Taking big risks for big science: approaches to lowering the cost of large space telescopes

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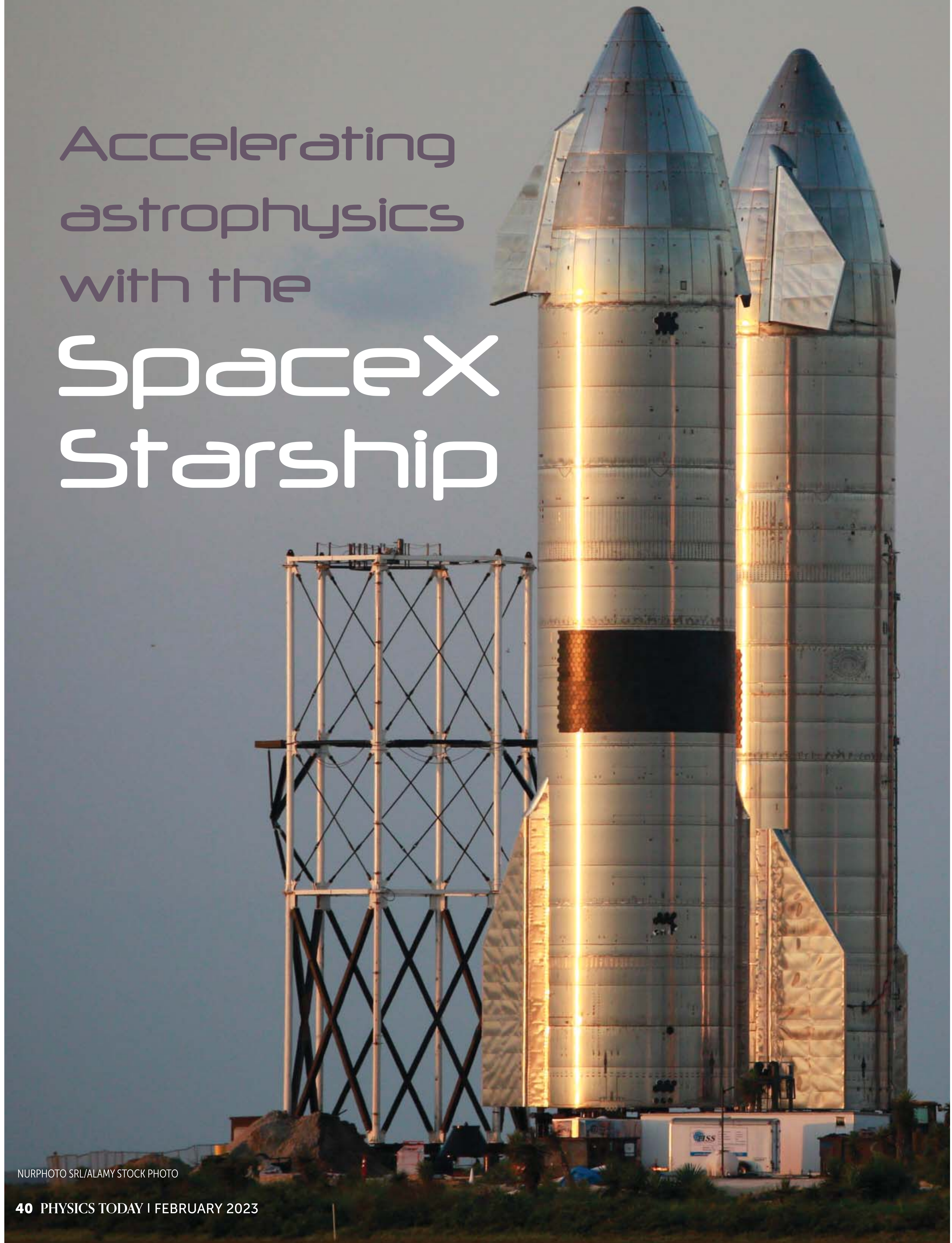


Accelerating astrophysics with the SpaceX Starship

NURPHOTO SRL/ALAMY STOCK PHOTO

40 PHYSICS TODAY | FEBRUARY 2023

PHYSICS TODAY
February 2023 • volume 76, number 2
A publication of the American Institute of Physics

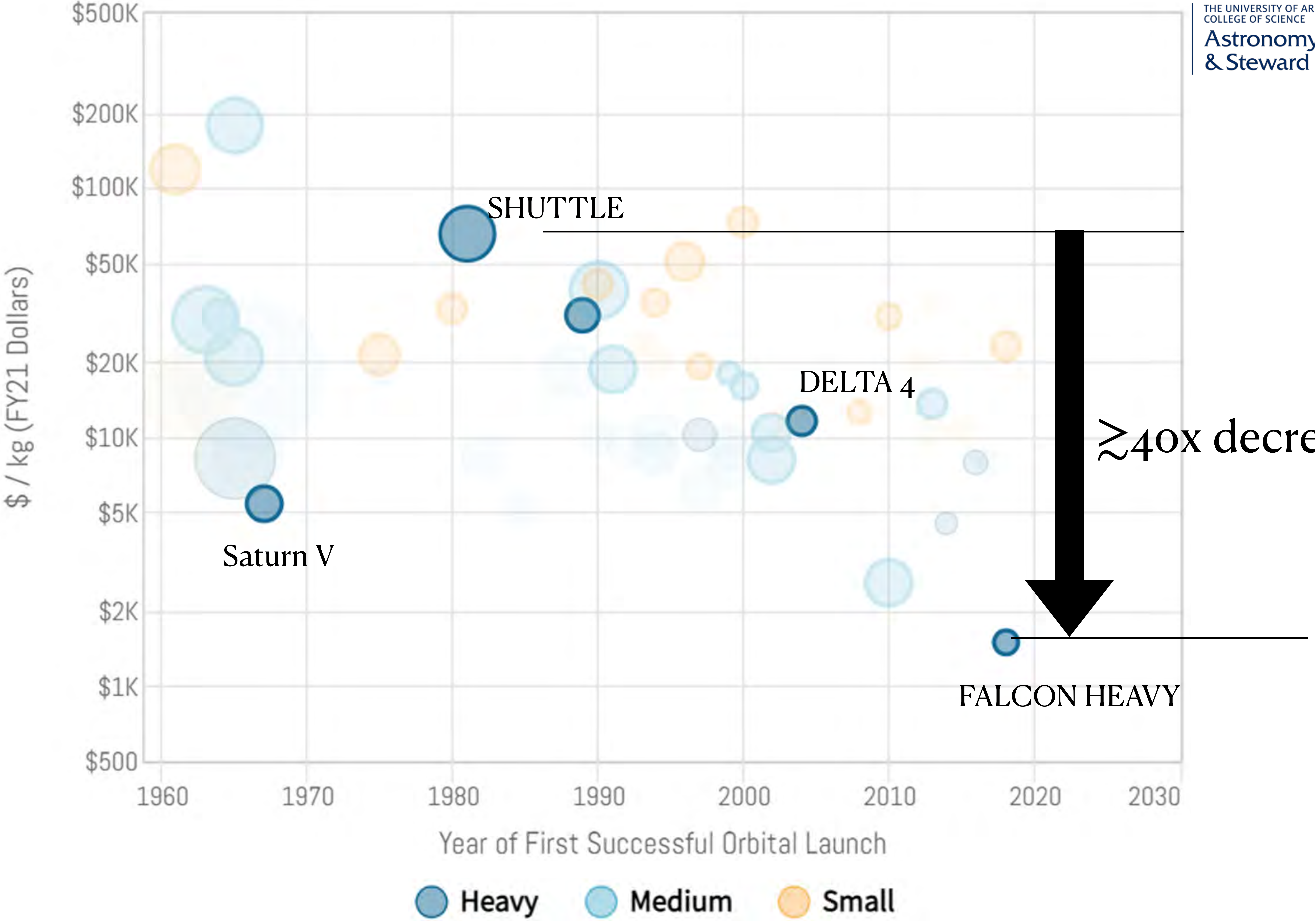
Martin Elvis, Charles Lawrence, and Sara Seager

By substantially increasing the mass and volume of its reusable transportation system without raising costs, SpaceX may enable NASA to implement future missions years ahead of schedule.

Martin Elvis is a senior astrophysicist at the Center for Astrophysics | Harvard & Smithsonian in Cambridge, Massachusetts. **Charles Lawrence** is the chief scientist for astronomy and physics at NASA's Jet Propulsion Laboratory in La Cañada, California. **Sara Seager** is a physics professor at MIT in Cambridge.

Physics Today. 2023;76(2):40-45. doi:10.1063/PT.3.5176

$\log \frac{\mathit{cost}}{\mathit{mass}}$



SHUTTLE

DELTA 4

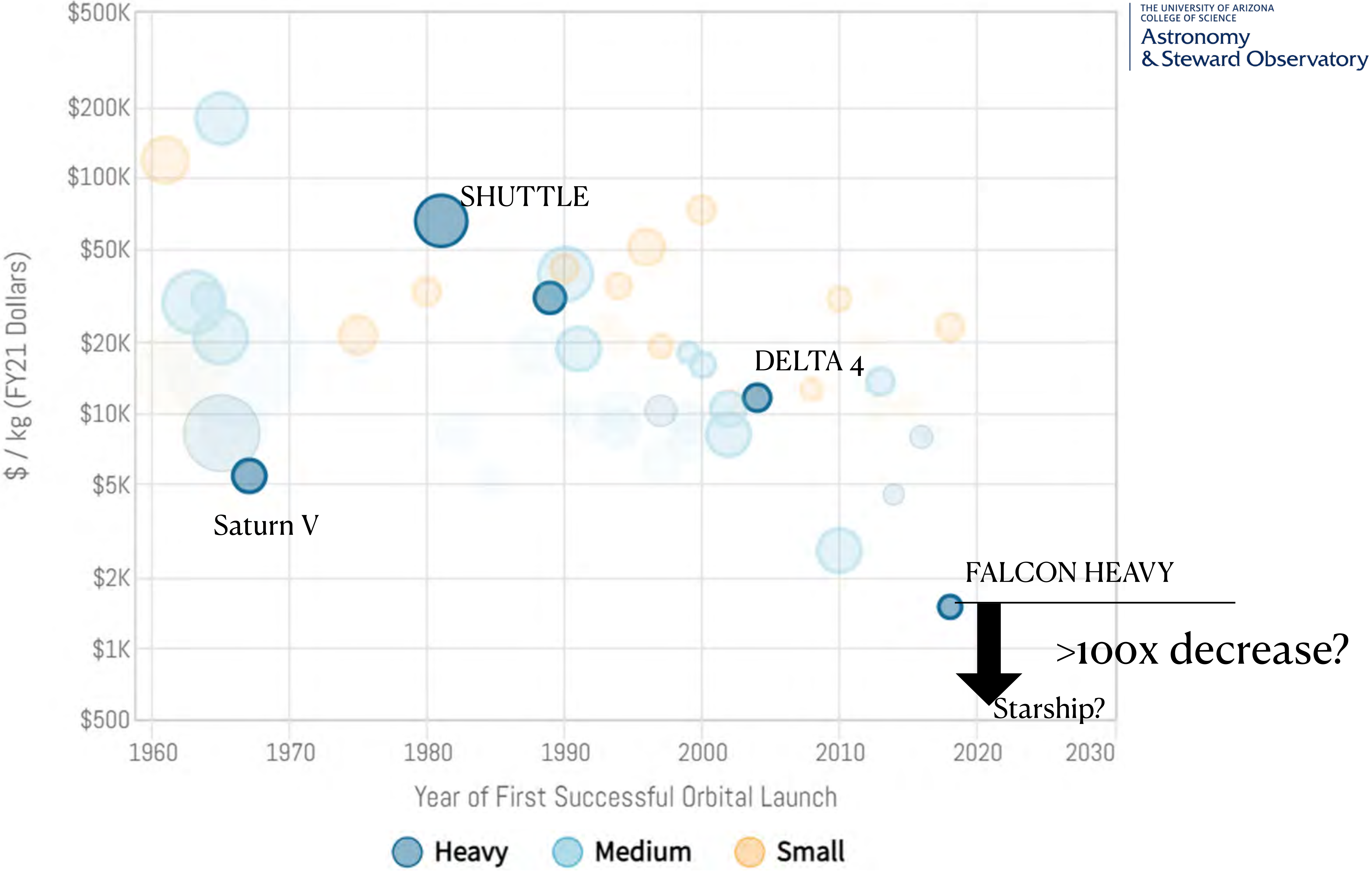
Saturn V

≳40x decrease

FALCON HEAVY

Source: CSIS Aerospace Security.

https://aerospace.csis.org/data/space-launch-to-low-earth-orbit-how-much-does-it-cost/



SHUTTLE

DELTA 4

Saturn V

FALCON HEAVY

>100x decrease?

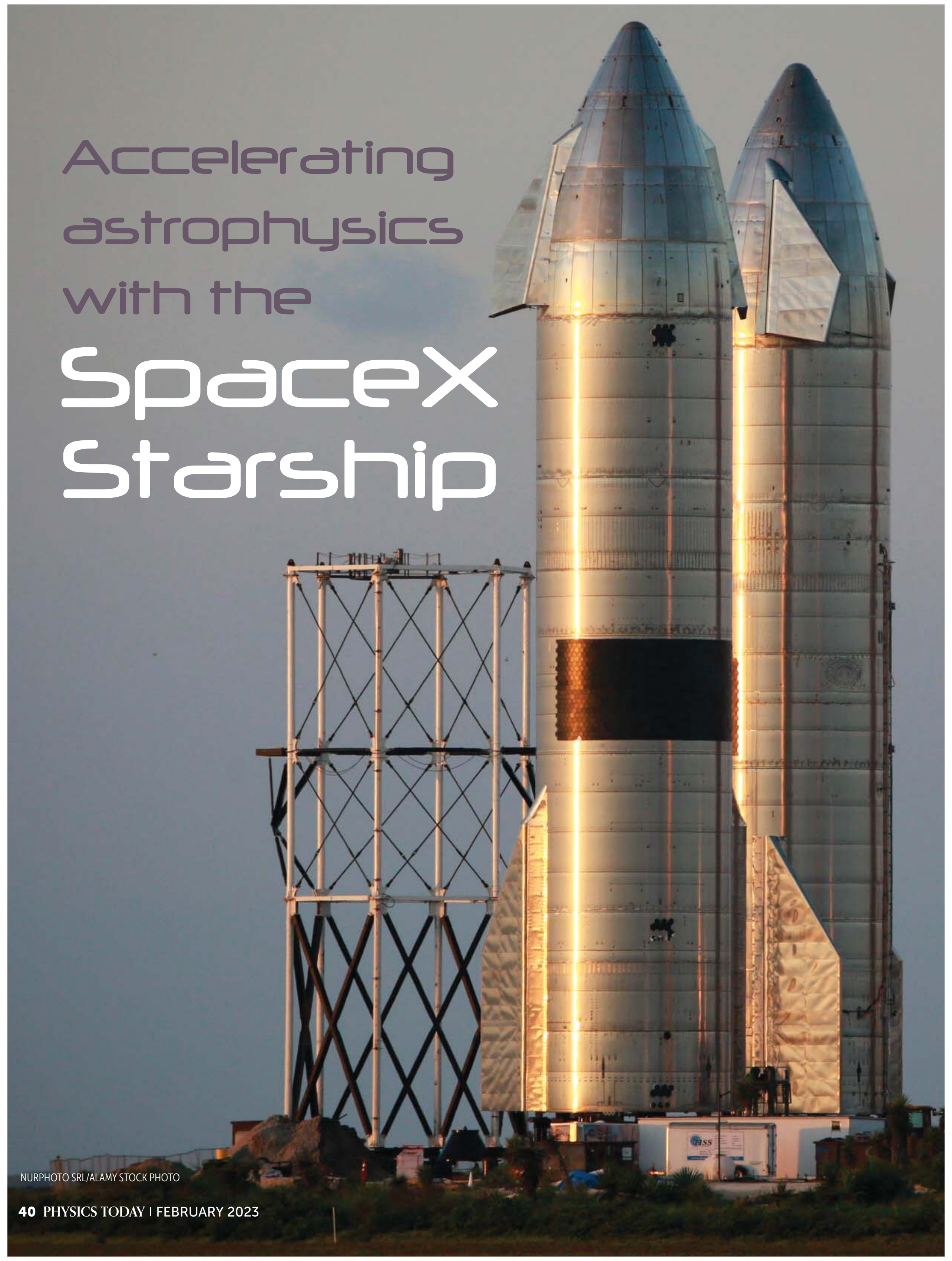
Starship?

Source: CSIS Aerospace Security.

https://aerospace.csis.org/data/space-launch-to-low-earth-orbit-how-much-does-it-cost/

MMT 6.5m monolith

+

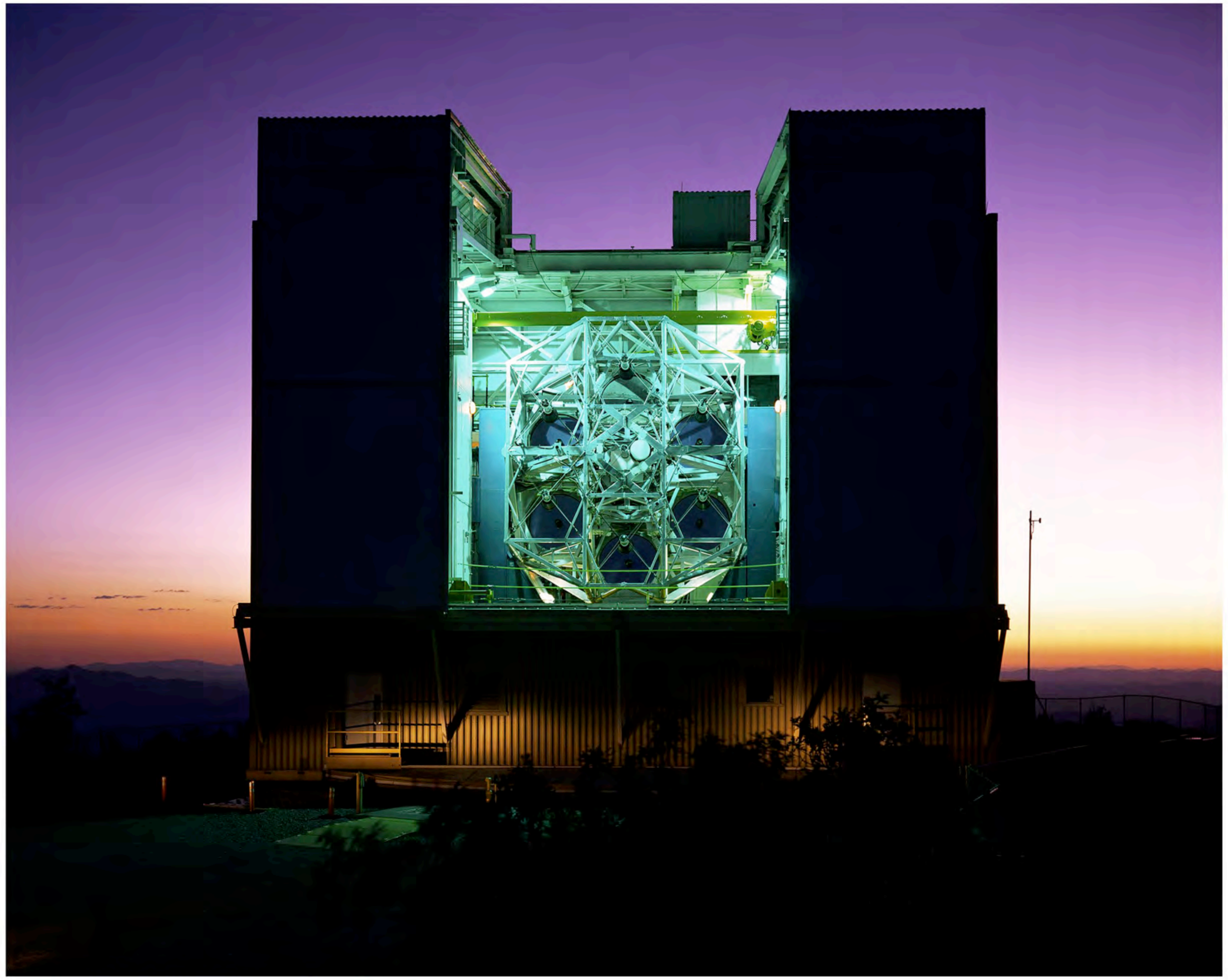


Accelerating astrophysics with the SpaceX Starship

NURPHOTO SRL/ALAMY STOCK PHOTO

40 PHYSICS TODAY | FEBRUARY 2023

=?



Historical Observatory Costs

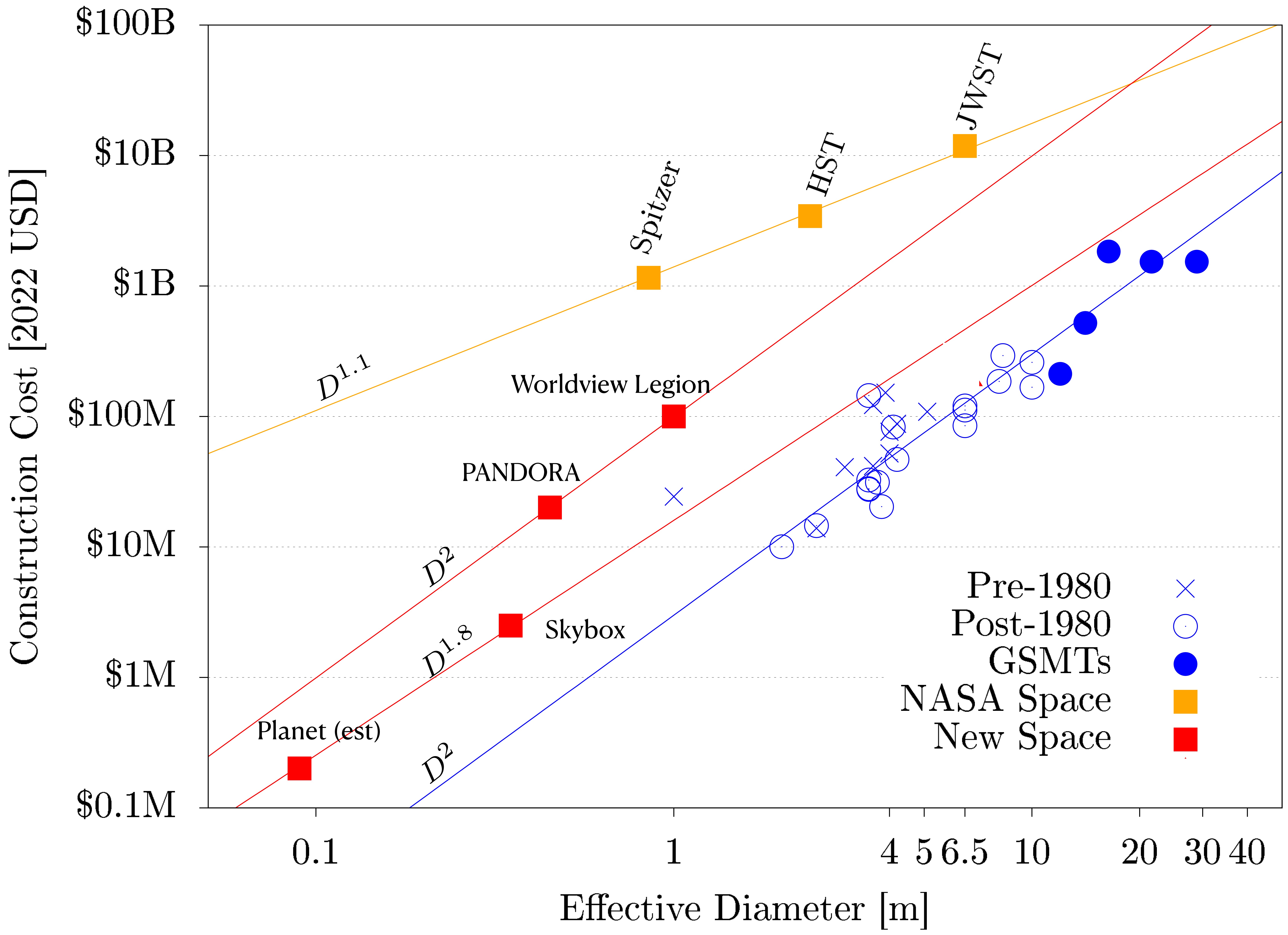


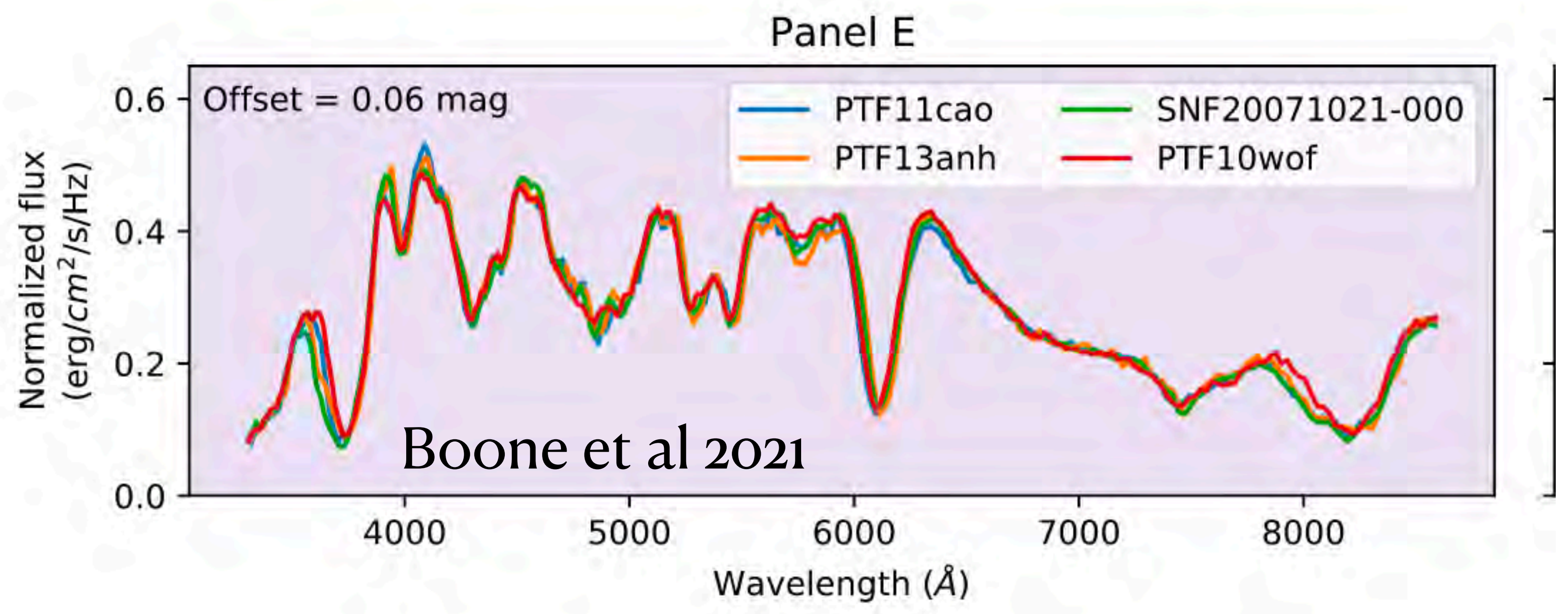
Figure: Jared Males & Ewan Douglas
Includes observatory building
Or launch costs

How to break the cost curve?

	Possible Approaches	Assumptions
Design	Minimize new design work, create production lines	Maintain Flexible Science Requirements to Adapt to Prior Art
Analysis	Simple requirements and build with extra margin via control	Create tolerance envelopes for controls based approach
Test	Minimize on-ground testing and instrument for on-orbit testing	Multiple revisions
Documentation	Minimize redundancy and maximize automation	Git
Materials	Maximize use of COTS electronics, Minimize use of composites	Aluminum and Invar structures, rad-tol electronics processors

Two "simple" science cases to explore design space

Supernova Spectroscopy



Boone et al 2021

Parameter	Value	Notes
Wavelength range	λ= 400 nm to 1700 nm	Allows Type Ia supernova (SN) characterization at redshifts $0 < z < 2$
Wavelength resolution	R=100 at 1μm	S/N > 10 per resolution element (in the rest-frame B band for aa flux of AB=25 mag)
FOV	$\sim$1 arcsecond	Allows spectrophotometry, including subtraction of host galaxy from SN spectra
Photometric accuracy	3 millimag	Relative to standard stars

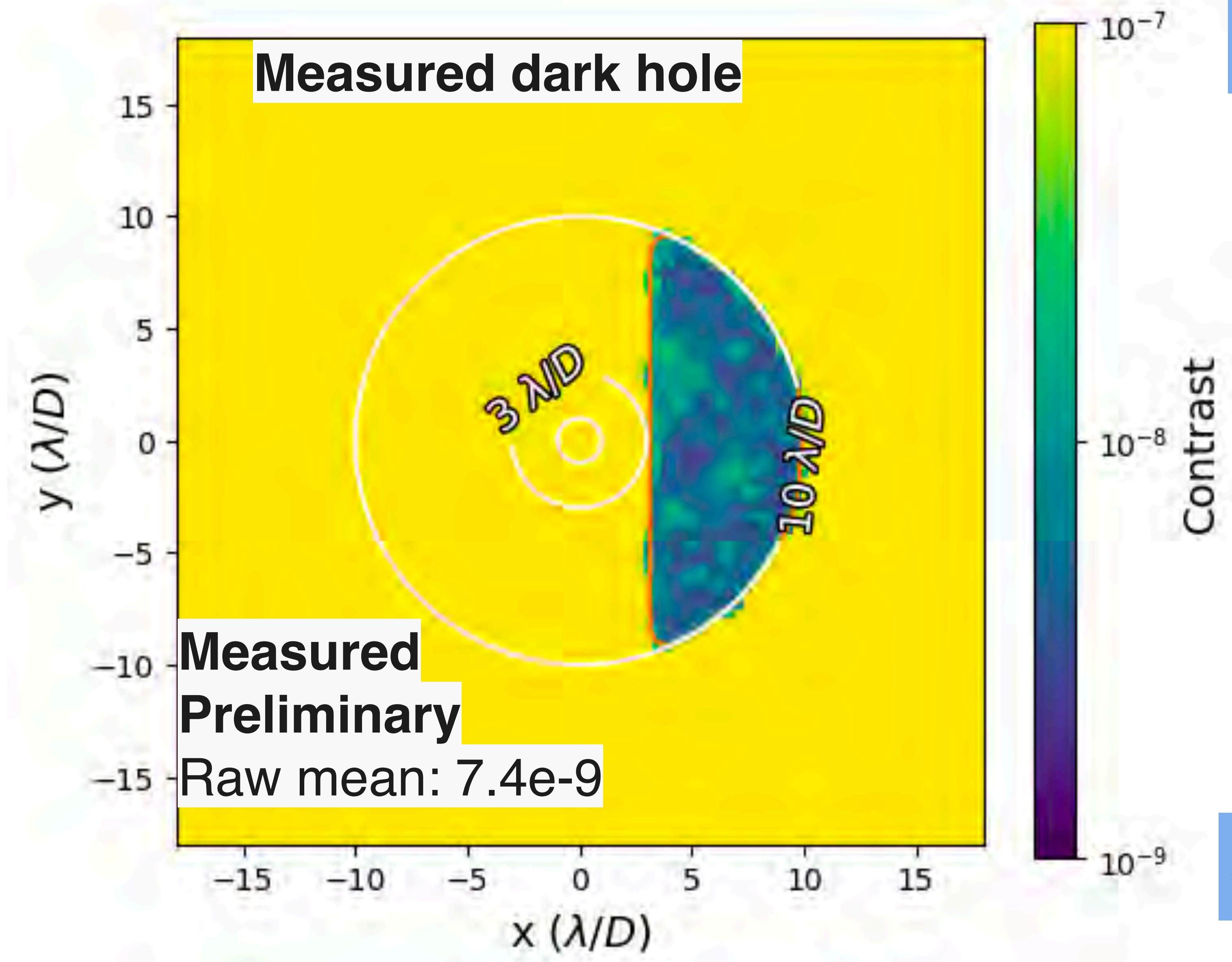
Table 1. Desired Spectrograph Instrument Parameters.

Concept heritage: SNAP (Elat et al 2004)

Exoplanet direct imaging

Primary operation wavelength	650 nm	
Nominal filter bandwidth	2%	minimizes sensitivity to WFE
Deformable Mirror Actuator Count	952	BMC Kilo-C DM 1.5um
Deformable Mirror Actuator Stroke (max)	1500 nm	BMC Kilo-C surface stroke for 4x4 actuators
Coronagraph mask	Charge-6 VVC	
IWA	$2.4\lambda/D$	depends on mask
OWA	$10\lambda/D$-$15\lambda/D$	depends on WFE
Sensitivity	1e-8 or dimmer star-planet flux ratio	sensitivity to debris disks and sub-Neptune size planets in habitable zones of nearby stars

Table 2. Desired ESC Coronagraphic Instrument Parameters.



Measured Preliminary
Raw mean: 7.4e-9

<—1e-7

<—1e-9

Concept heritage: CDEEP/SCoOB (Van Gorkom et al 2022), PICTURE-C/D balloon (Mendillo et al, Monday's talk)

Enabling Technologies and economies of scale

Mirrors

- RFCML has cast over 20 honeycomb Ohara E6 borosilicate mirrors*, **seven** 6.5 m f/1.25

Sensors:

- Commercial CMOS sensors make feasible gigapixel arrays with low read-noise affordable (e.g. Alarcon et al 2023)

Computing:

- Rad-tolerant embedded computing enables active on-board control (e.g. Derby et al, Kang et al and Belsten et al Thursday 4:50 PM, in 11A)

Document management

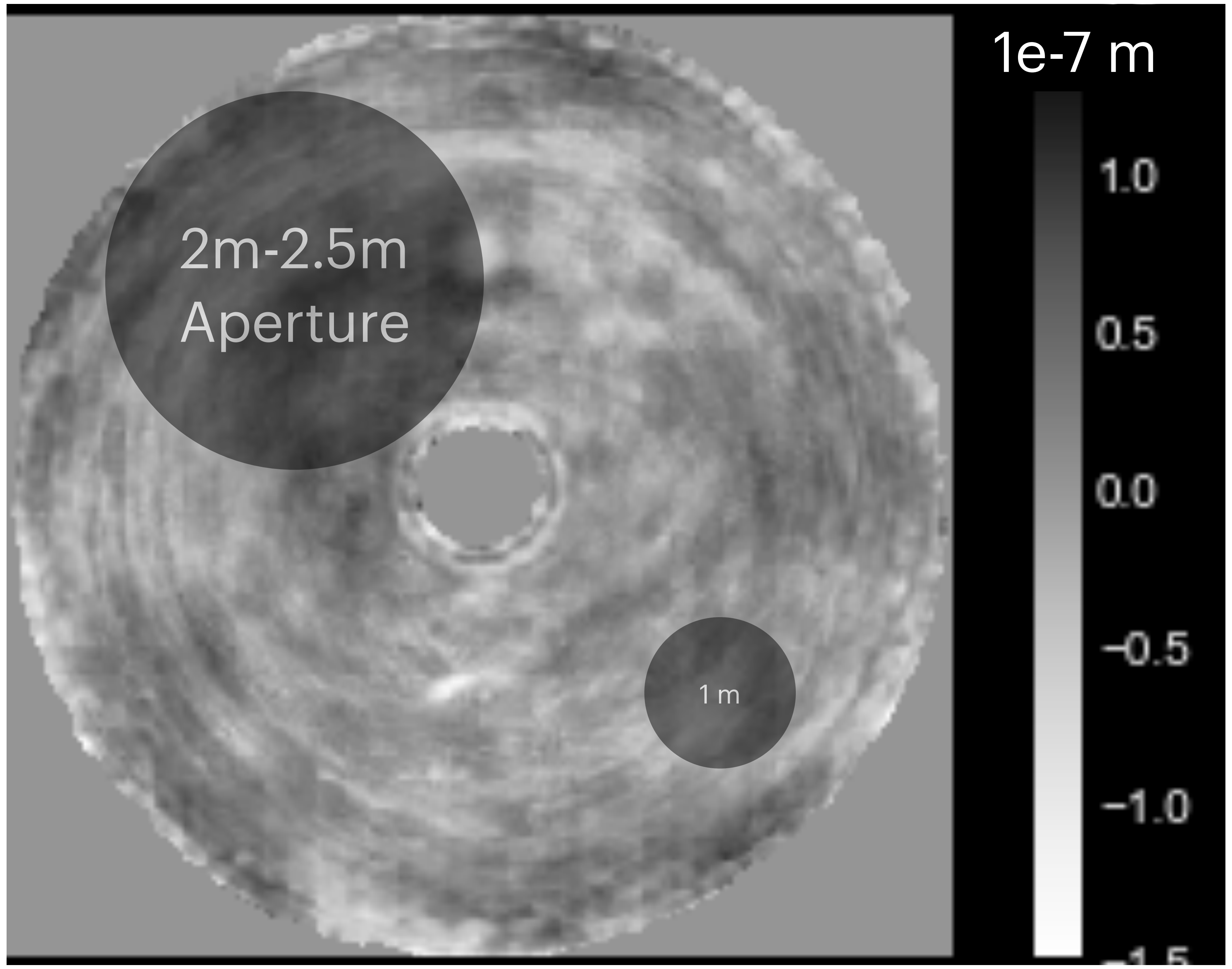
- Automation of interface and document management can allow nimble teams and minimize document waste (e.g. Douglas et al 2018, O'Mullane et al 2022)

Optical Design

- Improved simulation tools and affordable computing resources (subsequent talks)

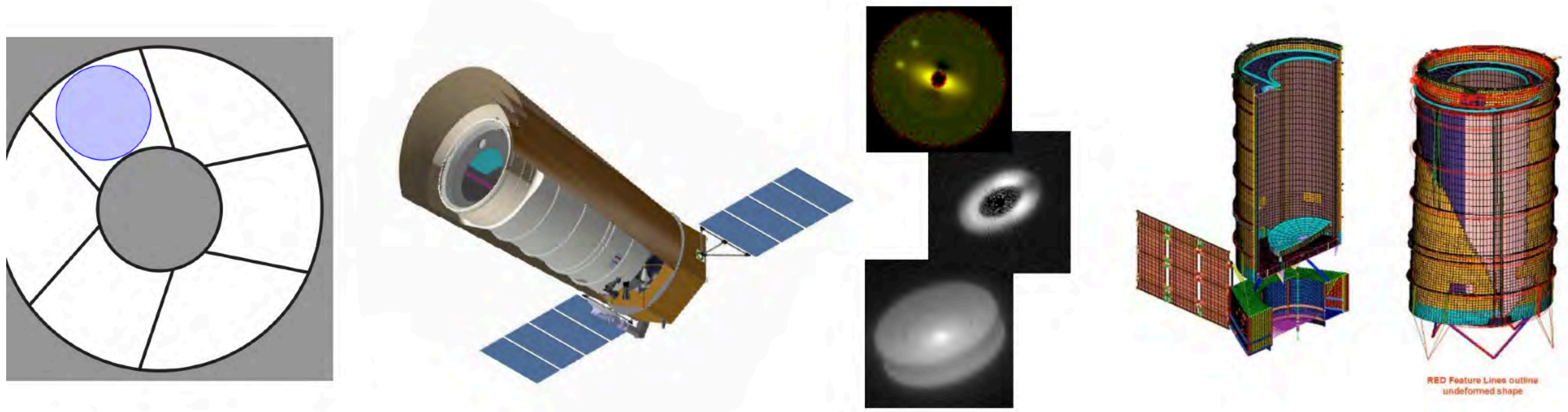
*https://mirrorlab.arizona.edu/content/mirror-castings

Sub-aperture coronagraphy is simpler



We have been here before:
JPL/Caltech Princeton NRO Telescope Workshop
John Trauger, 6 September 2012:

Case 1: an unobscured off-axis subaperture of the NRO



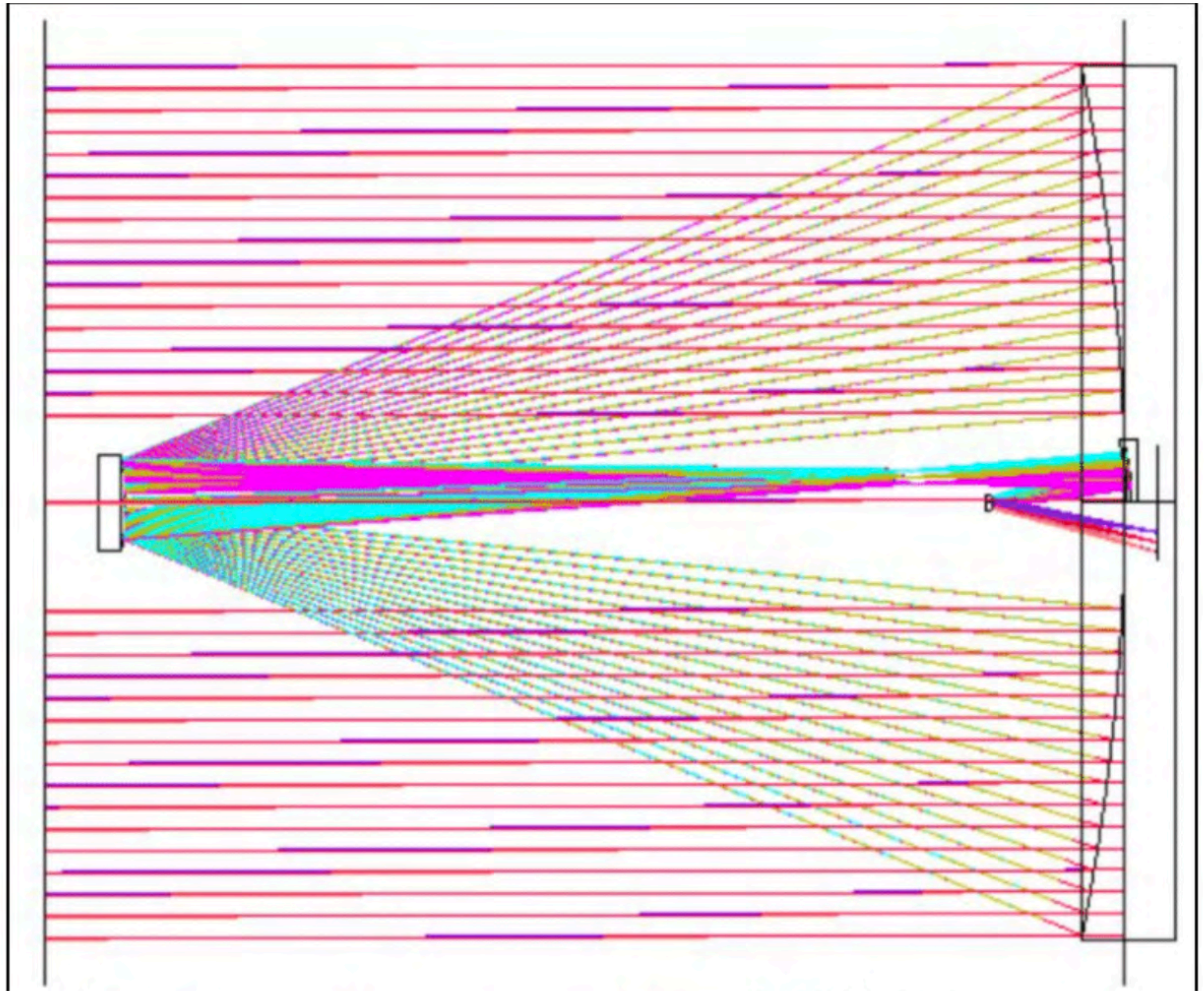
"So coronagraph performance with the NRO subaperture is immediately understood in terms of the ACCESS study.
Inner working angle is increased, while the contrast floor is possibly unchanged from ACCESS. **Technology readiness is high.**"

Goals are different:
Nearer stars
Brighter stars
Telescope is bigger
Schedule is 5x shorter
Tech is even more mature

design to eliminate deployables

A telescope that fits in a rocket fairing

—> see Daewook Kim’s talk next



Economies of scale

Mirrors

- UA RFCML has cast over 20 honeycomb Ohaha E6 borosilicate mirrors, including **seven** 6.5 m f/1.25 with the Multiple Mirror Telescope Conversion design

Sensors:

- Commercial CMOS sensors make feasible gigapixel arrays with low read-noise affordable (e.g. Alarcon et al 2023)

Computing:

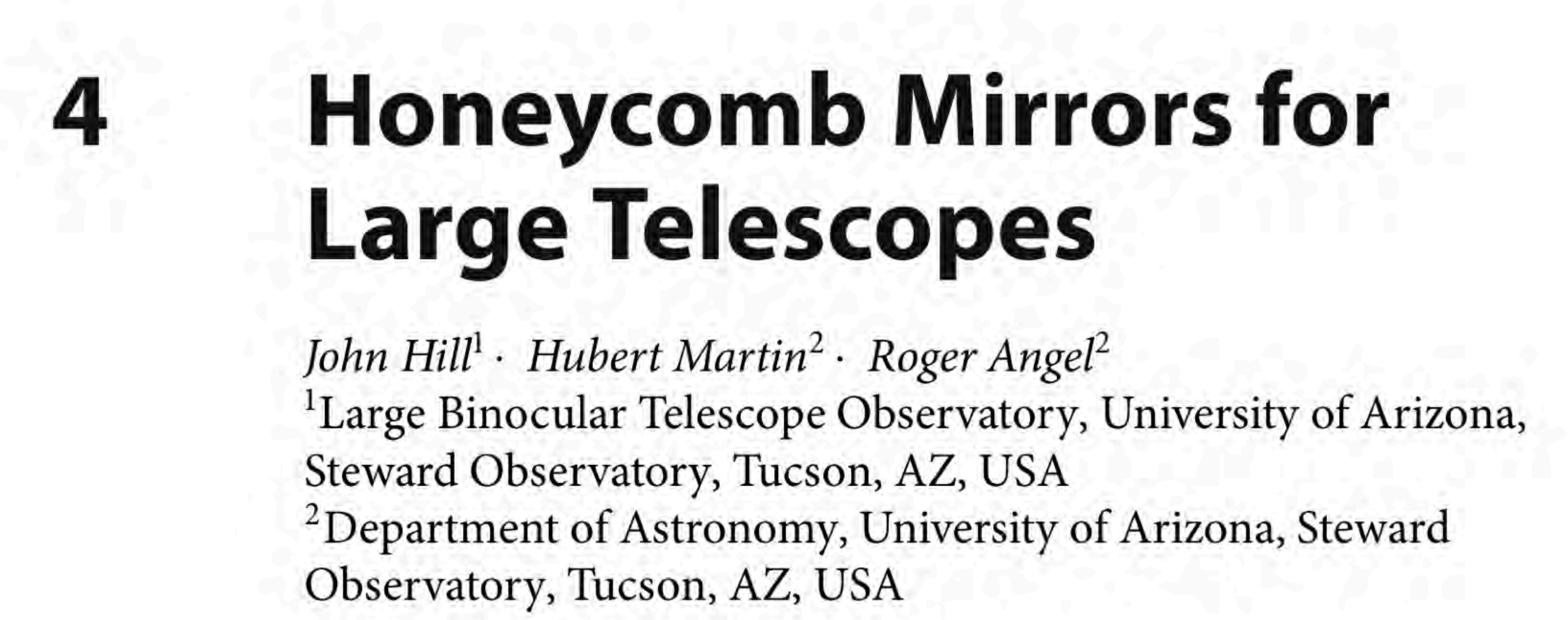
- Rad-tolerant embedded computing enables on-board control (e.g. Evaluating embedded hardware for high-order wavefront sensing and control, Belsten et al Thursday 4:50 PM, in 11A)

Document management

- Automation of interface and document management can allow nimble teams and minimize document waste (e.g. Douglas et al 2018, O'Mullane et al 2022)

*https://mirrorlab.arizona.edu/content/mirror-castings

Use a heavily analyzed primary mirror



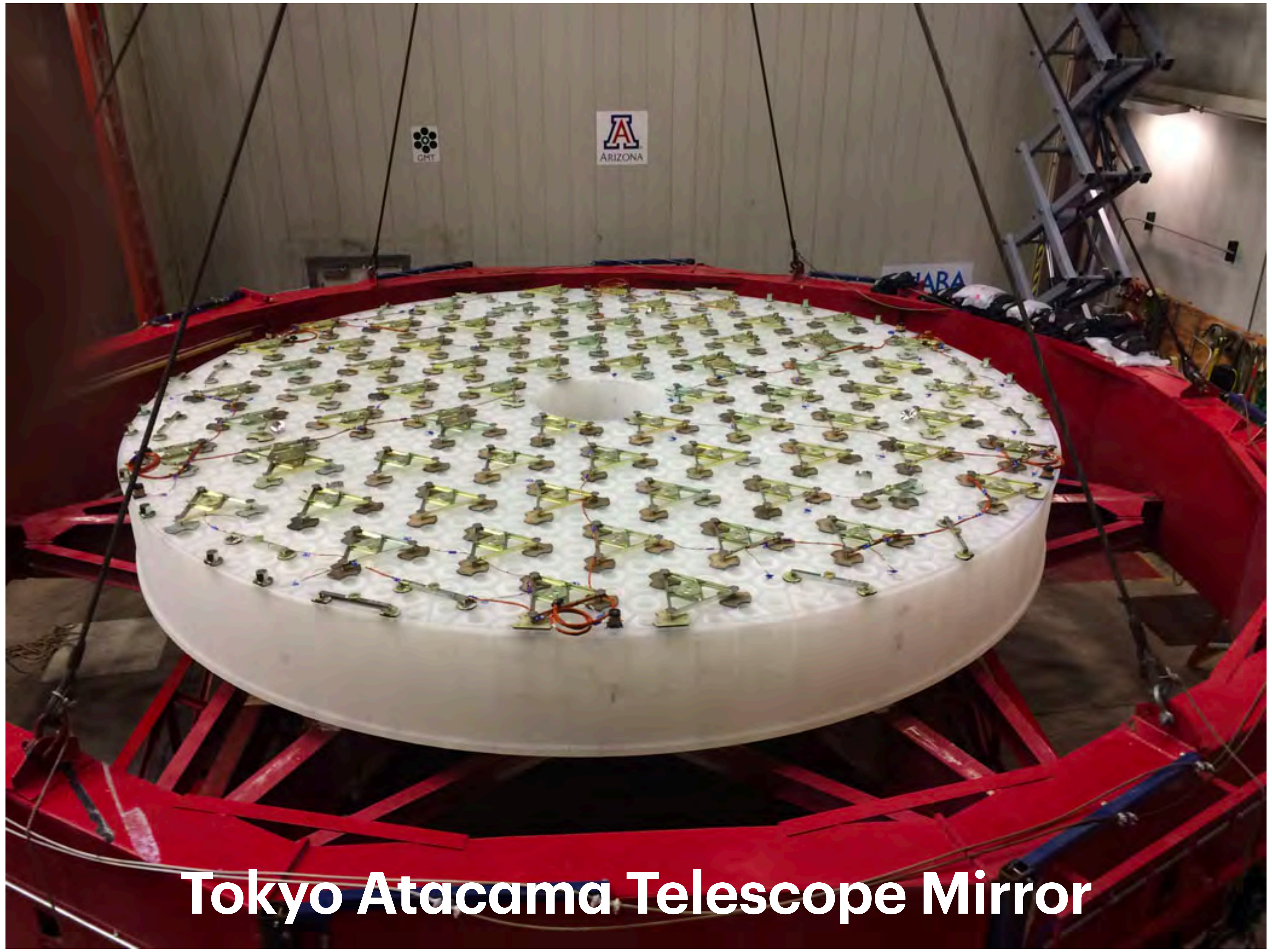
4 **Honeycomb Mirrors for Large Telescopes**

John Hill[1] · *Hubert Martin*[2] · *Roger Angel*[2]
[1]Large Binocular Telescope Observatory, University of Arizona, Steward Observatory, Tucson, AZ, USA
[2]Department of Astronomy, University of Arizona, Steward Observatory, Tucson, AZ, USA

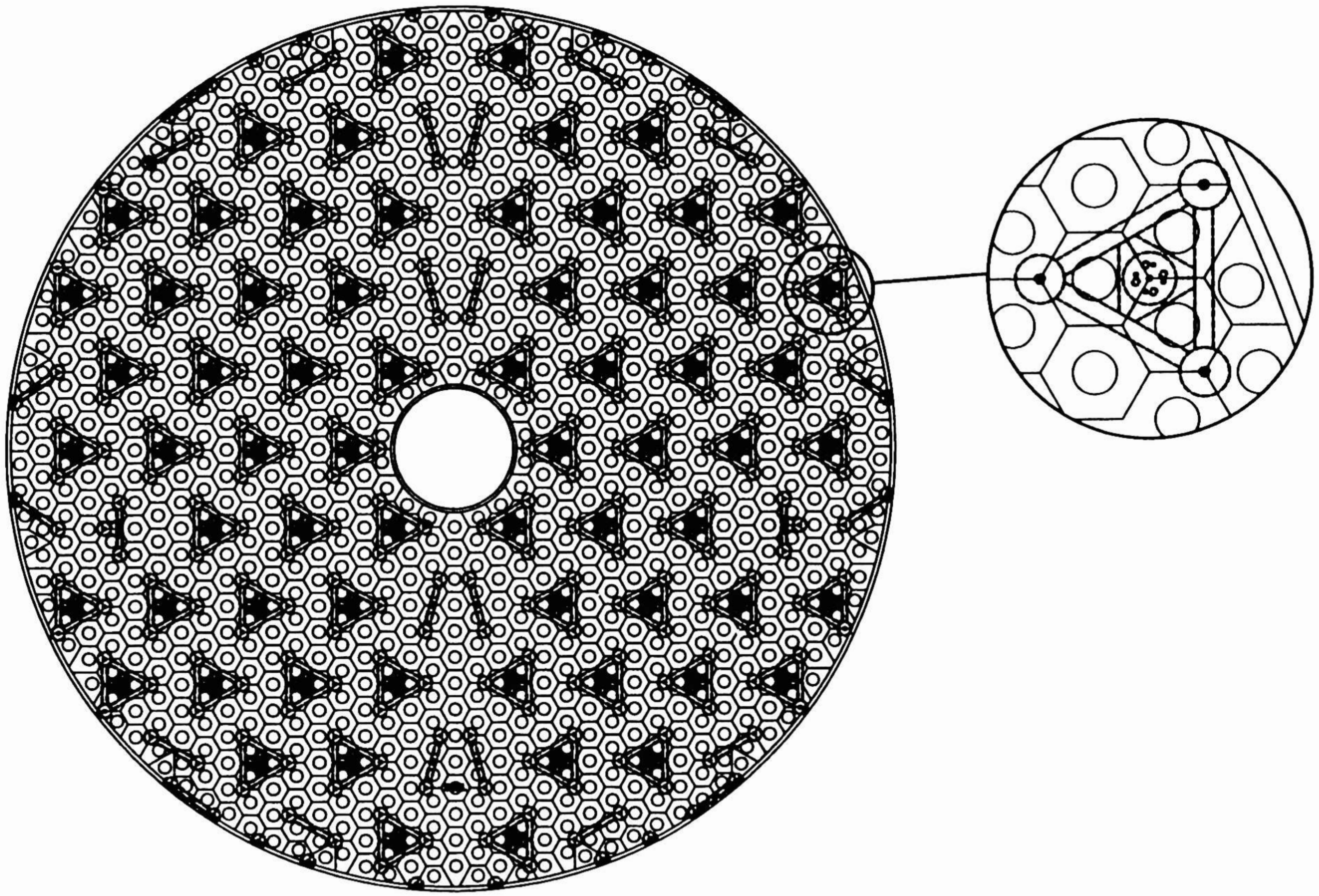
http://link.springer.com/10.1007/978-94-007-5621-2_4

UArizona Richard F. Caris Mirror Lab
4+ 6.5m mirrors to date


MMT monolithic primary

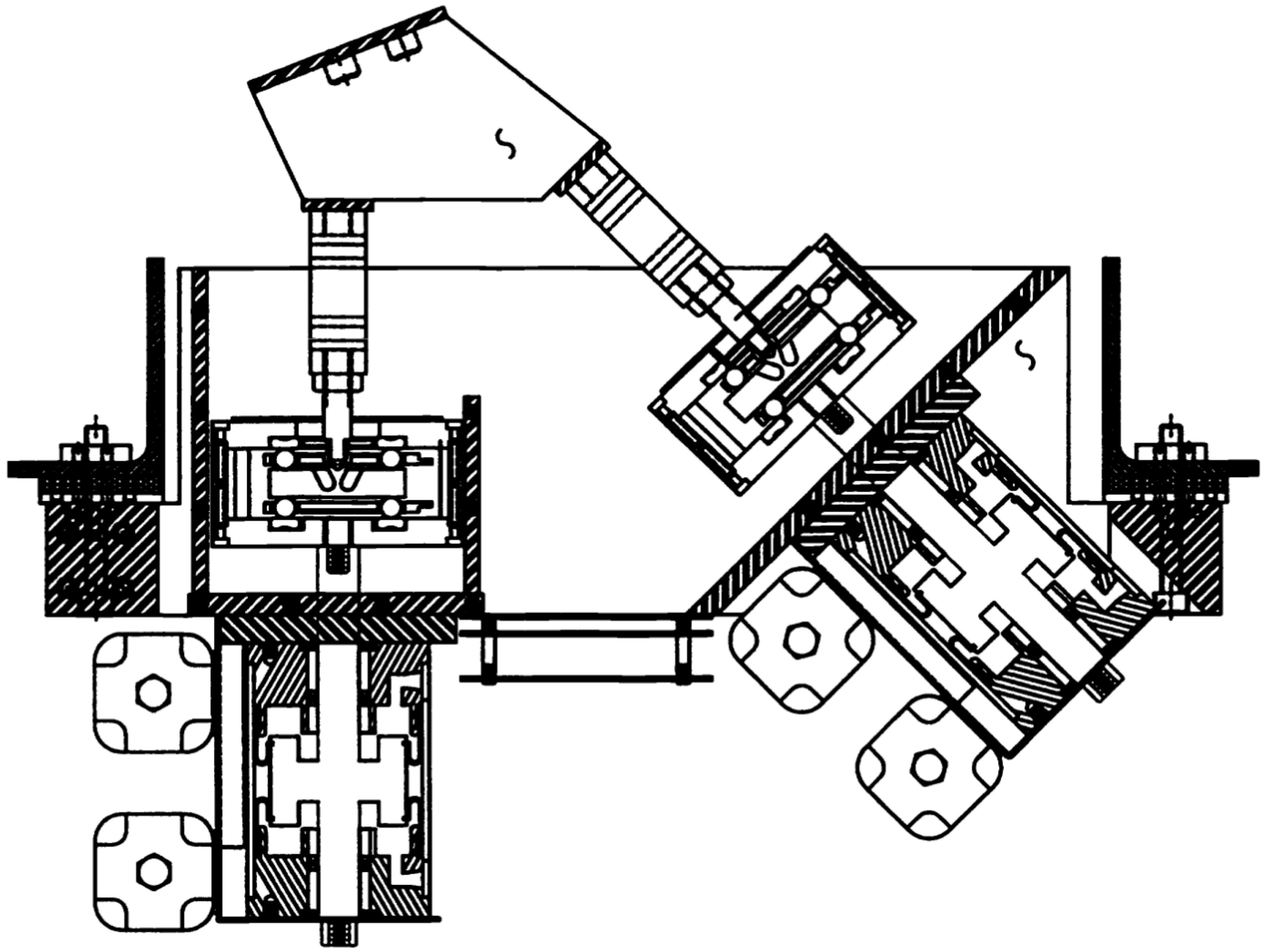

Tokyo Atacama Telescope Mirror

- UA RFCML has cast over 20 honeycomb Ohaha E6 borosilicate mirrors, including **seven** 6.5 m f/1.25 like the Multiple Mirror Telescope Conversion (cast in 1992)



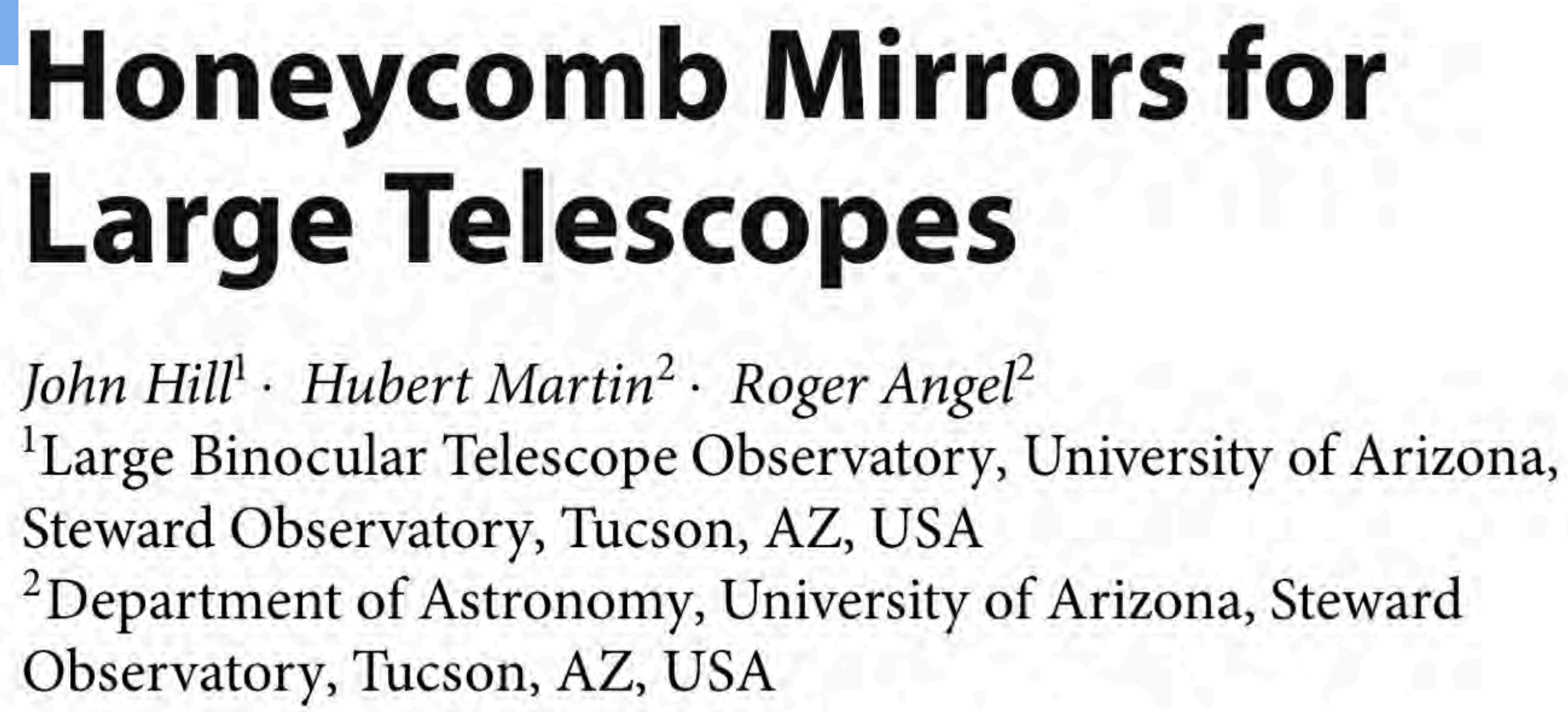
ure 1. Support pattern for the MMT primary mirror. Most actuators, including all dual axial-lateral actuators, ply force through 3-point loadspreaders. Some axial-only actuators have 2-point loadspreaders or single pucks.

Martin et al
http://proceedings.spiedigitallibrary.org/proceeding.aspx?articleid=945198



Dual axial-lateral actuator. Each actuator comprises two opposed pneumatic cylinders with press s, a load cell for feedback, and a ball decoupler to eliminate transverse forces and moments. Coml itted to back plate of mirror through a 3-point load spreader (not shown).

More info:



Honeycomb Mirrors for Large Telescopes

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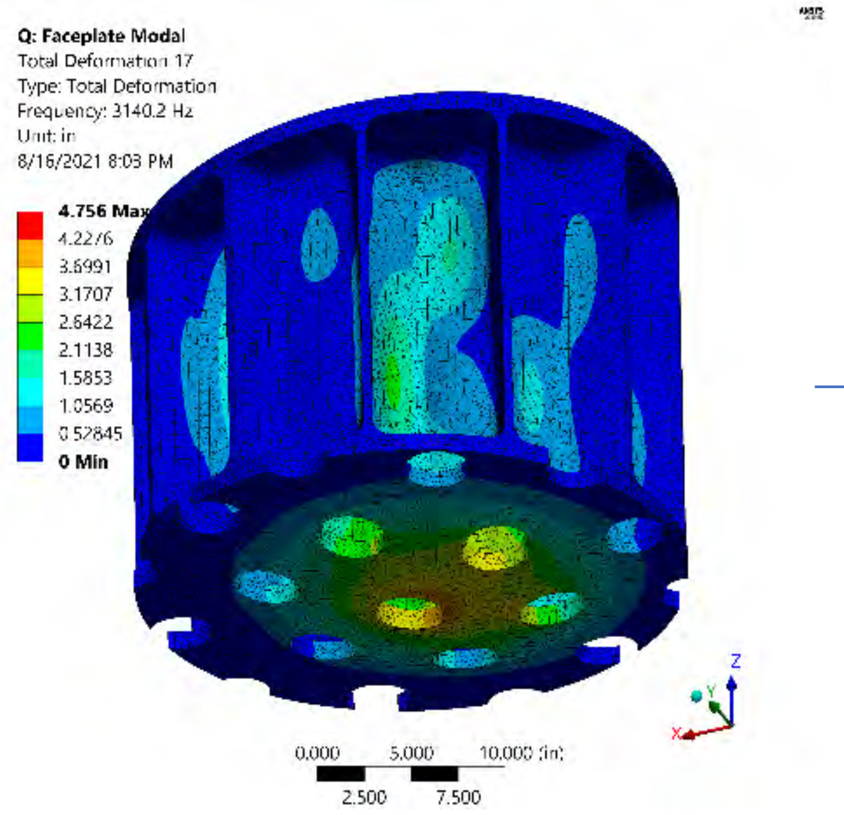
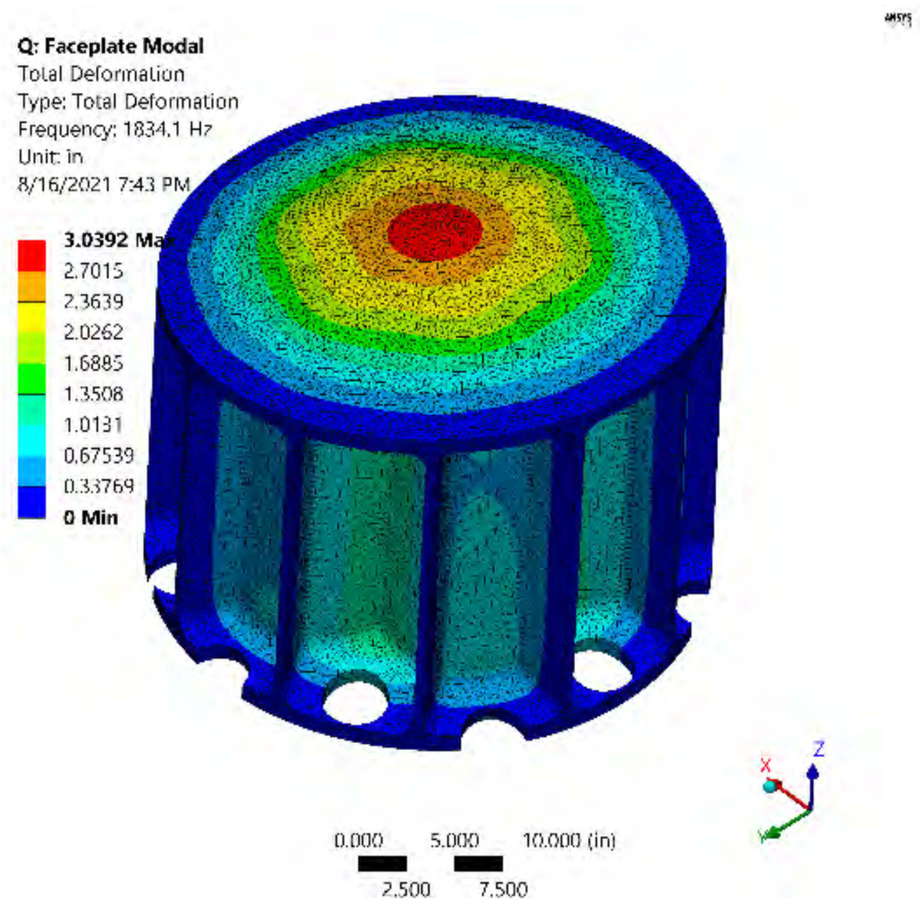
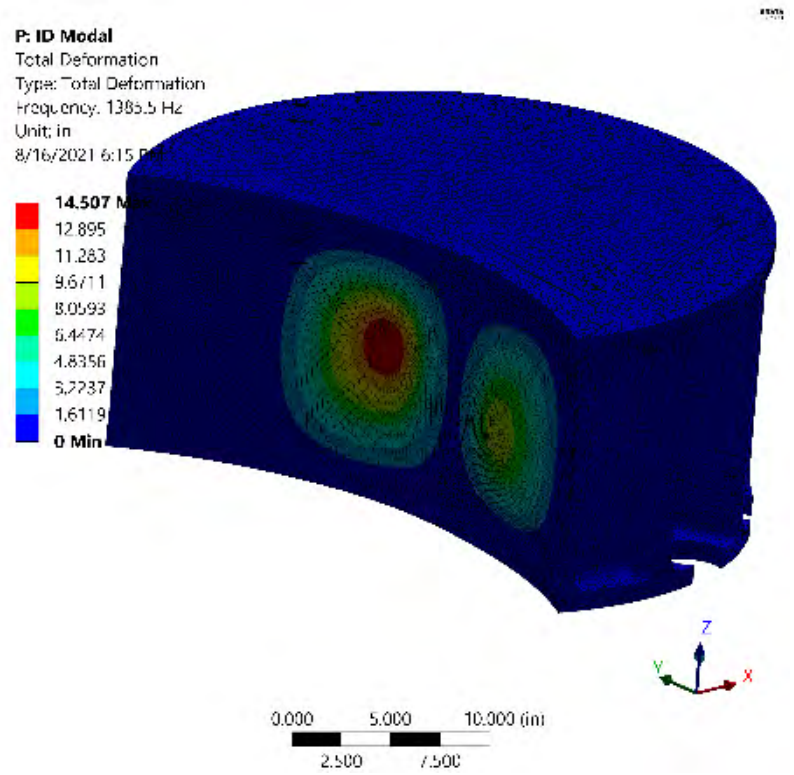
http://link.springer.com/10.1007/978-94-007-5621-2_4

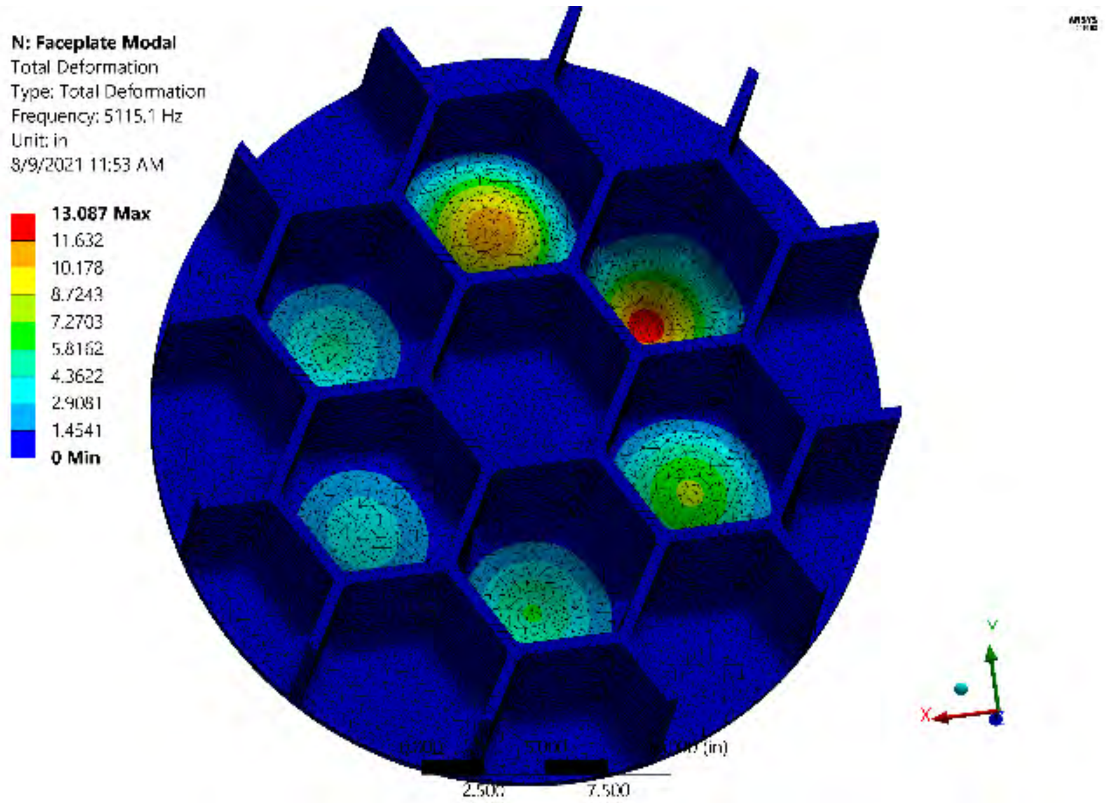
High Frequency Modes (EAR99)

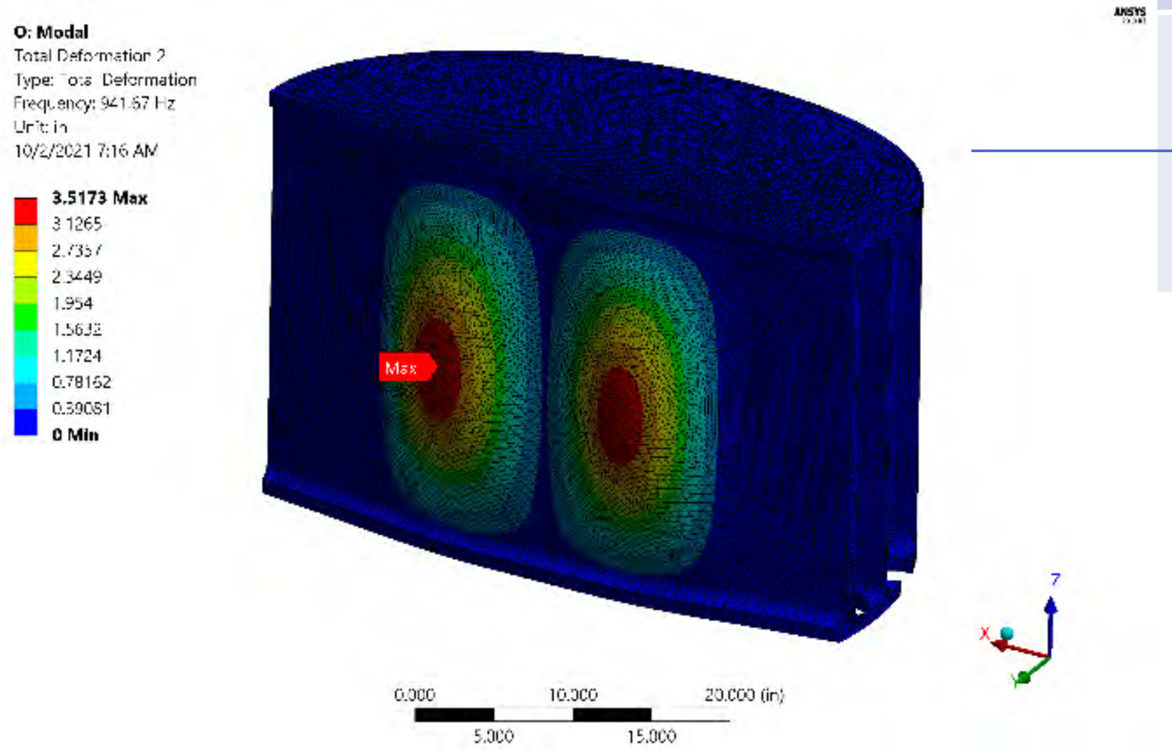


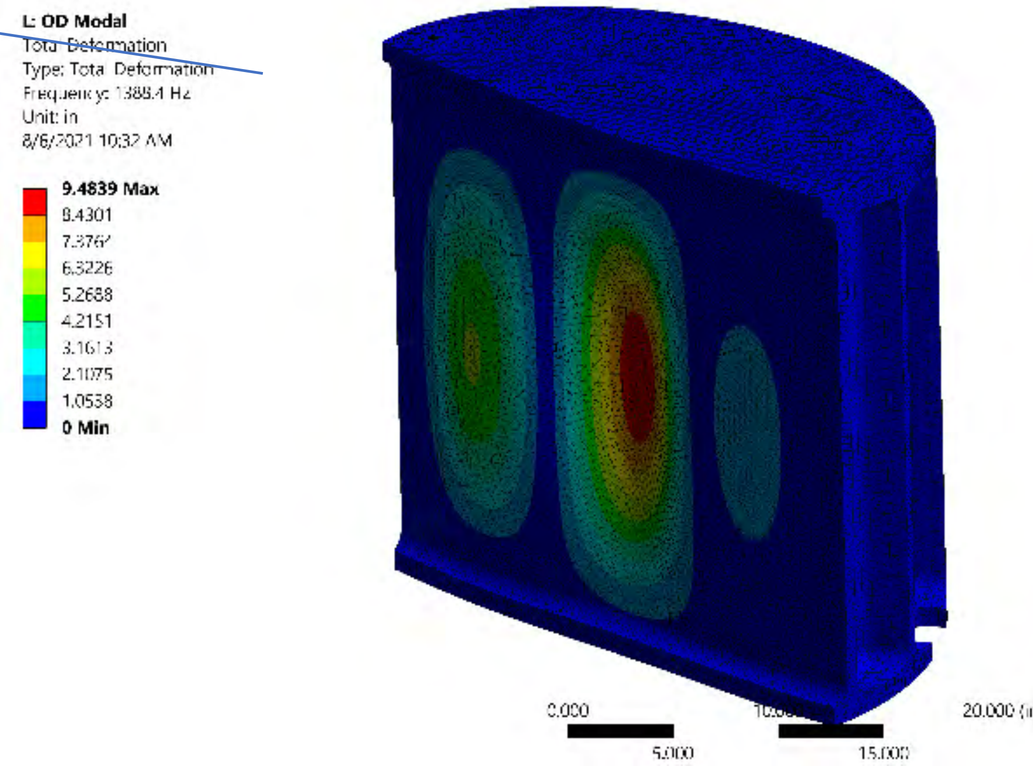


Model	Boundary Conditions	Mode	Frequency (Hz)
Face Plate	Outer Diameter of Model constrained. Backplate unconstrained (rib-only bending modes not included)	Piston of face sheet with back sheet in same direction	1834
		Piston of face sheet and opposing piston of back sheet	3140
	Adjacent ribs constrained around a single core	Piston of single face sheet core	5115
ID	Outer Diameter of Model constrained. Backplate unconstrained	Inner Wall Deflection	1386
OD	Outer Diameter of Model constrained. Backplate unconstrained	Outer Wall Deflection	1388
Special OD Cores	Outer Diameter of Model constrained. Backplate unconstrained	Outer Wall Deflection	942



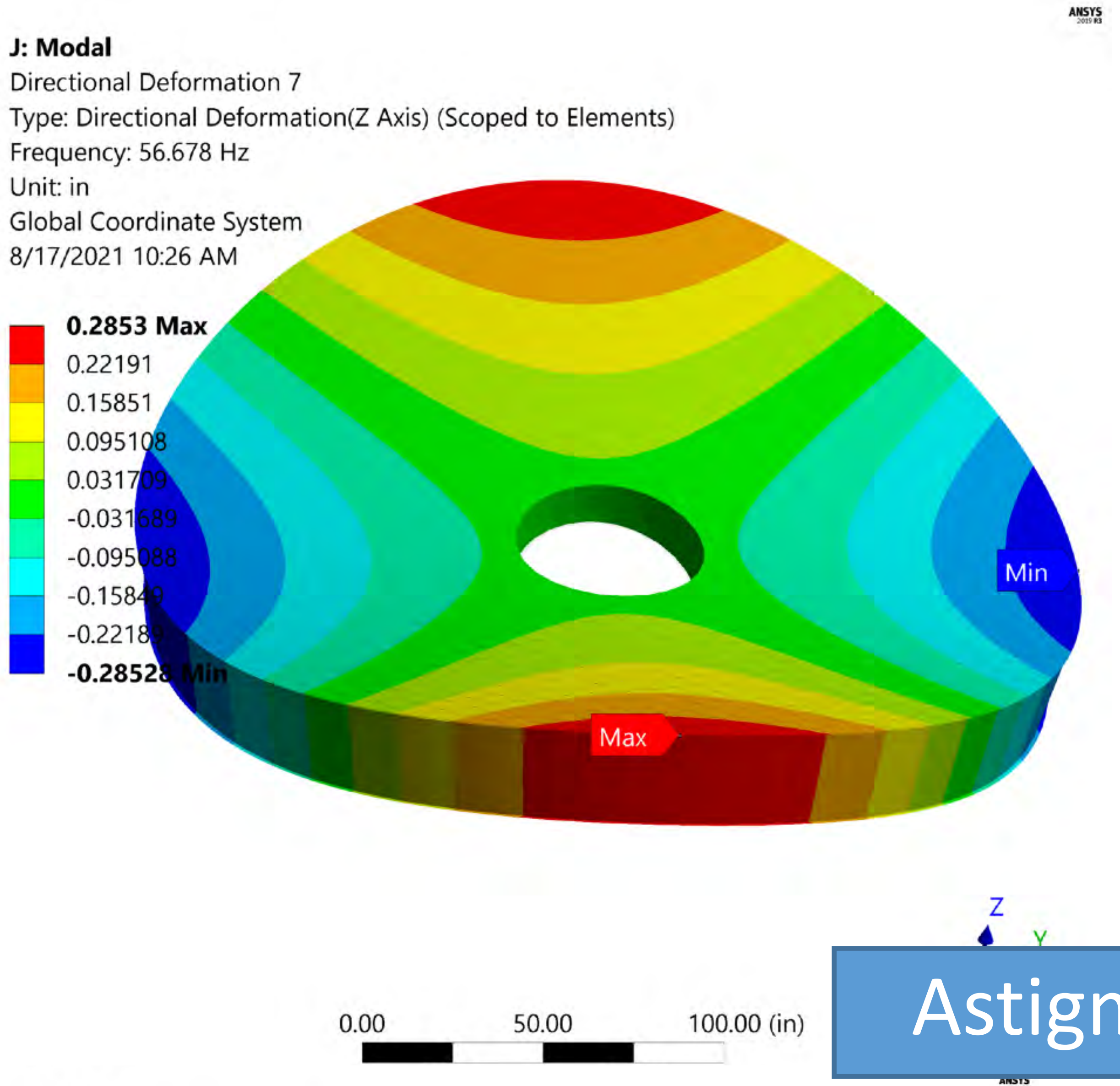






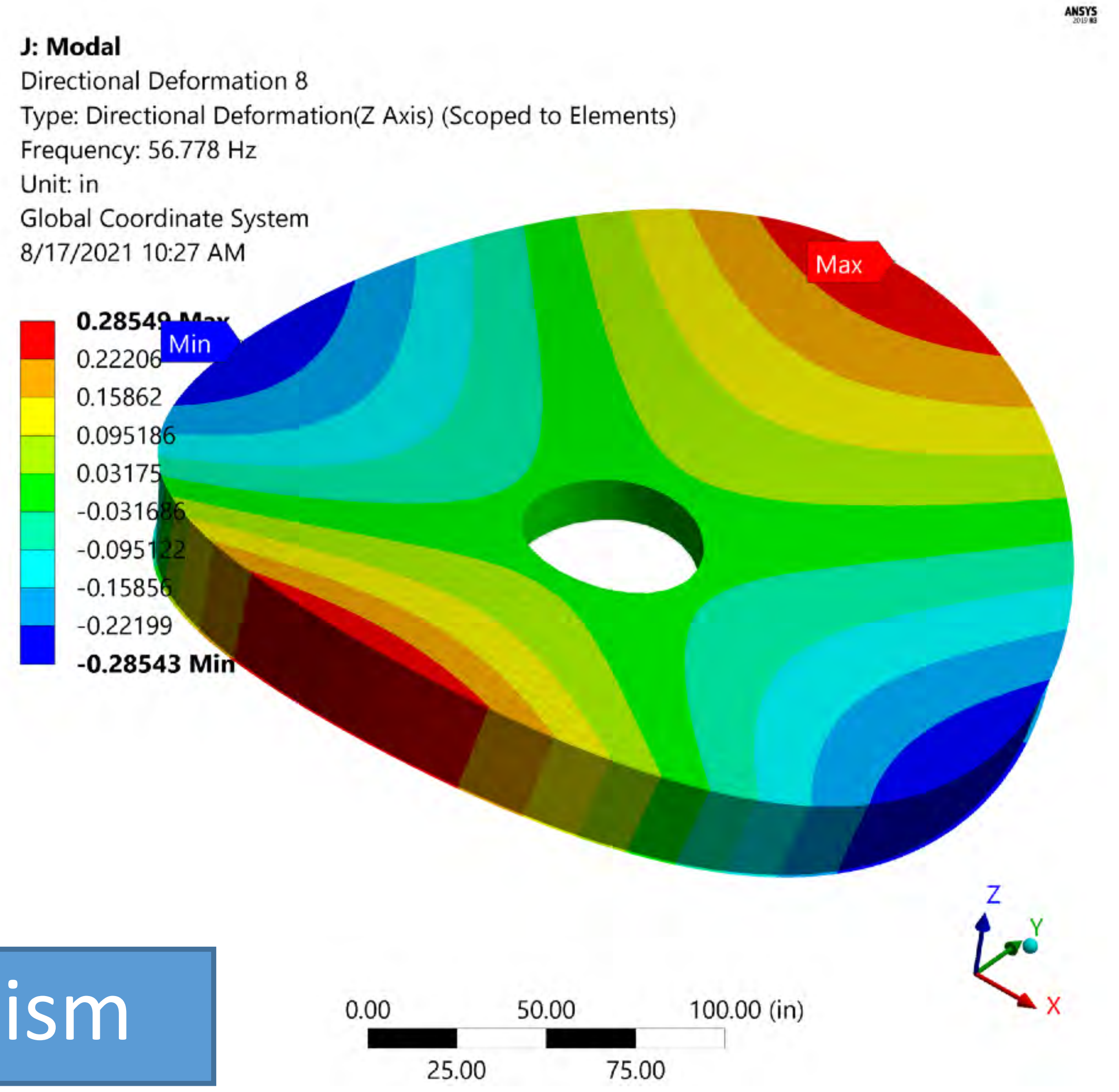
Jamison Noenickx, UA Steward Observatory Richard F Caris Mirror Lab

UA 6.5m Mirror Bending Modes (EAR99)



J: Modal
Directional Deformation 7
Type: Directional Deformation(Z Axis) (Scoped to Elements)
Frequency: 56.678 Hz
Unit: in
Global Coordinate System
8/17/2021 10:26 AM

Astigmatism



J: Modal
Directional Deformation 8
Type: Directional Deformation(Z Axis) (Scoped to Elements)
Frequency: 56.778 Hz
Unit: in
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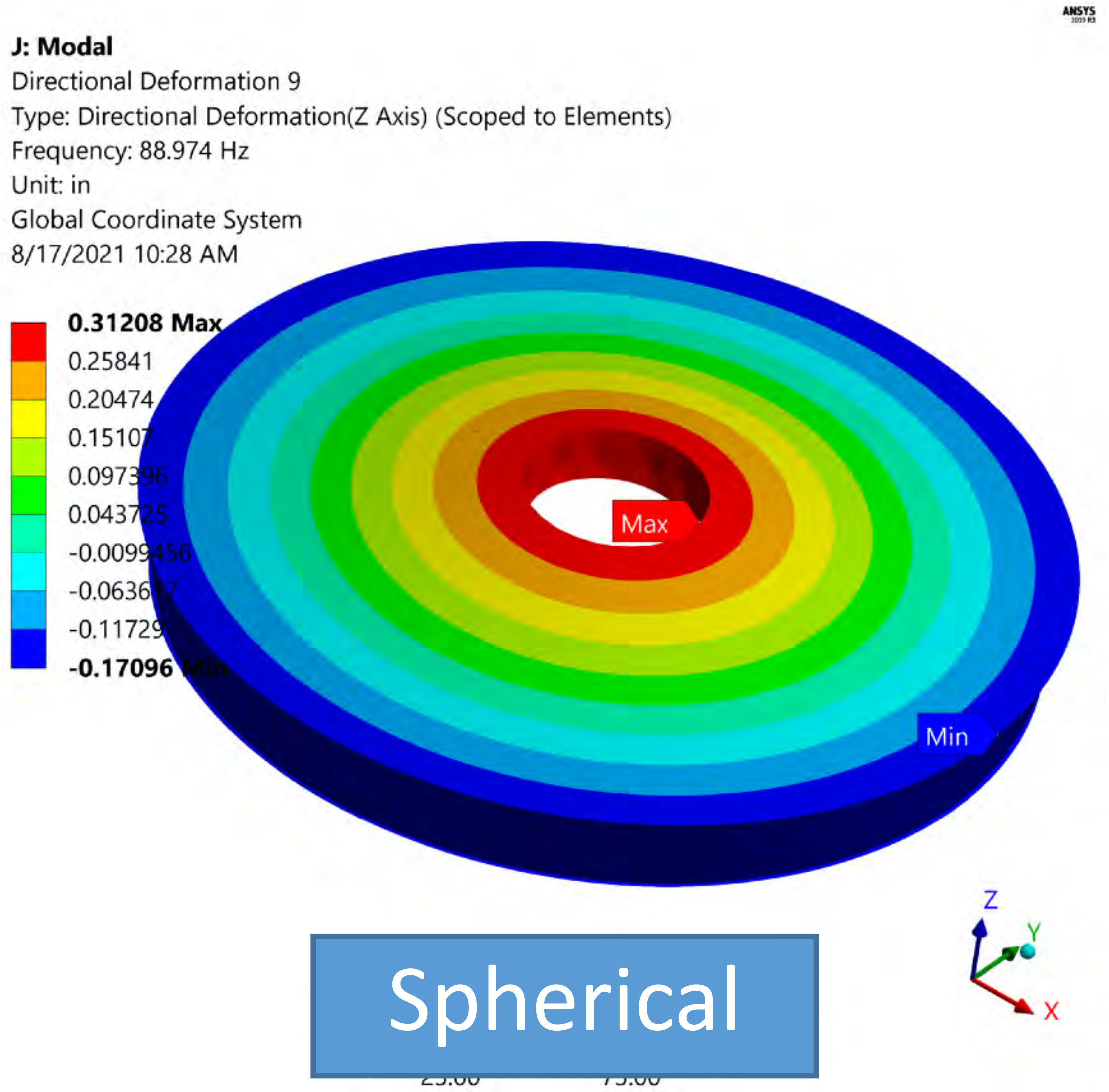
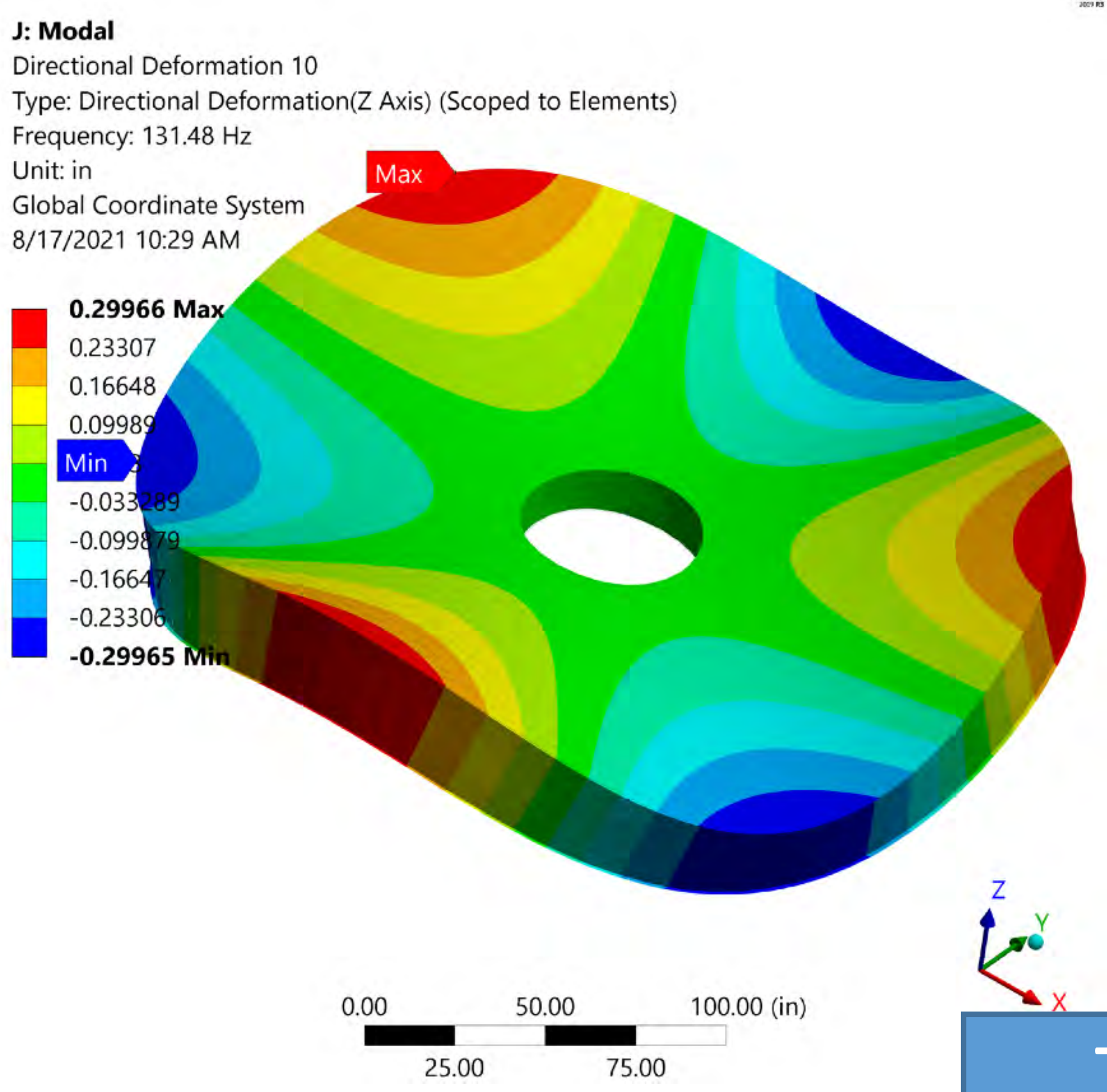
8/17/2021 10:27 AM



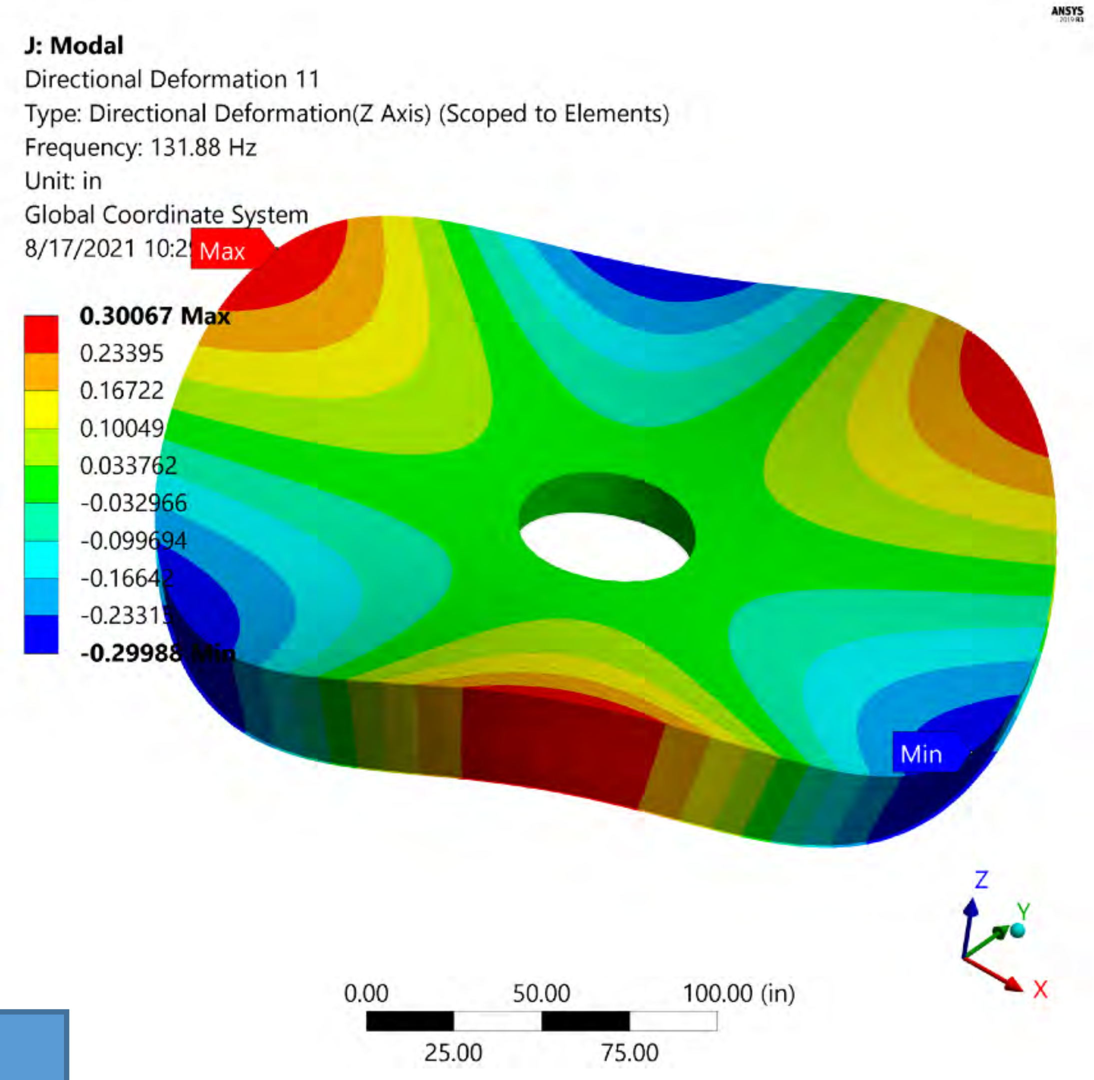
J: Modal
Directional Deformation 9
Type: Directional Deformation(Z Axis) (Scoped to Elements)
Frequency: 88.974 Hz
Unit: in
Global Coordinate System
8/17/2021 10:28 AM

Spherical

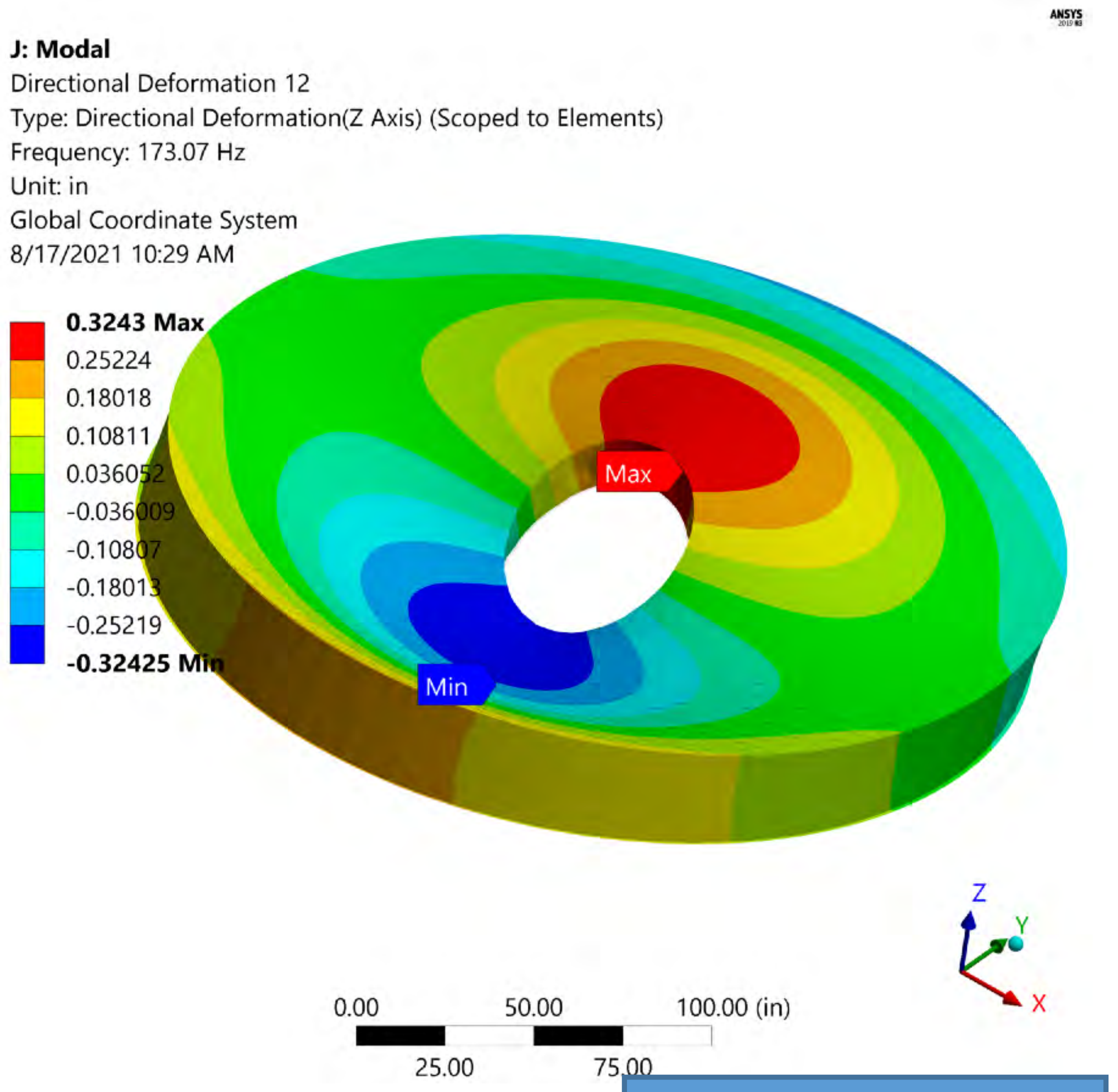


J: Modal
Directional Deformation 10
Type: Directional Deformation(Z Axis) (Scoped to Elements)
Frequency: 131.48 Hz
Unit: in
Global Coordinate System
8/17/2021 10:29 AM

Trefoil



J: Modal
Directional Deformation 11
Type: Directional Deformation(Z Axis) (Scoped to Elements)
Frequency: 131.88 Hz
Unit: in
Global Coordinate System
8/17/2021 10:2



J: Modal
Directional Deformation 12
Type: Directional Deformation(Z Axis) (Scoped to Elements)
Frequency: 173.07 Hz
Unit: in
Global Coordinate System
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Coma

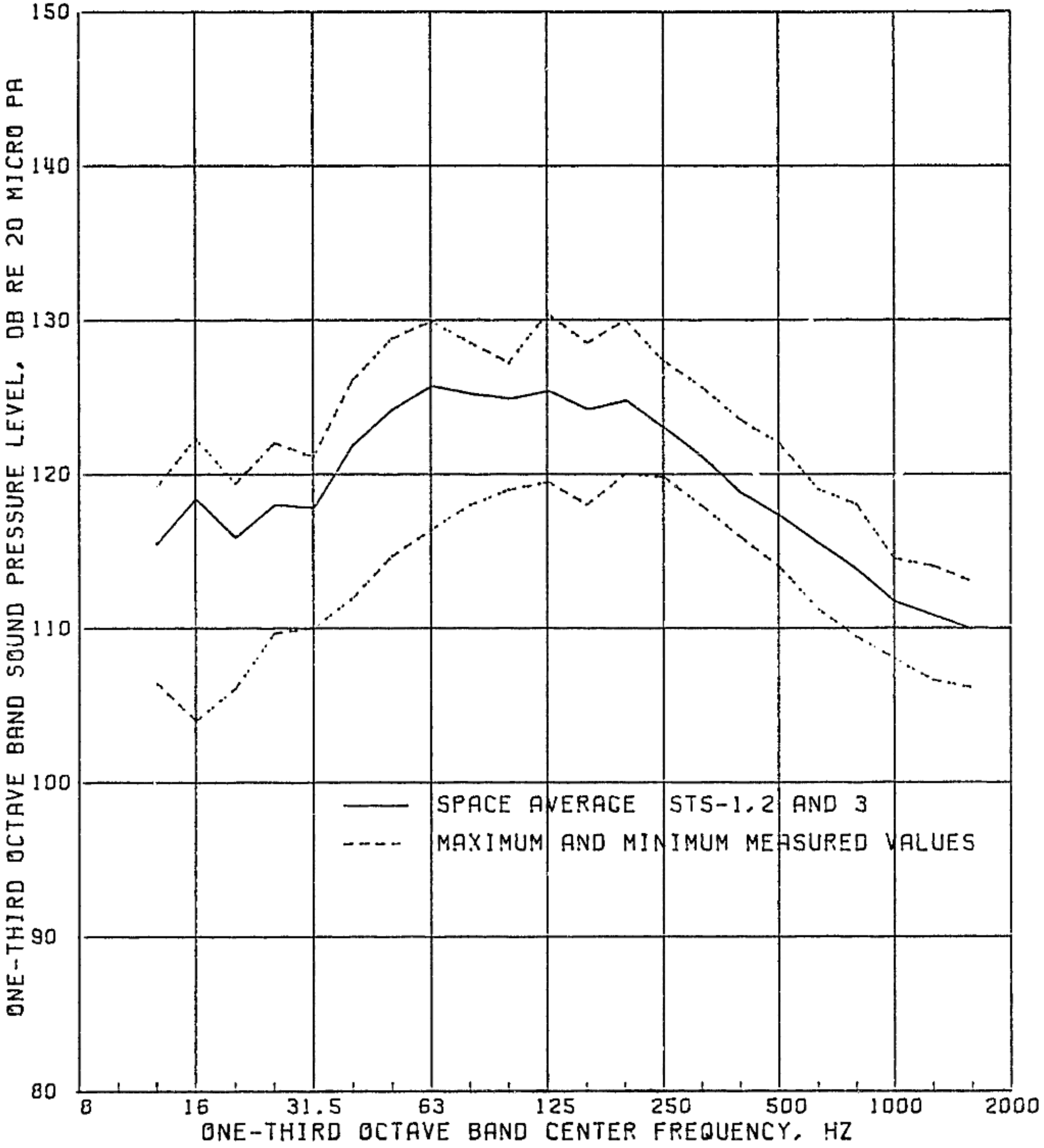
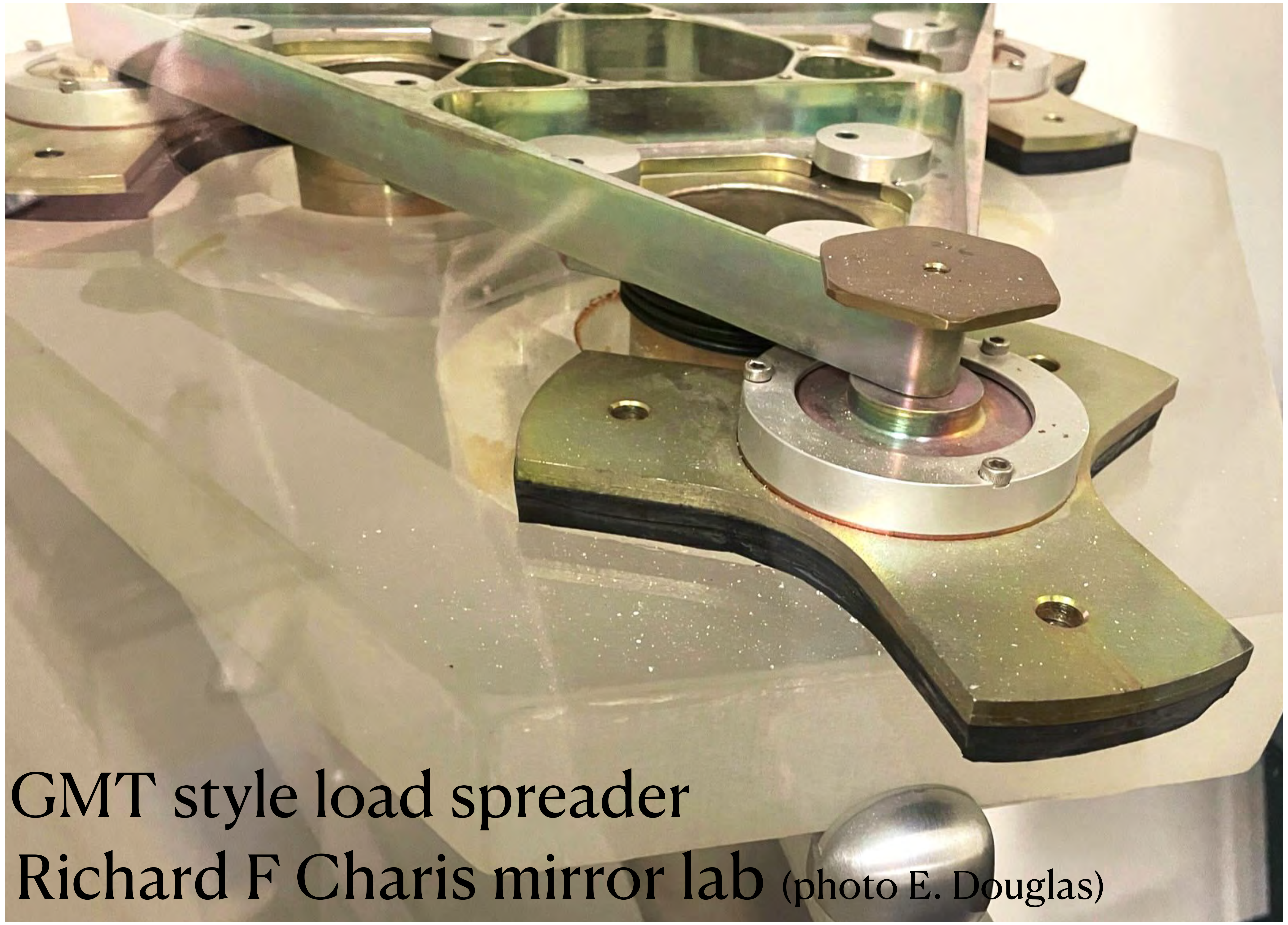


FIGURE 9. LIMITS ON SPATIAL VARIATION OF SOUND PRESSURE LEVELS IN PAYLOAD BAY AT LIFT-OFF (BASED ON STS-1, STS-2 AND STS-3 LAUNCHES)

https://ntrs.nasa.gov/api/citations/19830008969/downloads/19830008969.pdf



GMT style load spreader
Richard F Charis mirror lab (photo E. Douglas)

Leverage commercial sensor breakthroughs

Sensors

true 16-bit CMOS sensors (e.g. Sony IMX411, IMX455, IMX571).

~1e read noise

Low dark noise

Radiation tolerant

—> Affordable gigapixel arrays

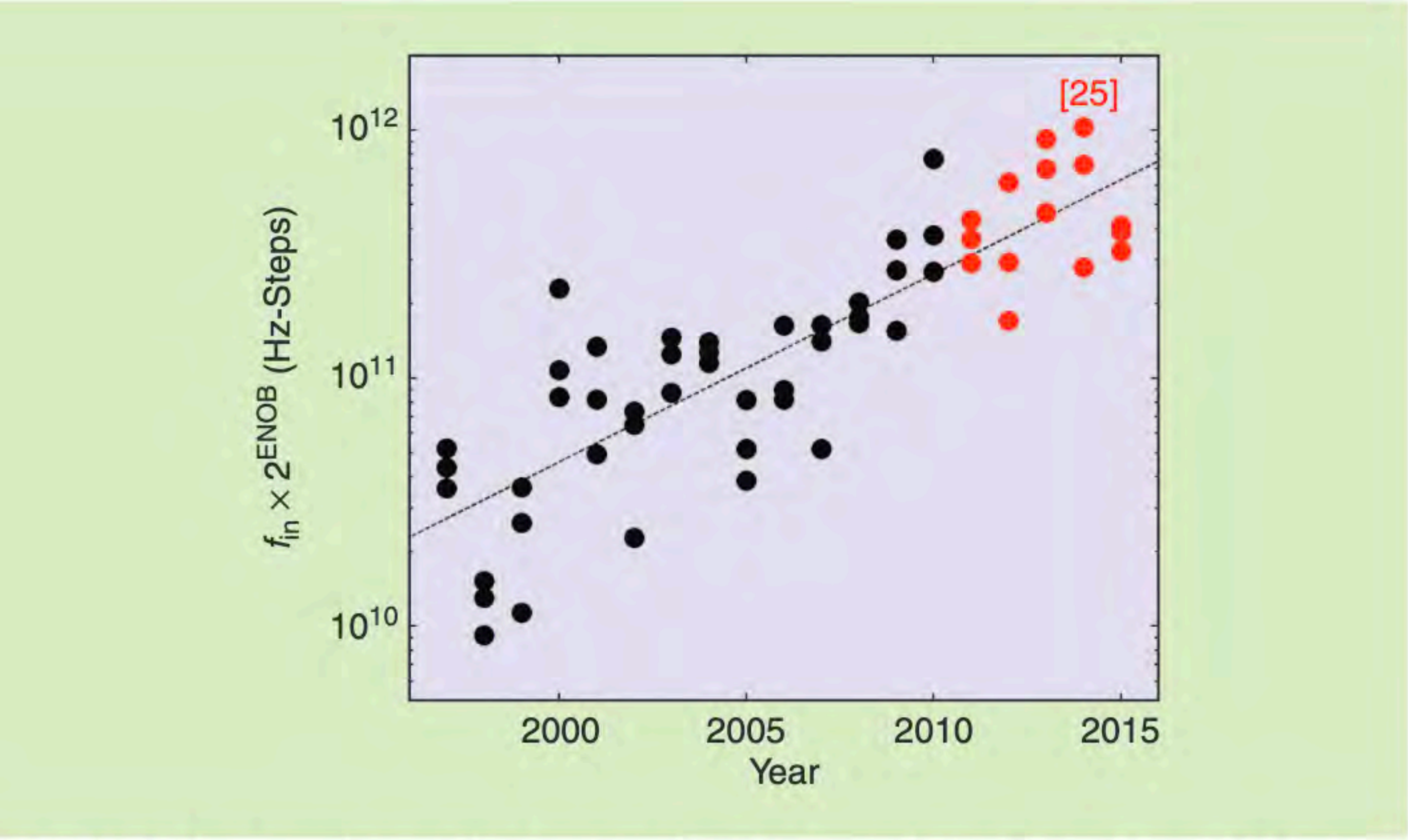
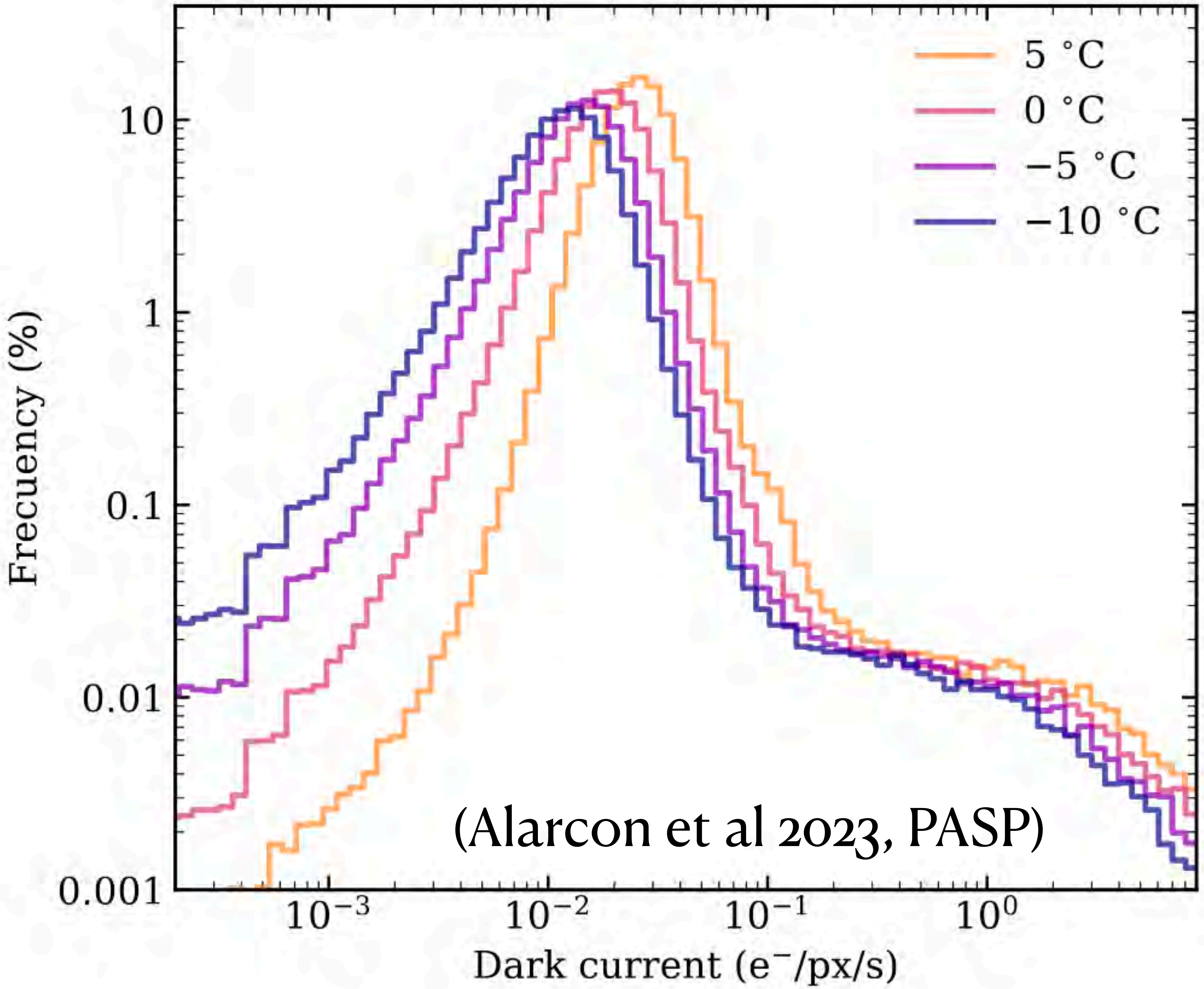


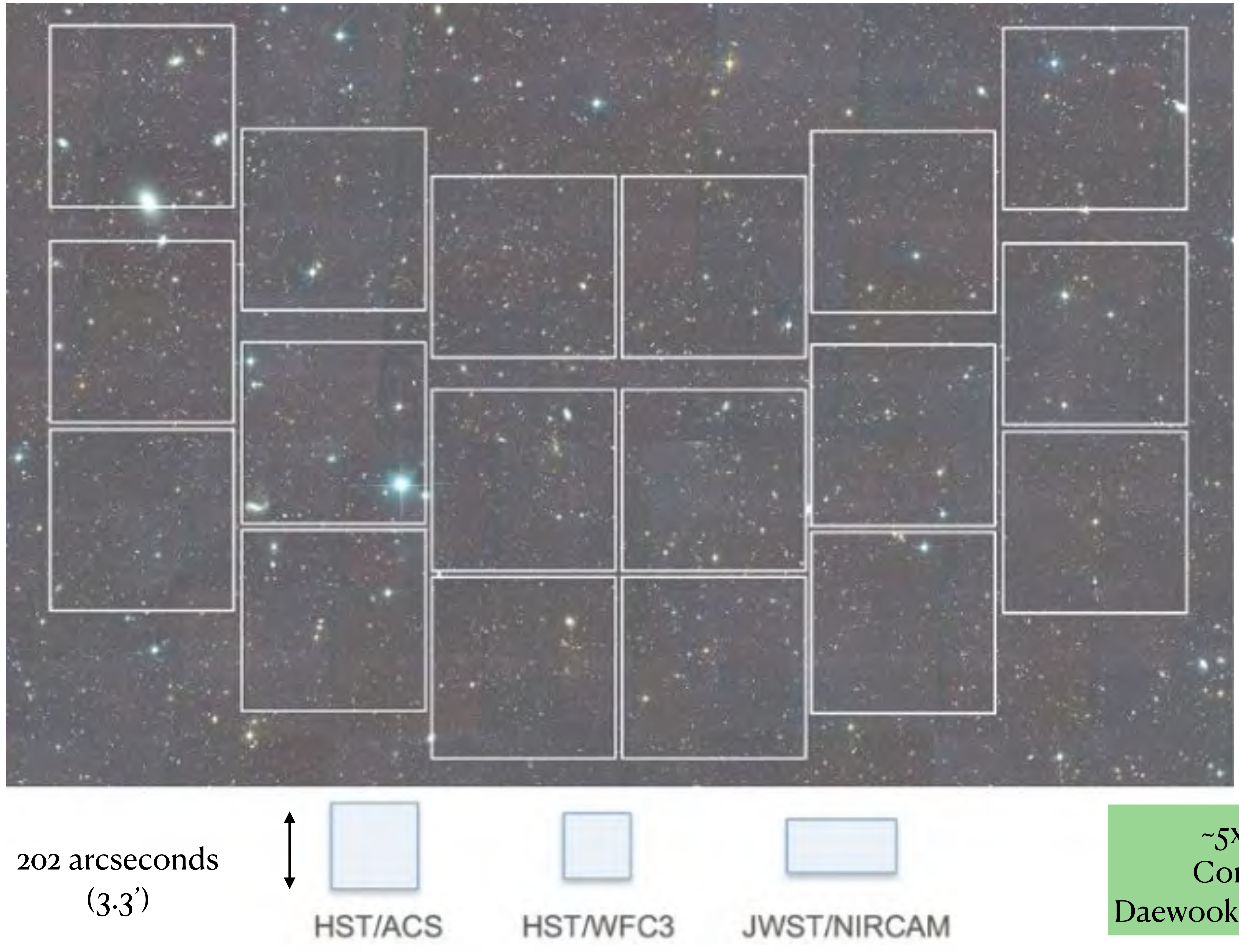
FIGURE 2: Fit to speed-resolution product of the top three designs in each year. The red markers indicate data reported after 2010. The fit line has a slope of 2x/4 years.

0.1109/MSSC.2015.2442393

Dark noise of IMX455



(Alarcon et al 2023, PASP)



~5x13 arcmin
Concept FOV
Daewook Kim’s talk (next)

Roman and TESS guide from the science cameras

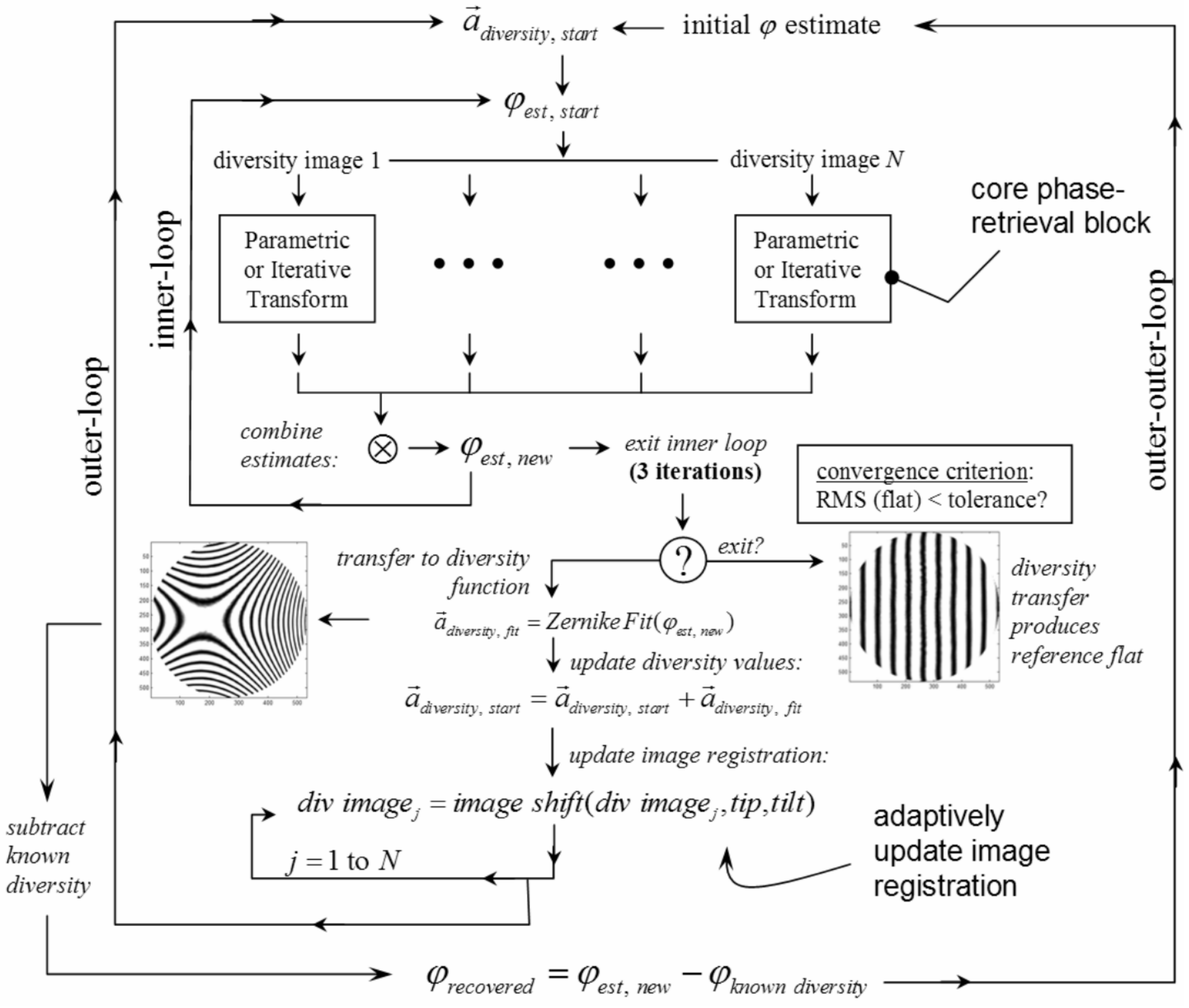
We propose guiding
+ continuous wavefront sensing

Figure 1. Comparison of Instrument Fields of View - Roman, Hubble, and James Webb Space Telescopes

Adapted from Bartusek et al 2022

10.1109/AERO53065.2022.9843415.

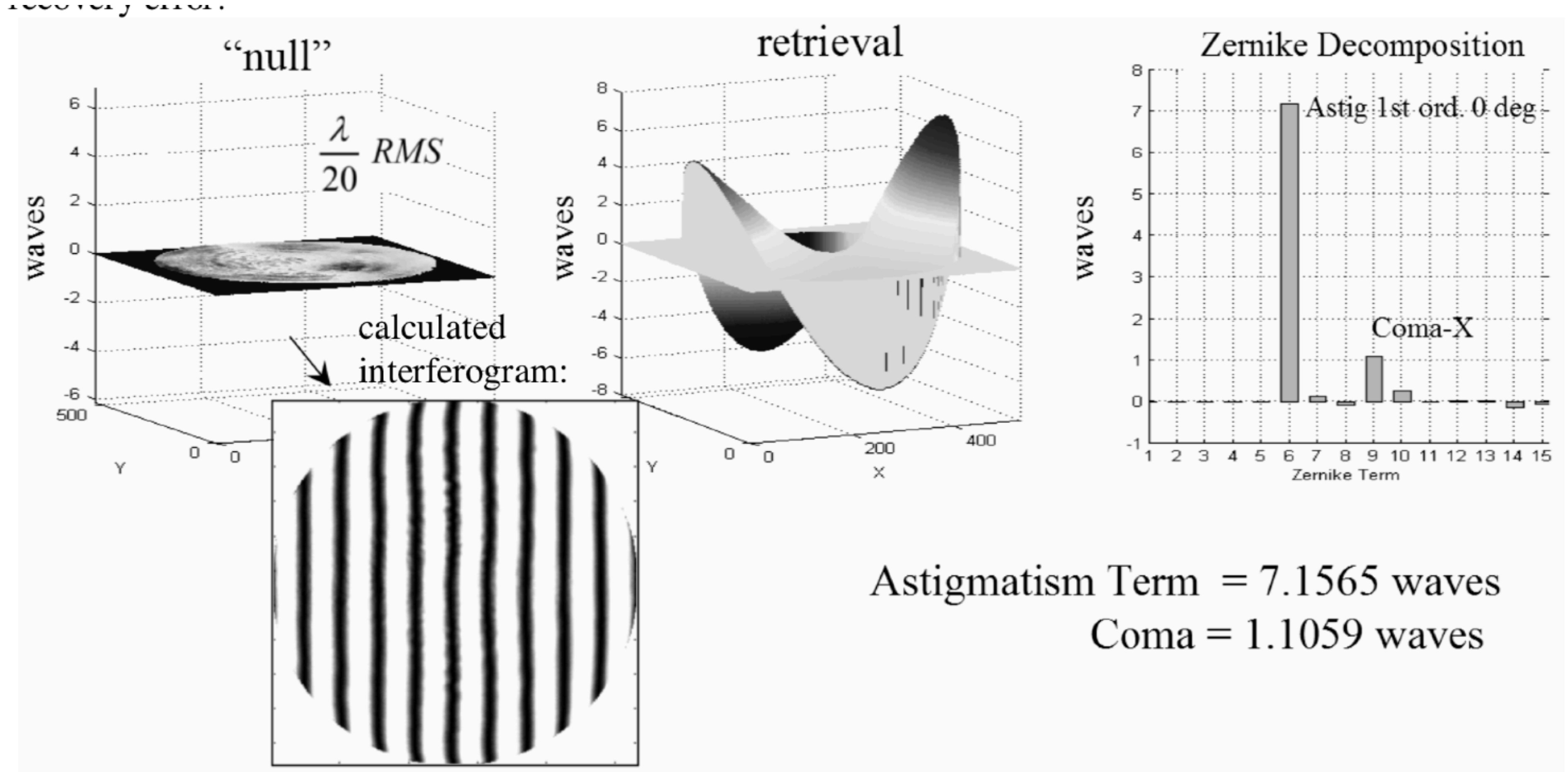
JWST phase retrieval (Dean et al 2006)



core phase-retrieval block

adaptively update image registration

Fig. 5. Hybrid Diversity Algorithm (HDA) block diagram.



Astigmatism Term = 7.1565 waves
Coma = 1.1059 waves

Fig. 3. Example of HDA phase estimation in the laboratory (1 λ = 633 nm).

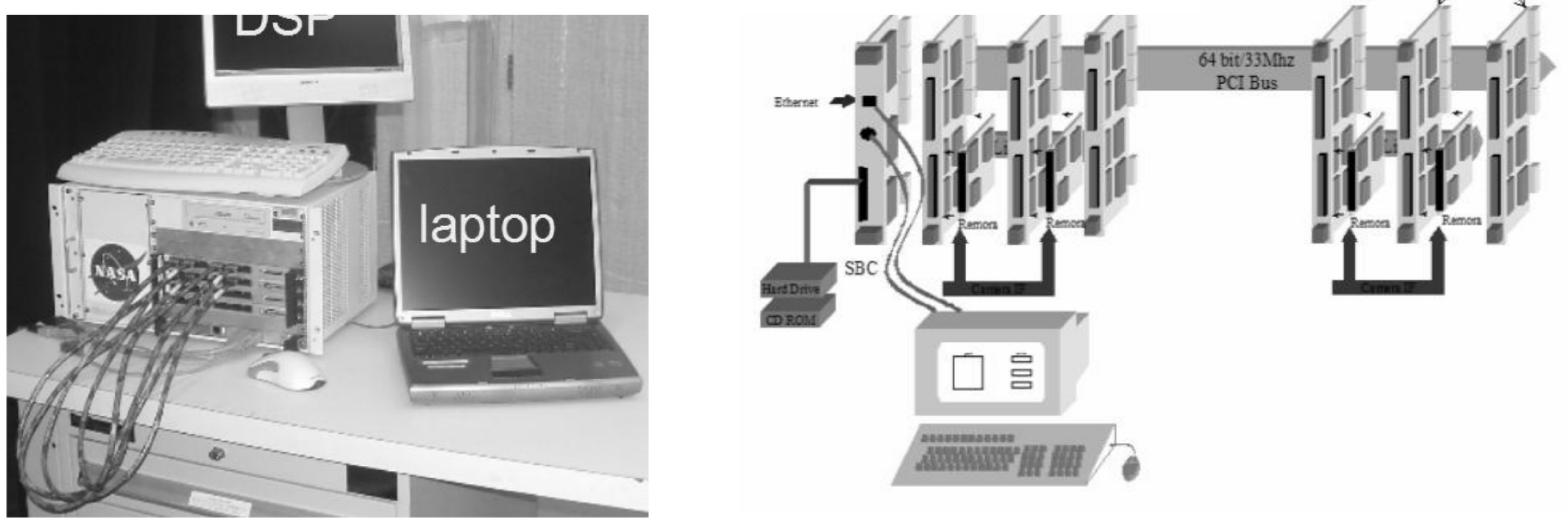


Fig. 15. High-speed parallel computing system for wavefront sensing.

10.1117/12.673569

Field of view

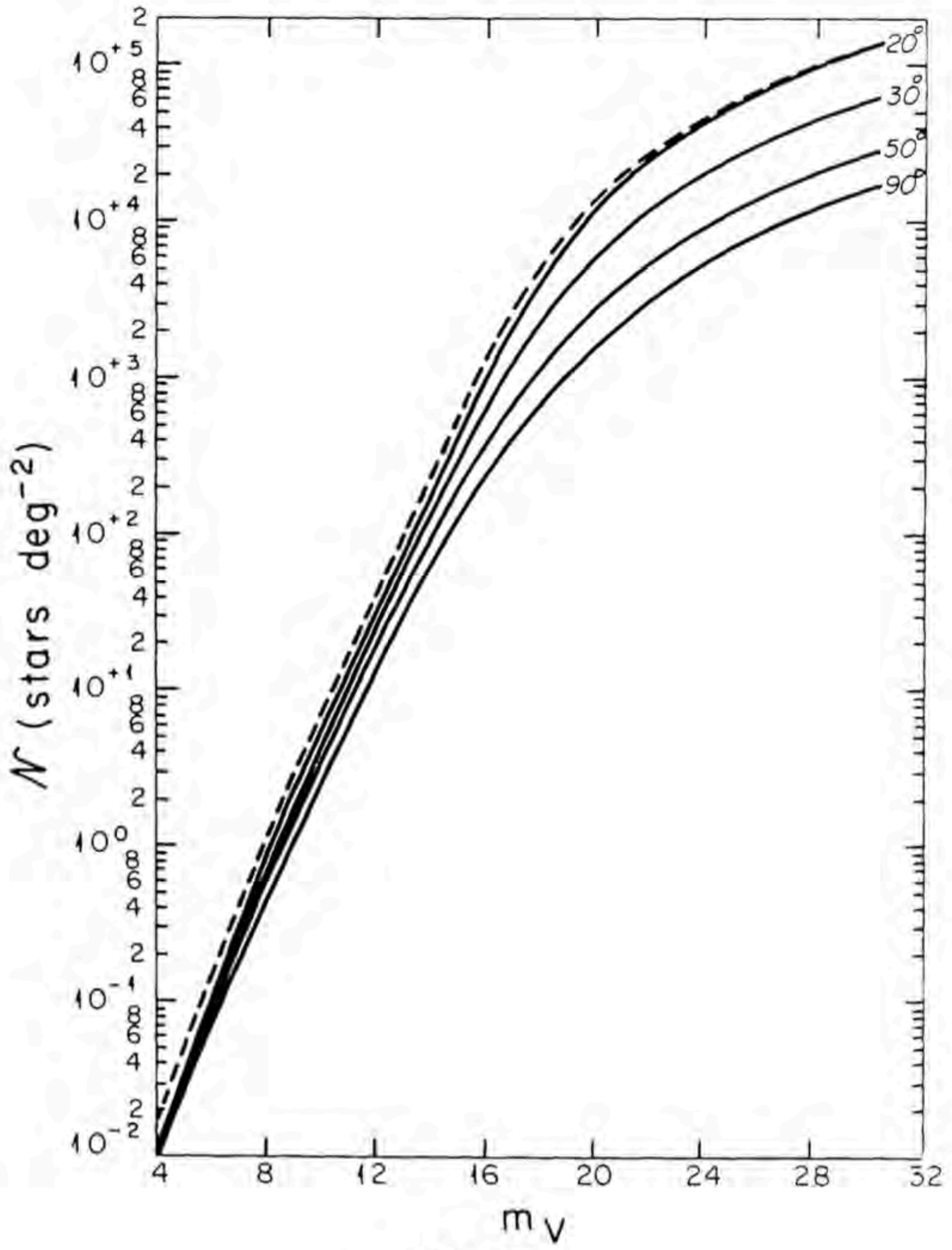
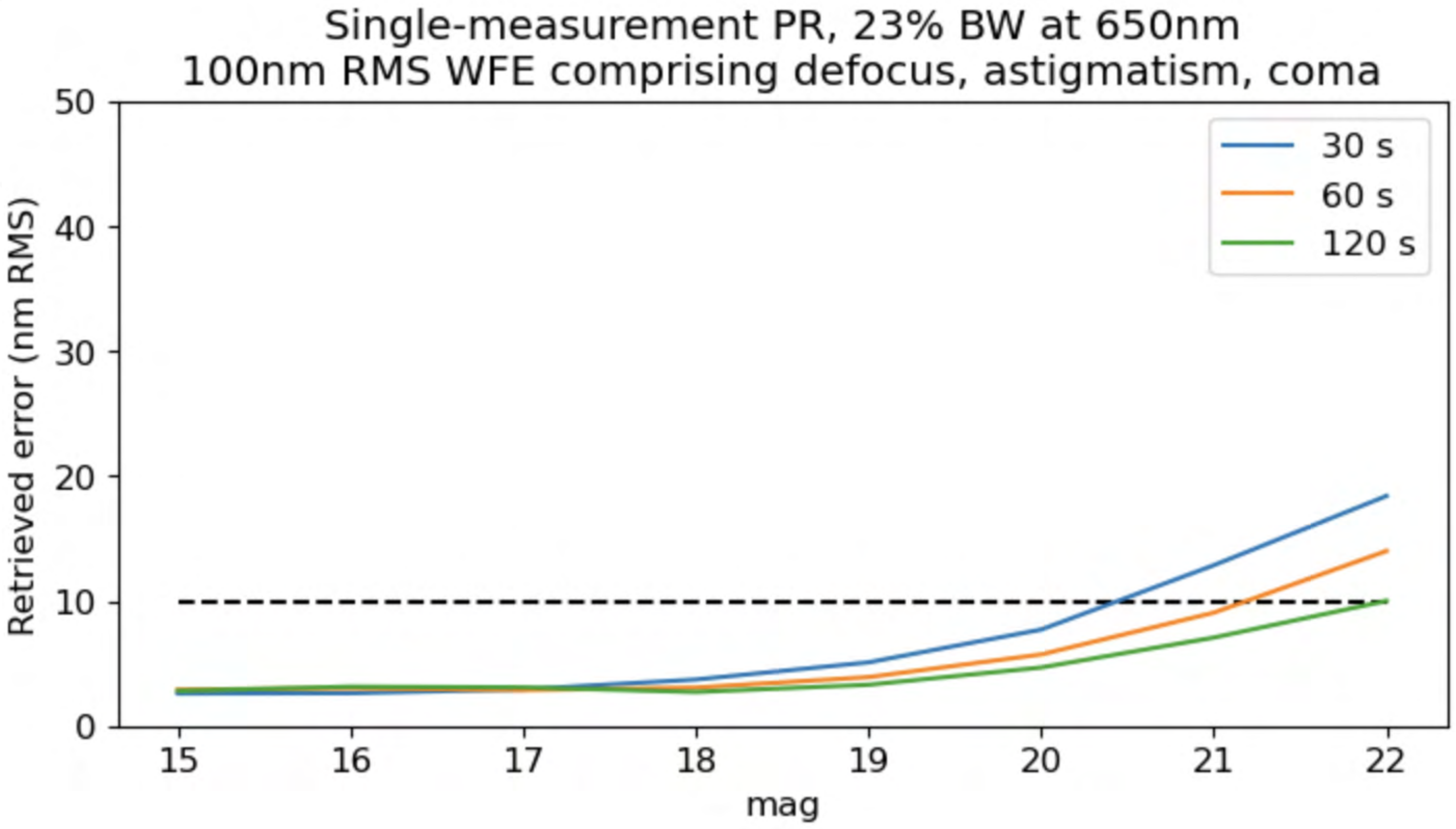
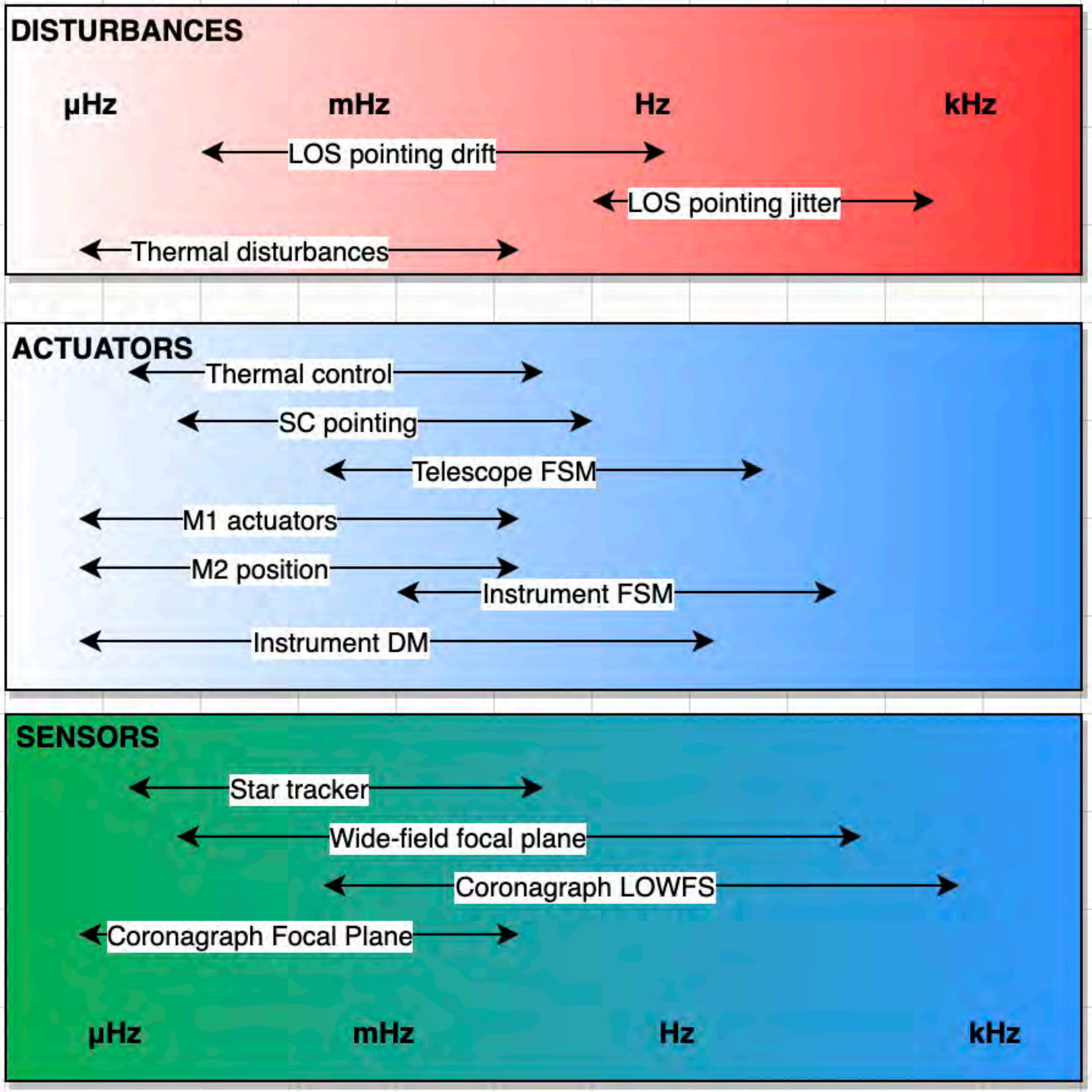


FIG. 4c



Bahcall 1980ApJS. . .44. . .73B



DISTURBANCES

μHz mHz Hz kHz

LOS pointing drift

LOS pointing jitter

Thermal disturbances

ACTUATORS

Thermal control

SC pointing

Telescope FSM

M1 actuators

M2 position

Instrument FSM

Instrument DM

SENSORS

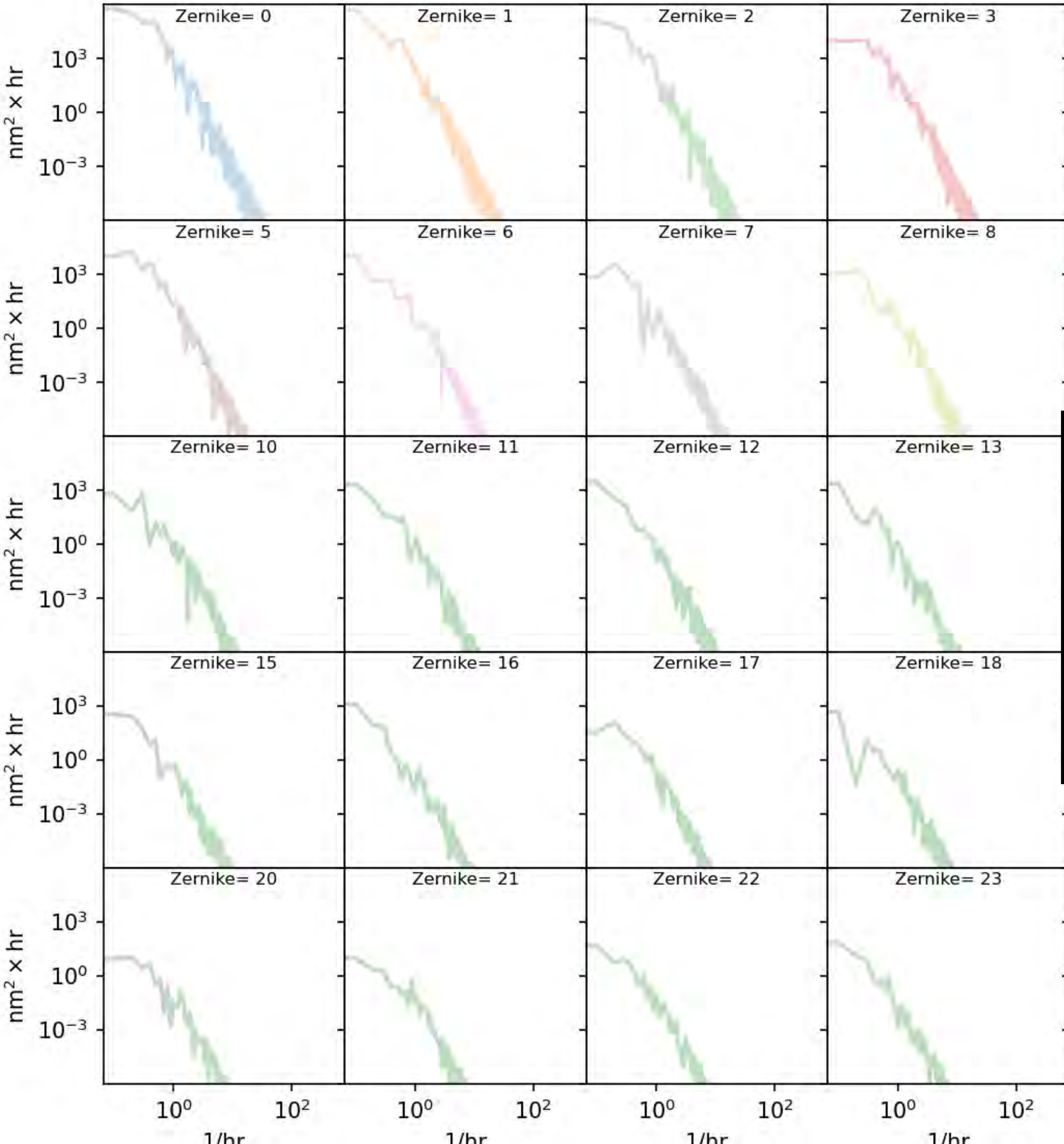
Star tracker

Wide-field focal plane

Coronagraph LOWFS

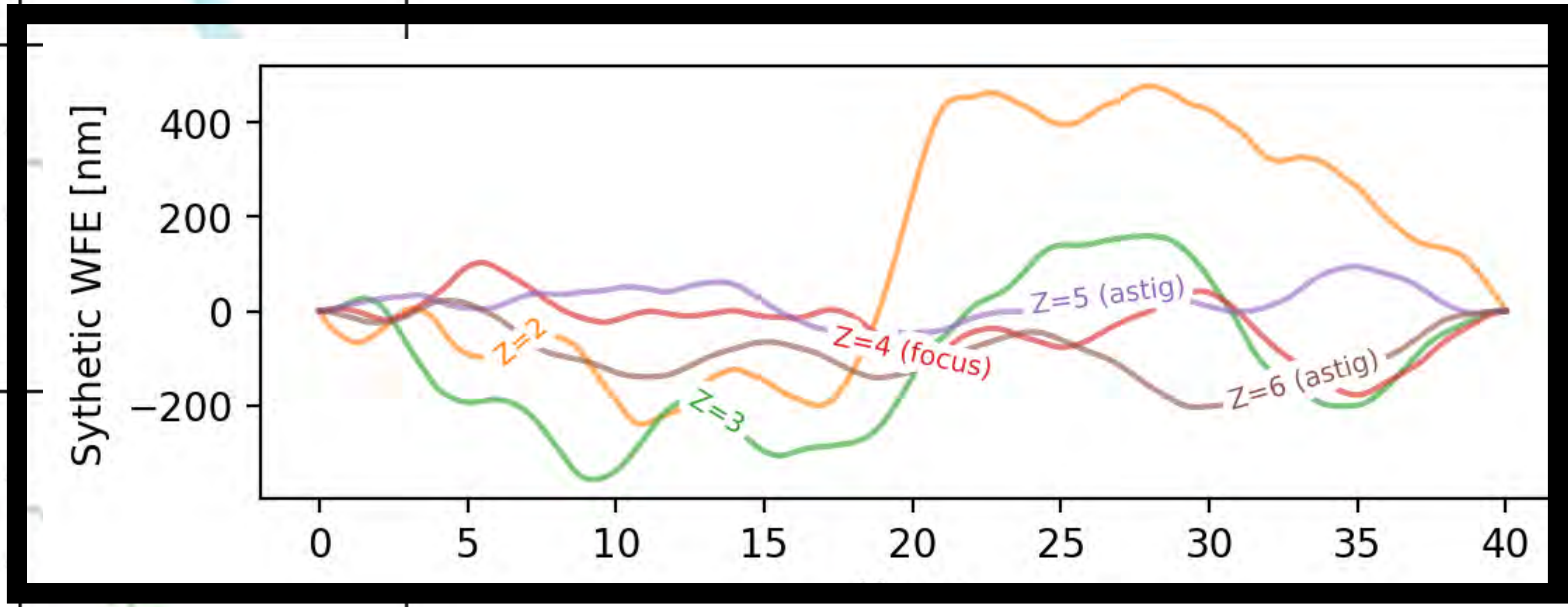
Coronagraph Focal Plane

μHz mHz Hz kHz



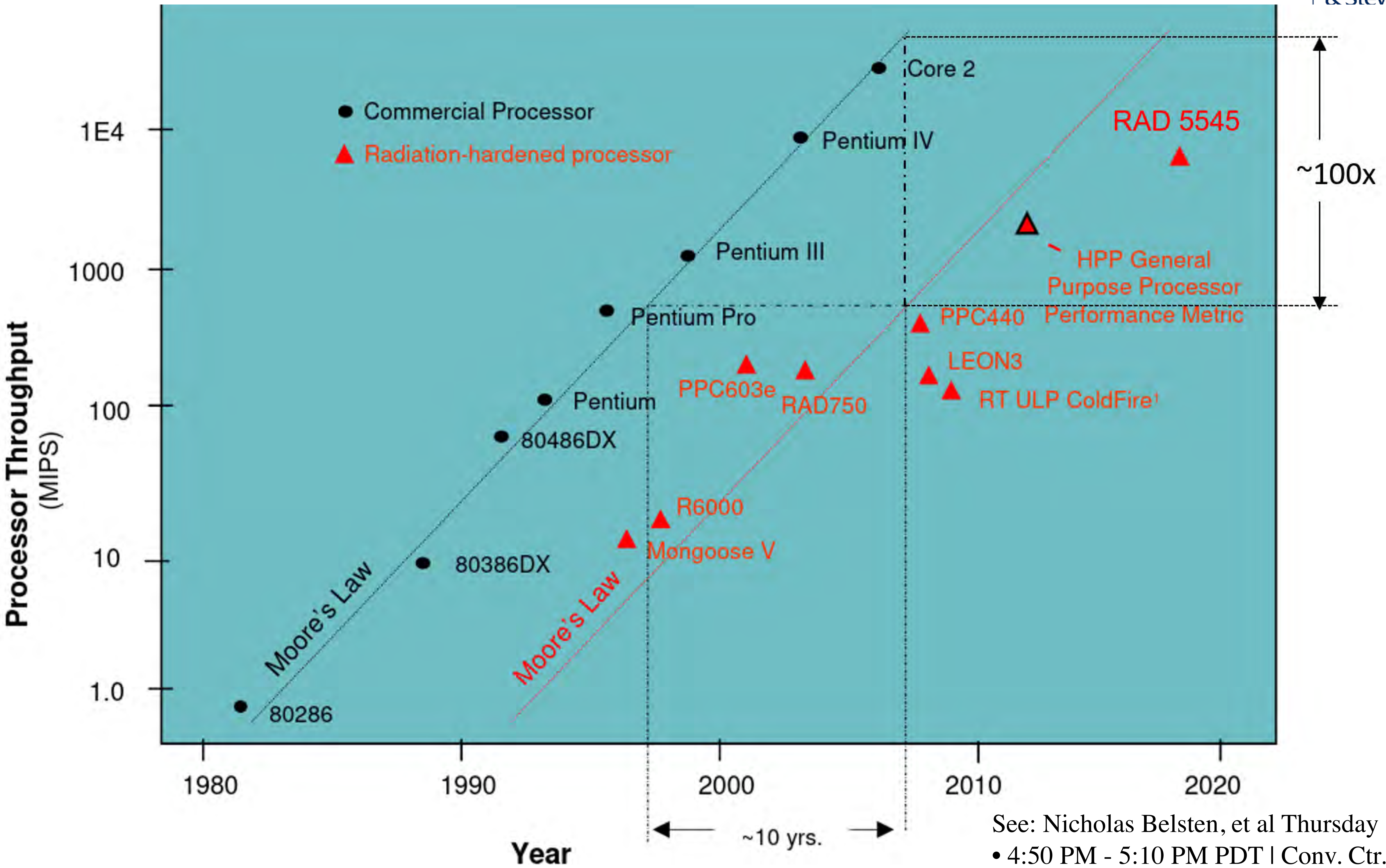
Lesson from ground-based AO: Parameterize the disturbance with PSDs (e.g. Males and Guyon 2019):

$$PSD(f) = \frac{\beta}{(1 + f/f_n)^\alpha}.$$

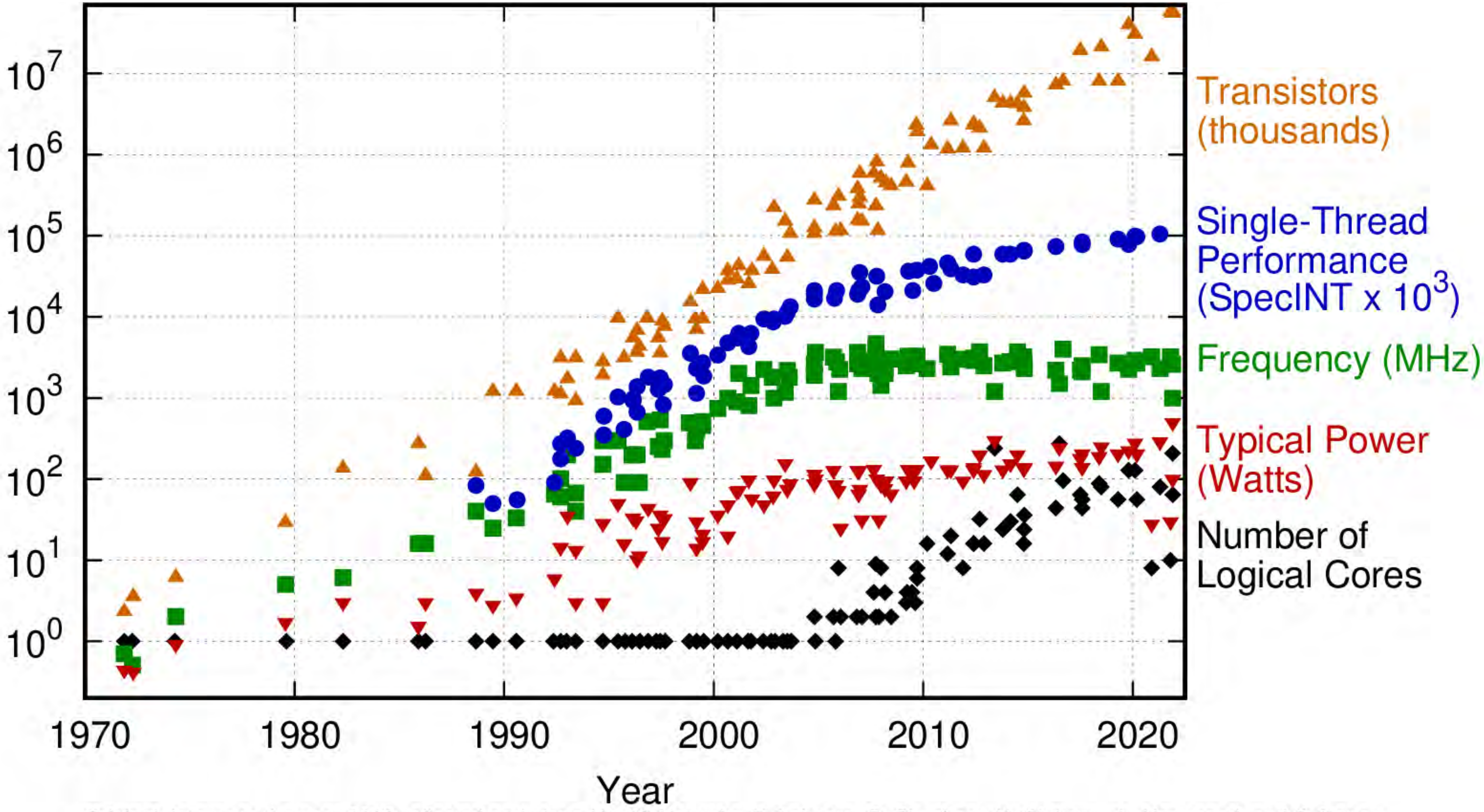


Ohara E6 has a room temperature CTE of ~27.8 × 10−6/°C (Hill et al 2013)

This allows us to put requirements on thermal control system ΔT and then extrapolate a optical residual



See: Nicholas Belsten, et al Thursday
- 4:50 PM - 5:10 PM PDT | Conv. Ctr. Room 11A



Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2021 by K. Rupp

https://github.com/karlrupp/microprocessor-trend-data

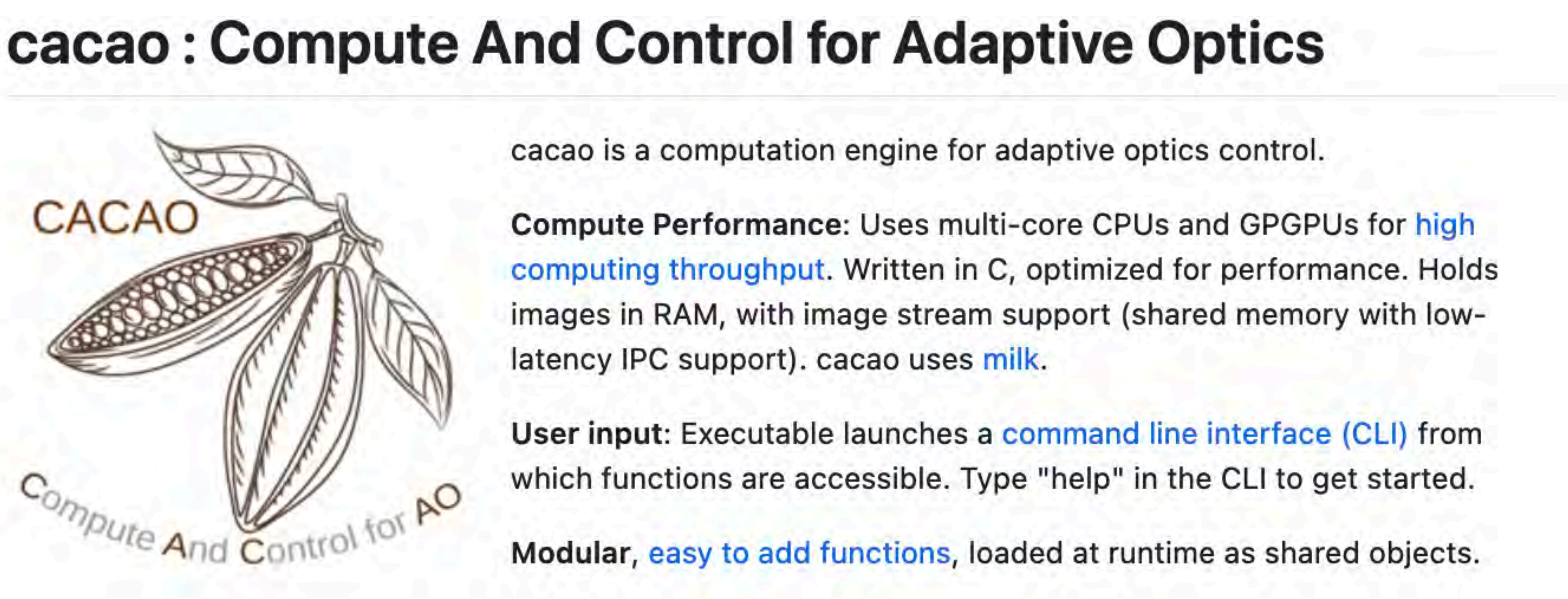
GPUs are going to space

Company	Component	Performance	Software Support	ECC protection	Radiation Results Available	Flight board available
NVIDIA	Xavier	Best	CUDA/Vulkan	Yes	Yes	No
NVIDIA	TX2	High	CUDA/Vulkan	Yes	Yes	Yes
AMD	V1605B	Medium/High	OpenCL/HIP/ Vulkan	Yes	Yes	Yes
ARM Mali-G72	HiKey 970 HiSilicon	Medium	OpenCL	No	No	No
AMD/Unibap	DDX-i5	Medium	OpenCL	Yes	Yes	Yes
AMD/Unibap	DDX-i10	Medium/High	OpenCL/HIP	Yes	Yes	Yes

Kosmidis, L., Rodríguez, I., Jover, Á., Alcaide, S., Lachaize, J., Abella, J., et al. (2021). GPU4S (GPUs for Space): Are we there yet. In *Proceedings of the European Workshop on On-Board Data Processing (OBDP), Online* (pp. 14–17). https://zenodo.org/record/5520783

GPUs in space allow us to leverage existing ground-base AO software built on CUDA

We've already begun work on code testing and reliability in public repos



cacao : Compute And Control for Adaptive Optics

cacao is a computation engine for adaptive optics control.

Compute Performance: Uses multi-core CPUs and GPGPUs for high computing throughput. Written in C, optimized for performance. Holds images in RAM, with image stream support (shared memory with low-latency IPC support). cacao uses milk.

User input: Executable launches a command line interface (CLI) from which functions are accessible. Type "help" in the CLI to get started.

Modular, easy to add functions, loaded at runtime as shared objects.

(Guyon et al 2018, Proc SPIE)

MagAO-X

ANT
ASCENDING NODE
TECHNOLOGIES

https://xwcl.science/

https://github.com/milk-org/ImageStreamIO
https://github.com/magao-x/

Then

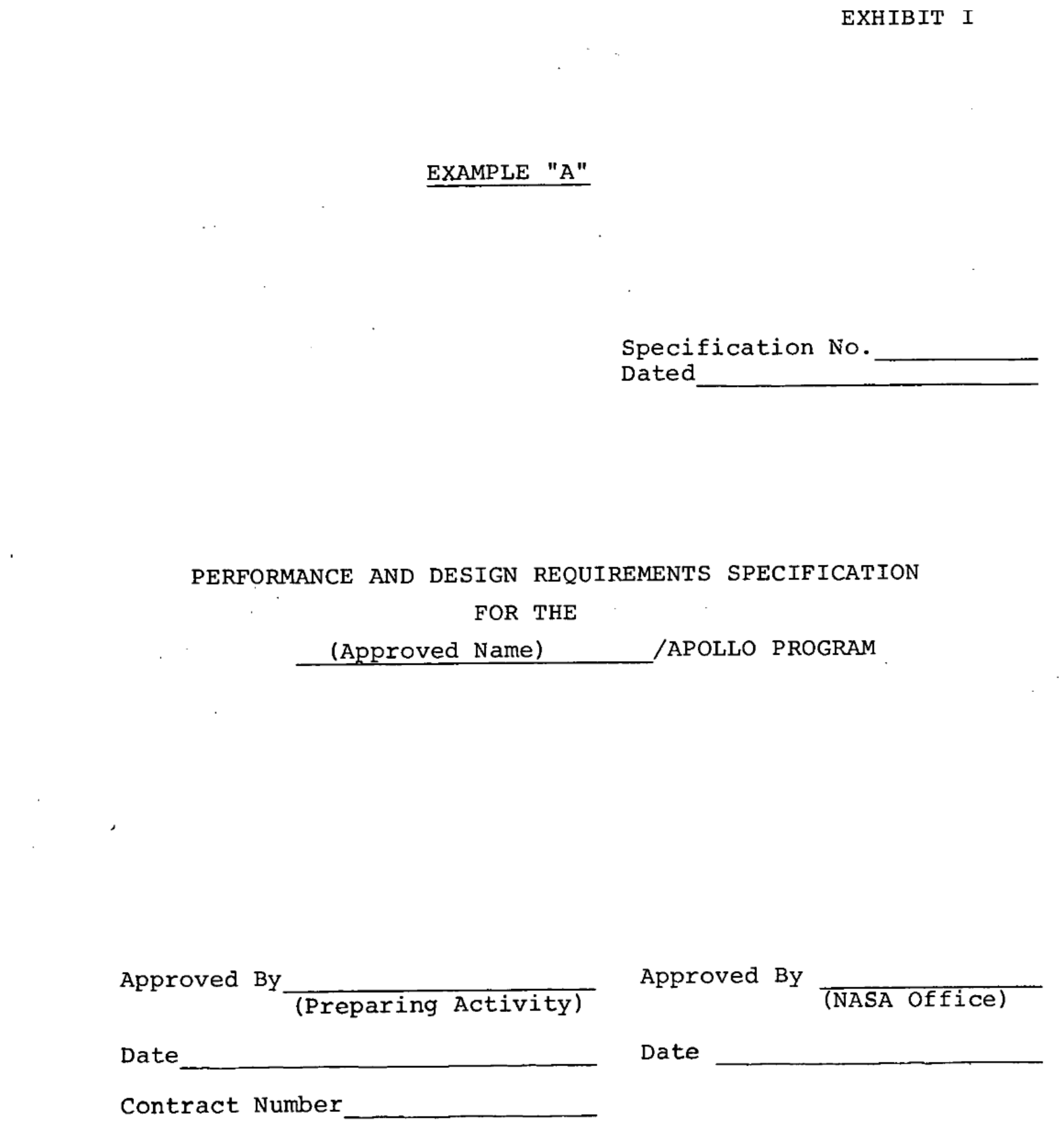


EXHIBIT I

EXAMPLE "A"

Specification No.____________
Dated__________________________

PERFORMANCE AND DESIGN REQUIREMENTS SPECIFICATION
FOR THE
____(Approved Name)________/APOLLO PROGRAM

Approved By____________________
(Preparing Activity)

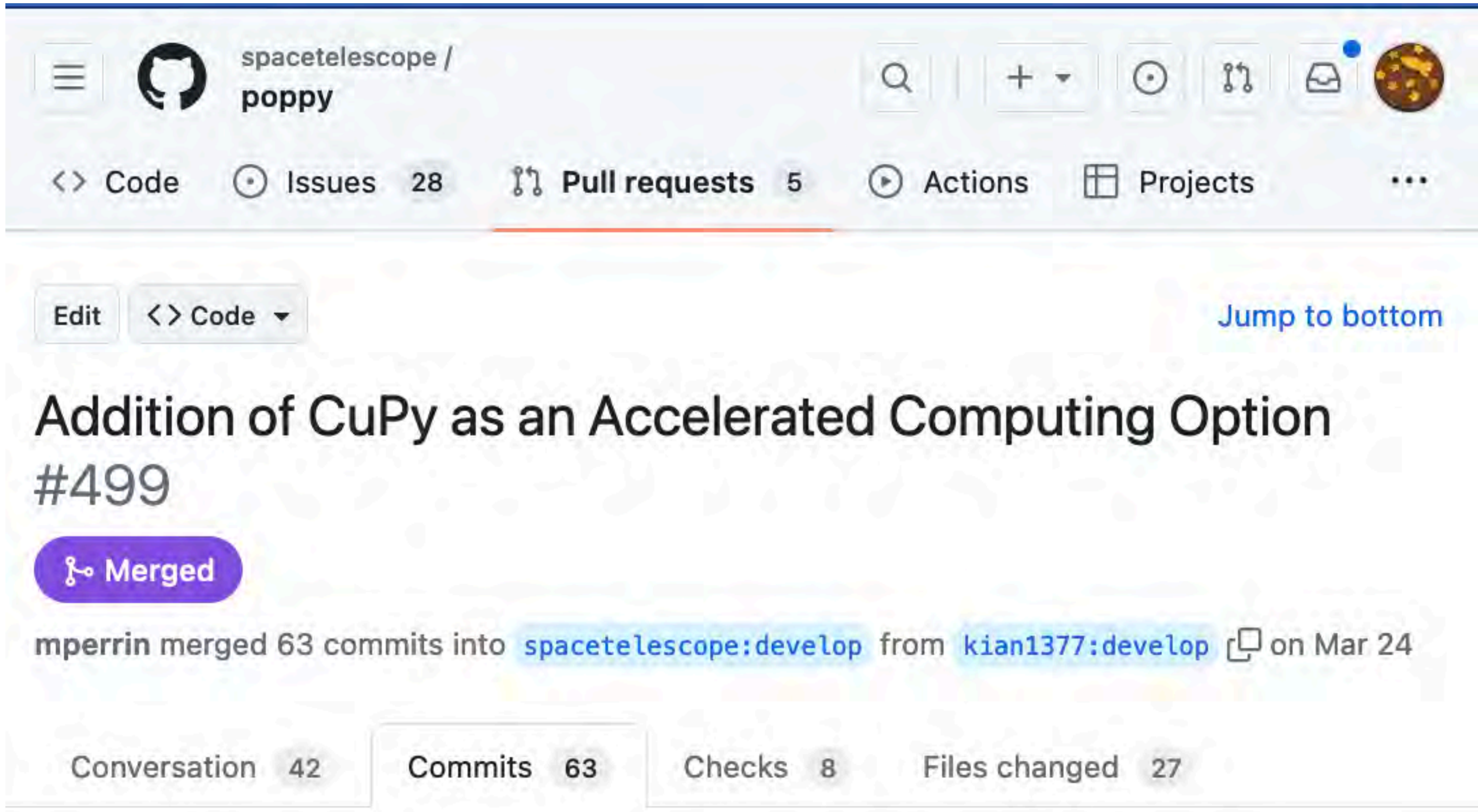
Approved By ____________________
(NASA Office)

Date____________________________

Date ____________________________

Contract Number__________________

Now



Addition of CuPy as an Accelerated Computing Option #499

mperrin merged 63 commits into `spacetelescope:develop` from `kian1377:develop` on Mar 24

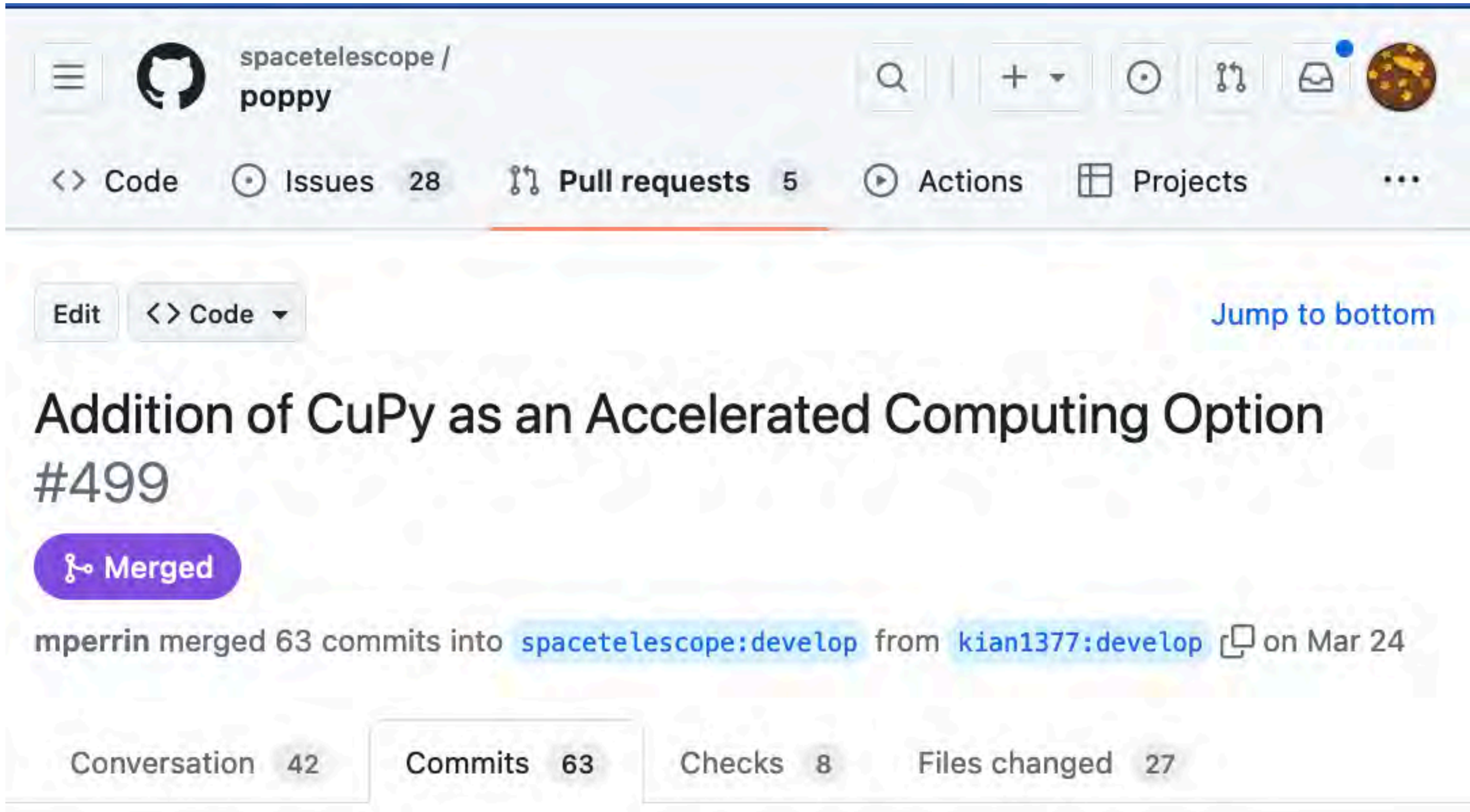
https://github.com/spacetelescope/poppy/pull/499/commits

https://www.ibiblio.org/apollo/Documents/Apollo%20Configuration%20Management%20Manual%20%281970%29.pdf

Git, not just for software

Doc management:

- automates tracking of all document changes, eliminating human error in change control.
- In use for legal document management (https://www.athennian.com/) and Excel (https://hdl.handle.net/1822/68730)
- Integrated with overleaf.com
- Used for requirements tracking (Browning 2014, Douglas 2018 (https://arxiv.org/abs/1807.05422)
- Requires cultural shift for non-software teams but many science teams are already comfortable (See “CAOTIC”, Iva Laginja et al, Proc SPIE 2022)



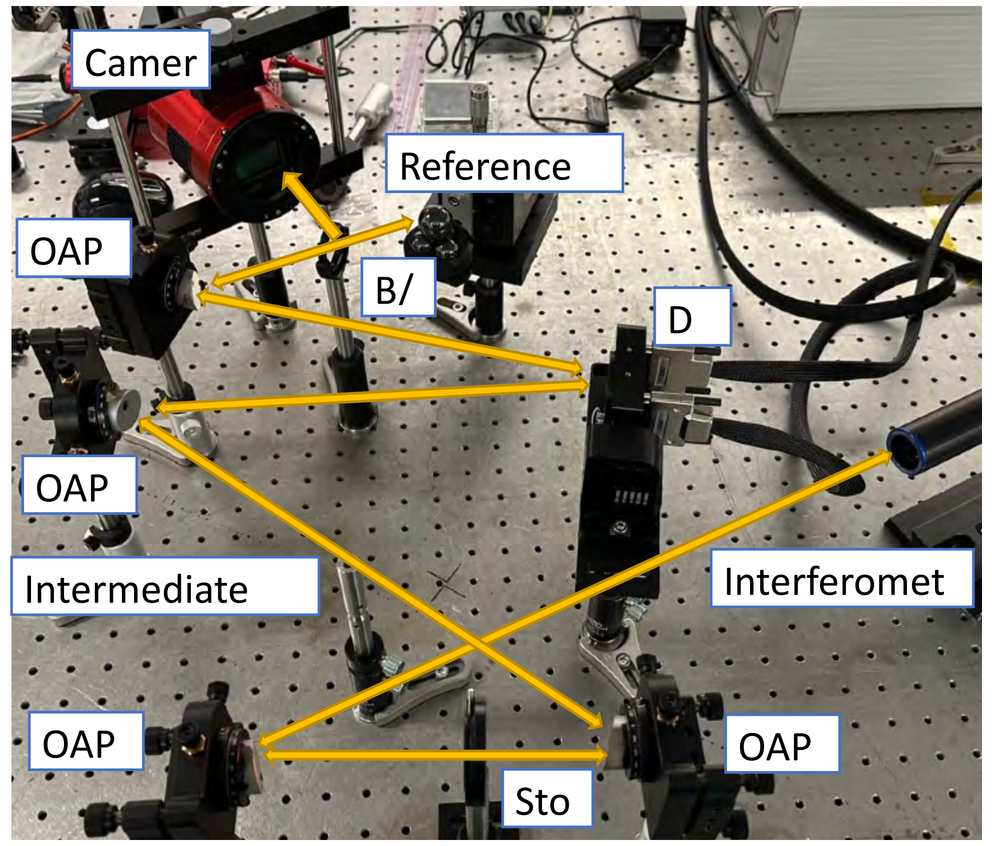
Addition of CuPy as an Accelerated Computing Option #499

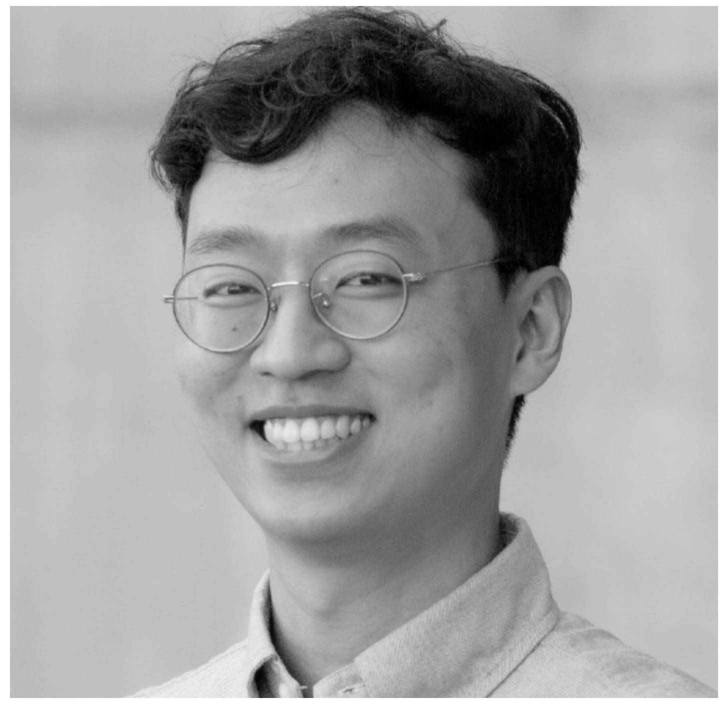
Merged

mperrin merged 63 commits into `spacetelescope:develop` from `kian1377:develop` on Mar 24

What’s next today?

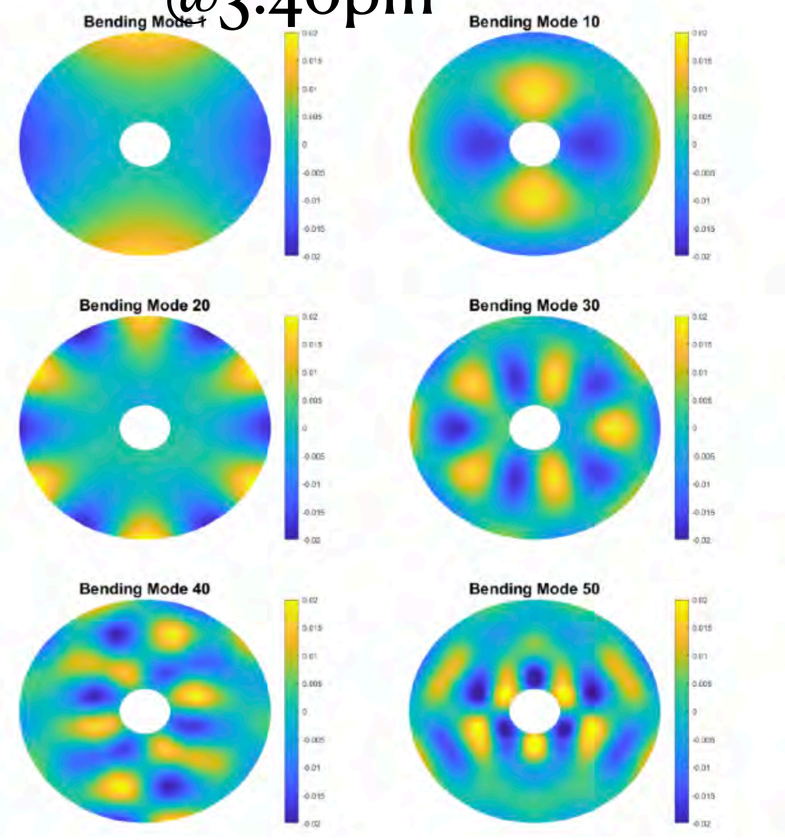
Lab validation
@3:20pm





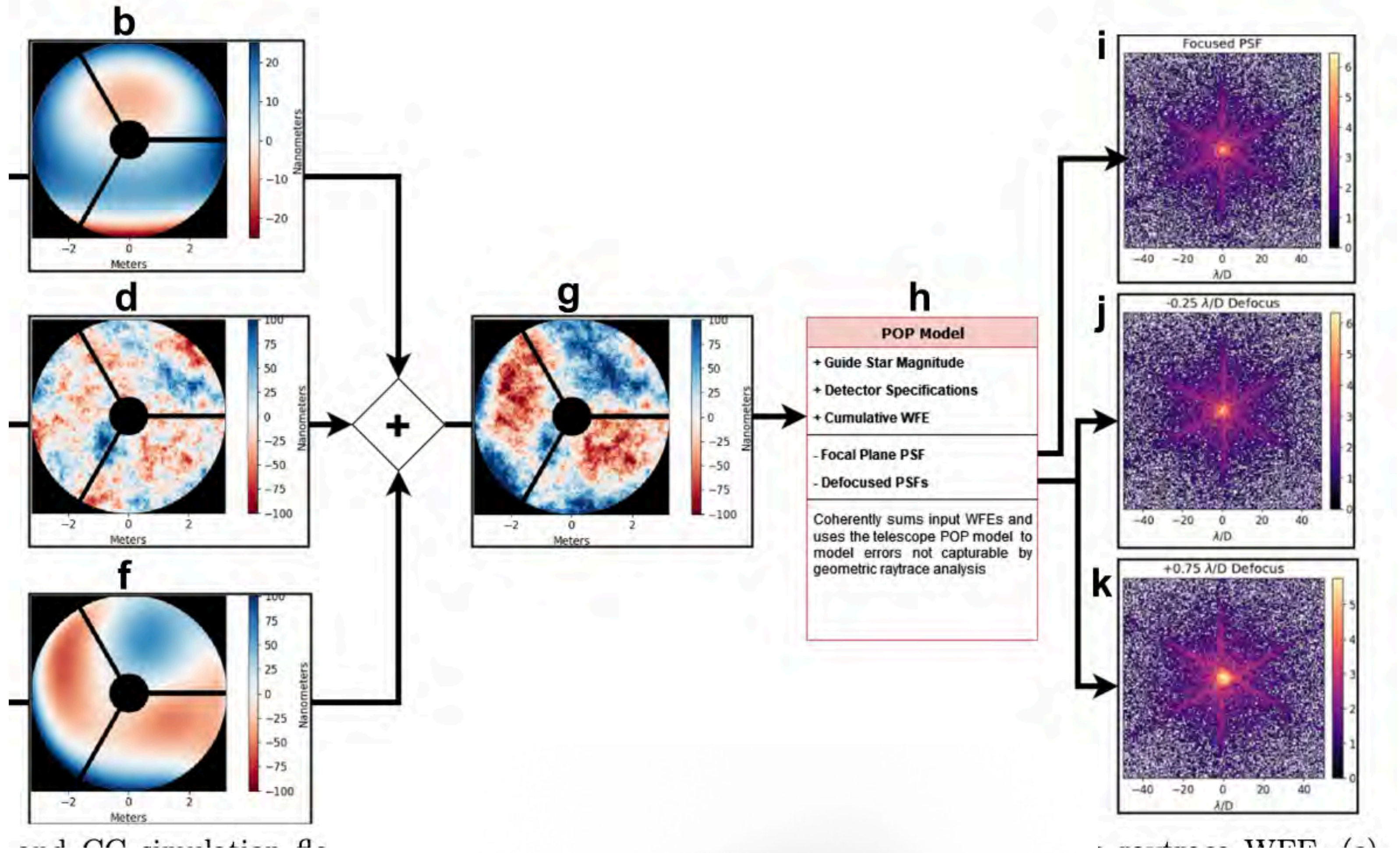
- Dr. Hyukmo Kang,

Mirror bending modes — fitting a basis set
@3:40pm



Solvay Blomquist

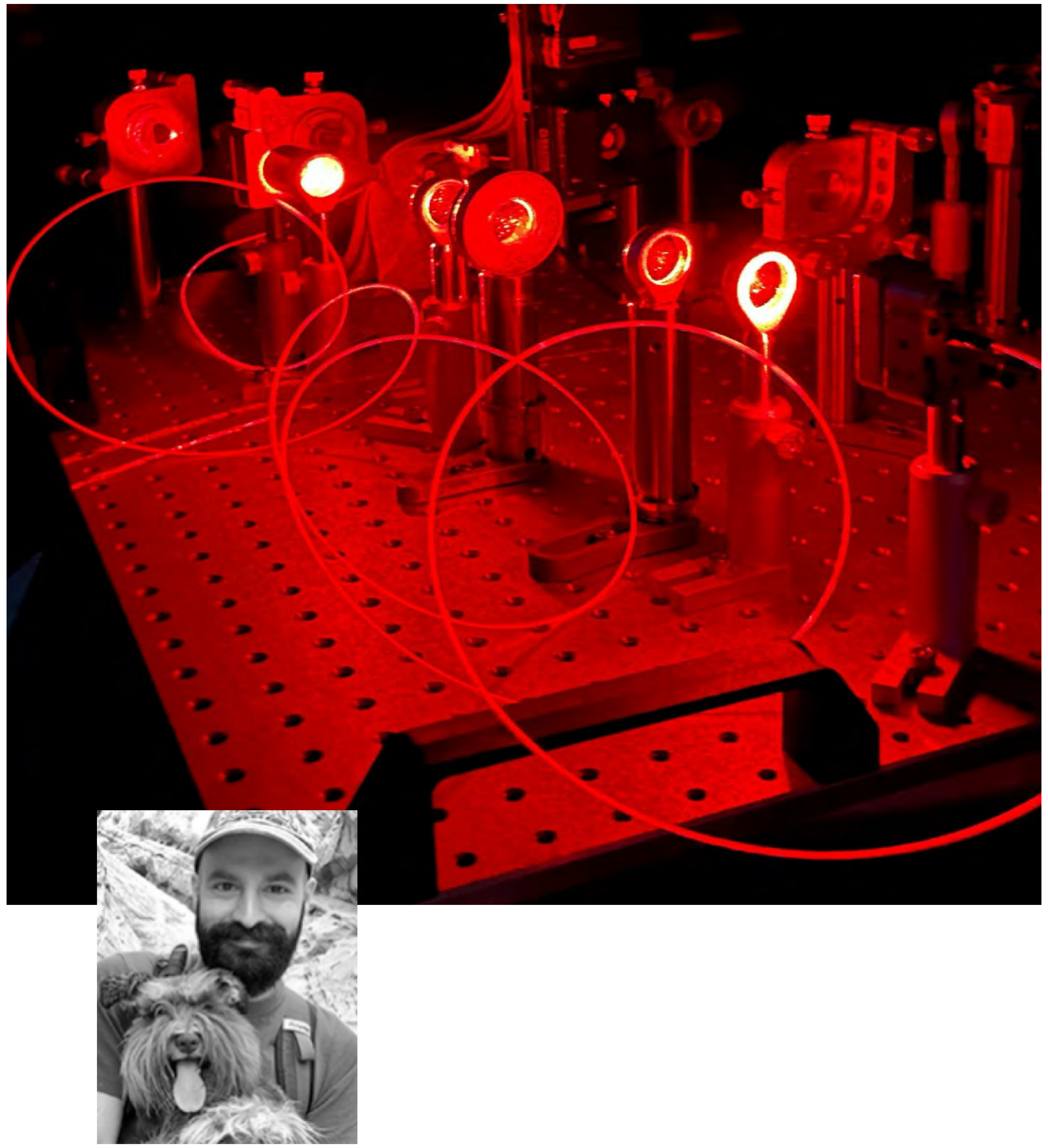
End-to-End simulation
@4pm



Kevin Derby

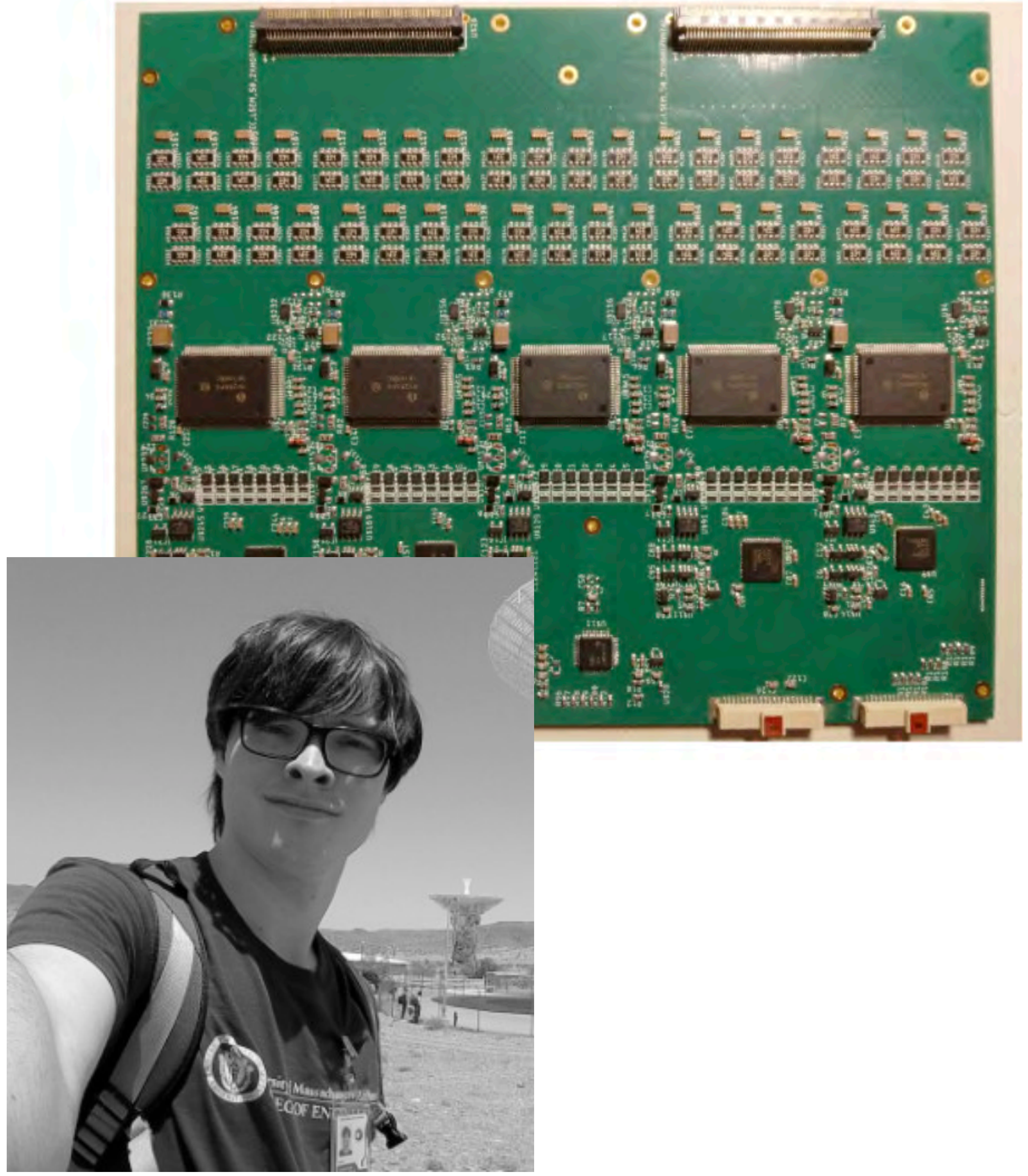
What's else?

Electronics testing for
Vacuum coronagraph testbed
@4:20pm



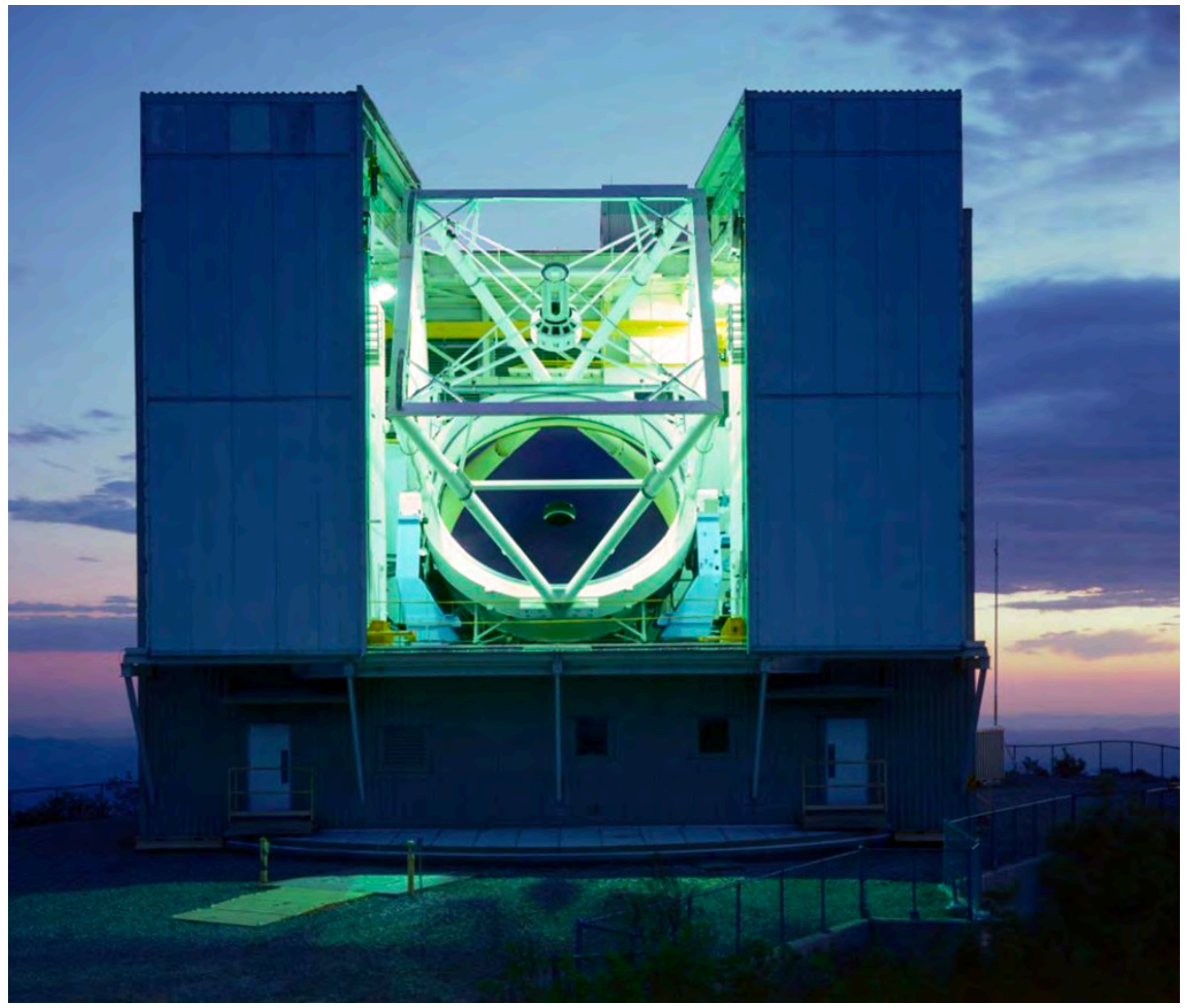
- Dr Kyle Van Gorkom

Flight DM electronics design
(Yesterday, see SPIE proceedings)

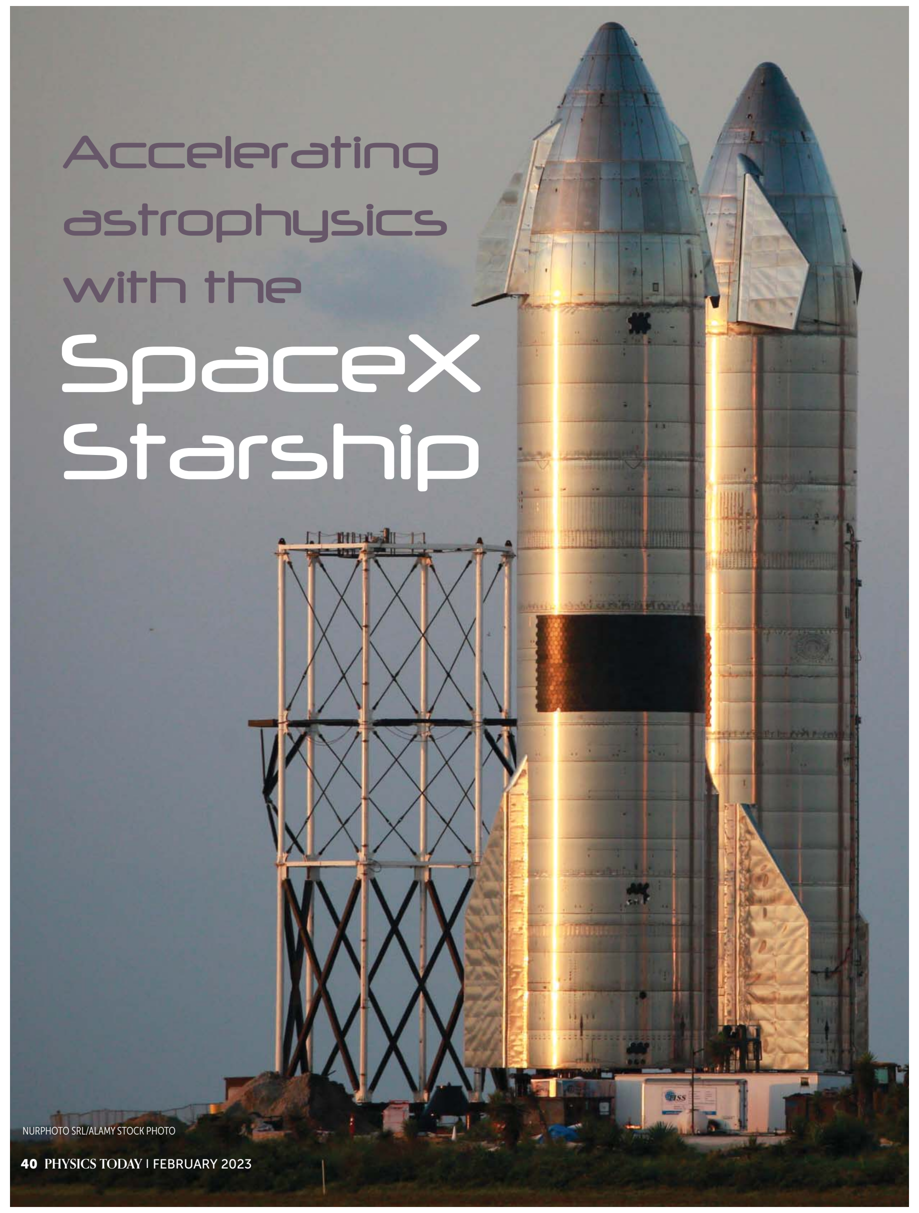


- Dr Christian Haughwout

+ next two talks on optical design



+



Accelerating astrophysics with the

SpaceX Starship

NURPHOTO SRL/ALAMY STOCK PHOTO

40 PHYSICS TODAY | FEBRUARY 2023

=?

Dedication

Dr. Michael Logan Lampton
(1941-2023)

Dr. James Breckinridge
(1939–2022)

Portions of this research were supported by funding from the Technology Research Initiative Fund (TRIF) of the Arizona Board of Regents and by generous anonymous philanthropic donations to the Steward Observatory of the College of Science at the University of Arizona.