Nautilus Probe

A Very Large Diameter, Ultralight Space Telescope for Exoplanet Exploration, Faint Objects, and Time-domain Astrophysics

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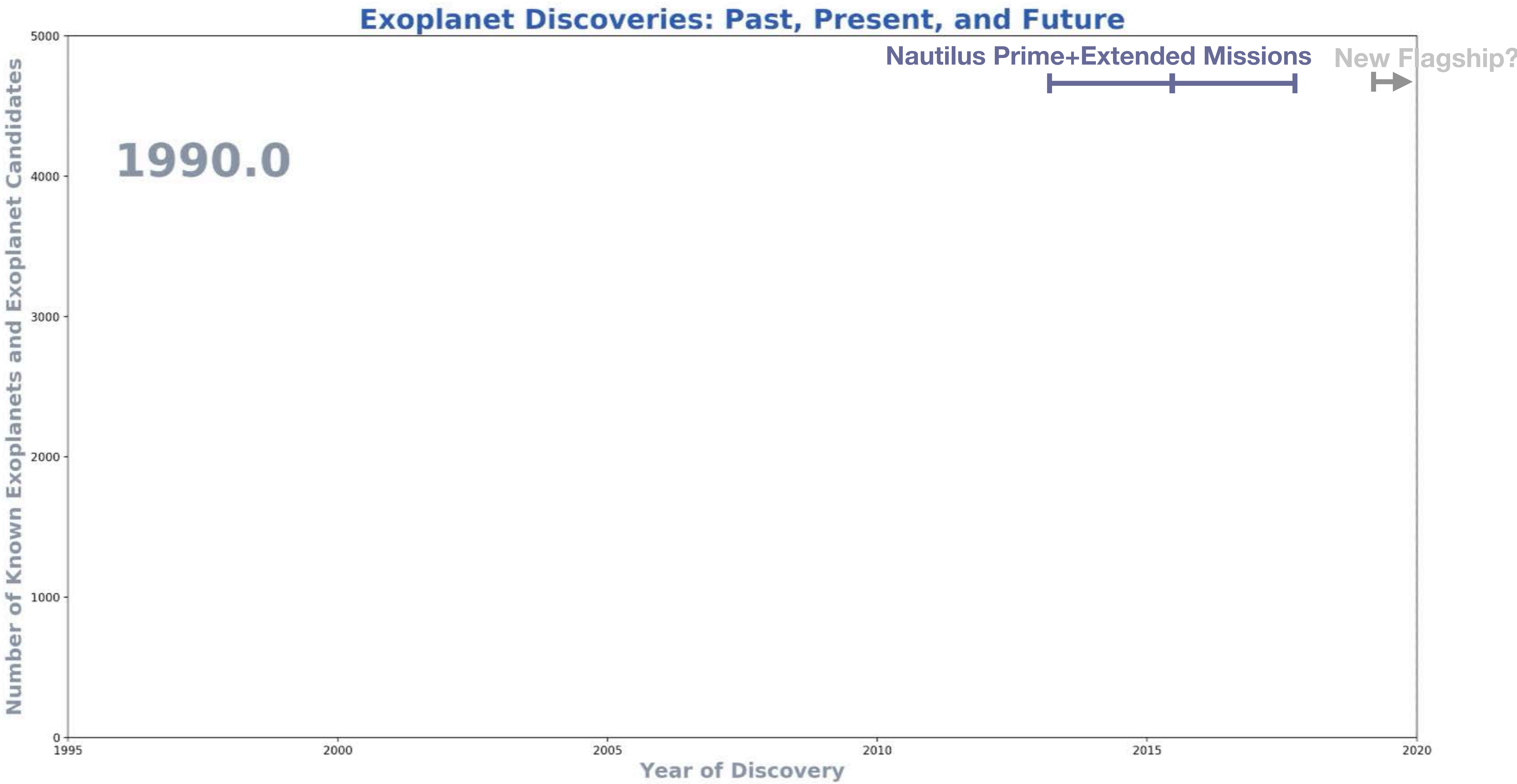
Jonathan Arenberg (Northrop-Grumman Aerospace Systems)

Benjamin Rackham (MIT), Kevin Heng and Chloe Fisher (CSH, U Bern)

THE UNIVERSITY OF ARIZONA | THE UNIVERSITY OF ARIZONA Wyant College of Optical Sciences | THE UNIVERSITY OF ARIZONA COLLEGE OF SCIENCE Astronomy & Steward Observatory | COLLEGE OF SCIENCE LUNAR & PLANETARY LABORATORY | GORDON AND BETTY MOORE FOUNDATION


Exoplanet Discoveries: Past, Present, and Future
Nautilus Prime+Extended Missions
New Flagship?
1990.0
Number of Known Exoplanets and Exoplanet Candidates
5000
4000
3000
2000
1000
0
1995
2000
2005
2010
2015
2020
Year of Discovery

Nautilus Probe Science Objectives

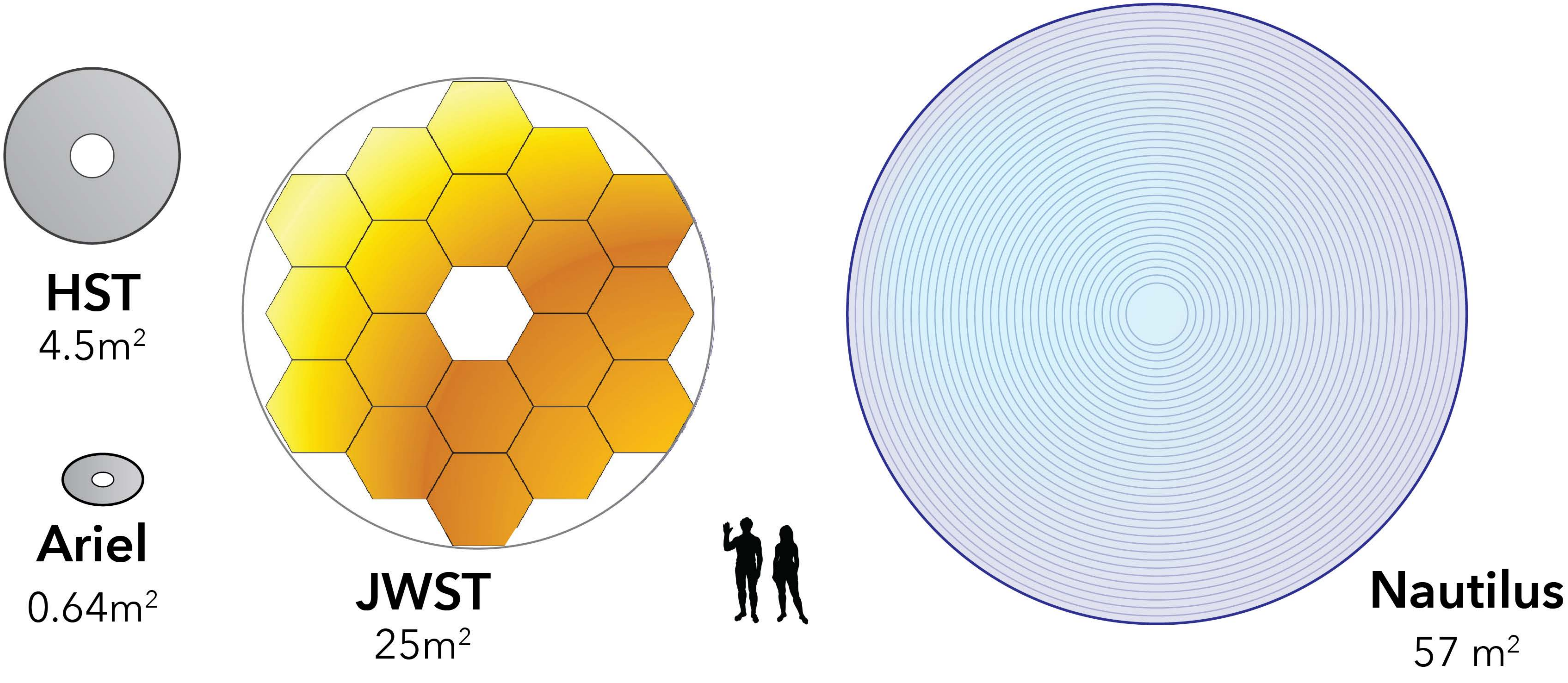
Objective 1) To understand the diversity of extrasolar planet atmospheres by building a large, uniform transmission spectral library of the atmospheres of small extrasolar planets, from sub-earths to neptune-sized worlds.

Objective 2) To determine the atmospheric compositions of ~500 extrasolar planets.

Objective 3) To identify the processes that shape planetary atmospheres by testing connections between atmospheric composition, orbital properties, stellar irradiation, planet mass, and planet density.

Objective 4) To identify and characterize habitable planets with atmospheric abundances that are unlikely to be consistent with abiotic processes.

Nautilus Probe Offers Greater Collecting Area for Exoplanet Transmission Spectroscopy than HST, JWST, and ARIEL combined

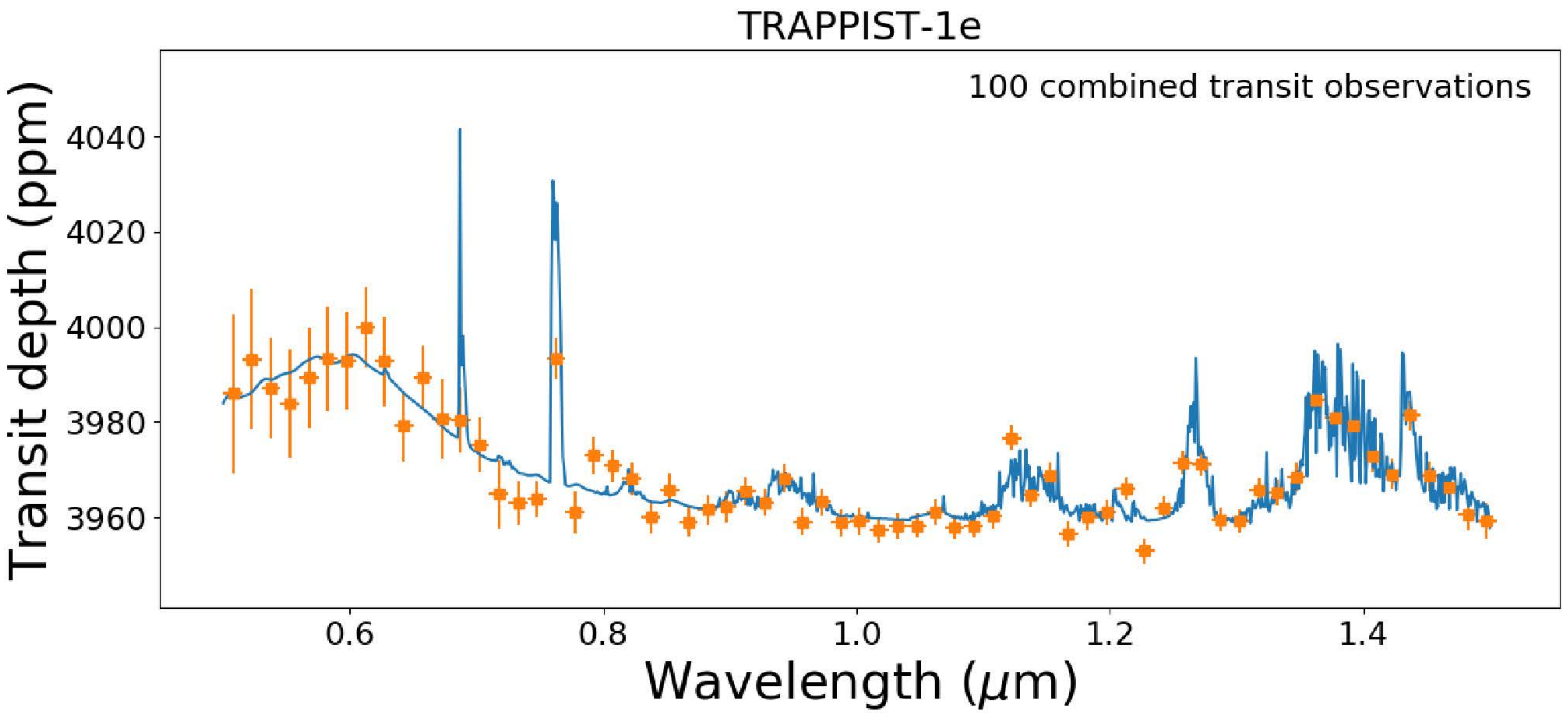


Nautilus Probe

Nautilus Science Program

Program	Time
Exoplanet Diversity Survey What is the atmospheric diversity of rocky exoplanets? Which processes shape the atmospheres of rocky exoplanets? Which nearby transiting planets are habitable? Which planets are likely to harbor life?	**65%**
Time-domain Astrophysics Program What are the properties and nature of gravitational wave sources? What mechanisms fuel transients?	**10%**
General Observer Program Community-driven program exploring the most important questions from asteroids to the high-red shift universe	**25%**

Earth-like Atmosphere without cloud opacity



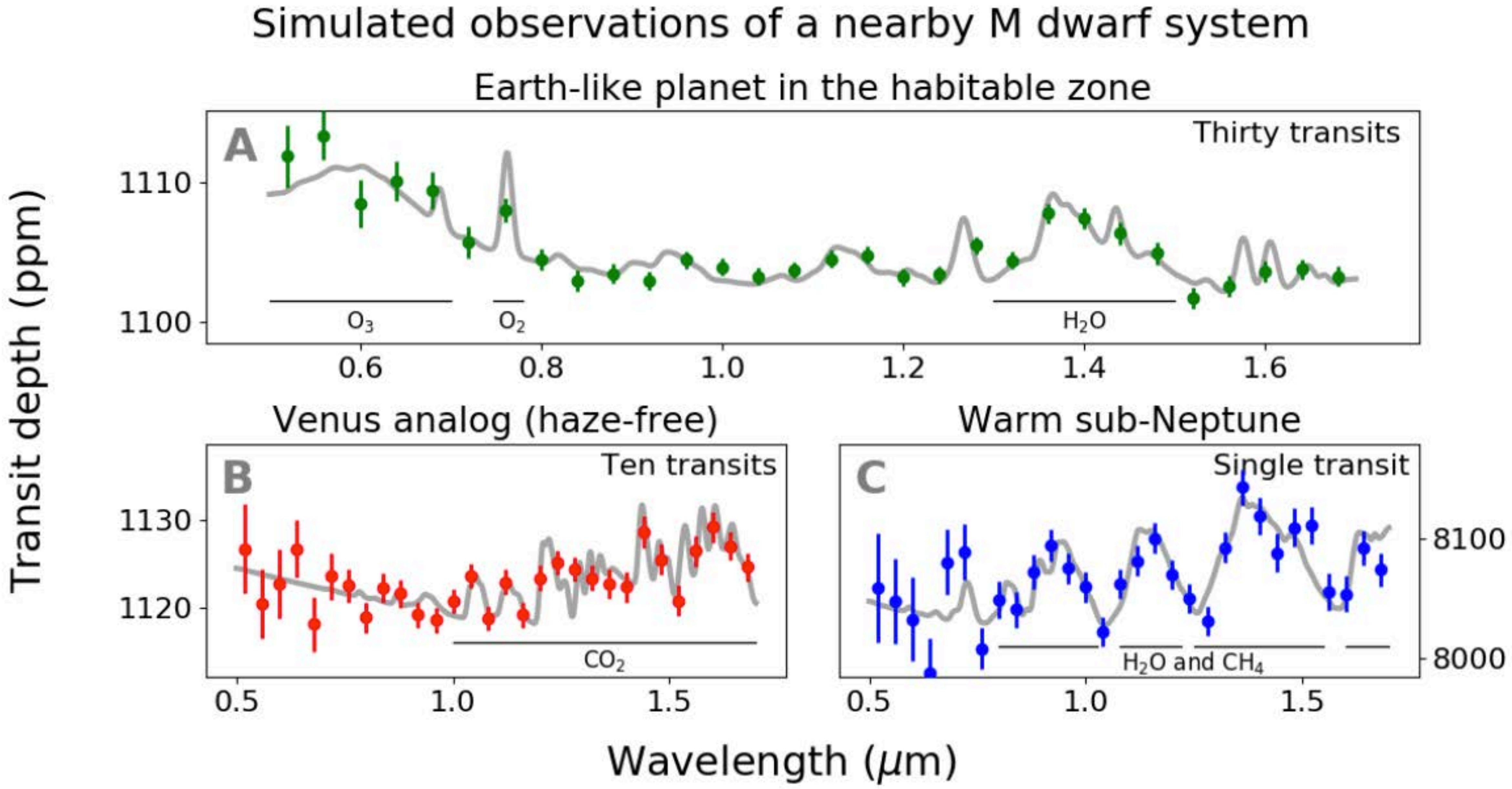
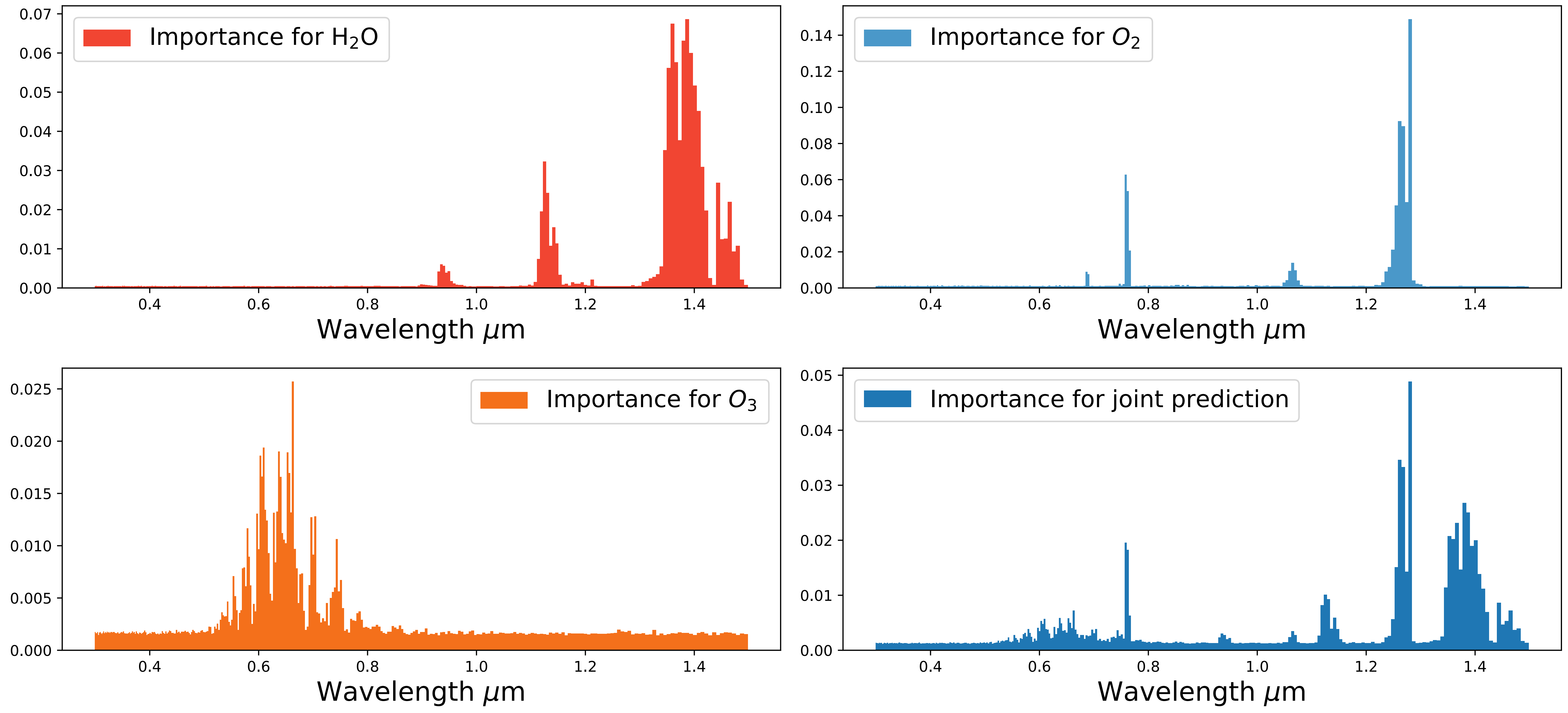


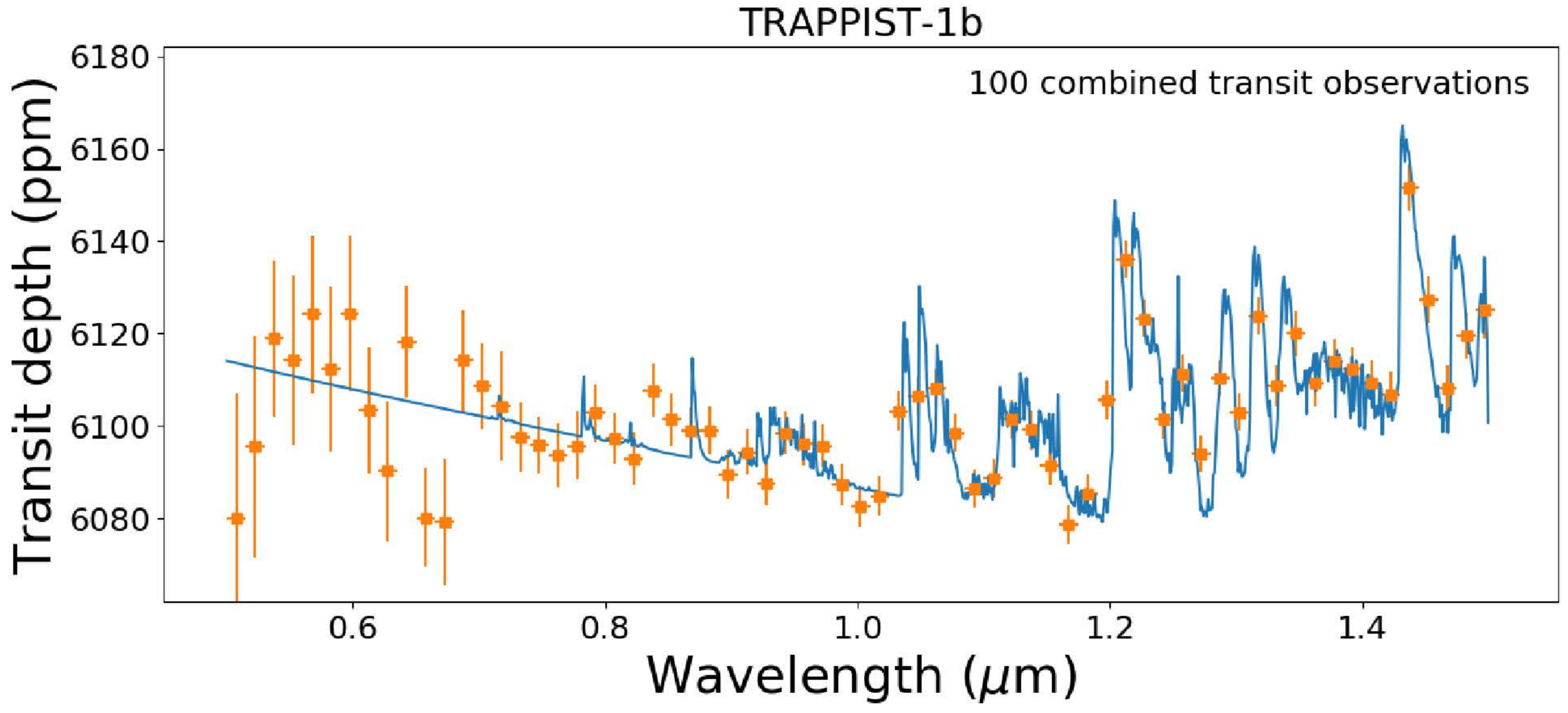
Table 1: Science requirements and design solutions.

SCIENCE OBJECTIVE	PERFORMANCE REQUIREMENT	DESIGN
Detect O_2, O_3, H_2O in M-dwarf exo-earth at 15pc		
	3 ppm-level photometric precision	D=8.5m Aperture
		High-efficiency instrument
		Earth-Sun L2 Orbit
	Pointing stability <0.2"/hr	Four reaction wheels
	Wavelength range: 0.5– 1.7 μm	VIS + NIR channels
	Spec. Resolving Power>100	VIS and NIR Grisms
	Continuous Obs. >24 h	Earth-Sun L2 Orbit
Observe 1,000 transits to establish exoplanet diversity		
	15,000 h of transit observations	Mission Lifetime > 5 yr
Search for and characterize optical counterparts of transients		
	FOV 15'×15'	VIS+NIR 2K×2K detectors
	Image resolution <100mas	Color-corrected optics
	Broadband filters	Two filter wheels

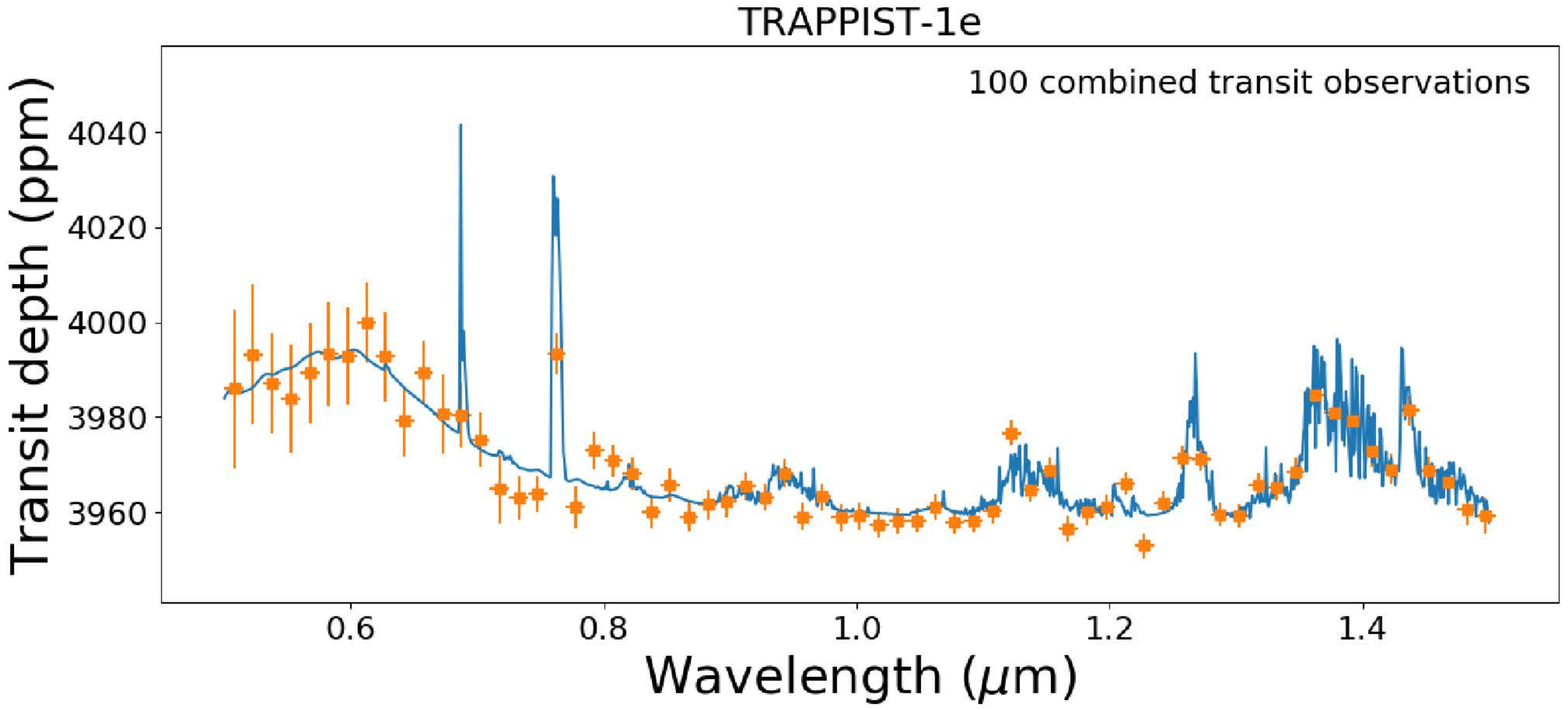


Earth-sized Planets in TRAPPIST-1

Venus-like Atmosphere without cloud opacity

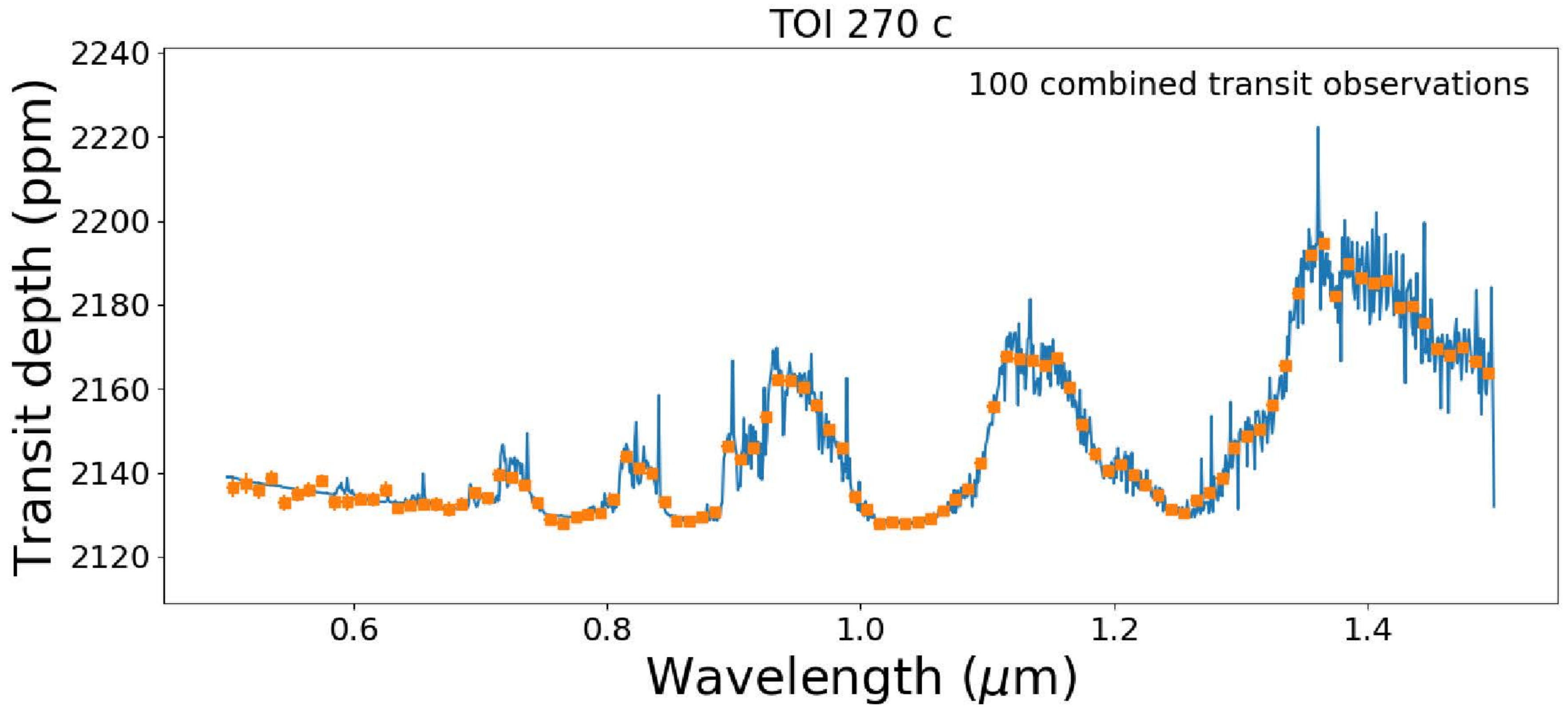


Earth-like Atmosphere without cloud opacity

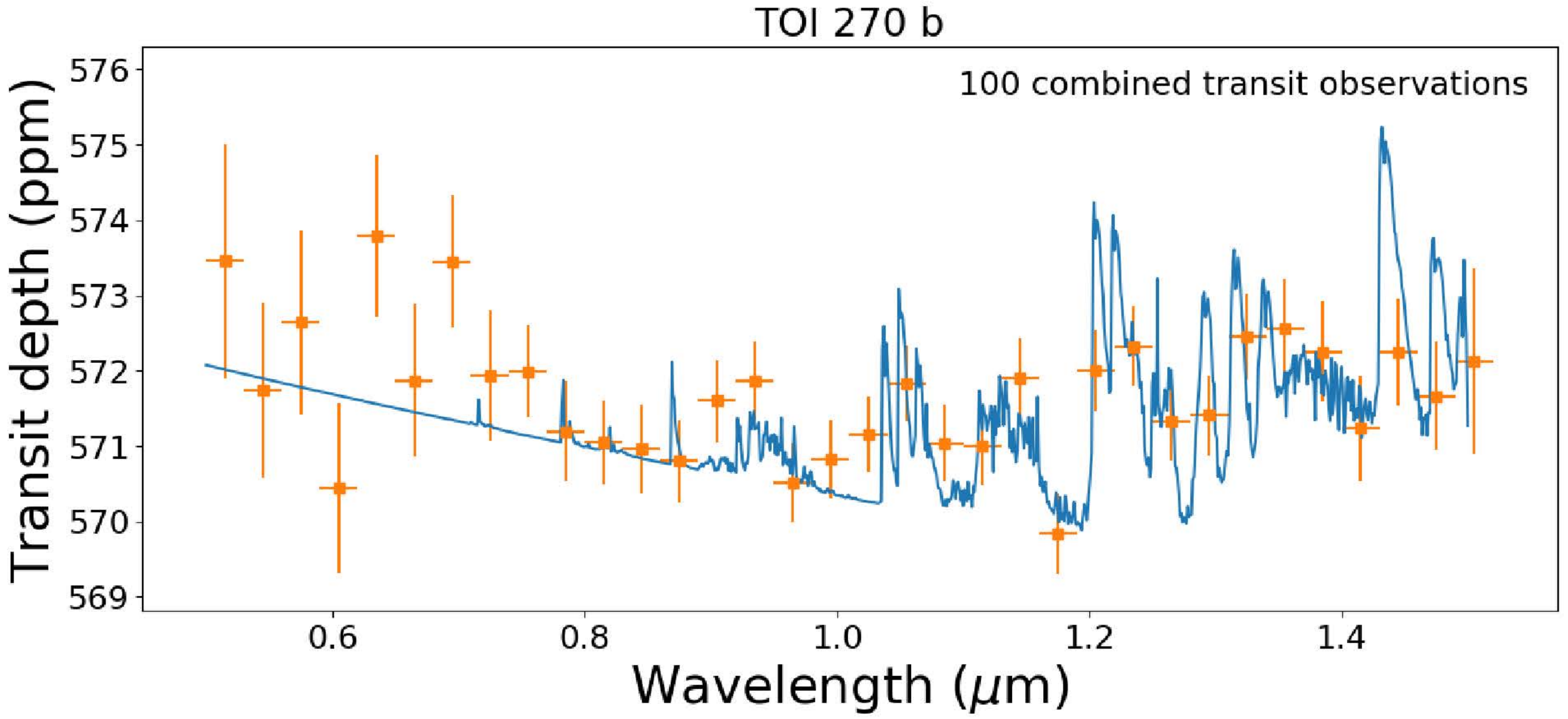


Sub-neptune and Super-earth in TOI270

Sub-neptune with Neptune-like Atmosphere

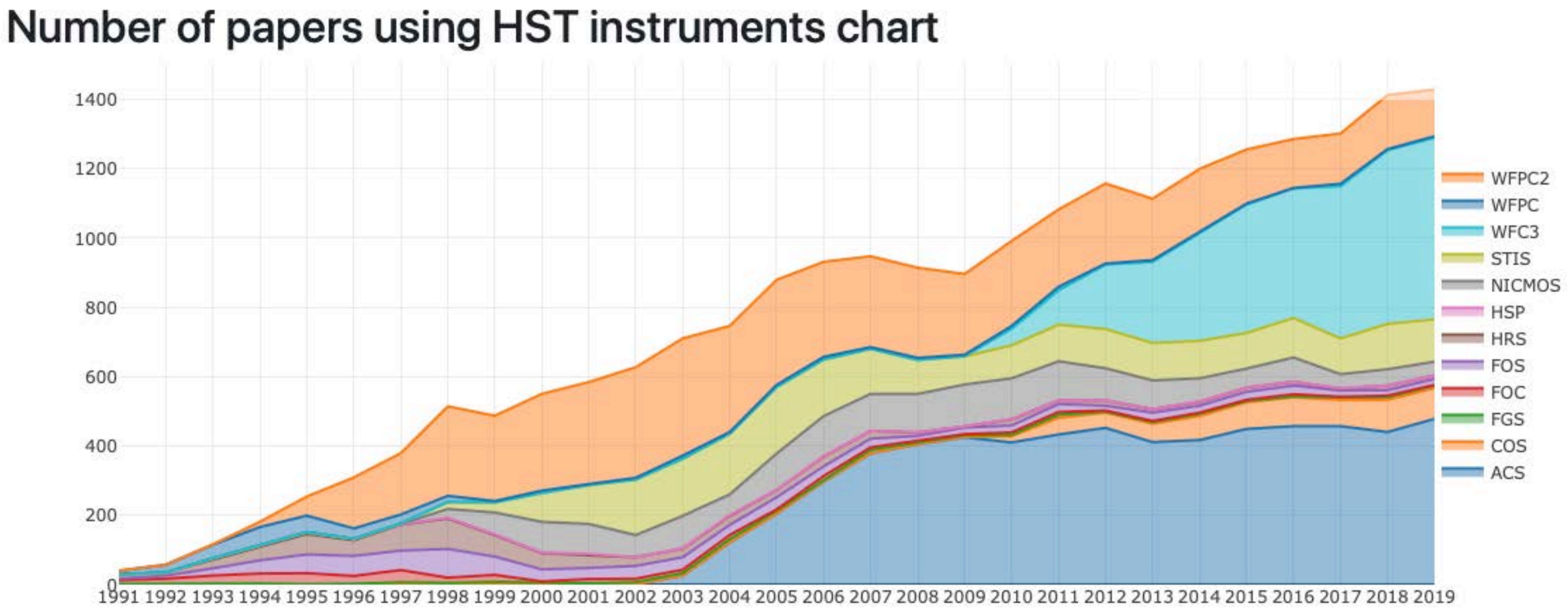


Super-earth with Earth-like Clear Atmosphere



Collecting Area: 12x HST
3 magnitude fainter objects than HST
Same resolution as HST

Not a wide-field survey instrument but for narrow-field studies it provides superior sensitivity and same resolution as ACS, STIS,WFC3



79% of HST papers WFC3, STIS, ACS = Large fraction of that science could be done 10x better with Nautilus!

Possible Highlights

Highest redshift quasars

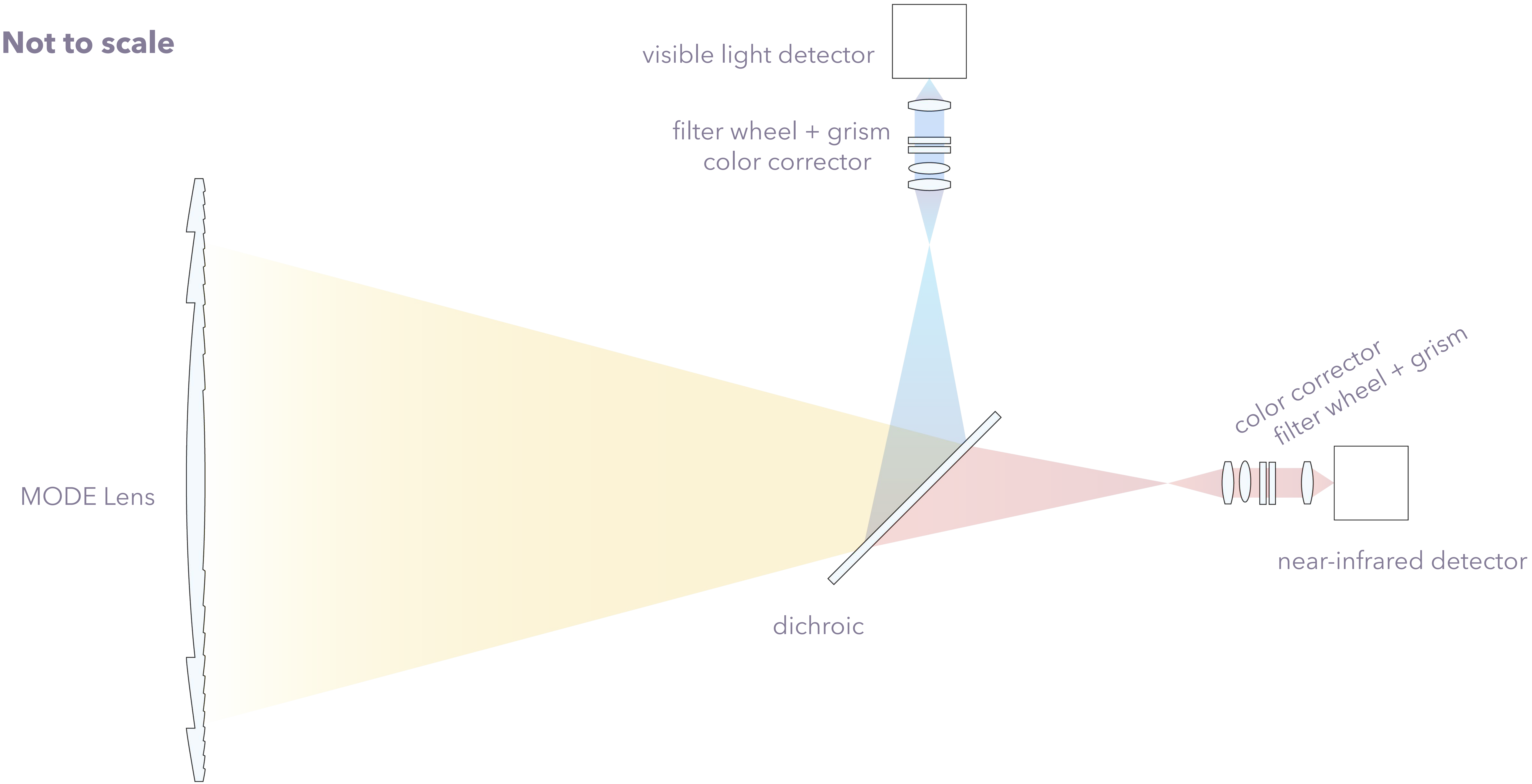
Increase sample of multiply lenses quasars

Order-of-magnitude deeper SN surveys

3-4x smaller KBOs

Nautilus Probe Optical Path

Not to scale

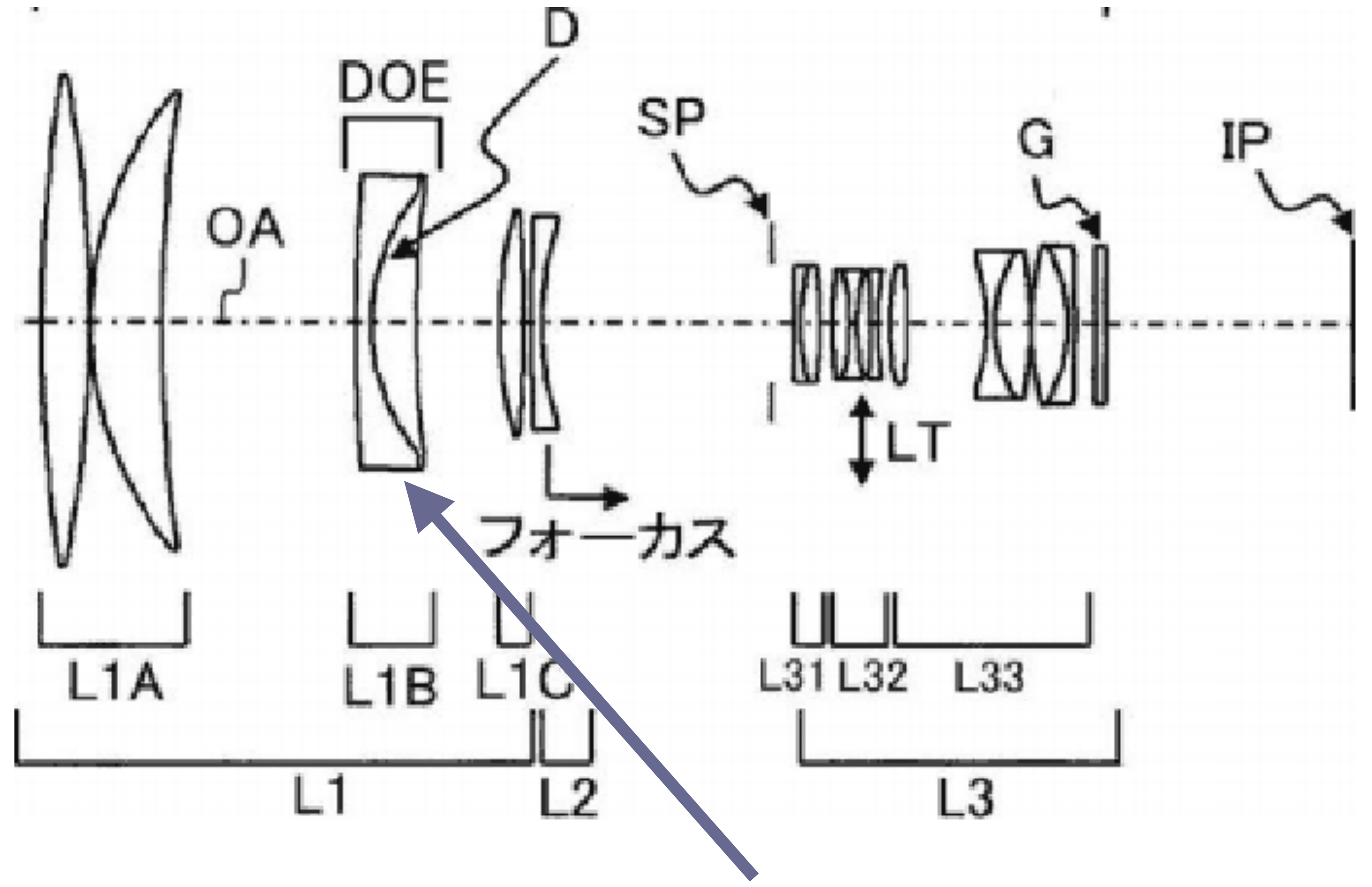


MODE Technology

Nikkor PF lenses

Canon DO Lenses

Nikon's Phase Fresnel lens



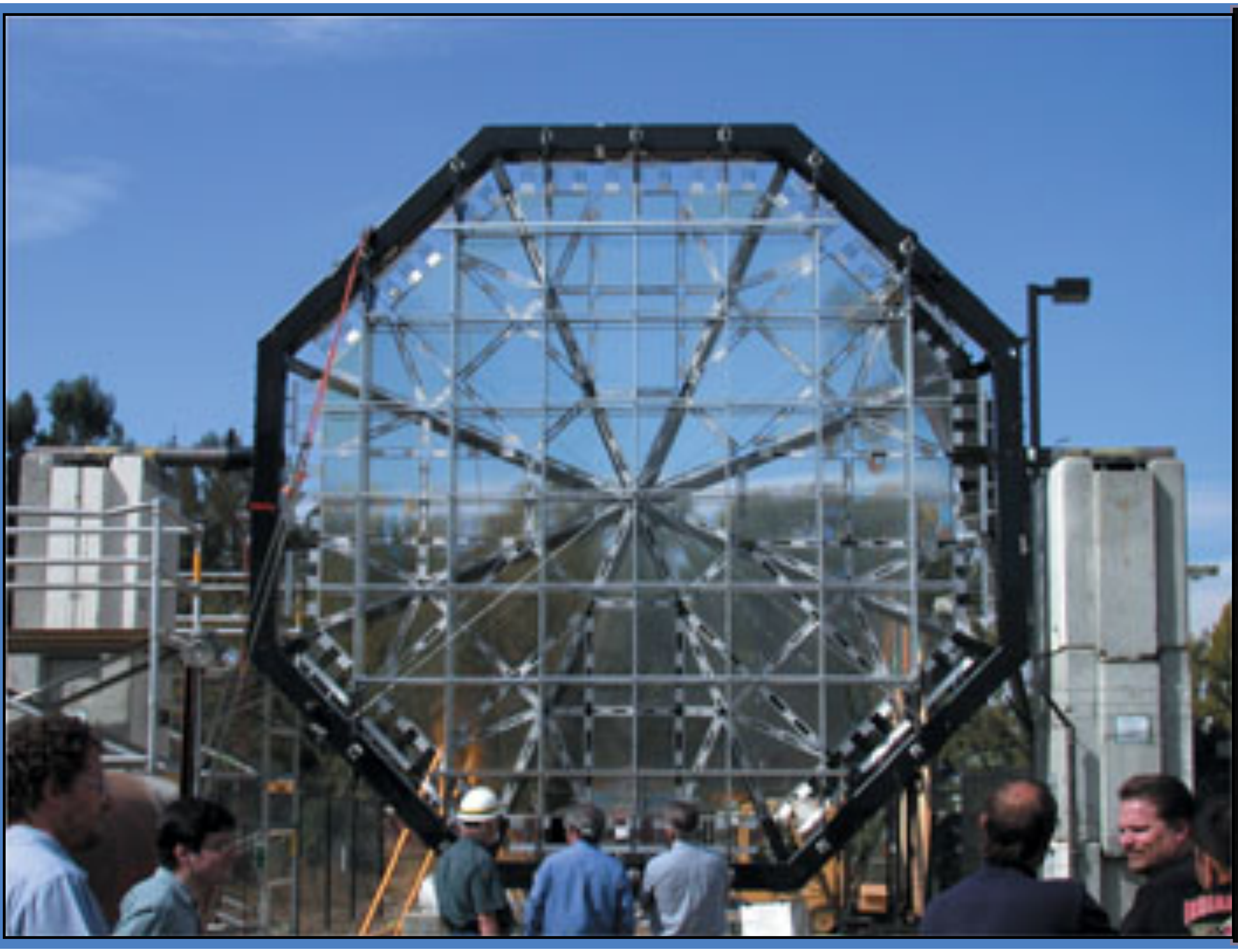
Canon's Diffractive Optical Element (DOE)

Eyeglass

Lawrence Livermore National Laboratory

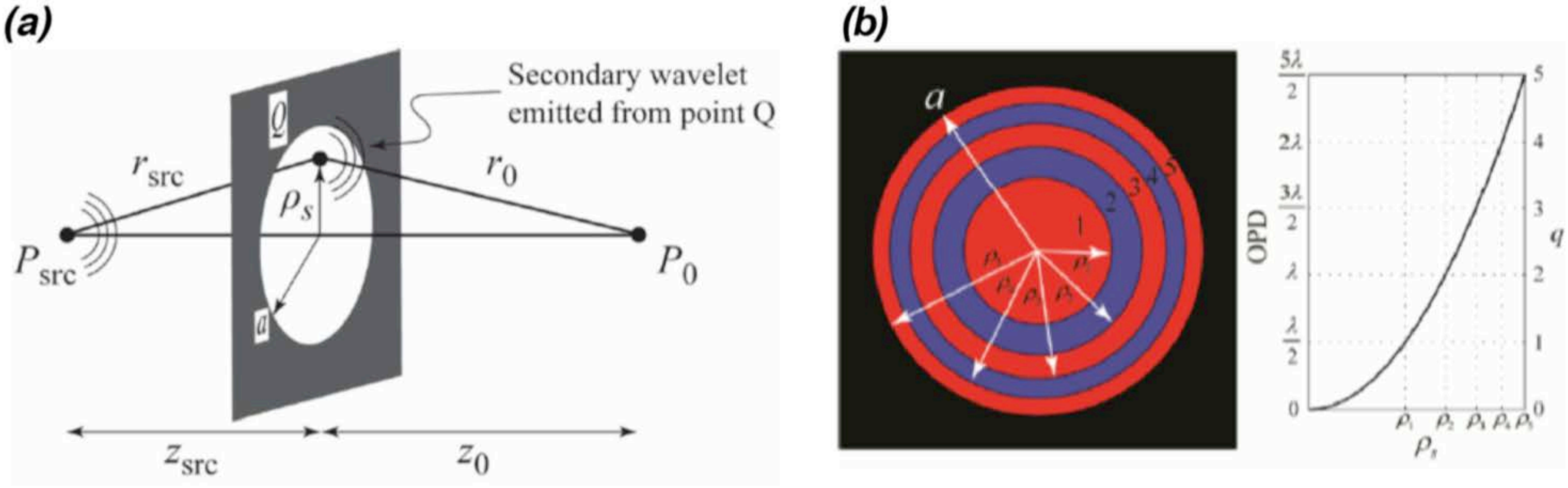
MOIRE

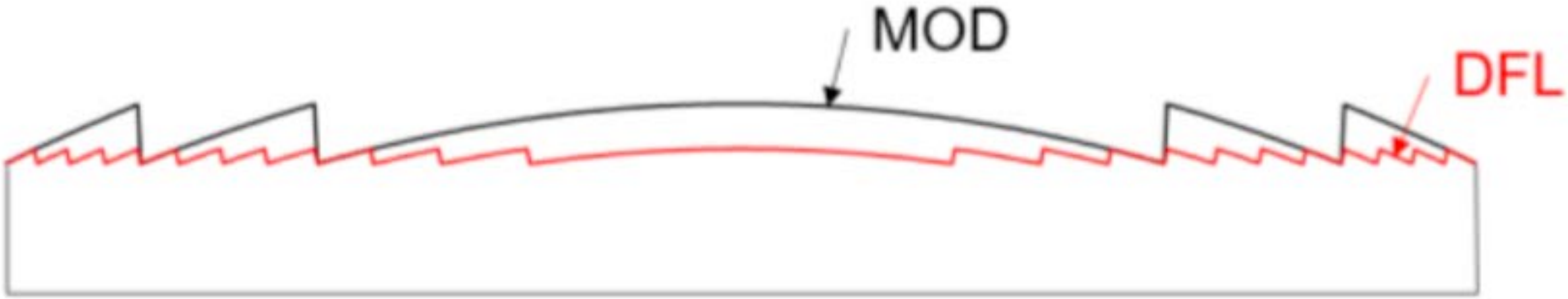
DARPA & Ball Aerospace



Hyde 1999 Appl. Opt.
Hyde et al. 2001 SPIE

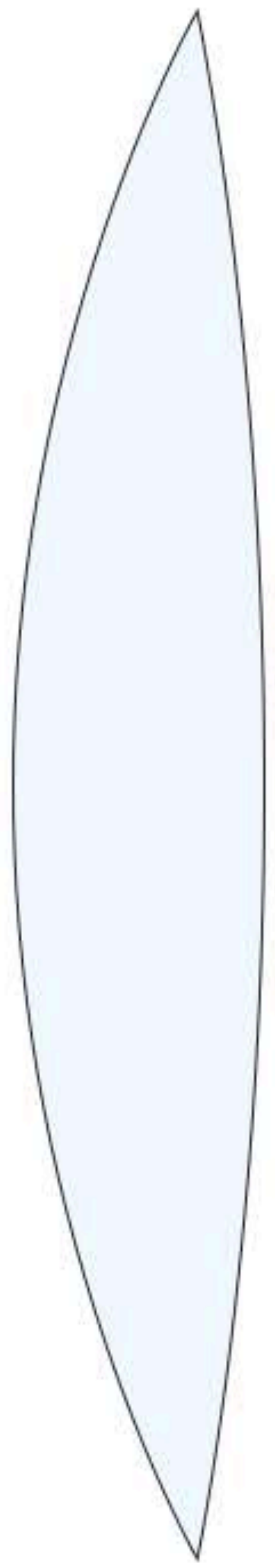
Atcheson et al. 2012
Atcheson et al. 2014

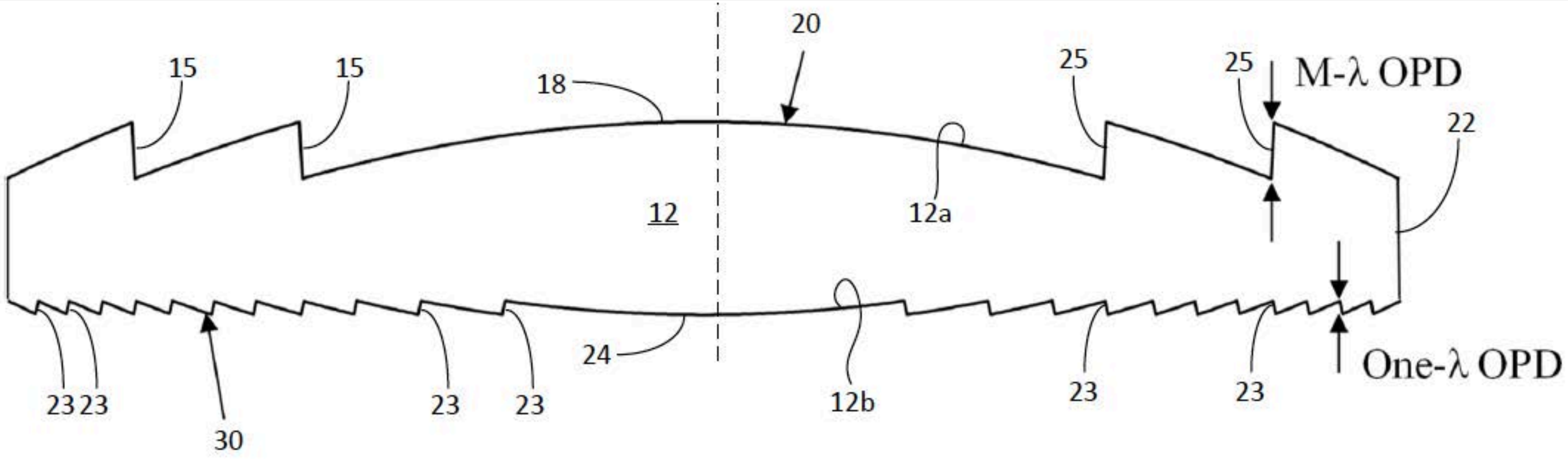


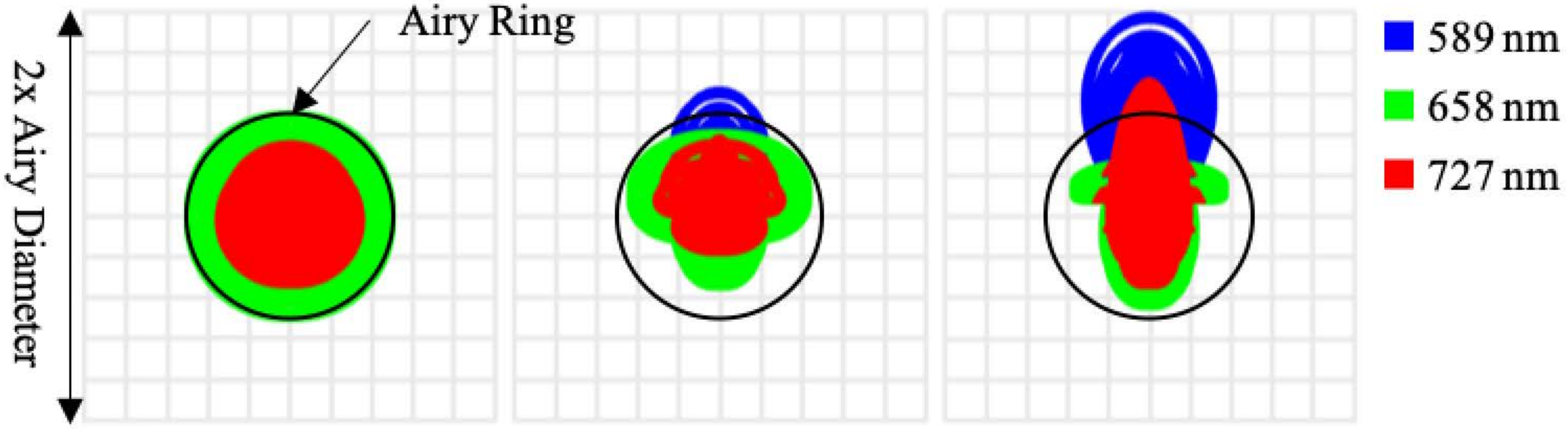


Apai, Milster, Kim et al. 2019

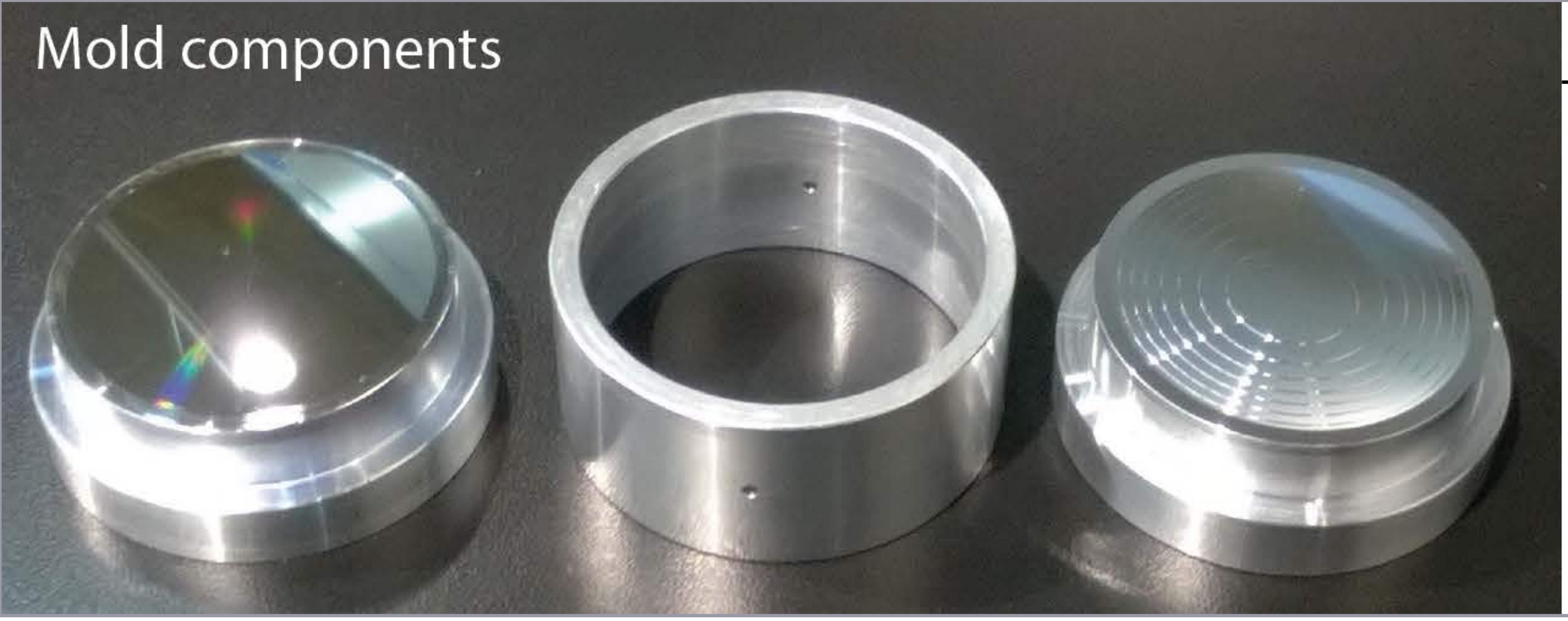
Four patents pending on MODE design and applications

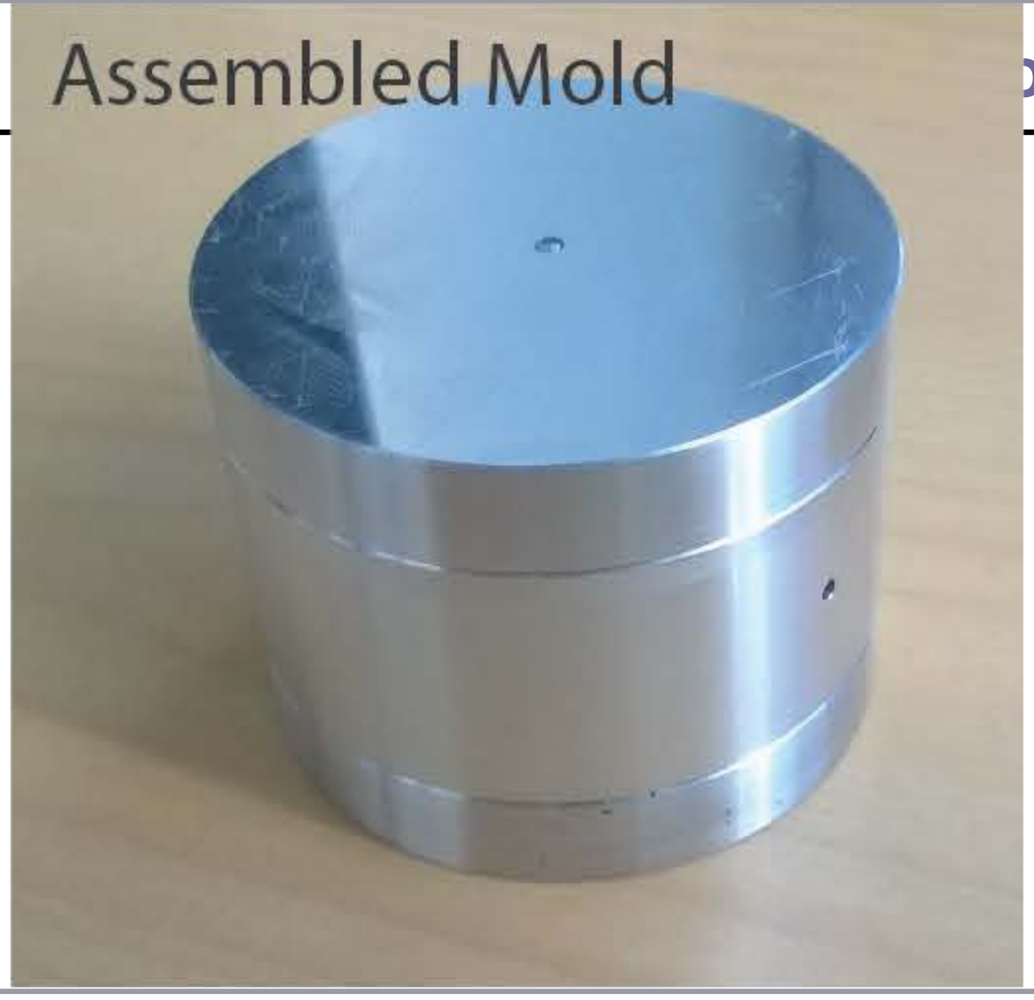

Lens

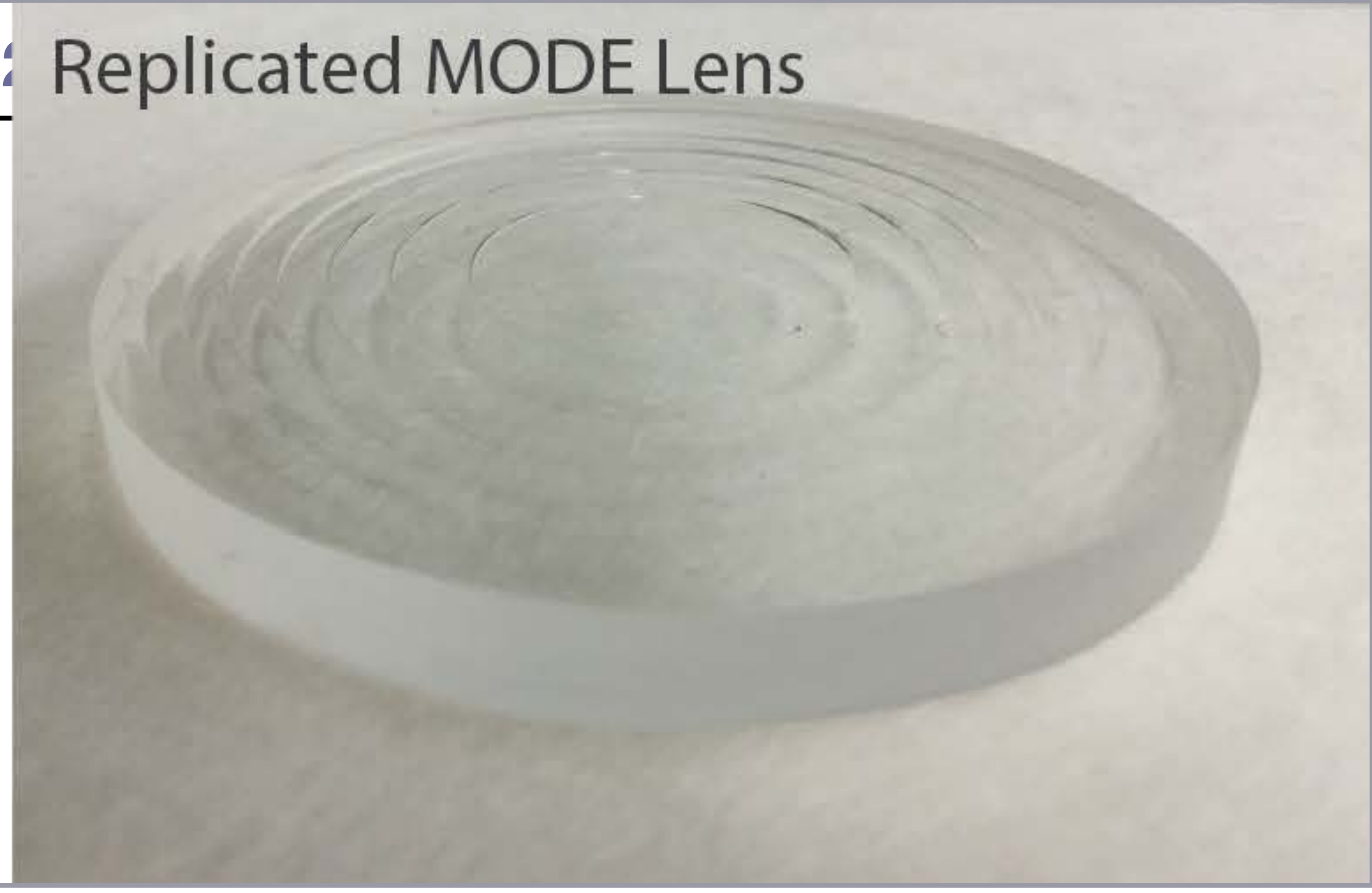


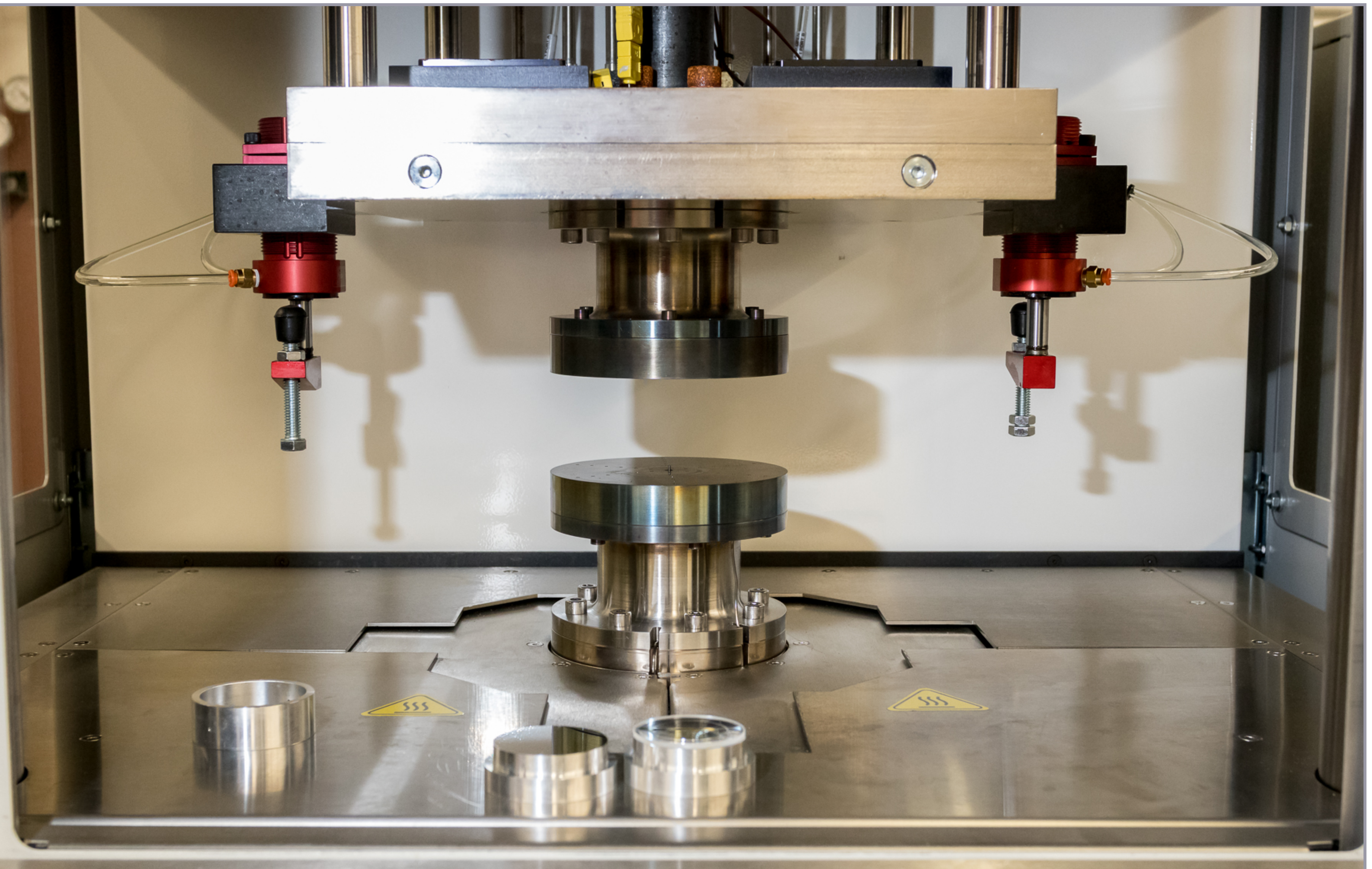


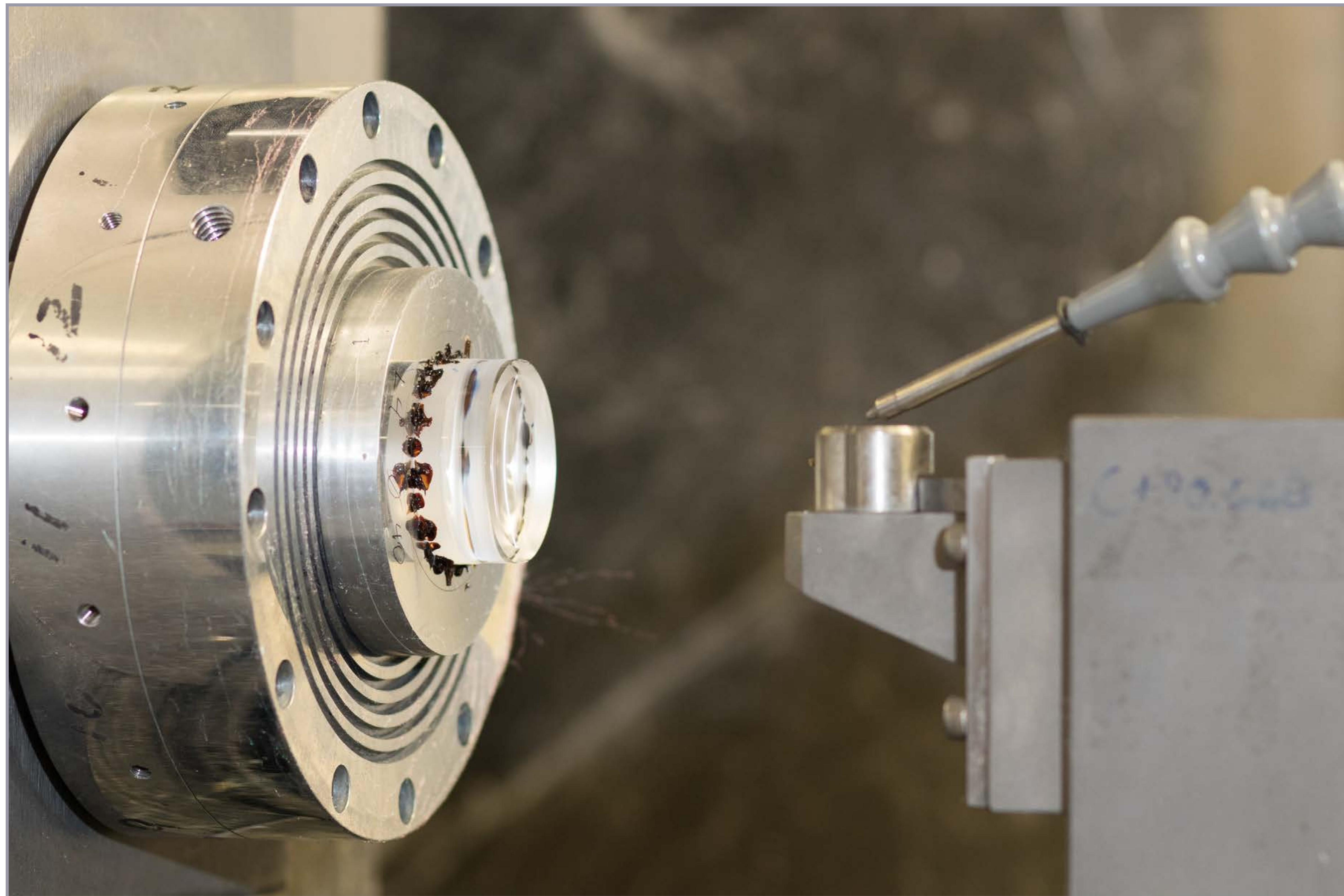
On-axis **10.5’** **15’**


Mold components


Assembled Mold


Replicated MODE Lens





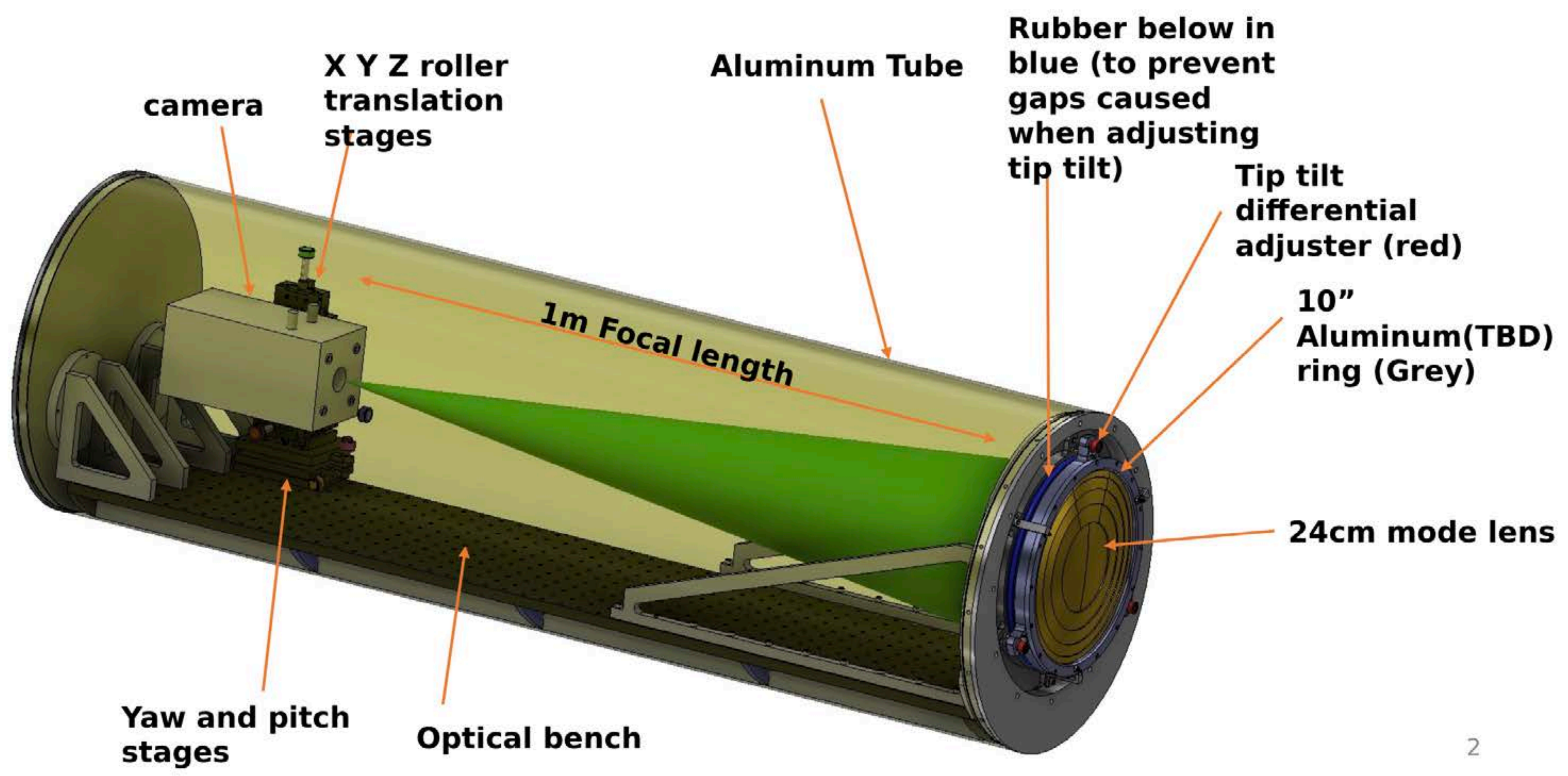
PMMA prototype diamond turned at KBSI

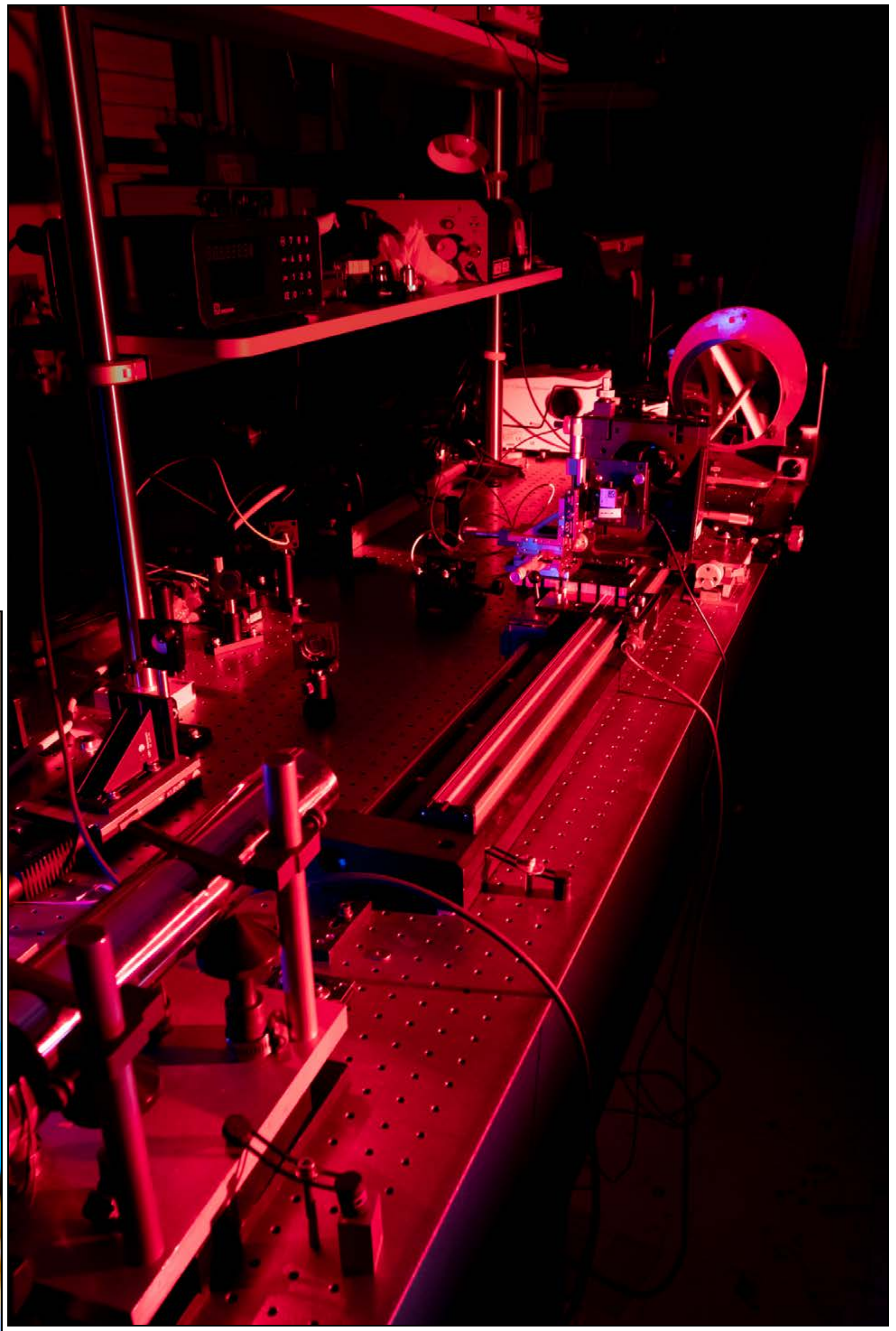
GORDON AND BETTY MOORE FOUNDATION

Ongoing work at UArizona

Main focus on optical technology development
- Increase lens size and demonstrate efficient replication
- Optical quality assessment and surface metrology
- Laboratory and on-sky demonstration on MODE telescope

Currently between TRL 2 – TRL3





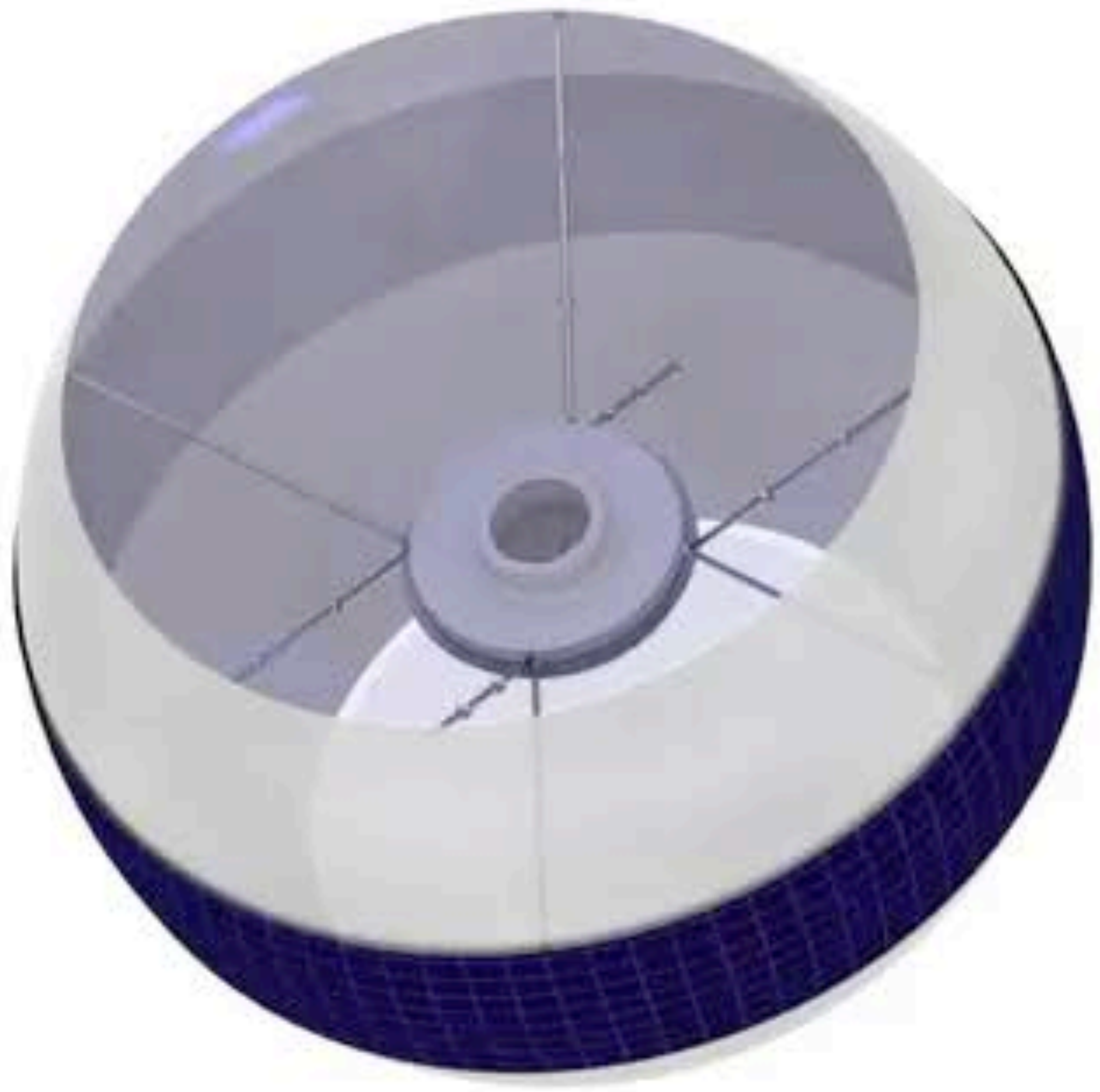
Advantages

a) 100x lower weight than traditional mirrors
b) 100–1,000x less sensitive to misalignments
c) shaped through controlled, direct/local process
d) fabricated with replication technology
e) more flexibility in optical design
f) can incorporate simple instrument in the lens design

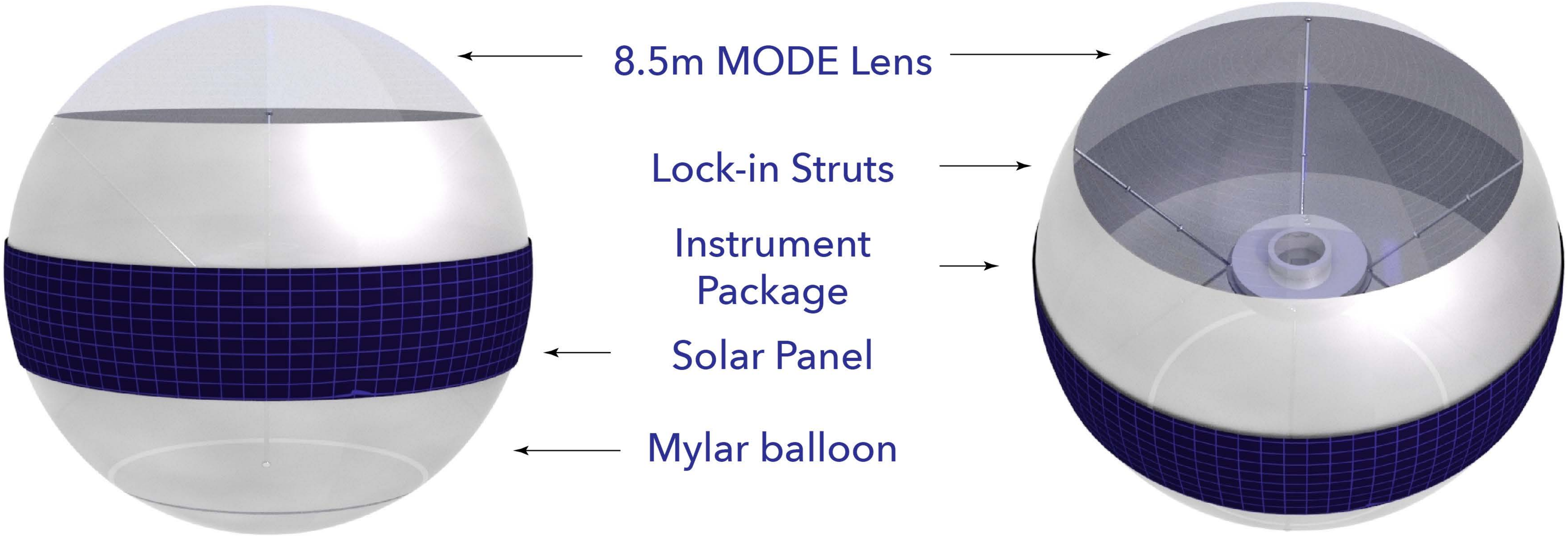
Disadvantages

a) Potentially narrower wavelength range with diffraction limited performance

Nautilus Probe



Deployed Nautilus Unit Telescope



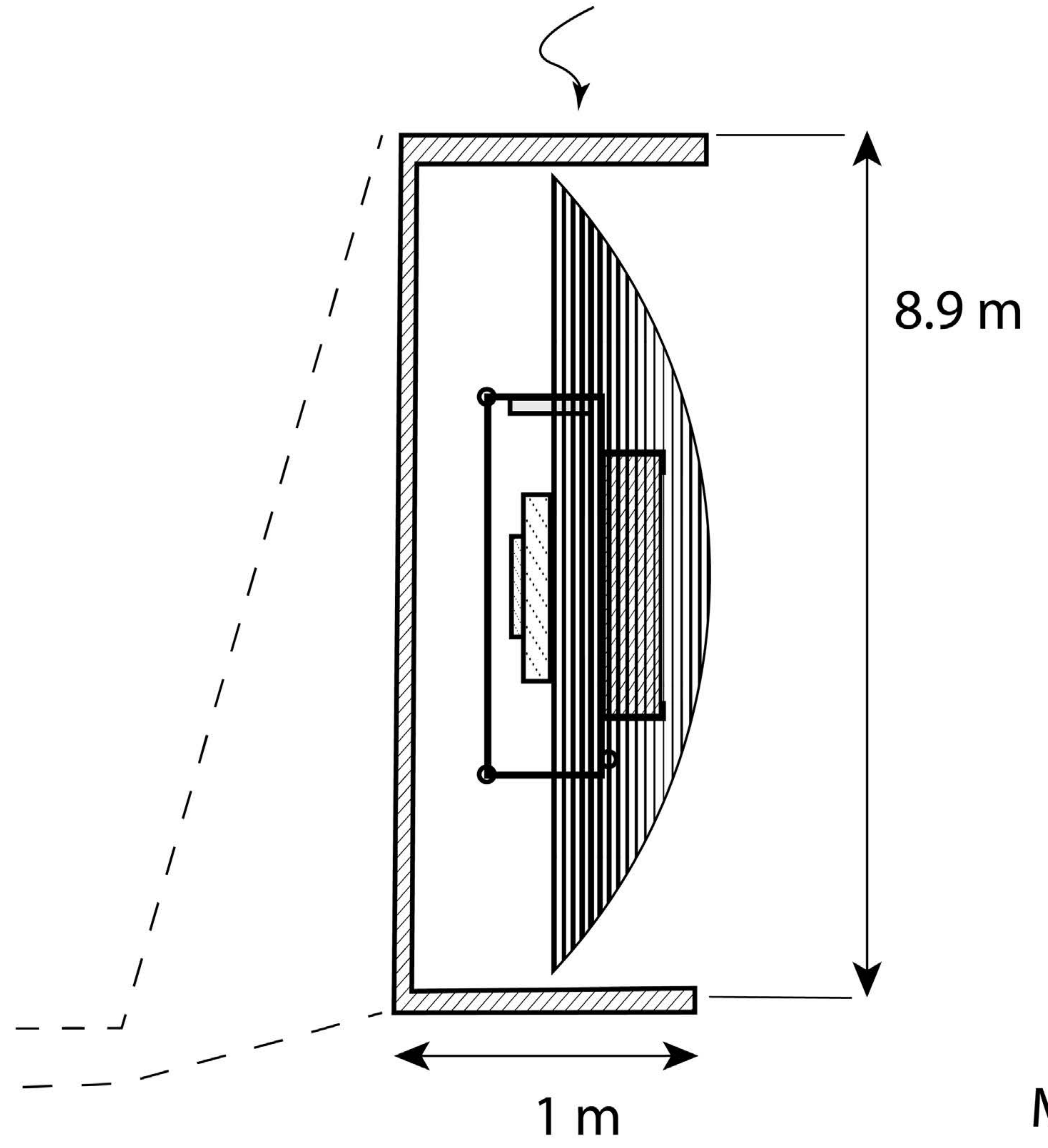
Inflatable Space Antennas

NASA's ECHO Satellite

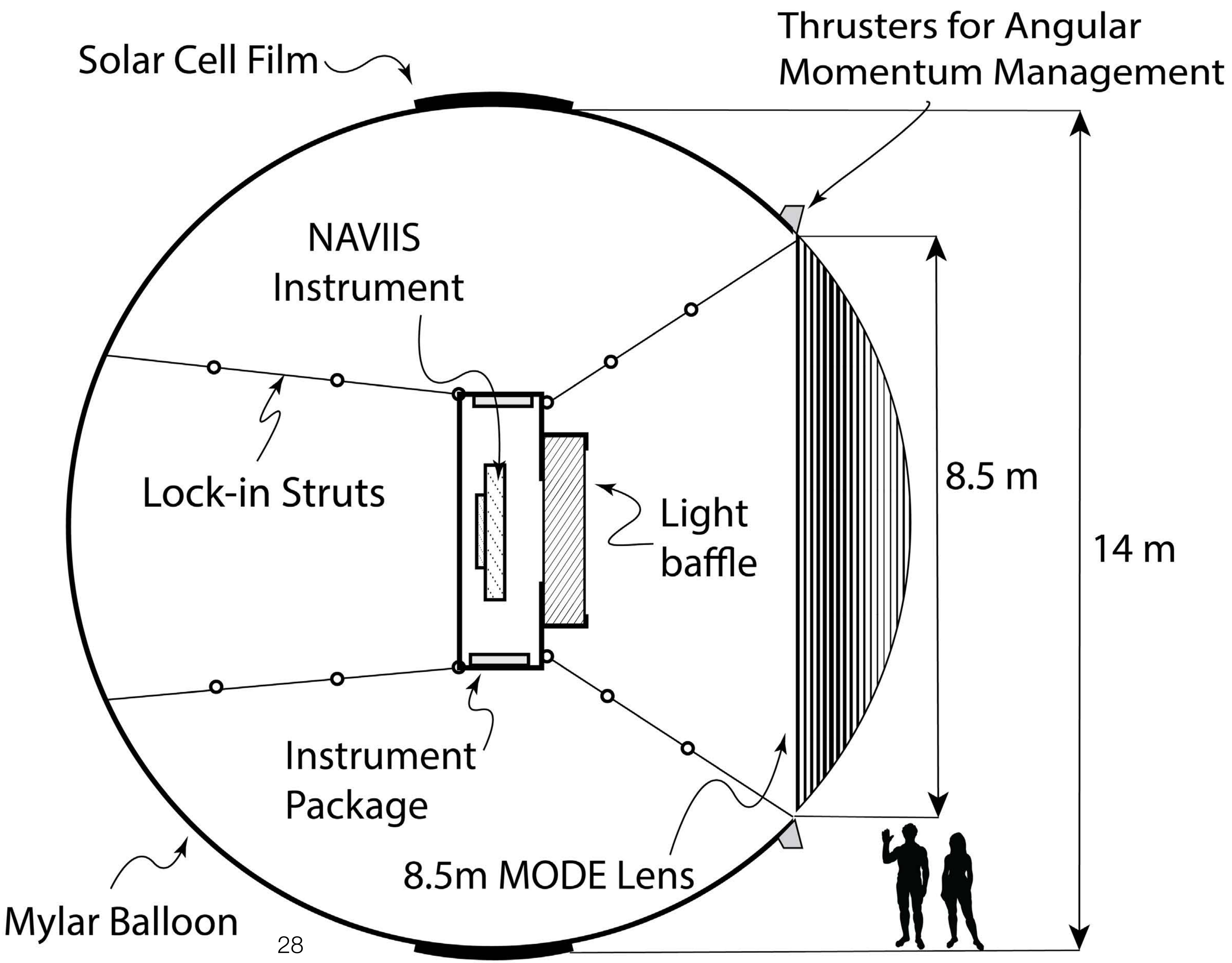
Freefall demonstration C. Walker et al.

pe

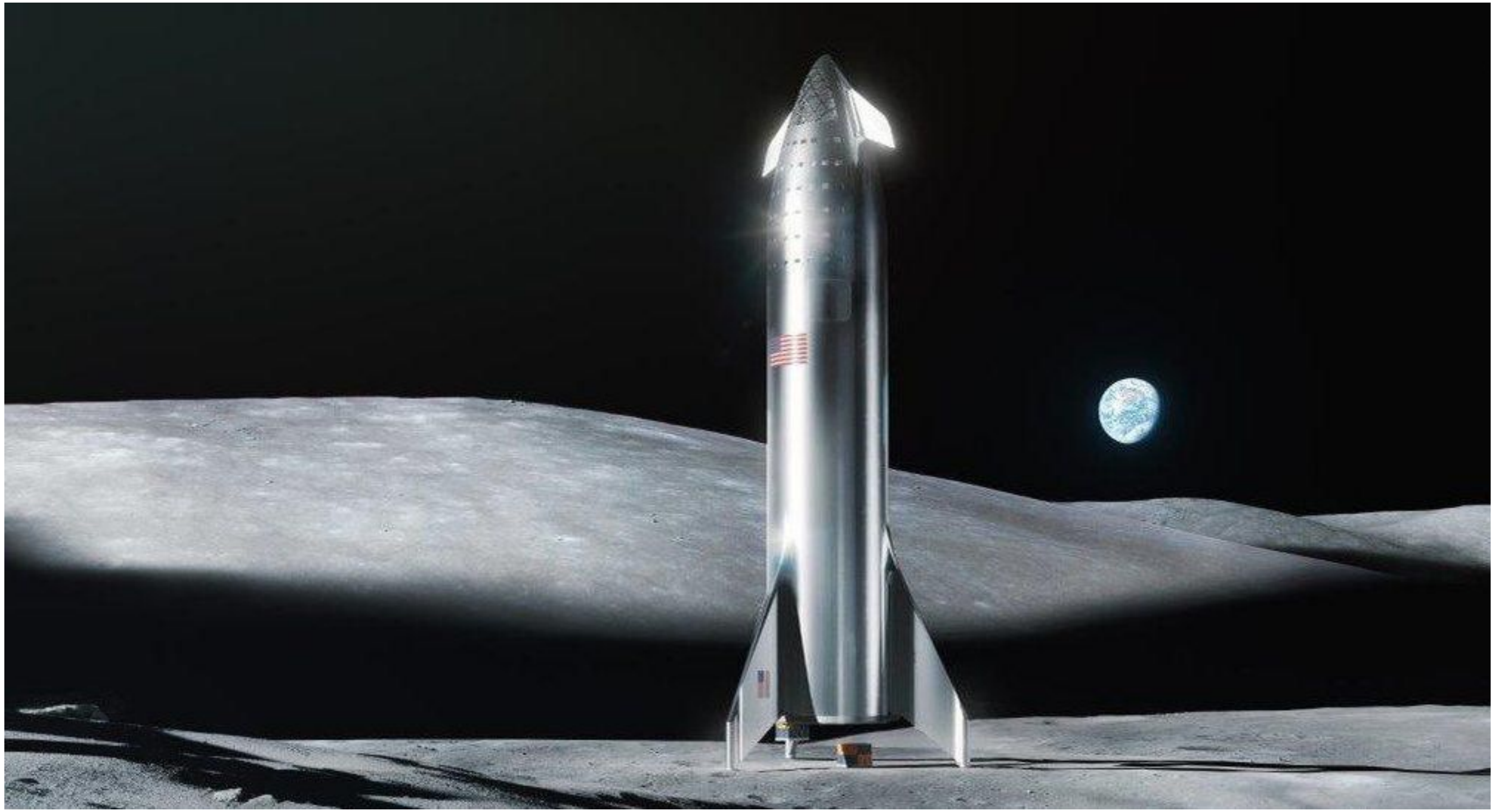
b) Launch Configuration



c) Deployed Unit, Side View




a) Nautilus Unit Telescope in SpaceX/BFR Fairing
b) Launch Configuration
c) Deployed Unit, Side View
Unit 15
Unit 14
Unit 13
Unit 12
Unit 11
Unit 10
Unit 8
Unit 8
Unit 7
Unit 6
Unit 5
Unit 4
Unit 3
Unit 2
Unit 1
17 m
9 m
Launch container
8.9 m
1 m
Solar Cell Film
Thrusters for Angular Momentum Management
NAVIIS Instrument
Lock-in Struts
Light baffle
8.5 m
14 m
Instrument Package
8.5m MODE Lens
Mylar Balloon
Booster composed of four 16-meter BFR tools
113 meter BFR




1 Mold segments diamond-turned
2 Segmented mold
3 Monolithic lens
Path 1
Path 2
1 Mold segments diamond-turned
2 Lens segments molded
3 Segmented lens

Scaling Up Fabrication

Step 1: Diamond turning mold segments

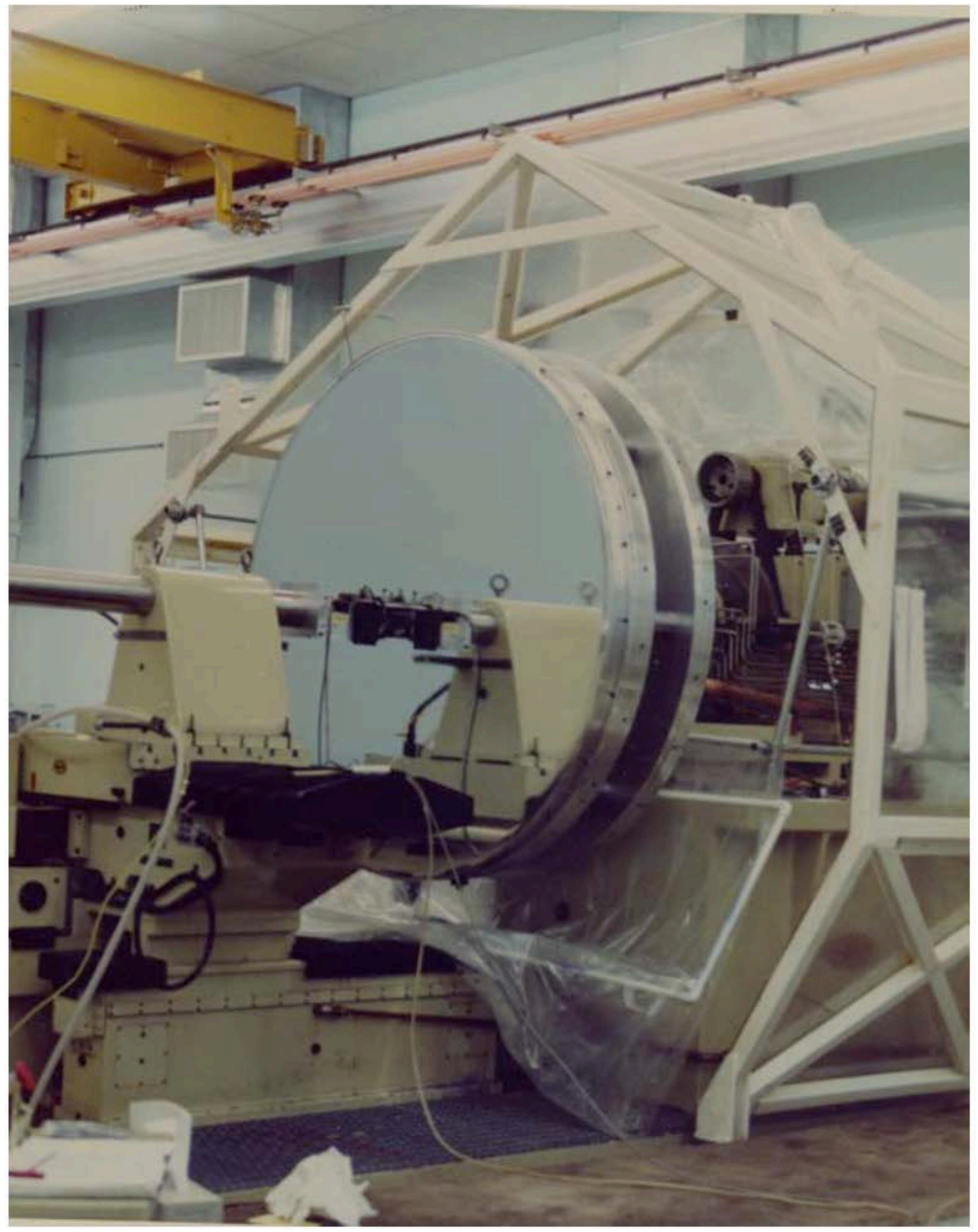
Strategic Defense Initiative: Precision diamond-turning (LLNL, ORNL) funded by DARPA
Lawrence Livermore Labs: Large Optics Diamond Turning Machine
(D~1.5m, 28nm radial figure accuracy and 12.5 nm azimuthal figure accuracy over the entire distance)
Keck secondary mirror (~1.5m) was diamond-turned with LODTM
D=3m diamond turning machine: TRL5-6 (Caststevens et al.)

Step 2: Aligning and fusing mold segments

MODE lenses have well-defined physical surface structures that make them easier to align.
Tech Dev in progress

Step 3: Molding a monolithic lens

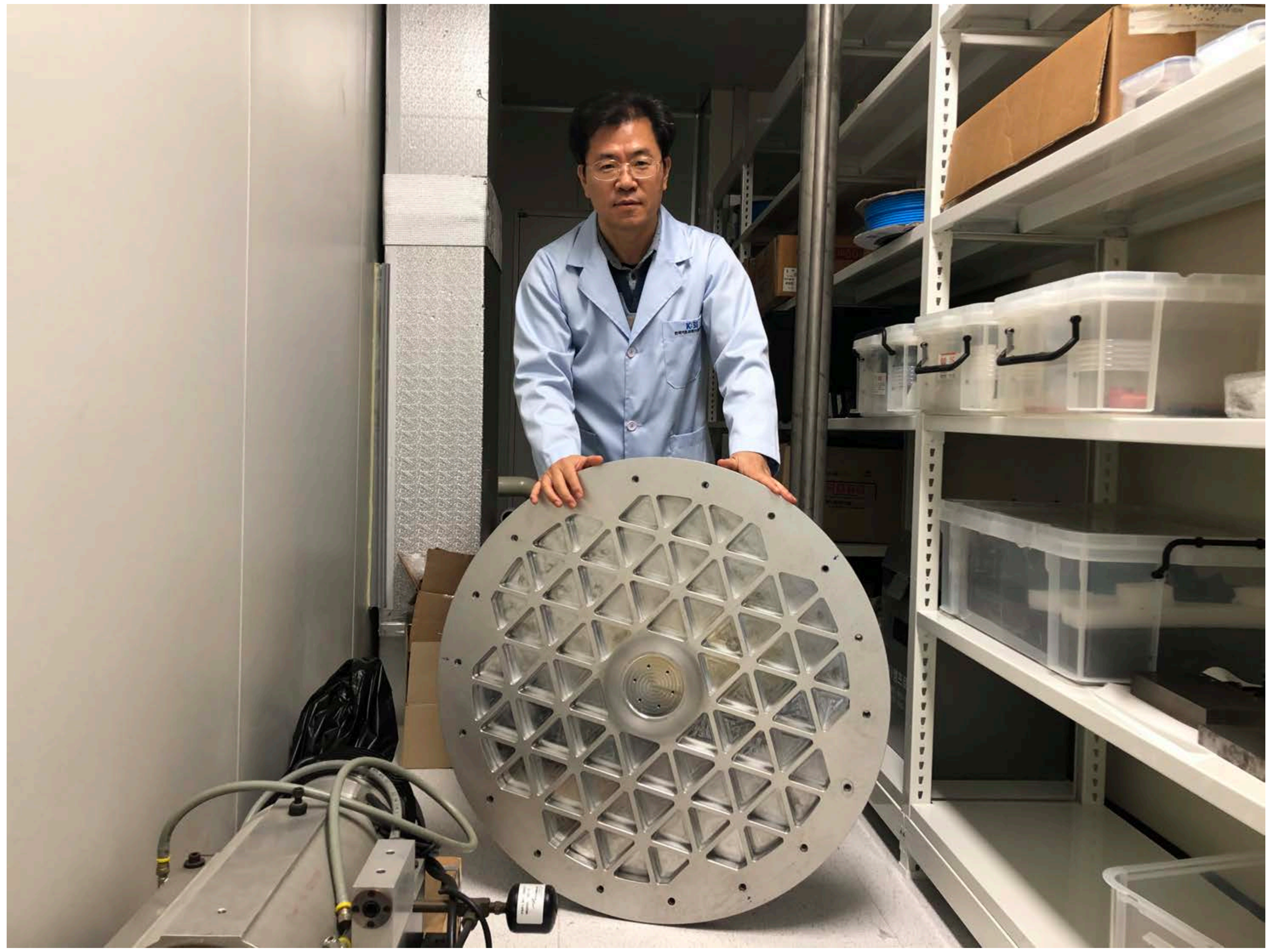
Largest existing molding machine: D~1m
Molding machines are relatively easily scaleable
Key requirement: Temperature/pressure control



D=2m diamond turning machine
Moore Tool Co.

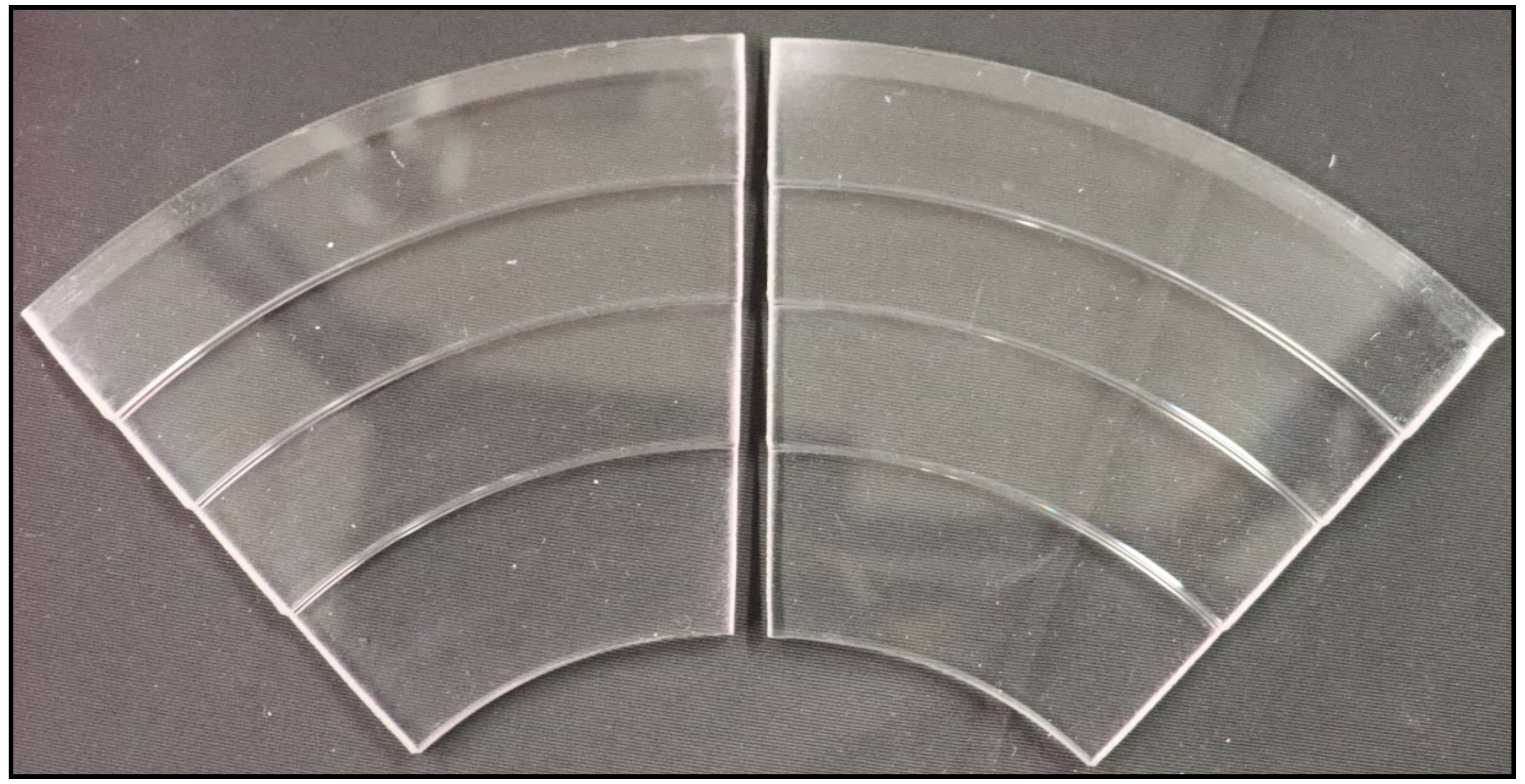
D=2m diamond turning machine
at Oak Ridge N. L.

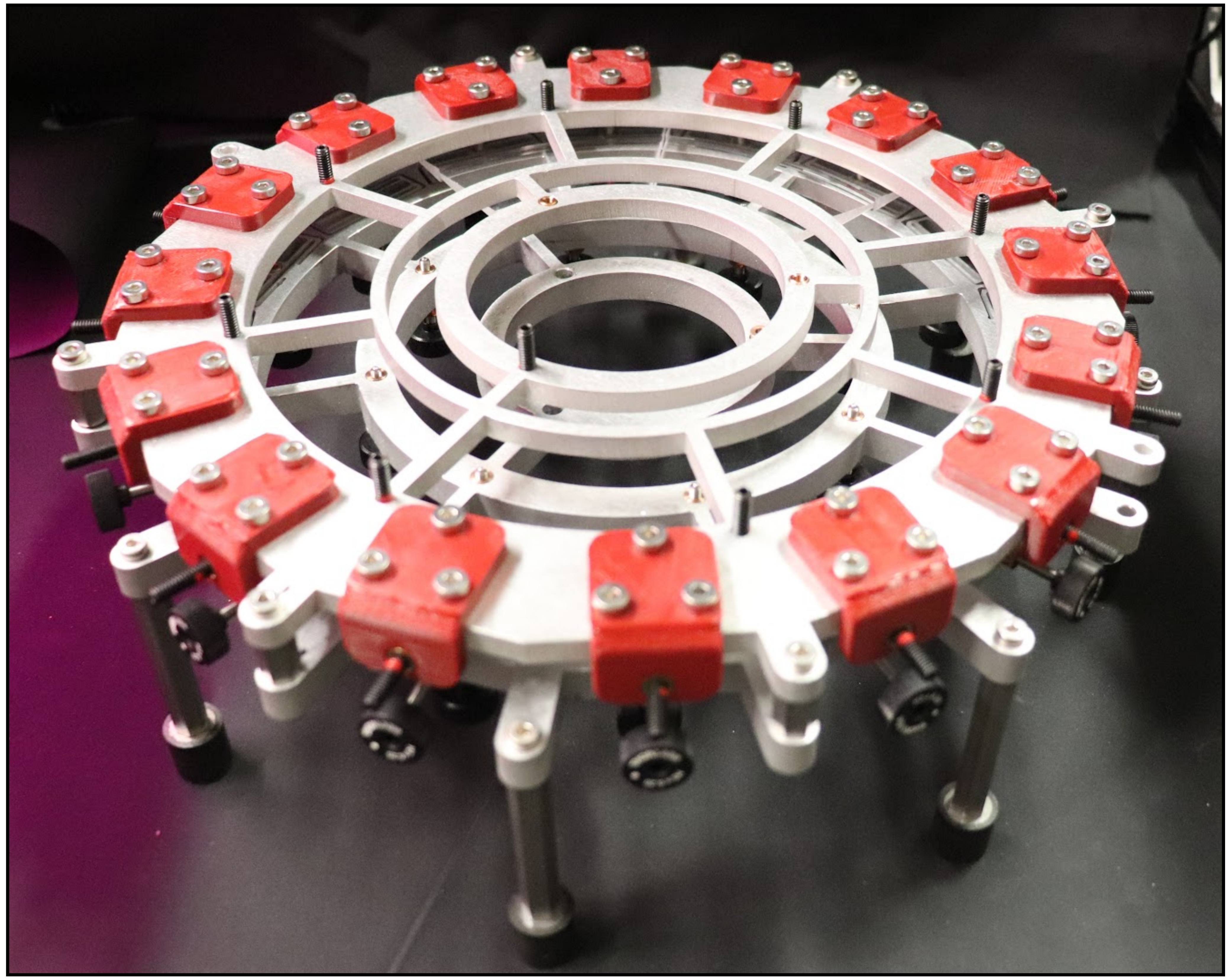
Scaling Up Fabrication: Diamond Turning

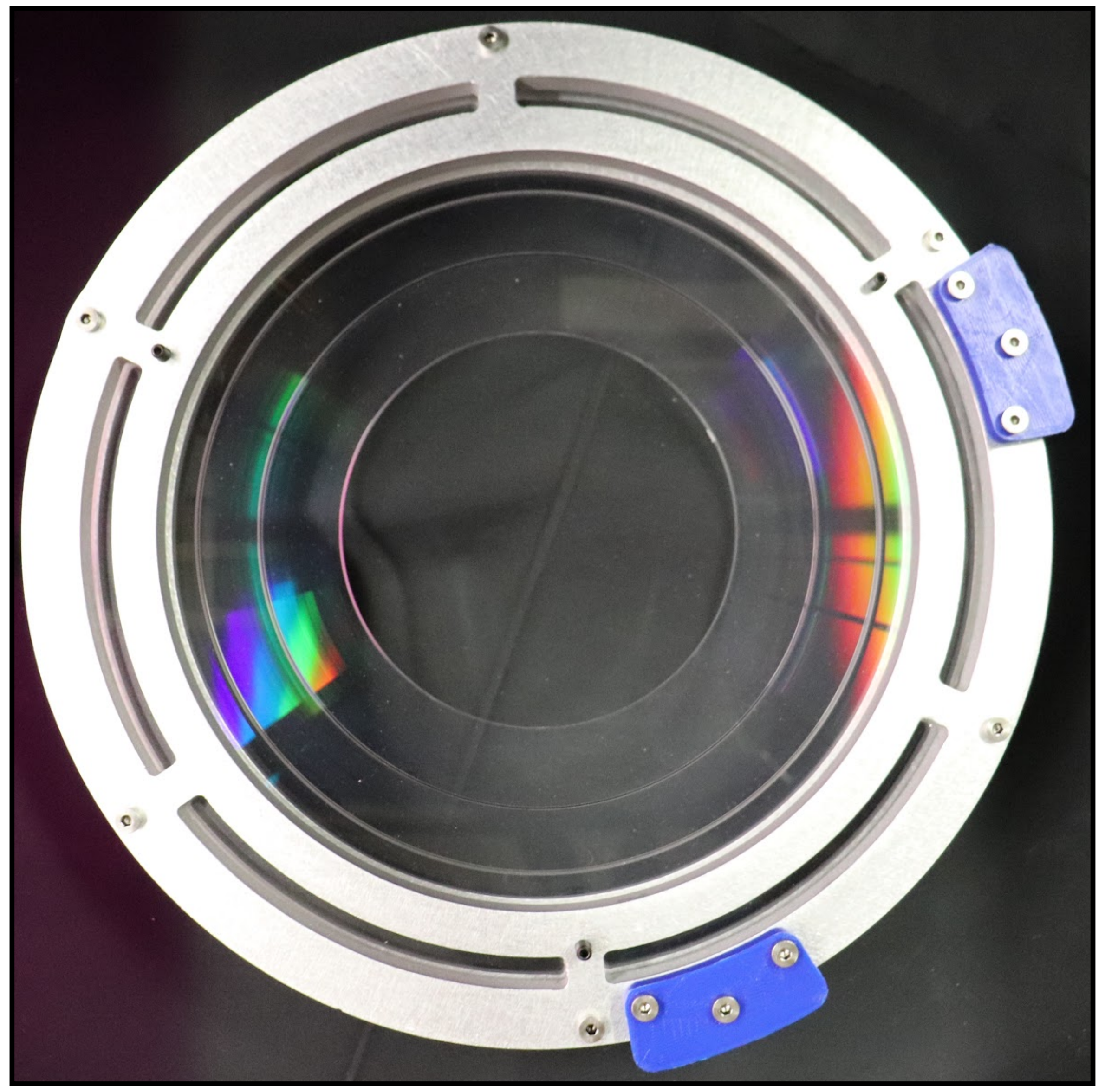


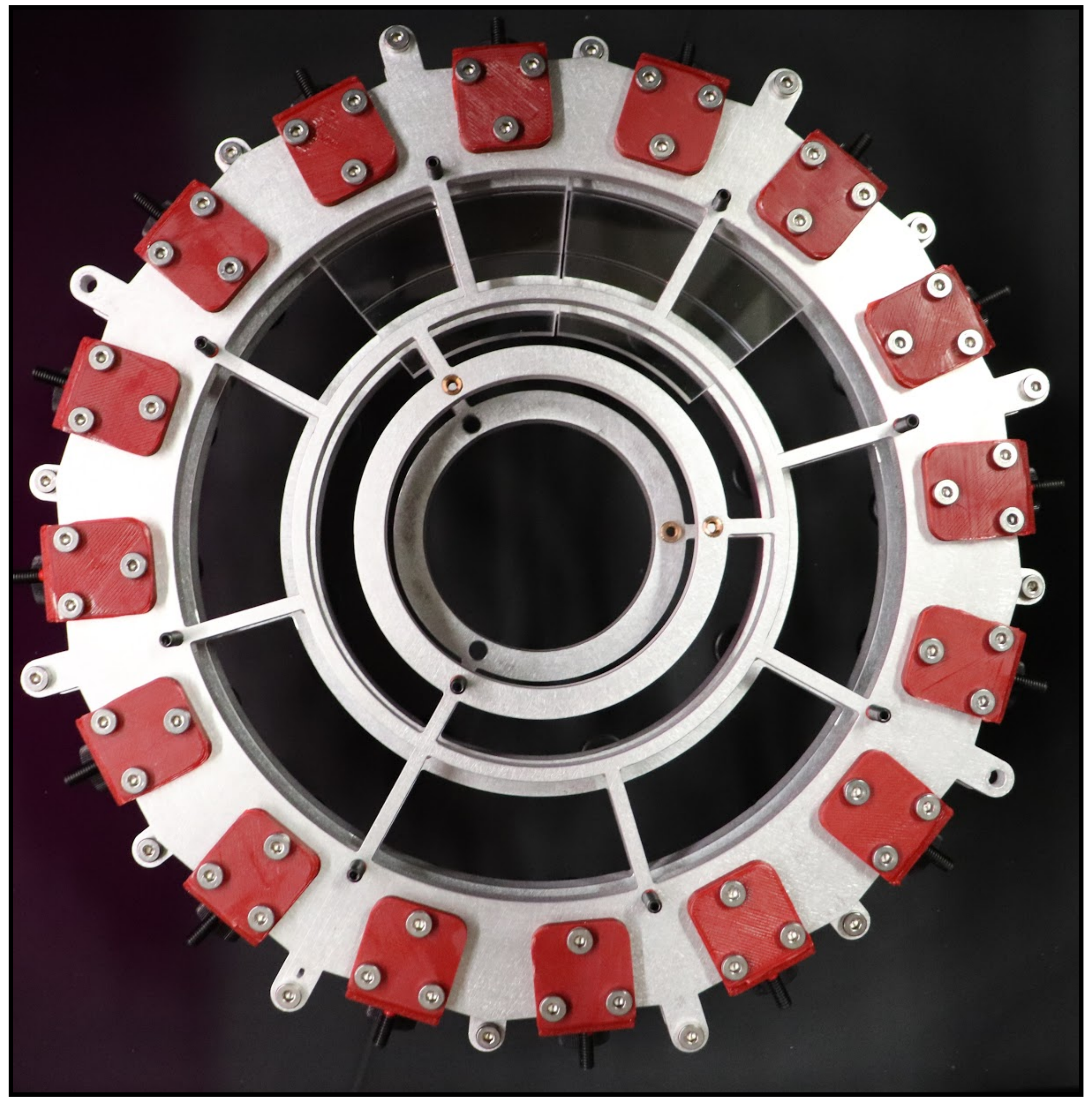
High-performance diamond turning machine with ultrasonic tool vibration upgrade at KBSI

Aligning Mold and Lens Segments



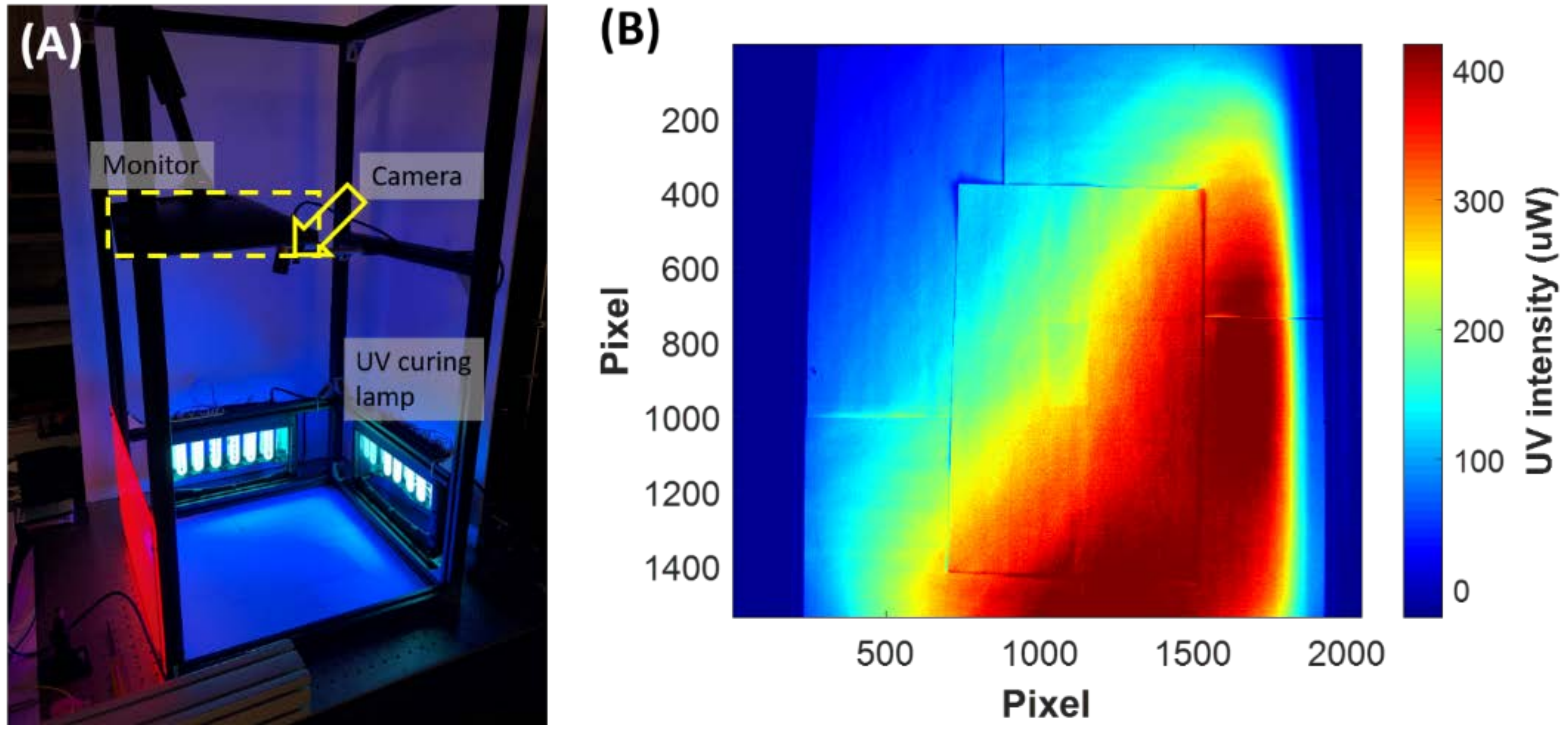


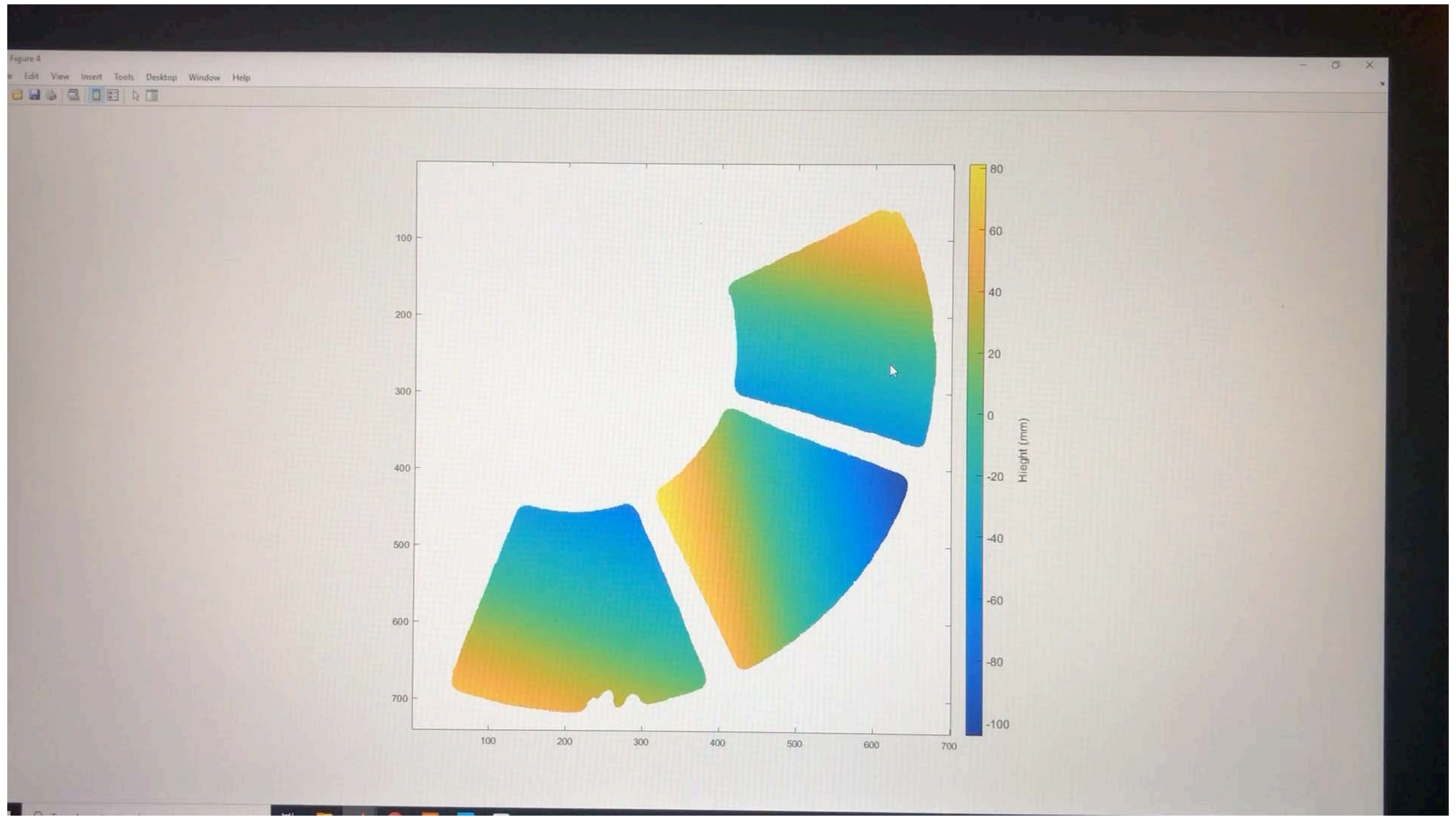


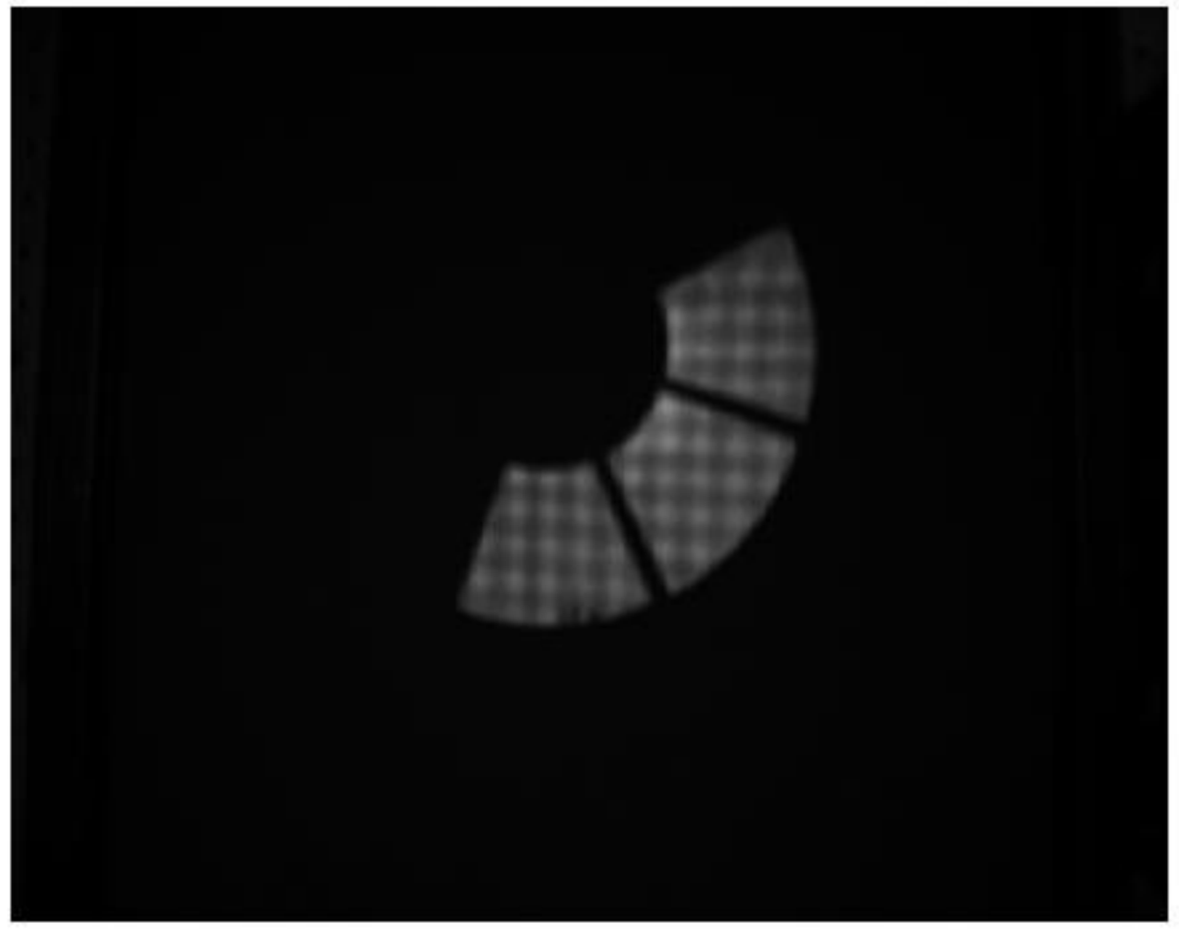


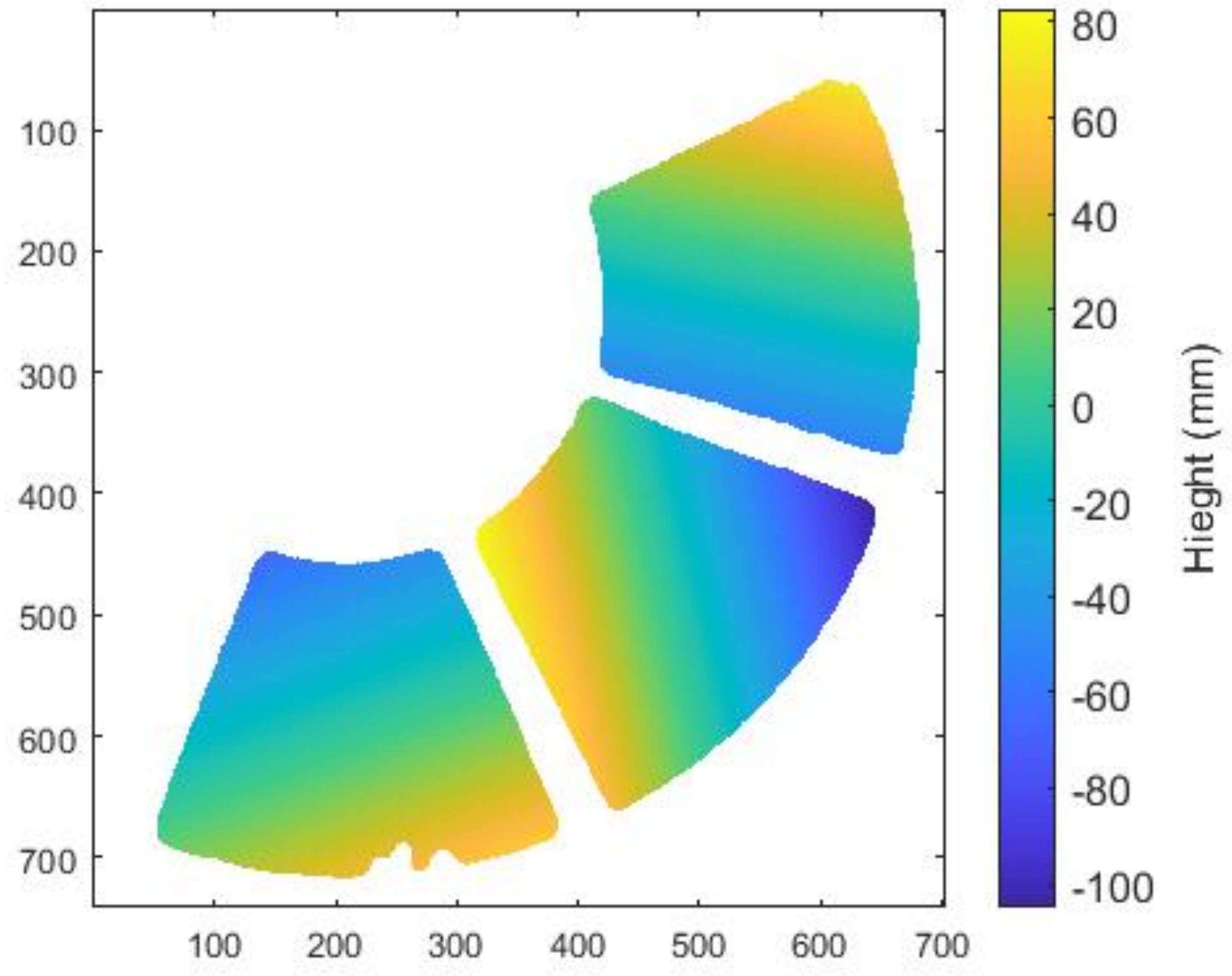
Three patents pending on alignment methods and KEYS mechanism

Segment Alignment









Nautilus Probe: Development, Integration, and Operations Schedule

Revised: Monolithic lens from segmented mold; no balloon flights; utilizing ORNL's large diamond-turning facility; more realistic task duration estimates

Cost Estimates

Cost Estimate 1: Scaling from JWST

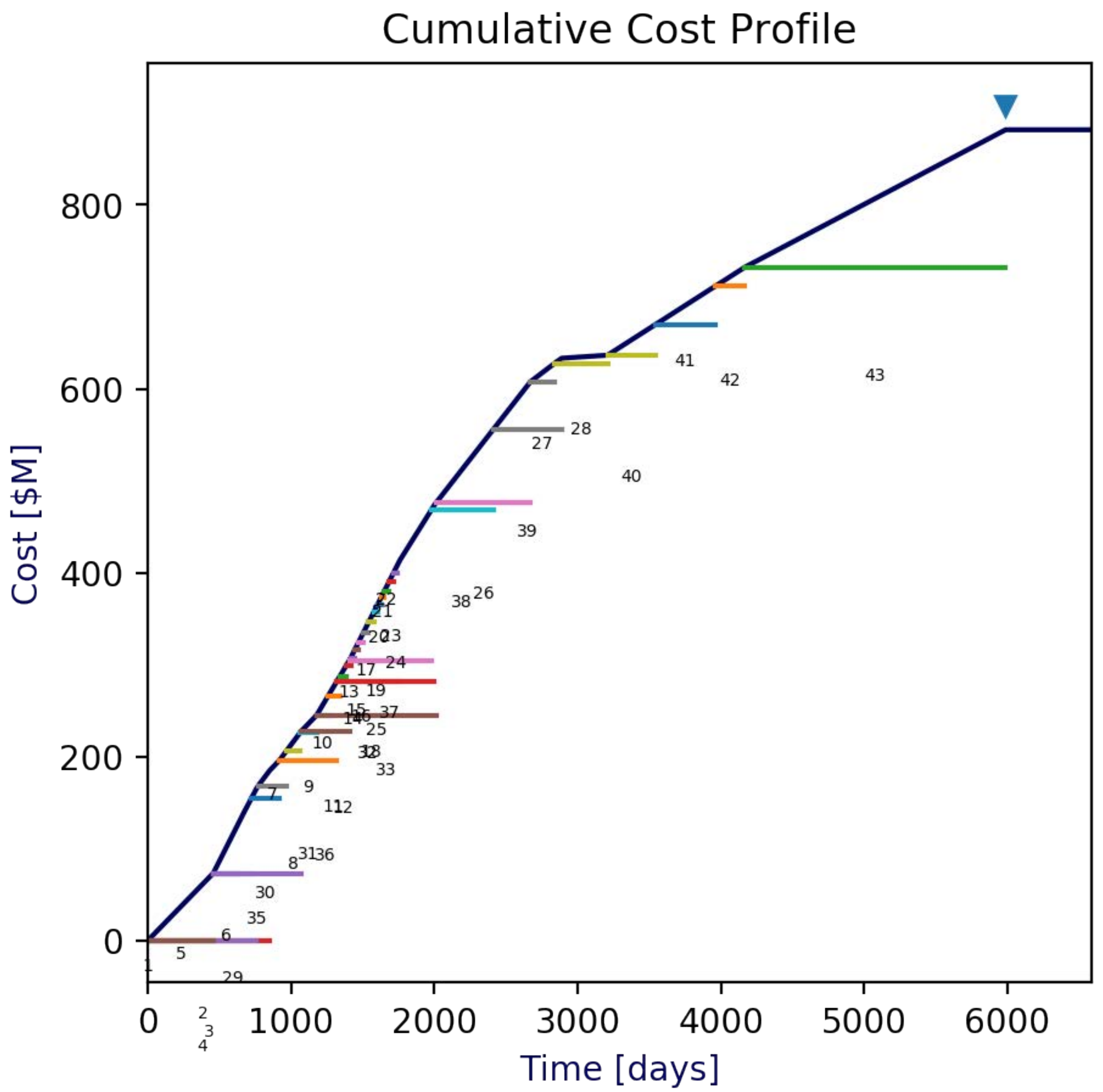
1) Starting from GAO FY2013 estimate for cost category breakdown
2) Inflating total cost to $2021: $7.4B
3) Assume actual cost is $8.5B, but keeping same cost distribution
4) Scaling from 6.5m to 8.5m diameter
5) Matching scope to Nautilus (eliminating instruments not needed, relaxed tolerances, etc.)
6) Accounting for MODE lens instead of mirrors

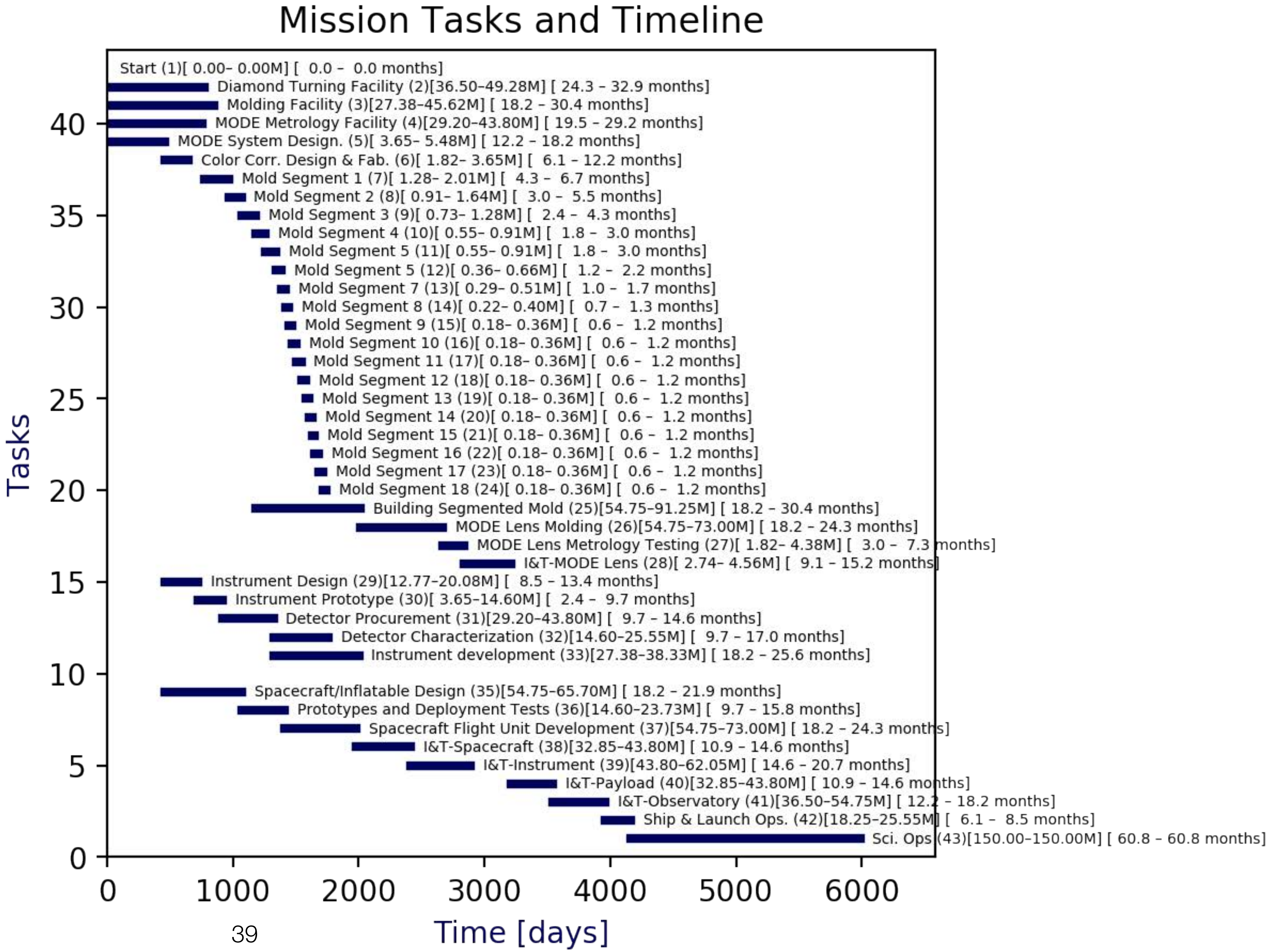
Estimate ~$2.2B

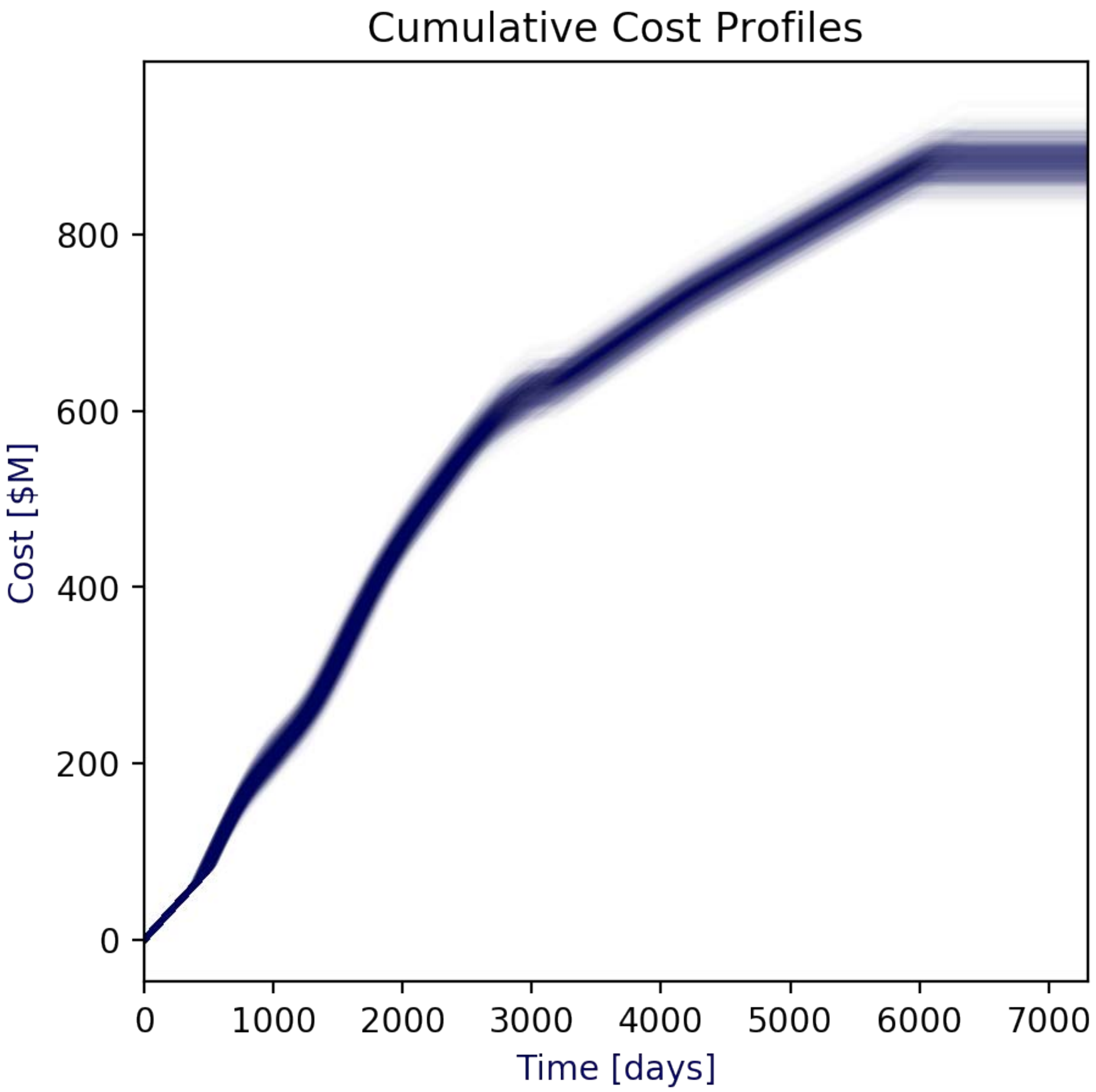
				Cost	8.5m Mirror-diameter	Cost	1x8.5m MODE
	JWST FY13	**JWST FY2021**	**JWST Scaled to 9B FY2021**	**Scaling Factor**	**JWST [$M]**	**Scaling Factor**	**Nautilus Probe [$M]**
Spacecraft & OTA	2955	3,600.38	4,291.59	2.01	8,620.51	0.15	1,293.08
Other Direct Costs	1563.5	1,904.97	2,270.70	1.38	3,133.04	0.15	469.96
Payloads	695.1	846.91	1,009.50	0.10	100.95	1.00	100.95
Ground Systems	652.3	794.76	947.35	0.50	473.67	0.25	118.42
Launch Vehicle (not included)	0	0.00	0.00	1.00	0.00	1.00	0.00
Systems I&T	288.4	351.39	418.85	0.65	272.25	0.30	81.68
Science/Tech	42.7	52.03	62.01	0.70	43.41	3.00	130.23
Total	**6197**	**7,550.44**	**9,000.00**		**12,643.83**		**2,194.31**
					Results		
	Correction factor between for 2013 and 2019 cost estimates:			1.19	**Relative cost of MODE vs. Mirror:**		**0.17**
Spacecraft & OTA		Diameter Cost-scaling Power law index:		1.3			
Spacecraft & OTA		Correspoding Diameter cost scaling factor:		2.01			
Direct costs		Diameter Cost-scaling Power law index:		0.6			
Direct costs		Correspoding Diameter cost scaling factor:		1.38			

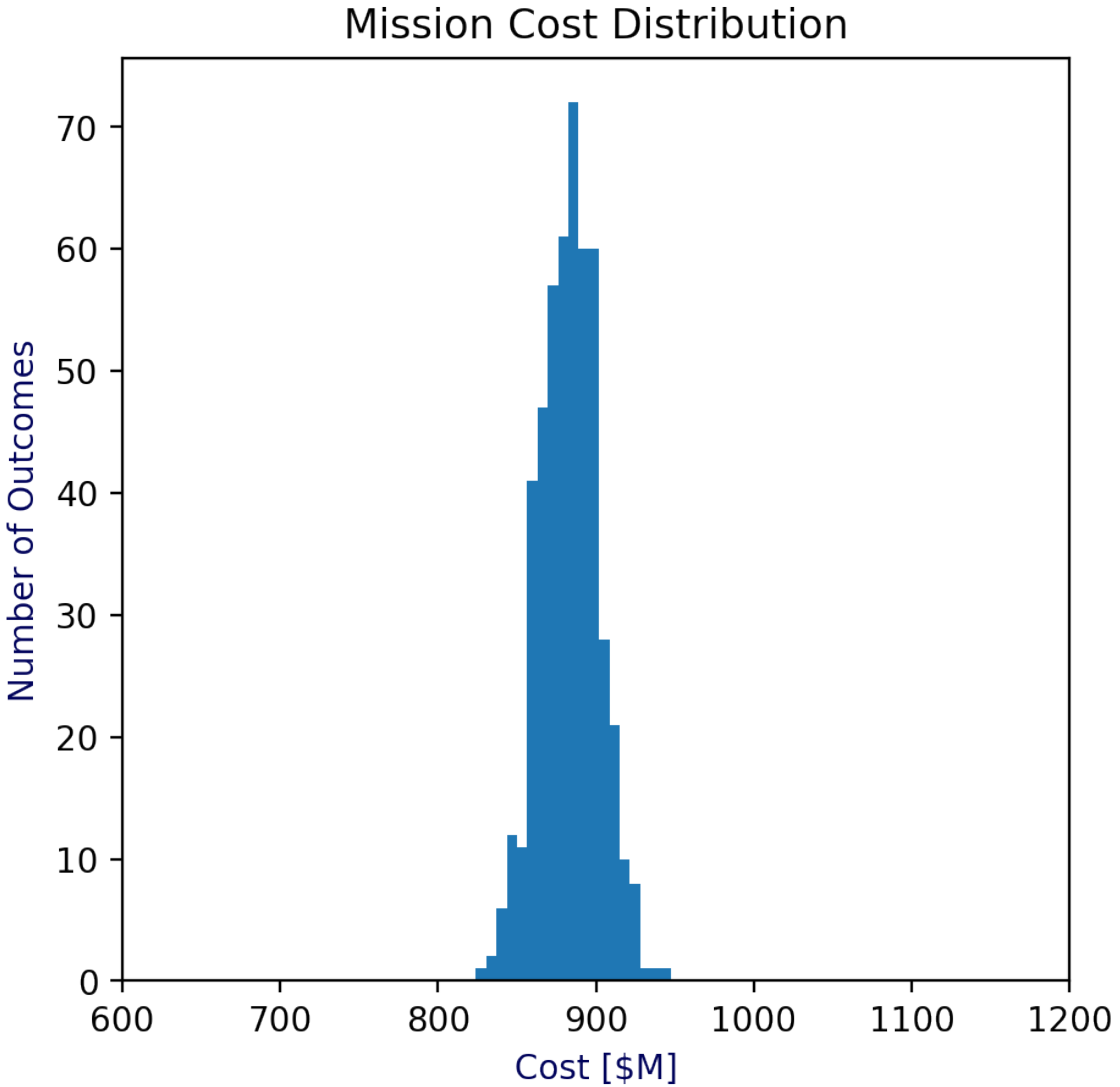
Cost Estimate 2: Bottom up

Work breakdown: 42 tasks
Each task: Duration range + cost/day estimate
Actual Task dependencies defined
Monte Carlo simulation: 500 realizations
Critical path assessment






Cumulative Cost Profiles
Cost [$M]
0
200
400
600
800
0
1000
2000
3000
4000
5000
6000
7000
Time [days]


Mission Cost Distribution
Number of Outcomes
0
10
20
30
40
50
60
70
600
700
800
900
1000
1100
1200
Cost [$M]

Nautilus Space Observatory

Nautilus Space Observatory

Science Goals:
1) Determine the diversity of Earth-sized planets
2) Search for life

Science Objective:
To spectroscopically characterize 1,000 Earth-sized, habitable zone planets

Nautilus Space Observatory

A 50m-equivalent space telescope

Transits: no need for coherently combined light

* - equivalent collecting area

A THOUSAND EARTHS: A VERY LARGE APERTURE, ULTRALIGHT SPACE TELESCOPE ARRAY FOR ATMOSPHERIC BIOSIGNATURE SURVEYS

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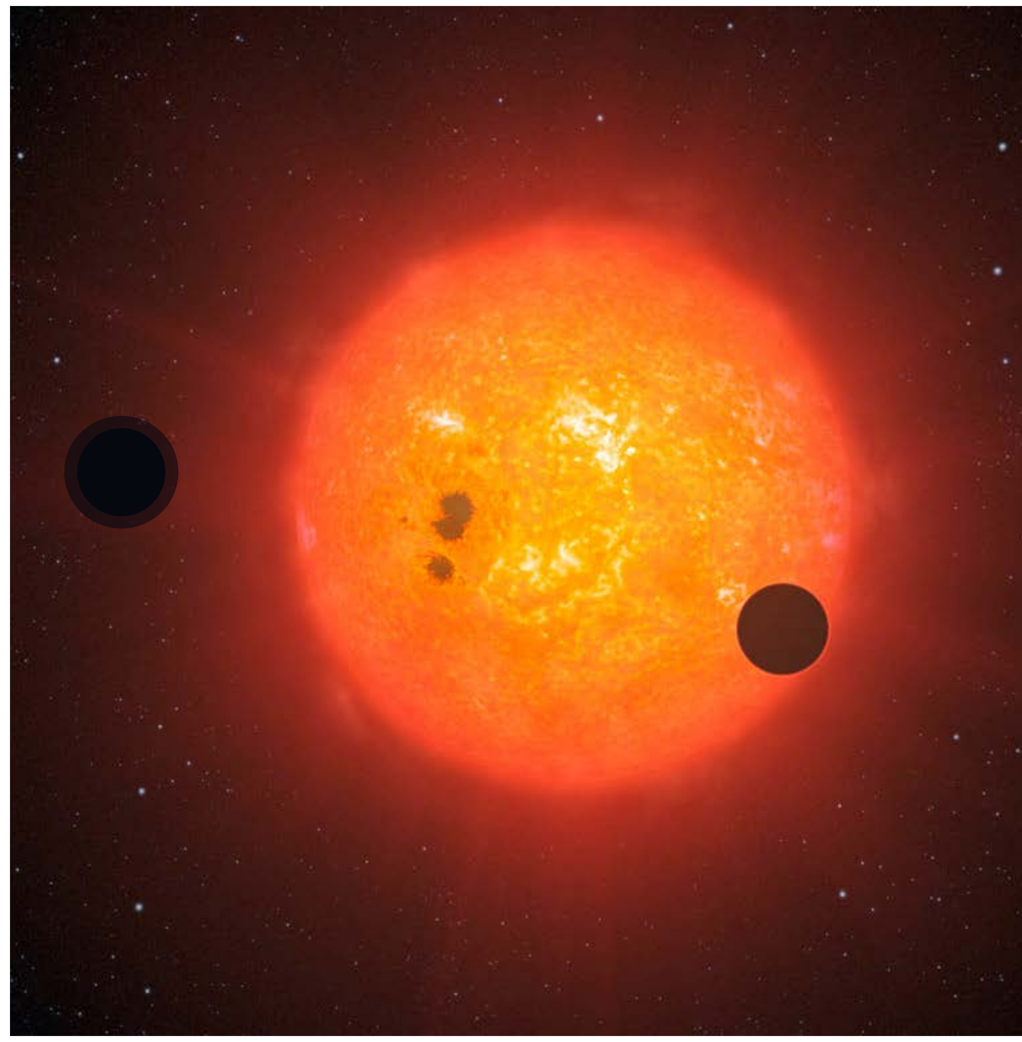
[3] *Steward Observatory, The University of Arizona, Tucson, AZ 85721*

[4] *Northrop Grumman Aerospace Systems, Redondo Beach, CA 90278*

How far do we have to look?



Based on Kepler occurrence rates

Space density of stars, geometric transit probability

Closest planets: 50 pc

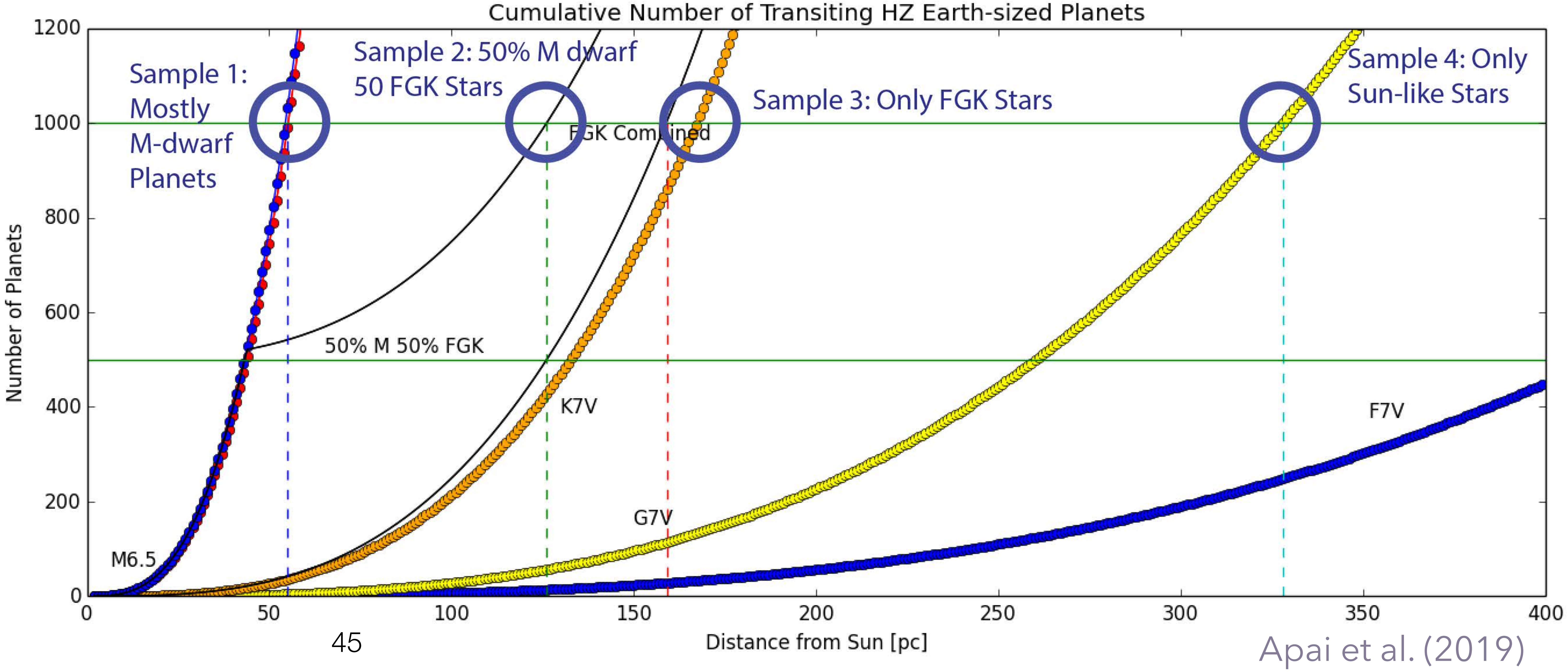
M-star planets only: 53 pc

50% M + 50% FGK: 126 pc

FGK star planets only: 159 pc

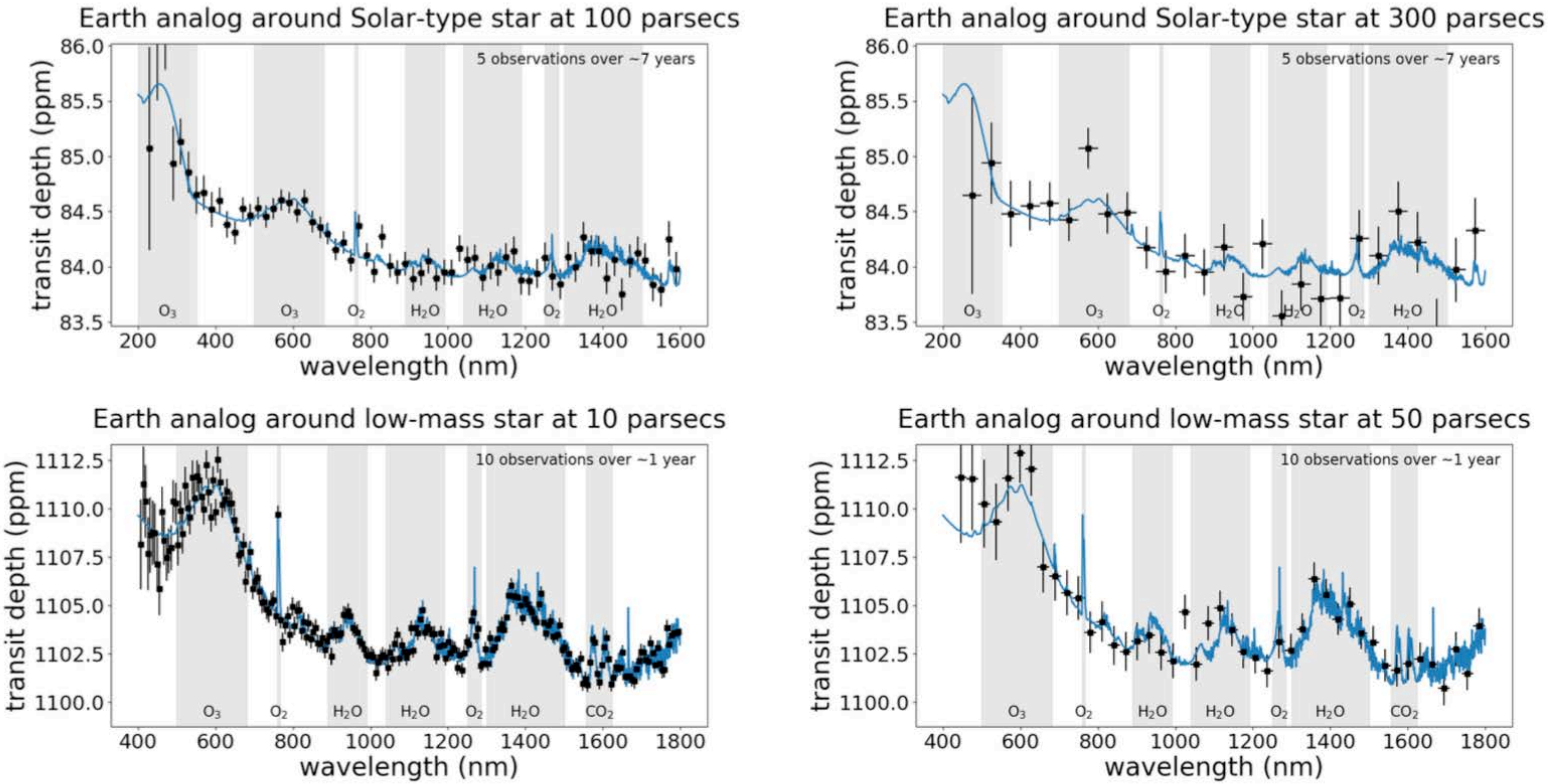
Only G stars: 330 pc

Faintest planet hosts: I=12–16.5



Apai et al. (2019)

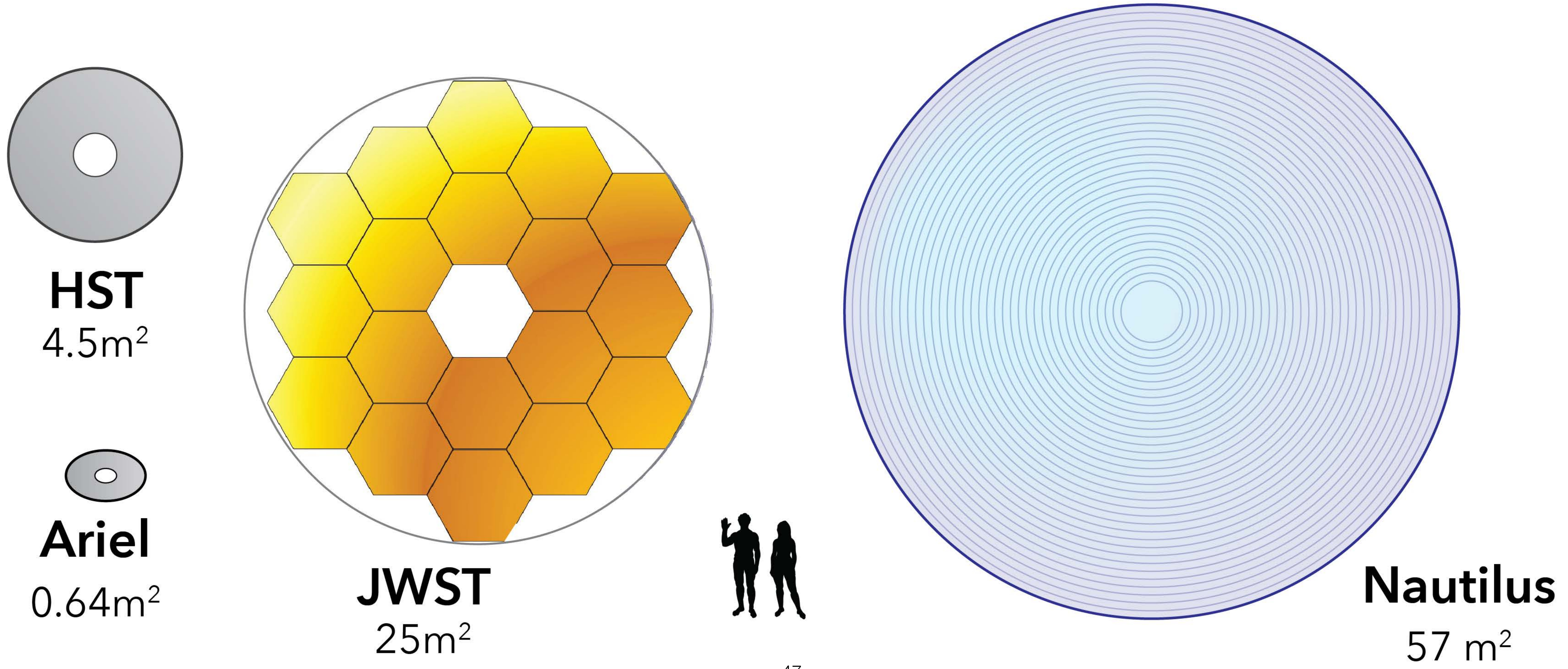
Transiting Earths with a 50m space telescope



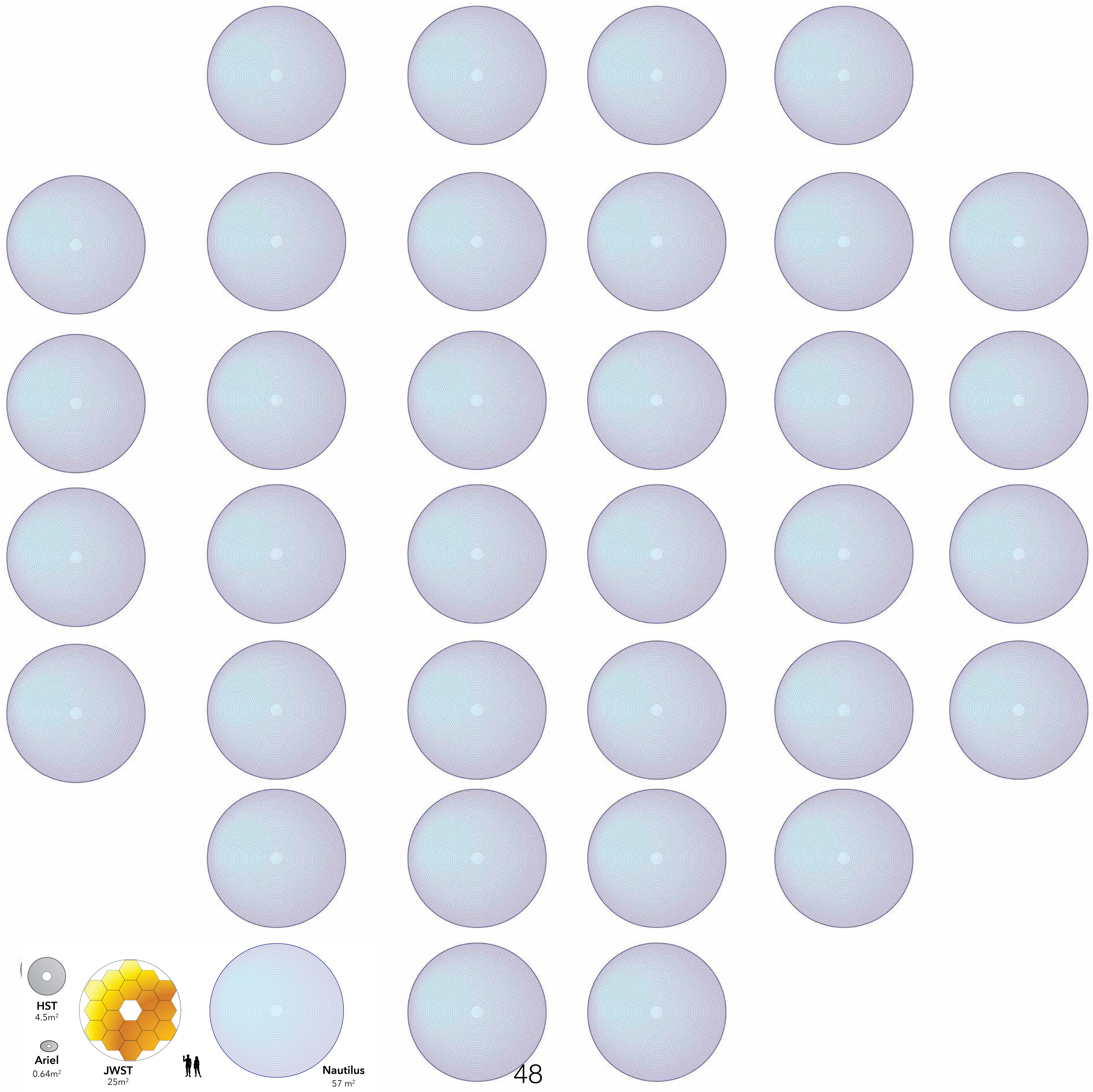
GSFC's Planetary Spectrum Generator

Kepler already reaches 2ppm;
sensitivity not spatial resolution

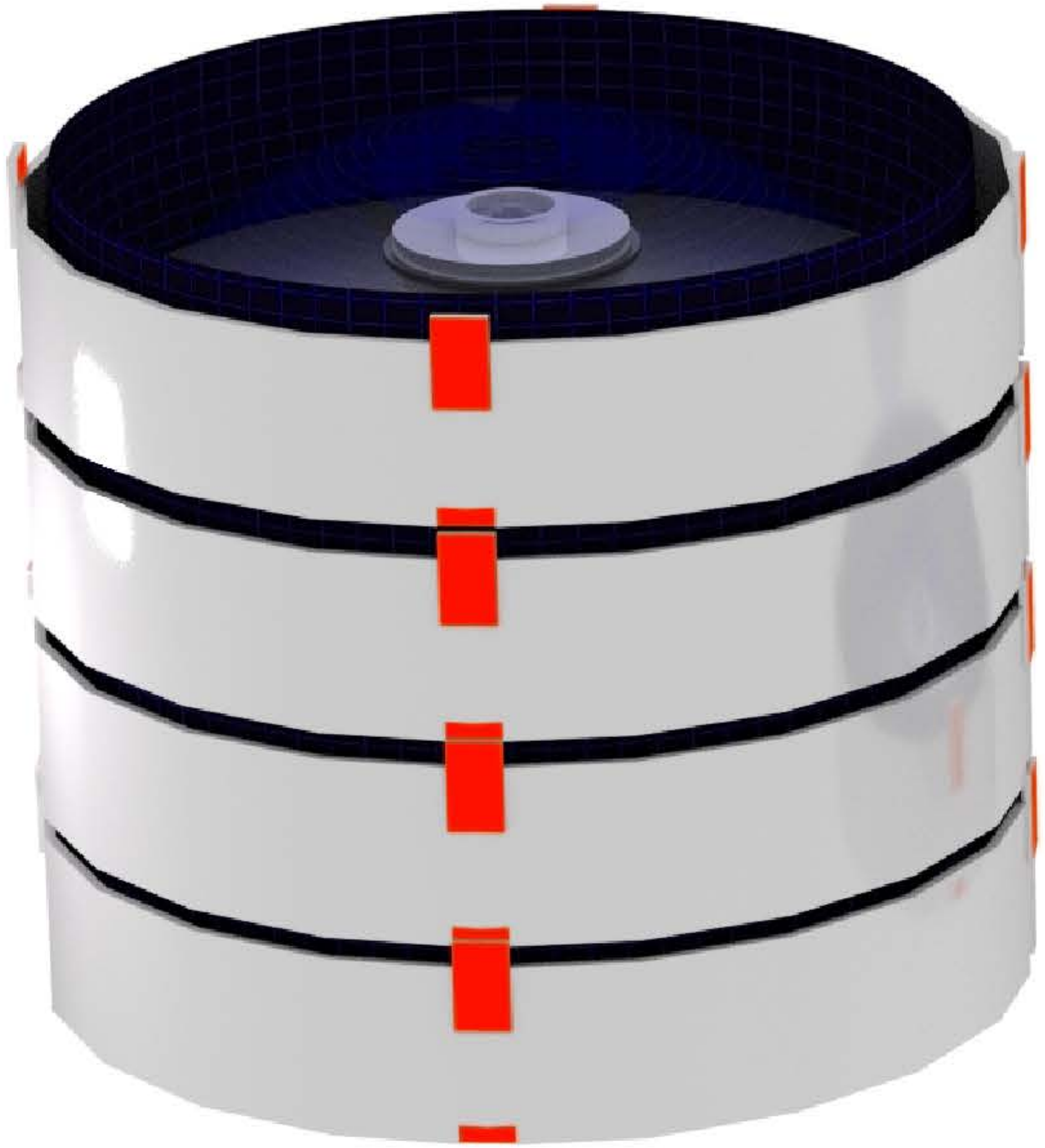
Apai et al. (2019)


HST
4.5m²
Ariel
0.64m²
JWST
25m²
Nautilus
57 m²

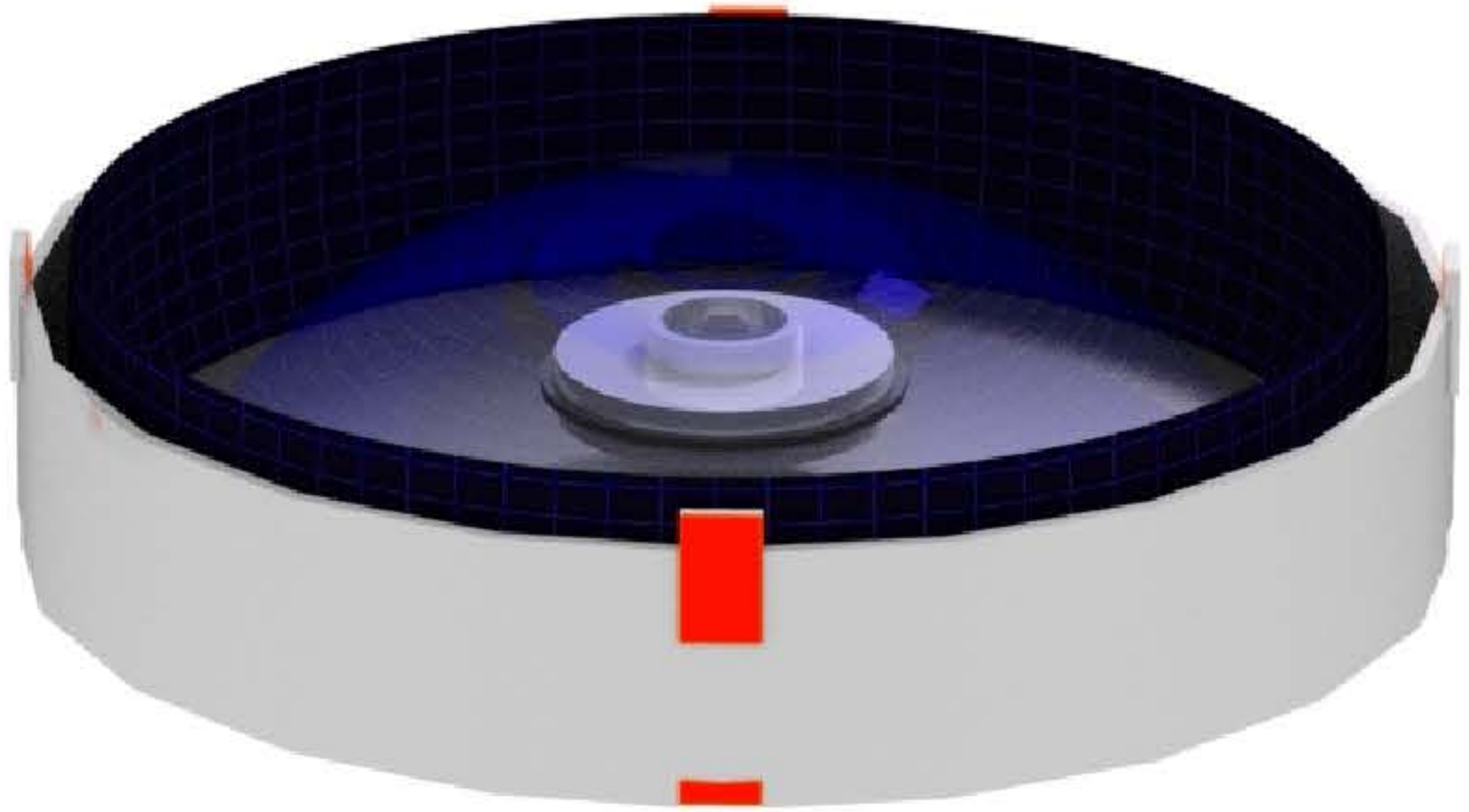
Nautilus Observatory



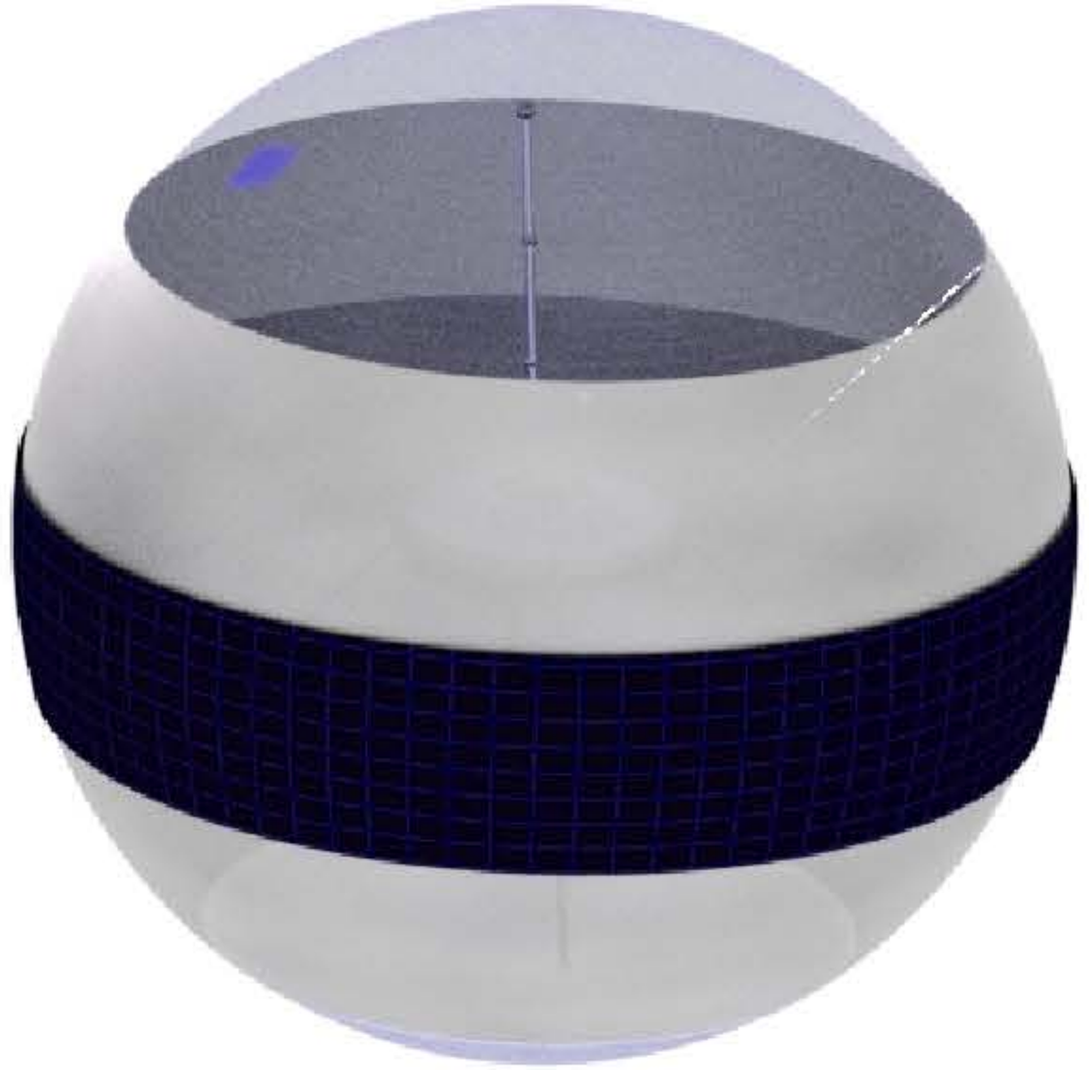
Nautilus Observatory Concept



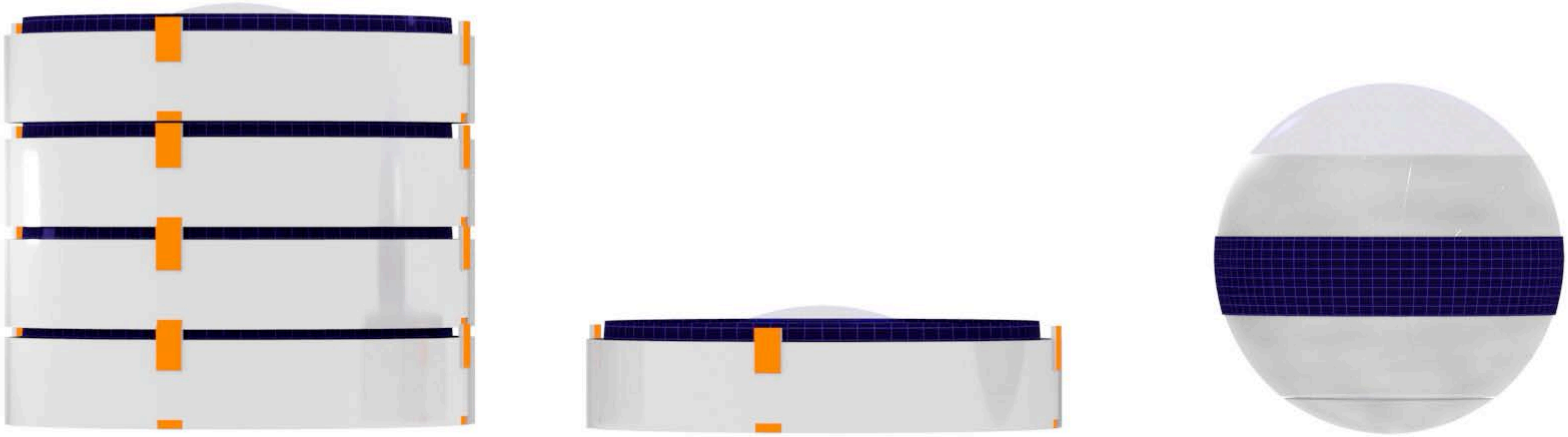
Multiple Unit Telescopes
in Single Rocket Fairing

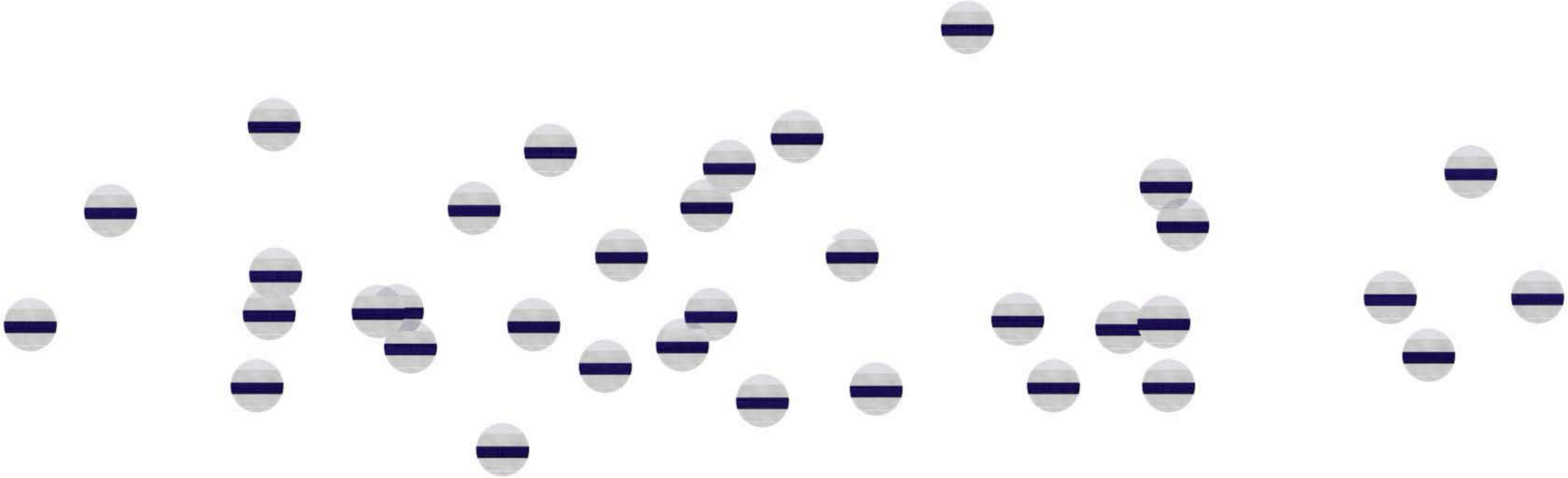


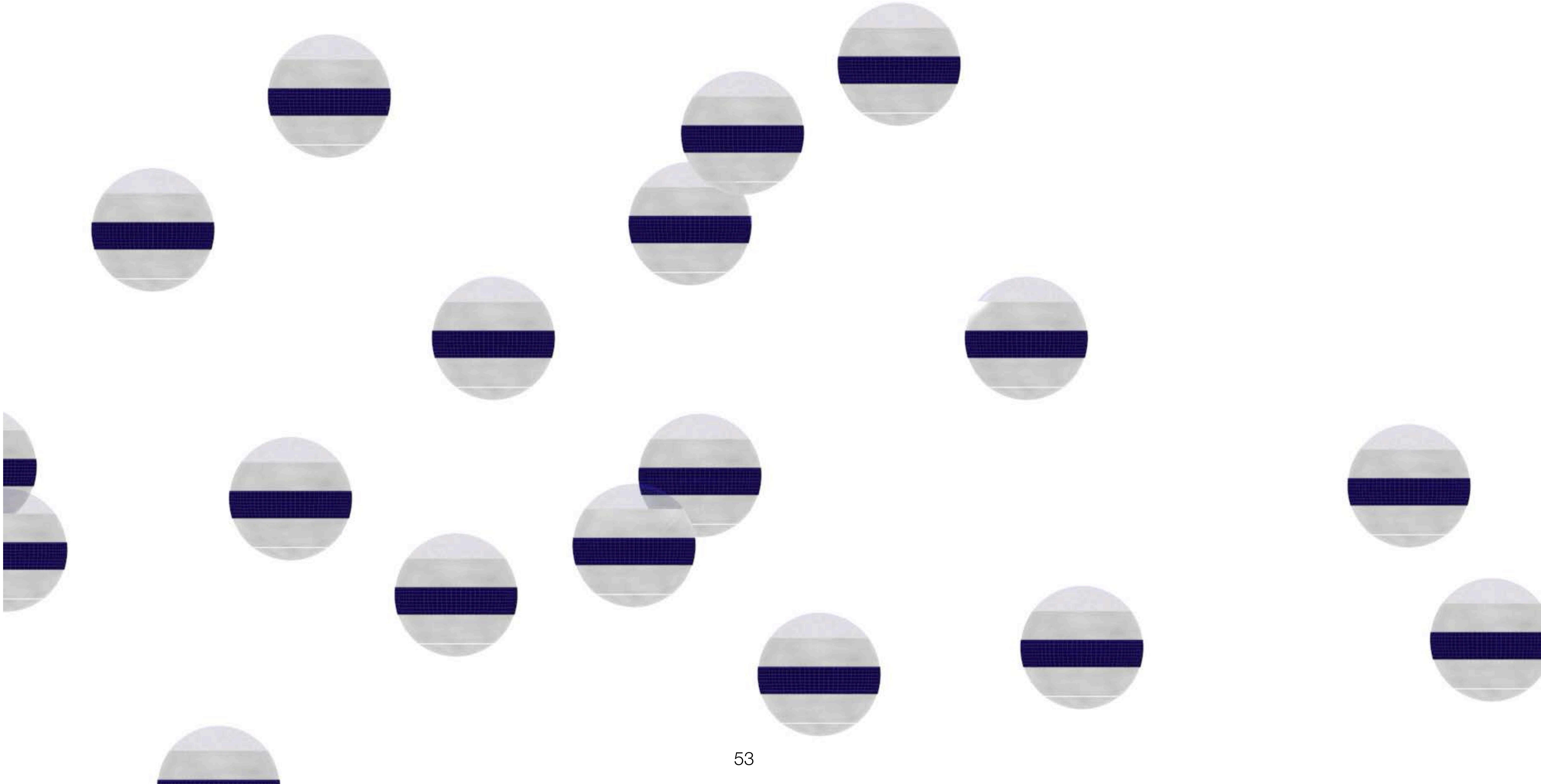
Unit Telescope
in Launch Container

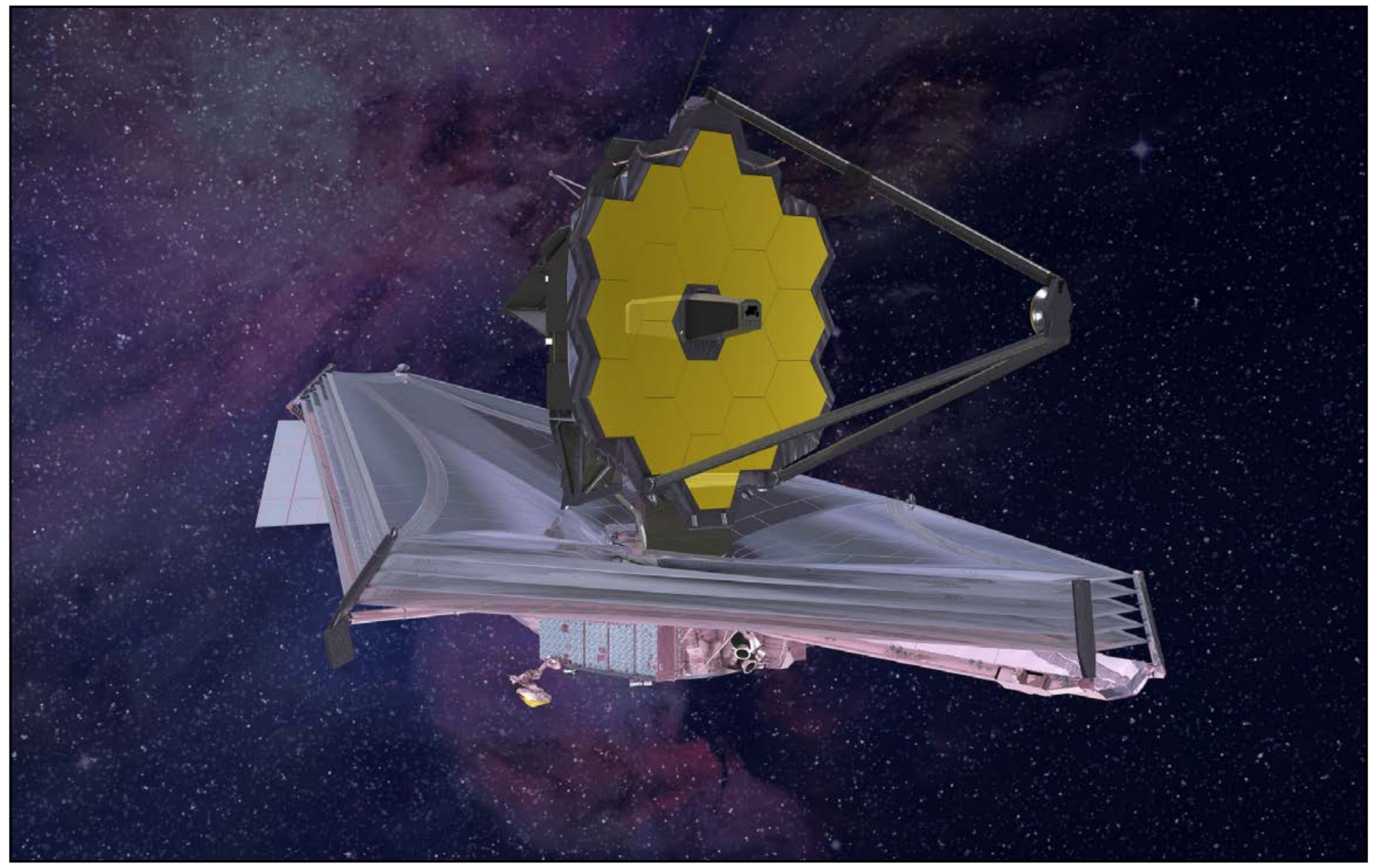


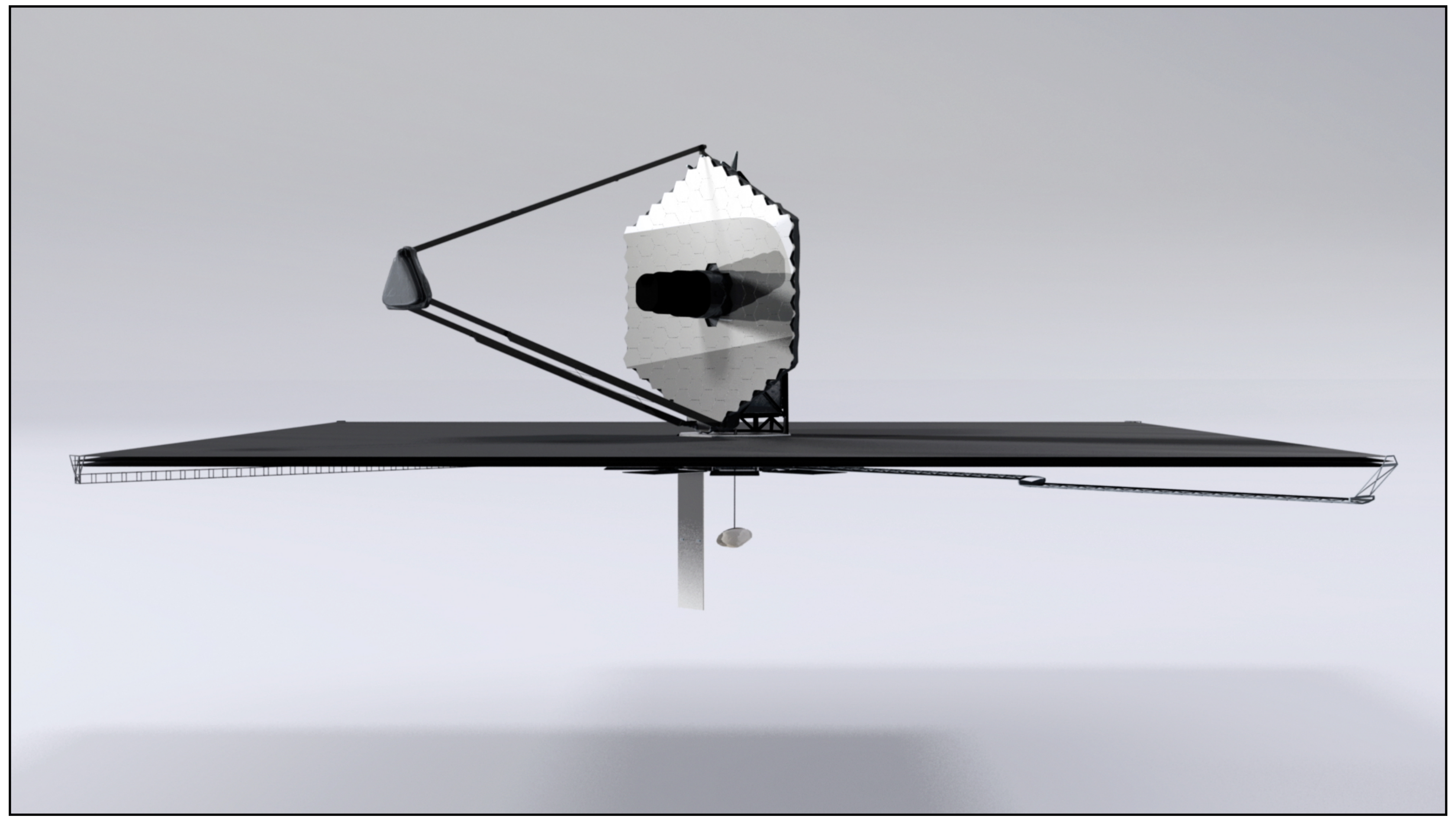
Deployed
Unit Telescope











	JWST	LUVOIR Concept (Interim Report)	Nautilus Observatory
Collecting Area	33 m^2	201 m^2	1960 m^2
# Habitable Planets Searched for Life	1-3??	30-60	1,000
Max. Distance for life detection	~14 pc?	~50 pc	300 pc

Nautilus Probe

Transformational Science Mission with Transformational Technology

Characterization of 1,000 exoplanets

Time-domain astrophysics and faint objects

Technology:

Multi-order diffractive engineered-material lenses

Key Step to Nautilus Space Observatory

Ultralight-weight optics cost-efficiently replicated

Array of light-weight, low-cost telescopes launched simultaneously

Risks and functionality shared between units

Paradigm change for space telescopes: scalable, highly sensitive, low-cost

GORDON AND BETTY MOORE FOUNDATION

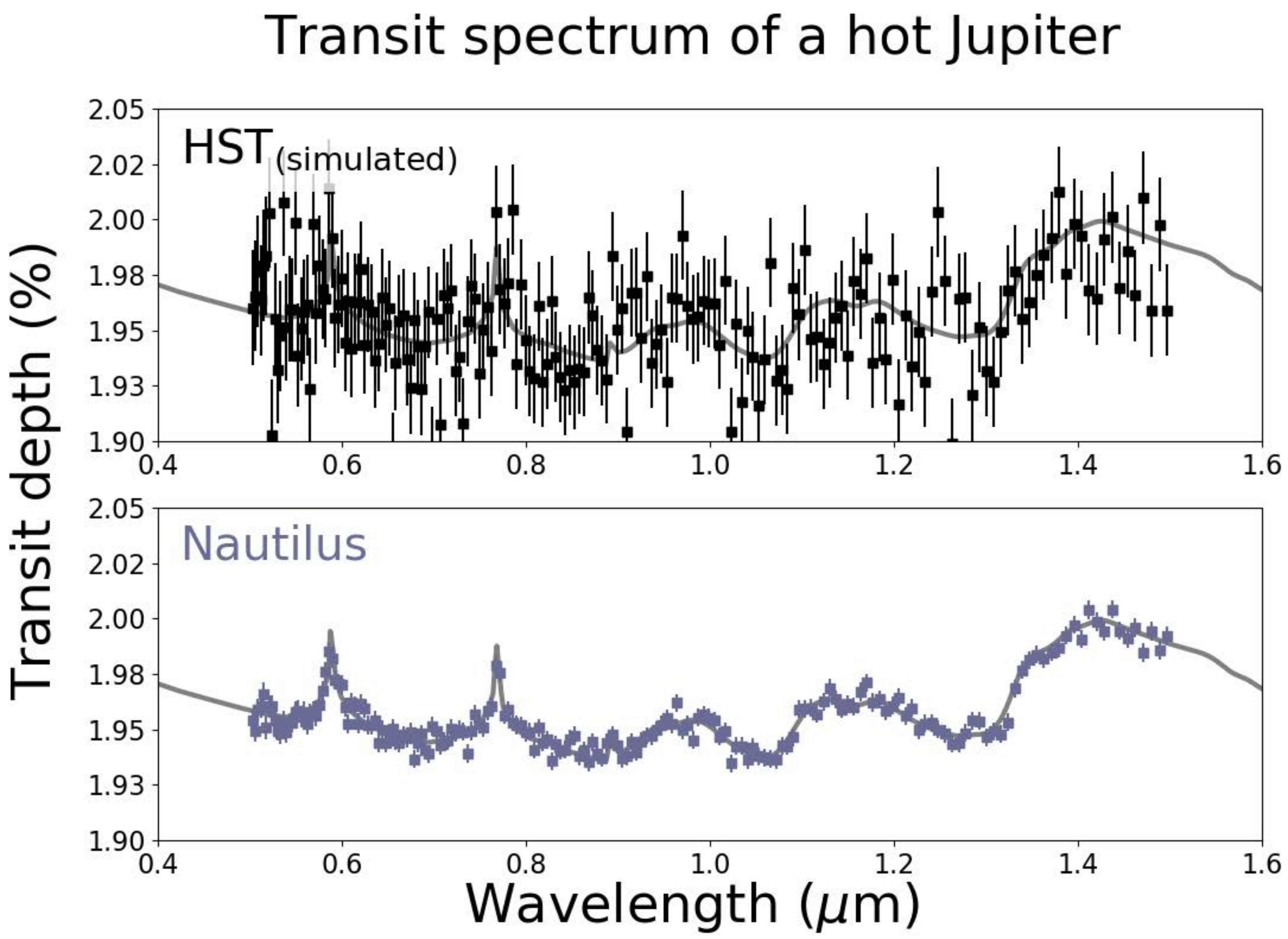
THE UNIVERSITY OF ARIZONA

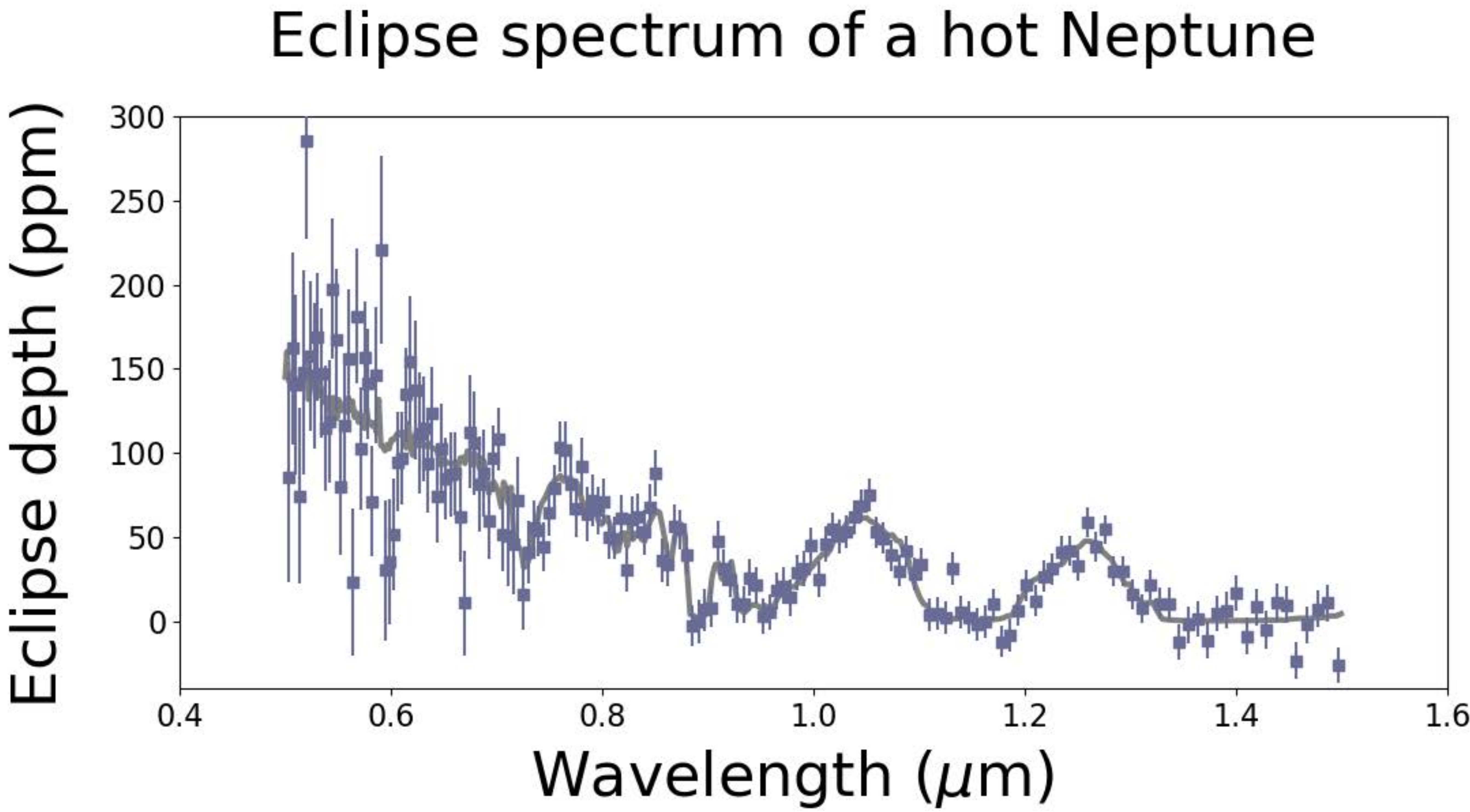
THE UNIVERSITY OF ARIZONA Wyant College of Optical Sciences

THE UNIVERSITY OF ARIZONA COLLEGE OF SCIENCE Astronomy & Steward Observatory

COLLEGE OF SCIENCE LUNAR & PLANETARY LABORATORY

Extra Slides


Transit spectrum of a hot Jupiter
HST(simulated)
Nautilus
Transit depth (%)
Wavelength (μm)
2.05
2.02
2.00
1.98
1.95
1.93
1.90
0.4
0.6
0.8
1.0
1.2
1.4
1.6


Eclipse spectrum of a hot Neptune
Eclipse depth (ppm)
Wavelength (μm)
300
250
200
150
100
50
0
0.4
0.6
0.8
1.0
1.2
1.4
1.6

Technology Development Path

a) Fabrication and on-sky demonstration of 0.24m telescope with mold MODE lens (Dec 2020)

b) Scaling up molding capabilities to D=1m

c) Building a D=1m ground-based telescope

d) Designing / reviving a D=2.0m-class diamond turning facility

e) Scaling up molding capabilities to D=2m

Launch Vehicle Options

NASA SLS B2 and Starship could both launch 10-20+ D=8.5 Nautilus units

New Glenn, Falcon Heavy, etc. expected to be able to launch D=4.5m Nautilus units

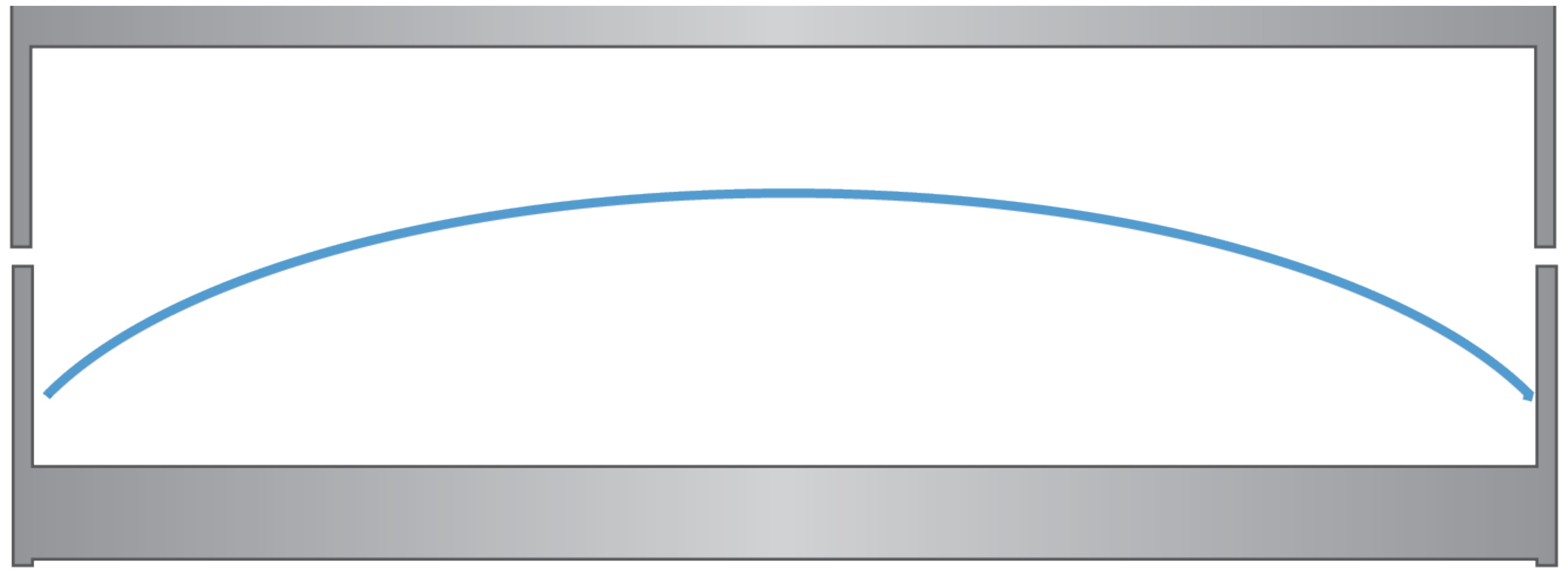
NASA SLSB1

SpaceX Starship prototype

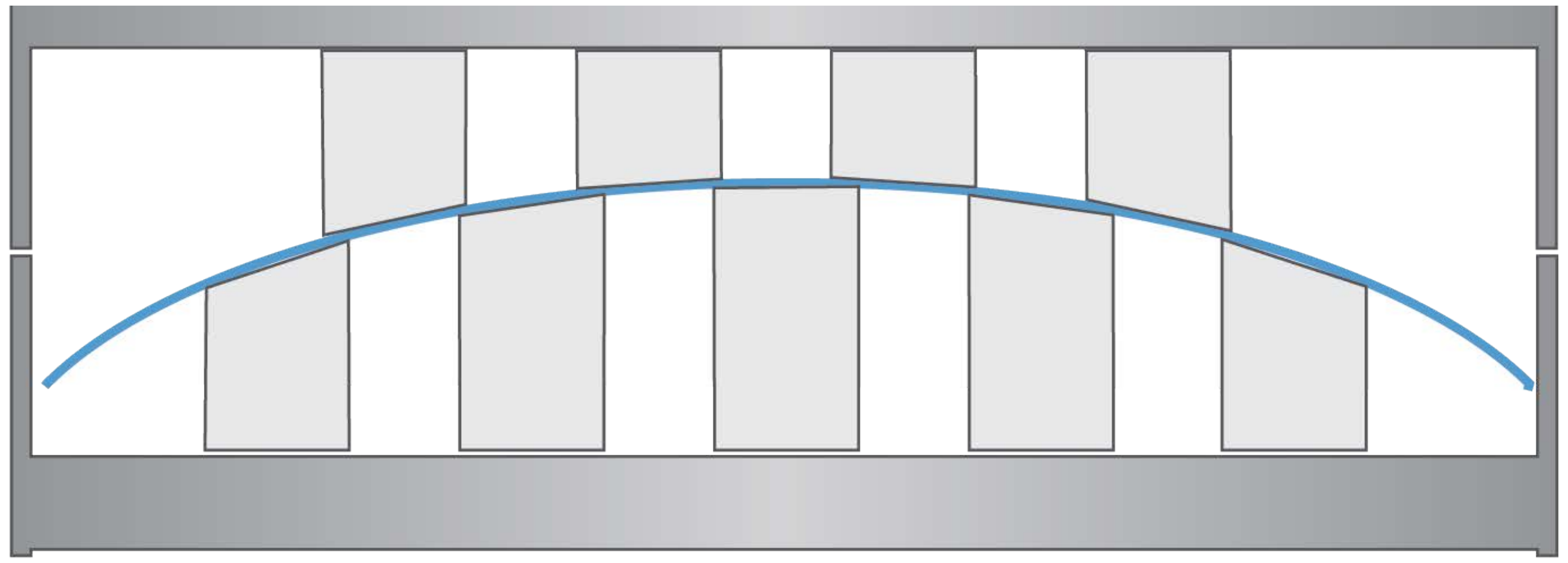
Launch Survivability

Large glass-metal structures in space: ISS solar panels

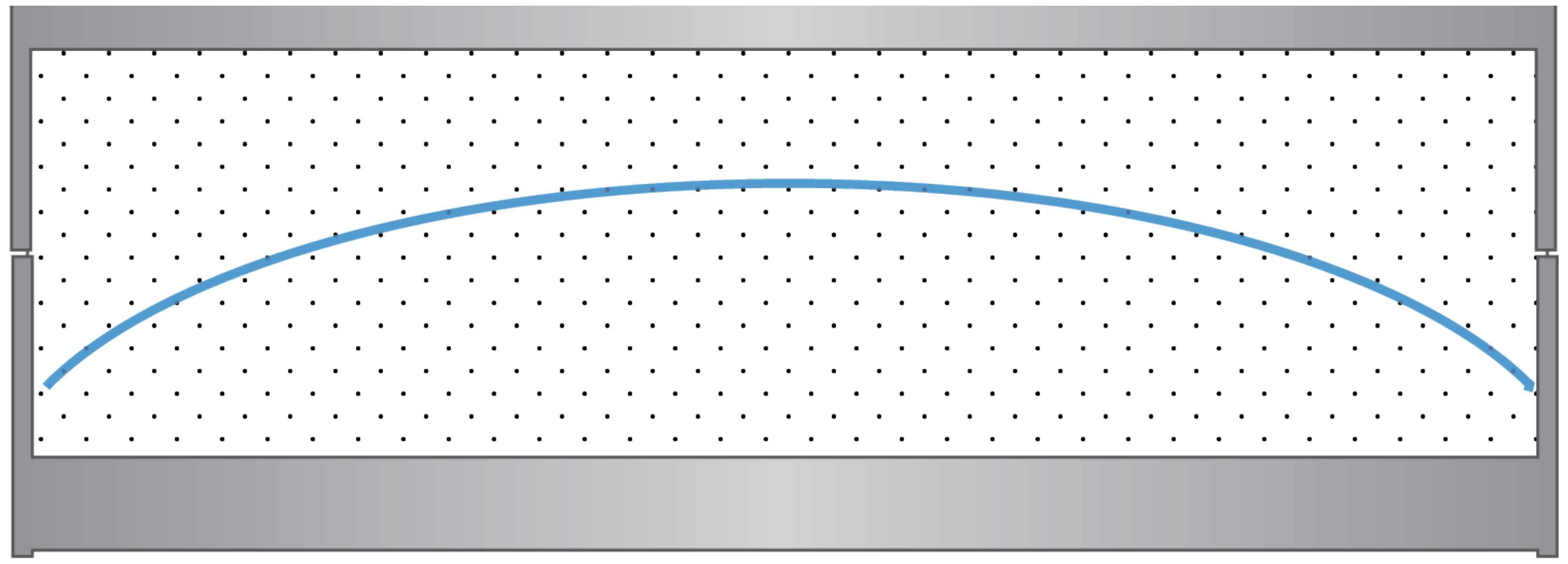
Multiple potentially viable options identified



Advanced, self-supporting structure to maximize launch survivability

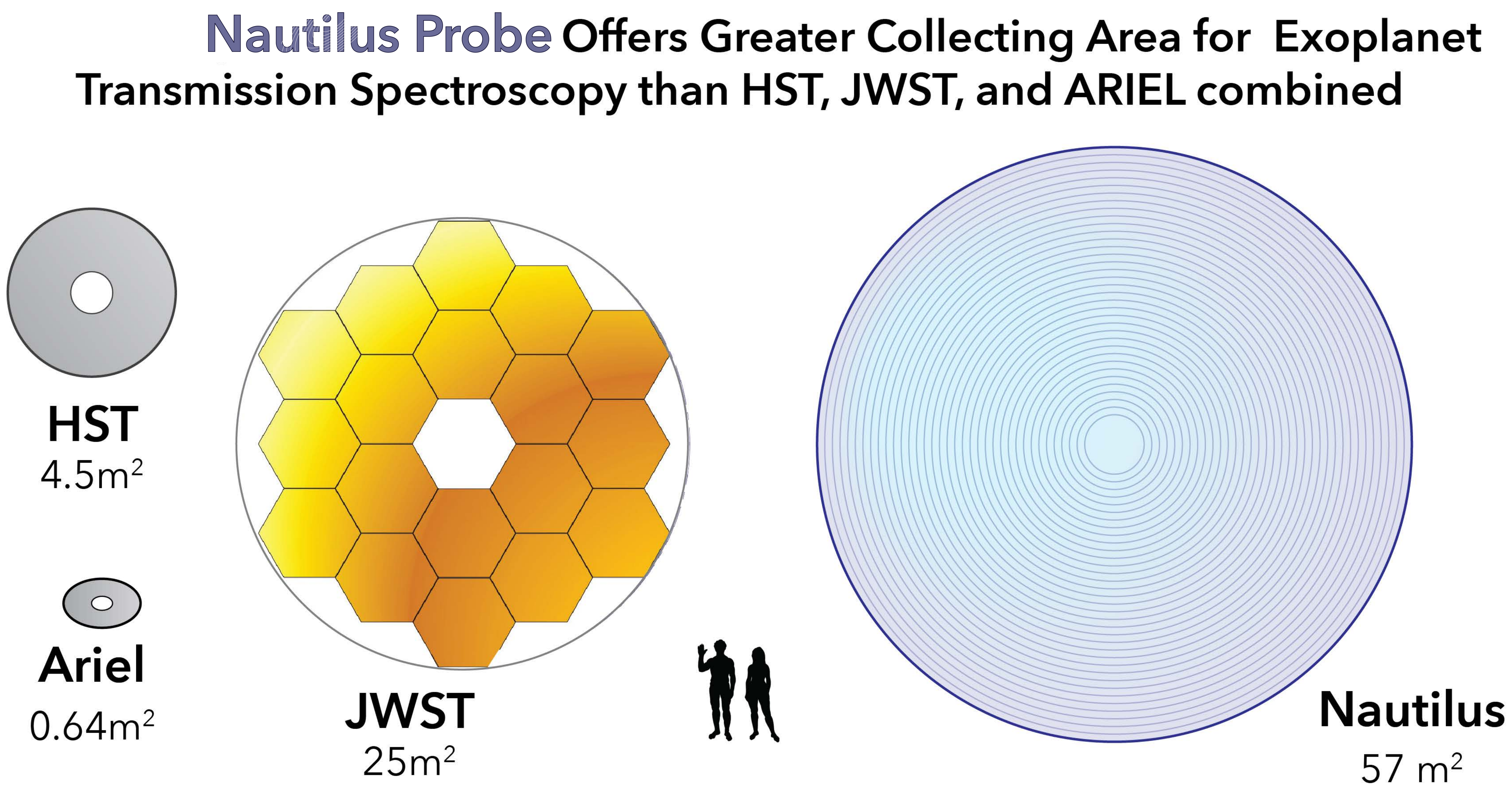


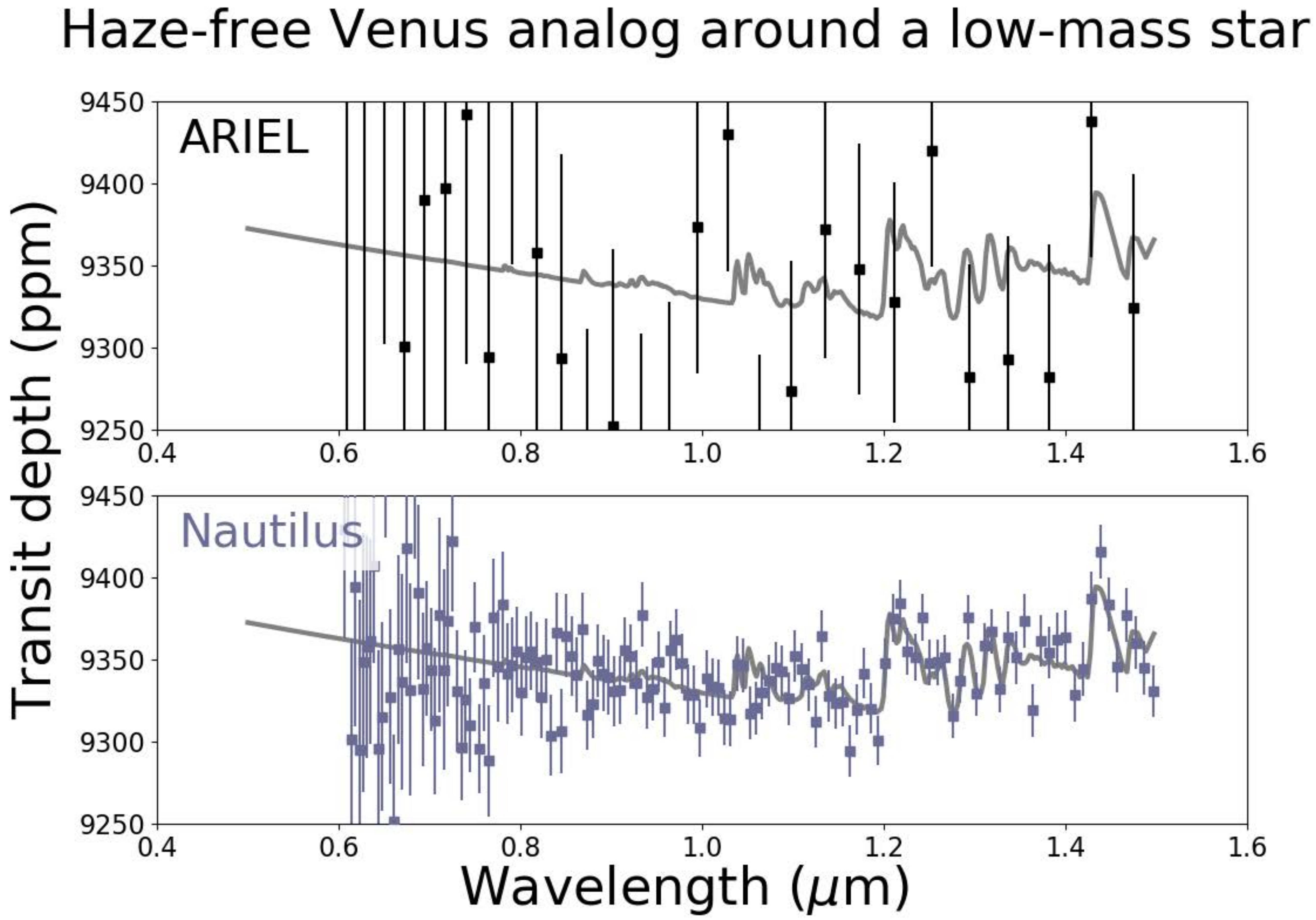
Passive, fixed support structures to suppress vibrational modes



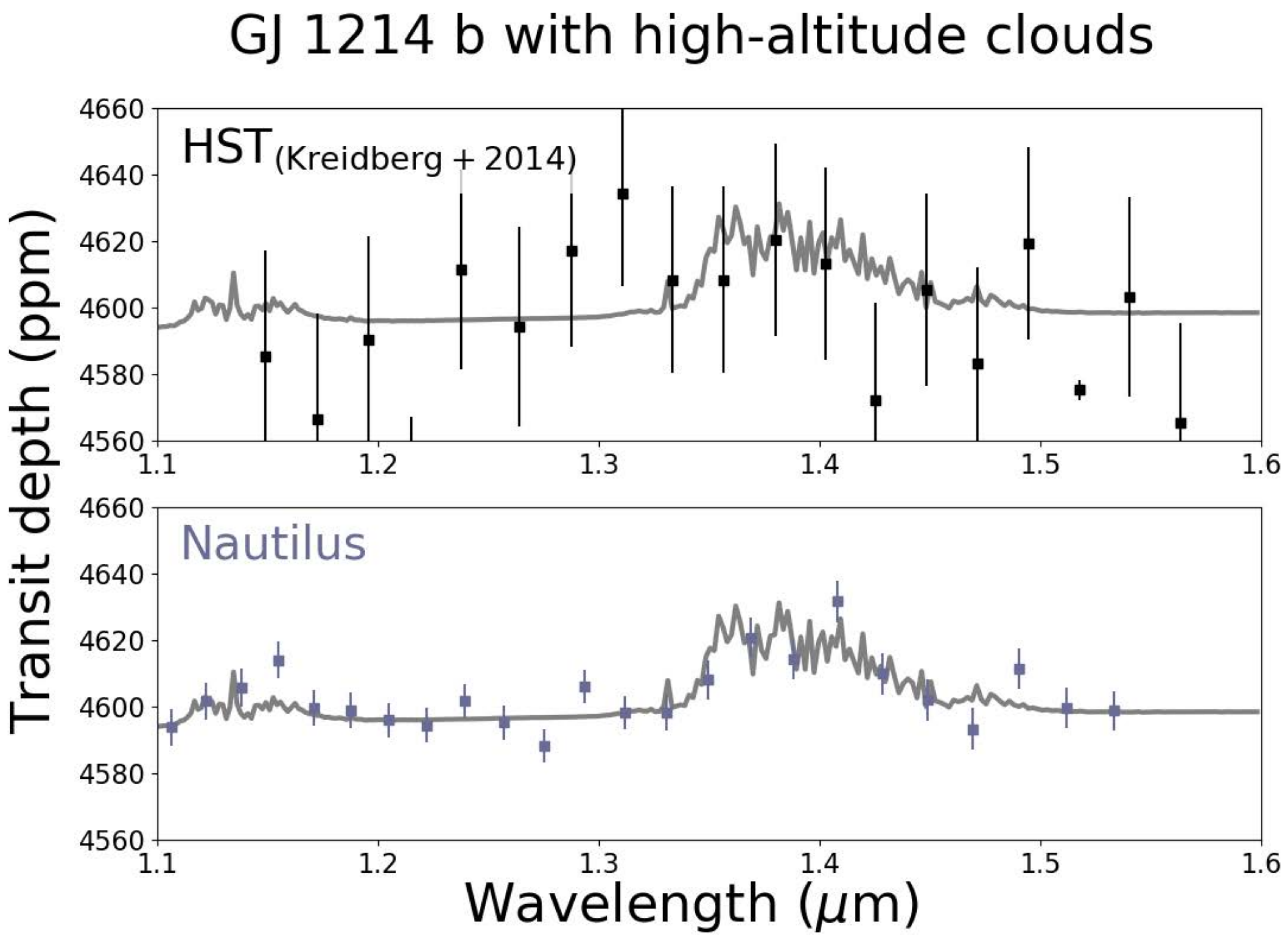
CO_2 ice to minimize membrane-like vibrations

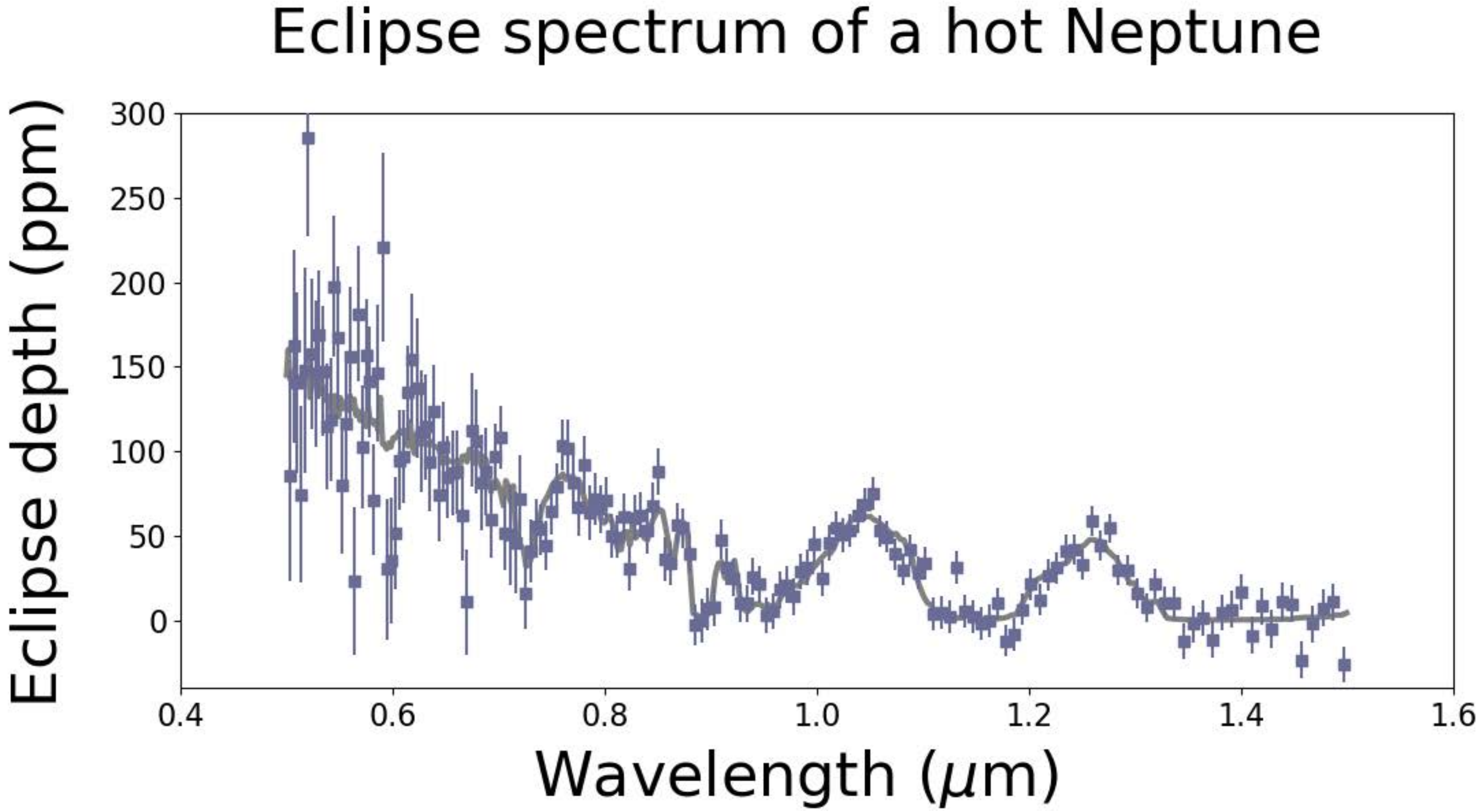
Comparison with ESA's Ariel





Clouds?


GJ 1214 b with high-altitude clouds
HST(Kreidberg + 2014)
Nautilus
Transit depth (ppm)
Wavelength (μm)
4660
4640
4620
4600
4580
4560
1.1
1.2
1.3
1.4
1.5
1.6


Eclipse spectrum of a hot Neptune
Eclipse depth (ppm)
Wavelength (μm)
300
250
200
150
100
50
0
0.4
0.6
0.8
1.0
1.2
1.4
1.6

Case	HST Honeycomb	JWST Segmented	MODE 0.5 cm	MODE 5 cm
Current Design	2.4m, 826 kg	6.5m, 710 kg	–	
Assuming $M \propto D^{2.0}$ scaling for HST and JWST:				
Scaled to 8.5m	10,360 kg	1,214 kg	425 kg	4,255 kg
Assuming $M \propto D^{2.8}$ scaling for HST and JWST:				
Scaled to 8.5m	28,494 kg	1,505 kg	425 kg	4,255 kg

Table 6. Assessment of Elements of Cost.

Element of Cost	Traditional Approach	MODE Relative Cost
Design	Same	Same
Materials	Larger due to the greater mass of materials. Structure more costly than	Lower
Manufacturing Tooling	Larger due to the need for more types of machines	Lower
Manufacturing Recurring Cost	Larger due to greater time to produce and optic, each steps is longer in time that the MODE molding step	Lower
Alignment, Integration & Testing	Larger due to need to integrate mirrors on to structure	Lower
Verification	Same	Same

Why Can't we Build a 50m Space Telescope?

Not using economy of scale

Can't build very large mirrors

The "Space Spiral"

Higher-cost Missions

Low number of missions

Unique Telescopes

Challenging Science Requirements

Complex Missions with no tolerance for failure

The "Space Spiral"

Upper limit on possible costs

Higher-cost Missions

Complex Missions with no tolerance for failure

Low number of missions

Challenging Science Requirements

Unique Telescopes

The Cost of Large Mirrors


Telescope Collecting Area
Monolithic Mirrors and Conventional Refractors
Structure too Heavy/Complex
EELT
GMT
LBT
Keck
LUVOIR?
JWST
Palomar 5m
HST
Light-weight Multiple or Segmented Mirror Telescopes
Mirrors too heavy
Yerkes
OAO-2
OAO-1
Lens too heavy
Refractors
Ground
Space
Primary Mirror Area [m^2]
Deployment [Time]
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
1600
1700
1800
1900
2000
2100
2200


Telescope Collecting Area
Monolithic Mirrors and Conventional Refractors
Structure too Heavy/Complex
Nautilus
EELT
GMT
LBT
Keck
LUVOIR?
JWST
Palomar 5m
HST
Light-weight Multiple or Segmented Mirror Telescopes
Mirrors too heavy
OAO-2
OAO-1
Yerkes
Lens too heavy
Refractors
Ground
Space
Primary Mirror Area [m^2]
Deployment [Time]
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
10^4
1600
1700
1800
1900
2000
2100
2200