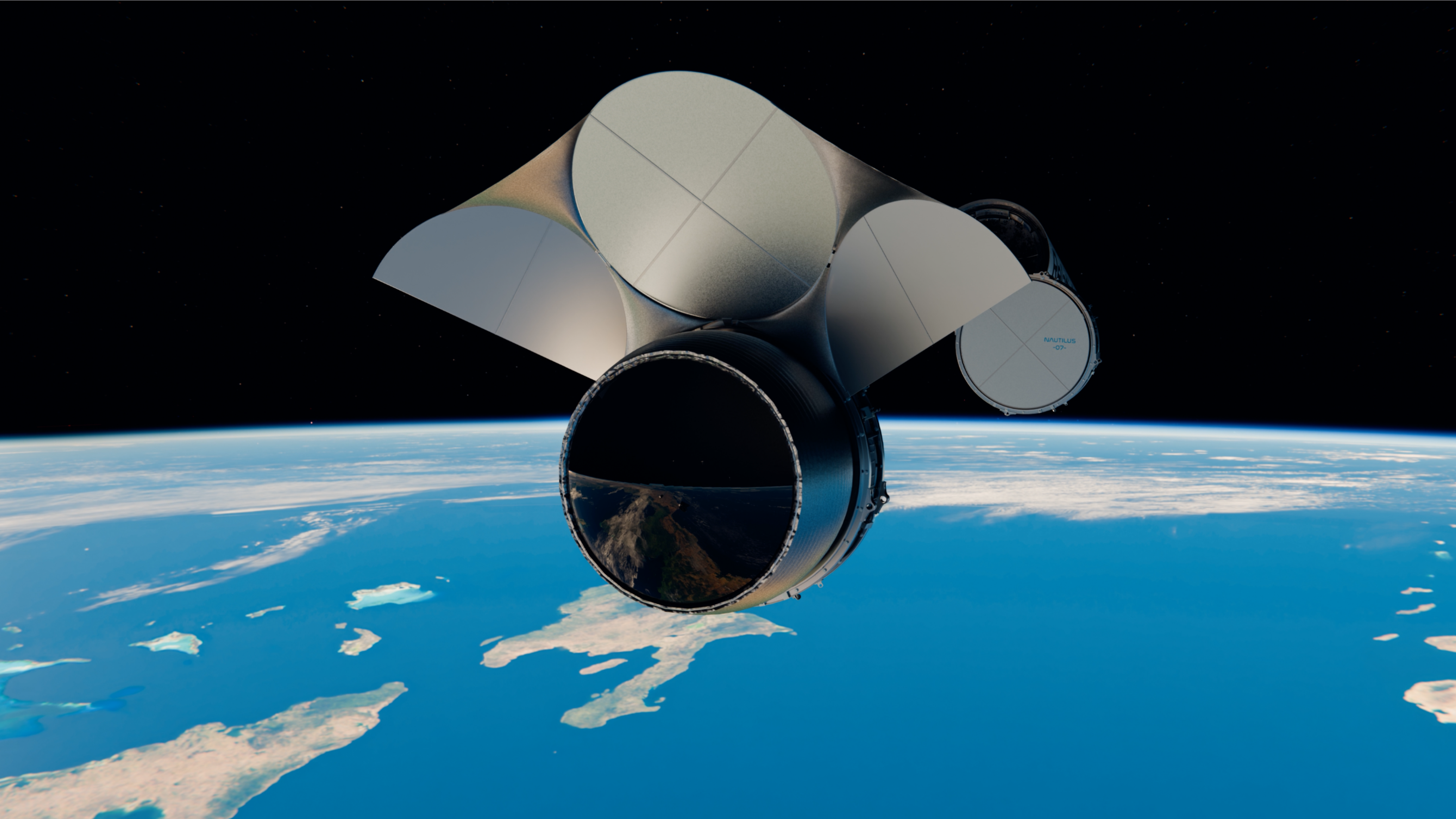
NAUTILUS
-09-

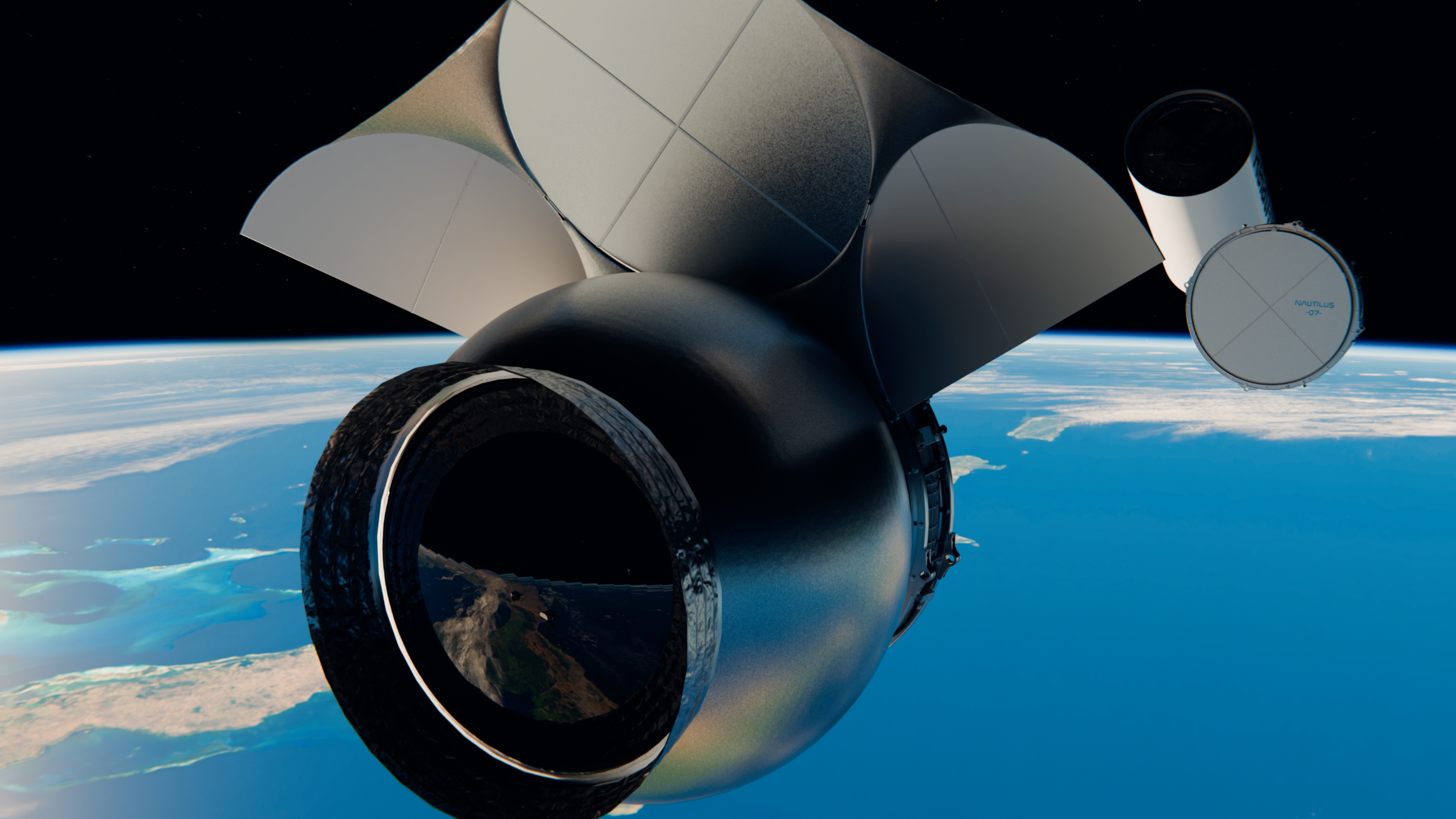
Relativity

 THE UNIVERSITY
OF ARIZONA

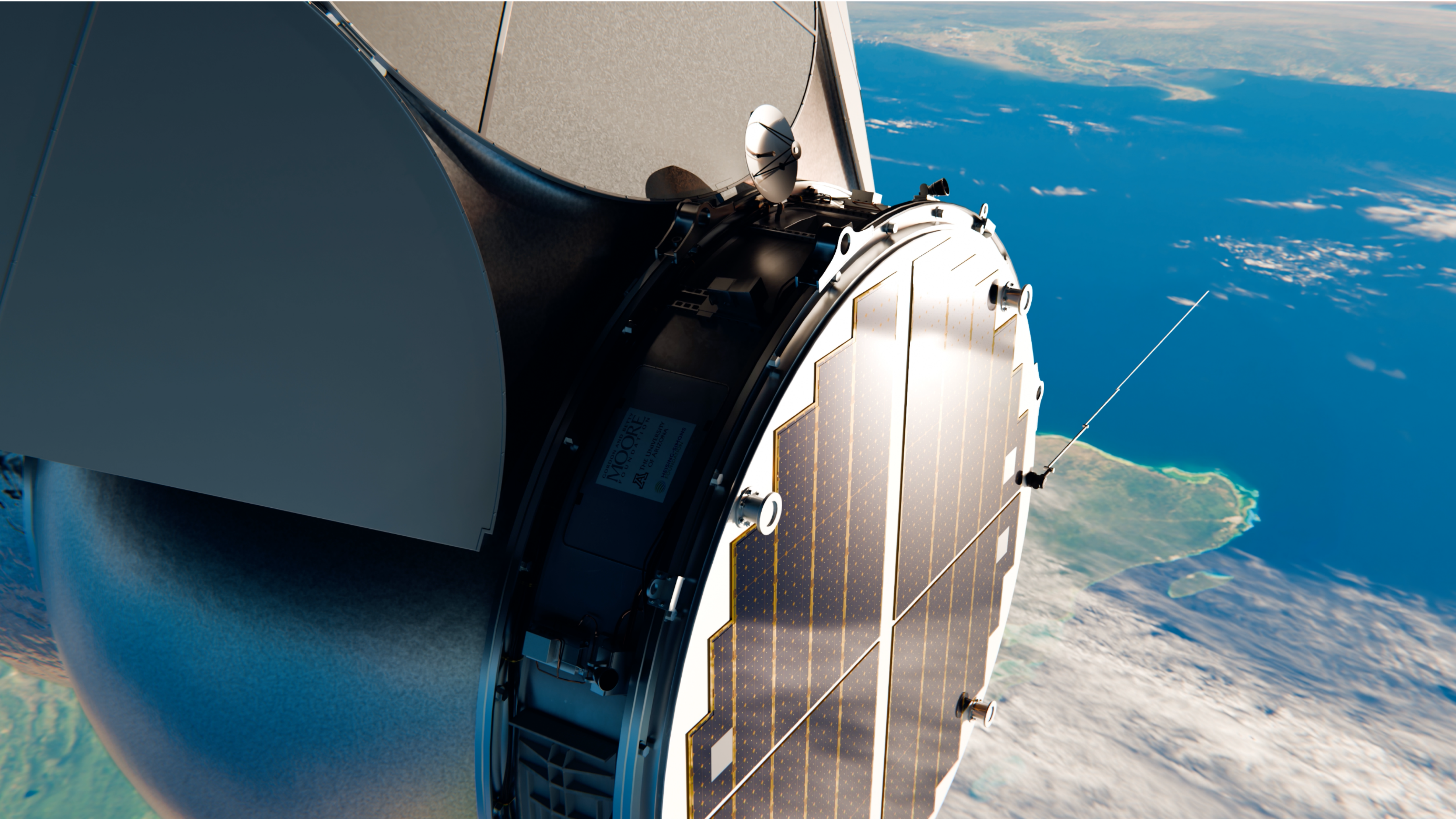
 HEISING-SIMONS
FOUNDATION

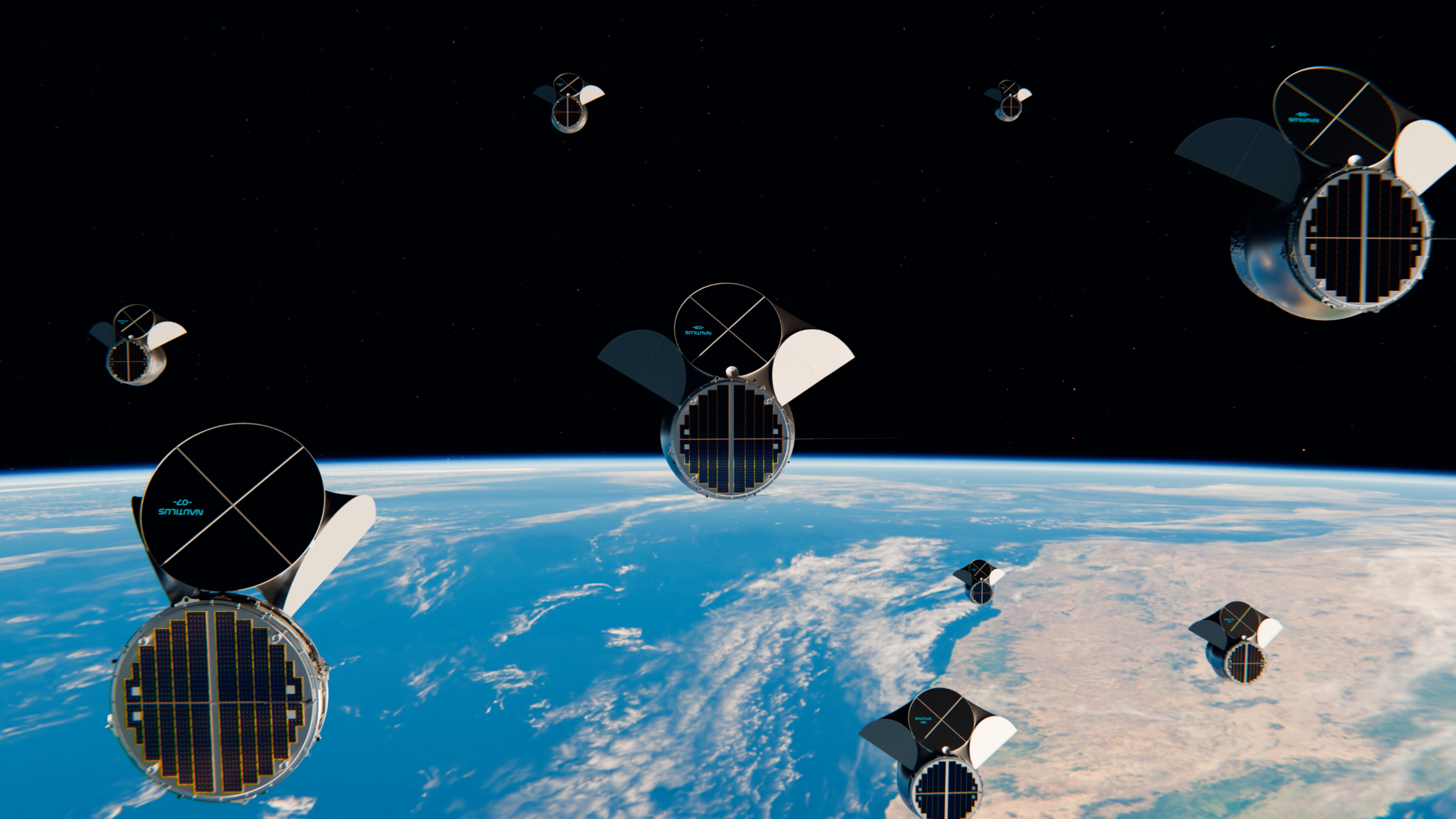


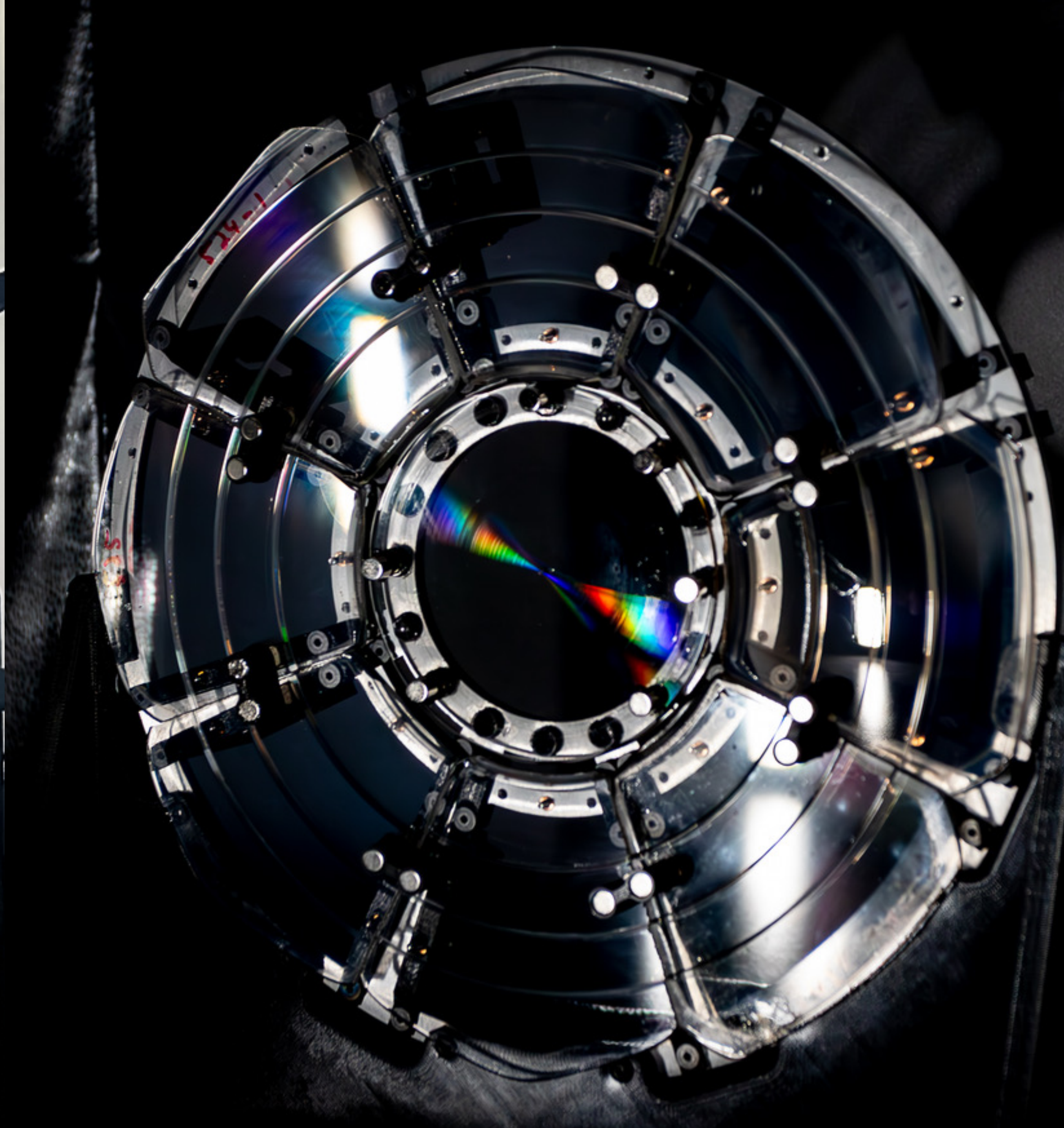




NAUTILUS
-07-







World's largest multi-order molded diffractive lens in alignment mechanism



Integration tests of a 24cm ground-based demonstrator



On-sky Tests of a 24cm ground-based demonstrator in the Mt Lemmon Sky Center



On-sky Tests of a 24cm ground-based demonstrator in the Mt Lemmon Sky Center

Nautilus Sessions at SPIE Optics & Photonics 2022

Double session at SPIE 2022 – Room overflow, very enthusiastic reception

- 12221-13** *Nautilus Space Observatory: A very large aperture space telescope constellation enabled by scalable optical manufacturing technologies* Daniel Apai et al.
- 12221-14** *Type 2 longitudinal chromatic aberration from a high-harmonic MODE lens and color corrector*
Thomas D. Milster, Youngsik Kim, Zichan Wang
- 12221-15** *Fabrication, assembly, and testing of a MODE lens color corrector,* Zichan Wang et al.
- 12221-16** *Stray light analysis and testing of a MODE lens telescope,* Youngsik Kim et al.
- 12221-17** *Precision glass molding technology for the MODE lens telescope,* Nick Brar et al.
- 12221-18** *Autonomous closed-loop control for multi-segmented optic aligning and assembly,* Heejoo Choi et al.
- 12221-19** *Automatic alignment of multi-order diffractive engineered (MODE) lens segments using the kinematically-engaged yoke system (KEYS) for optical performance testing,* Marcos A. Esparza
- 12221-20** *Initial testing of a MODE lens telescope,* Youngsik Kim et al.